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Proceedings of the 3rd

Sustainability *in* Ship Design *and* Operations

Conference

November 6-7, 2023
Volume 1 Part 1: Papers

Conference Information

The Sustainability in Ship Design and Operations conference aims to bring together industry and academia to discuss the concepts, technologies, case studies, and success stories related to sustainability in ship design and the greater maritime industry. Academic papers and technical presentations are shared by experts and practitioners, bringing innovative ideas and information to a wider audience. The papers and presentations are collected in these conference proceedings. Part 1 publishes submitted and reviewed technical papers while Part 2 gathers all presentation slide decks.

The ultimate goal of maritime sustainability is to create and operate ships and infrastructure that are more efficient and environmentally friendly, making the maritime industry more sustainable in the long term.

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LastName, F.I., Second Author, "Title of article," *Proceedings of the 3rd Sustainability in Ship Design and Operations Conference*, Glen Cove and Kings Point, NY, November 6-7, 2023, Volume 1 Part 1, pp. XX-XX.

Table of Contents

Coastal And Inland Shipping In The Northeast US: A Plan For Expanding The Fleet And Zero Carbon Shipping.

Steven Woods

Abstract: Any expansion of Sail Freight and sustainable maritime coastal shipping in the United States will need to be made within the next decade, and preferably in a rational manner with mutually supporting projects. Without a coherent plan around current cargo and passenger flows, and taking advantage of existing projects and bordering waters, the success of any new project is less probable. New sail freight endeavors which can use both mutual support networks and the published plan as part of their business case when seeking investors will have a significant advantage.

By ensuring a plan is laid out and publicized early, alongside supporting handbooks and training programs, there is a higher chance of overall success. Further, the carbon emission savings impact of mutually supporting maritime transport projects is likely to be more significant than a number of independent projects which are unable or unwilling to cooperate.

The proposed plan covers the US Coastline from Maine to the Delaware River, and inland waterways such as the New York Canal System, Great Lakes Exclusive. The proposed deployment of infrastructure uses established and published open-source designs, such as spud barge ports, or existing commercial or recreational infrastructure capable of handling small scale cargo operations. Scaled out through 2030, this plan gives the latest desirable date for each expansion, a preliminary look at the required types of vessels, capital expenses, and potential cargos for each portion of the operational theater. By expanding from the only region with an operational sail freighter, mutual support links are maintained. With this proposed plan sketched out, a coherent investment strategy can be developed for launching more vessels, creating the appropriate sailor training resources, and recruiting supporters such as maritime academies, community colleges, and cargo owners. Without this type of strategic planning, there is little chance for isolated projects to succeed on the scale necessary to capture a large volume of coastwise trade during the coming energy transition.

Keywords: Sustainable Transportation, Sail Freight, Coastal Trade, Small Vessels, Energy Transition.

The only region of the US currently home to a sustainable maritime cargo initiative is the Hudson Valley with the Schooner *Apollonia*,[1] making this region the natural starting point for a national revival of sustainable maritime trade. This said, expansion of this trade should be encouraged in a particular sequence, specifically designed to maximize mutual support and thus economic survivability of the enterprises. Using small vessels and relatively short packet routes as the proving ground for solar, electric, and wind propulsion for coastal and inland maritime trade, this model also democratizes the fields of cargo transportation and energy,[2] and sheds a polytechnic[3] outlook on transportation for the anthropocene. This

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[1] Apollonia is only considered here for the simple reason that the actual sustainability and carbon intensity of maritime operations by Harbor Harvest has not undergone peer-reviewed evaluation. Until this is accomplished, their sustainability compared to other efforts remains in doubt.

[2] Energy Sovereignty is very rarely linked to sustainability, as Food Sovereignty is linked to food and social justice, but will become progressively more important as the energy transition continues. Food sovereignty for urban populations is effectively impossible without energy and transportation sovereignty to move the food from rural to urban regions. See: Pablo Cotarelo, David Llistar y Alfons Pérez, Àlex Guillamon, Maria Campuzano, And Lourdes Berdi. "Defining Energy Sovereignty" *El Ecologista, Ecologistas en Acción Magazine* n° 81, summer 2014 http://www.ecologistasenaccion.org

[3] For more information on polytechnics, see: Lewis Mumford. *The Pentagon Of Power: The Myth Of The Machine, vol two.* New York: Harcourt Brace Jovanovich, 1974

is a plan which admits of participation by both professional sailors and amateurs interested in taking practical and immediate action to counter the climate crisis. To successfully scale to a large operation making a significant impact on climate forcing emissions in the northeast, there will have to be an eventual construction of dedicated larger vessels, professional crew trained and recruited, and some degree of professionalization, but this need not displace non-professional operations, especially on shorter routes from ports of aggregation that larger vessels will operate from. The ideal outcome from this plan over the next generation would be integration of maritime transport in the Northeast to the point it becomes integrated seamlessly into the lifeways of the region once again, with a lively small vessel fleet and a low environmental impact.

The specific benefits of coastal and canal trade under sail and using electric vessels has been explored elsewhere and will not be covered in detail here. Suffice it to say the reductions to carbon emissions, fuel demand, roadway congestion, noise pollution, air pollution, traffic casualties,[4] infrastructure-based emissions, and other hazards are significant, and if scaled could have a major impact on the carbon emissions, public health impacts, and economics of transportation in the Northeast.[5] With roadway congestion costing 18.2 Billion dollars in the New York Metro Area alone in 2019, it can be plainly seen that removing vehicles reduces congestion, as 2020 resulted in a mere 11.2 Billion dollars under the effects of the COVID-19 Lockdowns.[6] Further, the number of hours lost annually to congestion per commuter in the New York Metro Area dropped from 96 to 56 in the same period.[7] This congestion wasted just short of 336 million gallons of fuel in 2019, with all the associated greenhouse gas, particulate, and noise emissions which go with this expenditure of fuel.[8] The benefits for towns and cities in creating a climate resilient working waterfront are similarly discussed elsewhere, but are wide-ranging; economic, social, financial, and environmental benefits are to be found in resilient combined working and recreational waterfronts.[9] This plan aims to bring these benefits to the Northeast United States in an expanding and reliable manner over the coming years.

The boundaries of this plan are defined as the six New England States, New York, and New Jersey, Great Lakes Exclusive. Each of the Great Lakes needs their own sail freight plans,

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[4] Morency, Patrick, Lise Gauvin, Céline Plante, Michel Fournier, and Catherine Morency. "Neighborhood Social Inequalities in Road Traffic Injuries: The Influence of Traffic Volume and Road Design." *American Journal of Public Health.* June 2012, Vol 102, No. 6. 1112-1119. doi: 10.2105/AJPH.2011.300528.

[5] Woods, Steven, and Sam Merrett "Operation of a Sail Freighter on the Hudson River: Schooner Apollonia in 2021." *Journal of Merchant Ship Wind Energy* 2 March 2022. www.researchgate.net/publication/358971392

[6] BTS "Table 1-72: Highway Congestion Cost." *National Transportation Statistics*. Washington: Bureau of Transport Statistics, 2023.

[7] BTS "Table 1-69: Annual Person-Hours of Highway Traffic Delay Per Auto Commuter" *National Transportation Statistics*. Washington: Bureau of Transport Statistics, 2023.

[8] BTS "Table 4-28: Annual Wasted Fuel Due to Congestion." *National Transportation Statistics*. Washington: Bureau of Transport Statistics, 2023.

[9] Willner, Andrew. "Rondout Riverport 2040: A Comprehensive Plan for a Working Waterfront and the Transportation of Goods and People in a Carbon Constrained Future." Originally Presented At The Royal Institute of Naval Architects Wind Propulsion Conference, 15-16 September 2021. Courtesy of RINA. *Proceedings Of The Conference On Small Scale Inland And Coastal Sail Freight*. Kingston: Hudson River Maritime Museum, 2022. hrmm.org/uploads/2/6/3/3/26336013/sail_freight_conference_proceedings_hrmm_5nov22.pdf

due to the complicating nature of the Canadian Border and the population centers along their shores. However, as these waterways link to those treated in this plan, there is reason to take care any developments in Lakes Erie and Ontario are coordinated with any action taken on this plan. For example, if a sail freight project were to start on Lake Erie before Lake Ontario, it would be wise to push for a connection to Buffalo before Oswego when the next opportunity for expansion presents itself. The same general rule applies to any developments in the Chesapeake Bay or other nearby regions.

It is apparent that small sail freighters are only economically viable on relatively short routes, and larger vessels with a better Tons-Per-Sailor ratio are needed for mid- to long-distance trade.[10] However, this plan concentrates mostly on short- to mid-distance trade where relatively low tons-per-sailor values are tolerable during initial stages of exploration and expansion. As volumes of trade increase and longer inter-regional links are made, larger vessels for long distance trade can be considered for addition to the fleet. It is assumed here that small groups may employ their own recreational vessels, as occurred during the 2022 Northeast Grain Race, to carry some freight, meaning not all the ships employed in the sustainable freight systems will be designed as freight vessels.

The use of varying electric canal vessels and sail freighters in different fleet districts will be required to access some ports. For example, the identified Sail Ports in this plan can be accessed by sail freighters or low-air-draft electric canal boats, while Steam Ports are effectively accessible only to canal boats because of bridges or other circumstances which make them unfavorable to sailing vessels.[11] Various vessel plans have been identified as usable on these routes, including *Ceres*-Class sailing barges,[12] and designs by Derek Ellard,[13] Tad Roberts,[14] Bruce Roberts,[15] and TransTech Marine,[16] among other possibilities. Solar Sal vessels designed similarly to the Hudson River Maritime Museum's tour boat *Solaris* would be well suited to steel construction for unsupported cargo use in canals; a wood prototype was employed on the New York State Canal system in 2015 hauling 4 tons of cardboard over 300 miles.[17]

The plan as outlined with the following ports will require at least 4 sail freighters and 1 canal vessel, though 4 Canal Vessels and 5 Sail Freighters would be a more reasonable minimum. The division of the plan into routes is the preferred means of determining capacity needs, with at least 10 packet routes as defined later in the paper. This is exclusive

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[10] Woods, Steven. "Sail Freight Revival: Methods of calculating fleet, labor, and cargo needs for supplying cities by sail." Master's Thesis. Prescott College, 2021. www.researchgate.net/publication/354841970

[11] Koltz, Bruce George. "The reintroduction of sail for marine commerce: and the consequent effects upon small port economy and trade routing" Master's Thesis, University of Notre Dame, 1980. https://calhoun.nps.edu/handle/10945/19039

[12] Woods, Steven, (Editor). *The Sail Freight Handbook* 2ed. Kingston: Center for Post Carbon Logistics, 2023. www.postcarbonlogistics.org/publications

[13] Ellard, Derek. "Electric Clipper 100." . Accessed 30 November, 2020. www.gosailcargo.com.

[14] Tad Roberts Yacht Design. "60 Ft Cargo Schooner" www.tadroberts.ca/services/new-design/sail/steelcargoschooner60

[15] Roberts, Bruce. *Roberts Yacht Design*. https://bruceroberts.com/ Accessed 14 May 2023.

[16] Uttmark, Geoff. *Eriemax: Assessment of Green Ship Technologies and Plan for Deployment on the Erie Canal/NYS Barge Canal System* New York: NYSERDA, 2015.

[17] Conversation with Solar Sal Designer Dr. David Borton, 2022.

of long-distance fleets and interregional links which may be involved, such as the Transatlantic Fleet, currently involving Schooner *Grain de Sail* and soon the 3-masted Schooner *Vega* of Sail Cargo Inc.. Longer-distance coastal routes such as links to the Chesapeake Bay, Gulf of Mexico, or other locations along the coast are possible, but will only be viable once local networks are established in those areas. Any plans or progress which can be made to create independent regional networks like that outlined in this paper should be encouraged, and once they are established a concerted effort to establish at least an annual voyage to link the networks must be made.

Port infrastructure should be assumed to start with commercial marinas and public docks, evolving into Spud-Barge Depots as trade volume demands and capital becomes available. Described in detail in the *Sail Freight Handbook*, these barge depots can be self-supporting, easily deployed, and modularly chained together to create an appropriately sized depot for any protected location. With appropriate warehousing provided by on-barge sheds or intermodal containers, these depots can serve as an interim measure until permanent shoreside infrastructure is created, then moved to new locations as the trade network expands and the backlog of inland waterway and port infrastructure repairs are worked through.[18] If they are found especially useful, the barge depots can be left in place as a permanent piece of infrastructure.[19] To retain symmetrical terminology, facilities are classified using the Anchorage-Harbor-Port hierarchy used in the *Sail Freight Handbook*:

> Anchorages… are the most basic type of accommodation for shipping, and may be no more advanced than a sandy beach to pull a boat ashore safely. The classification also covers single quays and jetties, places where lightering can be accomplished easily from anchor…
>
> Harbors… are more developed than anchorages, and… normally have at least limited support services, such as warehousing, shipwrights, and shore gear for handling cargo, but can still be quite small and relatively undeveloped.
>
> Ports, on the other hand, have everything and are primarily based around maritime trade, as opposed to simply having the capability…. These are also the points normally associated with Customs offices, international and transoceanic trade, and other large scale maritime activities.[20]

Most Anchorages as indicated in this paper will rely on either public docks or commercial marinas as the sole infrastructure, while Harbors have the potential for shore gear, space, and additional support dedicated to cargo operations. Many Anchorages would qualify to be upgraded to Harbors after the installation of a barge depot. Ports require a major city and extensive support structures, including Customs Entry for connection to international sustainable maritime freight networks.

The business models and vessels for some of these trade routes have already been developed. Schooner *Apollonia* is actively creating trade routes along the Hudson River.[21] TransTech Marine has developed a model for carrying wine and foodstuffs between the

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[18] American Society Of Civil Engineers. *2021 Report Card For America's Infrastructure: A Comprehensive Assessment Of America's Infrastructure*. Reston: ASCE, 2021. https://infrastructurereportcard.org/

[19] Woods, *The Sail Freight Handbook*. Pp 141-170

[20] Woods, *The Sail Freight Handbook*. Pp 141

[21] Woods and Merrett "Operation of a Sail Freighter on the Hudson River."

Finger Lakes and Long Island Sound.[22] The Vermont Sail Freight Project’s temporary success at bringing Champlain Valley produce to New York City was fundamentally sound, though short lived due to a lack of human and financial resources.[23]

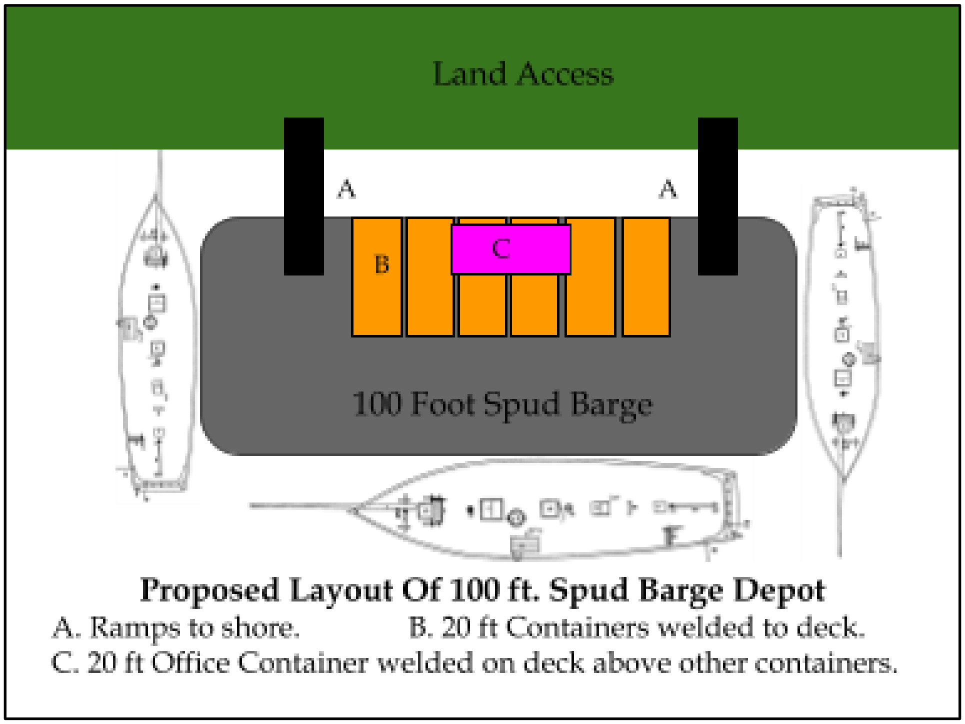

Figure One: Proposed Spud Barge Layout as given in the *Sail Freighter Handbook*, Pp 169-170.

The Logical Topology of the plan as outlined relies on the hub-and-spoke model illustrated in the *Sail Freight Handbook*, page 16. Each of the ports listed on the following tables will likely have its own feeder networks, and serve as aggregation points for other cargo on smaller vessels. Trunk Lines between the major ports using larger vessels at a relatively low frequency should be established only when volume becomes significant; early long-distance trade should be effected by down-the-line trading. Interlocking packet routes are assumed for all vessels and some vessels may be used on more than one route until trade volume makes further ship construction necessary.

Estimates for shipbuilding costs in steel have ranged from $300,000-2,500,000 for sail freighters, approximately $1,000,000 for solar-electric canal vessels, and up to $300,000 for barge depots. Each of the proposed steel vessels would be approximately 65 feet in length over all, and capable of carrying up to 30 tons of cargo. Small vessels for scouting routes could be built using the far less capital-intensive design of the Sailing Barge *Ceres* on well-protected canals and rivers, or refit recreational cruising sailboats offshore, neither of which should cost over 20% of the lowest estimate for new, purpose built vessels.

Recruiting and training sufficient sailors will also be a challenge; to not incorporate this element into the expansion plan is to prepare for failure at the first stage of expansion. Exclusive of longshore crews, brokers, sailmakers, shipwrights, chandlers, and other supporting trades, each canal vessel requires two crew, and each schooner requires four. For

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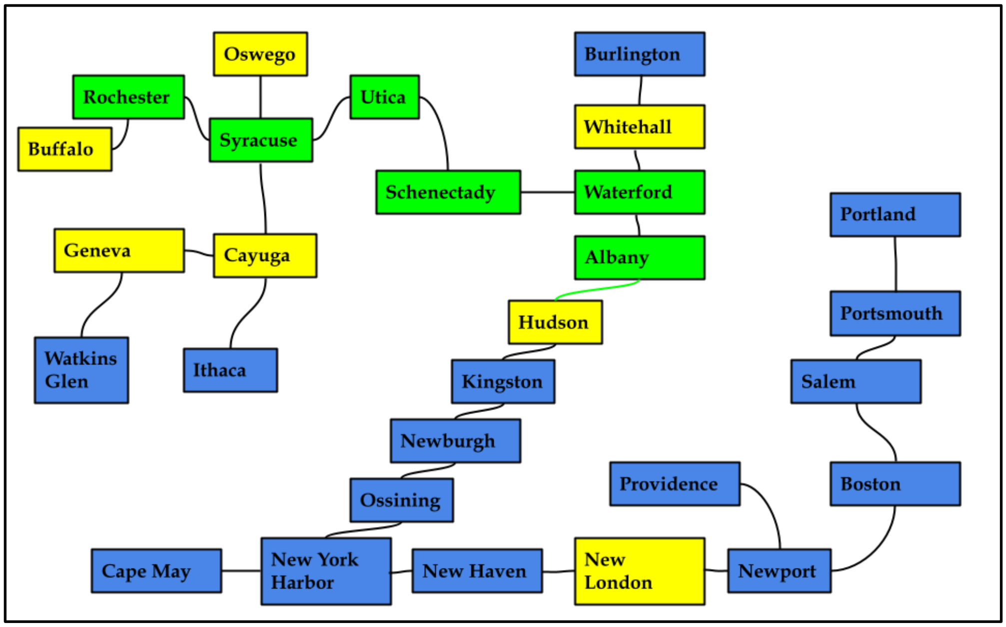
[22] Uttmark, *Eriemax.*

[23] Woods, Steven. “Sail Freight Revival”

continuous operations, two alternating crews should be arranged, requiring four and eight people with the appropriate licenses and credentials per vessel type respectively. For the fully developed minimum plan outlined here, an absolute minimum of 40 sailors, at least 12 of whom are licensed master mariners is required. An additional buffer of 50% should be added to deal with scheduling difficulties which may routinely arise. Incentives should be given to make cargo sailing more appealing than charter sailing on other tall ships or charter boats, and pay must be sufficient. In addition, training efforts should be taken seriously on the cargo vessels themselves, to ensure those who are interested in the field but have no experience are able to join it without paying massive sums for formal sail training. The more small vessels there are involved in this trade, the more sailors will be needed, inflating the need for good training programs for both knowledge and practical skill. Recruitment for future windjammer sailors must begin now so that a sufficient number can take over vessels as they are launched, and so they can begin to create these sustainable transportation businesses and projects elsewhere with whatever vessels and partners present themselves.

The following tables outline the existing infrastructure, potential support, and expansion priorities for sustainable maritime freight operations in the Northeast. A list of ports has been identified as important to developing regional trade in the Northeast. As current Sail and Sustainable Maritime Freight projects and attention are focused in and around the Hudson Valley[24] and Long Island Sound[25] this plan assumes infrastructure and further projects should be designed to support and intermesh with these developments as much as possible. Some of the locations identified have further spur routes from their local area which will generally be less than a day's sailing and can be served entirely on inland waters, as mentioned in the Notes column. Ports identified as Sail and Steam Ports are major intersections of open water and sailing systems. Ports to develop are given in rough priority order; those already in service in Italics.



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[24] Schooner Apollonia. www.SchoonerApollonia.com Accessed 15 May 2023.

[25] Harbor Harvest. www.harborharvest.com Accessed 15 May 2023.

Identified Sail Ports, Northeastern United States:

Facilities: A=Anchorage; H=Harbor; P=Port. Cargo Capabilities: B: Breakbulk; P: Palletized; C: Containerized

Location	Draft	Air Draft	Facilities			Cargo			Notes
			A	H	P	B	P	C	
Kingston, NY	16	50	X	X		Y	P		First experimentation with Barge Depots made here in 2023.
Hudson, NY	10	---	X	X		Y	P		Air Draft dictated by Hudson River Bridges.
Ossining, NY	6	---	X			Y			Low tide depth is problematic for many vessels.
Poughkeepsie, NY	16	---	X			Y			
Newburgh, NY	30	---	X			Y	P		
Tarrytown, NY	9	---	X			Y			
Carteret, NJ	9	---	X	X		Y	P		There is one lift bridge on the Arthur Kill which closes twice daily.
Albany, NY	12	21	X	X		Y	P	P	Air Draft must pass under multiple Bridges, one low turn bridge.
Troy, NY	12	24	X			Y			One drawbridge involved which could slow travel significantly.
RETI Barge, Red Hook, NYC	22	---	X	X	X	Y	P		Prototypical Barge Depot. Trunk Line to Boston.
Burlington, VT	15	---	X	X		Y	P		
New Haven, CT	13	62	X			Y	P		Air draft with lift bridge up.
New London, CT	15	---	X	X		Y	P		Aggregation to Mystic, New Haven.
Newport, RI	12	---	X	X	X	Y	P	P	Aggregation Point to Providence, Fall River, Martha’s Vineyard, Montauk.
Port Henry, NY	11	---	X			Y			Aggregation Point for West Coast of Lake Champlain.
Oswego, NY	12	-/15	X	X		Y	P	P	Oswego Canal has same restrictions as Erie Canal: 12ft draft/15ft Air Draft. Aggregation point for Lake Ontario.
Boston, MA	17	---	X	X	X	Y	P	P	Principal Destination of NH and Maine Cargos. Trunk Line to NYC.

Portland, ME	9	55	X	X		Y	P		Aggregation Point for Down East Maine harbors. Berths before bridge.
Portsmouth, NH	8	---	X	X		Y	P		Lift Bridge in harbor. Depth given for public docks, channel depth 35 ft.
Ithaca, NY	8	---	X	X		Y	P		
Cayuga, NY	12	-/15	X			Y			Air Draft in Seneca lake unrestricted; 15 ft in canals. Aggregation Point for Seneca and Cayuga Lakes..
Cape May, NJ	8	---	X			Y	P		
Providence, RI	14	-/35	X			Y	P		Berths may be available before fixed bridge.

Notes: Facilities indicated as in *Sail Freighter Handbook*. Draft and Air Draft in feet, over 100 ft indicated by “---” UNK indicates unknown value. Cargo Type Capabilities, Y=Yes; N=Not Practicable; P=Possible.

Identified Sail Ports, Northeastern United States, Con't:

Facilities: A=Anchorage; H=Harbor; P=Port. Cargo Capabilities: B: Breakbulk; P: Palletized; C: Containerized

Location	Draft	Air Draft	Facilities			Cargo			Notes
			A	H	P	B	P	C	
Salem, MA	21	---	X			Y			Beverly Harbor Inclusive.
Gloucester, MA	16	---	X			Y			
Bath, ME	19	70	X			Y			Lift bridge present in harbor.
Newburyport, MA	9	---	X			Y			
Sandwich, MA	8	---	X			Y			

Identified Steam Ports, Northeastern United States:

Facilities: A=Anchorage; H=Harbor; P=Port. Cargo Capabilities: B: Breakbulk; P: Palletized; C: Containerized

Location	Draft	Air Draft	Facilities			Cargo			Notes
			A	H	P	B	P	C	
Troy, NY	12	15	X			Y	P		One drawbridge involved which could slow travel significantly.
Whitehall, NY	12	15	X			Y	P		Aggregation Point for Lake Champlain Basin.
Waterford, NY	12	15	X			Y	P		Junction of Erie and Champlain Canals.
Schenectady, NY	12	15	X			Y	P		
Utica, NY	12	15	X			Y	P		Mid Central New York Aggregation Point.
Syracuse, NY	12	15	X	X		Y	P		Initial Western Aggregation Point. Juncture of Oswego Canal.
Finger Lakes, NY	12	-/15	X			Y			Air Draft in the lakes in unrestricted; 15 ft in canals. Seneca and Cayuga lakes inclusive.
Oswego, NY	12	15	X	X		Y	P	P	Oswego Canal has same restrictions as Erie Canal: 12ft draft/15ft Air Draft. Aggregation point for Lake Ontario.
Rochester, NY	12	15	X	X		Y	P	P	

Buffalo, NY	12	15	X	X		Y	P	P	Access point to Lake Erie.
Cayuga, NY	12	-/15	X			Y	P		Air Draft in the lakes in unrestricted; 15 ft in canals. Aggregation for Seneca and Cayuga Lakes inclusive.
Norwich, CT	20	75	X			Y			Subsidiary to New London Sail Port.
Hartford CT	12	81	X			Y			Subsidiary to New London Sail Port.
Camden, NJ	16	---	X			Y			Subsidiary to Cape May Sail Port.
Ocean City, NJ	8	15	X			Y			Subsidiary to Cape May Sail Port. One swing bridge inland route.

Notes: Facilities indicated as in *Sail Freighter Handbook*. Draft and Air Draft in feet, over 100 ft indicated by “---” UNK indicates unknown value. Cargo Type Capabilities, Y=Yes; N=Not Practicable; P=Possible.

Potential Supporting Organizations

Support Types: $= Financial; L= Logistical; T=Training; O= Other. N= None; P= Possible; Y=Yes.

Organization	Location	Support				Notes
		$	L	T	O	
Center For Post Carbon Logistics	Kingston, NY	P	Y	Y	Y	The CPCL a driving force for sustainable maritime shipping in the US over past 3 yrs.
Hudson River Maritime Museum	Kingston, NY	N	Y	Y	Y	Currently Supports Apollonia and has Sail Freight Exhibit.
South Street Seaport Museum	NYC, NY	N	Y	P	Y	SSSP Already provides docking.
Mystic Seaport Museum	Mystic, CT	N	P	P	P	
The Gundalow Company	Portsmouth, NH	N	P	P	P	Previously expressed interest in Northeast Grain Race.
Lake Champlain Maritime Museum	Vergennes, VT	N	P	N	P	Supported VSFP.
Erie Canal Museum	Syracuse, NY	N	P	N	P	
SUNY Buffalo Sustainable Transportation Graduate Program	Buffalo, NY	P	P	N	P	Research funding may be available.
UVM Sustainable Development Graduate Program	Burlington, VT	P	P	N	P	Linked to Civil Eng prog/ NIST. Research funds possible.
National Institute For Sustainable Transportation	UC Davis, CA	P	N	N	P	Research funds possible.
Northeast Grainshed Alliance	Northeast Region	N	P	N	P	The NGA participated in the 2022 Northeast Grain Race.
The Greenhorns	Northeast Region.	P	P	N	P	Supported VSFP, Maine Sail Freight Project.
Tall Ships America	Newport, RI	N	N	Y	P	
University of Washington Graduate Program in Sustainable Transport	WA	P	N	N	P	Research funds possible.
International Windship Association	UK	N	N	P	Y	Advocacy, Policy, and Advertising support.
Grain de Sail	France	P	N	N	Y	Met Apollonia in New York.
WindSupport NYC	NYC	P	P	P	Y	

American Sailing Association	National	N	N	Y	P	
US Sailing	National	N	N	Y	P	
Nat. Working Waterfront Network	National	N	P	P	P	Port design and implementation support possible.
Future Of Small Cities Institute	Troy, NY	N	P	N	P	Supports Apollonia’s Operations.
Transportation Sust. Research Ctr	UC Berkeley	P	N	N	P	Research funding possible.
Cycling Logistics Association	New York	P	P	N	P	Zero-carbon last mile transportation networks.
Sustainable Transport Council	National	P	P	P	P	

Suggested Packet Routes:

Packet Name	Covered Ports Of Call
Hudson River Sail	Hudson-Kingston-Poughkeepsie-Newburgh-Ossining-Tarrytown-New York
Hudson River Electric	Hudson-Albany-Troy-Waterford-Whitehall
Erie Canal	Waterford-Schenectady-Utica-Syracuse-Rochester-Buffalo
Oswego Canal	Syracuse-Oswego
Finger Lakes	Syracuse-Cayuga Lake-Ithaca-Seneca Lake-Watkins Glenn-Geneva
Narragansett Bay	Newport-Providence-Fall River-Martha’s Vineyard
Gulf Of Maine	Bath-Portland-Portsmouth-Newburyport-Gloucester-Salem-Boston
Lake Champlain	Whitehall-Port Henry-Burlington
Long Island	New York-New Haven-New London-Newport
New Jersey	New York-Carteret-Ocean City-Cape May-Camden

Expansion Plan By Year Through 2030

Year	Expansion	Notes
2024	1. Barge Depot installed, Kingston. 2. Andrus Fellowship funded yearly. 3. Solidify backhaul cargo flows. 4. Expand existing cargo flows. 5. Explore Long Island Sound Cargo.	Requires 1 Schooner, already in service. Hudson River Sail Packet in service since 2020.
2025	1. Permanent Captains Hired. 2. Depot Established in Hudson. 3. Explore canal E. of Utica/S. of Whitehall. 4. Use existing solar boats on canals. 5. Create social events around all port calls.	Requires 1 Schooner, 1 Canal Boat. Existing Solar Boats may be hired from Solar Sal Boats for the next few years. Bicentennial of Erie Canal Opening.

	6. Establish Hudson River Electric Packet.	
2026	1. Depot In New York Harbor. 2. Depot In Waterford, NY. 3. Solar Freighter Under Construction. 4. Establish Erie Canal Packet to Utica. 5. Establish formal brokerage firm. 6. Create Annual Long Island Run.	Requires 1 Schooner, 1 Canal Boat. Integration of Transatlantic networks should be initiated via NY Harbor. Zero-Carbon Last-Mile transport at all ports.
2027	1. Depot Established Ossining. 2. Canal Traffic to Finger Lakes. 3. Establish Long Island Packet. 4. Create Annual Gulf Of Maine Run.	Requires 2 Schooners, 1 Canal Boat. Consider hiring commercial schooner for Gulf Of Maine experimental runs.
2028	1. Depot Established Whitehall 2. Establish Lake Champlain Packet 3. Establish New Jersey Packet. 4. Expand Canal Traffic to Rochester. 5. Establish Narraganset Bay Packet.	Requires 3 Schooners, 1 Canal Boat. Initial Explorations for Boston-NYC Trunk Line around Cape Cod.
2029	1. Depot Established Ithaca. 2. Expand Canal Traffic to Buffalo. 3. Establish Finger Lakes Packet. 4. Establish Depot: Newport. 5. Establish Depot: Syracuse.	Requires 3 Schooners, 2 Canal Boats. Finger Lakes packet requires 2 small sailboats and 1 canal boat. Canal service provided by Syracuse-Oswego Packet Boat.
2030	1. Depot Established Buffalo. 2. Establish Oswego Packet. 3. Establish Gulf of Maine Packet. 4. Establish Depots: New London, Portland.	Requires 4 Schooners, 2 Canal Boats. Explore Great Lakes Cargo Opportunities. Initial Exploration of Chesapeake Bay Trunk Line.

INTERESTED PARTIES FROM 2022-2023 NORTHEAST GRAIN RACE PLANNING

Party	Location	Cargo Source	Notes
Schooner Ardelle	Gloucester, MA	N/A	Interested in Sail Freighting.
Blue Ox Malt House	Lisbon Falls, ME	(Producer)	
Short Path Distillery	Everett, MA	Lisbon Falls, ME	Looked for 1 ton of Malt for special edition liquor.
New York Cider Co	Ithaca, NY	(Producer)	Ships Cider to Brooklyn.
The Gundalow Company	Portsmouth, NH	N/A	Interested in Sail Freighting
Schenectady Distilling Co	Schenectady, NY	(Producer)	Shipping Whiskey to NYC.

N.B.: Direct participants via *Apollonia* and *Solar Sal* Exclusive. All these participants had the potential and connections to draw in additional participants within their networks, though efforts to organize a cargo between Bath, ME and Boston, MA were not successful for a number of reasons.

There are a number of organizations which may be willing to support the expansion of Sail and Sustainable Maritime Freight in the Northeast. The above table is exclusive of those cargo owners actively shipping their products with Schooner *Apollonia*. Organizations and institutions such as MARAD and other similar State and Federal programs are not enumerated here as both redundant and thus far completely unhelpful in establishing or expanding sustainable small scale shipping operations. Those organizations already giving active support to *Apollonia* are noted, as are those which supported other sail freight endeavors in the past. Shipyards have not been included in these tables, but alongside marinas will be critical to effectively expanding the sustainable cargo fleet.

These ports and organizations will be used to support minimum fleets on 10 identified packet routes, many of which link to each other. Tramp vessels have not been incorporated into this plan or analysis as they have not proved economically viable with small vessels in the past. If there are sufficient free days for vessels involved in regular packet runs, some tramping operations may be possible as a form of additional revenue and activity, but should not be relied upon in the short- or mid-term revival of zero-carbon coastal trade. It should be possible to use the packet arrangements outlined above to establish minimum linking services in early developmental stages of this system. Where possible, depots should be concentrated around the interfaces between packet routes, and routes should only be grown out one link at a time so as to have the longest distance chain possible for down-the-line trade.

It is worth noting that the list of ports given above is not exhaustive, and only covers the major nodes of such a network. For example, a vessel operating on the Narragansett Bay route may call at Fall River, New Bedford, Little Compton, Martha's Vineyard, and East Hampton. Overlap between packets may also occur at more than designated nodes, though the targeted nodes will most likely be the first to receive additional infrastructure. An example of this would be Erie Canal packets going as far as Albany or Hudson to transfer cargo instead of at Waterford; this can be helpful in reducing labor requirements for transferring breakbulk cargo. However, this must be managed carefully in early stages of establishing trade so as not to create competition where cooperation should be the rule.

Clearly, the fleet outlined in the above table will need to be matched to shipping volume and sailing frequency; by keeping vessels in constant use very few will be required in the early stages of this project. With any luck, trade volume will be sufficient to drive fleet numbers higher, though this cannot be guaranteed in initial stages for every packet line. In some of the exploratory stages for each route *Runcible Spoon*-esque[26] uninspected cargo vessels may be the least expensive and most useful way to make the expansion; these vessels can then be re-assigned as needed to scout the next route. If necessary, they can remain in place to act as feeder vessels to the major ports, especially where the small vessels are part of a local Farmer's Ships or Community Supported Shipping initiative.

Where local sustainable maritime shipping movements present themselves, these should be supported even if it requires modifying previous plans. For example, if a Gulf of Maine or Lake Champlain sail freight project forms before expansion is made into the Erie Canal, expansions to link to these projects should be prioritized over Erie Canal expansion. This would mean either moving into Long Island Sound or the Champlain Canal before the Erie canal is developed. Where possible in early stages, small steps should be encouraged, such as connecting the Hudson Valley to the Erie Canal as far as Utica, for example. Once

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[26] Boykett, Tim. "Danube Clean Cargo: Prefigurative Experiments and Arts-based Research" *Proceedings Of The Conference On Small Scale Inland And Coastal Sail Freight*. Kingston: Hudson River Maritime Museum, 2022. https://www.researchgate.net/publication/365669016

these links are consolidated, the packet can expand out along its planned route as far as cargos present themselves. The steps to expansion in the tables above are guidelines given with the latest desirable date for each occurrence; faster progress is not to be avoided if circumstances permit. Advantage should be taken of the 200th anniversary of the Erie Canal's opening, and the 8-year 250th anniversary of the American Revolution to use historic commemorations and grant funding to assist in expanding sustainable cargo operations, even if this requires some concessions to be made to using historically patterned vessels in initial stages of expansion. The proof-of-concept work, trade relationships, and market creation which can be part of such commemorative events will at the very least lay the foundation for more permanent and modern operations in the years following. Hiring replica ships for cargo operations in addition to their public history mission may be possible, and can bring more vessels into the fleet at least on a tramping model for the proof-of-concept and reconnaissance phases.

Further research remains to be done for these plans. Lists of interested cargo owners, additional supporting organizations, funded research opportunities for university departments, and designing suitable cargo vessels all need to be accomplished for this plan to have a solid shot at success. Some of these elements have been accomplished already, but must be prioritized. Small-scale pilot projects, even on as little as an annual-voyage basis using improvised vessels, should be established in regions with a short link to the existing theater of operations in the Hudson Valley, such as Lake Champlain and Long Island Sound, to prepare the ground for later operations. Similar regional plans for the Chesapeake Bay, Gulf of Mexico, each of the Great Lakes, and possibly other regions should be made, with the express purpose of creating similar networks in those areas which can be connected at a later date.

A directory of interested cargo owners, supporters, and businesses should be built for the region, with the object of identifying where small pilot projects are likely to succeed. For example, if sufficient support can be found ranging from Boston to Northern Maine, a new Maine Sail Freight Project should be established immediately for at least annual voyages. By taking the time to create an open list of supporters, other projects can more quickly evaluate their prospects and build business plans to secure financing, a serious obstacle to getting any sail freight venture off the dock. Creating Open Letters of Intent or Pledges for businesses along each packet route to sign, declaring a willingness to ship by sustainable maritime means if a critical mass of, say, more than twelve businesses sign on to the letter, would be a significant development and assist in creating many smaller maritime freight projects. Special attention should be paid to recruiting marinas, city docks, boat clubs, food co-ops, local businesses, farmers, and small producers in each area.

As previously expressed, leaving sustainable maritime coastal trade to grow organically is unlikely to succeed in the time remaining to decarbonize the economy, at a level capable of taking up the slack from trucks and trains rendered inoperable by energy shortages. By establishing and openly publishing expansion plans, a mutually-supporting business model can be encouraged regionally, while spurring others to form their own plans and take action toward building this critical re-emerging industry. Without cooperation and mutual aid among vessels in the initial stages of re-establishment, however, there is little hope for a lively sail freight sector in the Northeast US or anywhere else; planning expansions to match both demand and ability to give mutual support is a good way to ensure success for all.

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A second look at the Propeller Sail high lift device for sailing cargo ships, using distributed, wing-mounted propellers

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Abstract:

The Propeller Sail, in this case consisting of 2 powered propellers mounted on the aft end of a ship wing-sail, is analyzed using computational fluid dynamics (CFD) in 3-dimensions at Reynolds number between 5E5 and 1E6. The wing-sail is set to a 30-degree angle to the relative wind, and is 6.9 meters high with a chord of 2.4 m and 1.4 m diameter propellers. The results may be summarized as follows:

- In the limited configuration tested, the Propeller Sail used about 4 times more power than a Flettner rotor to produce the same lift force, at a lift coefficient Cl of 3.4.
- High lift coefficients are possible as long as sufficient power is available.
- With enough power applied, the propeller thrust can become greater than the drag force on the wing, counteracting the downwind drift force normally experienced by sailing vessels, while simultaneously producing lift.
- With only one propeller mounted on the wing, a mid-wing-mounted propeller generates more lift and greater Lift/Drag than a wing-tip mounted propeller. As tested, there appears to be no advantage to a single wingtip mounted propeller.
- When two propellers are acting concurrently, the mid-mounted propeller produces more lift.
- Two distinct regions of lift generation are identified with the airfoil at an angle of attack of 30 degrees: at low propeller rotation speeds, lift increases rapidly with increasing propeller rotational speed due to reduced separation and greater flow velocity over the wing. At higher propeller rotation speeds, when the flow is no longer separated, increasing the propeller rotational speed increases the lift force at a slower rate, presumably because of greater flow velocity only. For greatest economy, designers may choose to keep propeller operation out of this critical region, if possible.
- When the propellers are activated, the greatest gains in lift on a percentage basis occur at low relative wind speeds.
- A model Propeller Sail ship was found to be stable and move well under wind power alone as well as with combined wind and engine power.
- Determining the viability of the Propeller Sail will require further research. This is a concept in its infancy, and many important factors were not investigated, such as varying the angle of attack, propeller tilt, propeller diameter and wing profile, to name a few.

1. BACKGROUND

In [1] the Propeller Sail concept was first introduced, consisting of ship wing-sails with powered propellers. This was a preliminary work using two-dimensional CFD (Computational Fluid Dynamics) simulations, which determined that the Propeller Sail may be a viable method for propelling ships, with lift coefficients as high as other high-lift devices such as Flettner rotors and suction sails. It was also found that tilting the propellers down by 20 degrees and placing the propellers on the trailing edge of the wing might produce high lift with low drag forces, as compared to other configurations. Several possible usage methods were proposed: Propeller Sails mounted at the bow and stern of a ship to function as thrusters, and using Propeller Sails in lieu of propellers in the water, which may reduce construction costs and increase hull efficiency. A one-propeller Propeller Sail test model is presented in Figure 1.

Figure 1. The Propeller Sail model with one propeller.

In this work, 3-Dimensional CFD simulations were conducted with a NACA 0030 wing section mounted on a smooth and un-obstructed deck. Simulations were made without propellers, with one propeller alone operating at the wingtip, with one propeller alone operating at mid-wing, and with two propellers operating concurrently. Only 30-degree wing angles of attack were tested in this work, with the propeller rotation axes at ten degrees below the angle of the wings, at a variety of propeller rotational speeds. No attempts were made to optimize the design of the propellers, their angle or position relative to the wing.

Limited model tests were also conducted with the 1m model displayed in Figure 1.

2. CFD SIMULATIONS

SimScale [2], a RANS (Reynold Averaged Navier-Stokes) CFD (Computational Fluid Dynamics) product, was used for the 3-dimensional CFD simulations. SimScale accesses the well-tested OpenFOAM CFD platform [3], and provides cloud-based parallel processing.

The simulated wing uses a NACA 0030 profile, with 6.9 m height and 2.29 m chord. The mesh is composed of 13.3 M cells, and is divided into four regions of mesh size refinement, as partially shown in Figure 2. The regions include the surface of the propellers, the area near the propeller, a near-field region and a far-field region. Overall mesh quality is calculated by the SimScale software as 0.499688 (the acceptable range is from 0.035 to 1.0), and is based on non-orthogonality of the cells (please see

Appendix 1 for a mesh-quality summary). Simulation runs typically used about 100 “core-hours” while running in parallel mode for about 1-2 hours of real-time.

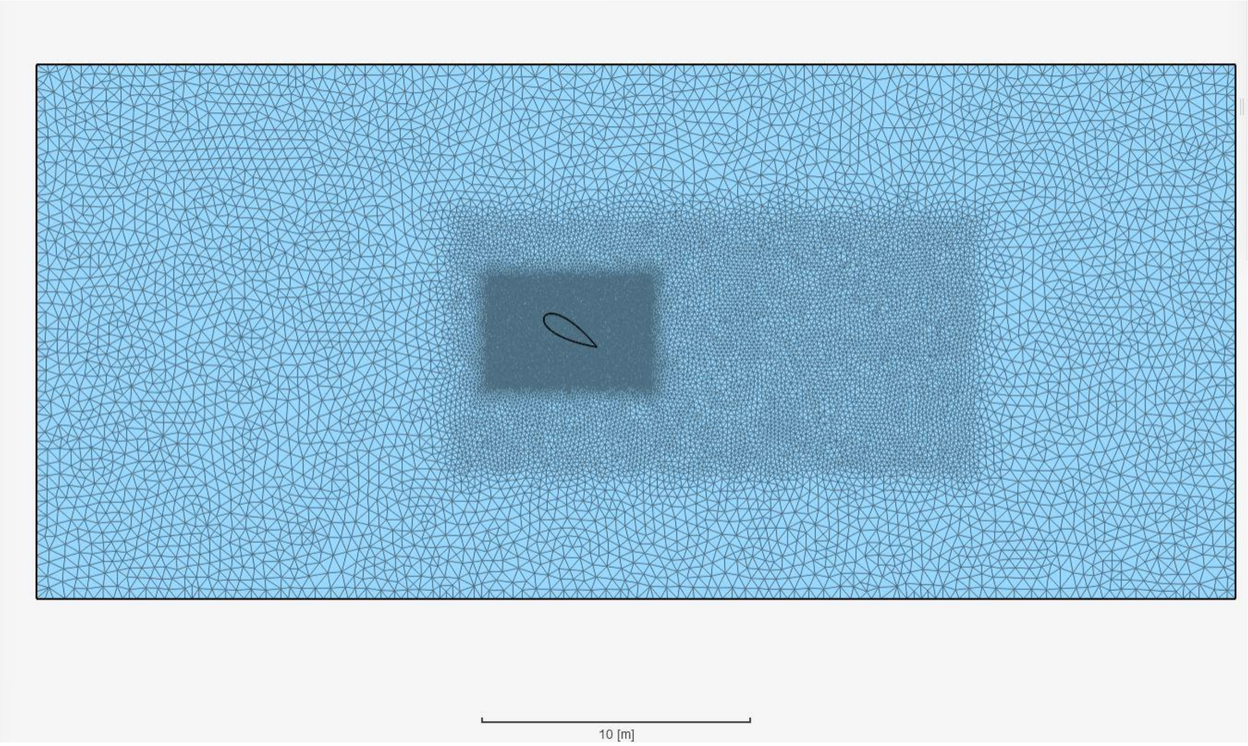

Figure 2. The simulation domain and mesh refinement regions. The wing is seen from above.

Modeling the rotation of the propellers in SimScale is simplified by the use of a Modified or Moving Reference Frame (MRF) around the propellers, in which the propellers are static, but rotating flow is imposed around them in the MRF.

A mesh refinement study was conducted, with a range of total cell counts ranging from 5 to 13.1 million cells. The mesh size was varied in all of the refinement regions, but not always in a uniform way: if the propeller faces had a finer mesh, the near field and far field might be made slightly coarser. The 13.1 M mesh used the finest overall mesh.

Figure 3 shows the wing lift and drag results used for the mesh refinement study. 2 propellers in simultaneous operation on the wing were modeled, turning at 100 rad/s, with 10 m/s winds. It appears that the difference between the results from mesh sizes greater than 5M are fairly small. The 13.1M cell was used for this study.

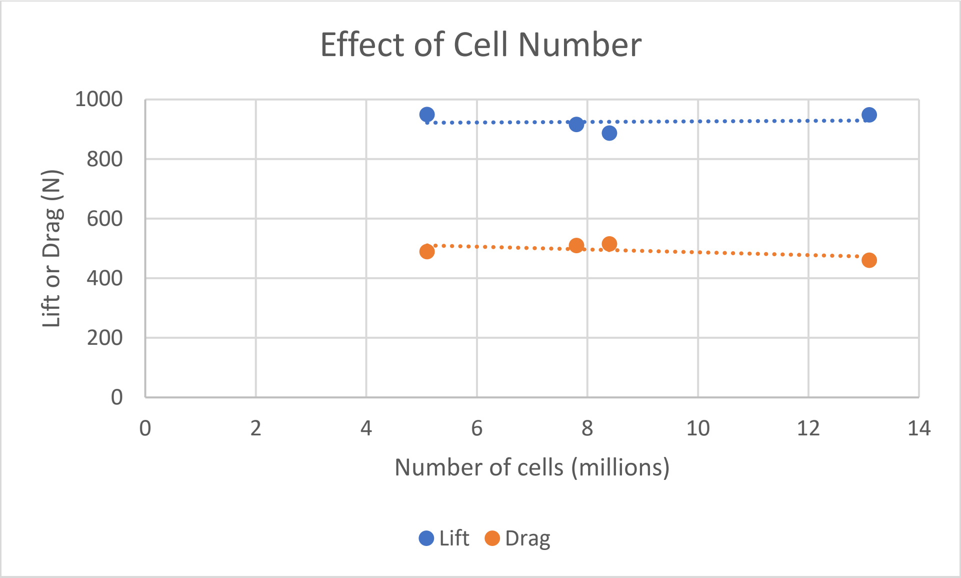

Figure 3. Mesh refinement study.

We can also say in general terms that similar CFD simulations using far less than the 13.1 million cells used in this study have produced acceptable results. For example, in [4] a drone propeller was modeled with Thrust and Pressure coefficients within 8% of experimental values, using 1 million cells. Initial calculations performed for this work showed that using the automatic physics-based meshing tool of SimScale with 3.1 million cells on a NACA 2424 wing (closely resembling the NACA 0030 used here) gave lift coefficients that were within 6% and drag coefficients 16%-29% of experimental values.

The propellers were “stock” 3D files downloaded from an open-source 3-D geometry library [5], and placed on the aft end of the wing. As will be seen in the Results section, the propeller efficiency was quite low. The motors driving the propellers were assumed to be inside the wing, but the shafts connecting the wing and propeller were not modeled. The propeller axes of rotation were tilted downwards ten degrees from the wings, and the wings were set to an angle of attack of 30 degrees into the incoming flow. Propeller diameter was 1.42 m. No attempt was made to optimize the propeller design, size, angle or placement on the wing. Figure 4 shows the Propeller Sail as modeled.

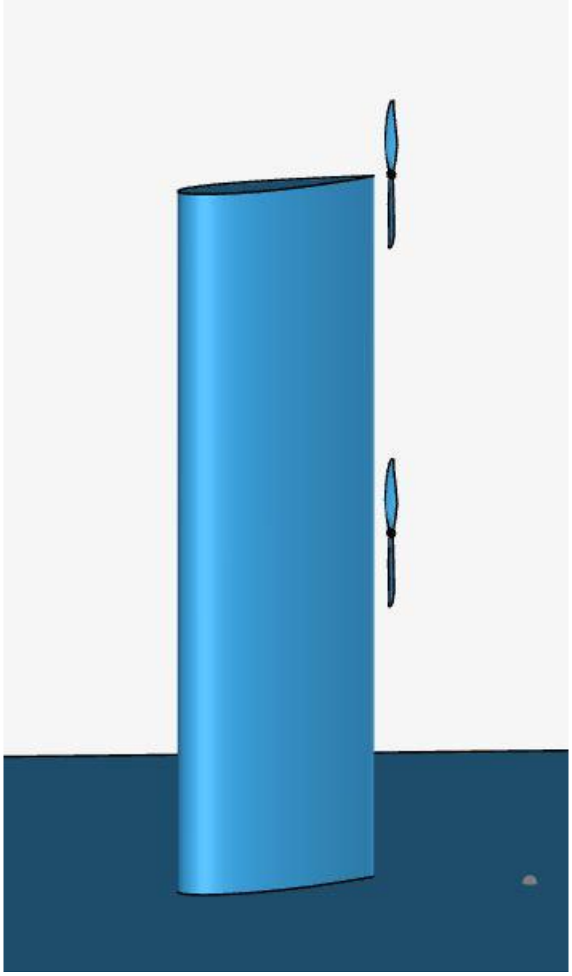

Figure 4. The wing and propeller configuration.

Figure 5 shows the computational domain, with air flow entering from the left side (4 faces have been hidden for clarity). Boundary conditions were set to “Pressure” at the exit, “No-slip” at the bottom and “Pressure inlet-outlet” at the sides and top of the virtual tunnel.

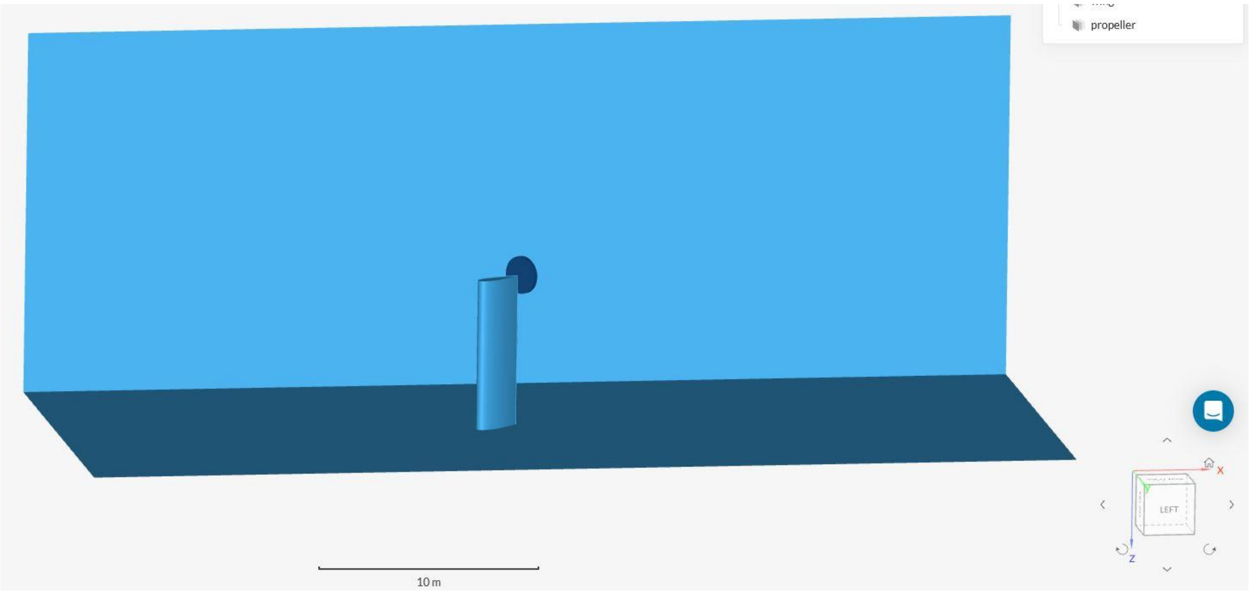

Figure 5. Virtual wind tunnel. Only one propeller zone is visible. The disc seen at the wingtip is the MRF zone which encloses the propeller.

SimScale was run at wind speeds of 4 and 10 m/s, and rotational speeds of 50, 100, 200 and 400 radians/s. The program output provided lift and drag forces as well as moments on the wing and propellers.

3. RESULTS

3.I One propeller only: Wingtip mounted vs mid-mounted

A possible use of the Propeller Sail involves only one propeller on the wing. The question arises: is there an advantage to mounting the propeller at the wingtip as compared to a point closer inboard? CFD runs were made at propeller speeds of 200 rad/s with a relative wind of 10 m/s (the relative wind is the vector sum of the wind and vessel velocities), with the propeller on two positions: on the wingtip and "mid-wing" (2 meters below the wingtip, as shown in Figure 4). The propellers were turning in a contra-vortex direction.

The results are presented on Figure 6. At the conditions tested, the mid-wing configuration generates about 50% more lift, with a 50% higher Lift/Drag ratio than the wingtip mounted configuration.

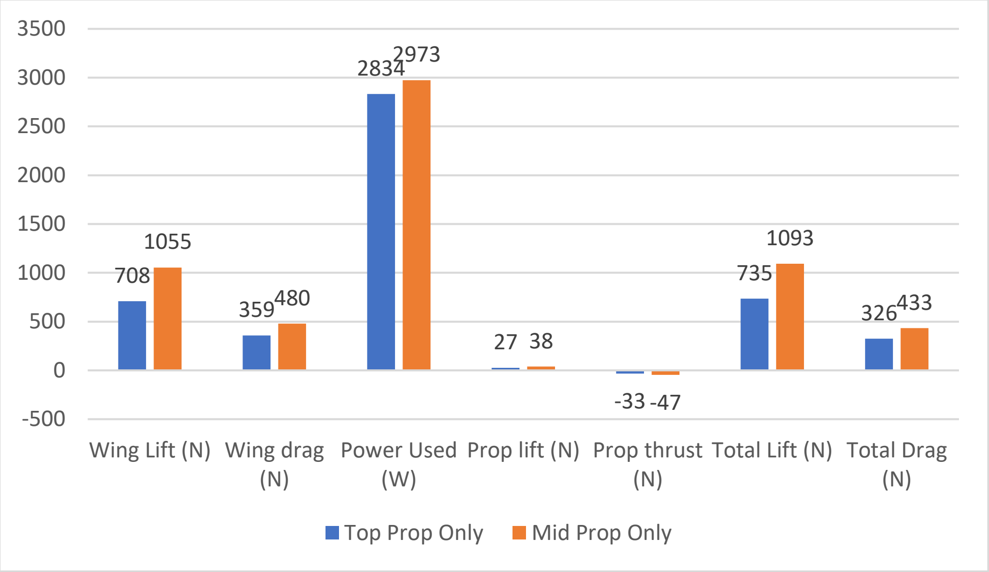

Figure 6. Lift, drag and power for Propeller Sails with wingtip mounting vs mid-wing mounting, at 10 m/s, 200 radians/s, and 30 degree angle of attack.

On figure 6, Wing Lift and Wing Drag represent the force experienced by the wing alone as the propeller turns. We note that the propeller thrust has a component in the opposite direction as the wing drag, and hence has a negative sign. The total lift and total drag represent the sum of wing and propeller forces – the thrust from the propeller has a component that minimizes total wing drag and increases wing lift.

It appears that, if only one propeller is to be used, the mid-wing configuration is the better choice under the limited conditions tested. In [1], it was postulated that the contra-vortex rotation of wingtip mounted propellers could minimize drag, as discussed in [6] and [7], but the results in the current work show that, while the drag force on the wingtip mounted configuration is lower, the lift force is substantially lower. As tested, there does not appear to be an advantage to using a wingtip mounted propeller vs a mid-wing mounted propeller.

3.2 Two-propeller results:

Effect of propeller power:

CFD runs were conducted on the 2-propeller configuration shown in Figure 4. Figure 7 below shows Total lift and drag on the Propeller Sail as a function of total power into the propellers, with a relative wind of 10 m/s. Once can see that, at low power (less than about 2 kW), a small increase in power results in a relatively large increases in lift and drag. At power values greater than about 2 kW, there is a transition in behavior where drag and lift are much less sensitive to power. In addition, drag decreases after the transition point due to the increasing thrust of the propellers.

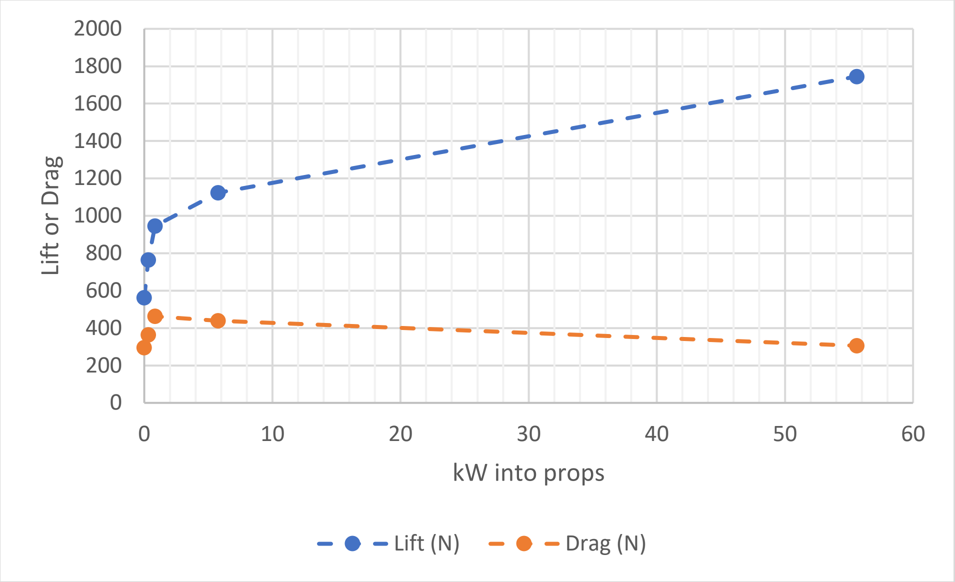

Figure 7. Total lift and drag on the wing (including contributions from 2 propellers), with relative wind speed of 10 m/s.

The change in behavior after the transition may be attributable to the elimination of flow separation on the suction side (top) of the wing. CFD images in Figure 8 show separating flow at 0.3 kW and 50 rad/s, which is well below the transition point occurring at about 2 kW. The figure also shows very little separation at 200 rad/s and 5.7 kW, supporting this hypothesis.

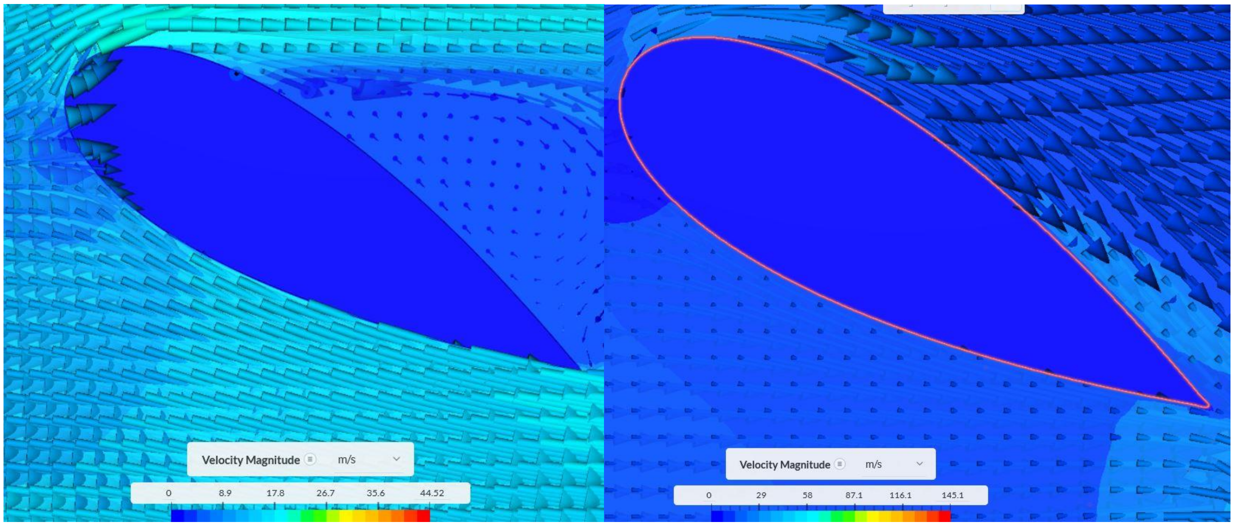

Figure 8. At left, separation at low propeller power of 237 W, and at right, separation is greatly diminished at 5.7 kW.

We may then propose that, below the transition point, any increase in lift is due to a combination of reduced separation and increased flow speed over the airfoil, resulting in a greater rate of change in lift than after the transition point, when lift increases are due to increased flow speed only.

It appears that lift and drag will continue to increase to very high numbers as long as sufficient power is provided.

Effect of incoming flow speed:

As might be expected, the faster the relative wind entering the Propeller Sail, the greater the lift and drag forces. Figure 9 shows that when the propeller is activated there is a proportionately higher increase in lift and drag at low relative wind speeds: at a relative wind speed of 4 m/s, lift increases from 89 to 207 at 1.04 kW (increase in lift by a factor of 2.32 times), while at 10 m/s lift increases from 562 to 945 N (increase in lift by a factor of 1.68 times).

Figure 9 also shows that the lower the wind speed, the less power is required to achieve zero drag.

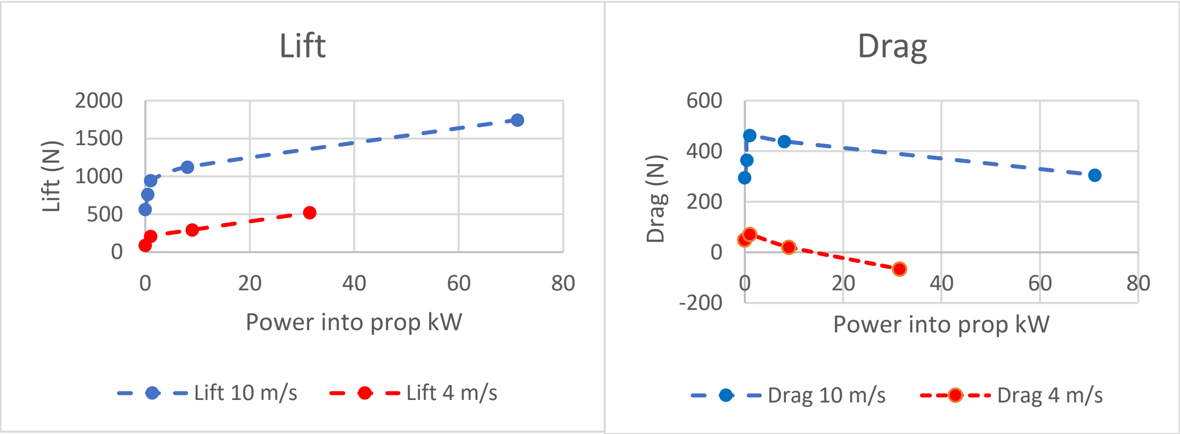

Figure 9 Effect of relative wind on lift and drag of Propeller Sail

Lift and Drag Coefficients

The normal expressions for lift and drag ($Lift\ = 0.5\rho V^2 A$ Cl and $Drag\ = 0.5\rho V^2 A$ Cd, where Cl and Cd are lift and drag coefficients) must be used with care, as Cl and Cd also depend on relative wind speed, propeller size, design, power input, tilt angle, number and arrangement. But Cl and Cd can be useful for comparing very specific Propeller Sail designs with other lift-producing methods at the same wind speed, size and power.

Consider the Cl and Cd plots for two identical Propeller Sails, but exposed to different relative wind speeds, as shown in Figure 10. The blue lines represent Cl, and the red lines Cd. Solid lines are at 10 m/s and dashed lines at 4 m/s. Clearly, despite the Propeller Sails being identical, the lift and drag coefficients at one relative wind speed can be quite different from lift and drag coefficients at another wind speed.

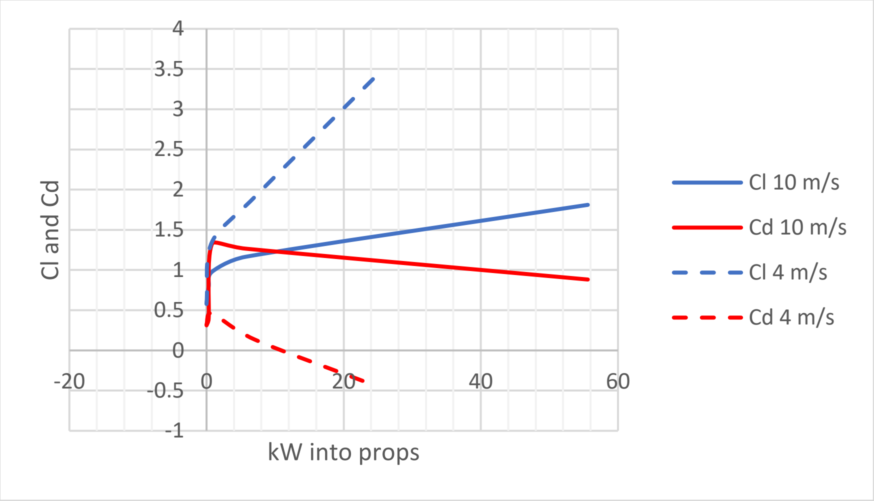

Figure 10. The effect of wind speed and power on Cl and Cd.

We note that turning on the propeller power to about 24 kW caused an increase in Cl by a factor of almost 6 times, for 4 m/s wind speed from 0.46 to 3.4. At about 0.7 kW, the lift coefficient increased by a factor of about 3 times, from 0.46 to 1.34. The rather low non-powered wing lift coefficient of 0.46 is due to the 30 degree angle of attack of the wing.

Propeller Performance Characteristics

SimScale CFD software gives moments (Mx, My and Mz) and forces (Fx, Fy and Fz) on the propellers in the x, y and z axes. These were used to calculate propeller parameters:

Thrust $= (Fx^2 + Fy^2 + Fz^2)^{1/2}$ (1)

Torque = $(Mx^2 + My^2 + Mz^2)^{1/2}$ (2)

Thrust Coefficient Ct = $\frac{Thrust}{\rho D^4 n^2}$ (3)

Torque Coefficient Cq = $\frac{Torque}{\rho D^5 n^2}$ (4)

Power Coefficient Cp = 2 π Cq (5)

Advance Ratio J = $\frac{V}{n\,D}$ (6)

Efficiency = $\frac{Ct\,J}{Cp}$ (7)

Power = Torque x nrad (8)

In the equations above, ρ is air density = 1.22 kg/m^3, D is the propeller diameter, n is the propeller revolutions/s and nrad is propeller radians/s.

Figure 11 below shows the very low efficiency of the propeller mounted at mid-wing, as a function of advance ratio J. As mentioned earlier, the propeller was a “stock” open-source model from a 3D model website [4] which was not optimized in any way. Real propellers can have efficiencies of about 0.8 and greater, and have efficiency plots of similar form to Figure 11 [7].

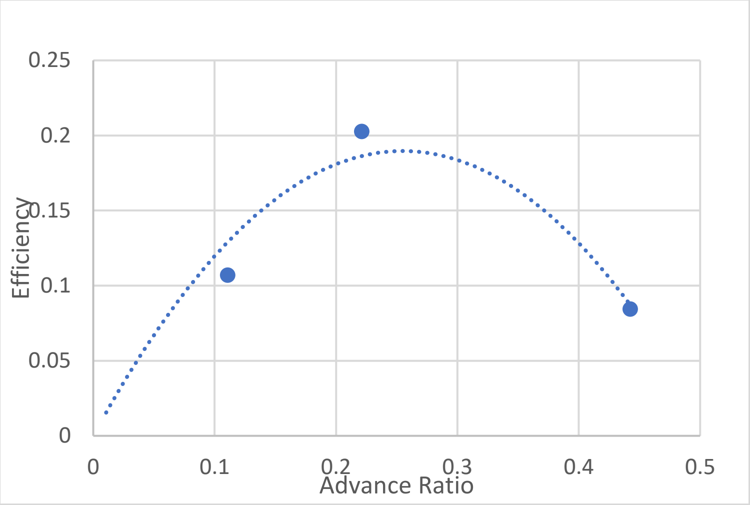

Figure 11. Mid-Wing propeller efficiency at 10 m/s relative wind velocity.

Comparison with Flettner rotors

The authors of [8] give lift, drag and power data for Flettner rotors with infinite aspect ratios at Reynolds numbers of 1.8E5 to 1E6. Data from [8] were used to produce Figure 12, which shows Cl and Cd as a function of spin ratio ($V_{\text{tangential rotor}}$/ V_{wind}), as well as Figure 13 showing Power coefficient $Pw = \frac{Power}{\frac{1}{2}\rho V^3 Area}$. The area is the product of Flettner rotor's height and diameter.

The Flettner rotor and Propeller Sail were compared at the same wind velocity (4 m/s) and dimensions (6.9 m x 2.29 m), but not at the same aspect ratio. The effective aspect ratio (wingspan x 2 / chord) of the Propeller Sail wing is 6, while that of the Flettner rotor from [8] is infinite (the rotor extended to the top of the wind tunnel test section). In [9], the authors tested Flettner rotors at a variety of aspect ratios. It appears that, at the Flettner rotor spin ratio of 1.8 used here, the effect of aspect ratio on the lift forces from 6 to 8 is relatively small, indicating that the difference in Cl between AR = 6 and AR = ∞ might give an advantage to the Flettner rotor on the order of about 10%.

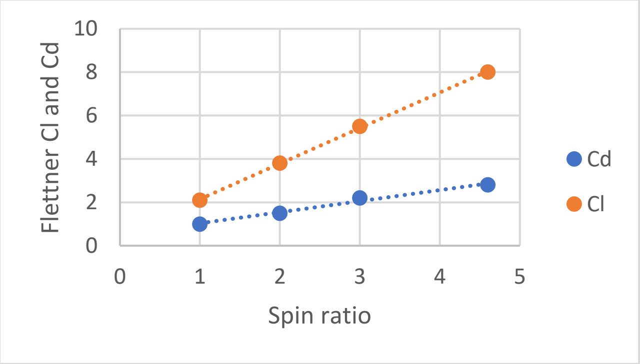

Figure 12. Cl and Cd results (for Flettner rotor) as a function of the spin ratio $V_{tangential}/V_{freestream}$.

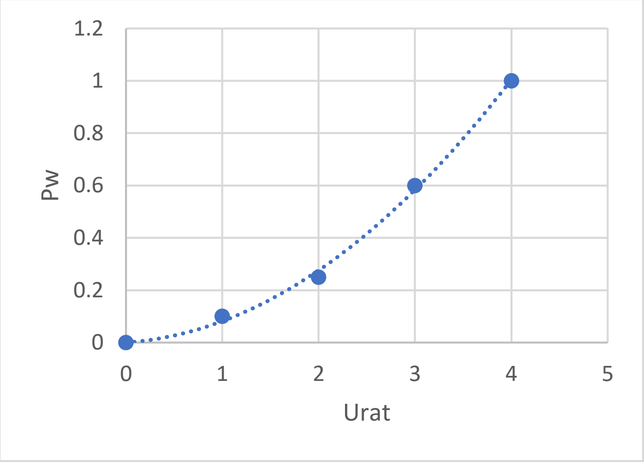

Figure 13. Flettner rotor Power Coefficient Pw as a function of spin ratio.

Figure 14 below shows that the Propeller Sail requires about 4 times the power as the Flettner rotor to produce the same lift coefficient of 3.4 at 4 m/s wind speed.

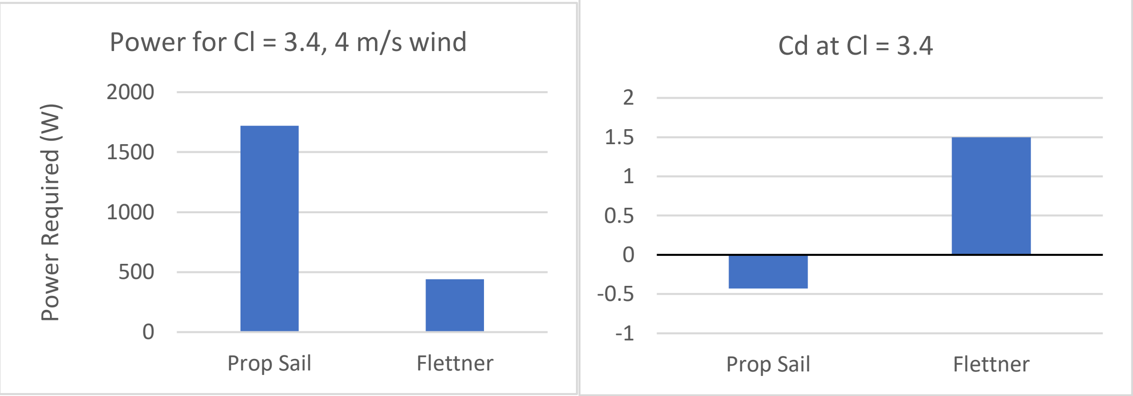

Figure 14. Left: Power required (Watts) for Cl = 3.4 in 4 m/s winds. Right: Drag coefficient Cd at Cl of 3.4.

Since the efficiency of the propeller is so poor, in Figure 14, the "Power required" for the Propeller Sail has been multiplied by the calculated efficiency 0.0570 and divided by 0.8, to represent a more reasonable estimate of power to turn the propellers.

The drag coefficient shown on Figure 14 gives reason for optimism: the Propeller Sail has a negative drag coefficient, indicating that downwind drift is being resisted by the propeller thrust, while the Flettner rotor gets pushed downwind. The upwind force created by the Propeller Sail can be traded for greater lift by tilting the propeller further into the wind.

3.3 Model testing Results

A ship model was assembled using a discarded 1m balsa hull with similar lines to a Series 60 C2 ship, a multi-engine model airplane wing, electric motor/propeller, battery, and radio control equipment, seen in Figure 15 before and after finishing. Since to the best of our knowledge a ship like this had never been built, the goal of the tests was modest: to determine if there were any obvious impediments to using the Propeller Sail concept to move a ship.

The propeller spin rate and rudder could be controlled remotely, but the angle of the sail relative to the ship model was set before each run. The propeller spun in a contra-vortex direction.

Figure 15. Ship Model before- and after full assembly. Figure at right shows remote controlled rudder and propeller. The aileron was not used in tests.

The ship model was ballasted to bring the water level to the fully-laden design water line. Tests determined that:

- The ship model can stably move in any direction into the wind when power is applied.
- Rudder control is quite effective as long as speed is not too low.
- The ship model sailed quite well with and without the propeller activated.
- When the ship model was in pure sailing mode, an increase in speed was evident when the engines were activated even at relatively low propeller RPM's.
- Application of maximum power in directions away from the longitudinal produced a noticeable (but not de-stabilizing) list. This was at power levels far higher than what might normally be used.

Videos of the model may be seen at:

- Downwind run with low power on https://youtu.be/ofmo3aFl0nc

- Moving directly into wind at low power, followed by downwind turn: https://youtu.be/D13Rzl8eIHI
- List when high power is applied while sailing downwind: https://youtube.com/shorts/bO34Hl8lSBo
- Two laps in light winds using two levels of power: https://youtu.be/MuRGIxDHTfU

4. CONCLUSIONS

Our results show that the Propeller Sail, a concept still in its infancy, requires further study to determine its viability for wind-assisted shipping, especially in bringing power consumption to levels similar to Flettner rotors. This may be possible by using smaller propellers than used here, by designing propellers specifically for Propeller Sail use and by adjusting the position and orientation of the propellers relative to the wing. The use of wingtip fences as in [6] and [7] may be beneficial as well as investigating airfoil profiles other than the NACA 0030.

Nevertheless, the results are encouraging, as the Propeller Sail was shown to produce negative drag coefficients that resist or negate the downwind drift normally experienced by sailing vessels, while concurrently generating lift.

Also, to be considered in any viability analysis are the fuel savings the Propeller Sail might afford when used in pure sailing mode, the maneuvering benefits of bow and stern Propeller Sails, as well as the reduction in hull drag and ship construction costs that using only wing-mounted engines might provide (that is, no conventional propeller under the water surface).

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[2] SimScale, https://www.simscale.com

[3] OpenFOAM, https://www.openfoam.com

[4] Validation Case: Drone Propeller Study, https://www.simscale.com/docs/validation-cases/drone-propeller-study/

[5] GrabCAD, https://grabcad.com

[6] Effects of wingtip-mounted propeller on wing lift, induced drag and shed vortex pattern; M. Snyder, Ph.D. thesis, Oklahoma State University, May, 1967

[7] Wingtip-mounted propellers: aerodynamic analysis of interaction effects and comparison with conventional layout; Tomas Sinnige, Tom Stokkermans, Nando van Arnhem, Georg Eitelberg, Journal of Aircraft, November 2018

[8] Experiments on a Flettner rotor at critical and supercritical Reynolds numbers G. Bordogna, S. Muggiasca , S. Giappino, M. Belloli, J.A. Keuning, R.H.M. Huijsmans, A.P. van 't Veer, Journal of Wind Engineering and Industrial Aerodynamics, 188 (2019) 19-89 https://doi.org/10.1016/j.jweia.2019.02.006

[9] Flettner Rotor Concept for Marine Applications: A Systematic Study, A. De Marco, S. Mancini, C. Pensa, G. Calise, and F. De Luca, International Journal of Rotating Machinery Volume 2016, http://dx.doi.org/10.1155/2016/3458750

Appendix:

```
****************************************************************************
**********************************
SimScale incorporates Simulation Modeling Suite(TM) software by Simmetrix
Inc. © 1997-2023. All Rights Reserved.
****************************************************************************
**********************************
Model import took 4.631900971s.
Maximum precision of model and its entities: 2.7244077608409207e-05 m.
Absolute small feature tolerance: 0.00024578644961199104 m.
Surface meshing took 3m35.820114222s.
Number of cells after 5m23.748154465s: 319692
Number of cells after 7m11.640438659s: 9124597
Number of cells after 8m59.550717453s: 11935179
The mesh may be finer than desired. Please check the model and the mesh
settings
Number of cells after 10m47.497306174s: 11576363
Number of cells after 12m35.421802035s: 13202029
Number of cells after 14m23.312525853s: 14528030
Number of cells after 16m11.190953464s: 13264977
Number of cells after 17m59.110667262s: 13263074
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Mesh quality metrics:
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Acceptable range: 0 to 100
        min: 1.0000000000000009
        max: 20.078545752398234
        average: 1.6921194980580068
        standard deviation 0.2602519165882951
        median: 1.6854332552083646
                99.9-th percentile: 2.669404959272894
                99.99-th percentile: 7.2847162902410245
                99.999-th percentile: 11.210901206392863
quadMaxAngle
Acceptable range: 90 to 200
        min: 89.50855908783534
        max: 206.13586363715666
        average: 90.17323720538215
        standard deviation 2.1971038468751374
        median: 90
                99.9-th percentile: 128.47631900015136
                99.99-th percentile: 156.08465130182734
                99.999-th percentile: 175.11571470369145
triMaxAngle
Acceptable range: 60 to 160
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        average: 80.18341966910695
        standard deviation 13.015130217014363
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Acceptable range: 0.035 to 1.0
Overall mesh quality is computed from:
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1.00)
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A Service-Pattern Sail Freighter: The Need For A Scalable Open-Source Sail Freighter Design.

Steven Woods

Abstract: As sail freight gains traction in the sustainable shipping debate, there is a need for accessible and versatile coasting ship designs capable of serving a wide variety of harbors, which can be built quickly and at relatively low capital intensity. These vessels will then take over what would otherwise be mid to long distance transport by rail or road along the most congested corridors in the US using near-zero carbon emissions propulsion. This not only reduces emissions from the transport itself, it reduces congestion and makes the entire land transportation system more efficient and safe.

These vessels must be made to fit regulatory boundaries for captain licensing, length, tonnage, etc. There is a distinct need for a liberty-ship like sail freighter specifically maximizing each step of the regulatory ladder to encourage the building and operating of these coastal traders in the Northeastern US. The uninspected cargo vessel category is already covered by a variety of simple and easily available vessel designs which can be modified for cargo use and built inexpensively as Farmer's Ships and other democratic pilot projects in plywood or other less-durable materials.

The proposed modular/scalable sail freighter design is still theoretical and requires the attention of a naval architect but lays out the requirements for such a set of vessels. By designing around regulatory and small harbor restrictions, this design attempts to get the absolute maximum out of each category to allow for a rapid build-out of a coastal sailing fleet. These vessels will be relatively low capital, require only small crews, and serve as a proving and training ground for an expanding windjammer fleet. The proposed vessels will be single chine steel hulls in four sizes, and with two possible rigs. A loaded draft of 6-8 feet allows for use of a wide range of harbors, single chine construction in steel simplifies and speeds construction. The choice of simple gaff or marconi schooner rigs broadens the applicable regions and trade which the vessels can effectively undertake. The application of roller furling, and modern winches keeps crew requirements relatively low.

Where designs which fit or nearly fit these requirements exist, they should be bought out (including any necessary modifications) and made open source where possible. This set of designs may be a good starting place to make this effort realistically possible and immediately implementable. Further work can be started from this foundation or started anew, depending on where interest and funding can be acquired.

Keywords: Sail Freight, Small Vessels, Coastal Trade, Open Source, Wind Propulsion.

The use of sail freight for displacing cargo from land-based modes to seaborne zero emissions transport is a viable and historically proven way to reduce energy requirements and carbon emissions. The theoretical economic and emissions benefits of wind propulsion for large vessels on transoceanic routes has already been established by several studies,[1,2] but there has been little attention paid to the potential carbon offsetting available from coastal

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[1] 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. www.jmwe.org/uploads/1/0/6/4/106473271/jmwe_17_august_2021.pdf (Accessed 22 Jan 2022)

[2] Wind Ship Development Corporation, *Wind Propulsion For Ships Of The American Merchant Marine* Norwell, MA: WSDC, 1981. books.google.com/books/about/Wind_Propulsion_for_Ships_of_the_America.html

trade under sail.[3] The use of sail in coastal trade reduces particulate emissions, noise pollution, traffic congestion, and their associated medical and climate impacts in both port areas and directly inland.[4] These are desirable in terms of transport decarbonization and as a form of jobs program for the maritime trades, however, the main bottleneck in the short- to mid-term will be producing a sufficient fleet of windjammers to take up the cargo necessary. For example, New York City, if provided with its minimum food needs by sail, would require around 2 million tons of shipping. The majority of current sail freighters worldwide are refit vessels which were built decades ago, and the supply of these vessels is extremely limited, even including the addition of rigs to motor vessels below 300 tons as was accomplished with the currently-serving SV *Kwai* and others during the 1970s Oil Crisis.[5] Construction of a large fleet in a short time will be necessary to ensure there is sufficient transport capacity to feed major cities without cooking the planet.[6]

There are few available plans for sail freight vessels currently available, and most of these are optimized for sailing, as opposed to getting the maximum out of the restrictions they will have to operate under. These restrictions come not from harbor depths, air draft, or other physical restrictions, but principally from regulatory barriers such as inspection requirements, captaincy license categories, and the availability of trained crew. These constraints will likely be the main things which need to be kept in mind and designed around. The second priority is to design for simple, rapid construction of a large fleet. These regulatory hurdles can be maximized as much as possible through good design around these constraints before others.

Vessels under 15 GRT and 40 feet in length fall under the heading of Uninspected Cargo Vessels and should be included in this design process for a number of reasons. These are already covered by a number of designs suitable for backyard boatbuilding, such as a number of plans by George Buehler,[7] Bruce Roberts,[8] and the now open-source plans of the Vermont Sail Freight Project's sailing barge *Ceres*.[9] These (very) small vessels are well suited to the role of Farmer's Ships,[10] feeder vessels, operations in low volume trade routes, and where unlicensed sailors are the only crew available. They are a form of democratic and egalitarian sail freighter which will likely proliferate in the near future, especially as scout ships establishing trade routes. In many ways, these are frontier vessels like the Scow Schooners of the 19th century Great Lakes and other locations, mostly made where low

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[3] Woods, Steven, and Sam Merrett "Operation of a Sail Freighter on the Hudson River: Schooner Apollonia in 2021." *Journal of Merchant Ship Wind Energy* 2 March 2022. www.researchgate.net/publication/358971392

[4] American Society Of Civil Engineers. *2021 Report Card For America's Infrastructure: A Comprehensive Assessment Of America's Infrastructure*. Reston: ASCE, 2021. https://infrastructurereportcard.org/

[5] C.J. Satchwell "Preliminary analysis of of log data from the Fiji windship 'Cagidonu'" Ship Science Report No. 24 (University of Southampton, April 1986) www.wind-ship.org/en/research/

[6] Woods, Steven. "Sail Freight Revival: Methods of calculating fleet, labor, and cargo needs for supplying cities by sail." Master's Thesis. Prescott College, 2021. www.researchgate.net/publication/354841970

[7] Buehler, George. *Buehler's Backyard Boatbuilding*. Camden: International Marine, 1991.

[8] Bruce Roberts *Roberts Yacht Design*. https://bruceroberts.com/ Accessed 14 May 2023.

[9] Woods, Steven, (Editor). *The Sail Freight Handbook* 2ed. Kingston: Center for Post Carbon Logistics, 2023. www.postcarbonlogistics.org/publications

[10] Shaw, Earl B. "The Aland Islands." *Economic Geography* 15, no. 1 (1939): 27–42. DOI: 10.2307/141003.

capital reserves and limited skill were the limiting factor in shipbuilding,[11] and will likely have an economic role similar to the Galway Hookers of Northwestern Ireland.[12] However, they cannot reasonably take up the strain of longer trunk routes, high-volume packet routes, or transoceanic trade where the larger Service-Pattern vessels will have a more prominent role.

Despite the passing of the 1969 convention on tonnage measurement of ships, US regulations are still written using Gross and Net Register Tons of 100 cubic feet each for regulatory purposes.[13] There have been a number of ship designs based around maximizing profits through manipulating multiple tonnage systems; in many cases this has both endangered ships and their crews.[14] This should be avoided for any open-source sail freighter, as the maximization is not for profits, but the optimal use of captain’s licenses. Care should be taken to make these designs compatible with STCW and other similar regulations, including measurement under the 1969 Convention rules; this makes for simpler regulatory compliance and easier adoption worldwide. Keeping lengths under 24 meters, for example, solves two problems: The vessels need not be measured under the Convention rules, and most STCW regulations will not apply.[15] Similarly, for inclusion under USCG subchapter T regulations the vessel must be under 65 feet in length, which may be quite possible for the 25 and 50 GRT vessels described in this paper. As the vessels grow larger, they will need to abide by progressively stricter regulations, but these vessels will require a much higher capital outlay regardless, and their crews will need to become progressively more professional. This is a good thing, and these regulations exist for very good reason; however, there is no reason to have a potentially viable ship design become unavailable to a sail freight endeavor simply because it is two feet too long or 1.5 GRT over a regulatory limit as is the case with some designs discussed in this paper.

The proposed service pattern sail freighters should fit the available licenses, all of which are *up to* the tonnage limit. This means each should be just barely shy of the targeted number, for example 14.9/24.9/49.9/99.9 GRT, but labeled for convenience at the next full integer. As they are designed as coasters, there is less worry about STCW requirements, though compliance would not be amiss for the larger vessels as it will open up further markets if they can trade easily across international borders. The basic requirements of the designs are as follows:

Service-Pattern Schooner Requirements:

☛ 4 Hull varients: 15GRT/25GRT/50GRT/100GRT
☛ 2 Rig variants: Schooner (Marconi and Gaff).

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[11] Martin, J. C. “‘Scows, and barges, or other vessels of box model’: Comparative capital investment in the sailing scows of the Great Lakes of North America and in New Zealand.” *Int’l Journal of Maritime Hist*, 30(1), 2018. 89–105. doi.org/10.1177/0843871417746290

[12] Ó Sabhain, Pádraig Seosamh. “The centrality of the Galway hooker to dwelling in the island and coastal communities of south west Conamara.” PHD Thesis. NUI Galway, 2019. https://aran.library.nuigalway.ie/handle/10379/15935

[13] USCG Marine Safety Center. *TG-1 CH2 Simplified Measurement.* Washington: US Coast Guard, 2022.

[14] Vasudevan, Aji. “Tonnage measurement of ships : historical evolution, current issues and proposals for the way forward” Master’s Thesis. World Maritime University, 2010. https://commons.wmu.se/all_dissertations/214/

[15] USCG Marine Safety Center. *TG-1 CH2 Simplified Measurement.* Washington: US Coast Guard, 2022.

☛ ≤ 9 foot loaded draft.
☛ CDWT of at least 7.5/15/35/70 tonnes at Stowage Factor of 2.6 m^3/tonne.
☛ Simplified, inexpensive, rapid construction in steel.
☛ 15/25 GRT model should include scantlings for plywood home builds.
☛ Under 65 feet LOA where practicable (T-Boat Regulations).
☛ Sufficient motor power for docking and emergency use.
☛ Small enough fuel or energy storage to prevent reliance on motoring.
☛ Optimized for breakbulk/palletized/super sack (non-containerized) cargo.
☛ Sufficient ship’s gear to handle drafts to and from the dock.
☛ Use of roller furling, winches, etc. to reduce crew requirements.

Single chine construction and avoidance of complex curves wherever possible will make the construction not only faster, but simpler and possible without a large amount of specialized equipment. By keeping the crew requirement low through the application of winches and other mechanical aids, the cost of operation will be kept to a reasonable minimum, an important consideration for these vessels as the energy transition is in early stages. As the freight rates of trucks and trains are kept artificially low by a number of factors,[16] and these are the modes which coastal and inland trade will be competing against,[17] labor aboard these vessels must be kept to a safe minimum. Additional crew members who are included simply for hauling on lines make no sense when winches can do the same job reliably for a fixed initial cost.

These vessels should be able to provide a wide range of services on varied waters and at varied levels of capital intensity. Further, they can be grown with the fleet’s demands and the captain’s license tonnage, while serving as training vessels for deckhands and other crew members. The most common types are likely to be 50 and 100 GRT types. However, the inclusion of the 25 GRT vessel is important due to the likely prevalence of 25 GRT Masters when compared to other license types. These smaller schooners will also have a role to play as feeder vessels, training platforms, and scouting ships for new markets, so their construction should not be ignored or belittled in favor of the more capital-intensive larger vessels.

The use of traditional sail and traditional rigs is well supported in this role by several factors: Traditional sail is well understood, has low capital requirements, and performs well in a wide variety of conditions.[18] In the sizes of vessel dealt with here, not all crew need be licensed, which simplifies most recruitment issues which might arise. There are a wide variety of training programs through commercial and recreational associations on the handling of traditional sail in a racing or cruising context, as well as training on square rig sailing from organizations such as Tall Ships America. Trained sailors will therefore be easier to find for these vessels than for a flettner rotor equipped ship, and the rig will be more affordable overall. The strategic materials and energy requirements of traditional rigs are

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[16] Austin, David. *Pricing Freight Transport to Account for External Costs*. Washington: Congressional Budget Office, 2015. https://www.cbo.gov/sites/default/files/114th-congress-2015-2016/workingpaper/50049-Freight_Transport_Working_Paper-2.pdf.

[17] Woods and Merrett “Operation of a Sail Freighter on the Hudson River”

[18] Scott, H.F. Morin. “The Case For Traditional Sail.” *Journal of Wind Engineering and Industrial Aerodynamics* 19(1-3), (1985) 335-349. doi.org/10.1016/0167-6105(85)90068-6

also low, making them a more climate positive option than more complex systems better left to larger vessels.[19] Schooners are also a highly efficient rig in terms of crew requirements, an in 1906 averaged a crew of 5 and 42.9 Tons Per Sailor, though they ranged from 10-4914 Net Register Tons, across a sample of 5,947 vessels.[20] On a less objective note, there are also few things more worth watching than a traditional sailing vessel making its way up the coast, and this romantic, esthetic appeal may well be a significant influence on getting a sufficient mass of people behind the sail freight movement to keep it commercially viable. Flettner Rotors, Wing-Sails, and similar modern wind propulsion techniques lack this particular quality.

There are similarities between the proposed Service Pattern vessels and oil-crisis era vessels, such as those proposed for use in the Kingdom of Tonga,[21] among others. Some of these designs already effectively exist and can be purchased into the open source field without much further modification or effort beyond funding the purchase. For example, Tad Robers has a cargo schooner design which fits these requirements, but at 60 feet the larger design is 28.6 GRT, as opposed to the 25 which should be targeted.[22] The proposed Electric Clippers of Derek Ellard are specifically designed for mass production, and fit some of these requirements as well at various sizes.[23] The River Sea Ship designed by Trans-Tech Marine for NYSERDA in 2015 is a similar idea, and currently open-source.[24] Another open source design by the Greenheart Project is slightly too large for the 100 GRT license.[25] A cargo schooner design by Thomas Colvin, found in his book *Steel Boat Building,* is available but not only exceeds the Uninspected Cargo Vessel parameters for length overall, it carries only 7 tons of cargo, making it effectively uneconomical due to initial cost and possible revenue with such a small hold capacity in a license-demanding vessel size.[26] The use of unmodified historical designs, while viable, are still unlikely to max out the regulatory categories necessary to maximize the utility of a modern fleet.[27]

Avoiding cargo containerization for these vessels is an important point. Not only is moving containers a waste of space and energy,[28] it is inefficient at this scale of operation. Palletization should provide all the necessary efficiency gains from unitization without a significant investment at every port to handle containers. Specifically, the Euro-Pallet

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[19] Woods, Steven. "Strategic Materials, Maritime Trade, And The Energy Transition" *Proceedings Of The International Academic Conference On Shipping, Sustainability & Solutions*. Hamburg: KLU, 2023. www.researchgate.net/publication/369033136

[20] Woods, Steven. "Sail Freight Revival"

[21] Palmer, C. and E.M.J Corten "Preliminary Design Study Of Intraisland Transport Vessels For The Ha'apai Group Of Islands In The Kingdom Of Tonga." Pp 133-172 *Proceedings of Regional Conference on Sail-Motor Propulsion.* Manila: Asian Development Bank, 1985.

[22] Tad Roberts Yacht Design. "60 Ft Cargo Schooner" www.tadroberts.ca/services/new-design/sail/steelcargoschooner60 And email correspondence with Tad Roberts, 29 August 2022.

[23] Ellard, Derek. "Electric Clipper 100." . Accessed 30 November, 2020. www.gosailcargo.com.

[24] Uttmark, Geoff. *Eriemax: Assessment of Green Ship Technologies and Plan for Deployment on the Erie Canal/NYS Barge Canal System* New York: NYSERDA, 2015.

[25] Scherpenhuijsen Rom, Erik, Et Al. "Evaluation and Adaptions to the Greenheart Project zero-emission vessel for service in the Pacific Islands." *International Journal of Maritime Engineering* 163:A4 (2021) www.intmaritimeengineering.org/index.php/ijme/article/view/735

[26] Colvin, Thomas. *Steel Boat Building*. 2 Vols. Camden: Internat'l Marine Publishing Co, 1985.

[27] Davis, Charles G. *American Sailing Ships: Their Plans And History* Mineola: Dover Publications, 2012.

[28] Woods, Steven. "Strategic Materials, Maritime Trade, And The Energy Transition"

dimensions should be used due to their provision for full and half pallets which can be used according to the ship's hold size.[29] Ship's gear can handle palletized or breakbulk cargo without a significant challenge or supporting infrastructure, a critical consideration when

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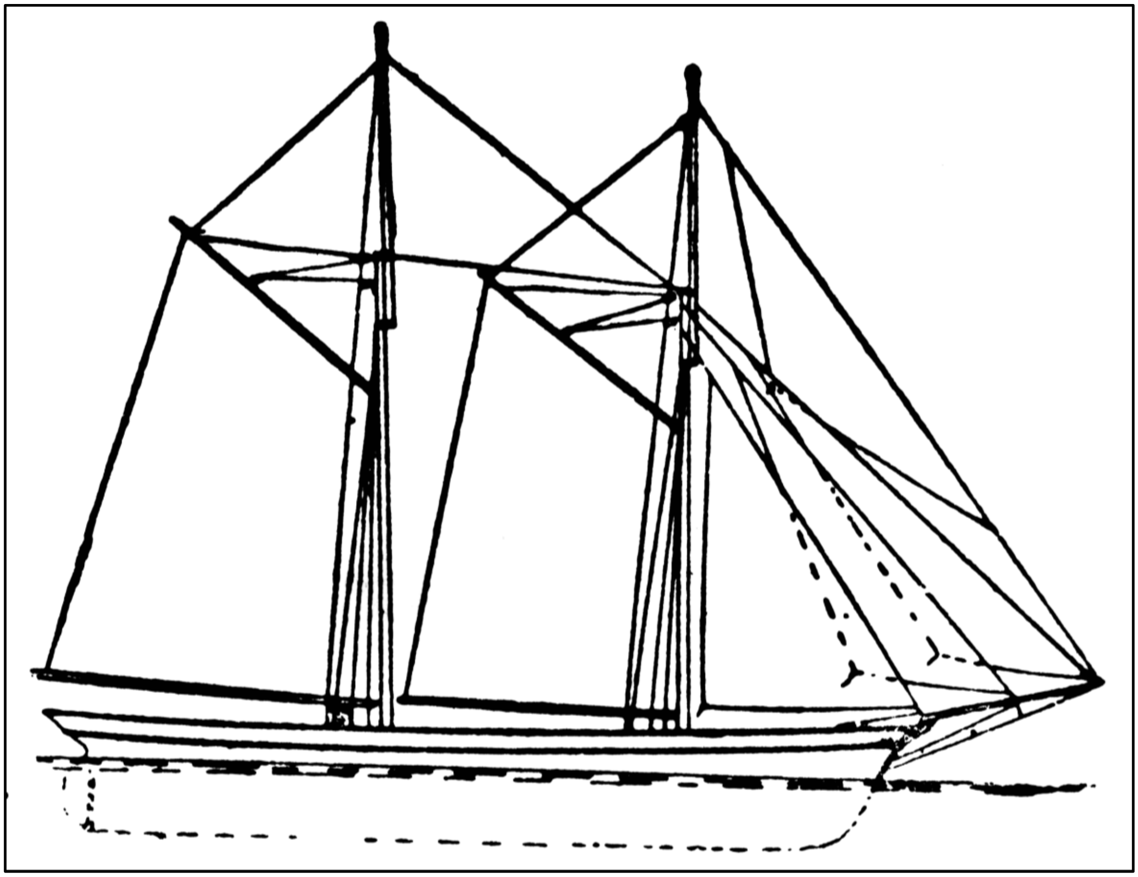
[29] EPAL. "Load Carrier Overview" www.epal-pallets.org/eu-en/load-carriers/overview Accessed 14 May 2023.



Schooner Illustration from Mee and Thompson, *The Book Of Knowledge* 1912.

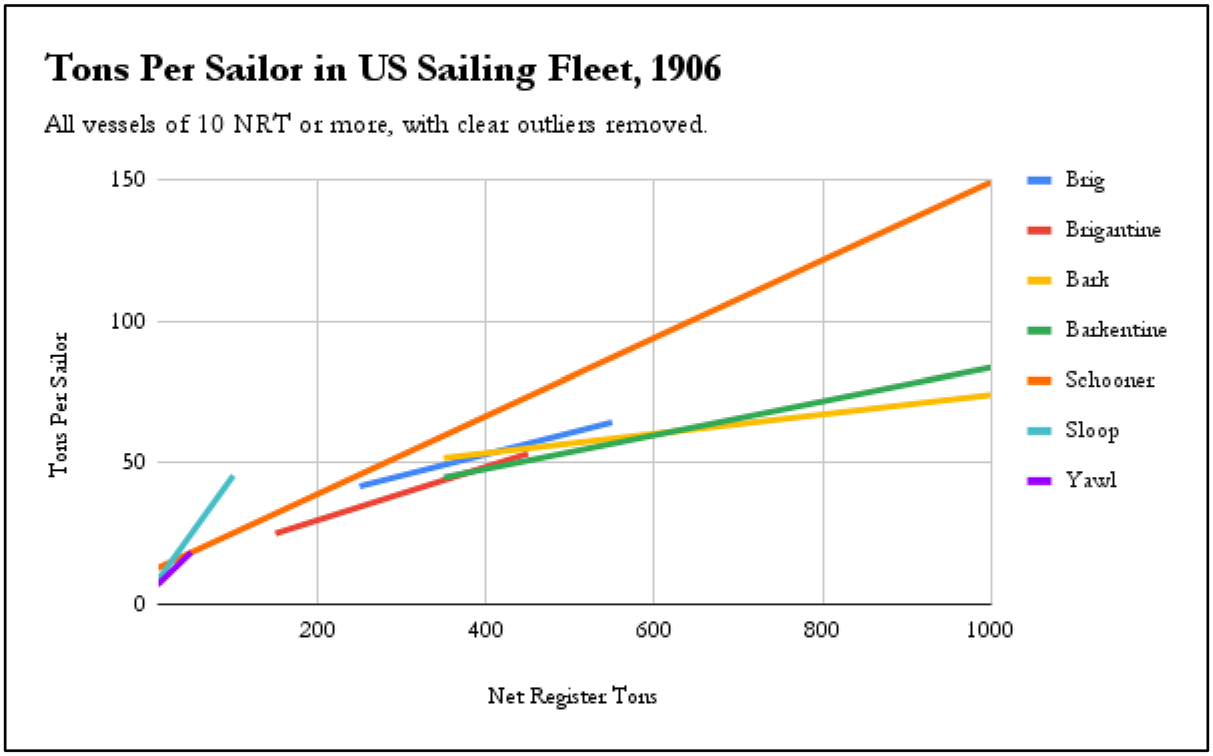


Image from Woods (ed), *Sail Freight Handbook* pp 35. CC-BY-NC-ND 4.0.

small ports are just re-establishing cargo operations,[30,31] with the additional benefit of loading and discharging cargo in a fifth of the time needed for breakbulk handling.[32] Most commodities which are easily shipped by sail freighter can be or are shipped with the highest economic efficiency on pallets or in super sacks, as this reduces labor and handling significantly compared to breakbulk handling. As sailors will likely have to be their own dockers through the early stages of the sail freight resurgence, there is a great advantage to be found in reducing dockside labor wherever possible. For short-sea container traffic, other designs will be needed, such as the Electric Clipper 180 designed by Derek Ellard.[33]

With the smallest Oceans license granted by the US Coast Guard being 200 GRT, and this being applicable to near-coastal waters as well, it would be logical to extend the design to 200 GRT. This would require further regulatory compliance work, such as meeting STCW requirements. These vessels would likely be involved in mostly longer distance trade such as long coastal runs between larger ports, and transoceanic trade in coffee, alcohol, and other high-value cargo in the early stages of their deployment. Whether a single chine simplified design for these larger vessels would be wise is a question for naval architects to answer. Vessels over 100 GRT should not be considered a priority for the early stages of this effort, however, and can be derived from the initial designs at a later date if needed.

A prudent designer for these vessels might also apply the same principles to canal boats, fitting them to the dimensions of the New York State Canal and other significant inland waterway lock and prism dimensions. The 15/25/50/100 GRT steps to suit captaincy requirements and keeping to less than 65 feet whenever possible to stay under T-Boat regulations will still apply; the greatest variation will be in the powering of the hulls and energy storage for a preferably electric motor vessel. Use of Lead-Acid batteries as dual-purpose ballast and a generous amount of charging capability should be included, by whatever means are available. Placing ship's gear in a tabernacle or other foldable mounting will also be important anywhere there are air draft restrictions, such as the 14-foot limit on the New York State Canal System. Again, some designs which can be adapted or used directly already exist, such as the River Sea Ship by Trans-Tech Marine, but they are not optimized for the regulatory categories treated in this paper.[34]

Similarly, for areas where a transition between canal and more open water environments are going to be frequent, such as the New York State Canals in the Central New York and Finger Lakes Regions, as well as small routes in many other areas, a derivative of the Norfolk Wherry would be in order. This vessel, if copied at similar tonnages (15/25/50) provides several advantages in its design for vessels in and out of canals frequently, notably the counter-weighted mast and tabernacle arrangement which made sailing in canals and the Broads viable.[35] For this particular vessel, removing or adding

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[30] Woods, Steven, (Editor). The Sail Freight Handbook

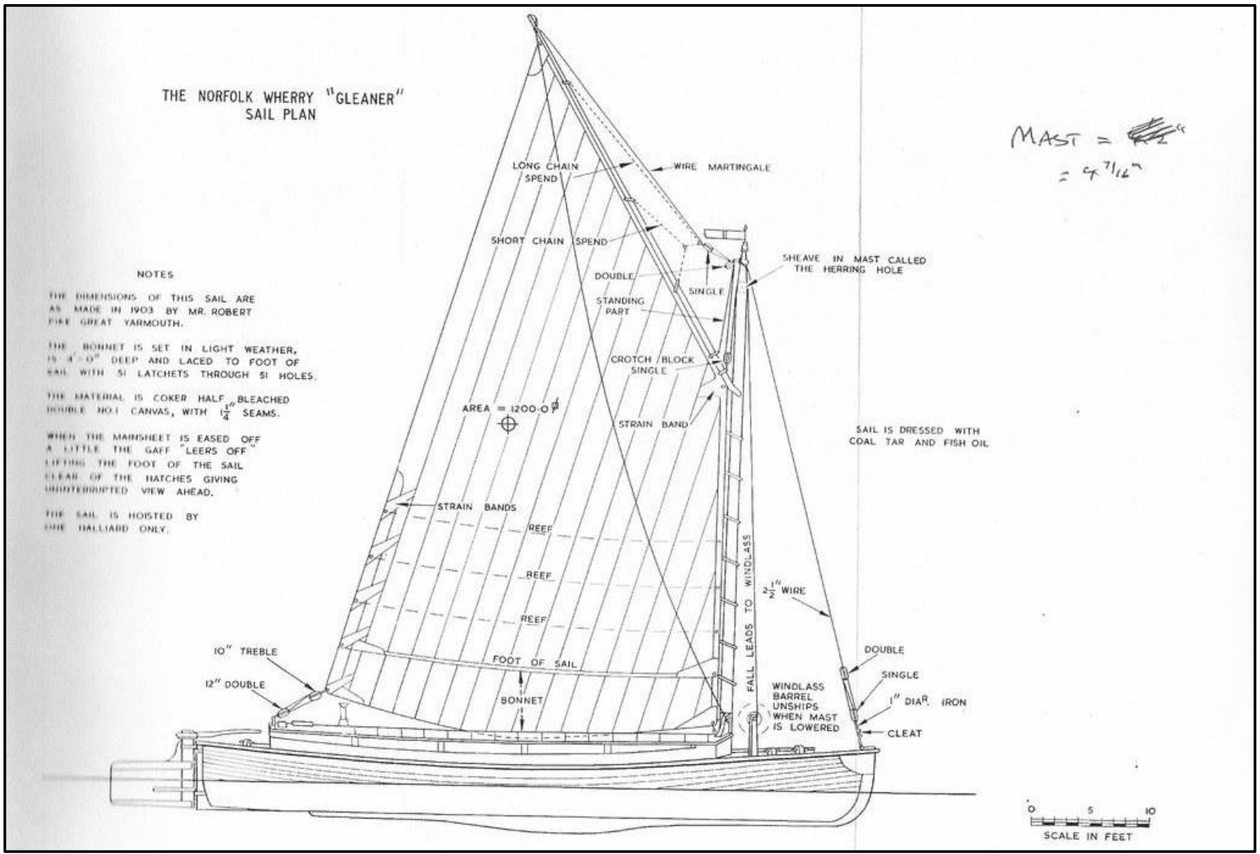
[31] Koltz, Bruce George. "The reintroduction of sail for marine commerce: and the consequent effects upon small port economy and trade routing" Master's Thesis, University of Notre Dame, 1980. https://calhoun.nps.edu/handle/10945/19039

[32] Janice Goertz. "Unitization in Distribution" in Business Logistics P.M. VAN BUYTENEN (Ed.) The Hague: Martinus Nijhoff, 1976. Pp 210

[33] Ellard, Derek. "Electric Clipper 180." Accessed 30 November 2020. www.gosailcargo.com.

[34] Uttmark, Geoff. *Eriemax.*

[35] Wherry Maud Trust https://wherrymaudtrust.org/ Accessed 15 June 2023.



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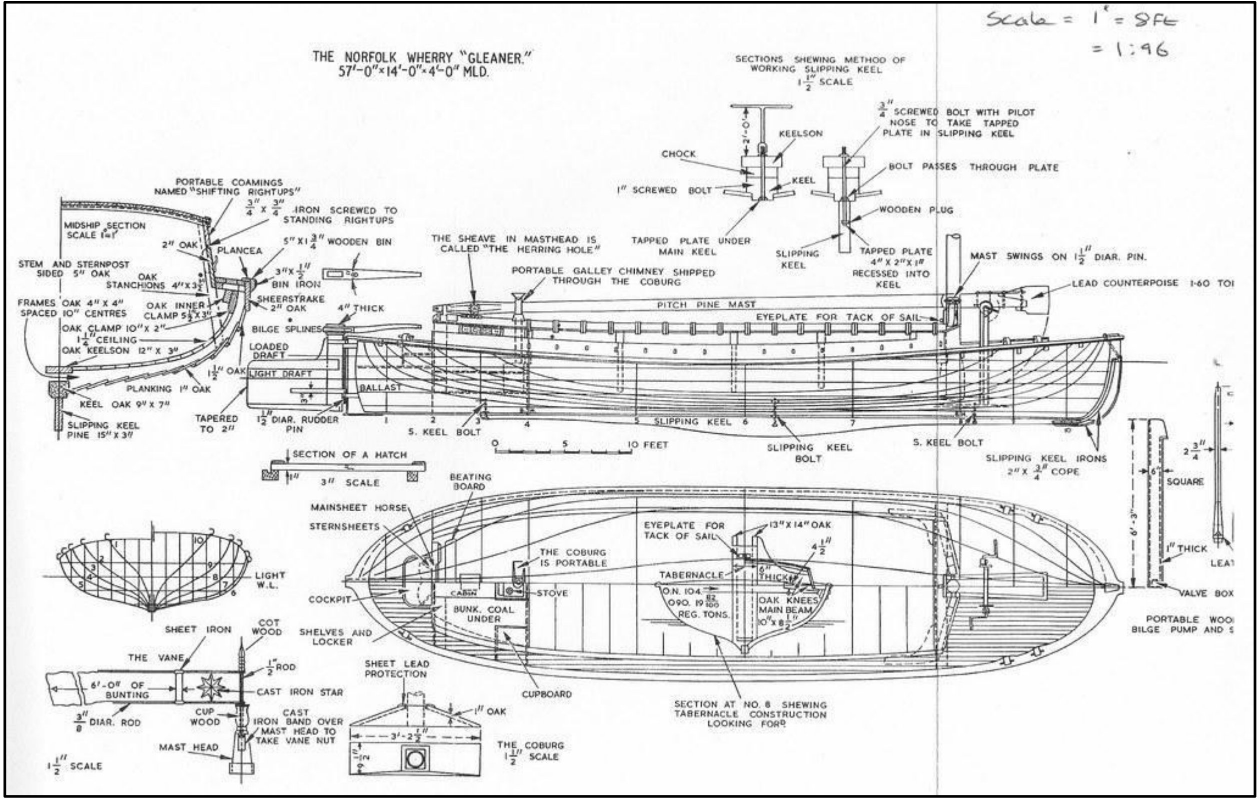

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Images from Clark, *Black Sailed Traders: Keels and Wherries of Norfolk and Suffolk*. London: David & Charles, 1972 central hull sections to the same plan (with associated changes to the rig) may be a useful design feature to adopt and will reduce work considerably. Their easily flattened Cat rig, when paired with an electric motor, would make traffic in areas like the intercoastal waterway, New York Canal system, and areas with frequent change between canal and lake operations possible mostly under sail. This means a lower capital expenditure, lower shore power demand, and lower strategic material commitments for these feeder fleets. Air Draft should be kept to 12 feet or less with the mast down, with a maximum length of 64 feet and a shallow draft. If carefully thought through, a solarized motor-only version of this wherry could serve as the canal boat described in the above paragraph.

Spud Barge Depots and other infrastructure components which will need to be deployed in the near future, and will not require a significant amount of effort for naval architects, should also be developed and published.[36] A Service-Pattern Barge Depot given in three sizes, for example 40, 80, and 120 feet in length, with a beam set at 50% of the length for a simple barge would be a few day's work to factor out the scantlings and instructions to make local construction without specialized facilities or tools possible. These barge depots should be designed for plywood or steel construction as economic pressures demand, based on the size of the barge.

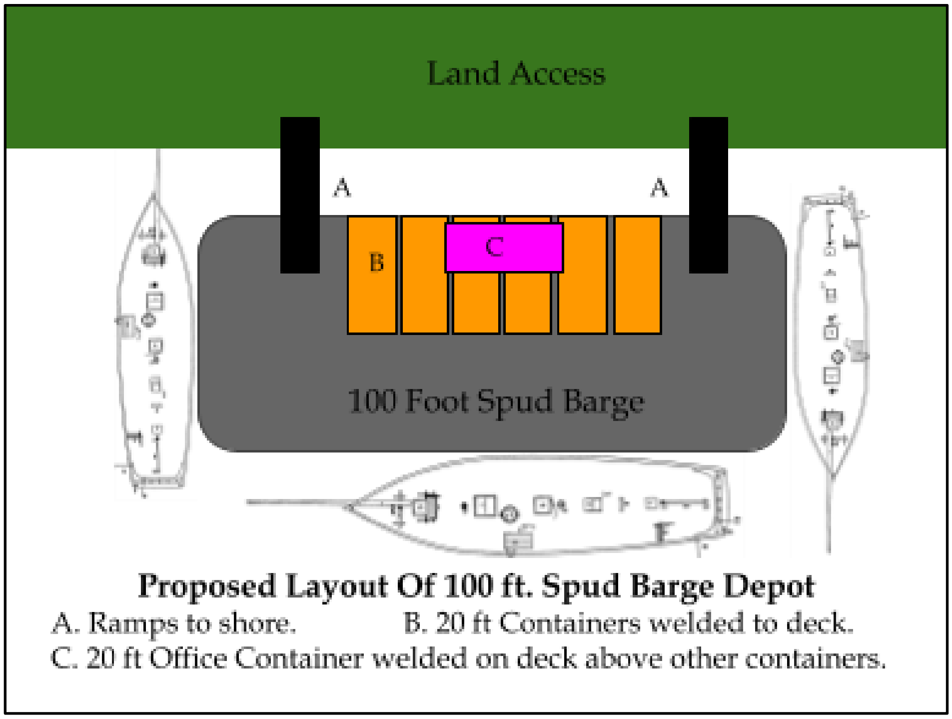

Image from *Sail Freight Handbook* 2nd Edition. Pp 170. CC-BY-NC-ND 4.0

By creating a ready and publicly available set of sailing vessel designs which take maximum advantage of regulatory categories, there is a better chance of getting as much capacity as possible out of any small vessel fleet and crews. There is a need for these vessels worldwide, from the South Pacific islands to New York Harbor, and the longer it takes to make these vessel plans available and build them, the worse the transport situation will become in terms of carbon emissions and congestion before any significant improvement

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[36] Woods, Steven, (Editor). *The Sail Freight Handbook* 2ed.

can be made. Potentially thousands of jobs on and off the boats are waiting to be created for this project, and what's needed to start the industry along is a reasonable set of ship plans.

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Appendix: Open Source Sail Freighter Requirements.

4 Schooners + Barge Depot + Wherry.

- ☛ Plans will be released into Public Domain/CC-BY-SA 4.0 in their entirety, as one set, via CPCL and likely the IWSA Small Vessels Publication.
- ☛ Plans to include Lines Plans, General Arrangement, Sail Plan(s), Stability Curves.
- ☛ Vessels max out just below 15, 25, 50, 100 GRT, designed for fast, easy construction.
- ☛ All vessels to be provided with ship's gear for cargo handling as specified.
- ☛ Palletized and breakbulk cargo only. No provision for containers at this scale.
- ☛ Target Stowage Factor to be 80 Cu Ft per short ton; 2.5 Cu M per Tonne.
- ☛ Outfitting should be made as work-boat and simple as possible. The owners can provide for more comfort if they decide it is necessary.
- ☛ Ship Class Designation: OSSF [GRT]

Open Source Sail Freighter 15:

- ☛ Under 40 ft and 15 GRT

- ☛ Preferably 32-36 feet LOA with 40 ft LOS, if possible, to save cash with capex/opex.
- ☛ Designed specifically for home-builds in plywood or steel (Beuhler or Roberts type plans). This requires a bit more detail and instruction than the others which will be built exclusively by shipyards. To include construction drawings, materials list, welding hours estimation.
- ☛ Minimally complex rig: Marconi or Gaff Sloop (preferably both options provided) with basic sailing skillset in mind. Self-tacking jib highly encouraged.
- ☛ Tabernacle and keel-stepped mast options if possible.
- ☛ Minimum 7 CDWT, preferably more, but not to exceed 14.9 short tons.
- ☛ Hold and gear compatible with half Euro-Pallets loaded to 125kg. (17.5 cu m)
- ☛ 2 crew design, with 3rd provided for in pilot berth or hammock.
- ☛ Design for minimal expense and low maintenance.

OSSF 25:

- ☛ Tabernacle rig or keel-stepped.
- ☛ Under 65 feet.
- ☛ Minimum 15 CDWT. 37.5 cu m.
- ☛ Hold and gear compatible with half Euro-Pallets loaded to 125kg.
- ☛ 2-4 Crew. 2 Watches of 2 people preferred.

OSSF 50:

- ☛ Tabernacle Rig as an option possible, otherwise keel-stepped.
- ☛ Topsail schooner option with roller furling would be nice but not required.
- ☛ Under 65 feet if possible.
- ☛ Minimum 30 CDWT. 75 cu m.
- ☛ Hold and gear compatible with Euro-Pallets loaded to 250kg.
- ☛ 4-6 Crew. 2-3 Watches of 2-3 sailors.

OSSF 100:

- ☛ 9-12 Crew (3 watches of 3-4 sailors)
- ☛ Under 79 ft LOA if at all possible.
- ☛ Minimum 60 CDWT. 150 cu m.
- ☛ Hold and gear compatible with Euro-Pallets loaded to 500kg.

OSSF-B: (Barge Depot)

- ☛ Designed to be linked together into the size of depot required. Not always permanent infrastructure, so an easily towable design would be useful.
- ☛ Preferably 60 feet long, 40 feet wide for working space.
- ☛ 4+ Spuds sufficient to hold in protected waters.
- ☛ Distribution pattern on deck for warehousing containers without destabilization.
- ☛ Cargo Handling Gear comparable to OSSF 50.

OSCW 15/25/50 (Open Source Cargo Wherry)

- ☛ 12 ft Air Draft with mast down and 6 foot maximum draft.
- ☛ Electric propulsion with multiple charging options preferred.
- ☛ Cat Rig and Counterbalanced mast as with originals.
- ☛ Marconi and Gaff Rig Variants, Marconi paired with roller furling into Mast.
- ☛ Requirements otherwise as with OSSF of same tonnage.
- ☛ Unrigged Variant with maximized solar panels for regions with unfavorable winds.

TRAINING SAILING VESSEL OFFICERS FOR CARGO OPERATIONS

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US Merchant Marine Academy

17 August 2023

ABSTRACT: Currently commercial shipping is undergoing a transformation from traditional heavy fuel oils, which emit significant amounts of Green House Gasses (GHG) into the air, to greener sources of energy. One such idea is a return to traditional build, sailing vessels capable of carrying cargo. Commercial Sailing Cargo vessels do not have a specified training or operational plan so other commercial vessels do. In this paper we will discuss the need for an industry recognition of training, whether or not it is a governmental program.

Disclosure: The author, Matthew Bonvento is a federal employee at the US Merchant Marine Academy carrying out this research as part of his official duties as an instructor. No entity has paid for, sponsored, or contributed any funds to this paper.

INTRODUCTION

Shipping is an industry that can be traced back thousands of years into the antiquities of human history. Throughout that time shipping has evolved from oar propelled vessels, to sailing vessels, to steam, diesel, gas, LNG and now apparently back to sail.

The international maritime industry has been propelled to use greener and more environmentally friendly methods of vessel propulsion under the IMO 2020 amendments to MARPOL Annex VI (International Maritime Organization). This regulation bans the use of fuels that have more than 0.50% sulfur content unless the vessel has a scrubber system that can lower emissions below this threshold (Det Norske Veritas).

As the new regulations have been met with resistance (Christina and Khasawneh, 2019) due to cost and availability of low sulfur fuels, various opportunities have arisen to meet the demands of international trade. The exploration of fuels such as Ammonia and Methanol are being investigated, kite and sail auxiliary propulsion technology, as well as battery powered vessels have all been proposed to assist in fuel savings/elimination. There have been some intrepid entrepreneurs who have decided to build and flag traditional rigged, wooden, sailing vessels for the carriage of cargo.

SAIL CARGO

Sail freight is defined as "The maritime movement of cargo under primarily wind power." (Woods, 2021). Currently the International Maritime Organization does not keep track of the number of commercially operated traditional build sailing vessels. These vessels do not fall under the scope of SOLAS (International Convention for the Safety of Life at Sea) as per Chapter 1, Regulation 3 (iii and iv) that exempt vessels "not propelled by mechanical means" as well as "Wooden ships of primitive build." However, as with all commercial vessels, even sailing vessels must meet the requirements set by MARPOL. This is where sailing vessels are making waves. Until these vessels turn on their auxiliary engines, sailing vessels are emission free (Langelaan, June 2023). Engines, when used, are primarily for the purpose of maneuvering in a harbor (EcoClipper, 2023). That is why in recent years there has been an uptick in the design and implementation of these vessels to meet the emissions requirements as laid out in MARPOL Annex VI.

Emissions are not the only driving factor behind drive for sailing vessels, but to have a positive impact on the environment overall, social awareness, an economic impart, as well as to serve as a platform for education (Woods, S. and Merrett, S. 2022). Education may take place in the form of school visits and opening the vessel up to the public when in port, but also by way of having on board trainees who pay for the experience (FairTransport, 2023). Trainees may or may not have any sailing experience, or even maritime experience.

As stated, the IMO does not maintain information on the registration of sailing vessels, industry associations such as the *International Windship Association* confirm that there is an increasing interest in the use of traditional build sailing cargo vessels in Europe (Allwright, G. July 2023). With this increase of interest, it is feasible to expect an increase in the interest of persons wanting to sail on board these vessels as crew members, trainees, or passengers (such as on vessels like the *SV Rembrant van Rijn)*.

CASE STUDIES

Much can be learned by studying the unfortunate mistakes of others. Legislation in the maritime industry is often driven by accidents and death. One case which made the news, but did not spur any change was that of the *SV Bounty.* The case study is not referencing the 1789 mutiny led by William Fletcher against the well-known Captain Bligh.

ON 29 October 2012 the *SV Bounty* sank off the coast of Cape Hatteras, North Carolina after an encounter with Hurricane Sandy. Two crew members were lost, including the Captain. Many other were injured. The vessel was lost at sea. Not considered a passenger vessel, or a cargo vessel the *Bounty* was an attraction as well as frequently used in cinema.

As with many case studies before and since a chain of errors occurred long before the actual sinking that led to the accident. Since the *Bounty* was a tourist attraction, visitors flocked to visit her while in port. However, the vessel had to receive permission from the US Coast Guard in every port prior to allowing visitors on board. The vessel was also not considered safe enough to carry passengers while underway, with the watertight integrity of the vessel being a concern. (NTSB, 2014).

In addition to the safety concerns by the USCG, the vessel's crew was largely composed of mariners with little experience at sea, some of the crew only having experience on board that vessel. Most of the crew with less than 2 years of sea time. Accordingly, the knowledge on how to maintain the ship was called into question by the shipyard brew the previous September when the crew used inappropriate caulking for the setting of vessel seams. Considering this information, the ability of the crew to perform in an emergency could viably be called into question. Even though this was not a sailing cargo or sailing passenger vessel, in the next section of this paper it will show that there is an insufficient training standard for these vessels past what is learned by “on the job” experience.

The tragedy of the Tall Ship *Pamir*, all be it earlier, highlights how lack of knowledge and experience coupled with improper shore side management can lead to disaster.

LOSS OF GENERATIONAL KNOWLEDGE

In his book *Tallships Down* (Parrott, D. 2003), expressed the sentiment that at the close of the era of sailing cargo vessels there was a lack of knowledge passed down to the younger generation of seafarers as the older mariners retired and left the sea in droves. Knowledge sharing is an activity participated in by both the transmitter and the receiver (Nguyen et al, 2021). With the loss of the experienced sailors, such as the Cape Horners, there is no one left to transmit that knowledge. As was evidenced in the case of the Tall Ship *Pamir* (Parrott, 2003).

CREW REQUIREMENTS

The global standard for seafarer training is based on the International Convention on Standards of Training, Certification, and Watchkeeping for Seafarers, 2010, as amended. This is the baseline training all seafarers must have to serve on a commercial vessel. Predominantly cargo sailing vessels are under 500 GT. A GT, or Gross Ton, is a term that describes the cubic measurements of the interior carrying capacity of the vessel and is not a connotation of weight. The requirements for Officers in Charge of a Navigational Watch and Masters for vessels under 500 GT can be found in STCW, Chapter II, Table A-II/3. Tables A-II/4 and A-II/5 list the requirements for Ratings forming part of a Navigational Watch (RFPNIW) as well as Able-Seafarer Deck. There is a significant amount of both theoretical as well as practical knowledge necessary to obtain these certifications. Unfortunately, the STCW requirements do not cover the skillset necessary to safely operate a sailing vessel. As such, the flag state, when writing a minimum safe manning certificate does not have a manner in which to require a sailing license for these vessels as none exist. Depending on how the vessel is registered, it is possible to sail the vessel as a commercial yacht.

CURRENT TRAINING OPTIONS

Even though there is no international standard or requirement for sailing vessel officers, there are options and opportunities for interested mariners in obtaining training. Currently, the available options vary widely in program delivery as well as content. According to Geoff Boerne (2023), a vessel under 24m, not under the requirements of SOLAS may opt to train the crew under the UK Royal Yachting Association. Although cargo handing and stowage is not covered, topics such as basic sailing, safety, tides and currents, navigation, and radio communications are taught (Royal Yacht Association, 2023).

Another option is the *Picton Castle*, a sail training barque based out of Nova Scotia Canada. The 6 week Bosun school focuses on seamanship and maintenance skill. This rigorous program is land based, meaning that there may be some vessel operations involved, the bulk of the work is done dockside. No underway, and with no cargo on board.

Finally, the Enkhuizen Nautical College in The Netherlands has a two year program specifically designed for the training of sailing cargo vessels. Topics include seamanship skills, sailing theory, square rig sailing, and sailing vessel stability. Additionally, candidates receive basic instruction in engineering in order to work with what machinery is found on board.

CONCLUSION

It is evident that the sail cargo industry is lacking sufficient training standards to grow as an industry in the current market. The lack of standardized training brings a level of uncertainty to regulators who have the overall responsibility of ensuring that these vessels are safe. There are training options as evidenced above that could be used as models for training standards. There does not need to be an STCW endorsement, such as the case with Dynamic Positioning vessel officers who received industry recognized training. The author is not stating that sail cargo operators and officers are not capable or knowledgeable, but merely that there would be a benefit to an industry recognized standard in order to ensure safety of all.

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Sustainability in Ship Design and Operations Conference, SISDO, November 6-7, 2023, 1–5

RESEARCH PAPER

Optimal Deck Position of Rotor Sails and DynaRigs for a Bulk Carrier Retrofit Installation

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Published 2023

Abstract

This scientific study aims to compare the significance of onboard positioning for retrofit installations to maximize fuel savings using high and low side forces wind propulsion systems on a real bulk carrier ship. The primary objective is to identify the most efficient placement of these two distinct systems, considering their respective lift-to-drag ratios, to achieve maximum fuel efficiency while complying with relevant rules and regulations. The investigation involves a comprehensive analysis of available deck spaces, and computational modeling is employed to estimate potential fuel savings for a typical route followed by the vessel. By examining the impact of different wind propulsion system positions, this research provides valuable insights into enhancing the ship's energy efficiency and reducing its environmental impact in the maritime industry.

Keywords: wind propulsion sytems; windships; optimal position; performance prediction; cost-benefit analysis; decarbonization

1. Introduction

In recent years, the global maritime industry has faced increasing pressure to address its significant contributions to greenhouse gas emissions and climate change, IMO (2020). As governments and international organizations continue to advocate for sustainability, the shipping sector seeks innovative solutions to reduce its environmental footprint and embrace a greener future. Among the various strategies to achieve shipping decarbonization, Wind Propulsion Systems (WPS) have emerged as a promising avenue to significantly cut fuel consumption and emissions.

WPS, long employed in sailing vessels of the past, is an impactful emissions reduction technology for shipping, with an abundant, widely available, and cost-free energy source waiting to be harnessed. However, wind propulsion ship dynamics differs from both conventional cargo ships and sailing yachts. The aerodynamic loads on the WPS introduce side forces and moments, which are no present in a conventional motor driven commercial ship, where the thrust is usually directed along the centreline. Thus, one key challenge lies in determining the optimal positioning of wind propulsion systems for retrofit installations on board conventional cargo vessels. The effectiveness of such systems can vary significantly depending on their position relative to the ship's hull and cargo arrangement. Consequently, a thorough understanding of the interplay between wind propulsion systems and their on-deck placement becomes crucial to unlock their full potential and maximize fuel savings.

In light of this, the present study sets out to investigate the significance of onboard positioning for retrofit installations of two different wind propulsion systems: with high and low side forces. These two distinct types of systems represent varying lift-to-drag ratios and call for tailored approaches to achieve maximum energy efficiency. The research focuses on a real bulk carrier ship, a representative vessel of the global shipping fleet, where the available deck spaces are scrutinized to determine the most favorable locations for installing the wind propulsion systems. By assessing the potential fuel savings resulting from the retrofit installations of the two different WPS, this study seeks to provide practical insights for shipowners and operators on enhancing the cost-effectiveness and environmental sustainability of their vessels.

2. Problem Definition

Integrating wind propulsion systems into conventional cargo ships necessitates careful consideration of their impact on the vessel's hydrodynamics. Unlike conventional ships that solely rely on engines for propulsion, the addition of wind systems introduces aerodynamic side forces. To maintain stability and counteract these side forces, a drift angle is generated. Thus, the cross-flow generates a hydrodynamic side force, but it also results in an added resistance . These two lateral forces also exerts yawing moments. A crucial factor affecting the ship's performance is the position of the wind propulsion system relative to the hydrodynamic center of effort of the hull. In conventional hulls, the hydrodynamic center of effort is typically located at approximately 16% of the waterline length. Depending on how far the wind propulsion system is positioned from this center, it may induce yawing moments that necessitate rudder deflection to maintain course stability. However, rudder deflection introduces additional added resistance, further impacting the ship's overall efficiency.

The primary question that arises in this context is determining the trade-off between two factors, namely, the drift angle generated by placing the aerodynamic center of effort closer to the bow and the rudder angle required to counteract yawing moments caused by positioning the system farther from the hydrodynamic center of effort towards the aft. To identify the most fuel-efficient solution, it is crucial to comprehend which aspect incurs a lesser penalty in terms of added resistance: a larger drift angle or a larger rudder angle.

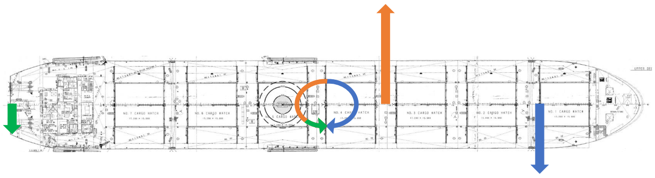

Figure 1. *Equilibrium Condition*

3. Methodology

In the present study the own developed 4 degrees of freedom Performance Prediction Program (PPP) for wind propulsion ships is used. The tool follows a generic approach based on ship main particulars and generic engine data as input data. The methods used are widely known naval architecture semi-empirical methods as Hollenbach's method for the calm water resistance calculation. The aerodynamic data used is gotten from previous publications.

The drift model is based on the equations from Inoue et al. (1981), which are basic maneuvering equations for ships sailing with leeway angles Skogman (1985).

The rudder model is based on Bertram (2011) for sharp-edged rudders where the force coefficients are given with respect to the aspect ratio.

The main assumptions of this generic approach are the negletion of aerodynamic interactions between WPS and WPS-hull. The assumption that the engine and propeller efficiency is kept constant during the trip.

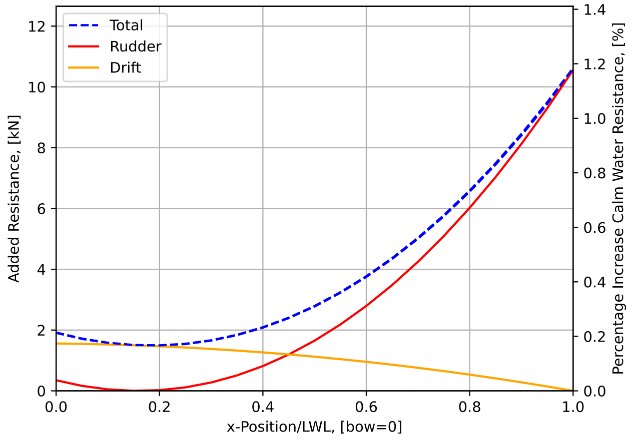

Figure 2. *Total Added Resistance due to drift and rudder angle as function of WPS position on board for 200 kN of side force.*

It is seen that the rudder deflection tends to have a bigger impact in the overall added resistance, which leads to placing the WPS as closest as possible to the hydrodynamic centre of effort to maximise WPS performance.

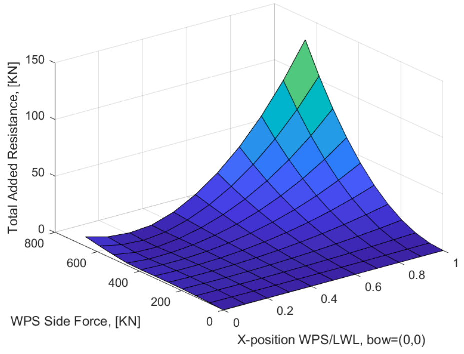

Figure 3. *Total Added Resistance due to drift and rudder angle as function of WPS position on board and side force.*

4. Deck Arrangement and Visbility Check

4.1 Rotor Sail

The rotor sail is low cl-to-cd ratio wind propulsion system. It is a compact device generating big forces for a small sail area.

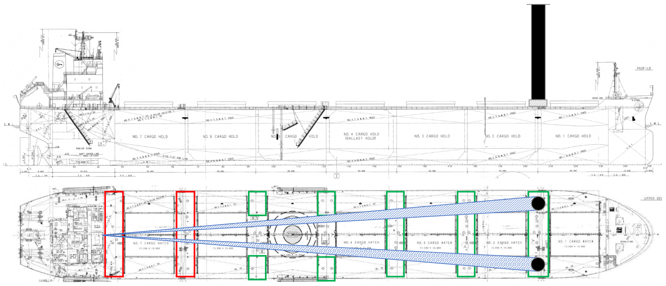

Figure 4. *Rotor Sail Position on Deck.*

The two 35x5m rotor sails are firstly placed on the foremost available position on deck. Their position fulfills with the SOLAS (2022) Regulation 22 - Navigational bridge visibility. This rule states that no blind sector, caused by cargo, cargo gear or other obstructions outside of the wheelhouse forward of the beam which obstructs the view of the sea surface as seen from the conning position, shall exceed 10°. The total arc of blind sectors shall not exceed 20°. The clear sectors between blind sectors shall be at least 5°. However, in the view described in .1, each individual blind sector shall not exceed 5°. This is fulfilled as each rotor sail only blocks 1.8 deg.

Next, the same configuration of two rotor sails are placed at the aftest available deck space to check the performance. In this set up, each rotor is blocking 5 deg, which also fulfills SOLAS. However, it is worth noting that cameras or extra radars could be installed in case WPS would block too much visibility and still be accepted. However, this would be extra CAPEX needed to be accounted in the calculations.

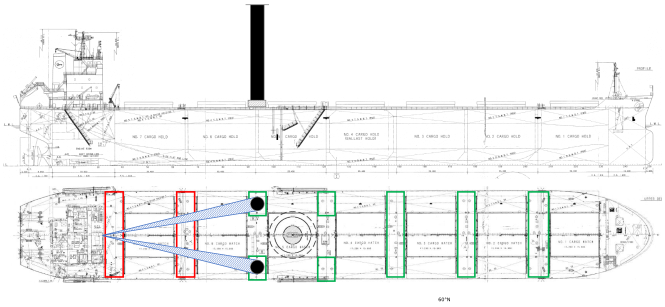

Figure 5. *Rotor Sail Position on Deck.*

4.2 DynaRig

The DynaRig is a high cl-to-cd wind propulsion system. Unlike rotor sails, it requires bigger sail area to generate similar force but the side force are also smaller.

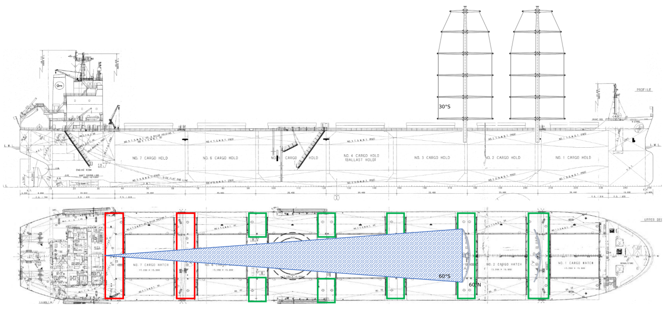

Figure 6. *DynaRig Position on Deck.*

In this configuration, the visibility is blocked at the maximum of 8.5 deg, when the sails are placed at 90 deg with respect to the longitudinal. Unlike rotors, visibility will vary depending on how the sail is trimmed. Normally, the sail will be trimmed in the upwind conditions, with closer angle of attack and bigger visibility.

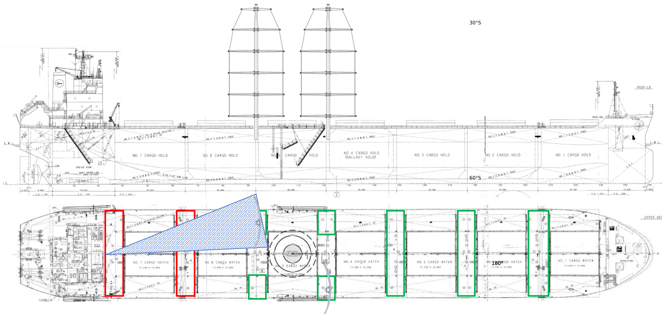

Figure 7. *DynaRig Position on Deck.*

In this other one, the visibility is blocked at a maximum of 19.30 deg on each side. This exceed the maximum allowed and would require extra cameras.

5. Performance Prediction over a Route

The typical route that the studied ship follows is Baton Rouge in the USA to Immingham in the UK. It takes 14.31 days, with a total of 343 hours at a constant speed of 14.2 Knots. Note that all results showed in percentage are highly related with the sailing speed of the vessel. This is the designed speed which is higher than the real sailing speed that the ship normally follows.

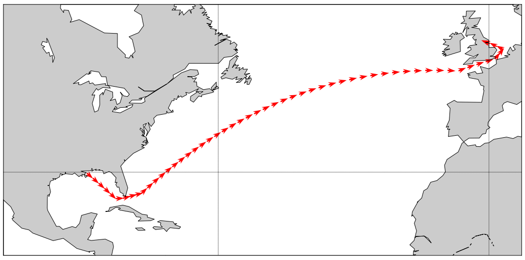

Figure 8. *Route Baton Rouge (USA) - Immingham (UK).*

The weather data used in based on ERA5 Copernicus data yearly-averaged from 2000 to 2022. The results are expected to be conservative as yearly-average tend to show lower wind speeds. As seen in the following figure, in the route 1, from USA to UK, the wind tends to come from the aft, while the reversed route, route 2, is mainly an upwind route. This will also influence the overall savings. Both routes are modelled.

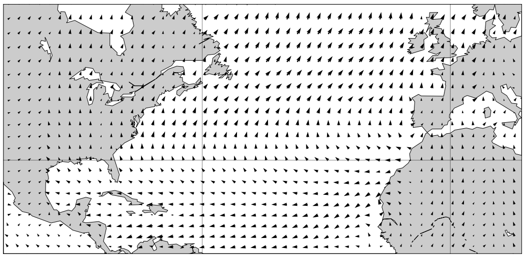

Figure 9. *Average Weather on Route Baton Rouge (USA) - Immingham (UK).*

5.1 Rotor Sail Configuration

The savings over this route for the given ship with the two flettner rotors in the aft, the fuel savings are 4.74%. In the bow, 4.81%.

The reversed route, from UK to USA, at the bow is 4.15%, and at the aft is 3.86%. The bigger difference is upwind conditions, where the rotor sail experience higher side forces and the penalty is bigger when placing the WPS farther from the hydrodynamic centre of effort.

Bigger sway forces in the route 2, where the wind comes mainly from the front. The bigger differences between placing it in the bow or in the aft are explained due to the bigger heel achieved when placing the rotor in the aft, then the projected force in y-axis is less and due to the equilibrium condition. However, the brake power is greatly reduced when placing it in the bow.

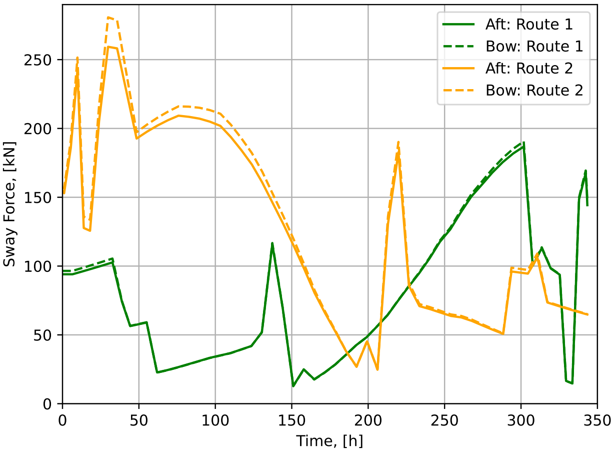

Figure 10. *Sway Force of the two rotor arrangement for the two configurations: bow and aft.*

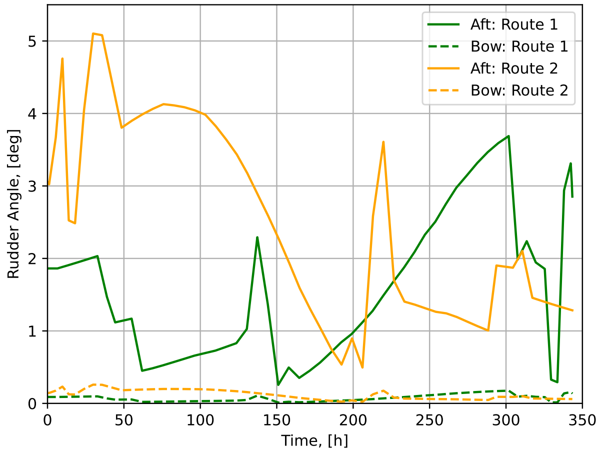

Figure 11. *Rudder angle of the two rotor configuration.*

Higher rudder angles when placing the rotor in the aft, and for the route 2, the upwind conditions route. Higher drift angles when placing the rotor in the bow, and higher drift angles for the route 2, the upwind condition.

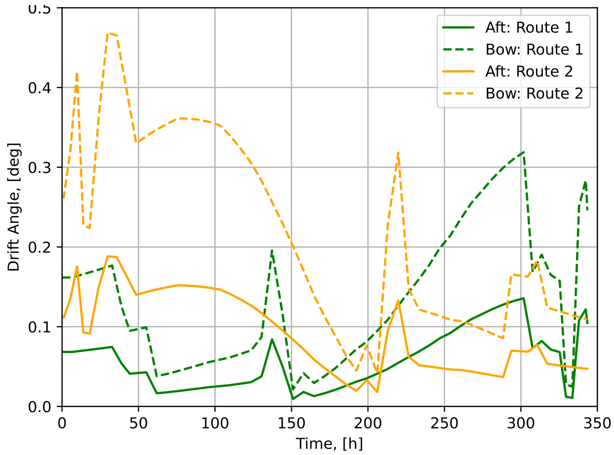

Figure 12. *Drift Angle of the two rotor arrangement for the two configurations: bow and aft.*

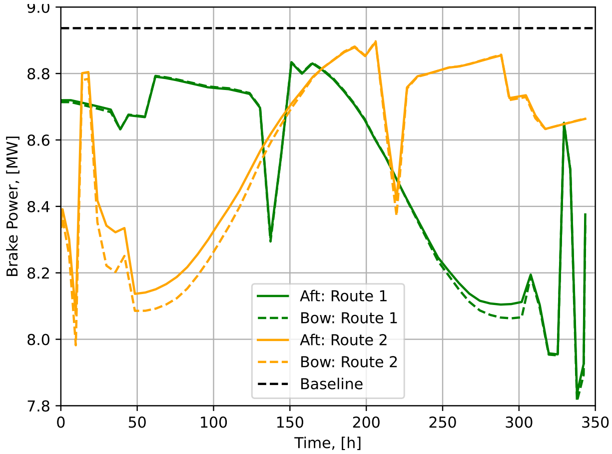

Figure 13. *Brake Power of the two rotor configuration.*

5.2 DynaRig Configuration

DynaRig are high cl-to-cd wind propulsion systems. In the upwind condition, the penalty is not as big as the rotor sail when placed in the aft. Same trends though.

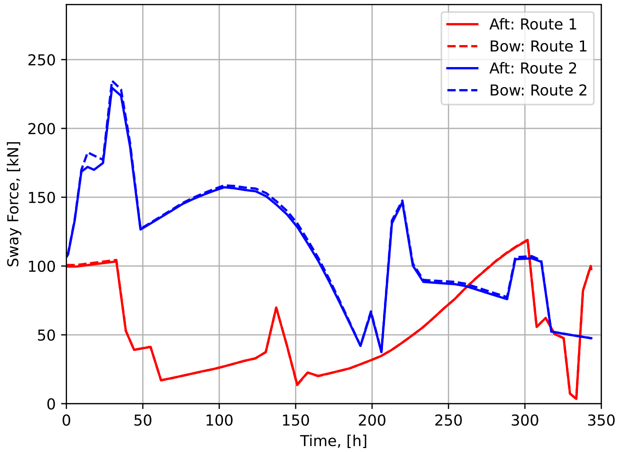

Figure 14. *Sway Force of the two DynaRig arrangement for the two configurations: bow and aft.*

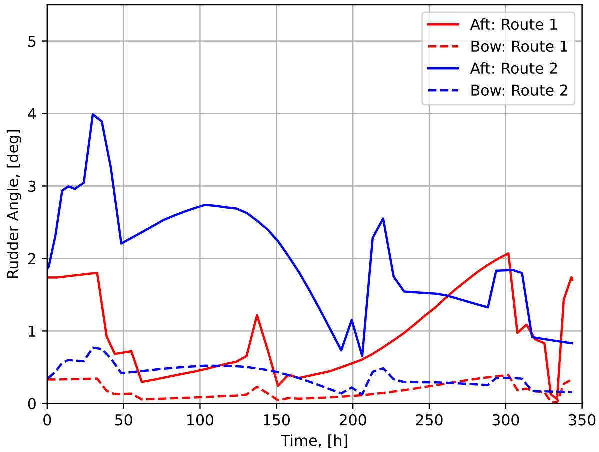

Figure 15. *Rudder angle of the two Dyna configuration.*

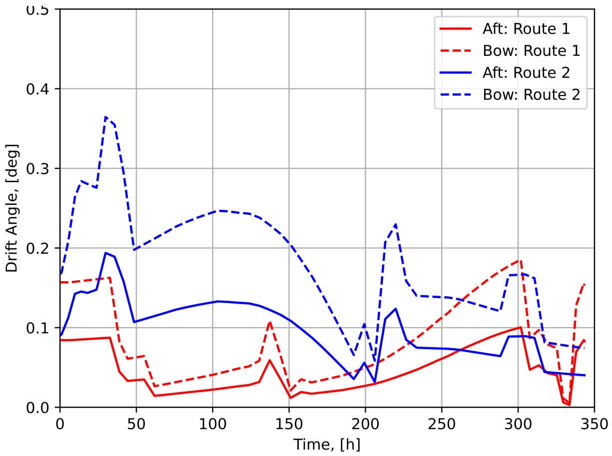

Figure 16. *Drift Angle of the two Dyna arrangement for the two configurations: bow and aft.*

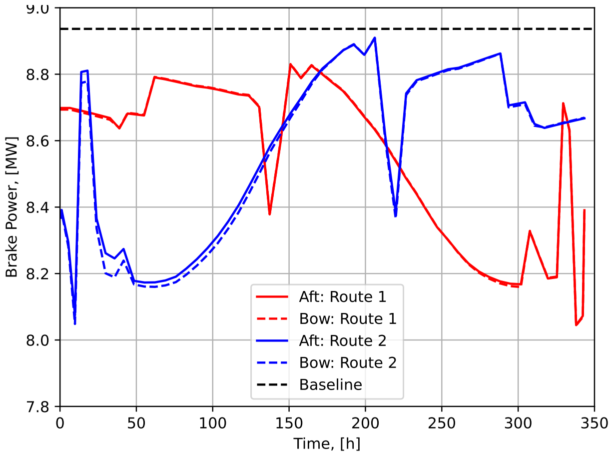

Figure 17. *Brake Power of the two Dyna configuration.*

6. Comparision

Note that the aim here is not to compare the performance each system independently and make business case conclusions but study the trend of high and low lift-to-drag ratio and its impact on the position on board. Note that the dynarig installation centre of effort and the rotor one is not exactly the same, the bow one is farther than the Hydro centre of effort than the rotor and the aft is closer, this is due to the available deck space and the dimensions of the system making it unrealistic to install side to side as rotor sails.

Table 1. Rotor Sail fuel savings over Route 1 and Route 2 in absolute values in Tonnes and in percentage.

Route 1		Route 2	
Bow	Aft	Bow	Aft
24.66T	24.30T	21.29T	19.77T
4.81%	4.74%	4.15%	3.86%

Table 2. DynaRig fuel savings over Route 1 and Route 2 in absolute values in Tonnes and in percentage.

Route 1		Route 2	
Bow	Aft	Bow	Aft
21.93T	21.93T	21.11T	20.44T
4.28%	4.28%	4.12%	3.99%

7. Conclusion and Discussion

Low lift-to-drag ratio wind propulsion devices such as rotor sails have a bigger impact in the position on deck, as side forces are bigger and depending on the position on board, bigger rudder angles are required to keep course, which results in bigger added resistance. For high lift-to-drag ratio, this is not as important.

We should include the hydrodynamics in the sail control for retrofit installations where the hull was not designed to withstand side forces.

Acknowledgement

The technical support and information provided by the leading global dry bulk operator UltraBulk is greatly appreciated. This work received funds from Innovation Fund Denmark and the Danish Maritime Fund.

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Nuclear-Electric Shipboard Power Plant Design as a Senior Project

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Abstract

Senior design projects teach students many important skills. One of the major goals is to prepare students to apply effective problem solving techniques to a problem that represents a real world situation. This includes the ability to define the problem, compare alternative solutions, identify the best solution, and design the system. This paper describes the design of shipboard power plant as a senior project in the Marine Engineering program at the U.S. Merchant Marine Academy. The design project was supervised by faculty members who guided a multidisciplinary group of seniors. The research project was sponsored by the Office of Naval Research. Each group of seniors focused on one of the main design aspects of the project including electric power system, nuclear power plant, ship hull design, and economics.

Introduction

Multidisciplinary capstone senior design projects have been adopted by a large number of engineering programs as an effective way to expose students to a complete design engineering experience, from conception to the delivery of a working prototype. The measure of the senior design project outcomes is one of the most important tools to assess how an engineering program meets its learning outcomes [1]. Considerable effort and time are spent by faculty and students on the successful completion of these projects to ensure and maintain the quality of an engineering program [2].

Senior Design projects should involve significant design requiring students to utilize much of the knowledge attained in their previous years of engineering education. Traditionally, senior design courses have been administered by individual faculty members with fairly discipline specific areas of interest and varied course delivery mechanisms [3]. This multidisciplinary senior design course was conducted including the electrical, nuclear, steam power plant, naval architecture, and economic aspects of Engineering. These individual areas were led by faculty who had specific expertise in the particular area.

This paper will outline the technical requirements and parameters that are required for the concept to be investigated. The interdisciplinary design concept that resulted was developed by midshipmen and faculty advisors using a multidisciplinary systems capstone project approach. The views expressed in this paper are those of the authors and are not necessarily those of the United States Maritime Administration, Department of Transportation or U.S. Government.

Background

Currently there are no navy auxiliary ships that will operate at very high speeds, essentially limited by hull configuration, and transport large payloads to any coastal area in the world without refueling [5]. Furthermore, no navy auxiliary ship supplies electric power to the national grid when the vessel(s) are not deployed and are ported in a domestic port, which could save millions of barrels of fuel oil per year while generating revenue. Given the development of higher speed vessels utilizing novel propulsion and ship hydrodynamics that now allow very large vessels to travel at more than 40 knots, there is rationale to consider if this approach can be utilized on Navy Auxiliary Ships. Furthermore, there is a perceived potential that advanced technology can be used to help satisfy both the needs of high speed, long distance transport and high power supply of electric power to the national grid.

This paper outlines a concept that meets the needs of a high speed auxiliary ship using a nuclear power plant and novel propulsion that achieves at least 40 knots to deliver cargo and then return to a domestic port to provide 300 MW of power to the national grid using a shore grid conversion module (substation). Large gains in incorporating transformers and high power density motor drives along with newly developed large-scale propulsion motors allows high torque to be delivered to water jet propulsor. Highly reliable power electronics and tight control of power parameters enables the ship to provide 300 MW of power to the national grid. All of this can be shown to be economical and within technical grasp.

The analysis and design was performed by four teams of midshipmen addressing the following issues: ship hull design, nuclear plant design, electrical power system, and economics. A total of 33 midshipmen worked under the guidance of four faculty advisors. The economic analysis of using naval auxiliaries as electric power generating plants servicing the nation grid shows the potential for the system to be a revenue generator for the Navy. Each team was required to submit a final technical report and to make an oral presentation at the end of the term. This project was sponsored by The Office of Naval Research.

The Office of Naval Research (ONR) coordinates, executes, and promotes the science and technology programs of the United States Navy and Marine Corps through schools, universities, government laboratories, and nonprofit and for-profit organizations. It provides technical advice to the Chief of Naval Operations and the Secretary of the Navy and works with industry to improve technology manufacturing processes. ONR plays a critical role in advancing scientific knowledge to support the generation of naval technology with a vision focused on future capabilities, hedging against the uncertainty of warfare. ONR, with headquarters in Arlington, Virginia, reports to the Secretary of the Navy through the Assistant Secretary of the Navy for Research, Development and Acquisition. It executes its mission through:

- Science & Technology (S & T)
- Naval Research Laboratory (NRL)
- ONR Global (ONRG)
- Naval Reserve S&T Program.

Senior Project Description

The nuclear-electric powered naval auxiliaries' concept contained in this paper is an untested design of an SL-7 hull form using a combination of novel propulsion technology, powered by a nuclear power generating plant. Ship propulsion is developed mostly with electric driven water-jets configured without stopping or steering mechanisms. Additional "high speed" power, steering and stopping is accomplished utilizing high diameter/length motors, wrapped around the propulsor, and recessed into the canned stator housing called "rim-driven propulsor pods." Slow speed maneuvering is aided by use of tunnel thrusters. Furthermore, the concept includes the use of the vessel's nuclear electric plant to generate power for the national electric grid when it is not being used to propel the vessel.

The concept design addresses power issues such as vessel resistance and loading, propulsor types, placement of the water-jets and propulsors, and sea-keeping characteristics of the redesigned vessel. The original goal of the nuclear-electric powered naval auxiliary concept was a sealift ship capable of sustaining 50 knots for long distances. Due in part to vessel length restrictions and powering constraints, under favorable conditions the maximum speed of this design concept was determined to be 40 knots. The concept vessel does, however, fulfill other key mission parameters, which are addressed later in the report. In order to meet the 40+ knot maximum speed, hull enhancements improving hydrodynamics along with reductions in ship displacement are required. The major reduction in ship displacement was accomplished primarily by reducing large component weights and volumes associated with the storage of fuel.

The pressurized water reactor produces steam supplying one 300 MW steam generator set. The Generator provides 13.8 kilovolts (kV) electricity to three (3) internal superconducting motors driving three (3) water-jets and two (2) rim-driven propulsor pods. The pods are configured with canned Permanent Magnet AC synchronous motors. The pods and motors are all controlled by individual transformer / motor drive controllers. The controllers are the same for both the water-jet motors and pod motors. The propulsion system installed enables reduction in displacement due to lighter propulsion components than previously utilized on the SL-7 consequently supporting the 40 knot speed. Evaluation of major propulsion equipment was based on utilizing existing designs or engineering development models (EDM) recognizing that the components are not optimized for the modified SL-7 characteristics. The component designers predict that significant weight and geometry improvements can be achieved when ship specific design parameters are established. Existing designs were incorporated because the scope of this task did not include funding for vendor efforts to redesign equipment optimized for this concept. However, future redesigns of the propulsion equipment can result in more choices for the concept.

The concept includes the use of the vessel's nuclear electric plant to generate up to 300 MW power for the national electric grid via a shore "fly-away" grid conversion module (substation). The substation is to be designed for accepting a vessel voltage of 13.8 kV and then stepped up to match the shore side power grid, which could be 69 kV to 745 kV. The final voltage will be determined by the local voltage rating where the vessel is to be connected to the electrical grid.

In order to evaluate the economic viability of the concept, Kings Point selected the economic reference bench-mark as the "Electricity Price Indexes" as published by the Wall Street Journal. The Government owned, bare-boat chartered to utilities and the dual ownership and commercially operated options appear to be economically viable. Although not fully studied, it appears that the Government owned, operated (civilian crew), power sold to utilities option might also be viable. A more thorough explanation of the approach, terms and results is documented later in the report. Additional analysis is needed to confirm the findings based on the concept. Based on the studies performed, several approaches appear to be economically promising showing a potential for the proposed system to generate surplus funds above the full operating and amortization costs. Further study is recommended to confirm the study results.

Approach

The overall objective of the project was to expand on the concept of using fast nuclear-electric powered naval auxiliaries (the concept) as sources of electrical power for the national grid when the vessels are not deployed.

This project was developed from the embodiment of work originating from four (4) distinct groups of midshipmen. The midshipmen were focused on different aspects of the concept and each team was assigned a faculty advisor as noted in this report. Additionally, industry experts were assigned either as adjunct faculty or as guest lecturers. In addition, several private companies provided key industry input in support of this project. The four midshipmen groups were divided as follows:

Naval Architecture and Ship Balance;
Electrical Distribution, Electric Propulsion and "Fly-away" Grid Conversion Module
Nuclear Module, Support Systems, and
Economics, Security and Licensing.

Allocation of Resources

The nuclear-electric naval auxiliary ship research project was a combined student/faculty undertaking and was commenced after notification by the Office of Naval Research (ONR) award. The initial phase of the project was focused on having each of the four faculty members assemble volunteer teams of students interested in the four elements of the project as defined above in the introduction section.

As a result of this organizational phase, the four teams were assembled. All of the students undertook the work as a 3-credit directed research elective under the guidance of the respective faculty advisor.

The students enrolled in the respective directed research course of record for their phase of the project. The faculty members were relieved of one course from their normal teaching schedule so that they could devote the necessary effort to their phase of the research project. Adjunct faculty was hired to teach the normally scheduled courses removed from schedules of the four faculty members. Additionally, various industry individuals were formally contacted to assist with the project either in a consulting capacity via distance support or in situ lectures, or as a Research Adjunct Professor capacity.

At the start of the semester, each faculty member assigned their respective team various reading assignments related to their element of the project. There were weekly meetings of the teams and the respective faculty advisors and periodic multi-team coordination meetings. As the students became more knowledgeable of the issues, the industry experts traveled to the campus and worked with both students and faculty.

The consultants provided numerous technical presentations providing the most recent technical status of the respective elements being discussed. About a dozen such "subject matter expert" meetings were conducted. Additionally, appropriate field trips were scheduled to sites that would add to the student's understanding of the issues and their knowledge base. For example, the nuclear plant team visited the Indian Point nuclear site in upstate New York.

Several interviews and meetings were conducted with industry including power plant operators, designers and technicians and industry manufacturers of novel, electric propulsion technology. The industry manufacturers are recognized as leading industry developers of their respective novel, electric propulsion technology. Site visits and technical discussions by engineers and corporate staff were held as follows. Entergy Corporation held discussions with two groups of students reviewing power plant technology and associated support systems at its Indian Point Nuclear Power Plant; Long Island Power Authority hosted an electrical group of students at its engineering headquarters and at a high voltage substation.

Pedagogical Observations

At first students in different teams struggled to find a "commonality of purpose" even though they knew what needed to be accomplished. They had to learn to work as a team and find value in what they could offer each other. Soon, they found "comfort in difference" because they became aware of each other's strengths and learned how to have a meaningful dialogue with each other. Ultimately, they realized that an interdisciplinary team has a larger skill set to work with to master their common goals. This process of team building was one of the major advantages from having four populations.

In addition to faculty supervision, students also engaged in self directed learning during their senior project. This will make them better prepared to engage in life-long learning throughout their careers [4].

Key technical data that was generously provided by the associated industry helped improve the midshipmen's understanding of technology and provided for increased technical data addressed within this project.

Conclusions

Based on the findings of this project, there is potential for the Navy to have access to a fleet of fast, large naval auxiliary vessels (40 knots) that will be revenue generators for the Navy. Depending on the economics used and the degree of Government and/or commercial investment, the vessels could be purchased at no cost to Government or could allow for the Government to recoup its investment over the life of the vessel. The concept utilizes a modified commercial ship hull and pressurized water nuclear reactor together with electric motors and ship propulsors in various stages of development. Each of the concept vessels could provide 300 MW of electrical power to the nation's electrical grid when not deployed or could supply a forward sea-base with 300 MW of power to support critical network security needs. Connection to the national grid will require shore transformer substations to raise the generated power voltage to the local grid voltage.

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Thermodynamic Assessment of Kalina Cycle as Alternative Hybrid Propulsion for Ships

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Introduction

Since 1751, the world has emitted [1] over 1.5 trillion tons of CO_2 into the atmosphere, with more than half of that having occurred since 1990. The earliest paper linking atmospheric CO_2 to global warming appears to have been published in *The American Journal of Science* (September 1856) and was authored by Eunice Foote [2]. Since then, evidence supporting that hypothesis has become overwhelming and provides additional urgency regarding the growing danger to human civilization, especially in developed coastal areas, to mitigate this problem.

About 90% of the world's global trade is carried by large seagoing vessels. Of these, the following three types are the highest fuel consumers on an annual basis: container ships, bulk carriers, and oil tankers. Combined, these types of ships consume nearly 2/3 (> 66%) of the annual global shipping fuel (HFO-equivalent) based on recent data analyses from the Janes Sea Module Global Shipping Database [3].

According to recent estimates presented in the Third Greenhouse Gas (GHG) Study [4] by the International Maritime Organization (IMO[2]), international shipping emitted 796 million tons of CO_2 in 2012, which accounts for about 2.2% of the total emissions volume for that year. Furthermore, the mid-range forecasted scenarios discussed during the Third IMO GHG Study showed that by 2050, CO_2 emission from international shipping could grow between 50% and 250% depending on the expected future economic growth, world maritime commerce, and energy developments. In 2018, the IMO announced goals for reducing shipping emissions: a 40 percent reduction compared to 2008 levels by 2030, and a 70 percent reduction by 2050. This is consistent with IMO's existing GHG emissions strategy 2030-2050 for decarbonization of the global commercial shipping maritime environmental conservation and protection efforts leading to, ultimately, zero GHG emissions later in this century.

The Fourth IMO GHG Study 2020 [5] provides a global perspective on ocean-going vessel fuel consumption. This is consistent with the earlier findings based on the 2018 data from the Janes Sea Module Global Shipping Database [3].

The fuels that power them and the related infrastructure need to change to meet these stringent environmental targets for the current merchant ships. In the meantime, increases in efficiency can not only reduce the rate of emissions, as the world weans itself off of fossil fuels; it will lead to the development of more fuel-efficient propulsion plants, regardless of the fuel used, and the concomitant reduction of the emissions that the combustion of the new fuels will generate.

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[2] IMO – International Maritime Organization – the United Nations specialized agency with responsibility for the safety and security of shipping and the prevention of marine and atmospheric pollution by ships

This work aims to assess the feasibility of using a Kalina cycle as the bottoming cycle during waste heat recovery (WHR) from various waste heat streams on board large, ocean-going merchant ships. The analysis considers power extraction (via WHR) from the most likely and available waste heat streams: exhaust gasses, scavenging air, main engine jacket water coolant, and engine lubrication oil.

Initial analytical cases are considered for a selected waste heat stream (say scavenge air) where known medium properties (T, P, ṁ, etc.) are known or can be assumed with a certain degree of confidence using Kongsberg K-Sim [6] marine engine simulation software package.

Next, multivariate analyses are conducted using Engineering Equation Solver (EES) software for multiple cases (scenarios) by varying ammonia mass fraction (m[NH3]) while keeping fixed other important parameters (T, P, ṁ, etc.) corresponding to different operational points of the main propulsion diesel engine. The goal is to determine optimal regions of performance where the implementation of a Kalina cycle as the bottoming cycle makes the most sense from a technological perspective.

Marine Waste Heat

The wasted heat on a marine vessel results from the thermal energy lost to the surrounding environment during normal engine operation (used for ship propulsion). A typical Sankey energy diagram from recent studies [7] shows in Fig. 1 the energy flow from a typical large 2-stroke low-speed marine diesel engine (MAN B&W 12K98ME/MC) operating at 100% SMCR[3] (powering typically a large container carrier ship). It can be seen that over 50% of the thermal energy is rejected to the environment while the rest of the fuel consumed is used to produce work for shaft power.

The three most significant waste heat streams are exhaust gas, air cooler (scavenge air), and engine cooling jacket water, respectively, of the total rejected waste heat. However, not all waste heat is created “equal”.

The temperatures of these waste heat streams govern the usefulness of the available waste heat streams. Typically, there are three main “categories” based on the available streams’ temperature ranges: high (> 650°C), medium (240 – 650°C) and low (< 240°C). The marine waste heat usually occupies the latter two temperature ranges (typically categorized as medium and low intensity).

From Fig. 1, it can be seen that the exhaust gas stream offers the highest available mass flow of all the waste heat effluents. Due to considerations related to sulfuric acid condensation in the exhaust gas (and, hence, resultant unwanted corrosion), the exhaust gas stream has historically been kept above a minimum temperature to avoid such adverse effects. Typically, this puts a lower bound on the temperature of the exhaust gas at approximately 165°C [7]. The use of cleaner fuels in the future can reduce the risk of acid formation at lower temperatures and can increase energy recovery from the exhaust gases. The Kongsberg K-Sim model described an option that brought the exhaust temperature down to approximately 108°C, which requires that the exhaust boiler be built of acid-resistant steel and equipped with efficient soot blowers. The WHR analysis in this paper uses the optional extended temperature range.

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[3] SMCR = Specified Maximum Continuous Rating – the specified maximum power the engine can continuously deliver [7]

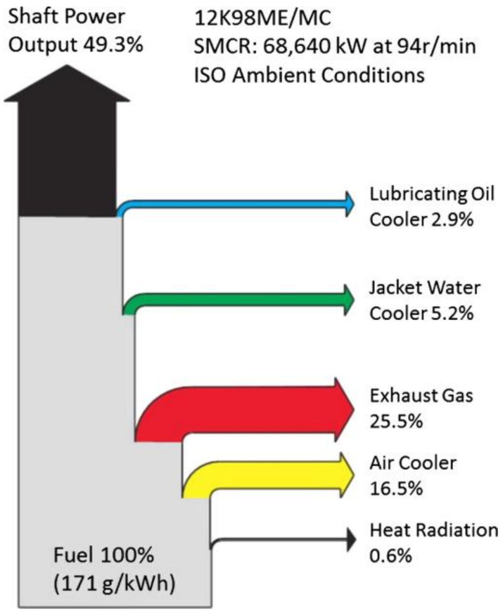

Fig. 1. A typical Sankey energy diagram for a marine diesel engine (MAN B&W 12K98ME/MC) operating at 100% SMCR under ISO[4] conditions

The next highest available gas stream is the air cooler, which is at the outlet of the compressor (from the turbocharger) which is also called the "scavenge air." The high temperatures of this compressed air stream are useful source of available energy for extraction and recovery as part of the WHR system onboard.

Next is the jacket cooling water, which is typically used as a heat source for boiling the seawater in the onboard desalination plants. Heat extraction from the hot jacket cooling water is another opportunity for the WHR system.

Lastly, we consider the lubricating oil and its temperature availability for heat extraction for WHR system purposes. Although a relatively small contributor, nevertheless, since lube oil has to be kept cool at all operating times of the main engine(s), this offers an uninterrupted heat source. The job of cooling the lubricating oil through a highly efficient compact heat exchanger (say, plate/fin, etc.) can provide the required heat source for harvesting for a WHR system

At a sub-1% contribution, heat radiation is perhaps too insignificant to be considered for WHR capture.

Reviews [9-14] of typical operating conditions of 2-stroke, large-bore, low-speed diesel engines (used as main propulsion for container carriers, bulk carriers, and oil tankers) show that the three major waste heat streams fall in the temperature ranges of 200°C – 350°C (exhaust gas), 100°C – 160°C (scavenge air) and 70°C – 95°C (engine jacket cooling water). Hence, most of the potentially available WHR energy is in the medium- to low-quality thermal ranges (say, 70°C – 350°C)

Main WHR Technologies

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[4] ISO conditions – International Standard Organisation conditions (288 K, 60% RH, 101.3 kPa)

Next, we consider the typical WHR technologies that have been used widely in ships. Regardless of whether the main propulsion is based on a diesel engine (2-stroke, low-speed; 4-stroke medium-/high-speed), gas turbine(s), or steam turbine(s), the onboard production of steam is needed either as source for main propulsion (steam turbines) or as heavy fuel oil (HFO) preheater (for 2-stroke, low-speed diesel engines).

In the case of gas turbine propulsion, the hot exhaust gas from the gas turbines is usually captured in heat recovery steam generators (HRSGs) and used to preheat compressed water used for the production of steam for the steam turbines.

For the purposes of this paper, it is assumed that steam turbines operate on a conventional steam Rankine cycle (SRC), the gas turbine engines operate on an open Brayton cycle, while the diesel engines, of course, operate on a Diesel cycle.

Many seminal works have described opportunities for successful WHR systems, including technologies related to conventional Steam Rankine cycle (SRC) [15-17], Super-critical Rankine Cycle (SCRC) [18,19], Organic Rankine cycle (ORC), etc. [20-35].

A recent work [36] provides a detailed review and analysis of these WHR methods.

Past research work [37-42] has considered the utilization of the Kalina cycle (KC) as an efficient and effective means of waste heat recovery from large, low-speed marine Diesel engines.

Next, a brief review and background of a “conventional” Steam Rankine Cycle (SRC), Organic Rankine Cycle (ORC), and a Kalina Cycle (KC) is included. The discussion further expands on the advantages offered by the KC to capture low-quality waste heat compared to SRC and ORC.

Steam Rankine cycle (SRC)

Steam Rankine cycle (SRC) is a thermodynamic cycle which converts heat energy into mechanical work. A typical diagram of a SRC is shown in Fig. 2. A circulating working fluid is continuously evaporated and condensed during the operation. A simple power plant operating with steam is comprised of four main components: boiler (and a superheater), turbine, condenser, and liquid feed-pump. The liquid water is compressed by the liquid feed-pump (P) between states 1 and 2. The compressed water enters the boiler (B) at state 2. The external combustion in the boiler changes the phase of the liquid water to wet steam (two-phase flow) between states 2 and 3. A superheater can further increase the temperature of the steam leaving the boiler at 3 before entering the steam turbine (T). The steam is expanded in the steam turbine between states 3 and 4. Any remaining steam is further condensed in the condenser (C), thus liquid water enters the inlet to the pump, at which point the steam Rankine cycle repeats itself.

A typical temperature-entropy (T-s) diagram is shown in Fig. 3. The opportunity of the SRC to produce steam at high operational temperatures (300°C – 400°C) diminishes when these source temperatures are low, as the operation becomes non-cost effective. Typical waste heat stream of the lower quality temperature range (< 240°C) would be prohibitively low to allow superheat operation in an SRC. Superheat is often employed as means of preventing (or at least delaying) condensation and resulting erosion of the turbine blades (esp. at the last few rows, following nearly complete expansion of the hot steam in the prior stages of the turbine). Also, low temperatures result in low-pressure steam, requiring significantly larger turbines to extract the energy and convert it to work. Hence, the temperature limitations of the heat source prevent the application of SRCs in low-quality thermal sources.

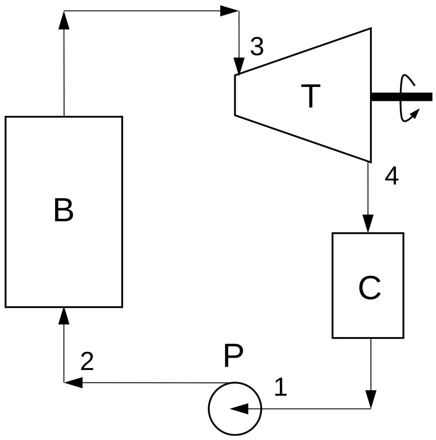

Fig. 2. Schematic of a typical steam Rankine cycle (SRC) plant

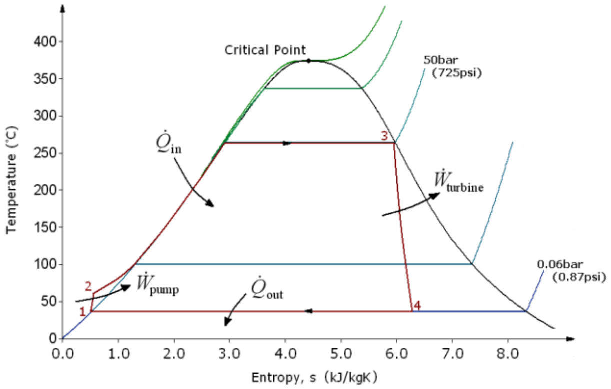

Fig. 3. Temperature-entropy (T-s) diagram for a typical steam Rankine cycle (SRC)

Organic Rankine Cycle (ORC)

The low-temperature heat source limitations imposed on the conventional SRC are not a challenge for the organic Rankine cycle which uses organic fluids (hence the name) whose specific heat of vaporization is much lower than that of water. Hence, ORCs can extract heat even from lower temperature sources. A schematic of a typical ORC is shown in Fig. 4. In place of the conventional boiler, the ORC uses an evaporator (E) that absorbs the low-quality heat from a heat source entering the evaporator at the heat source fluid inlet (HSFI) and exiting the evaporator at the heat source fluid outlet (HSFO) as shown in Fig. 4. Although not shown in Fig. 4, the typical cooling medium for the condenser (in marine engine propulsion systems) may be the freely available and abundant seawater. Although recognized, seasonal and geographical variations in seawater temperature are not considered in this analysis.

A typical temperature-entropy (T-s) diagram of an ORC is shown in Fig. 5. The ideal cycle is shown in the blue curve, while the red curve shows slight deviations due to losses associated with real cycle operations. Some of the typical organic fluids include (but are not limited to) hydrocarbon gases, refrigerants, etc.

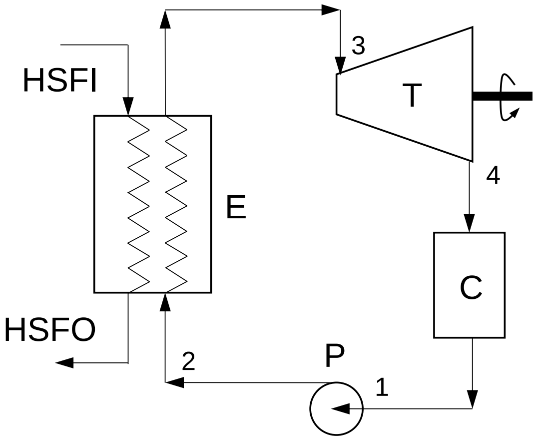

Fig. 4. Schematic of a typical Organic Rankine cycle (ORC) plant

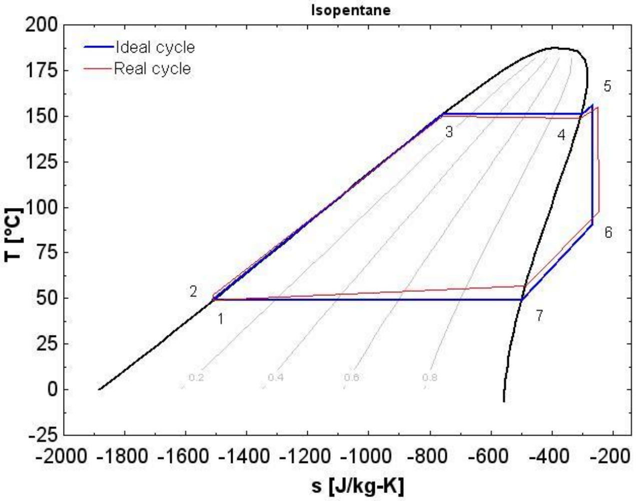

Fig. 5 Temperature-entropy (T-s) diagram for a typical Organic Rankine cycle (ORC) operating on isopentane fluid

Kalina Cycle (KC)

As a viable alternative to both SRC and ORC, the Kalina cycle (KC), invented by Dr. Alexander Kalina in 1983 [43], is a modified cycle using a binary mixture of ammonia (NH_3) and water (H_2O) as its working fluid to operate in varying composition (mixture fractions) with variable boiling and condensation temperatures between the heat source and heat sink. This allows the KC to capture low temperature ("low quality") heat, thus efficiently utilizing waste heat in a recovery system. This working fluid mixture, with its non-azeotropic behavior, allows the KC to have a gliding temperature phase change so that the temperature of the working fluid mixture closely matches the temperature from the low heat source, thus making the resulting heat transfer more efficient and reversible. This is shown in Fig. 6. A simple schematic of a KC system is shown in Fig. 7. Additional components (not used in the "conventional" SRC) include a recuperator, a separator, mixers, and flow control valves.

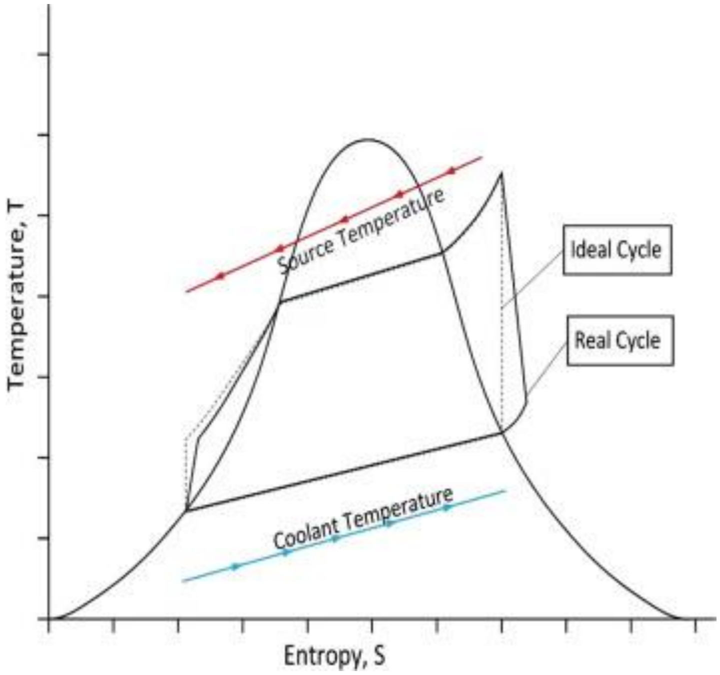

Fig. 6 Temperature-entropy (T-s) diagram for a typical Kalina cycle (KC) operating on ammonia/water mixture fluid (adapted from [44])

The waste heat from a low-temperature ("low quality") heat source ("flue gas") is transferred through a heat exchanger ("boiler"). This waste heat is absorbed by the binary mixture (70% NH_3 solution, green line) used as the working fluid for the KC. The heated vapor exits the **Boiler** and enters the **Turbine** ("expander"). The expansion in the **Turbine** provides power to rotate the turbine output shaft, which, connected to an electric **Generator**, provides rotation to the electric generator for useful power generation. The same binary mixture (70% NH_3 solution, green line) cooled to a lower temperature now exits the **Turbine** and enters **Recuperator 1**. **Recuperator 1** recovers some of the heat from the working fluid after leaving the **Turbine** and uses this heat to preheat the fluid flowing to the **Separator,** in essence reducing the amount of heat going to the **Condenser**. This also helps control the mass fractions of the rich mixture (95% NH_3 solution, blue line) and the lean mixture (34% NH_3 solution, brown line) going out of the **Separator** at its top and bottom, respectively (as shown in Fig. 7).

Two separate mixers are used to get the required composition fluid flows in the KC system. **Mixer 1** is located at the inlet of the **Condenser** where the lean mixture (34% NH_3 solution, brown line) stream from the bottom of the **Separator** (after passing through flow control **Valve 1**) is mixed with the exhaust stream from the **Turbine** (70% NH_3 solution, green line) after exiting **Recuperator 1**. Thus, these two streams mix to feed a lower concentration fluid (45% NH_3, red line) to the **Condenser**. The newly formed lower mixture stream exits the **Condenser**, is pumped by the **Feed Pump** back to the **Recuperator 1,** as well as split to the **Recuperator 2** where it exchanges heat with the lean mixture (34% NH_3 solution, brown line).

The second mixer, **Mixer 2,** is at the inlet of the **Boiler** where the remaining flow from the flow control **Valve 2** and rich mixture from the **Separator** (95% NH_3 solution, blue line) are mixed to feed the **Boiler** with higher concentration (70% NH_3 solution, green line) working fluid. This completes the KC.

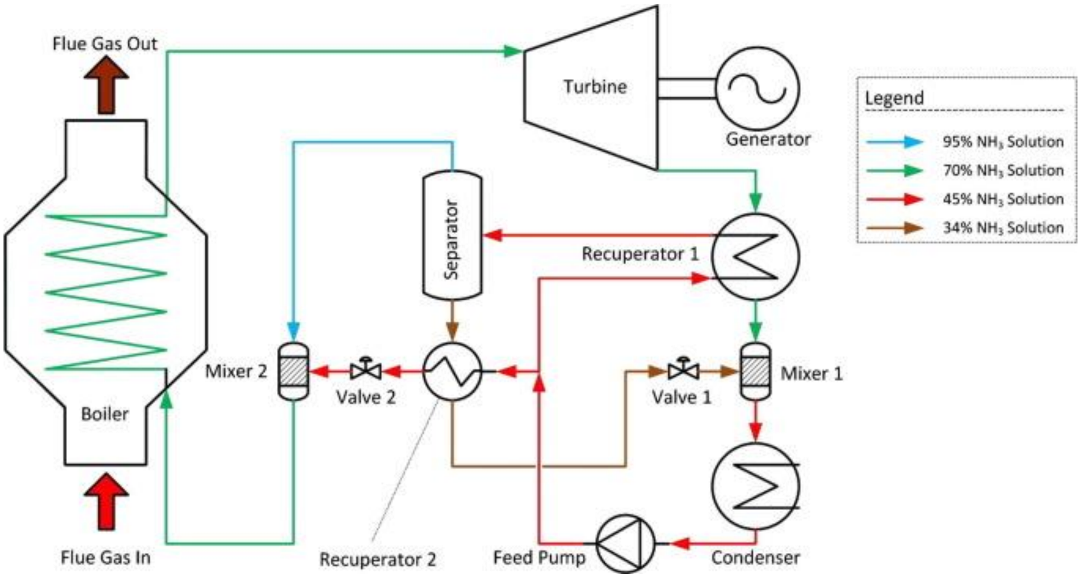

Fig. 7. Schematic of a typical Kalina cycle (KC) plant (adapted from [44])

Different KC configurations [45] have been developed over the years to suit various operational conditions. For example, the earliest versions, KC0, used only one heat exchanger, while the KC1 was developed as a student project [46]. Both KC1 and KC2 operated at similar efficiencies [45], while KC3 showed an operational efficiency improvement due to the use of a multi-stage turbine configuration with higher turbine inlet pressure and additional reheating and intercooling. KCS5 (Kalina Cycle System) was used for direct-fired power plants, while the KCS6 (Kalina Cycle System) was used for the gas turbine bottoming cycle [47]. KCS11 was developed for low-temperature resources [48] and has proven to be one of the most widely used KCS configurations. KCS11 uses low quality heat in the range of 121°C to 204°C, while its sister versions, KCS34 and KCS34g, were intended for combined power systems and small plants, respectively [49]. KCS12 was also developed for low temperature geothermal heat sources but has seen relatively limited applications mainly due to its system complexity [50]. Further details about the various KCS architectures and their associated performance parameters can be found elsewhere [51-53].

Simulations

Plant Architecture

The Kongsberg simulations used in this paper assumed a ship propulsion machinery based on the K-Sim Engine using the Wärtsilä (Sulzer) 12RT-Flex82C, low speed, 12-cylinder configuration, 2-stroke, turbocharged, reversible diesel engine of the crosshead type with uniflow scavenging [6]. A brief summary of the main engine particulars is listed below. A Kongsberg schematic showing the Wärtsilä (Sulzer) 12RT-Flex82C is shown in Fig. 8.

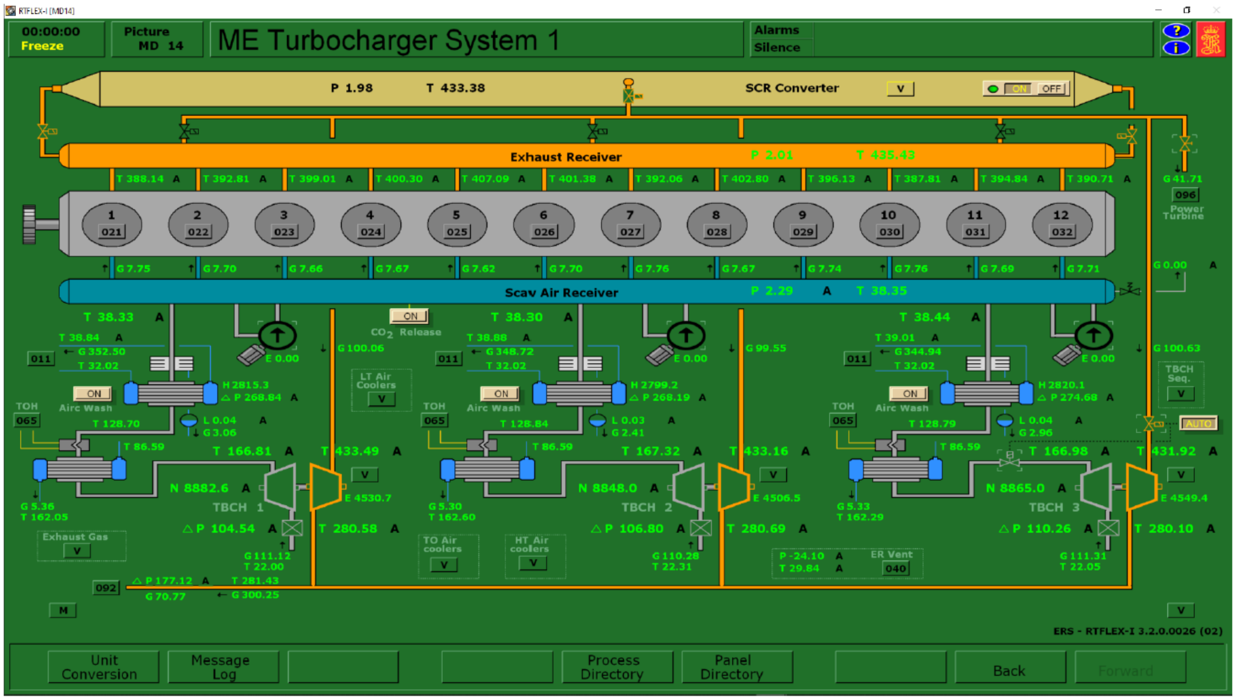

Fig. 8. Kongsberg K-Sim simulation layout of the Wärtsilä (Sulzer) 12RT-Flex82C engine

Main engine particulars

- Cylinder Bore	820 mm
- Piston Stroke	2646 mm
- Number of Cylinders	12
- Number of Air Coolers	6
- Number of Turbo Chargers	3
- Continuous Service Rating ME	54.24 MW
- Corresponding Engine Speed	102 rpm
- Mean Indicated Pressure	19.5 Bar
- Scavenge Air Pressure	2.30 Bar
- Turbine Speed	9000 rpm
- Number of Prop. Blades	5
- Propeller Pitch	1.08 P/D
- Specific Fuel Oil Consumption	167 g/kwh

This main engine is used as the main propulsion for a Panamax[5] container ship of 4800 TEU[6] capacity with 62000 DWT, and dimensions of 296.0 m x 32.2 m x 12.7 m (L x B x T), allowing a maximum cruising speed of up to 25 kt. The Kongsberg K-Sim model is based on real data which makes the dynamic behavior of the simulator very close to the real engine operational behavior.

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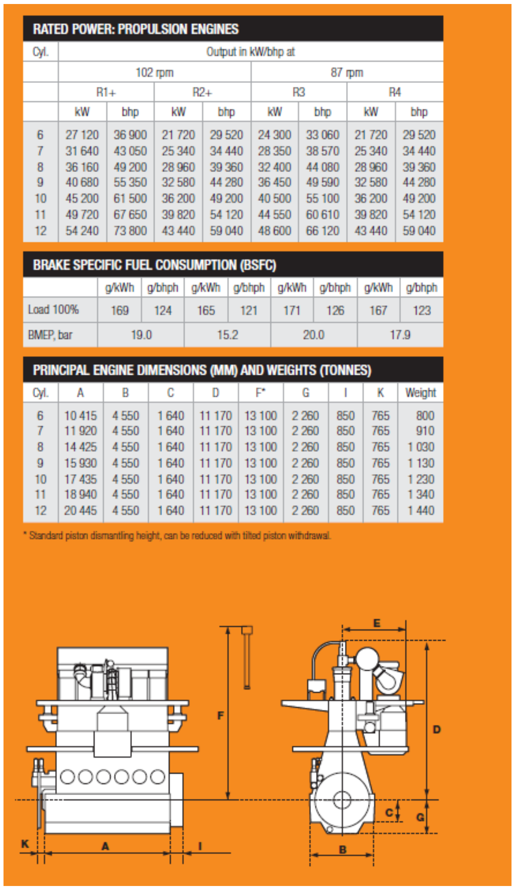
[5] Panamax – the size of the largest vessel that can fit through the Panama Canal, typically, at 296.0 m x 32.3 m x 12.8 m (L x B x T)

[6] TEU – Twenty-foot Equivalent Unit (typical container size based on a 20 ft length)

The electrical power plant includes three (3) diesel generators, one shaft generator, a steam turbine generator, and one emergency generator. The steam plant includes an oil-fired boiler as well as an exhaust boiler. The main engine dimensions and weights are shown in Fig. 9.



RATED POWER: PROPULSION ENGINES

Cyl.	Output in kW/bhp at							
	102 rpm				87 rpm			
	R1+		R2+		R3		R4	
	kW	bhp	kW	bhp	kW	bhp	kW	bhp
6	27 120	36 900	21 720	29 520	24 300	33 060	21 720	29 520
7	31 640	43 050	25 340	34 440	28 350	38 570	25 340	34 440
8	36 160	49 200	28 960	39 360	32 400	44 080	28 960	39 360
9	40 680	55 350	32 580	44 280	36 450	49 590	32 580	44 280
10	45 200	61 500	36 200	49 200	40 500	55 100	36 200	49 200
11	49 720	67 650	39 820	54 120	44 550	60 610	39 820	54 120
12	54 240	73 800	43 440	59 040	48 600	66 120	43 440	59 040

BRAKE SPECIFIC FUEL CONSUMPTION (BSFC)

	g/kWh	g/bhph	g/kWh	g/bhph	g/kWh	g/bhph	g/kWh	g/bhph
Load 100%	169	124	165	121	171	126	167	123
BMEP, bar	19.0		15.2		20.0		17.9	

PRINCIPAL ENGINE DIMENSIONS (MM) AND WEIGHTS (TONNES)

Cyl.	A	B	C	D	F*	G	I	K	Weight
6	10 415	4 550	1 640	11 170	13 100	2 260	850	765	800
7	11 920	4 550	1 640	11 170	13 100	2 260	850	765	910
8	14 425	4 550	1 640	11 170	13 100	2 260	850	765	1 030
9	15 930	4 550	1 640	11 170	13 100	2 260	850	765	1 130
10	17 435	4 550	1 640	11 170	13 100	2 260	850	765	1 230
11	18 940	4 550	1 640	11 170	13 100	2 260	850	765	1 340
12	20 445	4 550	1 640	11 170	13 100	2 260	850	765	1 440

* Standard piston dismantling height, can be reduced with tilted piston withdrawal.

Fig. 9. Wärtsilä (Sulzer) 12RT-Flex82C principal engine dimensions and weights

Assumptions

The EES (Engineering Equation Solver) calculations used for the Kongsberg K-Simulations were based on the following assumptions:

- Steady State, Steady Flow conditions
- Pressure and temperature losses in the piping are neglected
- Kinetic and potential energy changes are neglected
- Turbines and pumps are considered to be isentropic
- Throttle valves are considered to be isenthalpic
- Superheater Exhaust Gas inlet temperature = 282.2[°C]
- Evaporator Exhaust Gas outlet temperature = 108[°C]
- Heat added to working fluid by exhaust gas =18,200[kW]
- Working fluid at separator outlet state point 2 is a saturated vapor
- Working fluid at separator outlet state point 5 is a saturated liquid
- Working fluid at the turbine inlet is a superheated vapor
- Quality out of the turbine at >0.85

- Working fluid at the condenser outlet is a saturated liquid
- Condenser Terminal Temperature Difference is 2[°C]
- Condenser cooling water is a 3.5% aqueous solution
- Condenser cooling water inlet temperature is 20[°C]
- Condenser cooling water pressure is 3 bar

Results

In this paper a typical KCS11 architecture was used for WHR from a large 2-stroke low speed Diesel Engine. The simulations calculations were performed using the *Kongsberg RTFLEX-I Desktop* simulator [6], using the *Full Ahead Loaded* scenario for full power operation of the Sulzer RTFLEX-1 engine at its MCR setpoint. This choice is a good platform for this analysis and future comparative analyses, as it has several innovative waste heat recovery systems and all the (simulated) temperatures, pressures, flows, etc. that were sued for these analyses. There are other operational scenarios (e.g., *Full Ahead Unloaded, Full Ahead CPP, Full Ahead Tropic, and Full Ahead Arctic*) that were not used but may offer further research at a later time related to this topic. All the thermodynamic analyses were done using EES[7].

A simple schematic drawing of the complete KCS11 WHR system is shown in Fig. 10.

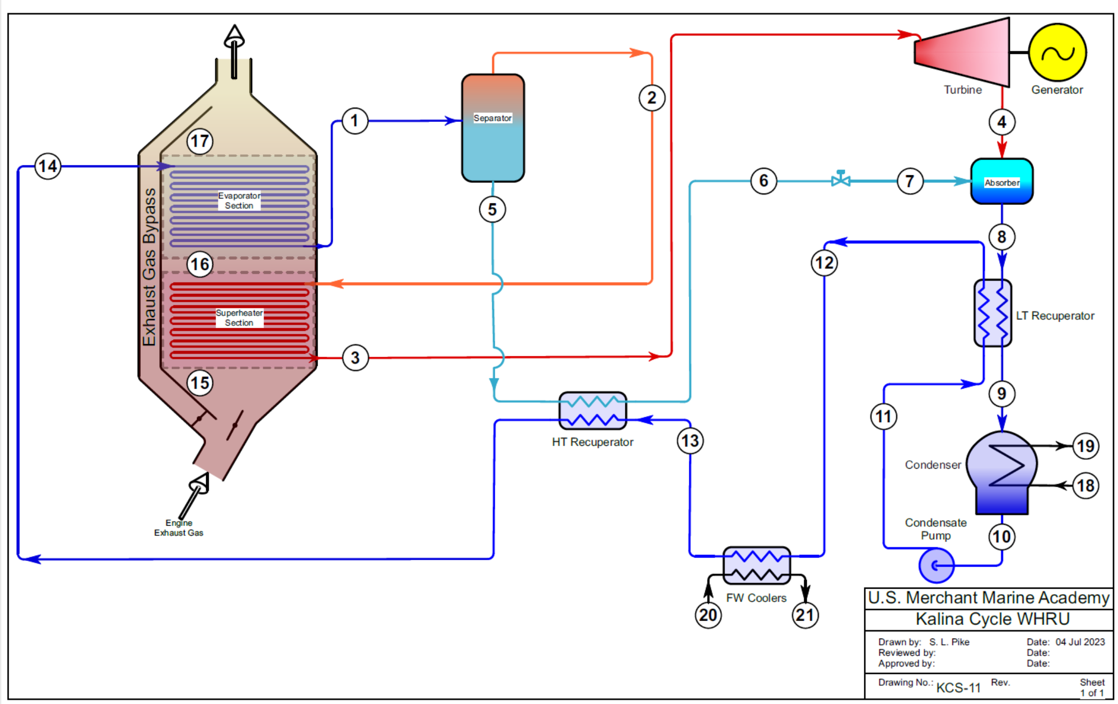


Fig. 10. Schematic of a Kalina cycle system 11(KCS11) architecture used for the simulations in this paper

Next, a component by component analysis, determining the best flow rates and concentration of the ammonia/water (NH_3/H_2O) mix for each component has been completed. Several operational cases have been compiled, based on varying ammonia mass fraction ($x_{[NH3]}$).

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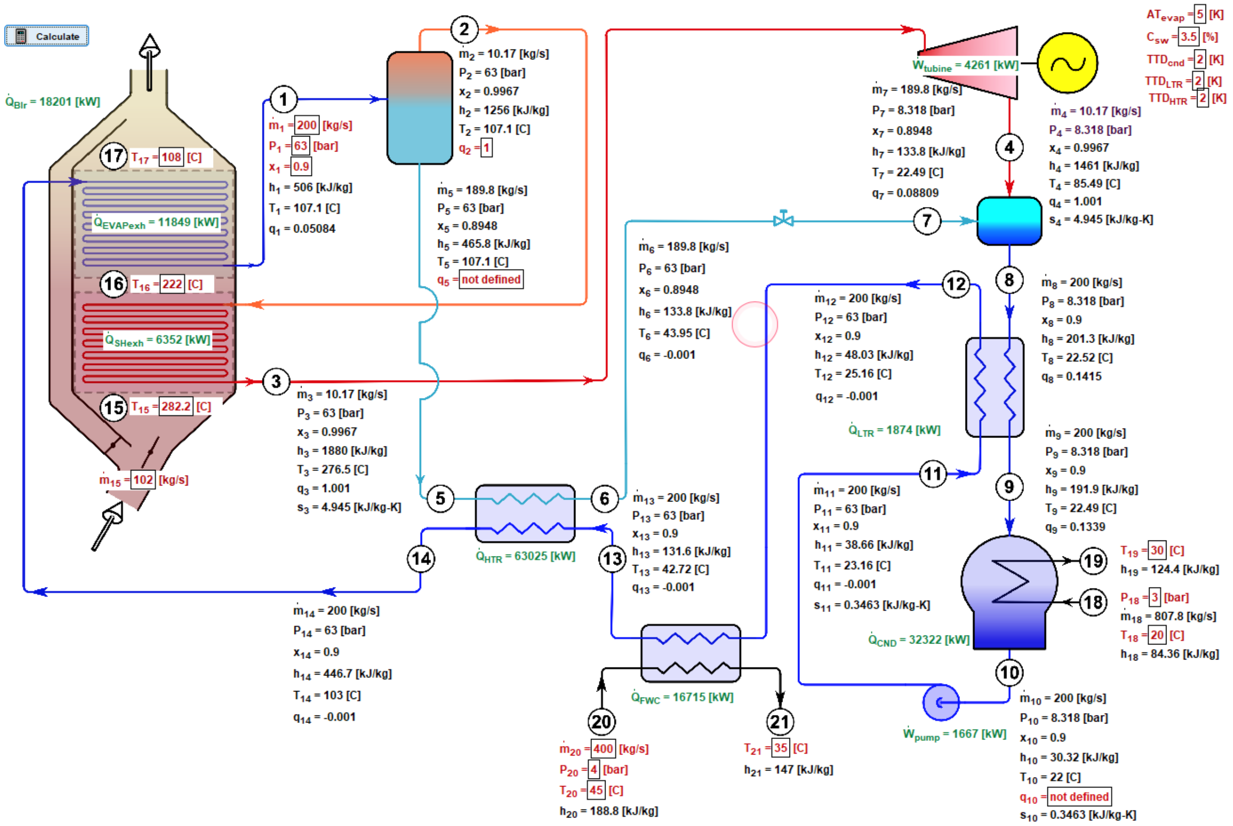
[7] EES – Engineering Equation Solver, https://fchartsoftware.com/ees/

This required modification of system pressures and the temperature at state point 16 (exhaust gas from superheater to evaporator transition) to maintain the operating conditions within realistic ranges.

Based on the completed simulations, and integration of all of the analyses into the complete system, the best overall ammonia concentration and flow rates to keep complexity to a minimum have been determined. The results show that a high concentration, 0.9 mass fraction NH_3 for the working fluid, was most effective.

Case: $x_{[NH3]}$ = 0.9

A schematic showing the points for Case 1 ($x_{[NH3]}$ = 0.9) is shown in Fig 11. The detailed analyses results follow.



$\dot{Q}_{Blr}$ = 18201 [kW]
$\dot{Q}_{EVAPexh}$ = 11849 [kW]
$\dot{Q}_{SHexh}$ = 6352 [kW]
T_{17} = 108 [C]
T_{16} = 222 [C]
T_{15} = 282.2 [C]
$\dot{m}_{15}$ = 102 [kg/s]

$\dot{m}_1$ = 200 [kg/s]
P_1 = 63 [bar]
x_1 = 0.9
h_1 = 506 [kJ/kg]
T_1 = 107.1 [C]
q_1 = 0.05084

$\dot{m}_2$ = 10.17 [kg/s]
P_2 = 63 [bar]
x_2 = 0.9967
h_2 = 1256 [kJ/kg]
T_2 = 107.1 [C]
q_2 = 1

$\dot{m}_5$ = 189.8 [kg/s]
P_5 = 63 [bar]
x_5 = 0.8948
h_5 = 465.8 [kJ/kg]
T_5 = 107.1 [C]
q_5 = not defined

$\dot{m}_3$ = 10.17 [kg/s]
P_3 = 63 [bar]
x_3 = 0.9967
h_3 = 1880 [kJ/kg]
T_3 = 276.5 [C]
q_3 = 1.001
s_3 = 4.945 [kJ/kg-K]

$\dot{m}_{14}$ = 200 [kg/s]
P_{14} = 63 [bar]
x_{14} = 0.9
h_{14} = 446.7 [kJ/kg]
T_{14} = 103 [C]
q_{14} = -0.001

$\dot{Q}_{HTR}$ = 63025 [kW]

$\dot{m}_{20}$ = 400 [kg/s]
P_{20} = 4 [bar]
T_{20} = 45 [C]
h_{20} = 188.8 [kJ/kg]

$\dot{W}_{tubine}$ = 4261 [kW]

$\dot{m}_7$ = 189.8 [kg/s]
P_7 = 8.318 [bar]
x_7 = 0.8948
h_7 = 133.8 [kJ/kg]
T_7 = 22.49 [C]
q_7 = 0.08809

AT_{evap} = 5 [K]
C_{sw} = 3.5 [%]
TTD_{cnd} = 2 [K]
TTD_{LTR} = 2 [K]
TTD_{HTR} = 2 [K]

$\dot{m}_4$ = 10.17 [kg/s]
P_4 = 8.318 [bar]
x_4 = 0.9967
h_4 = 1461 [kJ/kg]
T_4 = 85.49 [C]
q_4 = 1.001
s_4 = 4.945 [kJ/kg-K]

$\dot{m}_6$ = 189.8 [kg/s]
P_6 = 63 [bar]
x_6 = 0.8948
h_6 = 133.8 [kJ/kg]
T_6 = 43.95 [C]
q_6 = -0.001

$\dot{m}_{12}$ = 200 [kg/s]
P_{12} = 63 [bar]
x_{12} = 0.9
h_{12} = 48.03 [kJ/kg]
T_{12} = 25.16 [C]
q_{12} = -0.001

$\dot{Q}_{LTR}$ = 1874 [kW]

$\dot{m}_8$ = 200 [kg/s]
P_8 = 8.318 [bar]
x_8 = 0.9
h_8 = 201.3 [kJ/kg]
T_8 = 22.52 [C]
q_8 = 0.1415

$\dot{m}_9$ = 200 [kg/s]
P_9 = 8.318 [bar]
x_9 = 0.9
h_9 = 191.9 [kJ/kg]
T_9 = 22.49 [C]
q_9 = 0.1339

$\dot{m}_{13}$ = 200 [kg/s]
P_{13} = 63 [bar]
x_{13} = 0.9
h_{13} = 131.6 [kJ/kg]
T_{13} = 42.72 [C]
q_{13} = -0.001

$\dot{m}_{11}$ = 200 [kg/s]
P_{11} = 63 [bar]
x_{11} = 0.9
h_{11} = 38.66 [kJ/kg]
T_{11} = 23.16 [C]
q_{11} = -0.001
s_{11} = 0.3463 [kJ/kg-K]

$\dot{Q}_{CND}$ = 32322 [kW]

T_{19} = 30 [C]
h_{19} = 124.4 [kJ/kg]

P_{18} = 3 [bar]
$\dot{m}_{18}$ = 807.8 [kg/s]
T_{18} = 20 [C]
h_{18} = 84.36 [kJ/kg]

$\dot{Q}_{FWC}$ = 16715 [kW]

T_{21} = 35 [C]
h_{21} = 147 [kJ/kg]

$\dot{W}_{pump}$ = 1667 [kW]

$\dot{m}_{10}$ = 200 [kg/s]
P_{10} = 8.318 [bar]
x_{10} = 0.9
h_{10} = 30.32 [kJ/kg]
T_{10} = 22 [C]
q_{10} = not defined
s_{10} = 0.3463 [kJ/kg-K]

Fig. 11. Schematic of a Kalina cycle system 11(KCS11) architecture used for the simulations in this paper for $x_{[NH3]}$ = 0.9

Hot engine exhaust gases flow through the evaporator as waste heat is recovered by heating the working fluid (2 – 3) in the superheater section (15 – 16). In the evaporator section (16 – 17), the ammonia-water mixture is preheated (14 – 1) as it enters the separator at 1 with a mass fraction ($x_{1[NH3]}$) of 0.9. The higher concentration ($x_{2[NH3]}$ = 0.997), higher temperature vapor at 2 enters the superheater section (2– 3) where it is further heated (absorbing heat from the waste heat stream).

The superheated working fluid enters the turbine at 3 and is expanded by the time it leaves the turbine at 4. The extracted energy rotates the turbine shaft, which, coupled to the electric generator, produces useful electric power for onboard use.

The cooler high concentration ($x_{4[NH3]}$ = 0.997) working fluid (upon leaving the turbine at 4) enters the absorber where it is mixed with the lower concentration ($x_{7[NH3]}$ = 0.895) working fluid at 7 thus producing an output working fluid of ($x_{8[NH3]}$ = 0.9) at 8 as it leaves the absorber.

This fluid further enters the Low Temperature Recuperator (LT Recuperator) at 8 at T_8 = 22.52°C and exits it at 9 with T_9 = 22.49°C, thus preheating the re-pumped stream (11 – 12) from T_{11} = 23.16°C to T_{12} = 25.16°C. Next the fluid enters the condenser at 9 where it gives off some additional heat to the cooling seawater stream (18 – 19) thus dropping further to T_{10} = 22°C (while slightly raising the temperature of the seawater coolant stream by approximately 10°C from T_{18} = 20°C to T_{19} = 30°C).

The pressurized (63 bar) and preheated (T_{12} = 25.16°C) working fluid stream leaves the LT Recuperator at 12 as it is further preheated to T_{13} = 42.72°C in the Freshwater Cooler (absorbing heat from the freshwater stream (20 – 21) while maintaining its pressure (63 bar) and concentration ($x_{13[NH3]}$ = 0.9). At the same time, the freshwater stream loses 10°C in the process (from T_{20} = 45°C to T_{21} = 35°C)

Next the working fluid enters the High Temperature Recuperator (HT Recuperator) at 13 with T_{13} = 42.72°C where it absorbs additional heat from the intermediate concentration ($x_{5[NH3]}$ = 0.895) stream (5 – 6) thus raising the temperature of the working fluid to T_{14} = 103°C upon exiting the HT Recuperator at 14. At the same time, on the other side of the HT Recuperator, the intermediate concentration stream (5 – 6) is cooled from T_5 = 107.1°C to T_6 = 43.95°C.

Finally, the preheated, pressurized working fluid ($x_{14[NH3]}$ = 0.9) leaving the HT Recuperator at 14 re-enters the ammonia-water side of the evaporator. This completes the KCS11 cycle. During this process, a useful amount of approx. 4.3 MW is produced in the turbine/expander to generate electric power for use onboard the ship, resulting in effective energy recovery of approx. 8% (based on the ship's main engine continuous service rating of 54.24 MW).

"Properties for Ammonia-Water mixture are obtained using standard EES calls, with the liquid being entered as 'NH3H2O'."

"NOTE: in the instance of using NH3H2O for thermophysical property determination:
'x' is used for ammonia mass fraction;
'q' is used for quality;
three independent variables are required for property determinations;
SI units must be used (K, bar, kJ)."

"The correlations are applicable for temperatures between 230 K and 600 K at equilibrium pressures between 0.2 and 110 bar."

```
"Mass flow rate assumptions"
m_dot[3]=m_dot[2]
m_dot[6]=m_dot[5]
m_dot[7]=m_dot[6]

Duplicate i=8,14
    m_dot[i]=m_dot[1]
End

"Evaporator Section, Exhaust Side"
Q_dot_EVAPexh=m_dot[15]*(h[16]-h[17])
h[16]=enthalpy(Air,T=T[16])
h[17]=enthalpy(Air,T=T[17])
"Evaporator Section, Ammonia-Water Side"
Q_dot_EVAPaw=Q_dot_EVAPexh
Q_dot_EVAPaw=m_dot[1]*(h[1]-h[14])
h[14]=enthalpy(NH3H2O,P=P[14],x=x[14],T=T[14])
P[14]=P[1]
x[14]=x[1]
T[14]=T[17]-AT_evap
T14=temperature(NH3H2O,P=P[14],x=x[14],h=h[14])
q[14]=quality(NH3H2O,P=P[14],x=x[14],h=h[14])
T[1]=temperature(NH3H2O,P=P[1],x=x[1],h=h[1])
q[1]=quality(NH3H2O,P=P[1],x=x[1],h=h[1])


"Separator"
m_dot[1]=m_dot[2]+m_dot[5]
m_dot[1]*x[1]=m_dot[2]*x[2]+m_dot[5]*x[5]
m_dot[1]*h[1]=m_dot[2]*h[2]+m_dot[5]*h[5]
h[2]=enthalpy(NH3H2O,P=P[2],T=T[2], q=q[2])
P[2]=P[1]
T[2]=T[1]
h[5]=enthalpy(NH3H2O,P=P[5],T=T[5], q=q[5])
P[5]=P[1]
T[5]=T[1]
x[2]=massfraction(NH3H2O,P=P[2],T=T[2], q=q[2])

"Superheater Section, Exhaust Side"
Q_dot_SHexh=m_dot[15]*(h[15]-h[16])
h[15]=enthalpy(Air,T=T[15])

Q_dot_Blr=Q_dot_SHexh+Q_dot_EVAPexh

"Superheater Section, Ammonia-Water Side"
```

```
Q_dot_SHaw=Q_dot_SHexh
Q_dot_SH=Q_dot_SHexh
Q_dot_SHaw=m_dot[2]*(h[3]-h[2])
T[3]=temperature(NH3H2O,P=P[3],x=x[3],h=h[3])
P[3]=P[1]
x[3]=x[2]
q[3]=quality(NH3H2O,P=P[3],x=x[3],h=h[3])
s[3]=entropy(NH3H2O,P=P[3],x=x[3],h=h[3])

"Turbine"
W_dot_tubine=m_dot[3]*(h[3]-h[4])
h[4]=enthalpy(NH3H2O,P=P[4],x=x[4],s=s[4])
T[4]=temperature(NH3H2O,P=P[4],x=x[4],s=s[4])
q[4]=quality(NH3H2O,P=P[4],x=x[4],s=s[4])
P[4]=P[10]
x[4]=x[3]
s[4]=s[3]

"Fresh Water Coolers, Fresh Water Side"
Q_dot_FWCwtr=m_dot[20]*(h[20]-h[21])
h[20]=enthalpy(Water,T=T[20],P=P[20])
h[21]=enthalpy(Water,T=T[21],P=P[21])
P[21]=P[20]

"Fresh Water Coolers, Ammonia-Water Side"
Q_dot_FWCaw=Q_dot_FWCwtr
Q_dot_FWC=Q_dot_FWCwtr
Q_dot_FWCaw=m_dot[12]*(h[13]-h[12])
h[12]=enthalpy(NH3H2O,P=P[12],x=x[12],T=T[12])
q[12]=quality(NH3H2O,P=P[12],x=x[12],T=T[12])
x[12]=x[1]
P[12]=P[1]
T[12]=T[11]+TTD_LTR
h[13]=enthalpy(NH3H2O,P=P[13],x=x[13],T=T[13])
x[13]=x[1]
P[13]=P[1]
q[13]=quality(NH3H2O,P=P[13],x=x[13],T=T[13])

"HT Recuperator, Hot Side"
Q_dot_HTRhot=m_dot[5]*(h[5]-h[6])
T[6]=temperature(NH3H2O,P=P[6],x=x[6],h=h[6])
P[6]=P[5]
x[6]=x[5]
q[6]=quality(NH3H2O,P=P[6],x=x[6],T=T[6])

"HT Recuperator, Cold Side"
```

```
Q_dot_HTRcold=Q_dot_HTRhot
Q_dot_HTR=Q_dot_HTRhot
Q_dot_HTRcold=m_dot[13]*(h[14]-h[13])

"Throttle Valve"
h[7]=h[6]
P[7]=P[4]
x[7]=x[6]
T[7]=temperature(NH3H2O,P=P[7],x=x[7],h=h[7])
q[7]=quality(NH3H2O,P=P[7],x=x[7],h=h[7])

"Absorber"
m_dot[4]*h[4]+m_dot[7]*h[7]=m_dot[8]*h[8]
m_dot[4]+m_dot[7]=m_dot[8]
P[8]=P[4]
x[8]=x[1]
T[8]=temperature(NH3H2O,h=h[8],x=x[8],P=P[8])
q[8]=quality(NH3H2O,h=h[8],x=x[8],P=P[8])

"LT Recuperator, Cold Side"
Q_dot_LTRcold=m_dot[11]*(h[12]-h[11])
P[11]=P[12]

"LT Recuperator, Hot Side"
Q_dot_LTRhot=Q_dot_LTRcold
Q_dot_LTR=Q_dot_LTRcold
Q_dot_LTRhot=m_dot[8]*(h[8]-h[9])
T[9]=temperature(NH3H2O,P=P[9],x=x[9],h=h[9])
P[9]=P[8]
x[9]=x[8]
q[9]=quality(NH3H2O,P=P[9],x=x[9],T=T[9])

"Condenser, Ammonia-Water Side"
Q_dot_CNDaw=m_dot[9]*(h[9]-h[10])
h[10]=enthalpy(NH3H2O,q=q[10],x=x[10],T=T[10])
P[10]=pressure(NH3H2O,q=q[10],x=x[10],T=T[10])
x[10]=x[9]
T[10]=T[18]+TTD_cnd

"Condenser, Seawater Side"
Q_dot_CNDaw=Q_dot_CNDsw
Q_dot_CND=Q_dot_CNDsw
Q_dot_CNDsw=m_dot[18]*(h[19]-h[18])
h[19]=enthalpy(NaCl,T=T[19],C=C_sw,P=P[19])
h[18]=enthalpy(NaCl,T=T[18],C=C_sw,P=P[18])
P[19]=P[18]
```

```
"Pump"
W_dot_pump=m_dot[10]*(h[11]-h[10])
h[11]=enthalpy(NH3H2O,P=P[11],x=x[11],s=s[11])
T[11]=temperature(NH3H2O,P=P[11],x=x[11],s=s[11])
q[11]=quality(NH3H2O,P=P[11],x=x[11],s=s[11])
x[11]=x[10]
s[11]=s[10]
s[10]=entropy(NH3H2O,P=P[10],x=x[10],T=T[10])
```

Conclusions

This paper summarizes simulation results for applying a Kalina cycle system 11 (KCS11) architecture for utilizing waste heat recovery from marine propulsion systems. Although there are many prime movers used nowadays for ship propulsion, the main example for this study was a large low-speed 2-stroke Diesel engine (for a typical large container ship).

The dominating market share of globally installed power plants make the 2-stroke, low-speed Diesel engine the obvious target for continued improvement and application of WHR systems in the near future.

By careful selection of the mass fraction of NH_3 in the working fluid of the KCS11, one can select for a peak in overall performance (i.e., highest power produced by the turbine/expander) occurring at $x_{[NH3]} = 0.9$.

Other parameters (such as P, T, m(dot), etc.) were not varied for this study but can be considered as input variables for follow-on studies of this work. The goal is to provide a comprehensive view of the overall peak WHR capabilities using a Kalina cycle (say, KCS11) for optimizing thermal efficiency onboard a large merchant ship.

Acknowledgments

The nature of the present paper involves many resources and references of related past works from our colleagues in the broader global community of application of Kalina cycles for effective waste heat recovery on ships. The quotes, adaptations, and references of many of their relevant works are greatly appreciated. Due to publication length limitations, this paper cannot be exhaustive in its related technology coverage. Any inadvertent omission of relevant works is, therefore, nonintentional. It is t that this paper may expand into future studies and explorations of further system optimization in improving the operational efficiency of marine power propulsion systems using the Kalina cycle for waste heat recovery.

The authors welcome any related comments on improving the contents of this paper while expanding its scope, as well as suggestions for any future related follow-on review papers.

The authors wish to thank the organizers of the 2023 Sustainability in Ship Design and Operations Conference (SISDO 2023) for providing the platform and impetus for the completion of this paper.

S.P. acknowledges, first and foremost, the patience of Gloria Scher, wife of almost 30 years. Additionally, the author wishes to thank Dr. William Caliendo, Dr. Sergio Perez, Capt.

Anthony Nigro, and Prof. Erica Hansen of the U.S. Merchant Marine Academy for encouragement and guidance, and the opportunity to prepare this paper.

L.R. acknowledges the encouragement and guidance provided from the Dean and Provost Office, U.S. Merchant Marine Academy by Dr. John Ballard, Academic Dean and Provost (former), Capt. James Zatwarnicki, Academic Dean and Provost (acting), and Dr. Susan Comilang, Assistant Dean for Academic Affairs. Furthermore, the author wishes to thank Dr. William Caliendo, Capt. Anthony Nigro, Cdr. David Pulis, Dr. Sergio Perez, and Prof. Erica Hansen, Department of Marine Engineering, U.S. Merchant Marine Academy, for the opportunity to work on the preparation of this review paper. Lastly, any helpful reviews, advice, and suggestions offered by my colleagues and by my students are greatly appreciated. ANV.

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Flettner Rotor-Powered Marine Vessel – Design Evaluation and Systems Optimization

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Abstract

With the increase of Greenhouse Gas (GHG) emissions, carbon dioxide emissions, and awareness of environmental protection, the maritime industry has seen an influx of low emission and environmental protection solutions to reduce the GHG, CO_2, and Hydrocarbon (HC) emissions. Of these proposed solutions, the Flettner rotor is a proposed solution that utilizes wind and the magnus effect to generate lift for propulsion of the vessel. Notably, the Flettner rotor is a conceptual propulsion design that has already been previously researched. The purpose of the investigations, research, and analysis within this paper are to optimize and produce a Flettner rotor configuration for small vessels that will act as an effective and environmentally safe substitute for the current propulsion systems.

CFD analyses were completed (EasyCFD software) to determine the optimal system architecture in terms of number of Flettner rotors, rotor sizing (diameter, length, etc.), rotation speed and direction, surface roughness and material properties, end cap considerations, rotor spacing, relative rotor arrangement, etc. Optimal rotor rotational speed was be determined to optimize the Lift-to-Drag (L/D) ratios for various geometric rotor configurations. Through this analysis various vessel configurations will be investigated to determine the optimal number, position, and relative arrangement of the proposed Flettner rotors.

Prototypes of the Flettner rotor designs produced through the research conducted within this paper will be created via 3D printing. The prototypes will then be tested on a scale hull model of the series 60 Type C2 class cargo ship. From the prototype testing, the parameters that could not be tested with the EasyCFD software will be further investigated. Moreover, the prototypes will provide quantitative data on the application of Flettner rotors on sea-going vessels.

Problem Definition and Proposed Solution

The purpose of this paper is to address a reduction of pollution from hydrocarbon (HC) emissions present in the exhaust of heat engine-powered merchant ships, specifically, during operations of such ships both near, and in port. In a broad context, heat engines can include internal combustion engines (both Otto and Diesel cycles), external combustion engines with no phase change of the working fluids such as gas turbines (both open- and closed-Brayton cycles) or with phase change of the working fluid such as steam turbines (Rankine cycle), as well as any other (internal- or external-combustion) engines operating on various other cycles (Atkinson, Ericsson, Miller, Stirling, etc.) that burn hydrocarbon fuels (in both liquid and gaseous/vapor phases). Typically, these heat engines are predominantly used for main propulsion, although similar, smaller engines may be used on board a ship in the role of a supporting (auxiliary) function. Although hydrocarbon emissions are also emitted from these smaller auxiliary engines, it is believed that the majority of pollution reduction initiatives are focused on the emissions from larger heat engines used for main ship propulsion.

According to current estimates presented in this Third IMO GHG Study 2014 (Smith et al., 2015), international shipping emitted 796 million tons of CO_2 in 2012, which accounts for no more than about 2.2% of the total emission volume for that year. Furthermore, the mid-range forecasted scenarios discussed during the Third IMO GHG Study 2014 showed that by 2050, CO_2 emission from international shipping could grow by between 50% and 250% depending on the expected future economic growth, world maritime commerce, and energy developments

Our engineering team is focusing on the feasibility of the Flettner rotor in the maritime industry, which could be used to reduce HC fuel consumption and pollution production in marine-based ship propulsion towards green (or “more-green”) energy technologies to be implemented in ship propulsion systems. In 2018, the IMO announced goals for reducing shipping emissions: 40 percent compared to 2008 levels by 2030, and 70 percent by 2050. This is consistent with IMO’s existing GHG (Greenhouse Gas) emissions strategy 2030-2050 for decarburization of the global commercial shipping maritime environmental conservation and protection efforts leading to ultimately, zero GHG emissions later in this century. Through background readings, CFD Analysis, and model applications, we will further investigate the application of the Flettner rotor within the Maritime Service. Thus, our objective is to optimize a Flettner rotor for these purposes and test the feasibility of this concept.

History and Background

The Magnus effect is a phenomenon in which a lifting force occurs upon a rotating body when subjected to fluid flow and when perpendicular to its rotational axis. First discovered in 1852 by German Professor Gustav Magnus, this effect has been demonstrated to have numerous applications in sports, ballistics, aviation, as well as ship propulsion and stabilization. The first maritime use of the Magnus effect was sighted by Captain La Croix around 1895 when a sampan was fitted with a single rotor operated by hand gears. However, this phenomenon was not fully developed until 1926. It was then that a fuller application of the Magnus effect could be realized when the first transatlantic voyage was completed utilizing Flettner rotors, designed by Anton Flettner. Since then, Flettner, with his Magnus effect applications, went largely into hibernation, likely due to world economic issues and the abundance of cheap fossil fuels.

Those days are long gone, and these respective applications are experiencing a revival in the maritime industry as the world grows more concerned with fuel savings and environmental preservation all while considering cost efficiency. Therefore, a recent resurgence in Flettner rotor technology applications have seen a growing number of existing vessels being retrofitted with Flettner rotors as well as some new ship builds. In 2008, Enercon launched a hybrid rotor ship E-Ship 1 (Schuler, 2008) with operational fuel savings of up to 25%. Since then a growing number of existing vessels are being installed with Flettner rotors. While other wind propulsion systems are being explored such as wing-sails and turbo-sails, Flettner rotor technology appears to be leading the way with numerous options for growth, including tilt-rotor applications for maneuvering below bridges.

CFD Analysis and Optimization

Several parameters were investigated when determining an optimal Flettner Rotor design. The following are all of the parameters that we considered in our investigation of finding the most efficient and appropriate design.

Flettner Rotor Design Considerations:

- Diameter
- Rotation Speed and Direction
- Height (Length of Cylinder)
- Flettner Rotor(s) Configuration(s)
- L/D Ratio and H/D Ratio
- Maneuverability (Forward/Reverse)
- Material(s)
- End Cap Considerations

- Surface Roughness and Properties
- Drag and Lift Components
- Maneuverability (Forward/Reverse)
- Material(s)

Environmental Considerations:

- Wind Direction
- Wind Speed
- Sea Current
- Sea State
- Weather

Vessel Considerations:

- Size of Vessel
- Flettner Rotor Attachment
- Rudder/Steering Considerations
- Vessel Stability Considerations

EasyCFD Constraints and Limitations

Through our research, we found that our primary software, EasyCFD, was limited to basic calculations and computations. We did not have accessibility to alternative software at the time these simulations were conducted, so EasyCFD was utilized to find trends and general conclusions on design aspects. Due to the lack of 3D capabilities, we were unable to fully investigate the Height of the Rotor, H/D Ratio, Turbulence, End Cap Considerations, Surface Roughness, and Materials considerations. However, some of these considerations have been investigated through prior research; in turn, these parameters were based on this respective prior research (Flettner, 1926). For further/future investigations, more advanced software would be necessary to better optimize the Flettner Rotor analyses. Overall, any parameters not investigated will be supplemented with conclusions found through experimental work. Moreover, the parameters that cannot be demonstrated within the EasyCFD software will be tested with the 3D-printed prototypes to obtain quantitative data on the effects of varying these parameters. The 3D-printed prototype Flettner rotors will be potentially used on a scaled model of a Type C2 class cargo ship.

The model of the ship for the potential experiments was based on a Type C2 cargo ships which were designed by the U.S. Maritime Commission (MARCOM, later MARAD) in 1937–38. The Type C2 ships were all-purpose cargo ships which remained in active service until the early 1970s. Compared to older ships of similar class, the Type C2s were remarkable for their speed and fuel economy. The main characteristics and typical profiles of the Type C2 cargo ships are found elsewhere (Sawyer and Mitchell, 1981).

The Type C2 cargo ships were initially modeled by Series 57 model hulls. Subsequent studies aimed at improving the design and performance of the Type C2 ships resulted in the Series 60 model hulls. Five different parent ship forms were modeled by the Series 60 model hulls (Todd, 1963).

USMMA Ship Model

The ship model hull (approx. scale of 1:100) to be used for the potential experiments was an older USMMA model (Fig. 1A) constructed from balsa wood along the lines of the Type C2 cargo ships. Hull restoration and strengthening was completed[2] to ensure water-tightness of the USMMA model hull. Steel plates weights were distributed inside the hull the allow the model to reach its correct design draft. Careful balancing of the weighted model at the correct draft was completed in the experimental water tank at the USMMA Fluids Lab. Further details can be found in these two prior publications (Perez, 2023a; Perez, 2023b).

A museum-quality ship model (in similar scale to the USMMA model) of the C2-class currently on display at the American Merchant Marine Museum[3] is shown in Fig. 2A.

Fig. 1A. The USMMA ship model hull in its restored mode (painted hull and marked water line)

Fig. 2A. The AMMMA ship model of a C2 ship

A comparison between the basic dimensions of the Series 60 (Model 4212W) and the USMMA ship model hull are shown in Table 1.

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[2] We are grateful to Dr. Sergio Perez for this effort.

[3] American Merchant Marine Museum, Kings Point, NY, USA. https://www.usmma.edu/museum.

Table 1. Basic characteristics of Series 60 hull (Model 4212W) and the USMMA ship model hull

	Series 60 (Model 4212W)		Model (1:100)
Dimension	**English**	**SI**	**SI**
L_{BP}, ft / m	400.00	121.92	1.22
B, ft / m	53.33	17.42	0.17
H, ft / m	21.33	6.97	0.07
Δ, Tons	10456	10456	N/A
C_B	0.70	0.70	0.70
L_{WL}, ft / m	406.70	123.96	1.24
L/B (L = L_{BP})	7.50	7.00	7.00
B/H	2.50	2.50	2.50
W.S., ft^2 / m^2	31705.00	2945.49	29.45

The profiles of the Series 60 hull (Model 4212W), together with its body plan, are shown in Fig. 3A.

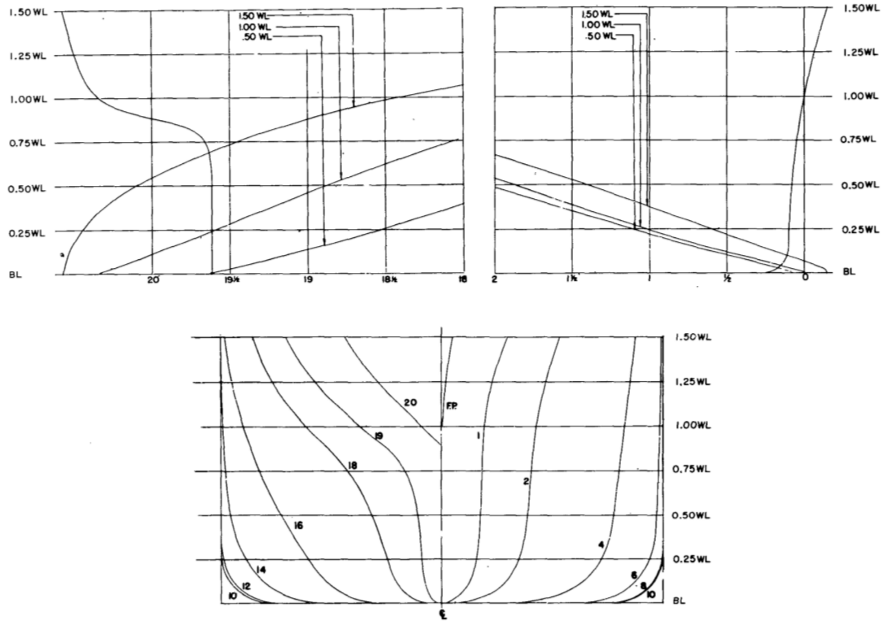


Fig. 3A. Stern and stem profiles and body plan of the Series 60 hull (Model 4212W)

Easy CFD Data and Analysis

Below are several Easy CFD calculations and data analysis conducted for our undergraduate research project paper. It is worth noting that warm colors correspond with higher pressures. CFD is color-coded with a spectrum ranging from red to blue, with red representing the regions with the highest velocity, while blue represents the regions with the lowest velocity.

Variable Diameter

To investigate the effects of varying the diameter, we held the rotation and wind speed constant at 5 m/s for both. From our results, we concluded that the increase in diameter causes an increase in lift (Figure 1). Notably, the lift to drag ratio (L/D) peaks at approximately 0.6 m rotor diameter (Figure 2).

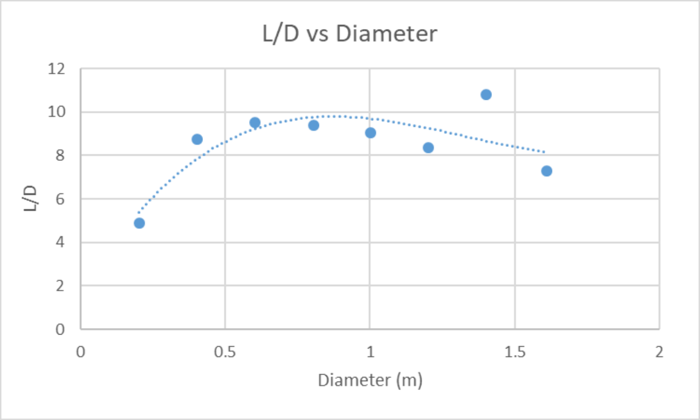


Fig. 1. Lift to Drag Ratio (L/D) vs Rotor Diameter (m)

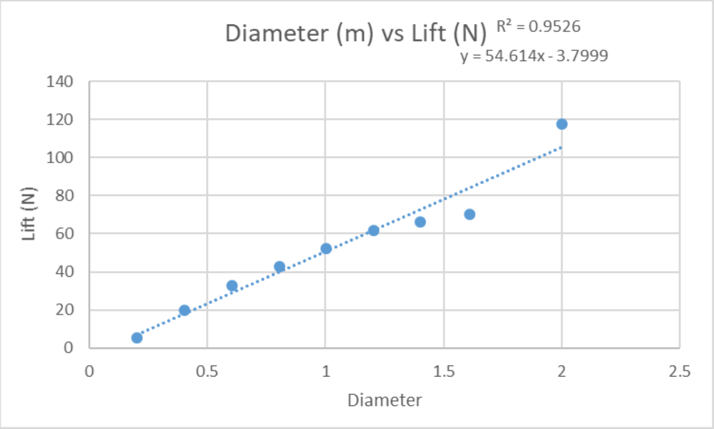


Fig. 2. Rotor Diameter (m) vs. Lift (N)

Examples of varying rotor diameter for the same constant wind speed and direction are shown in Fig. 3 (largest rotor diameter) and Fig. 4 (smallest rotor diameter), respectively.

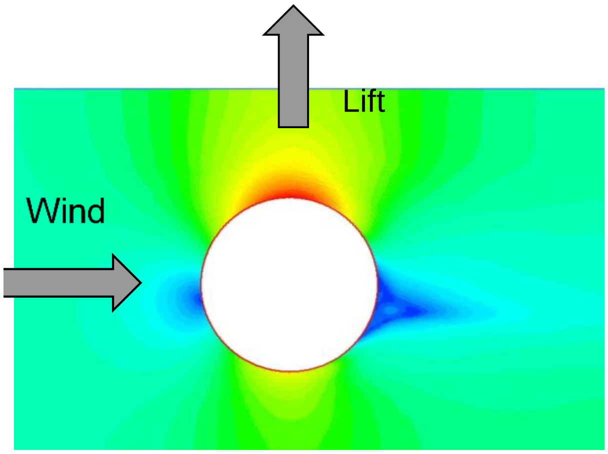


Fig. 3. Largest simulated rotor diameter (D = 1.61 m)

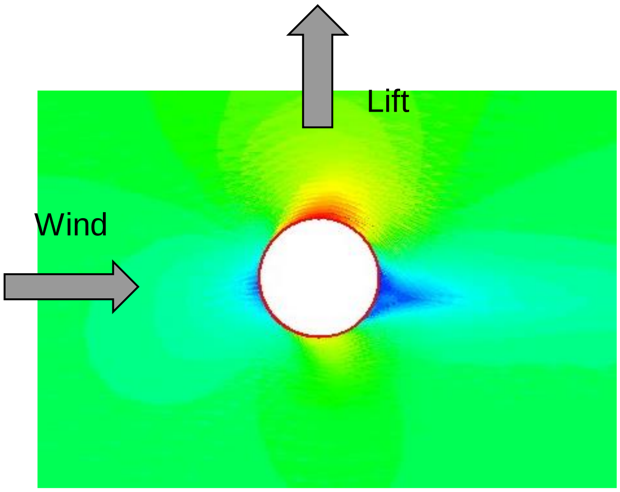


Fig. 4. Smallest simulated rotor diameter (D = 0.202 m)

Variable Rotation

To investigate the effects of rotor rotation on lift, the rotor's diameter was held constant at 0.3 m, and the wind speed was held constant at 5 m/s. From the results, and as expected from theory, lift increased as the rotor's rotational speed increased in a relatively linear manner (1^{st} degree polynomial curve fit $R^2 \approx 0.98$) as shown in Fig. 5. Additionally, the lift-to-drag ratio (L/D) peaked at rotational speed of 10-15 m/s (Fig. 6).

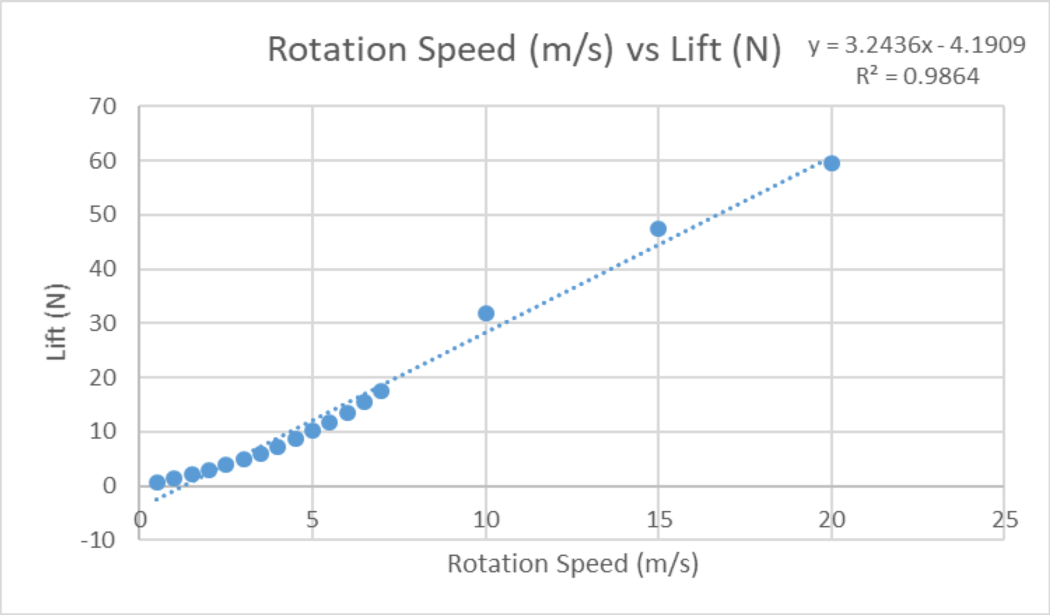


Fig. 5. Lift vs Rotation

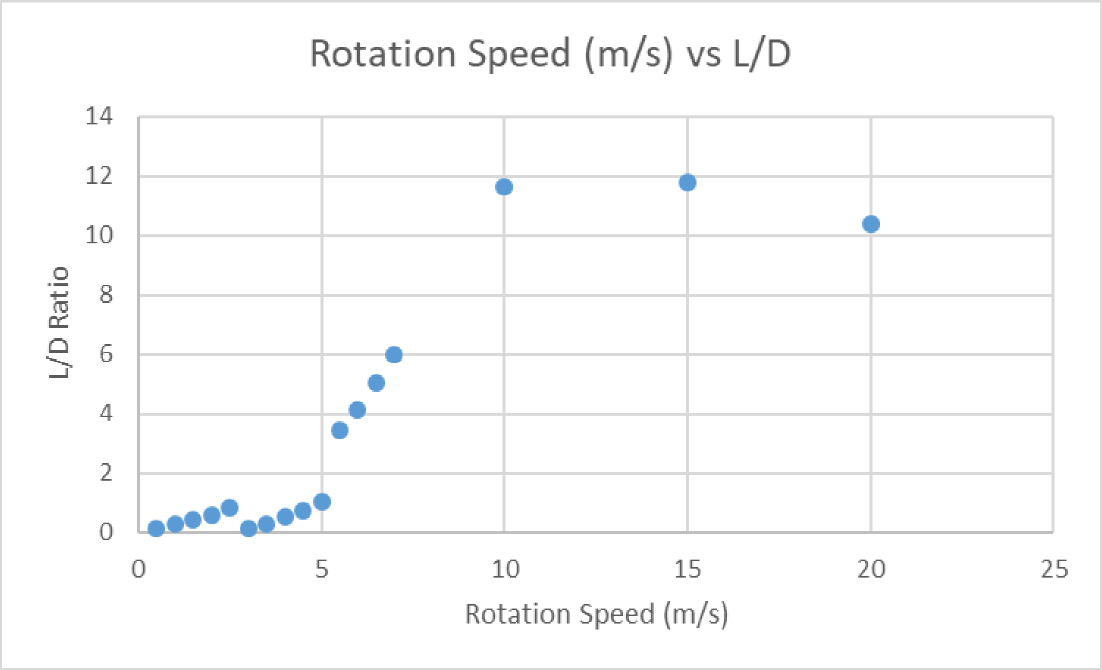


Fig. 6. Lift to Drag Ratio vs Rotation

Examples of varying rotor speed for the same constant wind speed and direction are shown in Fig. 7 (rotational speed = 1.5 m/s) and Fig. 8 (rotational speed = 20 m/s), respectively.

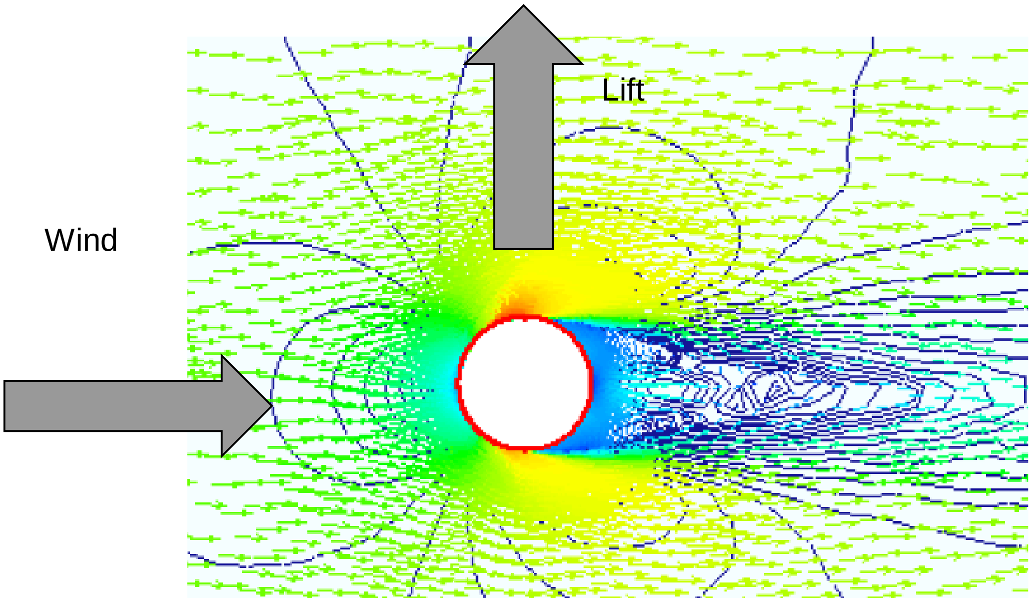


Fig. 7. L/D vs Rotation (1.5 m/s)

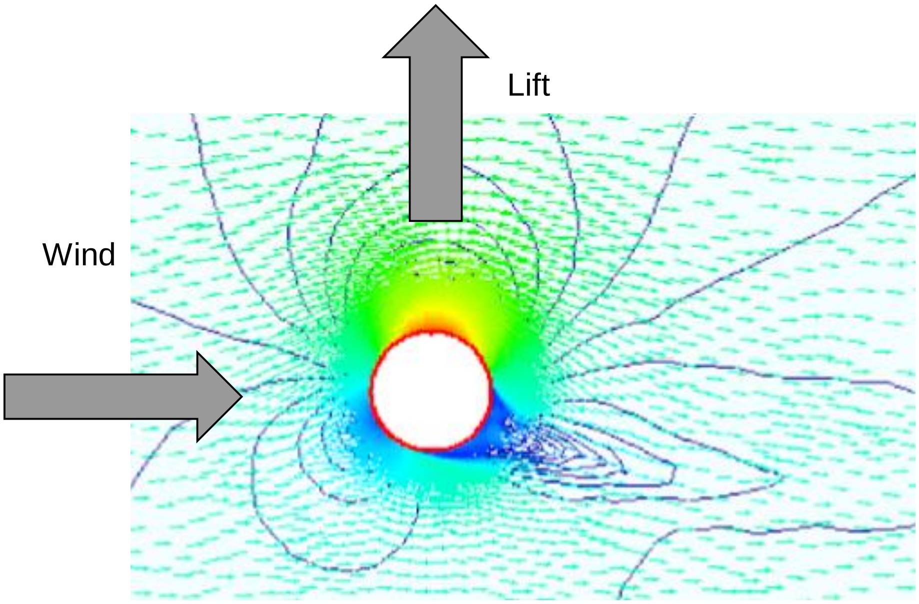


Fig. 8. Lift vs Rotation (20 m/s)

Variable Wind Speed

To test the effects of wind speed, we held the rotor diameter constant at 0.3 m and the rotation speed constant at 5 m/s. From the EasyCFD data, we found that lift increased almost linearly (1st degree polynomial curve fit $R^2 \approx 0.98$) as the wind speed increased (as shown in Fig. 9). However, the lift to drag ratio peaked at 1.5 m/s wind speed, then decreased as wind speed increased (Fig. 10). It can be concluded that although lift is increasing rapidly with wind speed

(Fig. 9), the associated drag is increasing at a higher rate, consistent with the findings shown in Fig. 10.

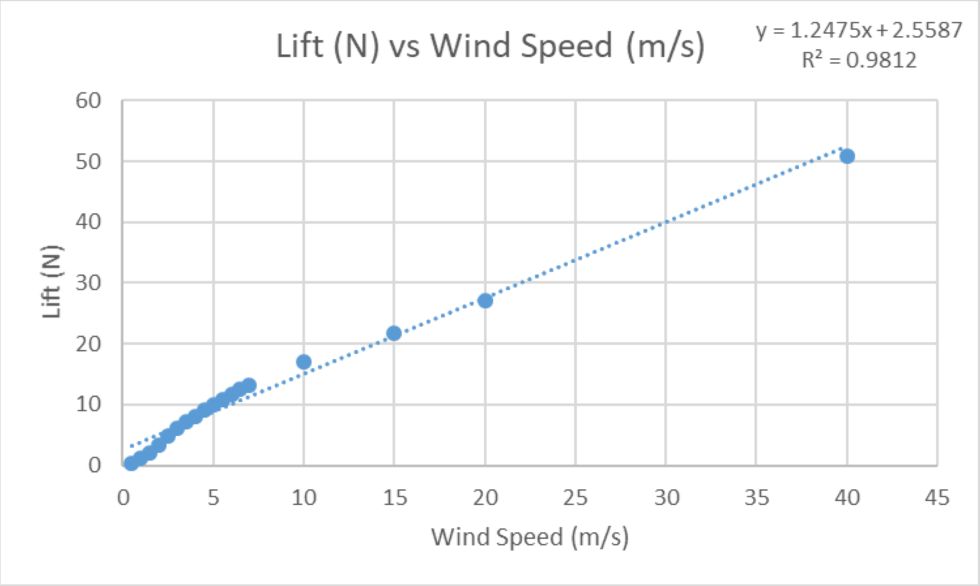


Fig. 9. Lift vs Wind Speed

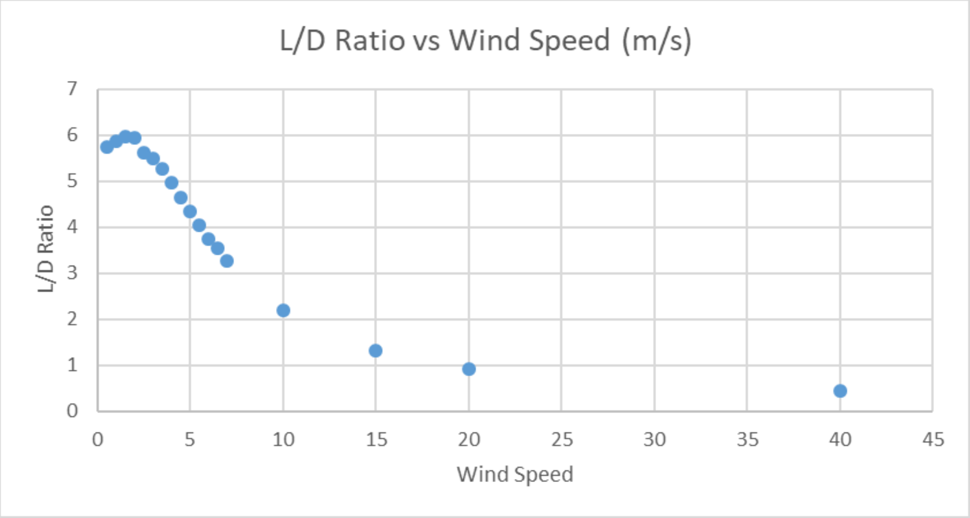


Fig. 10. L/D vs Wind Speed

Examples of varying wind speed for the same constant rotational speed (5 m/s) and diameter (0.3 m) are shown in Fig. 11 (0.5 m/s) and Fig. 12 (40 m/s), respectively.

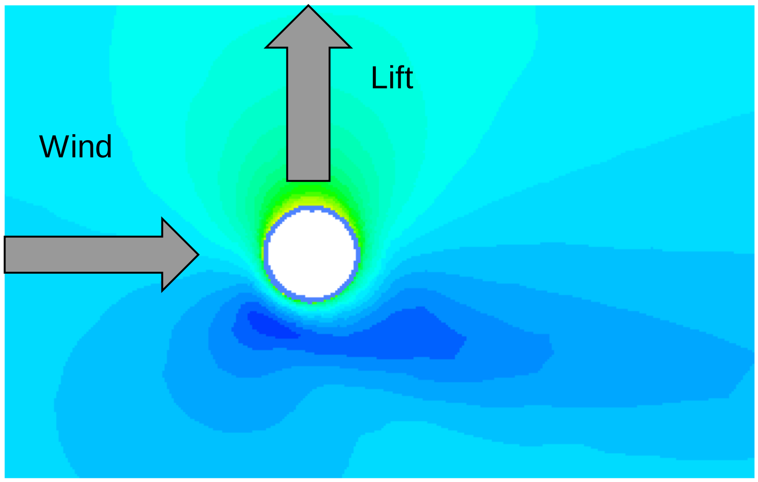


Fig. 11. Rotor dia. = 0.3 m, rotor speed = 5 m/s, wind speed = 0.5 m/s

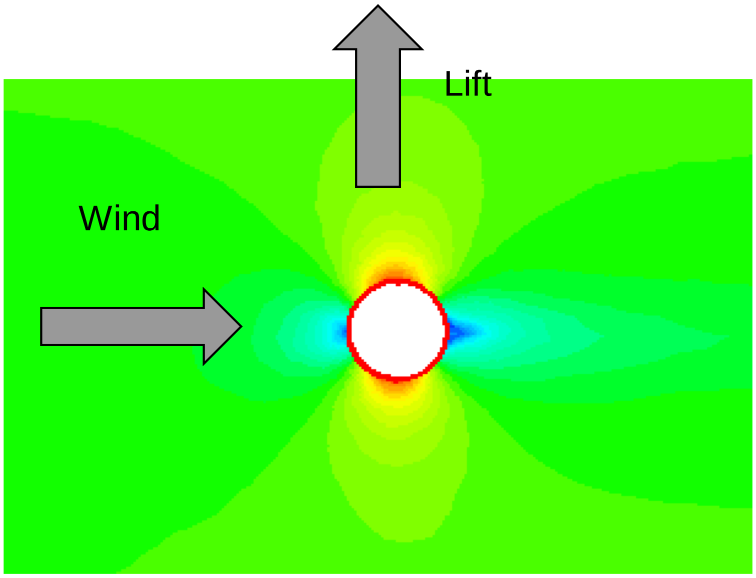


Fig. 12. Rotor dia. = 0.3 m, rotor speed = 5 m/s, wind speed = 40 m/s

Configurations

A very important consideration we investigated with the EasyCFD analysis was the effect of the configuration and the number of rotors on Lift and Lift-to-Drag Ratio. We tested several different configurations to find the appropriate and efficient options for shipboard applications. Below are some of the designs investigated through EasyCFD. Notably, there are several variations to each design that we investigated in addition to the designs presented below. (Note: The diameter for rotors in Figures 16, -17, and -20 was 0.6 m, and the diameter for rotors in Figures 23 and -24 was 0.3 m. The scaling may cause them to look larger or smaller.)

Two Rotors

Utilizing the EasyCFD software, several configurations of two rotors were investigated to find the most efficient and effective configuration for vessel propulsion. The averages of these simulations at various rotor spacings were used to compare the Lift-to-Drag Ratio, Total Lift, and Total Drag for each configuration.

The three primary configurations that were investigated were an "in-line" configuration (Figure 16) a "side-by-side" configuration (Figure 17), and a configuration with one rotor within the wake of the other rotor, referred to as the "in-wake" configuration (Figure 18). As can be seen within the figures below (Fig. 13, 14, and 15), each configuration had its benefits; however, of all the configurations, the "in-wake" configuration provided the best Lift-to-Drag Ratio without sacrificing total lift or gaining excessive drag. Subsequently, the "in-wake" configuration was more specifically investigated as will be shown below.

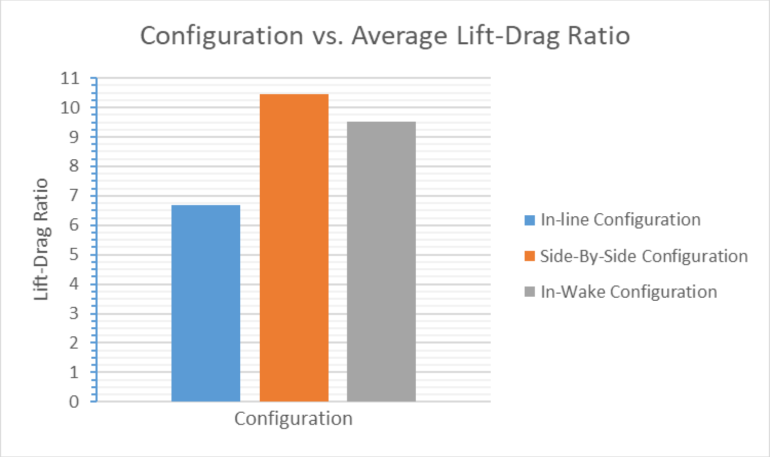


Fig. 13. L/D ratio as a function of rotors configurations

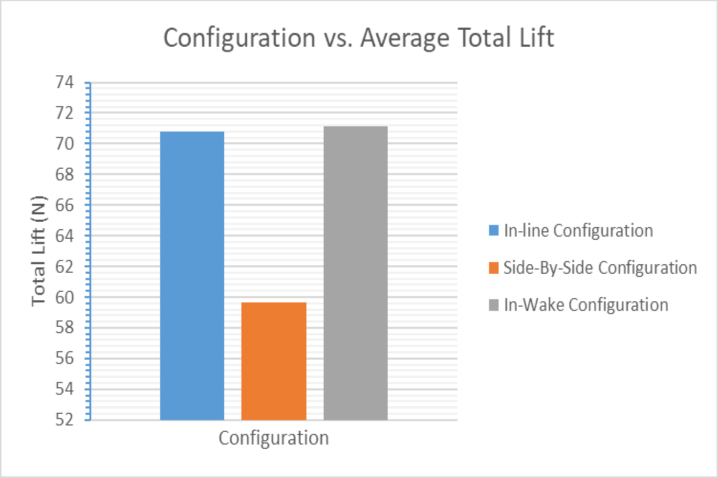


Fig. 14. Average total lift as a function of rotors configurations

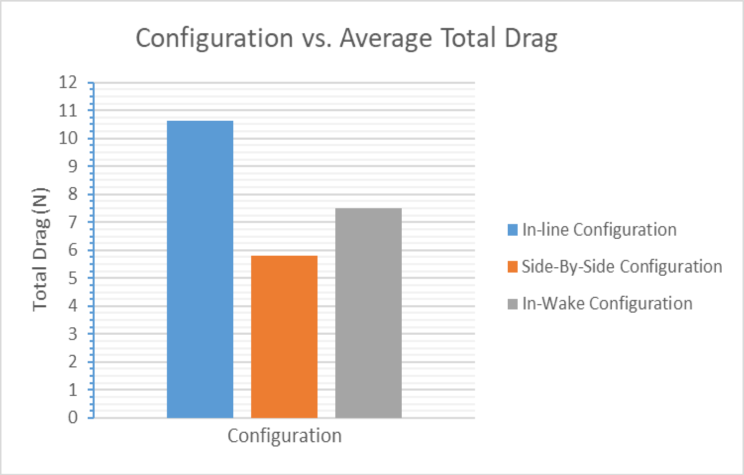


Fig. 15. Average total drag as a function of rotors configurations

A comparison of a longitudinal ("in-line") rotor configuration and transverse ("side-by-side") configuration are displayed below.

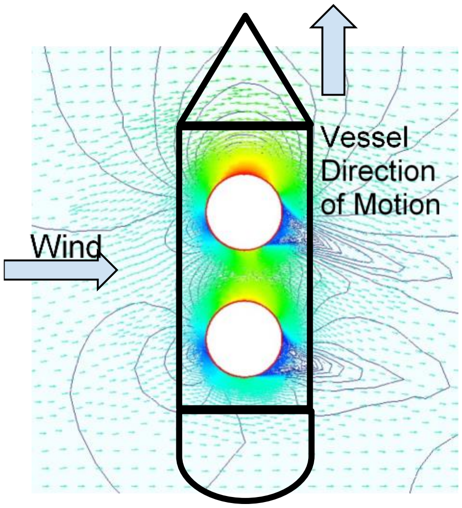


Fig. 16. Two Rotors configuration: "in-line," 1-m apart (rotor dia. = 0.6 m)

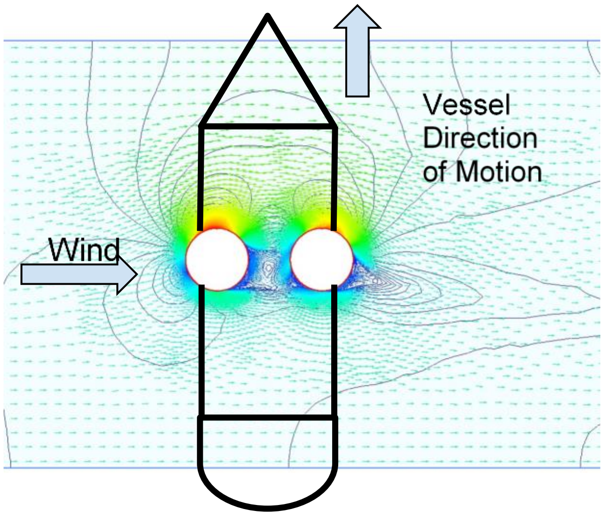


Fig. 17. Two Rotors configuration: “side-by-side,” 1-m apart (rotor dia. = 0.6 m)

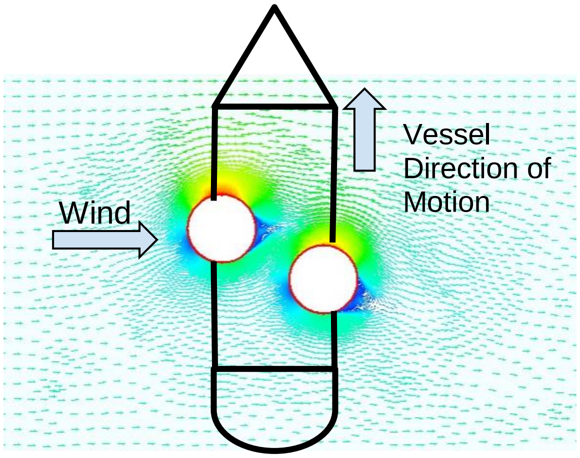


Fig. 18. Two Rotors configuration: one rotor “in wake” of the other rotor (rotor dia. = 0.6 m)

Two - Rotors: One within the Wake of the Other

After determining that the in-wake configuration was the most applicable configuration for shipboard application, more CFD simulations were conducted to produce the two graphs below investigating the effect of rotor spacing on the lift-to-drag ratio and the total lift/propulsion of the vessel. As shown in Fig. 19, the ideal spacing for the rotors was approximately 0.5 from the center of each rotor. At this spacing, the highest lift-to-drag ratio of about 25 was reached (Fig. 19). For these CFD simulations, the rotor diameters were reduced to 0.3 m, which is why the total force was lower than the previous iterations as shown in Fig. 20.

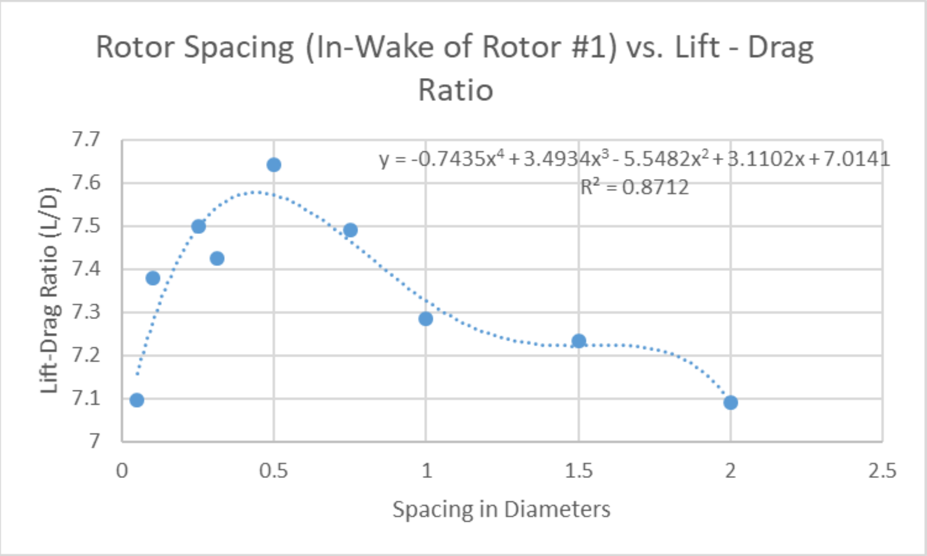


Fig. 19. L/D ratio as a function of rotor spacing (diameters)

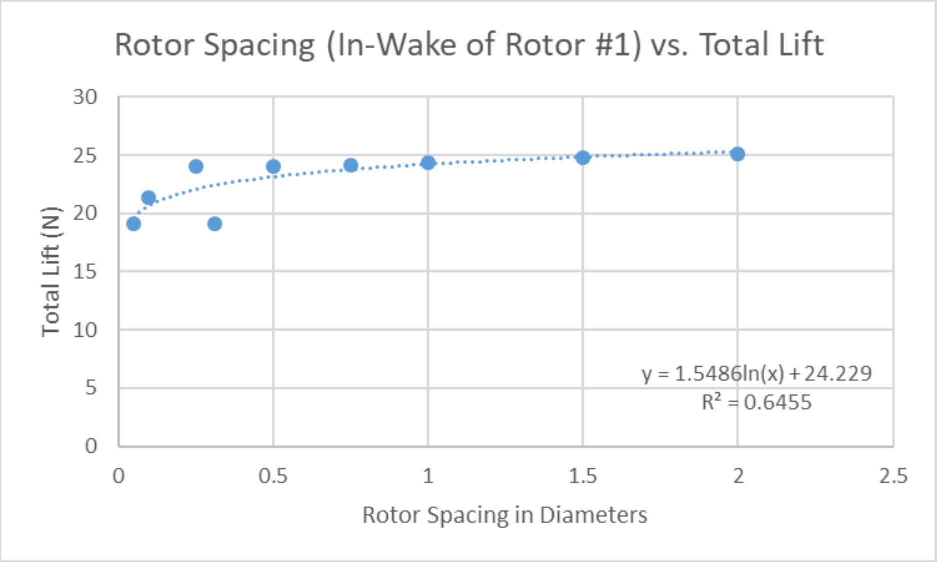


Fig. 20. Total lift as a function of rotor spacing (diameters)

Propulsion Force Based on the Angle of the Vessel to the Wind

Next, varying the angle of the vessel to the wind was investigated to understand the effects on the propulsion force that the vessel will experience. For these CFD simulations, the wind speed was 5 m/s, the rotation was 5 m/s clockwise for both rotors, and the spacing was -m apart. The plot in Fig. 21 shows the data collected, where the angle of 0° indicates the vessel is pointing directly into the wind, and 180° shows the vessel directly away from the wind. As expected, the maximum propulsion was achieved with the vessel perpendicular to the wind (at 90°). When the vessel was into- or away from the wind, the vessel only experienced forces that were orthogonal to the ship's direction of motion. Figure 22 shows the CFD results for different angles to the wind of the vessel, where the bottom left is the vessel at 0° to the wind and the bottom right is the vessel at 180° to the wind. The angle was simulated at 0°, 30°, 45°, 60°, 90°, 120°, 135°, 150°, and 180°. Notably, as the propulsion force component decreased, the component of force perpendicular to the vessel increased.

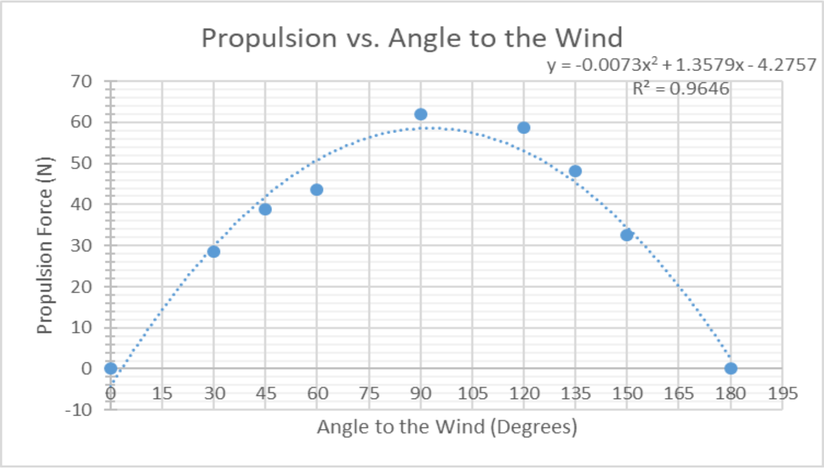


Fig. 21. Propulsion Force vs. Angle to the Wind (CFD Analysis)

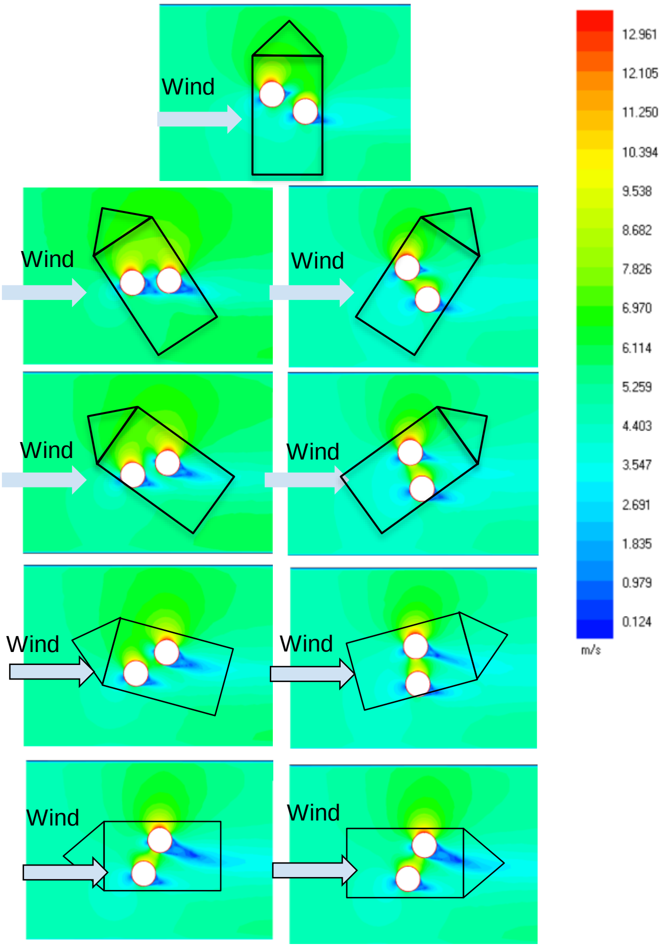


Fig. 22. Vessel at various angles to the wind (rotor dia. = 0.3 m)

Configurations with Increased Number of Rotors

Once the configuration for two rotors was determined, the addition of more rotors in similar configurations to the in-wake configuration were investigated; specifically, a 3-rotor configuration and a 4-rotor configuration were tested within the EasyCFD software. As expected, the addition of Flettner rotors increased the total lift experienced. Notably, the rotors in these simulations were 0.3 m in diameter similar to the in-wake CFD analysis done above. As can be seen by the results, the total force increased with some effects to the lift-to-drag ratio. Thus, it was concluded that having two sets of a 2-rotor in-wake configuration would be the ideal configuration to produce the highest total lift.

A rotor configuration with three (3) identical rotors (Fig. 23) is shown compared to a rotor configuration with four (4) identical rotors (Fig. 24) For the three-rotor configuration (Fig. 23), the computed data showed that for a lift-to-drag (L/D) ratio of 7.2, and a drag force of F_D = 5.28 N, we obtained a total lift of F_L = 37.95 N (i.e., 12.65/rotor). Similarly, for the four-rotor configuration (Fig. 24), the computed data showed that for a lift-to-drag (L/D) ratio of 5.9, and a drag force of F_D = 8.98 N, we obtained a total lift of F_L = 52.85 N (i.e., 13.21/rotor).

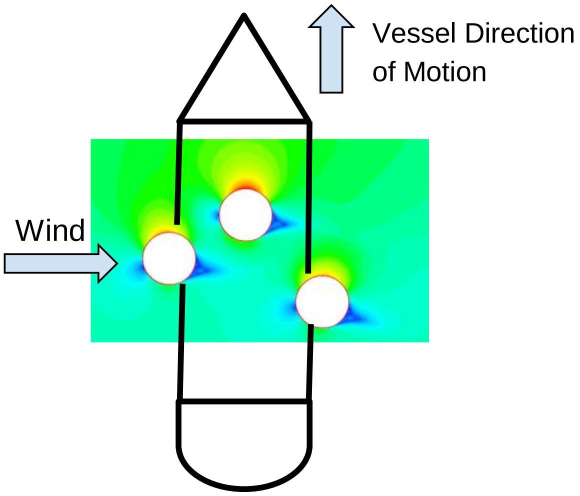


Fig. 23. Three (3)-Rotor Configuration (rotor dia. = 0.3 m)

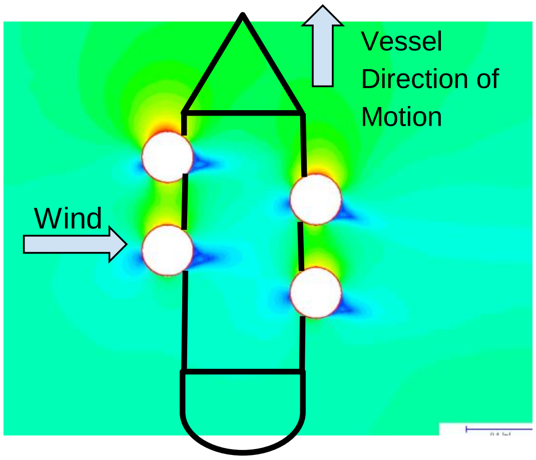
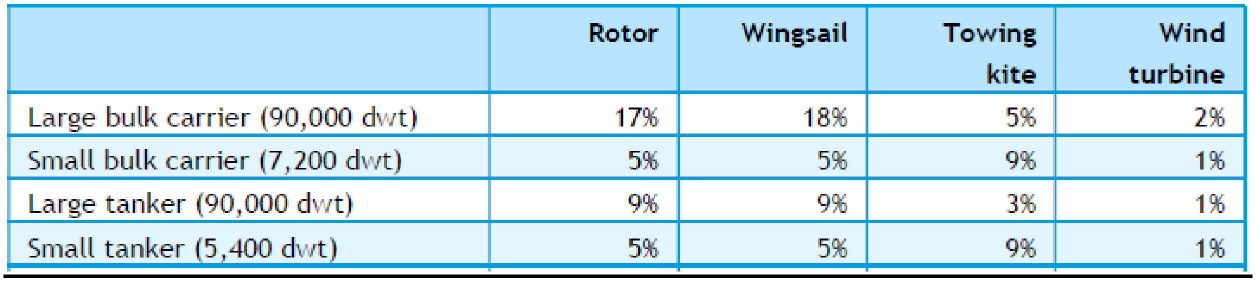


Fig. 24. Four (4)-Rotor Configuration (rotor dia. = 0.3 m)

Comparison to Other Wind-Assisted Ship Technologies

Flettner rotors are one of a few Wind-Assisted Ship Technologies being implemented in an effort to reduce CO_2 emissions. With limited time and resources, prior research works on other wind technologies were investigated to substitute further CFD Analysis for other wind propulsion designs. One report (Nelissen et al., 2013) presents these alternative Wind-Assisted Ship Technologies and a thorough comparison of the benefits and drawbacks of each piece of technology. Within this source, Sails, Kites, Flettner Rotors, and Wind Turbines are described. In general, the Average Relative Savings presented through this report demonstrate that Flettner rotors and wing-sails provide the most substantial savings over the example/sample vessels for large vessels, as shown in Table 2 below.

Table 2. Average Relative Saving Across Vessel Voyages



	Rotor	Wingsail	Towing kite	Wind turbine
Large bulk carrier (90,000 dwt)	17%	18%	5%	2%
Small bulk carrier (7,200 dwt)	5%	5%	9%	1%
Large tanker (90,000 dwt)	9%	9%	3%	1%
Small tanker (5,400 dwt)	5%	5%	9%	1%

In addition to presenting the relative savings for each Wind-Assisted Ship Technology, the report further describes the operation and effective applications of each technology. Specifically, the effective thrust force of each type of Wind-Assisted Ship Technology is plotted within a polar coordinate graph. Using these plots (Nelissen et al., 2013), the versatility and general application of each technology is comparable.

Figures 25 - 28 are the polar-coordinate graphs for each of the aforementioned types of Wind-Assisted Ship Technologies.

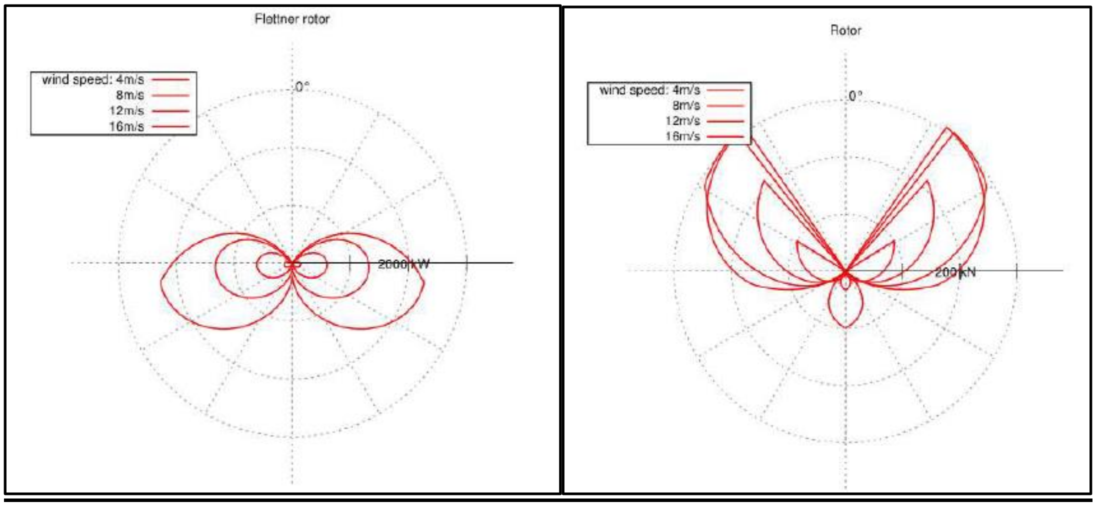


Fig. 25. Flettner Rotor Thrust Force vs. Wind Direction (Nelissen et al., 2013)

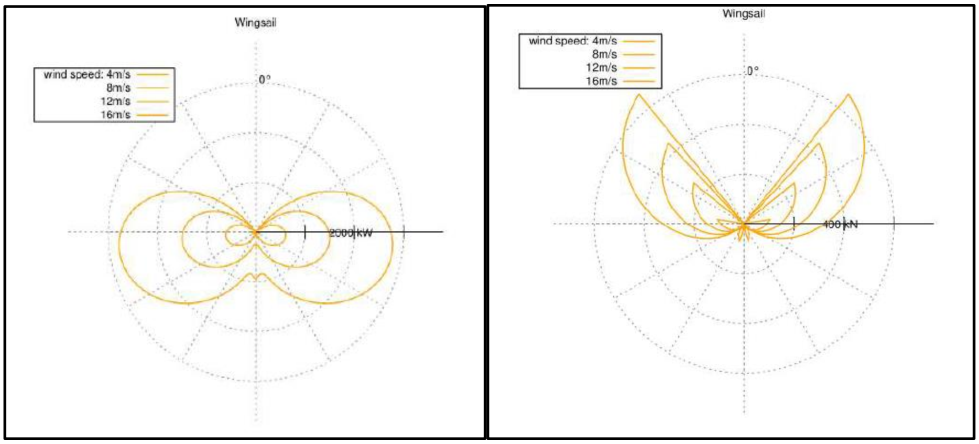


Fig. 26. Wing Sail Thrust Force vs. Wind Direction (Nelissen et al., 2013)

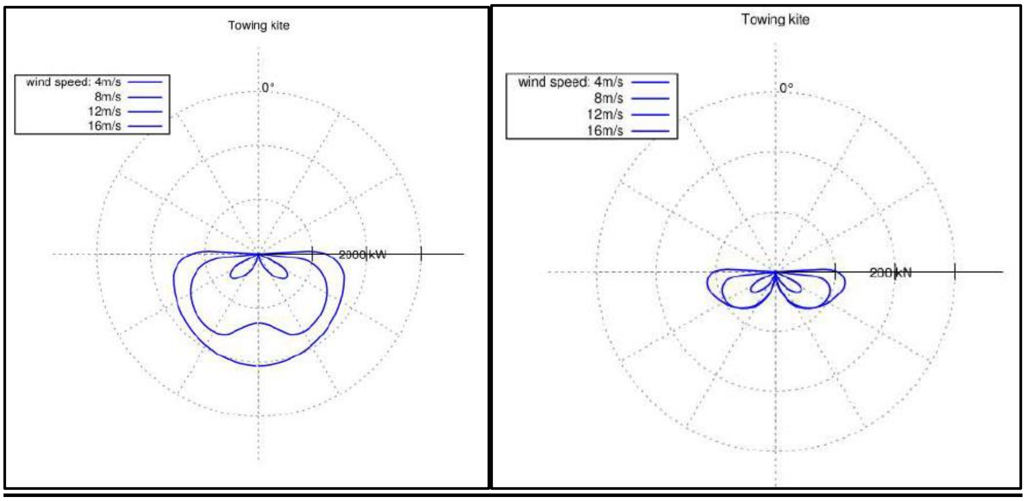


Fig. 27. Towing Kite Thrust Force vs. Wind Direction (Nelissen et al., 2013)

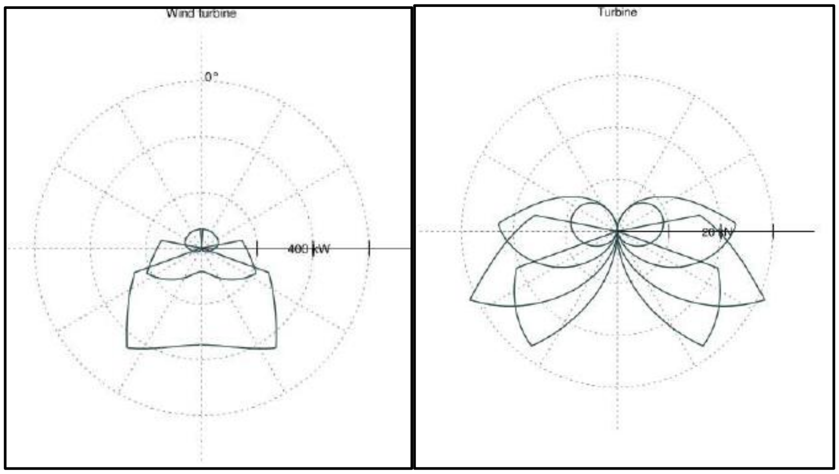


Fig. 28. Wind Turbine Thrust Force vs. Wind Direction (Nelissen et al., 2013)

As shown in the polar graphs above, the wing sail (Fig. 26) and Flettner rotor (Fig. 25) both produced the best versatility at variable wind speeds, which is further supported by the data gathered and presented within figure 21 presented above. The Flettner rotor is able to produce a thrust force/propulsion force at any wind angle except 0 degrees and 180 degrees, or parallel to the vessel's motion. Whereas towing kites (Fig. 26) and wind turbines (Fig. 28) are heavily affected by the wind direction, Flettner rotors have the ability to operate in a wide range of wind angles relative to the vessel; thus, the Flettner rotor has a higher versatility. While the wing sail technology has a similar thrust force vs. wind direction polar graph (Fig. 26), the Flettner rotor plot (Fig. 25) shows a greater thrust force [kN] for a large area; thus, the Flettner rotor produces thrust force at a larger variety of wind angles with a higher thrust force. In any case, both options would be a good choice for sea-going vessels, and the application/occupation of the vessel itself may warrant one design over the other.

Conclusions

In conducting extensive CFD analysis, we built a foundation of trends and relationships based on several aforementioned parameters. Our CFD analysis suggests that there is a directly proportional relationship by which an increase in Flettner rotor diameter results in an increase in lift. Our data suggest that this relationship is optimized at 0.6 m in terms of the lift to drag ratio. Furthermore, our CFD analyses suggest there is a directly proportional relationship between Flettner rotor rotational speed, and resulting lift. When the Flettner rotor rotational speed increases, so does the force of lift, and this appears to be optimized with respect to the lift to drag ratio at approximately 10 to 15 meters per second. With respect to wind speed as a variable for consideration, there also appeared to be a directly proportional relationship such that a higher wind speed corresponds to a higher force of lift. It is also noteworthy that, while previous variables when tested for optimization with respect to the lift to drag ratio presented some resemblance of an upside-down parabola, the optimized lift to drag ratio proved to peak much earlier at approximately 1.5 meters per second. Finally, using these data we have determined that the 4-staggered Flettner rotor configuration is best option form the various configurations that were investigated in our work. This was determined after extensive CFD simulation testing with different combinations of rotors in tandem, as well as in a triangular configuration. We also tested for different angles of wind against the Flettner rotor configuration. Notably, as the propulsion force component decreased, the component of force perpendicular to the vessel increased.

Further Investigations

The re-introduction and modernization of Flettner rotors into the maritime world allows for many possibilities. Optimizing ship design for use with Flettner rotors could possibly be its own rising sub-specialty in terms of naval architecture. Yet, it is not just Flettner rotors that are making an impact in ship propulsion; more traditional airfoils are also being experimented with in terms of ship propulsion, and generating a component of lift. Being able to compare the coefficients of lift to each other, and optimizing their configurations based on the needs of any given ship being designed, is certainly worth investigating further. Moreover, with the appropriate software, further and more accurate CFD analysis can be done to better optimize the Flettner rotor design. Additionally, further investigation is to be conducted using the physical model presented earlier in the paper, in lieu of CFD analysis limitations.

Acknowledgments

This paper represents the research work into Flettner rotor propulsion systems which, due to its specific nature, involves many resources and references of related past works from our colleagues in the broader global community of wind assisted ship propulsion. The quotes, adaptations, and references of many of their relevant works are greatly appreciated. Due to publication length limitations, this paper cannot be exhaustive in its related technology coverage. Any inadvertent omission of relevant works is, therefore, nonintentional. It is hoped that this paper may expand into future studies and explorations of further system design integrations leading to improved operational efficiency of marine power propulsion systems using Flettner rotor propulsion systems.

The co-authors welcome any related comments on improving the contents of this paper while expanding its scope, as well as suggestions for any future related follow-on papers.

The co-authors wish to thank the organizers of the 2023 Sustainability in Ship Design and Operations Conference (SISDO 2023) for providing the platform and impetus for the completion of this paper.

The co-authors gratefully acknowledge the guidance and support provided from the Dean and Provost Office, U.S. Merchant Marine Academy by Capt. James Zatwarnicki, Academic Dean and Provost (acting), and by Dr. Susan Comilang, Assistant Dean for Academic Affairs.

Furthermore, the co-authors wish to thank Dr. William Caliendo, Capt. Anthony Nigro, Cdr. David Pulis, Dr. Sergio Perez, and Prof. Erica Hansen, Department of Marine Engineering, U.S. Merchant Marine Academy, for the opportunity to work on the preparation of this paper.

The helpful support, expertise, and wisdom offered by Dr. Sergio Perez during the rebuilding of the USMMA experimental ship model is greatly appreciated.

We wish to thank Dr. Josh Smith, Director of the American Merchant Marine Museum (AMMM), for his enthusiastic support in providing access to the beautiful Type C2 ship models.

Lastly, any helpful reviews, advice, and suggestions offered by the co-authors' classmates and colleagues are greatly appreciated. ANV.

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WEBB INSTITUTE SUSTAINABILITY IN SHIP DESIGN CONFERENCE 2023

November 6 and 7, 2023

Sustainable Maritime along M87; Build a Little, Test a Little, Learn a Lot

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ABSTRACT

Marine Highways has been a laudable goal for a few decades in the United States, but just does not seem to get the traction it deserves. Substantial amounts of money have been spent of revival attempts and have mostly failed. Still, many lessons have been learned and it appears that there are some glimmers of light along M87 (the Hudson River and Erie Canal marine highway designation). A very interesting case can be made that small to very small scale projects can have more significant and lasting impacts than large commercial projects. These small scale projects rely on the Build a Little, Test a Little, Learn a Lot concept (BALTALLAL) This paper discusses the advantages of focusing on the integrated benefits of combining many small efforts into a larger revival of trade along M87, both with the goal of reducing carbon emissions and reviving water born trade. The combination of those goals along M87 has very significant national benefits that can become the incubator for a larger national effort.

INTRODUCTION:

Maritime is inherently very dynamic and in commercial applications completely lacks any sentimentality and continually drives for maximum efficiencies.

Efficiency is the central driver in maritime and that in turn is driven by commercial attractiveness. If a maritime venture can't make any money it will fail.

Over the ages that reality has actually resulted in a transition from a 100% sustainable approach, Wooden ships and Wind, to an approach where in the 1960's it became apparent that shipping was ruining the world's oceans and waterways, which resulted in the IMO MARPOL regulations in the 1970's.

MARPOL and in the US the Clean water Act, has resulted in a remarkable recovery of the maritime environment but does not address our latest environmental crisis; climate change.

In shipping, that crisis is related to the almost total adoption of carbon fuels for the movement of cargo and passengers both for inland and offshore maritime transportation.

While the MARPOL approach was related to leave no trace in the water, to deal with climate change, today maritime has to focus on zero carbon emissions.

Almost bizarrely maritime has been extremely effective at zero carbon transportation for over 2000 years and only in the last 200 years have we abandoned that approach.

That approach was abandoned due to the availability of cheap fossil fuels, but without regard to the damage its use has inflicted on our climate and the prospects of the coming generations.

It should never be forgotten that civilization advances and human progress are very strongly dependent on the development of maritime sail.

Trade is humanity and humanity is trade. Before sailing ships, trade was dependent on mules, llamas and camels. Horribly inefficient devices that required a high level of manpower, a high level of investment (breeding, rearing and training) continuous fuel in the form of fodder or forage, continually needed water to operate and when loaded with cargo, were extremely exposed to theft.

Wheels and wagons were nice and increased efficiency to some extent, but required roads which were expensive to build and maintain. Almost inevitably humans naturally tended to congregate near the water's edge where transportation by water enabled massive growth in trade and wealth.

The Nile, Tigris and Euphrates were rivers where early advanced civilizations were established. The Romans used the Mediterranean as their main logistics asset and in the Northern Europe the Rhine and the Baltic were great settings for economic expansion. Similar civilizations arose in Asia.

Even though native Americans used all the great American waterways, the transfer of European sail technology to the American waterways were the prime source of emerging American Hegemony.

The Mississippi River system is thought of as the great romantic waterway, but a more interesting example is the Hudson River.

The Hudson River is an east coast sweat spot. Bizarrely it was overlooked by settlers until Henry Hudson made note of it in 1608. He had hoped the Hudson River connected to Asia and the Pacific, and he was disappointed in that regard, but when he got back to Holland he slipped in a good message with the bad news. He pointed out that this part of the American East coast is a pretty interesting place. It is in a climatic sweet spot, it is easy to find the harbor entrance in a huge coastal bight and its main river is deep and tidal for over a hundred miles, with excellent resources along both its banks.

The tide makes it easier to navigate this river, which the natives called Mahicantuck, the river that flows both ways, than the Rhine or just about any other civilized river in Europe.

Initially the river served as a conduit for trade based on beaver and other (like otter) pelts. This was not extremely profitable as compared to other Dutch trade hubs and in 1667 under the Treaty of Breda the victorious Dutch ceded New Netherland to the English in exchange for much more valuable control of the East Indies.

The Hudson between New York City and Albany is a spectacularly suitable river for unimproved navigation. There are no waterfalls or even significant rapids, it is deep and quite wide and the current reverses twice per day.

Anybody who has ever sailed a river will appreciate these features. Beating upwind on a narrow river with the current against you is a mind-blowingly frustrating task and this makes many rivers unsuitable for sail navigation. On the Hudson river there may be adverse wind or current conditions, but, eventually, by using the tides you will arrive in Albany.[1] The downriver ride, like most rivers is a joy and only require a few hours at anchor when the tide and wind are against you.

It is somewhat frustrating that navigation becomes more difficult and even impossible in the winter when the river and, in a later era, the canals freeze.

Contrary to the Dutch[2], the English were much more interested in settlement and New York became a powerful trading city supporting a growing settlement population upstream.

While growing gradually, New York City did not truly rise to the fore until the Revolutionary War. At that time it was occupied by the British, because it was considered to be the key to control of the rebellious colonies. This was expressed by the British attempt to cut the colonies in half by taken control of the Montreal, Lake Champlain, Saratoga, Hudson River New York City corridor.

They did not succeed, but it was the blueprint for the future of New York City. Besides the North South corridor, there was also an East West corridor that started at Albany and ran almost due west to what is now Buffalo. Both these corridors were canalized and by the middle 1800 a maritime hinterland extended from New York City to Buffalo (including many of the great lakes) and Montreal.

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[1] Something which Henry Hudson did without charts in 1608.

[2] Since the Dutch economy concentrated on trade, there was relatively little interest in settling New Netherland by the Dutch. In order to provide defense against British colonies to the North and South, the Dutch in New Netherland maintained an open door policy which allowed settlement by many nationalities and religions and even included English settlers who had been forced out of the New England colonies. There is substantial recently discovered evidence that the English Gravesend (Brooklyn) settlers bit the hand that fed them by being instrumental in the 1664 British military invasion of New Netherland.

The Hudson River, Erie Canal and Lake Champlain canal system became an immense maritime infrastructure that dominated inland transportation until railroads built along the exact same corridors became dominant in the transport of freight and passengers.

The advent of the railroads actually shut down certain branches of the canal system that had covered most of New York State.[3]

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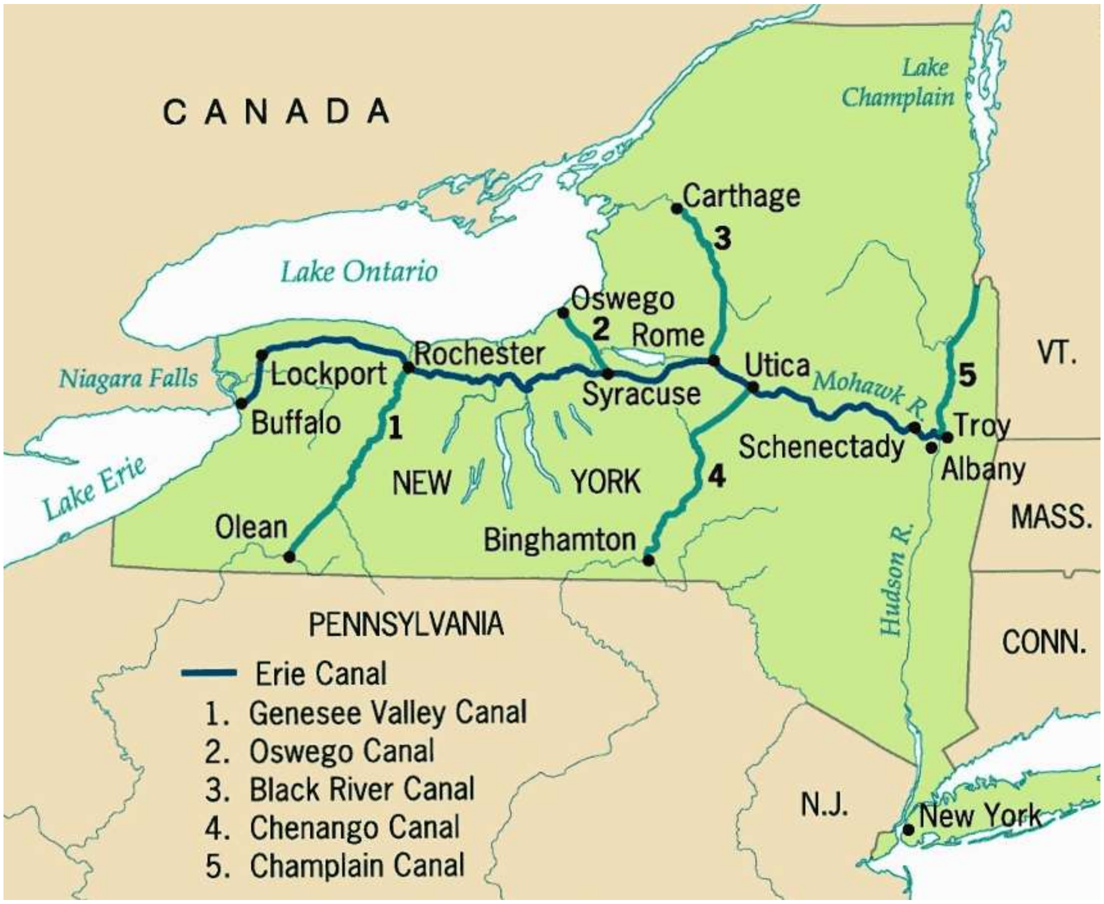
[3] It is less well known that New Jersey also had an impressive canal system, but it did not survive the advent of the railroad and the system is no longer operable.



With increasing miles of railroads, maritime passenger and freight services declined to a miniscule fraction of its original size. Essentially except for passenger excursions up the beautiful Hudson River and bulk (generally overseas) and oil (generally inland barge) service to Albany the maritime use of the corridor stopped.

The decline of the maritime trade was not only caused by competition of rail but also due to the decline of manufacturing in upstate New York, particularly along the Erie Canal. The Erie canal had been a powerhouse manufacturing hub, but economies of scale in both farming and manufacturing and cheaper labor in other locations resulted in a serious decline of the New York City hinterland.

The very nadir of maritime service up the Hudson River system occurred in the 1980's at which stage passenger excursion traffic had pretty much seized.

This did not go unnoticed and there have been various efforts at reviving the New York Harbor inland trade.

Some have been quite large scale such as MARAD support for a scheduled barge container route between Port Newark and Albany, and there are hints of revivals of the excursion passenger trade and even a little cruise trade along the Hudson.

The Erie Canal, Lake Champlain and Hudson River corridor has been given a federal maritime highways designation and has been named M87.[4]

This designation will be used in the rest of this paper.

A CLOSER EXAMINATION OF M87

Cargo transport:

At its peak the M87 was a fully integrated commercial economy spanning a huge portion of New York State. It supplied and transported raw materials, fuel, food and manufactured products along the marine highway. M87 comprised a massive part of the national economy in mid 1800’s.

At one time Kingston was the largest coal port in the United States, Cementon is an abbreviation of Cement town that provided massive amounts of cement up and down M87, and all the brick that has been laid in New York City was manufactured along the Hudson river.

Massive amounts of lumber were rafted down the Hudson from the Adirondacks to Glenns Falls, where it was milled and transported to Albany. At one stage Albany was one of the largest lumber ports in the United States.

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[4] The MARAD map of Marine highways is poorly designated. It is possible, and actually makes more sense, that the East West Erie Canal would be M90, while the Hudson, Champlain canal and Lake Champlain route would be M-87. For the purposes of this paper the entire system will be designated as M87.

Food ranging from beef to diary to bulk grain to processed foods such as preserves and cheeses traveled south from northern Vermont, the Great Lakes and even Canada to New York City. There it was transshipped and distributed all over the world.

In addition to this, manufactured goods ranging from GE products to structural steel components were also transported on M87.

Even when railroads started to play an important part in transportation, a manufacturing location along M87 would still be attractive since it generally had great access to electricity both from giant generation plants such as Niagara Falls, but also from smaller plants at various locations along M87 north of Troy. Moreover, many manufacturers needed large quantities of water and the ability to dispose of waste water.

Schenactady (GE and Alco) and Amsterdam (Carpets) were major manufacturing centers and so were Buffalo, Syracuse and Rochester, and even further outlying towns such as Ithaca had canal access to M87.

As noted, railroads affected the use of the canal, but so did the St. Lawrence Seaway which, when opened in 1959, eliminated much Great Lakes traffic through the canal.

Industry along the Hudson River also declined and commercial vessels designed to operate along the canals and the Hudson River virtually disappeared.

Remarkably New York City was little affected from the loss of commercial traffic along M87. This was a testament to the commercial power of New York City, but also coincided with the advent of containerization in the early 60's. Containerization completely turned the Port of New York upside down.

Where it used to be heavily focused on Manhattan as the main logistics hub which was designed as a ship to ship transshipment point, almost overnight the lion's share of logistics moved to the Port Newark and Port Elizabeth, where it had excellent intermodal connections.

Moreover, since containerization moved cargo faster, putting containers on slower smaller marine transports along M87 for subsequent last stop delivery by truck removed the central attractiveness of intermodal transportation along M87. Moreover, due to the seasonality of canal navigation, train and truck delivery along, instead of on, M87 was simply more convenient and simpler to schedule.

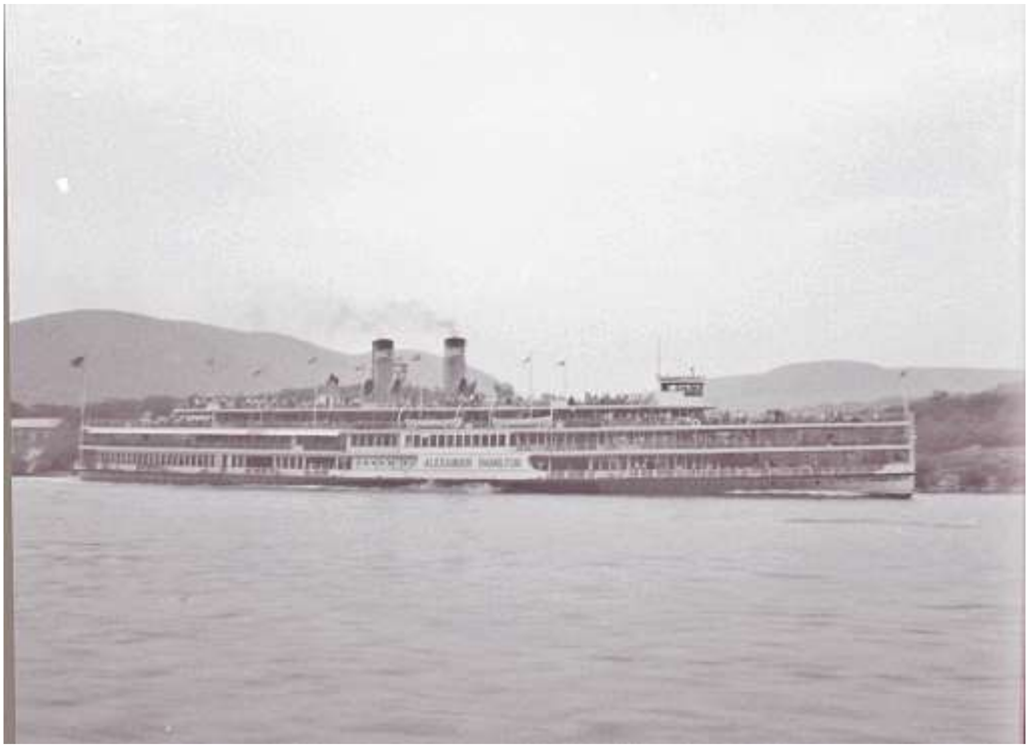
Passenger Transport

Since first human settlement, M87 and its rivers (the canals are powered by the tributary rivers such as the Genessee, the Mohawk and the Hudson, but upstream of the canals are only navigable with small craft such as canoes) served as major passenger thoroughfares and with western settlement they were the primary connectors for people, especially the Hudson between New York City and Albany.

The entire M87 Corridor vastly improved passenger service even in the earliest days of the Erie canal, and steam transportation as pioneered by Robert Fulton literally exploded passenger traffic along M87.

While trains soon took over passenger transportation along the M87 corridor, the passenger excursion trade to many of the exceptionally beautiful points along the M87 corridor maintained a presence well after WWII, but eventually also surrendered to the train and, more significantly, the personal automobile.

The last mighty Hudson River excursion steamer, Alexander Hamilton, was taken out of service in 1971. She was towed to a Navy pier in Raritan Bay where she sank and presently is a nationally registered historic shipwreck.



The reduction of trade and manufacturing along M87 actually resulted in a population decline of the M87 corridor that only recently has somewhat stabilized.

All of M87 remained active in one function though, and that was as a general sewage and industrial waste disposal drain to the ocean.

In addition, the canals provide an inland transit for recreational vessels between the Great Lakes, Canada and New York. Unfortunately, these transients see M87 as a Marine Highway to reach other more "attractive" cruising grounds and only stop when absolutely necessary.

M87 TODAY

There were various simultaneous efforts that arose in the 1960's and 1970's that addressed M87's last remaining commercial function as an open sewer.

The two main factors were Pete Seeger's Clearwater effort in the late 60's and the Clean Air/Clean Water acts of the early 70's. These efforts, and follow ups by many other stakeholders, resulted in the elimination of most sewage and industrial waste discharge into M87 and a remarkable improvement in water quality.

In particular Clearwater also drew attention to the almost forgotten beauty of M87. Pete Seeger himself continually emphasized its beauty and it needs to be remembered that the Hudson and many other portions of M87 were the inspiration for the Hudson River School of painting.

it needs to be noted that the massive area that M87 serves is quite sparsely populated. The largest cities on M87 are Albany and Buffalo and just a few miles outside New York City there are very large natural areas such as Harriman Park, Bear Mountain, and the Catskills. Further north, M87 touches the Adirondacks at Lake Champlain, the Finger Lakes to the west and in between there are huge very sparsely populated areas.

This natural beauty and the general restoration of the environment along the Hudson River cannot be ignored and if we think of the waters as a Marine Highway we should never forget that it should really be designated as a Scenic Marine Highway with many Scenic Marine Byways, or maybe better as a Marine Parkway.

The natural beauty of M87 is a central feature and an asset that needs to be taken into account when the sustainable redevelopment of M87 is considered.

M87 contains one of the largest population centers in the United States in the form of New York City and environs. We tend think of this metropolitan area as an overpopulated wasteland, but that is a misconception.

New York City happens to be the gateway to one continuous park that runs from the Adirondacks, past New York City, all the way to the new Hudson Canyon National Marine Sanctuary about 80 miles offshore.

While it is massive, it is also one of the most accessible parks in the world. It is served by three international airports with, as its entry hub, one of the most dynamic cities in the world.

Every park has its entry hub, this park just happens to have one of the best in the world.

It is one giant continuous park because one can explore the entire park in almost total self sufficient solitude, and everybody within the park is rarely more than a few miles away from true nature. Even those who live in one of most densely populated areas in the country, New York City, only have to walk to the water's edge and will immediately be confronted with true wildlife, whether it is osprey, striped bass or even whales. From that point on they have continuous water access to some of most carefully preserved natural areas in the world to enjoy remarkable self-sufficient natural solitude.

It is this solitude on the road or rather river less traveled that is the most striking feature of this giant park. Along its entire length from the Canadian border, along Lake Champlain to the East, along the Erie Canal to the West and as far offshore as the Hudson Canyon, it is all connected continuously by solitude and nature only occasionally interrupted by resupply points. This access to nature even extends ashore where, for example, the Appalachian Trail crosses the Hudson and runs through New Jersey within sight of New York City and there are designated bikeways along the Erie Canal that follow the old tow path.

In many ways this giant park is a copy of the original Adirondacks as a mixture of public and private property. While, on a percentage basis, this much larger park has less public property than the Adirondacks, there is much more public property than we realize (The Hudson River itself, all of the water around New York City, Gateway National Recreation Area, Harriman Park, Bear Mountain, Palisades Park, the entire New York Canal system, and the list goes on and on.) and new public access is continuously being added while air, water, and wildlife quality are continuously improving.

Where the size and continuity of this park becomes immediately apparent is on the water. From New York City it is possible to travel to the Adirondacks by boat, and to detour West along the Erie canal and find an incredible amount of nature, peace and solitude that is never engaged with when rushing along interstate highways.

To leave the Jersey Shore, to travel by boat on the Hudson River past New York City and to arrive at Lake Champlain is actually one continuous trail of natural beauty only occasionally interrupted by humans.

It should also be noted that M87 is fully connected to all the Great Lakes, equally impressive Canadian canals north of the Great Lakes and the St. Lawrence Seaway, the Intercoastal Waterway and all of the Mississippi river system.

This is a massive asset, but why is it not better known?

The above history shows that M87 is the setting of an incredibly dynamic society. To shift from a deeply polluting commercial aspect to a sustainability approach requires a huge perceptional change.

Meanwhile, with the demise of polluting commercial use, many assets that may be of interest in the sustainable development of M87 have disappeared due to improper development or just decay.

Central to this is the development of rail on both sides of the Hudson and the canals. This was a convenient right of way at the time of construction of the railroads, but effectively isolates the river and the canals as nothing more than a ditch between two railroads. It also cuts the river and canal towns off from the waterfronts.[5]

With the towns cut off from the waterfronts, most waterfront structures in the forms of piers, small harbors, bulkheads and wharfs have been abandoned and decayed to a level where they are no longer serviceable. The loss of work in most towns and the abandonment of their waterfronts also have very much reduced the charm of most human settlements along M87.

In this regard any initiatives for cargo or people movement along M87 need to be focused on the remaining waterfront infrastructure along M87 and there is not much left.

Moreover, what is left, is poorly promoted and often not visible from the water (or through the internet) or simply not inviting for waterborne commerce or passenger trade.

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[5] And the railroads add significant noise pollution

The Hudson River still has large, even ocean going commercial traffic, but there are remarkably few commercial entry and exit ramps along the Hudson River part of M87.

Large ship entry points north of the Tappan Zee Bridge are Cementon, Coeymans and the Port of Albany. Albany is a versatile and substantial port, but Cementon, Coeymans and a few other stops are generally single cargo terminals, although Coeymans has recently seen impressive expansion.

Small vessel cruise lines, especially American Cruise Lines do cruise up the Hudson River, but there are only a few points to actually tie up. The cruise mostly focuses on the fall foliage season and has the below itinerary.[6]

The visuals are beautiful, but access to the Hudson River's cultural heritage is very poor. While most of the shore features are actually on the waterfront, they are generally accessed with buses from almost improvised berths. There are many opportunities for waterfront culture berths. For example dock and dine at the Culinary Institute of America would be great. To be able to tie up at Hyde Park (FDR's home) would be great and even a lovely town like Cold Spring is a nightmare as far as vessel berths is concerned.

Up until COVID, Blount Small Ship Adventures operated an Erie Canal capable cruise vessel, that could cruise the length of M87.

The Grande Mariner is the maximum size vessel that can transit the Erie Canal and is presently for sale.

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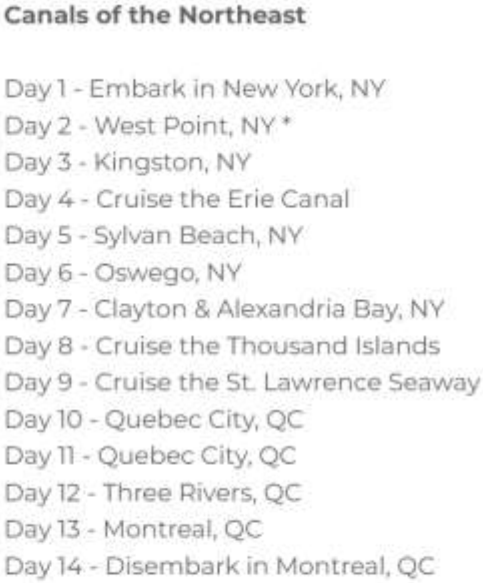
[6] These cruises cost $5000 and up per person for a 7 day cruise.



Canals of the Northeast

Day 1 - Embark in New York, NY
Day 2 - West Point, NY *
Day 3 - Kingston, NY
Day 4 - Cruise the Erie Canal
Day 5 - Sylvan Beach, NY
Day 6 - Oswego, NY
Day 7 - Clayton & Alexandria Bay, NY
Day 8 - Cruise the Thousand Islands
Day 9 - Cruise the St. Lawrence Seaway
Day 10 - Quebec City, QC
Day 11 - Quebec City, QC
Day 12 - Three Rivers, QC
Day 13 - Montreal, QC
Day 14 - Disembark in Montreal, QC

The most recent itinerary showed 6 stops along M87.

New York State has made considerable investments in the upgrade of the canals and, in general ,they are quite functional. While there are portions of lock sections where it is possible to tie up, often the locks are far removed from other points of interest or facilities and lock berths lack facilities such as shore power or sewage pump outs.

There is still occasional commercial traffic through the canals. In 2022 the author witnessed the transit of a number of barges through the Erie Canal that had been constructed in Cleveland and were being transported to the US East Coast. Occasionally large equipment is transported on barges through the canal.

Regardless, most of the heavy traffic along the canal portion of M87 is maintenance barges and dredges for the Canal Authorities.

There are a substantial number of marinas along M87, they do serve transients, but mostly survive on local boaters and are often quite primitive.

And occasionally there are town docks some of which have survived and been modestly upgraded and other have seen massive waterfront development, often of abhorrently poor design where the Amsterdam waterfront deserves special mention for poor conceptional design.

As far as poor, or maybe unfortunate design is concerned, Syracuse stands out for simply filling in the portion of the canal that went through its quite attractive city center when the canal was enlarged. The canal portion that ran through the center would have made an astonishingly pretty downtown harbor.

Schenectady has an astonishingly well preserved colonial neighborhood, but there is no tie up there.

Fortunately, there is a very well designed modest transient marina on the opposite side of the canal (actually a river at that portion of the canal) and the colonial neighborhood can be reached in a 30 minute walk by crossing a road bridge across the canal.

Some towns have continued to depopulate and Whitehall at the North end of the Champlain canal has declined from a careworn but charming town 20 years ago to a near ghost town with an expensively redeveloped waterfront between the worn canal front homes and the canal itself that feels very unnatural in that setting.

All of this redevelopment was heavily focused on increasing tourism and recreational boating along the canal. Unfortunately, from a commercial point of view, it is unlikely that the investments in waterfront access resulted in positive returns.

WHY IS M87 TRADE NOT REVIVING?

The simple answer as to why M87 cargo trade is not reviving is that other methods are more cost effective. A more complicated answer is that sustainability heavily favors the high cargo weight-to-CO2 emission fraction of waterborne transportation and as such it should become more attractive, especially for slow cargo if it can be figured out how to do it.

But what cargo is slow today? Some containerized cargo may be slow. Large bulk cargoes are slow, but M87 no longer generates, nor requires, large bulk cargo. (Besides oil deliveries, which ironically and ideally will be phased out over the coming decades.)

There was an MARAD experiment to take containers off the road and to carry them on the Hudson from Albany to Port Newark/Elizabeth a number of years ago, but this trade failed to gain any traction. There are many causes for the failure, some of which will be discussed later, but a more significant question to ask is: What would constitute success? How much containerized cargo can actually be delivered more efficiently by boat rather than by train along the Hudson?[7]

Trains have close to the same efficiency as boats, are faster and can reasonably easily be made sustainable by electrification.

Meanwhile one may ask: What about the Rhine, it teems with commercial traffic?

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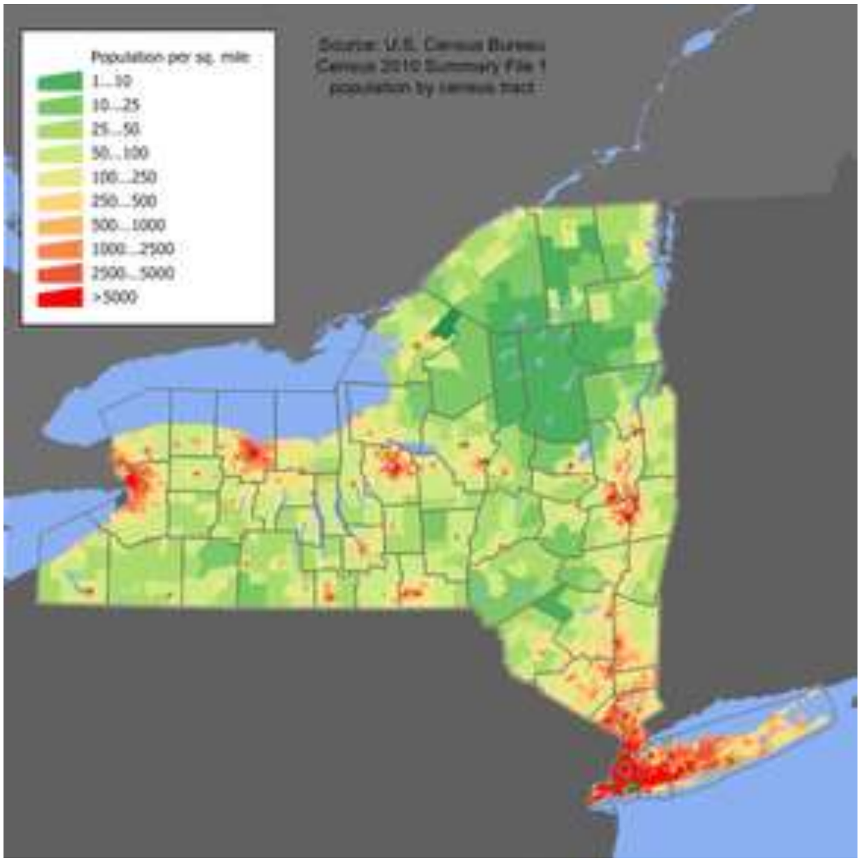
[7] A recent NYSERDA study also indicated that transporting farm products from upstate New York along the Erie canal and Hudson was not likely to be able to compete with truck transportation even from an emissions point of view. This would change if M87 transportation become zero emission, but road transportation can also become zero emission with Etrucks. The math changes when it is assumed that cargo will be loaded and unloaded along M87.

While there is some intermodal transportation (and lots of bulk cargo transport) along densely populated rivers such as the Rhine, it needs to be emphasized that the massive area that M87 serves is quite sparsely populated. The largest cities on M87 are Albany and Buffalo.



Albany has a population of 100,000 and an urban area population of 500,000

Buffalo has a population of 278,000 and an urban population of 950,000.

New York State has a population of a little less than 20 million people of which 2/3 live in the New York City metro area. That leaves only 7 million people for the rest of the state. New York state's population density is 416 people per square mile, but is much lower along the M87 corridor. Once the immense New York City population is discounted, it is unlikely to exceed 200 people per square mile for the M87 corridor.

All of the Netherlands is fully connected to the Rhine and has a population of 18 million people and a population density of 1350 people per square mile. Then, when the Rhine moves into Germany to Dusseldorf (a shorter distance than NYC to Albany, although on a much more difficult river to navigate) it encounters a city of 600,000 people and is within striking distance of four or five cities of similar or larger size. This results in river logistics access for at least an additional 10 million people. Moreover, the river logistical infrastructure never disappeared when trains and trucks became more dominant. With existing river front infrastructure, a maritime claw back becomes much easier.

It needs to be recognized that growing a trade is much easier than creating a trade. The often massive upfront cost of gaining consumer acceptance is often higher than the venture will actually produce in income.

Consumer acceptance and commercial success is a chicken and egg issue. “If I build it, people will come”, only makes partial sense. It assumes that people will know what one is building, and once built what it actually is.

This is an almost universal technology problem, but is particularly applicable in maritime trade.

Despite a very substantial start-up subsidy, the aforementioned Hudson River container barge trade never became profitable even though in theory it should be commercially viable and provide substantial environmental benefits. Undoubtedly, there was a fraction of the Albany to NYC container cargo that would be suitable for this trade. However, containers are routed by freight forwarders. These are humans that figure out how to move containers between different locations.[8]

A customer calls the freight forwarder and tells her what is in the box and when they want it delivered. Assuming it is a random cargo in Port Elizabeth that needs to be delivered somewhere in upstate New York, the freight forwarder will normally first grab a trucker they know to make the move. If a customer is cost conscious, or if it is a customer who receives multiple containers in a continuous stream, the freight forwarder may consider using a train for most of the trip and have a local hauler deliver the containers to the customer. In essence, the freight forwarder and his customer have two choices.

With a container barge service, the freight forwarder and the customer have three choices, with the third choice requiring a deeper think as in:

“Let me see. This cargo is not urgent. Oh, and it is going to a spot that is pretty close to Albany. Somebody told that there is now is another way. I can put out a freight slip where I direct the container to go onto a barge. How much less does it cost? Hmmm, yeah that may be worth it. So when does the barge move upriver? Oh bummer, a barge just left, so now I need to wait three days, but a truck or train are ready today. What is the cost difference again? Let me call the customer again to see if she can wait. Yes she can wait, so now I need to find a trucker who is familiar with the Albany terminal. This trucker will do it, but he needs directions and cannot pick that container up the day it arrives. It is still 20% cheaper than the train, but I am not going to put that much effort into it for every box. The next box like this is going on the train.

In business school this is defined as training your customer. Advertising is rarely sufficient to train a customer, and generally multiple rounds of substantial financial incentives are required. Because people do not change behavior based on one experience; multiple training rounds are required.

This process is no different for the start up of ferry services that only run occasionally. If it is not a perfect fit for a customer on the first try it becomes very difficult to have that customer occasionally decide to use the ferry over other more predictable alternatives.

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[8] Today there is a high level of automation in freight forwarding and AI will increase the automation, but the problem does not disappear.

Especially in New York City ferries have revived, and the mechanisms for success are well established, but almost universally it simply means that it requires a long period of loss before commercial viability starts to appear.

It also applies equally to cruise development and especially along M87. A cruise to Venice is easy. There will be a large number of people who know about Venice and who know about cruising and therefore only limited marketing is required to capture a crowd that can fill a cruise to Venice.

A cruise to M87 is inherently more difficult. First one has to find a customer who is not interested in Venice. Then one has to suggest M87 and inevitably the person will say: Why would I do a cruise up the Hudson? Then it is up to the cruise ship owner to do a show and tell about the Hudson. The customer will like the idea, but then is distracted with a cruise to Bermuda and forgets about the Hudson.

It can be done, but it takes hard work, persistence, and generally a large money losing investment. With regard to money losing investments, today's climate crises warrants investment and marketing under the umbrella of environmental responsibility, and achieving sustainability. Sustainability can only be achieved by two means: High taxes on fossil fuels which does not work in the United States, or subsidies to change consumer preferences.

But it begs the next question: "What is the best way to make the most effective losing upfront investment to change customer behavior?"

BUILD A LITTLE, TEST A LITTLE, LEARN A LOT (BALTALLAL)

"Build a little, test a little, learn a lot" (BALTALLAL) was first coined in the 1960's by Admiral Wayne Meyers, lead engineer for the AEGIS combat system in. He was frustrated by the continuous failure in deploying effective combat systems. In analyzing the problem, he became aware that, in an effort to solve a problem, engineers often went a bridge too far, and when the system did not work, it could not be reworked to a level where it would function satisfactorily.

To prevent that failure mode, Adm. Meyers started to develop a combat system that was comprised of many smaller components each of which could be altered or upgraded as needed or adopt new technologies as they became available. This persistent, but small step approach was quite successful and, in hindsight, can be determined to be the only way to solve complex problems.

A somewhat similar approach was also promoted by John Boyd in his OODA loop approach. John Boyd was an amazing fighter pilot, but instead of riding the mystique of the right stuff, John Boyd managed to figure out what the right stuff is and developed a fighter pilot training method to teach the right stuff. He called it the OODA loop.

It stands for Observe, Orientate, Decide and Act, and then do it all over again right away.

So this is what happens to a novice in the cockpit: He'd observe enemy fighters, and then will freeze in panic not knowing what to do until he gets shot down.

Instead, John Boyd would train the novice to observe, to figure out where the problem was, to engage the option that is most effective under the circumstances, to take action and to see what happened after the action was taken and start the loop all over again. That makes sense, but what is really interesting is that it gets to be real fun when you can do the loop faster than the enemy, whether the enemy is a bunch of other fighter pilots, a bunch of pirates, a sinking ship or climate change.

To engineers it is nothing but an information feedback loop, but what it adds is loop speed and step size.

If you take a large step that takes too much time, the situation can change too much to make an effective decision. Something similar occurs in large system design and implementation.

In this regard the introduction of containerized barge transport on the Hudson would simply be too large a step, and ignores the many intermediate steps that need to be successfully completed for the system to actually work.

In postmortem analysis of barged containers, it may have been worthwhile to first address the freight forwarder conundrum before the barge was chartered. The author has not made a deep study of that program, but it may have been useful to make a much smaller investment in freight forwarder training before the project actually started. Such training could be a reward system, where a number of freight forwarders will send notice of any cargo that they think may be more sustainably transported on a barge to a researcher and for every proper notice they will receive a small reward of, say $10. The freight will still move on truck or train, but the researcher now gets a data base that is filled by actual freight forwarders and based on that information a realistic prognosis of service viability can be made. If and when it is decided to implement such a trade, there are also actual trained freight forwarders who can engage with it.[9]

As already noted, sustainable development of M87, is a systems problem with many fuzzy variables.

There are many questions that need to be answered such as:

1. Can M87 actually play a significant part in the development of sustainable transportation?
2. Who would be the customers?
3. What will that transportation look like?
4. What will be the investment required to get it started?
5. What infrastructure changes will be needed?
6. Who will operate it?

And that is only the tip of the iceberg and when addressing these questions, it will quickly become apparent that there are massive unknowns.

Inherently there are two ways of homing in on solutions, reducing the unknowns and taking small steps towards a solution at the highest possible speed.

Interestingly some efforts have started in this regard and there are tremendous further opportunities that deserve further consideration and funding.

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[9] This is a technical suggestion; politically it will probably incur howls of protest from truckers and railroaders.

PRESENT EFFORTS

Aberration:

The author designed and built a Solar Hybrid Electric Wheelchair Accessible Catamaran, which was commissioned in 2021.[10]

The vessel is a 35 foot catamaran powered with twin 10kW electric outboard, which provides a top speed of 8 knots and an efficient cruising speed of 6 knots. She accommodates 5 people in two double cabins and a single cabin and is main deck wheelchair accessible.

At 6 knots the vessel can run on batteries alone for about 2 hours, but when throttled down to total propulsive output of 3kW she will still make 4.5 knots, which will then provide an endurance of 7 hours and a range of 31 nautical miles. She is also fitted with 4kW solar panels which on a sunny day can provide substantial additional power and range.

She is fitted with a 12kW diesel generator which, as a backup, can provide unlimited sustained 6 knot speed and burns about .75 gallons of diesel per hour.

The battery system is 48VDC (with independent, quite small 12VDC batteries for navigational equipment), but all accommodation systems are 110VAC through inverters which allow the use of reliable and inexpensive shore based appliances.

Since the vessel was built in Albany, and in the first few seasons was winter stored in Albany, it spent considerable time cruising on M87 as far south as Sandy Hook and as far north and west as Lake Champlain and Little Falls.

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[10] This vessel was not designed and built as an M87 testbed, but fortuitously became an M87 testbed and lots of lesson were learned. She is also a Solar Hybrid Electric testbed with lots of lessons to be learned.

During those trips all the hybrid modes are engaged, where for example the vessel may be repositioned from Albany to Red Bank, NJ (a little south from Sandy Hook) in a continuous 24 hour run, or may be exploring Lake Champlain in 3 hour hops.

During all its operations the power hierarchy is solar first, then shore power, and if there is no alternative the diesel generator is started.

In operation the diesel generator has run less than 50% (200 hours since commissioning), and those hours are mostly attributed to non-stop runs up and down the Hudson and a rush to do the Champlain Canal in one day.

Depending on her particular service, there are many operational modes and profiles, but this discussion will focus on lessons learned during canal operations.

In particular, during a six day roundtrip from Waterford to Little Falls, a distance of about 80 miles with 16 locks, on the way up the generator would be started towards the end of the run. There may have been sufficient battery capacity to make it to the next stop, but if there were no shore power, some reserves in the battery would prevent having to run the generator at the berth and also would provide some battery power early in the morning, since running the generator in the early morning quiet is least attractive on a cruising boat.[11]

Morning quiet is particularly significant in the operation of this vessel since it allows some crew to sleep with others enjoying the peace and quiet of the canal at 4.5 knots, while getting a nice head start at very little power consumption.

With regard to shore power, it is noted that documentation for shore facilities along the Erie Canal is poor and disorganized.[12] On the way up we discovered that each stop had sufficient shore power and therefore, every morning we left with a full battery charge.[13]

This resulted in a major change in the operational profile on the return trip. We used the same stops on the way back that we used on the way up, and because we knew we could charge at each evening stop we simply ran on the batteries till they were exhausted and it turned out we never had to start the generator on the way back.

This issue mirrors the present EV Car consumer hurdle of sufficient charging for road trips, but on a canal system the issue becomes even more interesting and particularly so in upstate New York.

Interestingly, since canals are linear, predictable shore power can be more easily implemented on a canal system than on a road network.

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[11] At less than 60 dB in the cabin the generator is far from noisy, and much quieter and smoother than just about any powerboat. However, if one considers that the next loudest sound source is the clicking of the autopilot electro hydraulic motor and the hissing of the coffee machine it seems excessively intrusive. As far as exterior noise is concerned, there is no exterior noise along most of the canal except the noise of passing trains.

[12] This is the case for the entire M87 system. An improvement in predictability with regard to shore resources would increase general enjoyment for a M87 cruiser, and also facilitate M87 cargo vessels and canal maintenance vessels.

[13] Paying for shore power is a very attractive because it inherently also provides propulsive power for the next day. For Aberration that saving in actual dollars is small. Shore powered electric boat operation in upstate New York is environmentally satisfying because so much of the electricity is hydro and therefore sustainable.

There are specific features that make it unusually attractive to electrify canal propulsion:

1. There are mandated stops; locks. This is a location where fast charging could be very attractive.
2. Solar and battery propulsion does not work on high speed vessels, but the canals are very heavily speed restricted which makes battery propulsion inherently viable.
3. Canals are water powered and excess water is often used for electricity production. However, there is a cost effectiveness trade off in hydro power and over the years a drop of less than 10 feet was not considered to be cost effective for hydro electricity. However, with new technologies (remote control, microgrids) this is changing and many locks that presently do not have a hydro electric generator could provide charging power for passing boats. (Especially with a shore battery fast charging set-up)[14]
4. The canals are day time operation only and that facilitates overnight charging when vessels are tied up.

So what was the BALTALLAL for this small real life experiment?

1. Noiseless sustainable canal cruising is nice. Really nice, and could be a marketing asset.
2. Predictable shore power does not require a large investment in battery powered propulsion equipment for canal boat transportation.
3. There is unused electric generating potential along canals that can be dedicated to electrified canal transportation.
4. The Erie and Champlain canal systems could be a completely sustainable operation

This would be the investment to achieve a higher level of sustainability on the M87 canals. That does not solve the issue of what cargo should be transported on the canal or how the canals can attract more cruise or recreational vessel income.

Canal recreation (recreational canal boating) is practically non-existent on the M87 canals. There is one operator (eriecanaladventures.com) along the canal in Macedon west of Rochester. For a number of years, the same boats were operated out of Troy, but stopped operating there a number of years ago. There are a few additional smaller operators.

One can only assume the operation in Troy was not profitable, and undoubtedly operating costs were a major factor. With what is known today about reduced operating costs of EV's and applying that to canal boats, with properly documented overnight stops and charging facilities, the profit picture may well change very drastically.

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[14] There is an adverse effect potential here. If canal use increases due to general electrification, the amount of excess water decreases and less hydro electricity can be generated, one way to solve that is to install solar panels near locks.

The present canal boats are diesel powered with LPG stoves and rather primitive equipment outfits. A battery powered boat experiment was started a few years ago with New York Power Authority funding, but appears to have stalled on a lack of shore based chargers. An electric drive canal boat would be much easier to operate by an inexperienced user and would cost much less to operate on a year by year basis, with only marginally increased purchase cost.[15]

While in theory one may want to provide these boats with at least 12 hours full speed operating range, this may not inherently be a benefit. For example, it may be much more attractive to force users to only run for a few hours per day between stops, but this requires that these stops are interesting. This provides an interesting system development opportunity. Rather than make the entire canal recreationally friendly it may be more attractive to do it section by section. A certain canal section would be supplied with boats of a certain range and the canal stops within range would be upgraded to make it attractive for cruisers and provide shore based activities that would be of interest (and profitable) to the canal boaters. To some extent Erie Canal Adventures has engaged in this where it appears they selected the location where the canal shore is most interesting.

At present there are very few interesting shore based activities within easy reach of canal boaters along most of the M87 canals. The development of shore based activities will be initially difficult since this is a factor of tourist density (at present about zero) and the seasonal nature of the canal.

However, Erie Canal Adventures has addressed this issue with a “Who would like this” page that suggests:

- History Buffs
- Foodies
- Wine Enthusiasts
- Beer Lovers
- Village Shoppers
- Engineering Fans

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[15] Mathematically because the propulsion portion is much smaller on a battery boat than an EV, the cost difference will be much less than an EV and IC car difference. The very sophisticated power setup with a backup generator on Aberration increased the cost by about 10%. It would be much less on a battery only canal boat.

- Outdoorsies
- Kid Unpluggers
- Hipsters

Except for village shopping, the author modestly partakes in all those activities, and the associated description did makes his juices flow.[16]

Most of all, Erie Canal Adventures is a BALTALLAL, and spreading their message, combined with improved technologies points at better things.

Apollonia:

Maritime transportation takes advantage of huge economies of scale, but even quite recently there were many maritime ventures in the United States that operated on quite a small scale.

Economies of scale are a complex subject. While the per pound, or per passenger, costs go down with economies of scale, almost inevitably there is something or someone that is left behind. In the past there was a strong connection between maritime at large and the public, but today, due to these economy of scale efficiencies, that connection has been mostly lost.

That disconnect between the public and our waterways has made it difficult to ensure that we establish a lasting re-connection.

Moreover, since technology, commerce and society change constantly, what was once an optimized economy of scale may today lumber along by sheer momentum. Newer opportunities at smaller scales may well be more attractive, they but don't develop because they cannot be seen in the large lumbering picture.

There is a BALTALLAL unfolding along the Hudson River that is working on the smallest scale.

That project is called Apollonia. (schoonerapollonia.com) Apollonia is the experimental revival of sail freight along the Hudson River. Apollonia is a 64 feet, 10 ton schooner operated by dedicated maritime experimentalists in an effort to shift cargoes from fossil fuel driven vessels and vehicles to sustainable energy driven vessels.

In the simplest terms, it is sail transportation along the Hudson. That is inherently slow and labor intensive, which would seem unattractive as compared to fossil fuel driven cargo transportation along the Hudson River.

However, that is a flawed comparison because, today, there is no cargo transportation along the Hudson River and it is not known if appropriate cargoes exist.

Appollonia is doing cargo distribution along both sides of the Hudson River as far south as New Jersey and as far North as the start of the New York State Canals. This is a two-way neighborhood cargo distribution system that also aims at zero emissions.

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[16] The author chartered a canal boat like this out of Troy about 20 years ago and ran it to Lake Champlain. A very enjoyable experience, but also tempered by the lack of shore facilities and activities.

Apollonia is sail powered, which on the Hudson means she is actually sail and tide powered. The typical average voyage speed with wind and tide is three knots, which is slow but also quite impressive for sail power and, if speed is not required, it is perfectly fine for cargo on boats that don't burn any fuel.

So far, Apolonia has sailed 15 round trips with cargo from Hudson to New York City and has delivered over 150,000 pounds of cargo on those trips. There is a wide variety of cargo, often quite small parcels, but real cargo all the same, such as malted barley for microbreweries, pumpkins, maple syrup, mushroom logs, beer, cider, solar panels, coffee beans, flour, honey, condiments and mead. Right now, there is more downriver cargo than upriver cargo, but that is just a matter of finding the right cargo to go upriver.[17]

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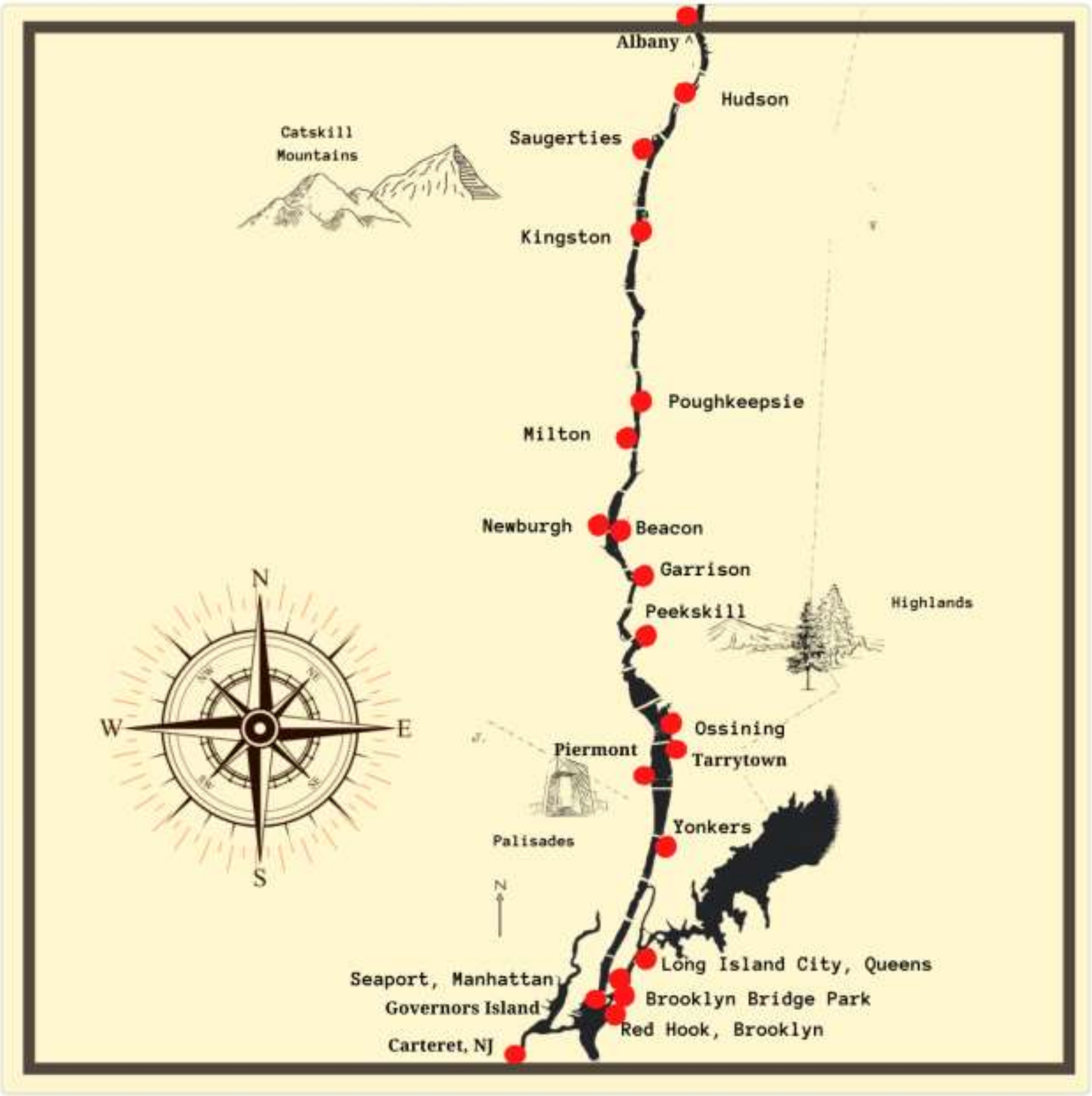
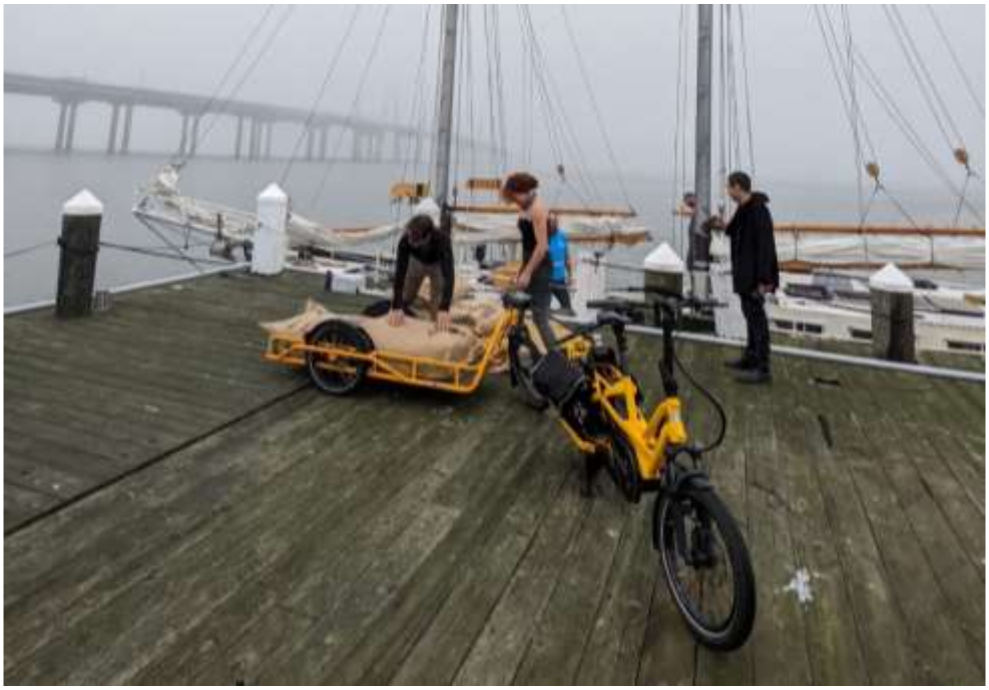
[17] For example, the author would like to see his local Monmouth County elixer, Laird's Applejack, carried upriver at zero emissions. A recent upriver cargo is coffee from the main NYC coffee distribution warehouse in Carteret, NJ.



The vessel's arrival at what is presently amounting to 20 different ports is becoming a community event and the focus of the repurposing of neglected community waterfronts to serve as recreational, commerce, tourism and educational hotspots. The community event character is growing into a waterfront market situation where the vessel is also selling cargo on the dock; a famous river trade tradition.

In its present guise, Apollonia uses a diesel engine to maneuver the vessel to the berth, but the crew is extremely parsimonious with the use of diesel and, at present, fuel consumption is 3 gallons for a 250+ mile voyage. She is actually an excellent candidate for solar powered electric drive to make the vessel zero carbon, and some design work in that regard is underway.

Moreover, the dedicated Apollonia team also focuses on zero emission door to door distribution, where they even carry a solar powered ebike and trailer, and will deliver cargo only to EV's for further inland distribution.



At first glance this may be regarded as a cute tree huggy idealistic money loser, but it is actually BALTALLAL at its best.

This is actually a low cost grass roots effort that, with modest support, can crack something that we have not been able to do with prior substantial government subsidies for river borne trade development.

Apollonia is cracking the chickens and eggs problem for river born trade. River borne trade requires two things: Vessels to carry cargo, and many places to pick up and deliver cargo along a route. Neither exist and one cannot function without the other. Therefore, we need both at the same time.

It needs to be emphasized that while this all looks like a return to 19th century technology, it is not. New technologies such as the internet are shifting the base 19th technology into a viable 21st century technology. There is no Amazon (basically a 19th century Sears style store) without the internet and there is no Doordash without the internet.

This experiment has already resulted in incredible insights. Apollonia is data driven, and collects excellent cost, environmental, cargo and commercial data. While the project feels grassroots; it is actually closer to a NASA program on a tiny scale.

Apollonia has recently invested in hiring a logistics manager/cargo broker/supercargo to further develop the data and marketing of the project. This could be the BALTALLAL step that will enhance port access and the flow of cargo to a level where additional vessels will need to be considered.[18]

Apollonia provides a unique opportunity for the following reasons:

1. Any sustainable river trade development is a step in the right direction, whether in port development, cargo development, tourism development or recreational development. Apollonia is the trailblazer for this development.
2. We need to engage both young people who know how to develop a sustainable energy economy and the next generation of mariners. However, young people cannot be attracted to an industry if they have no contact with the industry. Apollonia is the fun, low stress, entry point to our industry for young people.
3. Sustainability in maritime is incredibly complex, and solutions requires experiments. As Master Yoda says: “There is no try, there is only do” and Apollonia is doing.
4. While economies of scale reduce cost, cost is only a small part of happiness and success. Community is another major factor in happiness and success, and Apollonia is creating and reconnecting communities that often have been left by the wayside due to economies of scale. This is not charity; this is quality of life and sustainability for everyone.

Apollonia is an extremely low cost operation that actually generates a little money in freight and trade. However, its most important aspect is its ability to tie all the pieces together at a very small scale where then the individual pieces can be improved as needed at low cost.

Some of this is even organic. With their focus of door to door zero emission delivery, at certain locations EV owners are now volunteering to carry cargo from the dock to the receivers. With increasing trade this would become an independent sustainable local business.

This thinking becomes particularly interest when one considers that recent real estate developments have shown a remarkable increase in interest by young people in living in the smaller Hudson river

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[18] At present the supercargo position is funded by donations, but it should actually be a government paid research position.

communities. This real estate revival will inevitably result in a deeper focus on sustainability and river access.

The Port of New York and the Hudson River made history time and time again such as with the Half Moon in 1608, the Onrust in 1614, Fulton's North River Steamboat in 1807, and Pete Seeger's Clearwater in 1969, maybe Apollonia will add the next chapter; it certainly deserves wide and strong support.

FUTURE EFFORTS

The above BALTALLALs provide insight in what may be further BALTALLAL efforts to continually strengthen M87 Cargo and tourism.

The following sample experiments come to mind:

1. Provide each Hudson River town with a public dock that allows cargo landing and loading, and short term recreational mooring
2. Focus recreational marketing on Europe
3. Optimize and grow the Apollonia concept
4. Continue development of Erie Canal electric barges
5. Revive the Canal passenger cruise trade.

These experiments may not be initially profitable, but will provide systemwide and organic growth of M87 concept, and will allow for adjustments if the experiments are not successful.

Most significantly the knowledge gained/cost fraction is much higher than large experiments that focus on economies of scale on trades that do not (yet) exist.

Undoubtedly these experiments require subsidies, but in the total scheme of the costs to achieve sustainability, these costs are very small and have the benefit of addressing all aspects of sustainability rather than a singular focus on sustainable energy production and also serve a larger community than specialized large scale projects which tend to benefit only a small group of researchers or contractors.

True sustainability works on all levels, and while sustainable energy is core, as expressed in the United Nations Sustainable Development Goals, the fair and efficient use of the sustainable energy is the ultimate goal. These M87 experiments meet these goals more effectively than economy of scale projects.

Some further discussion on the above proposed future efforts is provided below.

Hudson River Public Docks

Apollonia has served as a riverfront dock explorer. Some Hudson River communities have some access to the water, but others, at the very least, require high water and often that needs to be combined with high levels of seamanship.

The type of river trade that Apollonia is developing would very much benefit from the installation of many simple (and standardized, like uniform freeboard) river front mooring arrangements. These berths would consist of a modestly sized spudded barge (60 by 40 feet would already do the trick), that has an 8 foot wide ADA[19] style gangway to the shore. The barge could be fitted with a modest sized solar powered storage shed for cargo storage and storage of cargo gear. While the placement of moorings is always a custom job, a barge of this type with its inherently very long gangway would provide a berthing solution at a wide range of locations along the Hudson River. These mooring barges may have to be seasonal in certain locations, but could be quickly removed and positioned.

Besides use for cargo, these barges can also provide a transient recreational boating tie up at various locations.

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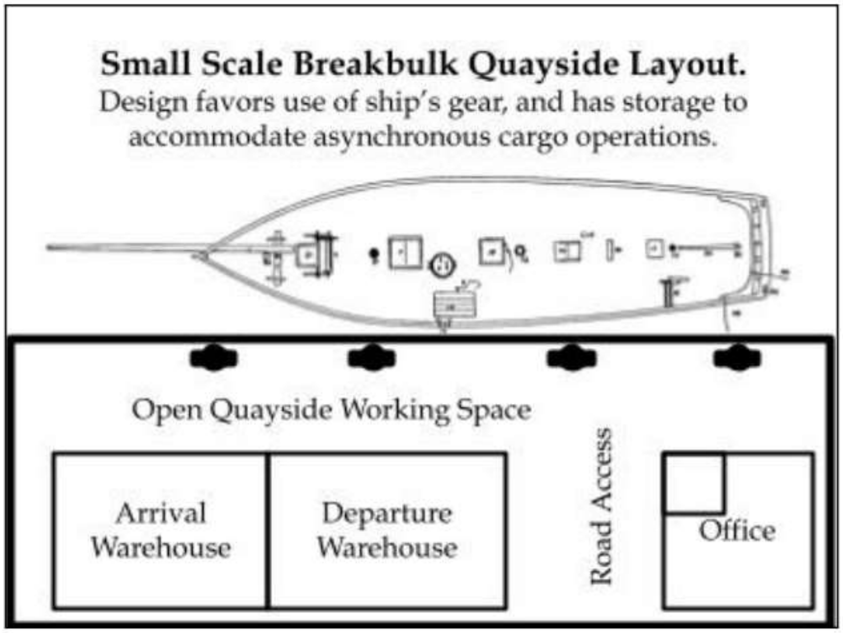
[19] If it is wheelchair accessible it is also rolling cargo accessible. Win/Win.

With increasing trade, these barges may soon become too small for certain ports, but can then be repositioned to develop new M87 on and off ramps.



Small cargo vessel quay layout as discussed in Steven Woods' Sail Freight Handbook

Focus Recreational Marketing on Europe.

Canal Adventures's website makes suggestions about the type of people who may want to charter a canal boat. In the United States the percentage of people who may consider chartering a canal boat is miniscule. This both results in a small market and in difficulties actually getting the marketing message to the tiny section of the US population that would consider chartering a canal boat.[20]

The picture in Europe is quite different. While the percentage of people who may consider chartering a canal boat is still small, it is probably orders of magnitude larger than the United States because canal boating is orders of magnitude larger as an industry. Moreover, people that enjoy canal boating always look for new areas to explore and, in this regard, M87 becomes a very interesting proposition. It has excellent access to Europe, it is part of a larger tourist industry that is extremely large and active, and provides a very interesting additional aspect to visiting the New York City area; the immense amount of nature that exists right outside New York City, which, at present, receives very little tourist attention.

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[20] In the US there is a culture of RV recreation. Europeans have culture of both RV and Canal Boat recreation. Europeans come to the US and rent RV's not because that is what they want, but rather because they are not aware of interesting canal boat rental opportunities. Interestingly there is a significant contingent of Europeans that rent house boats on the western reservoirs.

"Visit New York City and decompress with an Erie Canal trip", makes more sense than trying to convince a random New Jersey citizen to pick the Erie Canal over the thousands of other recreational opportunities that exist.

To grow the industry with European customers will increase visibility to US and European customers alike.

Optimize and Grow the Apollonia Concept

As an experiment the Apollonia concept is remarkably successful. It needs to be remembered that commercially successful cargo movement along M87 is only one standard of success. In many ways Apollonia is more comparable to an educational program, but with the unusual benefit of also developing income and with the potential of actually doing it profitably. The school aspect of Apollonia cannot be underestimated. It informs the public, it provides specific training in an industry that has good paying jobs and stability, and helps in the economic and sustainable revival of M87 communities. Even more remarkably, while schools generally have a fixed size student body, Apollonia is actually growing a beneficial student body through increasing trade along M87.

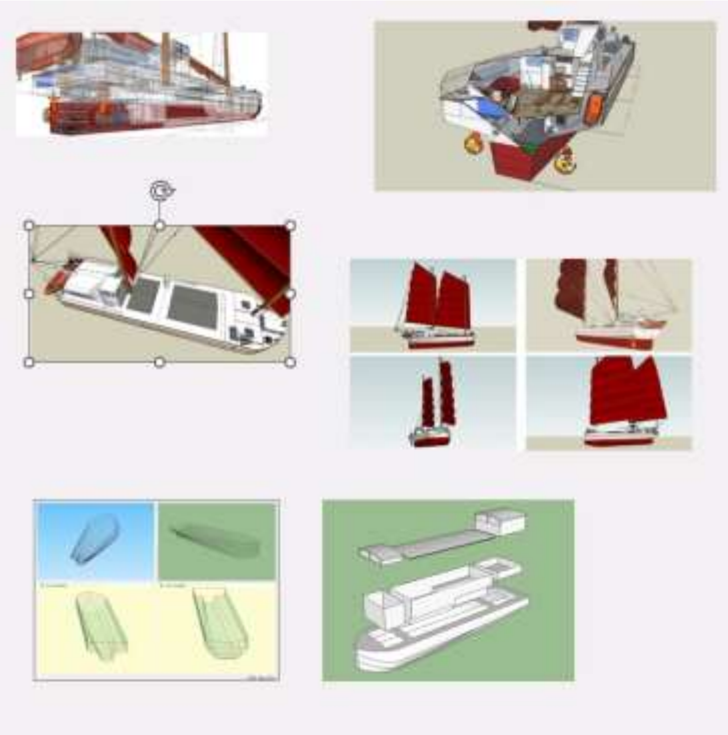
As such, the continued support of this project makes sense from a sustainability point of view. Interestingly, awareness of this program is actually growing trade that in many ways is completely unexpected. Last year an Albany shipyard shipped a part that needed to be fitted in a boat in New York City. It is highly unlikely to think that anybody would have predicted that commercial shipping of mechanical components on a sailboat is viable cargo. However, because the trade exists and because the shipyard became aware of it, they shipped it on the concept of "Why not?". Actually, "Why not?" is one of the best commercial motivations for sustainability.

Active, and let's call it aggressive, support of this project will generate new economic opportunities and new sources of sustainable income. This will then result in the development of new technologies to support that trade.

Apollonia modifications and upgrades (battery standby propulsion, improved cargo systems) are being considered, and more optimized total vessel designs are being developed for sail powered Hudson river cargo vessels.

While sail power may be a first propulsive consideration, it may well occur that other sustainable propulsion systems will displace sail. But that will only occur if the trade exists and creating that trade is being accomplished through Apollonia.

Geoff Uttmark already has done some advanced thinking under a NYSERDA grant.



Geoff Uttmark's NYSERDA funded Eriemax ship design and HEFTTCo. business plan was developed "to stimulate growth by creating a green, lower cost trade route using ship-kit, electric powered, owner-operated small freight ships."

RSS – 80 is a steel hulled, hybrid electric, 100 dwt sailing vessel built to carry 18 TEU equivalents designed for a crew of 4-9 including cadets. Her rig is set in tabernacles to enable her to navigate canals and under low bridges while doubling as cargo derricks. estimated delivered price of a lead ship is $1.5-1.75 million.

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Continue Development of Erie Canal Electric Barges

Technically there is no doubt that electrification of the Erie Canal is viable, but this needs to be accomplished by developing the chicken and the egg, which in this case is shore side charging and the construction of electric barges. Canal Adventures is an excellent candidate as a lead developer of an electrified fleet, but this is beyond the financial means of a company of this type.

Reportedly the New York Power Authority has converted a canal barge to electric propulsion, but this project is presently stalled (quite possibly because of the chicken and egg issue). Noting that Canal Adventures reportedly has more potential customers than available boats, a lease approach of New York State or MARAD funded boats may be the best possible approach, with investment by New York state and local communities in charging facilities along the canal starting from Rochester and spreading outward from there.

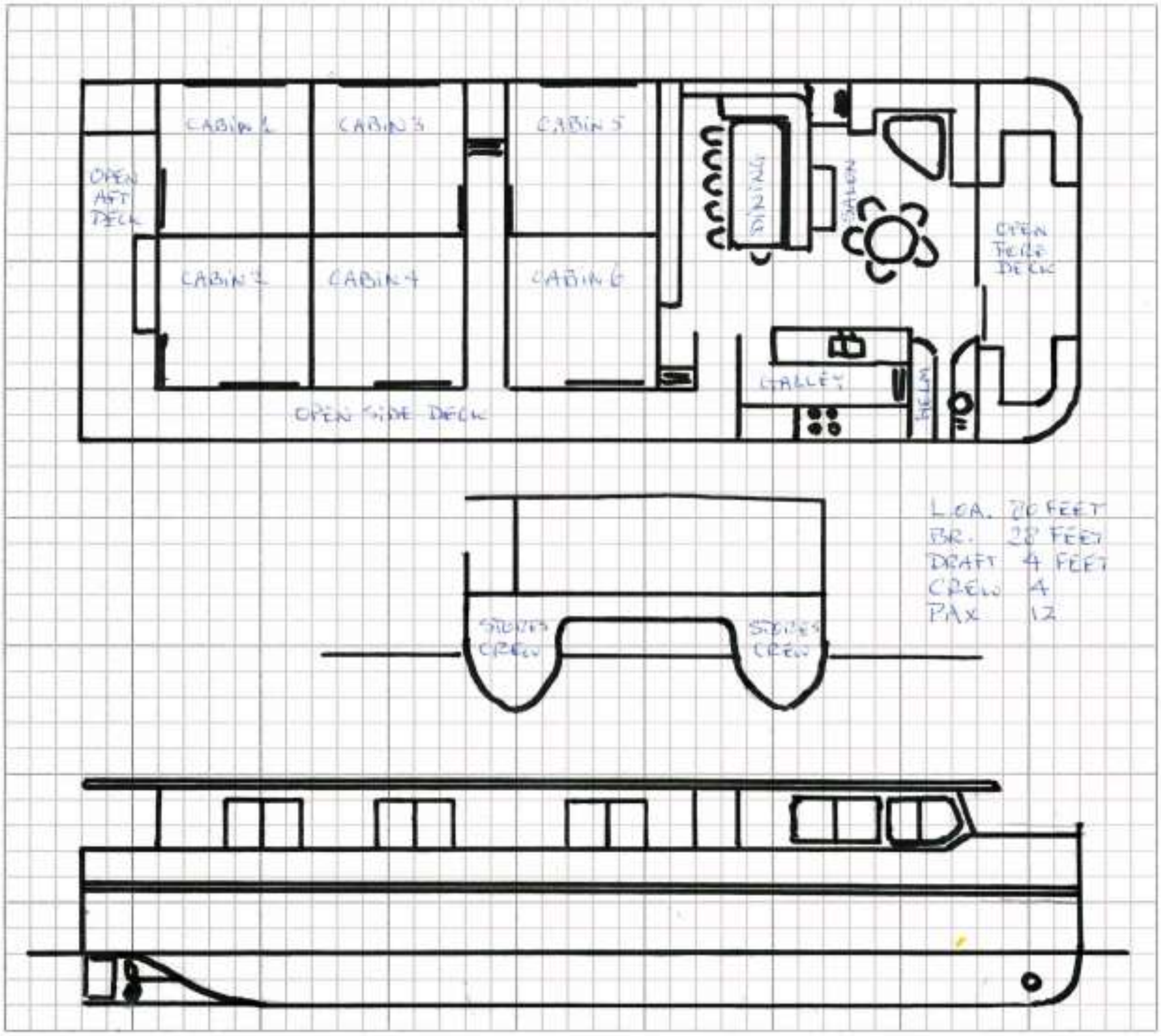
International marketing of Erie Canal (or all of M87) rental boating would help in ensuring that the stream of customers will grow.

Revive the Canal Passenger Cruise Trade.

Unfortunately, at present there is no active Erie canal passenger cruise operation. The vessel that was capable of these cruises is presently laid up and for sale. The decision to stop canal passenger cruise operations was not directly commercial but rather was the result of COVID, a need for equipment upgrades, and lack of available seasonal personnel.

The revival of that trade will require substantial investment, but there is no actual indication that it cannot develop into a viable trade. The existing vessel is diesel powered and from a sustainability point of view this would not be appropriate.

Experience with Aberration indicates that there is an intermediate approach by developing a larger version of Aberration that is configured for high end passenger cruising.



This vessel would be solar and shore electric powered similar to Aberration, but due to scaling efficiencies[21] would have increased range and speed that would allow it to operate in a weeklong cruise[22] starting in New York City and traveling to Lake Champlain or in consecutive steps along the Erie Canal.

This 80 foot vessel would carry 12 passengers in 6 cabins with a crew of 4 or 5.

These would be high end cruises similar to high end yacht charters in other parts of the world or the Maine schooner trade.

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[21] The physical advantage of scaling in ship design is not a blind disregard of the social problems of economies of scale.

[22] Leave New York City and leisurely travel all the way to Westport NY on Lake Champlain. Catch a return train to New York City, while the next set of passengers will start the cruise at Westport and travel back to New York City.

From a marketing point of view, these cruises or charters could be combined with a package vacation that includes a New York City stay and Amtrak travel to meet the vessel or return to New York City. While these cruises will be at the high end of exclusive luxury[23], they will focus on the sustainable nature of the transportation, the exceptional peace and wildlife in the cruising area, and local food, wine and history.

Initial cost estimates indicate that this design would be commercially viable as a single vessel small business operation similar to the Maine Schooner trade.

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[23] Exclusive luxury is not the size of the cabin, but rather the depth of the experience.

CONCLUSION:

Maritime highway development beyond the present state of the art is an extremely complex problem that increases in complexity when sustainable development becomes an additional factor.

Based on experience it appears the following conclusions and recommendations can be made with regard to M87 development and maritime highway development on a national basis:

1. Build a little, Test a little, Learn a lot, appears to be the only approach that has a chance of success in a Chicken and Egg problem
2. M87 is an excellent test bed for BALTALLAL
3. Marine Highways don't exist without on and off ramps, byways, cargo and scenic attractions. Marine Parkways may be a better designation.
4. Maritime trade development has always been organic, it takes advantage of the right conditions. Identify and develop the right conditions and trade will develop.
5. In multi customer situations (ferries, freight forwarders, recreational boaters, tourism) there are inevitable long start-up periods with no or low profits. If we want to achieve sustainability, we may have to bite that bullet every now and then.
6. Sustainability can only be achieved with proper fossil fuel taxes or with changing public perceptions.
7. The former does not exist in the United States.
8. The latter can be achieved by offering quality of life benefits and/or subsidies and incentives in the switch to sustainability. Quality of life can be as simple as reduced environmental noise and as complex as the emotional trade offs between pumpkins delivered with or without the use of fossil fuels. The ideal model is: Outlaw gasoline leaf blowers. The other approach is: Battery leaf blowers that outperform gasoline leaf blowers.
9. Nobody can predict what will work in the future. But a sustainable future can only be created by doing. Doing may not not result in immediate success but it will almost always open new doors in totally unexpected ways.
10. Remember that loop speed is central to OODA. It is imperative that BALTALLAL experiments do not stall.
11. Rapidly developing and reduced cost sustainability technology opens even more doors.
12. Do not allow non-sustainable technologies to engage in M87 trade revival, or even equipment upgrades.
13. Every failed experiment made public is valuable. But low cost failed experiments are preferred.
14. It is the CO2 stupid. Reduce CO2 first and try to fit in as many of the other sustainable development goals as possible.