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Proceedings of the 4th

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Conference Information

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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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Table of Contents

Solar Electric Ship Design and Sustainable Operation

Author(s): David Borton[1]

1. Solar Sal Boats division of Sustainability Energy Systems, Inc.

This paper explores the development of solar electric boats, demonstrating their sustainability and efficiency in passenger and cargo transport. Beginning with a solar-powered canoe prototype in the 1970s, the project evolved into larger vessels, including the 40-foot "Solar Sal" and the US Coast Guard-certified "Solaris," both achieving significant solar-powered voyages. These boats offer safety, low maintenance, and resilience, with continuous solar charging eliminating the need for shore-based infrastructure. The success of these vessels highlights the viability of solar electric marine propulsion as a sustainable alternative to fossil fuel-powered systems.

KEY WORDS

Alternative energy, environmental impacts, sustainable economics

INTRODUCTION

The physics of displacement boats applies to canoes and aircraft carriers alike. Commercial freight boats cover a wide range in between. Canoes are powered by people and people are carbon powered. Solar energy in the form of human food recycles current plant-based carbon into human food, and respiration returns carbon dioxide to the atmosphere. In contrast internal combustion vessels use ancient, buried carbon and add it to our current atmosphere.

I have been around boats since before I could walk, exploring upstate New York in canoes and Adirondack guide boats. Fast forward a few decades, to the early 1970s when the energy crisis hit. At the time I was pursuing a post-doc in chemistry at RPI. That experience, plus my prior PhD in physics, told me that solar energy was the way to reduce America's dependence on oil. A little later, when an older relative gave me his old Grumman aluminum canoe, it provided a way to combine my interests in solar energy and boats. I used it as an experimental test bed for a solar-electric powered prototype consistent with the solar energy engineering course I was teaching at the time. The older gentleman who provided the canoe was no longer strong enough to travel at will on the 14 mile Adirondack lake he had explored alone and with friends for a lifetime. The primitive addition of 94 Watts of solar panels, 3 kWhr of lead acid battery and a 300Watt trolling motor to that canoe restored his independent travel all over the lake. And a big smile.

Figure 1. Converted solar electric propulsion canoe.

SOLAR ELECTRIC DESIGN

Electric propulsion allows for simple metering of electric power. GPS technology provides instantaneous speed data. Speed and power inputs allow the physics of displacement-boat efficiency to be shown graphically in an easily accessible form. In contrast, the instantaneous power of an internal combustion engine is quite difficult to measure, and that obscures the inefficiency of fossil-powered marine travel.

Below is a simple diagram of a solar electric system. All solar electric systems are like this, but all are different in the details. By connecting the battery to a marine propulsion motor you have marine transportation that is not tied to a charging dock. By also connecting an inverter you have a resilient electric power generator that can propel itself to places where it might be needed at times that other electrical power may be compromised by wind, fire, flood or civil unrest.

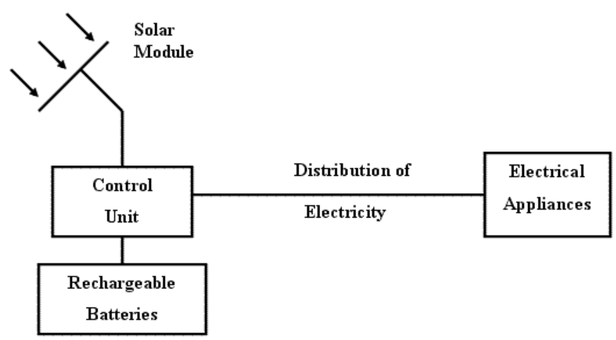

Figure 2. Solar electric system diagram.

In 2012 I built a "real" boat in my garage: a proof of concept vessel in the form of a wooden 25 foot 100% solar-powered electric boat. It provided the following Speed Versus Power Graph.

The data shows the expected approximate third power exponential relationship between speed and power for an object moving in a viscous fluid. Notice that halving the power from 2 kW to 1 kW reduces the speed by only 1 knot. Halving the power again reduces the power to 500 W but the speed is reduced only 1 more knot**.**

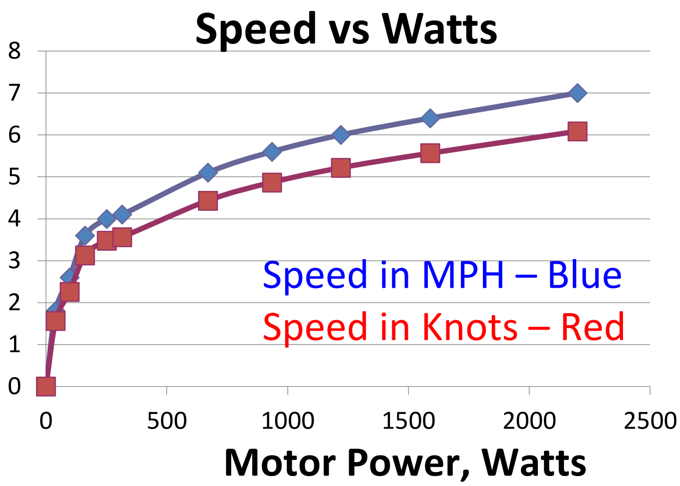

Figure 3. Speed versus Power graph.

This boat has been operating for a dozen summers on an Adirondack lake where there is no road and no electricity. As a launch it carries people, baggage, food and all manner of materiel.

Figure 4. Proof of concept solar boat in Adirondacks.

SOLAR SAL

The millions of tons of worldwide shipping knows that it takes remarkably little power to move large masses through the water slowly. On the Erie Canal a mule or a couple horses would power up to 30 ton barges (*Erie Canal*, 2019).

The physics of scaling laws show that it would be straightforward to build a similar 40 foot boat (*Scaling Law*, n.d.). We accepted a challenge to build such a boat in a year. With excellent volunteer help we built the boat christened "Solar Sal" in 7 months. The name comes from the old song covered *(performed?)* by Bruce Springsteen.

Solar Sal 40 was a multi-use prototype: She gave river tours to friends and relatives. She was a cabin cruiser for the trip out the Erie Canal to the Niagara River. She picked up 4 tons of cardboard at Lockport on the way back, as a cargo vessel she delivered the cardboard to a paper mill in Mechanicville up the Hudson River (Christoforos, 2015). That was a 750 mile round trip solar powered recycling cargo trip.

Figure 5. *Solar Sal* on Hudson River.

Some people still doubted the viability of solar electric marine propulsion. Working with author and Marine Architect Dave Gerr, the Wooden Boat School at Kingston, NY built a 44-foot Solar Sal designed for touring. After certification by US Coast Guard, she was purchased by the Hudson River Maritime Museum and christened *Solaris.* Since her debut in 2019, she has taken over 20,000 people on 100% solar powered tours (Hudson River Maritime Museum, 2018). She is the first USCG Certified 100% solar electric commercial boat. Her cargo is high value, people earning a 6 figure gross income even during COVID.

Figure 6. *Solaris*, a 44-foot Solar Sal.

We also worked with Sam Devlin Designing Boat Builders in Tacoma WA to build Solar Sal 27, christened Wayward Sun. This pleasure boat has a V-birth sleeping 2, with deck and bench space for 4 more. During COVID we took Wayward Sun 1400 miles from Bellingham WA to Glacier Bay Alaska. This was the first 100% solar powered voyage up the Inside Passage (Pike, 2021).

During this voyage the two captains, myself and my son, had an approximately 2 hour duty cycle, and we recorded insolation, speed, battery voltage and state-of-charge and motor power. Our hourly observations of battery Voltage versus State-of-Charge are shown graphically below.

Figure 7. *Wayward Sun*, a Solar Sal 27.

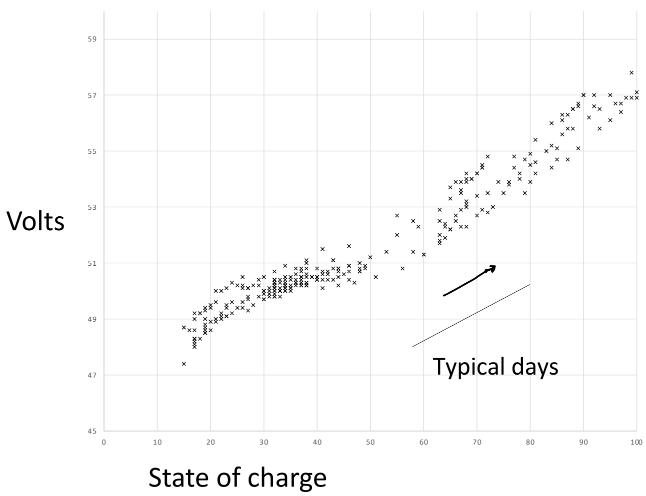

Figure 8. Voltage versus State-of-Charge during Inside Passage voyage.

Most electric boats and vehicles are charged at the dock and then run, discharging the battery, until they return to a dock and recharge. Solar boats operate differently. Wayward Sun's battery bank, like all Solar Sal models, are continuously charged during daylight hours. Underway, the batteries are either charging, discharging, or often idle as the solar energy goes directly to the motor, dependent on sun conditions and throttle setting, all controlled electronically.

On the graph each hour is represented by a point. A simplistic expectation is that each state-of-charge would correspond to a specific voltage. However, at any given time if the battery is charging the observed voltage will be higher that the corresponding state-of-charge. Likewise, if the motor is drawing more power than the solar panels are producing the observed voltage will be lower that the "expected" voltage for that SOC. These conditions produce the broad range of operating conditions in the battery as shown on the graph.

Our battery capacity is more than twice the capacity used on any given day. The short lines represent beginning and end conditions of the battery for two nominal days of travel.

A different small solar powered cargo trip was the winning entry in the NorthEast Grain Race of 2022. A Solar Sal 27 foot fiberglass boat took several types of wheat flour from the Erie Canal to Kingston delivering the grain door to door with solar electric transportation. A solar-charged electric car brought the flour to the boat on the canal. To insure no grid electrons were involved, batteries in the boat were used, through an inverter, to charge the electric car that took the grain the last mile from the harbor to its People's Place (food pantry) destination.

CONCLUSIONS

The sustainable design and operation features of electric passenger boats and cargo boats include:

- Safety: no flammable fuel, no toxic gasses, no oil spills
- Economy: no trips to the fuel dock, less maintenance, no oil changes
- Instantaneous power, full torque at all RPM, operation from 0 RPM, no idling
- Pleasure: quiet for conversation, observing wildlife, drinking wine
- Luxury: responsive with full torque at all RPM, operation from 0 RPM, no idling

Solar electric power provides all those advantages of electric propulsion, plus no fuels, no oil changes, and free solar energy forever. Additionally Solar powered vessels need no added shoreside infrastructure for charging and have no range anxiety.

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Jones Act LNG Carrier Development
A Global Priority for a Domestic Resource

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The United States needs a fleet of Jones Act LNG Carriers. This paper promotes the projection of clean American energy and specifically seeks to serve national interests by providing a means of domestic natural gas consumption, as well as international interests by providing necessary resources to our allies to promote energy independence from our adversaries. A complex membrane LNG vessel, the technology required for this effort, has already been successfully designed and built in the U.S. This paper presents a plan that builds on this success to seed the creation of a fleet of Jones Act LNG Carriers that minimizes the risk to owners and builders and successfully identifies the issues and resources needed to accomplish this goal.

KEY WORDS: Jones; Energy; Security; Carrier; LNG; Domestic; Naval Architecture; Marine Engineering

INTRODUCTION

The United States currently lacks sufficient and strategic means to transport clean domestic fuel for its energy needs. Long-standing government strategic policies, however, define the solution to this problem. "The Jones Act" requires that all ships that transport goods from one U.S. port to another must be both built in the U.S. and crewed by U.S. merchant mariners. Currently, the U.S. lacks a fleet of compliant vessels to transport American Liquefied Natural Gas (LNG) domestically and to our allies. Consequently, energy insecurity exists in regions of the U.S. (Northeast, Hawaii, etc.), our territories (Puerto Rico), and for our allies (Japan, Korea, Europe, etc.).

Fig. 1, *Conceptual 12,000 m^3 LNG Carrier.*

Energy insecurity is growing with the adoption of renewable energy (such as solar or wind) and the shuttering of coal and oil-fired power plants. Waiver of Jones Act requirements, often proposed as a temporary solution, is not a viable fix for this critical shortcoming. The larger reality is that the United States does not have the capability to build what are now the most advanced and high-value commercial cargo vessels on the seas. The recent problem of semi-conductor manufacturing is illustrative here (Williams, 2022). We cannot remain utterly dependent upon faraway supply chains and manufacturing in vulnerable or volatile regions.

Though it is not yet widely recognized, the latest Liquefied Natural Gas Carriers (LNGCs) are vital to national, economic, and energy security. The United States needs a fleet of state-of-the-art Jones Act LNGCs *and* the industrial base and maritime personnel and infrastructure to make this a reality (Fig. 1). Investment in Jones Act LNGCs can fill the need in these areas and provide additional environmental benefits. Government support to seed a fleet of U.S. LNGCs would thus advance national strategic, economic, and environmental interests and address urgent geopolitical problems.

GOAL AND BENEFITS

The goal of this proposal is to promote clean American energy both to U.S. regions and territories not served by pipelines and to our U.S. allies. Specifically, this proposal seeks to serve national interests, by providing a means of domestic natural gas consumption for energy production, as well as international interests, by providing necessary resources to our allies so that they are not beholden to our adversaries for their energy needs.

Specific benefits include supporting energy security, economic security, revitalization of the commercial shipbuilding industry and support of its industrial base and supply chain.

Additionally, while this effort will onshore both ship operations and seafarers, it will also uniquely develop domestic capability in design and engineering related to LNG transportation. The former will strengthen the U.S. Merchant Marine while the latter supports both national security and potential infrastructure investment in the U.S.

POLICY CONTEXT

"The Jones Act," also known as "The Merchant Marine Act of 1920," places restrictions on any ship that transports goods from one U.S. port to another U.S. port. Specifically, the Jones Act requires that such vessels must be both owned by a U.S. entity and crewed by U.S. merchant mariners. U.S. entities are companies that are controlled by U.S. citizens with at least 75 percent U.S. ownership. The goal of the Jones Act is to encourage the development of a national fleet, support national defense, strengthen the American maritime industry, and fuel economic growth.

Significantly, however, no "Jones Act compliant," LNG Carriers currently exist, exposing a vulnerability in terms of U.S. clean energy production and consumption. Although a small fleet was built before 1980, those vessels have either been decommissioned or are not part of the Jones Act fleet anymore.

STRATEGIC PROBLEM

The lack of Jones Act compliant LNG Carriers is problematic for the United States for many reasons. Notably, without such vessels, domestic supplies of natural gas cannot be transported to American consumers via waterborne vessels. This is troublesome because maritime shipping is one of the most economical and environmentally friendly ways to transport LNG.

A striking example of this problem exists in the northeastern United States. The New England electrical grid is predominantly fired by natural gas. However, due to a lack of adequate pipelines and storage, the domestic natural gas supply cannot satisfy the demand in New England, despite the fact that the Marcellus Shale deposit of natural gas is directly west of the Hudson River. This is because some states and jurisdictions (New York, in this case) will not allow new pipelines to be run through them, effectively cutting New England off from additional supply of domestic natural gas, via pipeline (Helman, 2022). The absurd result is that New England must purchase foreign LNG delivered to Boston on foreign vessels! (Natural Gas Distribution, n.d.).

Similarly, we currently cannot deliver domestic natural gas to Hawaii and Puerto Rico because they are not in the contiguous U.S. and thus are not served by pipelines. While small-scale LNG shipments are delivered on Jones Act cargo vessels using 20ft and 40ft cryogenic tanks, bulk cargo LNG must be delivered to these islands on foreign flag ships with foreign cargo.

New England governors have recently lobbied for waivers to the Jones Act to allow domestic LNG to be shipped via foreign LNGCs. However, we should build Jones Act compliant LNGCs instead. Information on additional benefits of seeding a Jones Act fleet of LNGCs including the commercial benefits to U.S. vessel owners and operators can be found in Appendix A.

A troubling corollary to the lack of a domestic LNGC fleet is that although the United States is capable of delivering domestic natural gas to our allies (Japan, Korea, and Europe for example), we cannot currently do so using U.S. ships. This is a significant problem because without domestic LNGCs, we cannot project American energy. An adversary could easily exploit this vulnerability and influence foreign operators not to carry U.S. cargoes. This is particularly concerning today, due to the growth of Chinese global hegemony, coincident with the rise of Chinese and China-dependent shipbuilding.

As a painfully relevant example, LNG carriers have already played a decisive role in the defense of Europe in the aftermath of the invasion of Ukraine and economic damage caused by cut-off Russian gas and the complex mix of energy embargoes. In 2022, Europe imported 58% more LNG than it had the year prior according to data from Refinitiv cited in the Financial Times. Without the U.S. LNG infrastructure and robust export capacity, the situation now unfolding in Europe would have undoubtedly turned out quite differently. Energy security and flexibility plays a vital role in the conflict.

Thus, this inability to supply our allies with domestic LNG on domestic "bottoms" (i.e., Jones Act vessels) was the primary concern of the *Energizing American Maritime Act,* H.R. 1240 floated in the House during the 115th congress (2017-2018), in the Senate as S.707 in the 117th Congress (2021-2022), and now in the House as H.R. 6724 in the 118th Congress (2023-2024). This Act, sponsored by Rep John Garamendi (D-CA-3) and Senator Roger Wicker (R-MS), aimed to require that a certain percentage of natural gas export be shipped on U.S. vessels. The Act, however, did not focus on shipping LNG domestically, which is a primary focus of this proposal. Furthermore, the act was commercially punitive because it required that more expensive U.S. vessels be utilized, which the Government Accountability Office (GAO) found could harm U.S. LNG export competitiveness (Office, U.S.G.A, 2015). Conversely, this proposal suggests a targeted and direct subsidy for design and approval of the vessels and training of the crews, and favorable financing for construction of the vessels, both of which are commercially beneficial.

Large, state-of-the-art LNGCs are complex vessels, and the majority use a membrane cargo tank system (not a pressurized, Type-C tank, the containment favored domestically for the small LNG vessels currently being built). Few shipyards are capable of building membrane LNGCs globally. Historically, three shipyards in Korea build membrane-type LNGCs: Samsung Heavy Industries, Hyundai Heavy Industries and Daewoo Shipbuilding and Marine Engineering. These yards have significant backlogs in part due to Qatar's massive North Field expansion, which has created opportunities for new entrants (Aizhu, 2022).

More recently, three shipyards in China: Hudong-Zhonghua Shipbuilding, China Merchants Heavy Industry, and Yangzijiang Shipbuilding – at least one of which is state sponsored (Funaiole, Hart, 2021) have begun building membrane LNGCs. As a case in point, it was announced that a shipyard in China will build an LNGC for Danish shipowner Celsius Tankers similar to one of the LNGCs discussed in this proposal (China Merchants Gets LNG Carrier Order as China Grows Market Share, n.d.). U.S. operators cannot follow suit to transport LNG domestically because a Chinese or Korean-built LNGC would not be Jones Act compliant, among other security concerns.

China has made LNGCs a top priority and a key element of its maritime strategy. The multi-year backlog in Korean shipyards is aiding China's aggressive moves at a time of huge economic opportunity. Information about the benefit to the greater U.S. industrial base, and specifically its defense related capabilities, is included in Appendix B.

In addition to the United States' current inability to project domestic natural gas (i.e., clean American energy) globally, more alarmingly, we also cannot currently adequately protect our domestic energy supply if we cannot transport it with domestic assets. Existing U.S. pipelines in the Northeast are currently running at capacity. If any of those pipelines should be shuttered, either deliberately or unexpectedly, the Northeast's reliance on LNG delivered by ship would increase dramatically, yet as aforementioned, we currently do not have the capacity to meet the demand with domestic ships. The vulnerability of our energy transport is real and foreseeable, as a pipeline can be shut down for a variety of reasons, including environmental regulation, damage (natural or manmade), sabotage (as was the case with Nord Stream 2) and cyberattack (such as the Colonial Oil Pipeline hack in 2021) (Kerner, 2022).

There is currently no redundancy for the supply of natural gas to the Northeast, should a pipeline be lost. However, Jones Act compliant LNGCs would provide this much needed redundancy with a transport system that could be deployed to any area of the country in need of domestic natural gas for any reason, as is currently possible for the transportation of oil. For these reasons, the domestic construction of Jones Act compliant LNGCs is in our nation's economic and security interests. A maritime fleet can provide flexibility and resilience to alleviate unexpected problems in unexpected places.

ENVIRONMENTAL PROBLEM

Many nations, including the U.S., are pursuing policies to increase renewable energy production (primarily wind and solar) and decrease the use of power plants with high greenhouse gas emissions (primarily those burning coal and oil). However, solar and wind are dependent on weather, meaning they cannot provide the same level of control and reliability of service as the fossil fuel plants they are replacing. This lack of predictable power on demand can lead to energy insecurity when wind and solar make up a significant percentage of grid capacity. Also, the current push to greater electrification of the transportation network magnifies the need for a more resilient, redundant, and reliable electrical grid.

While concepts exist for advanced renewable energy networks that could improve control and reliability in the future, (McCamey, 2021) the reality today is clear. Fossil-fuel power plants are required to provide baseload and standby power for regions adopting solar and wind.

Natural gas power plants are an ideal power source to pair with renewables because they are efficient, relatively clean, (Gould, McGlade, 2017) and are state-of-the-art for both baseload and standby power generation. The more solar and wind power that is added, the more environmental incentive there will be for natural gas-fired capacity to replace the coal and oil plants backing-up those renewable energy assets.

Natural gas power plants replacing coal and oil plants provide emissions reductions regardless of wind and solar usage, and switching to natural gas has largely driven emissions reductions in the U.S. electric grid in recent decades (McGrath, 2021). Global energy insecurity threatening natural gas supply leads to the emergency use of coal and fuel oil reserves, which is significantly worse for the environment than natural gas. Europe's recent recommissioning of coal-fired plants due to their former dependence on Russian natural gas is expected to more than cancel out the region's emissions reduction efforts, resulting in a net increase in CO_2 emissions (Blackburne & Naschert, 2022).

A fleet of Jones Act LNG Carriers would provide environmental benefits by reducing energy insecurity and supporting the replacement of coal and oil-fired power plants as more renewable energy comes online. Appendix C provides information regarding additional environmental advantages of LNG Carrier investment, including improved vessel efficiency and the potential to support renewable "e-fuels" in the future.

OBSTACLES & HISTORICAL CONCERNS

Despite the urgent issues that could be addressed by a Jones Act fleet of LNGCs, the U.S. industrial base in recent years has been poorly positioned to create such a fleet in light of several key obstacles and concerns. In the decades since the last U.S. LNGC was built, the technical capabilities and regulatory pathways to produce them have largely been lost or fallen behind the state of the global industry. Recent proposals to mandate the creation and use of a domestic LNGC fleet have raised prohibitive commercial concerns from the U.S. natural gas industry which are thoroughly discussed in the 2015 GAO report (Office, U.S.G.A, 2015). These concerns have centered around lack of a clear path to build up the missing industry capacities, jeopardizing existing export contracts, and hurting global competitiveness at a time of uncertain future demand for U.S. LNG.

Since 2015, the global market for U.S. LNG has changed dramatically. The need for a domestic LNG Carrier fleet is now more urgent than ever to address increasing economic, environmental and security stresses. Charter rates for modern LNGCs can reach hundreds of thousands of dollars per day in spot markets. This economic opportunity did not exist in 2015 when the GAO issued their report. Also, the global fleet is expected to come under additional pressure as older generation LNG carriers are retired at a brisk rate in way of the new carbon intensity regulations (Snyder, 2021). This paper presents a plan that directly addresses the concerns raised in 2015, establishing a step-by-step solution to restoring industrial capacity and utilizing targeted subsidies rather than punitive regulations.

SOLUTION

The solution is to incrementally seed a Jones Act fleet of 174,000 m^3 (174K) Membrane-Type LNG Carriers (Fig. 2). 174K is the size of the current state-of-the-art global fleet of LNGCs. Modern LNGCs of this size must have membrane tanks to compete with the global fleet.

Fig. 2, *FLEX LNG 174,000 m3 LNG Carrier.*

The plan to accomplish this is as simple as 1-2-3!

1. Develop U.S. capability to produce a small (12K) Membrane-Type LNG-carrying barge.
2. Develop U.S. capability to produce a small (12K) Membrane-Type LNG Carrier (self-propelled).
3. Develop U.S. capability to produce a large (174K) Membrane-Type LNG Carrier.

Step 1- Develop U.S. capability to produce a small (12K) Membrane-Type LNG-carrying barge

Jones Act 4K and 5.5K Type-C (pressurized) LNG Articulated Tug Barges (LNG ATBs) have been or are being built; a Jones Act 2.2K Membrane Barge has been built and is currently operating; and a Jones Act Type-C 12K Barge was recently delivered.

Putting these pieces together, a Jones Act 12K Membrane-Type LNG Barge can be combined with a dedicated tugboat and this combination, known as an Articulated Tug Barge (ATB), can be designed and built domestically now. Step 1 is complete!

Step 2- Develop U.S. capability to produce a small (12K) Membrane-Type LNG Carrier

A carrier is required in place of an LNG ATB because the LNG ATB cannot be scaled up as required to project domestic natural gas. Keeping the first domestic LNGCs the same size as the 12K LNG ATBs that can currently be built removes construction risk for the smaller of the two LNGCs proposed in this paper. To aid in this effort, the authors have already developed a conceptual design as illustrated below (Fig. 3, 4).

Fig. 3, 12K *LNG Carrier Conceptual Design Rendering.*

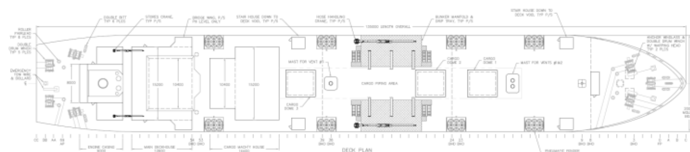

Fig. 4, 12K *LNG Carrier Conceptual Design General Arrangement.*

However, a <u>large</u> regulatory challenge must be mitigated to bring this conceptual design to life. Based on the authors' experience pushing the design of the <u>**first**</u> Jones Act LNG Bunker Barge, *CLEAN JACKSONVILLE* (Fig. 5), through the U.S. Coast Guard and American Bureau of Shipping regulatory process, the requirements for the <u>**design and approval**</u> of a Jones Act, membrane LNG vessel are identified. However, the challenges associated with this effort cannot be understated. The regulatory approval process for the *CLEAN JACKSONVILLE* spanned four years. This was an exceptionally long and commercially challenging process for all parties, including the owner, builder, and the designer. Regulatory approval of the design of a Jones Act LNGC is, therefore, the largest risk that must be mitigated and thus, must be <u>subsidized</u> to be economically practical.


Fig. 5, *CLEAN JACKSONVILLE.*

Step 3- Develop U.S. capability to produce a large (174K) Membrane-Type LNG Carrier

Completion of Step 2 will have removed the regulatory risk for the design and construction of a Jones Act LNGC, meaning a larger version similar to the current state-of-the-art 174K LNGC can be designed with minimal design or regulatory risk (Fig. 6).

Tier I shipyards capable of building the larger vessels can leverage the knowledge, skill and vendor base of the smaller yards that built the 12K LNGCs, minimizing the construction risk. Additionally, subsidized merchant mariner training on 12Ks will develop the cadre of officers and crew needed for this new fleet of 174K LNGCs.


Fig. 6, *FLEX LNG 174,000 m3 LNG Carrier.*

RISKS AND MITIGATIONS

The need for a fleet of Jones Act LNGCs to project American natural gas both domestically and worldwide is evident. This paper provides a stepwise solution to accomplish this goal. The commercial concerns raised by the industry in 2015 are mitigated primarily by using subsidies rather than new trade regulations. Commercial prospects today are also significantly improved noting that domestic regions and Europe are now high-demand consumer markets for American LNG, poised to support the necessary investments in the Jones Act fleet. This paper has identified, isolated, and mitigated specific risks associated with developing a Jones Act LNGC fleet, including design, regulatory approval, construction, and crew training.

In 2015, most of the U.S. capacity to produce LNG for export was already under long-term contracts primarily in Asia. However, exports from Australia and eastern Africa were poised to compete for the Asian market due to proximity; meaning any regulations that might hurt U.S. competitiveness were seen as prohibitive. The European market, despite representing a much cheaper shipping route from the U.S. Gulf of Mexico, was not expected to generate significant demand for U.S. LNG, given their cheap natural gas supply via pipeline (Office, U.S.G.A, 2015) primarily from Russia. Given the recent global shift away from Russia and the disruption to European pipelines, there is unprecedented opportunity for new export contracts of American LNG to Europe. This solution envisions these new markets as a driving factor in supporting growth.

The first step in the solution is already complete given the design experience which was acquired during the design and approval of the first U.S. LNG Bunker Barge, the *CLEAN JACKSONVILLE*, in 2014-2019. This first step therefore poses no new risks requiring mitigation. Although other LNG barges have been designed and built since then, none are membrane tank vessels. Significantly, a membrane tank is necessary for scaling the design.

The first serious risk is the regulatory approval of a Jones Act 12K LNG Carrier in Step 2. The approval of a Jones Act 12K LNG Carrier will be a long and challenging process which will require both financial and political assistance from the government, as the risk is prohibitive for commercial clients. Financial support should be in the form of a government subsidy to design both the 12K and 174K LNGCs sequentially, and to shepherd them through the long and tortuous regulatory process. This support provides necessary mitigation to the risk associated with design and approval of these novel vessels.

Once the risks associated with design and approval are mitigated, the 12K LNGC can be built without significant technical risk because similar sized LNG ATBs are already under construction domestically. However, there remains some commercial risk for the shipyard, and crewing the 12K LNGC and her potential sisters is the next major risk that must be mitigated. The former can be alleviated by commercially attractive financing options subsidized or guaranteed by the government for both the 12K LNGC and eventually the 174K LNGCs. The latter is more challenging as we do not currently have a large pool of U.S. mariners trained to operate these complex vessels. As noted by the GAO, training U.S. mariners to crew LNG vessels is challenging since few U.S. mariners are hired on foreign LNG Carriers which would be required to gain the necessary working experience (Office, U.S.G.A, 2015). Current government efforts to improve merchant mariner training resources (Ewing, 2021) will not be able to provide hands-on training for LNG vessels. To mitigate this concern, an integral part of Step 2 of the solution is to support over-sized crews including many mariners- in- training on the initial fleet of 12K U.S. LNG Carriers.

Operators will need support to cover the costs of training and additional crew. As such, the government should subsidize training for the crews of the 12K LNGCs. This serves two purposes. In addition to allowing advanced training for the initial LNG Carrier crews, it will offset the cost difference between crewing an LNG Carrier and an LNG ATB. One of the reasons ATBs are favored domestically is that they require lower merchant mariner credentials for their crew and a smaller complement, both of which serve as an impediment to commercial adoption of U.S. LNG Carriers. This targeted government subsidy is necessary to support the initial growth of U.S. LNG Carriers before a critical mass of vessels and mariners is achieved.

In order to maximize the benefit of subsidized crew training, the 12Ks should be designed with additional berthing so they can be used to train the crews of the larger 174K LNGCs. Further, the maritime academies and seafarer unions can be engaged to develop curriculum and place cadets and apprentices on the 12K's to build the domestic merchant mariner pool necessary to crew the 174K LNGCs.

Having successfully designed, gained regulatory approval for, built and crewed the 12K LNGCs, the 174K LNGCs can be designed and built in Step 3 with only construction and commercial risk. Although these larger vessels will likely have to be built by shipyards larger than those that built the 12K vessels, they can leverage the lessons learned building the 12K LNGCs at the smaller yard(s). One way to leverage the experience of the 12K yard(s) would be to subcontract their membrane tank construction teams to the larger yard. Construction of these tanks requires a high degree of skill and experience, as well as collaboration with, and certification by, Gaztransport & Technigaz (GTT), the French company that provides the most common containment technology. Obtaining this certification and experience was a concern raised by key candidate shipyards in 2015 (Office, U.S.G.A, 2015). By continuing to use the same teams, at least to train the larger yard tank construction teams, this risky technological leap can be mitigated and the 12K builder can remain commercially engaged in construction of the 174Ks.

CONCLUSION

The economy, environment, and national security of the United States currently has serious vulnerabilities regarding its energy production and consumption. These vulnerabilities must be strategically addressed to ensure that the United States can project and protect its clean energy, both domestically and with our allies. This paper presents a plan that minimizes the risk to the owner and builder, seeds the creation of a necessary fleet of Jones Act compliant LNG carriers and successfully identifies the issues and support needed from the government to accomplish this plan.

First and foremost, the design and regulatory approval of the small, 12K LNGC needs to be subsidized by the government using a grant or similar vehicle. This is crucial due to the regulatory resistance in the domestic marine industry which makes a commercial funding path for this impossible. To aid in this effort, the authors have already developed a conceptual design for a 12K LNGC as illustrated herein (Fig. 7). This was developed to prove the concept and provide comparisons with LNG ATBs, etc.

Once designed and approved, construction of the 12K LNGCs needs to be supported by the government as well. That said, due to the commercial viability of these vessels, we assume that favorable government debt or similar should likely suffice for the construction. As the intent is to use these small vessels as the training vehicles for our domestic LNGC officers and crew, the cost of the additional manning and training should also be subsidized by the government by a grant or similar vehicle.

Fig. 7, 12K *LNG Carrier Conceptual Design Rendering.*

With 12K LNGCs trading domestically (and potentially internationally, such as in the Caribbean) and crews trained, design and construction of the large 174K LNGCs needs to be supported with grants and favorable government debt similar to the mechanism used for the 12K LNGC construction.

Following this stepwise plan minimizes and mitigates risks so that a fleet of Jones Act LNG Carriers can be successfully designed and built.

Appendix A

ADDITIONAL STRATEGIC ADVANTAGES- COMMERCIAL

Additional commercial strategic advantages of developing a domestic fleet of LNGCs include speed, efficiency and range. The most capable LNG-carrying vessels being built in the U.S. today are small tug-and-barge combinations called Articulated Tug Barges (ATBs). LNGCs are faster than LNG ATBs as they do not suffer from the hydrodynamic penalties of the two-vessel combinations. As an example, preliminary hydrodynamic simulations indicate that the 12K LNGC concept design included herein can run at 17 kts (Fig. A1) using the same power that an equivalent LNG ATB demands at 12 kts (Fig. A2).

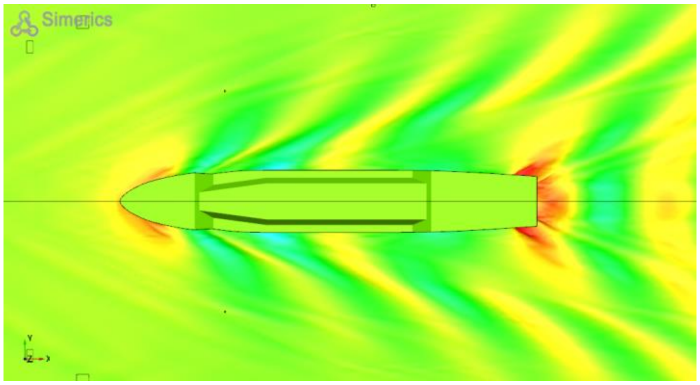

Fig. A1, 12K *LNG Carrier Concept at ~17 knots.*

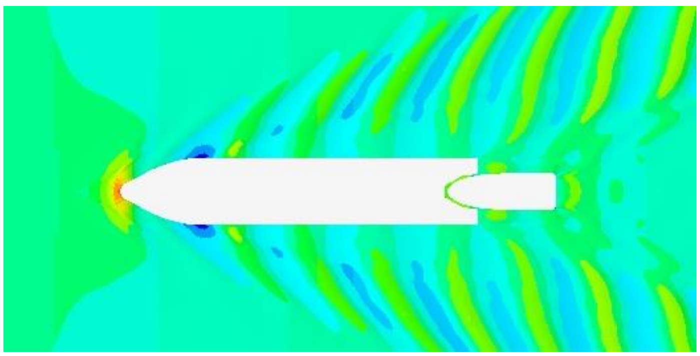
Fig. A2, 12K *LNG-ATB Concept at ~12 knots.*

This higher speed reduces the cost of moving cargo because the LNGC can travel 40% further than the LNG ATB consuming the same amount of fuel over the same amount of time. This efficiency saves costs (financial and environmental) on fuel consumption, and the longer range opens new domestic trading routes such as the U.S. Gulf of Mexico to U.S. Northeast, Puerto Rico, etc.

These additional domestic trading routes are obvious commercial opportunities for a Jones Act vessel owner or operator. However, domestic operators servicing domestic routes could also serve international routes using Jones Act LNGCs creating additional commercial opportunities for owners. In addition to being able to compete globally with large state-of-the-art LNGCs, one can envision trading routes, even for the 12K LNGCs, from the U.S. Gulf Coast to Mexico, Latin America and South American noting that Brazil was one of the largest importers of U.S. LNG in 2021 (U.S. Energy Information Administration, 2023).

Although not commercially attractive in the direct sense as they will cost more to build and crew than an LNG ATB, LNGCs are good candidates for a domestic fleet because LNGCs are the most advanced and high-value commercial cargo vessels in the world. They utilize complex machinery and containment systems and they require highly trained merchant mariners. These attributes serve to reduce the advantage that low-cost Chinese shipyards and foreign operators have over domestic shipyards and operators because the expense of the complex machinery and containment systems are the same for both U.S. and Chinese yards, and all LNGC mariners, both domestic and foreign, are highly trained and thus relatively expensive. The former is important as the expensive machinery and containment systems comprise much of the cost of the vessels thus minimizing the benefit of inexpensive foreign construction. The latter minimizes the benefit of inexpensive foreign crews that are not allowed on domestic Jones Act vessels.

Appendix B

ADDITIONAL STRATEGIC ADVANTAGES- DEFENSE


Fig. B1, *Artist Rendering of Columbia Class Submarine.*

It is well understood that the U.S. Navy's *COLUMBIA* program (Fig. B1) requires increased domestic industrial capacity to successfully complete the design and construction of this fleet of next-generation ballistic missile submarines (O'Rourke, 2024). Domestic outsourcing is becoming an important part of the government's plan to broaden the industrial base for submarine construction. The idea is to move the work to regions where workers are interested in joining the manufacturing industry. However, this expanded industrial base does not include workers with the advanced manufacturing skills needed for submarine component construction.

Developing a fleet of Jones Act LNGCs designed in the U.S. can aid in the development of this industrial capacity because they are technically advanced vessels that require complex design and analysis, state-of-the-art containment systems utilizing advanced manufacturing capabilities, and cryogenic handling systems that are more akin to rockets than ships. Design and construction of LNGCs would serve to stimulate and support the technical and industrial base needed for design and construction of military vessels, including submarines, which is a national priority (Fultz, 2014).

Appendix C

ADDITIONAL ENVIRONMENTAL ADVANTAGES- VESSEL EFFICIENCY

As stated in Appendix A, the conceptual 12K LNGC included in this proposal can run at 17 kts (Fig. C1) using the same power that a typical ATB demands at 12 kts. In naval architecture vernacular, this means that the propulsive efficiency of the LNGC is increased by 40%.

Fig. C1, 12K *LNG Carrier Conceptual Design Rendering.*

However, LNGCs offer additional fuel and emissions savings because they burn boil-off gas from the LNG cargo for propulsion and ship's service power. This not only allows them to easily use LNG as a clean fuel, but simultaneously solves one of the biggest challenges with transporting LNG, which is that boil-off from the cryogenic cargo builds up dangerous pressure in the tanks if not managed. ATBs by contrast must burn a separate fuel (almost always diesel oil) not only for propulsion and ship's service power, but **also** to power major equipment on the barge to reliquefy the boil-off gas. Thus, an LNGC produces far fewer emissions than an equivalent ATB because it burns LNG instead of diesel, and it can burn much less fuel on the same route due to propulsive efficiency and eliminating cargo reliquefaction.

ADDITIONAL ENVIRONMENTAL ADVANTAGES- LONG-TERM FLEXIBILITY AND E-FUELS

As renewable energy development and efforts to replace coal and oil-fired power plants continue around the world, regional demand for natural gas will be variable and difficult to predict long-term. A region currently served primarily by coal may want to switch to natural gas in the near-term while also pursuing renewable energy for the long-term. The hurdles to installing a new long-distance natural gas pipeline to such an area are often extreme and will only be made more challenging if the region cannot guarantee continuous gas demand for a typical 20-year contract. This dilemma could easily delay the region's emissions reduction efforts, but LNG Carriers offer a solution.

Jones Act LNG Carriers specifically able to serve domestic regions with domestic natural gas, provide an alternative to new long-distance pipelines, especially in North America. LNGCs can supply new demand in remote regions as it appears, and if fossil fuel demand in the region drops, the vessels can switch to serving other regions without losing the sunk costs of a pipeline no longer needed.

The flexibility of LNG Carriers pays additional dividends in light of the emerging industry of "electrofuels" (e-fuels). The term describes a new class of net-zero-emission synthetic versions of conventional fuels like natural gas. For example, methane (CH_4), the primary component of natural gas, can be synthesized as e-methane using carbon (C) captured from industrial plants combined with hydrogen (H) produced sustainably from seawater and offshore wind power. The major advantage of e-fuels over pure Hydrogen or other alternative fuels is that they are functionally the same as the fossil fuels they replace, meaning end-users can theoretically achieve net-zero emissions without needing to buy new equipment or significantly alter their operation.

LNG Carriers can transport liquid e-methane by design, and the technology to transport liquid hydrogen is fundamentally similar. As evidence, the membrane tank technology company, GTT, has announced approval-in-principal for a hydrogen-ready version of their tank technology (GTT reaches an important milestone…, 2022). The capability to produce LNG Carriers domestically would grant the U.S. access to the hydrogen and e-fuel transport markets as well, which are poised to expand significantly in the medium-term future. In contrast to pipelines, LNG Carriers and similar vessels offer the flexibility to meet emerging energy markets where they are, whenever demand is highest, and with the fuel or e-fuel of their choice.

The U.S. Gulf Coast region is particularly well-situated to enter the e-fuel industry, as there are already extensive plans for carbon capture and a network of pipelines for transporting CO_2 captured from industrial sources (Kortsha, 2021). E-fuel production creates a potential market to buy captured CO_2 and green hydrogen, and readily-available captured CO_2 would help mitigate the cost to produce e-fuels. There is potential for the U.S. Gulf Coast to become a key player in carbon capture and e-fuel production, and Jones Act LNG Carriers would enable projection of this domestic product around the country and the globe.

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A Concept For a Pallet-Size Intermodal Container

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The development of an intermodal container specifically designed for regional trade and urban delivery is an apparent need as coastal sail freight and urban cargo bike delivery begin to displace trucking during the energy transition. This paper suggests the regional and urban container of the future should be based on the Euro Pallet standard, and designed specifically around the constraints of sail freight vessels and cargo bikes to minimize cross-loading labor and time in urban and last-mile delivery of all types.

KEY WORDS
Containerization, Cargo Bike, Unit Loading, Urban Logistics, Sail Freight

INTRODUCTION

The time saving and safety benefits of intermodal containerization have yet to be effectively applied to cargo bike and sail freight deliveries, which still rely on either Roll-On/Roll-Off (RORO) delivery, or many laborious break bulk points in the distribution chain. A set of pallet-sized containers designed for cargo bike, short sea shipping, and truck interoperability will encourage the use of delivery bikes in urban distribution by removing significant amounts of redundant labor, and decreasing chances for injury or damage in last mile delivery.

While ISO Containers of 20 and 40 feet are international standards designed for intermodal use, their modes (ship, rail, and truck) are near-universally fossil fueled, and not designed for last-mile urban delivery or regional distribution work. The proposed containers in this paper are similarly intermodal, but based on a different trinity for a different environment: Windship, Light Truck (Light Electric Vehicle /LEV), and Bike. This changes the necessary constraints and design parameters significantly, especially when electric, wind, and human propulsion are the general rule for the vehicles involved, and short-range delivery of smaller loads to distributed locations is the objective.

Lift-On/Lift-Off (LOLO) capabilities allow a vessel to carry a significantly increased volume of cargo for a given tonnage when compared to a RORO vessel carrying previously loaded cargo bikes. Further, a LOLO arrangement allows for a more intensive use of available bike assets and reduces the overall labor and time required to complete a delivery. With the use of unitized containers there is also a degree of informal, temporary warehousing which can take place at the dockside, allowing slightly asynchronous operations between bike and boat in a hypothetical cross-harbor cargo operation. All of these are major efficiency assets currently unavailable in a micro-cargo context, but enjoyed at conventional scales of multimodal transportation.

The main use case for these containers is in regional trade and urban last-mile delivery, principally for pre-packing parcels for postal delivery routes, light weight retail goods delivery, farm-to-town deliveries, and similar applications. These will normally be carrying relatively light loads of bulky items, and thus they do not need to be as heavily built as the current generation of containers and pallets. The main purpose for these systems is to integrate into the current pallet-based infrastructure, while allowing unit-loading with lift-on/lift-off capabilities similar to ISO shipping containers, but for delivery bikes. Heavy unit loads will continue to move on conventional pallets in this new model, but significant time savings and safety improvements, as well as reduced plastic waste and greenhouse gas emissions, can be realized by adopting this intermediate container system in local logistics networks.

This is not a novel idea; the author first saw it suggested in Tim Boykett's work on sail freight along the Danube. This physical/experiential futures sail freight operation to deliver Community Supported Agriculture (CSA) shares to Lindz, Austria down the Danube failed mostly due to the lack of a cold chain and the effects of the COVID-19 pandemic. The suggested solution was a lift-on/lift-off insulated box capable of carrying a large number of CSA boxes and a block of ice or other cold source, which could then be lifted onto a cargo trike for last mile delivery: "One of the planned improvements in the logistics chain for the bike deliveries is to pre-pack groups of Biokisten stacks in an insulated box that is then transported by truck to the holding space, and from there is mounted straight onto the cargo trike. Each of these minicontainers would have the correct internal dimensions for the stacks, plus cooling, and would be attached to the trike for one delivery round. Using butterfly latches, these could be held solidly in place and then easily removed, lessening the transshipment issue… as it was summer, there was a necessity to have a documented… cold-chain, from warehouse to the customer's doorway" (Boykett, 2022). While the use of butterfly latches was suggested in the work of Time's Up, miniaturized ISO container twist locks are favored here for their familiarity and simplicity.

There is little to prevent a new standard from being adopted for last mile and regional intermodal transport, provided the standard works within the constraints of existing freight handling systems. A completely new standard is unlikely to catch on, as it will be capital intensive to adopt; a complimentary standard can be adopted immediately with significantly smaller capital investment, and will require a shorter time for widespread adoption. Further, basing this new standard on already-proven and well understood systems makes adoption more likely, as few major systems or procedure changes need to happen within working crews. This pallet container system could also encourage the adoption of new, more efficient delivery vehicle standards, such as a 5 foot (153 cm) width vehicle, better suited to urban delivery than the 8 foot standard used in the US (van Hemmen, 2016).

Transshipment in a breakbulk system is both labor and time intensive, and a point where errors can be made. This was a problem which was faced as a significant hurdle by Time's Up. "The transshipment is the most problematic part of the process. It takes time, effort and concentration. As the stacks leave the van to the holding space and are then re-stacked in the cargo trike container, mis-ordering can easily occur" (Boykett, 2022). This is one of the main reasons for currently favoring RORO systems in cross-harbor project designs using cargo bikes and trailers, despite the penalty in payload capacity per vessel and consequently higher capital intensity of the business both afloat and on land for the same freight movement capacity. When dealing with sequentially packed systems for door-to-door delivery, mis-sequencing can be a major problem, which can be avoided through either avoiding cross-loading (through RORO systems) or by packing a container only once (LOLO systems). So long as this container allows for higher intensity of use with the same number of transportation assets, and cost less per container than a cargo bike or trailer, it will be economically preferable to RORO systems.

PALLET-SIZE INTERMODAL CONTAINERS

Designing small vessels around this type of mid-size box instead of breakbulk containers or ISO Containers should be relatively simple, as small general cargo vessels have already been built around using conventional pallets. "In order to deliver the approximately 300 Biokisten that would be the daily deliveries to Linz, a speculative small boat using the minicontainer system described above would not need to be significantly longer or larger [than the experimental 5.4 meter sailboat]" (Boykett, 2022). As any vessel designed to work with these containers is also adapted to conventional pallets, the exact type of unitization becomes less important onboard, and the vessel remains highly flexible in its possible loading arrangements, and ships gear need not be changed between cargo types.

This new standard must work within several constraints, most importantly the weight and footprint capacities of commercially available cargo bikes. Most popular cargo bike systems are designed to work with the Euro Pallet sizes, mostly the EUR1 and EUR6 sizes, of 80x120 and 80x60 cm respectively. These pallets differ significantly from US standards, most commonly about 100x120 cm and 120x120 cm, but are generally compatible on the 120 cm face of the pallet. Figure 1 below shows the specifications for the basic EUR1 size Euro Pallet.

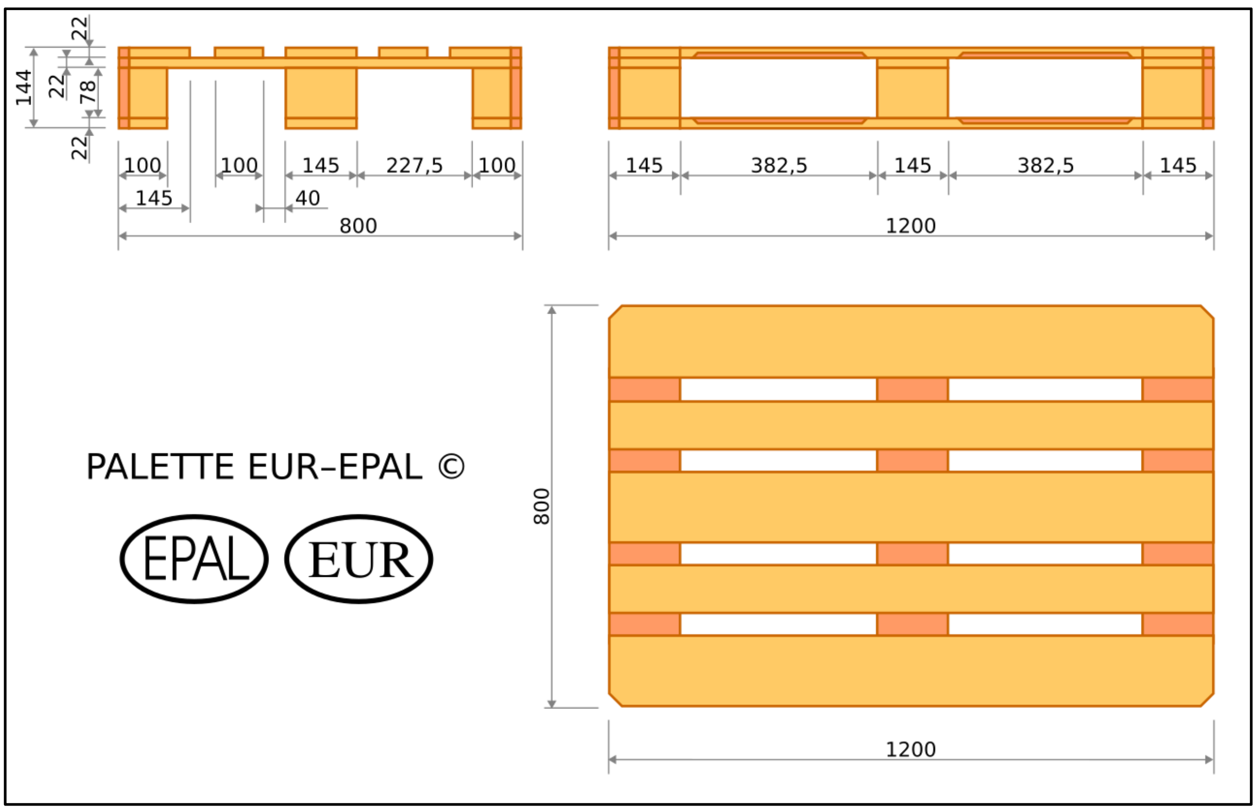

Figure 1. EUR1 pallet technical specifications. WhiteTimberwolf, 2010. CC BY-SA 3.0, via Wikimedia Commons.

As these containers are designed to work with Cargo Bikes and their associated systems, light weight construction is critical. Most cargo bikes have a maximum capacity of 200-220 kgs, which will be the maximum gross weight allowance (Fleximodal, n.d.; Carla Cargo, n.d.). Compatibility with conventional pallet jacks and forklifts is required, as well as the ability to stack three units high. Door patterns and hardware have not been determined, and will likely depend on the container's intended use. The default is a dry bulk container for parcel and retail deliveries, and should have doors on one wide face at a minimum. All 8 corners on these containers will have miniaturized ISO container corner casting-like twistlock fixtures for lifting, stacking, and handling of cargo boxes. The use of hollow corners with multiple openings also allows other methods to be used in securing these pallets to bike systems, such as conventional strap and hook arrangements, or rope ties. The frames and stacking abilities also allow for relatively easy vertical storage without the need for a pre-existing rack system.

Each unit should not weigh more than 20 kg if at all possible (10% of max gross weight). If necessary, absolute maximum container weight should be capped at 40 Kg (20% GWT). The significant reduction in carrying capacity and stacking heights compared to conventional pallets should make this possible through relatively small scantlings on all sizes of container.

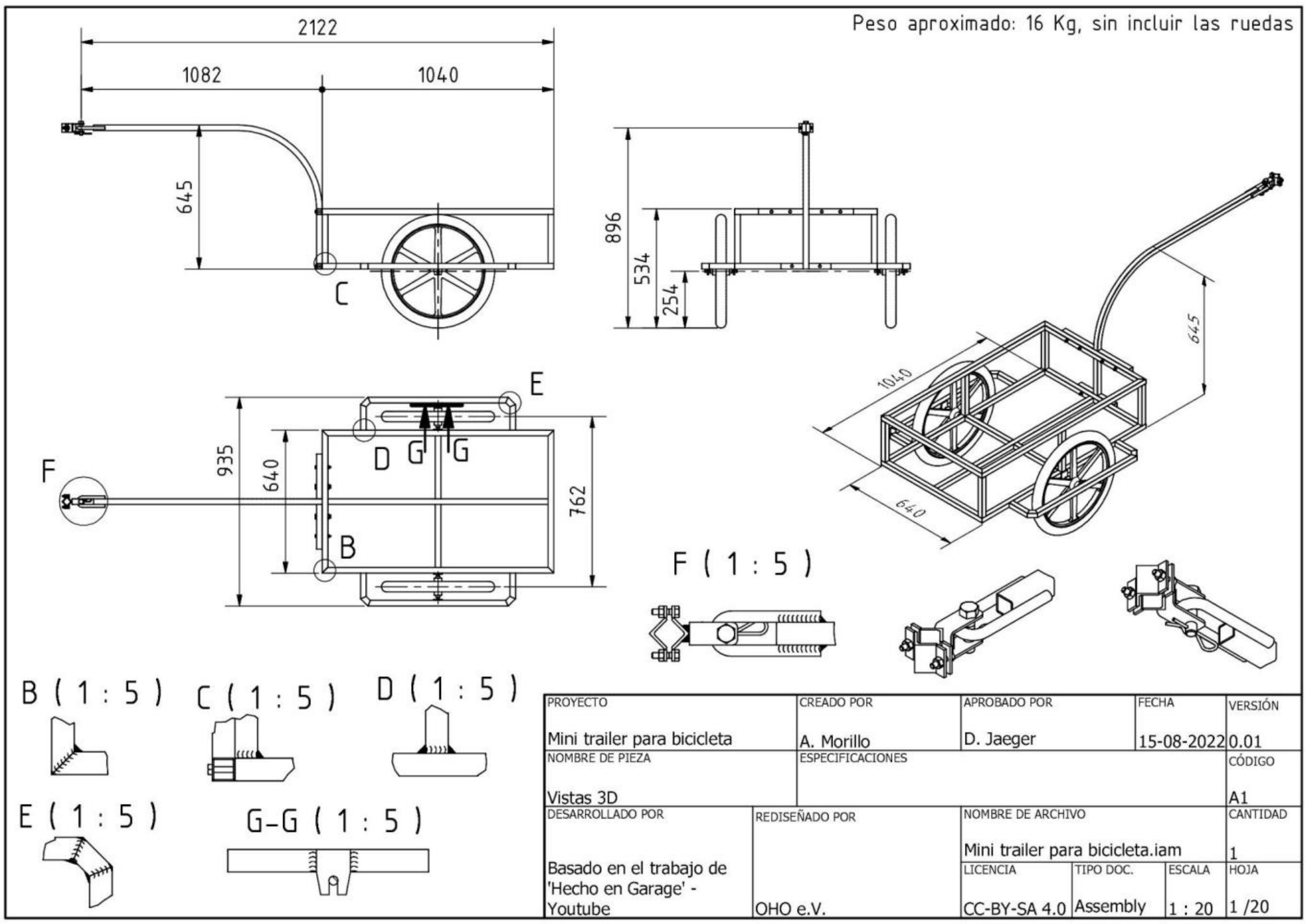

Figure 2. Compact Bicycle Trailer design from Open Hardware Observatory. Deck dimensions fit EUR6 Standard. Schematic by D Jaeger, 2022. CC-BY-SA 4.0. https://en.oho.wiki/wiki/Compact_trailer_for_bicycle

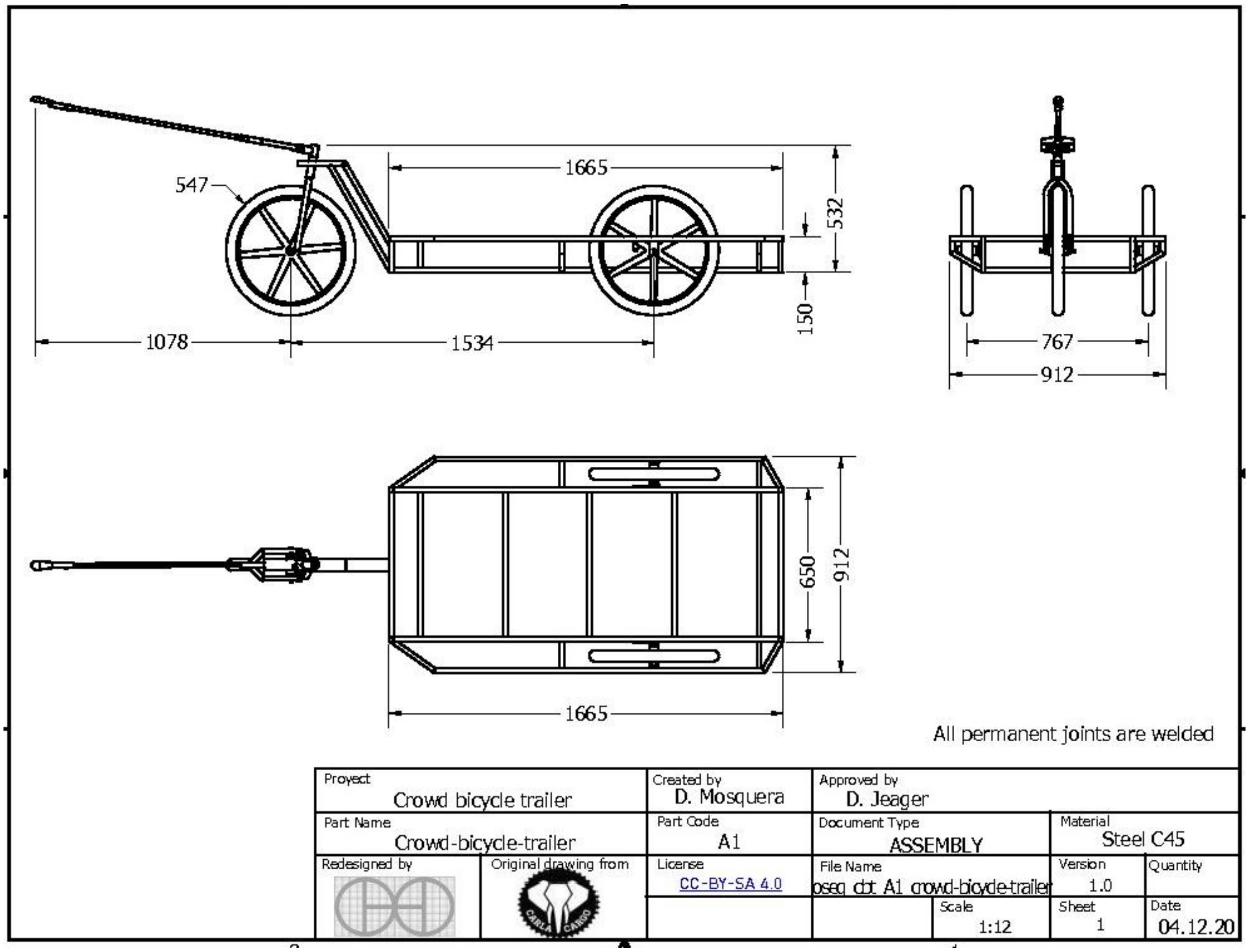

Figure 3. Technical drawing of Crowd Cargo trailer, based on the Cargo Carla model, showing design is ideal for use with two EUR6 pallets. D. Mosquera, 2020. CC-BY-SA 4.0. https://en.oho.wiki/wiki/Carla_Cargo_Crowd

It is likely possible to keep the weight of the container within these ranges, with the task becoming simpler for the smaller footprints. "Aluminum pallet base would be 9kg… 4mm plywood for the outside would weigh about 11kg for 6.1 m2. … Even 1mm aluminum has 2.7 kg/m2, while 4mm plywood has 1.8kg/m2. With metal fittings for corners and hinges, we might be able to keep to 25kg" (Personal correspondence with Boykett, 2024). Building in aluminum with corrugated sides to increase strength may allow relatively thin material to be used for dry box containers (Personal correspondence with Cottrell, 2024). Further engineering is needed to confirm the weight of each container setup.

As aforementioned, cargo bikes can generally carry around 200kgs, and are based around the Euro Pallet size standards of 80x120 cm (EUR1) and 60x80 cm (EUR6). The use of US standard pallets at or about 100x120 (EUR2/3) or 120x120 cm is also possible, as existing equipment is already designed to accommodate it. The gauge for height over these footprints should be set at 120 and 60 cm, to maintain stability and human scale containers. About 15 cm will be lost to the pallet base for both these heights, leaving boxes of 45 and 105 cm respectively.

Table 1 gives dimensions, volumes, and example cargoes for each type of dry box container when full at maximum weight.

As the containers grow, it is clear the types of cargo which will put them in a full and down condition become more restricted. Therefore, it is likely most efficient at smaller sizes, with the EUR1 and EUR6 sizes being most useful for most cargos. Using these containers with a more dense cargo than designed for can significantly increase broken stowage (wasted space) in a ship's hold or truck body, and should be discouraged in favor of a traditional pallet load if the cargo is considerably more dense to maximize system efficiency and the ability to stack pallets. For delivery to retail outlets, these containers will likely be packed with a variety of different materials of different stowage factors, which should even out to within the limit for that container size.

A suite of specific tools will be necessary for this container system in addition to those used with conventional pallets, none of which need to be expensive or complex. Two of the simplest would be an ultralight pallet jack, designed to be lighter and more portable than a conventional model, and only handle up to the 200 kgs of a loaded container. Some containers may need to have casters added to them for use when pallet jacks are not available, but this ultralight design is specifically suited to avoiding this problem (Personal correspondence with Zuman, 2024). For those handling mostly EUR6 size containers, a simple hand-truck with appropriately spaced 60 cm forks may be highly useful, especially if it is capable of handling a stack of three EUR6 Short containers.

Table 1. Dry Box Container Sizes & Load Information

Size	Height	Volume	Max SF	Example Cargo	Notes
60x80	60	216	1.23	Marmalade, Cases	EUR6 Short
60x80	120	504	2.88	Walnuts, Bagged	EUR6 Tall
80x120	60	432	2.47	Mushrooms, Dried	EUR1 Short
80x120	120	1,008	5.76	Pasta, Cases	EUR1 Tall
100x120	60	540	3.09	Tea, 60 Lb Cases	EUR2 Short
100x120	120	1,260	7.20	Cotton Shirts	EUR2 Tall
120x120	60	648	3.70	Hops, Bagged	
120x120	120	1,512	8.64	Facial Tissue, Cases	

All measurements in centimeters. Volume in liters. Stowage Factor (SF) given in cubic meters per tonne. Container weight is assumed to be 25 kg for all sizes, payload of 175 kg.

The two unique tools needed for this system are lifting handles and a crane lifting apparatus. Lifting handles, taking the form of a simple bar about 175 cm long can have the miniaturized ISO container twist locks on sliding collars which can be fixed at 60, 80, 100, and 120 cm using detents or set screws. Using two of these bars will allow up to a 4 person lift for a container, more if the bar is lengthened. Fixed width bars with immobile twist locks could also be used, but will be less versatile than adjustable lifting bars. Other possible configurations for this tool exist and should not be ruled out.

The crane lifting apparatus may present a challenge if it must fit all sizes of pallet container. The simplest solution would likely be a set of fixed toggles fitting into the corner pieces, with a ring securing it to a length of chain, and a stop engineered for when the toggle is facing parallel to the side of the container. With four of this apparatus linked into a common central ring, and the chain attachment sitting on the inside corner of the lifting toggle, the lifting action of the crane will pull the four corner locks into battery before lifting the load, and not release them until all tension is off the rig. Solid frames with appropriately positioned twist locks may also be developed and used, but these will be limited to single container sizes in many cases. This may present problems and delays for many operations while tools are swapped between lifts, and should be avoided if possible. Latching systems, spacers, side lift equipment, and other tools can simply be miniaturized from conventional ISO container tools.

Several types of container should be developed for this system, including dry boxes, reefers, tanks, and others. Dry Box containers are the default arrangement, allowing for the pre-packing of parcels, high stowage factor goods, and so on. These will likely be used in postal type deliveries, as well as mixed grocery and general goods delivery where cold chains need not be maintained. Door arrangements will have to be designed to allow access from multiple sides in some cases, likely leading to variant dry box containers for specific uses (Personal correspondence with Zuman, 2024). Other dry cargo variants could be adapted to compost collection, grains or aggregate transport, etc. Both 120 cm and 60 cm tall variants should be developed for all of these classes of specialist container.

Reefers will be necessary for cold shipment of produce, dairy, and other cold-chain goods including CSA shares from regional farms to urban centers. With a variety of possible arrangements for cooling and stacking, including a built-in refrigerator unit, there are a number of options which can be customized for specific requirements with different routes and cargoes. As was found with the Time's Up project on the Danube, maintaining the cold chain is one of the largest challenges for the zero-carbon delivery of regional produce via bike and boat (Boykett, 2022). Figure 3 shows several possible loading configurations with this type of reefer, using a cold source such as natural ice produced on-farm over the winter in cold climates as a central cooling tower. Such reefers should have a closable drain installed if natural ice or other such melting cold sources are used to allow for meltwater evacuation to prevent saturation of the payload.

A tank container based on a EUR6 short size standard should be capable of holding around 150 liters, including a take-off valve, etc. Assuming water is carried at 1 kg/l this would give a payload of 150 kg, allowing an empty container weight of up to 50 kg. This high container weight allows for internal baffles to reduce free surface effect in partially loaded conditions, and plumbing in valves, drains, and the addition of protective framing. Similar arrangements could be made for compressed gas bottles and related equipment; vacuum-insulated bottles could be used for the transport of dairy and other cold liquids.

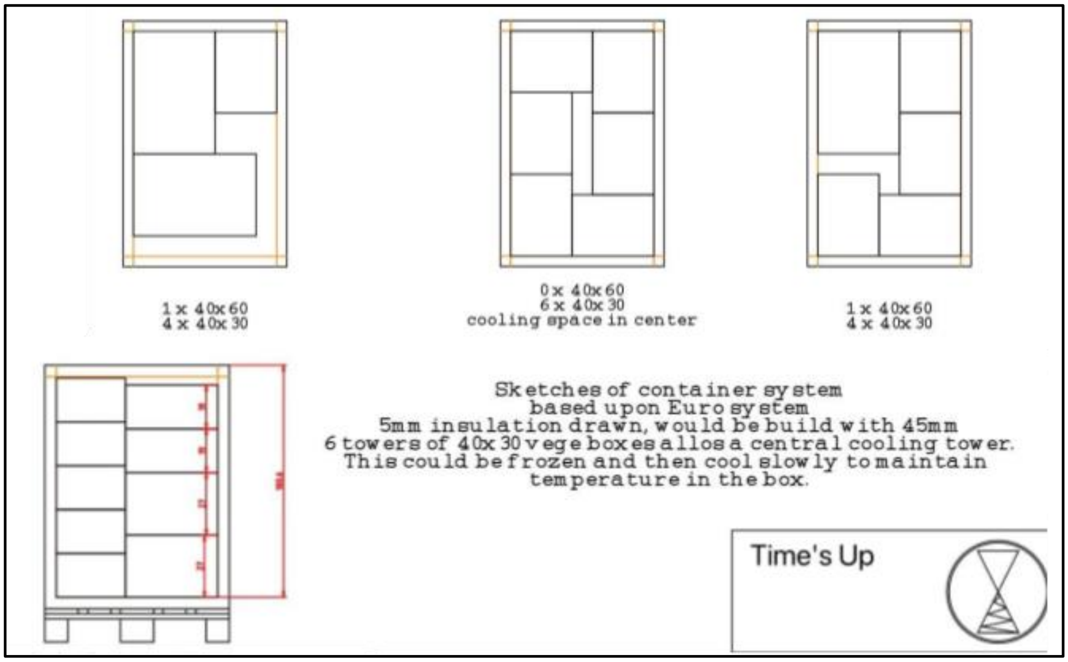

Figure 4. Packing diagram of potential reefer container with central cooling block. Illustration by Tim Boykett.

Specialized toolsets are also possible using this format of lift-on/lift-off container, making them easier to deploy on short notice, in austere environments, or simply making these facilities mobile. For example, using a modular approach, a field kitchen could be setup from 1-4 pallets, with gray water tanks, stoves, counters, sinks, and other tools and machinery incorporated into the pallet structure. Simply remove the outer covers, hook up supporting water tank containers, solar power & battery modules, a biogas bottle container, and get to cooking. Similar systems for power generation, small cranes (stiff leg derricks), welding and fabrication, decontamination stations, hazmat response kits, bike repair stations, field offices, first aid stations, lighting, pumps (manual or electric), wood shops, telecommunications, sanitary stations, and more could be designed and fabricated within this basic standard. Provided they are kept under 200 kg total weight, they will all be deliverable by cargo bike, pickup truck, LEV, pallet barge, sail freighter, or via conventional motor truck. This makes them ideal for deployment at social events, public works projects, and humanitarian or emergency response applications worldwide.

CONCLUSIONS

In light of bike-based disaster response trials, emergency response is especially interesting as a subset use of this container system. While an ISO container is effectively immobile in the face of congested or damaged streets, fuel shortages, or the absence of a number of large pieces of equipment, these containers could be pre-packed with a number of kits, and handled entirely by the “Armstrong Method” if necessary. They can be stored indefinitely after packing, deployed easily, and customized to the situation at hand. This type of system has significant potential for reducing the carbon intensity of emergency response and civil defense efforts as natural disasters intensify and increase in frequency due to climate change (Fitch-Polse, et al., 2024). Similarly, a small port’s worth of equipment could be deployed in a day using these systems, turning a leisure marina or disused piece of bulkhead into a functioning temporary port with little capital investment or time. Similar equipment can then be deployed at forward depots or staging points for the supplies offloaded at the temporary port. However, these systems will need to be developed after the basic suite of cargo containers and tools are in widespread service.

The final consideration for adopting this standard is the need for capital to produce these containers and the toolsets to handle them. As the detailed engineering drawings have not yet been made, a cost per container or tool cannot be reliably given, but the outlay for a container with a 25 year service life should not exceed the cost of conventional pallets, and will yield significant savings while in transit. At a systems scale, this regional-level container can be a tool for reducing overall labor requirements and safety risks associated with traditional breakbulk loading methods, while maintaining compatibility with the vast majority of existing warehouse and cargo handling equipment. For cross-harbor and regional boat and bike systems, such as those encouraged by New York City's Economic Development Corporation, these containers are a very useful tool (Office of the Mayor of New York, 2023).

This system is being developed for release as Open Source Hardware through the Center for Post Carbon Logistics. EUR1 and EUR6 sizes should be the prioritized sizes for initial implementation, with EUR2 and US sizes following on afterwards. Both will be reasonably compatible with US Pallet standards and handling equipment, while encouraging adoption worldwide. Anyone interested in supporting the development of this container system should contact the Center for Post Carbon Logistics for more information.

CONFLICTS OF INTEREST

This work was unfunded and the author declares no conflict of interest.

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Wing-in-Ground Craft, A Modern Perspective

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Alternative methods of transportation for freight and passengers are necessary to meet the growing demand for supply chain services. Wing in Ground effect craft is one method in which this may be accomplished. Renewed research into this field shows promising results for high-speed, energy-efficient, economical transport. This paper will briefly review the history of WIGs, discuss the basic principles of operation, and end with a discussion of current industry work focusing on the potential application of the Wing-in-Ground Craft.

KEY WORDS
Wing-in-ground, energy efficiency, high-speed craft

BACKGROUND

What is a WIG

Wing in Ground craft, Ground effect Vehicles, Ekranoplans are all terms used through the years to identify these vessels. The Caspian Sea Monster is the nickname given to the Soviet WIG craft built during the Cold War that captured the imagination of military minds. Whatever name is used, the basic principle remains the same, a craft using the ground effect to achieve lift and fly over a surface.

The US Code defines a WIG craft as "a vessel capable of operating completely above the surface of the water on an air cushion created by aerodynamic lift caused by the ground effect between the vessel and the water's surface" (Coast Guard, 2022). WIG craft that can carry passengers for hire falls under US Coast Guard jurisdiction when operating within US waters.

As defined by the Merchant Shipping Regulations 2010 of Singapore a Wing in Ground craft is "a multimodal craft which, in its main operational mode, flies by using ground effect above water or some other surface, without constant contact with the surface, and is supported in the air mainly by an aerodynamic lift generate on its wing or wings or its hull, or their parts, which are designed to utilize the ground effect action" (Singapore Statues online, 2010).

Brief History of the WIG

Wing-in-Ground craft can draw their origins to Orville and Wilbur Wright. These pioneering aviators discovered a cushioning effect during landing. It wasn't until Kaairo designed the "Aerosledge No. 8" that a purpose-built WIG was designed. Governments including the USA and Russia became interested in the concept of Ground Effect Vehicles, but it wasn't until the 1960s in the USSR that any application began. At this point, the Soviets further experimentation and development until developing several craft in the 1970s. The projects themselves did not gain much traction within the military application that they were designed for and ultimately the project was laid to rest in the 1980s. (Halloran, M. & O'Meara, S., 1999) (Rozhdestvensky, K., 2006).

Brief Technical Overview

Wing in Ground craft operates on the principle of ground effect. In essence, the ground effect generates a rise in the lift-over-drag ratio when a three-dimensional wing approaches a flat plane either over land or water or land. These crafts rely upon extended flat surface areas to maintain the ground effect (Pua'at et al., 2019).

Lift is defined as A component of the total aerodynamic force on an airfoil and acts perpendicular to the relative wind (FAA, 2023). Drag on the other hand is the aerodynamic force parallel to the relative wind (FAA, 2023). Therefore, the lift-drag ratio is the amount of lift generated by the wing or airfoil relative to the total drag on a craft (FAA, 2023).

In a WIG craft, this effect is accomplished as part of the design. This is accomplished through an alteration in the form of the air movement around the wing, also known as downwash. By altering the direction of the downwash, an increase in lift and a decrease in drag (Halloran, M. and O'Meara, S. 1999). The alteration in the downwash is accomplished in part by design, and in part by creating a boundary under the wing to change the airflow. For a WIG craft, this boundary is the water (Tofa, M. et al., 2013).

MODERN PERSPECTIVES

Potential Commercial/Military Applications

As previously discussed, the Soviets were the first to employ WIG craft for military service. Currently the Iranians lay claim to having a squadron of WIG craft, designated Bavar-2 for reconnaissance and scouting operations (Roblin, S., 2021). The U.S. Defense Advanced Research Projects Agency (DARPA) released a request for information in August 2021 seeking concept information for a WIG effect craft designed for payloads of 100 plus tons and capable of carrying amphibious vehicles (Ong, P., 2021). Gdansk Technical University in Poland is currently working on a design for an unmanned ground-effect vessel for military applications to meet the growing military needs of Poland in the Baltic Sea (Gdansk Tech, 2024). The potential for WIG craft for military needs is becoming more evident as this technology can also be coupled with autonomous controls. Mission types include but are not limited to deploying sensors, deliver cargo/personnel into contested areas at a speed like a plane, with the capacity of a small ship under radar over sensors (McCann, L., 2023).

The potential for these craft types is endless. Researchers have proposed utilizing Ground Effect Vehicles for intercity transportation in Mongolia (Kubo, S., Akimoto, H., & Gombodorj, B., 2004). The reasoning is that a WIG craft flies lower to the surface, not requiring pressurized cabins or the involved infrastructure that airplanes require. Certain land areas, such as Mongolia, have large flat land areas and can fly close to the surface without impediment, making the region an ideal candidate for WIG transportation.

Larger WIG craft, such as the “Caspian Sea Monster” have been proposed as rescue craft. Stationing WIG craft in strategic global bases researchers (Aframeev, E.A. & Yoshida, Y., 2013) theorize that these craft could provide global assistance to persons and vessels in distress in a timelier manner than traditional at sea rescue plans.

Recognizing the potential of WIG craft UrbanLink Air Mobility of South Florida has placed an order of 27 REGENT Viceroy Seagliders to operate between Miami and San Juan to begin operation in 2027 (REGENT, 2024). Turkey’s Eurasia Mobility Solutions has ordered 10 Airfish 8 to be used in tourist and private travel solutions (Chuanren, C., 2024).

Training and Certification

Both the REGENT Viceroy and the Airfish 8 are designed for 2 crewmembers. The International Maritime Organization has proposed training for Masters and Crew on board a WIG craft under a number of documents including the High Speed Craft Code, IMO MSC Circ.1162 and IMO MSC.1/Circ 1592. Crew on board will also need to be trained under national standards. For the United States one would begin by reviewing NVIC 20-14. NVIC 20-14 is designed for crew members on board High Speed Craft.

These craft can be considered High Speed Craft under the code as defined as “ craft capable of maximum speed, in metres per second (m/s), equal to or exceeding $3.7*\nabla^{0.1667}$ where: ∇= volume of displacement corresponding to the design waterline (m^3) excluding craft the hull of which is supported completely clear above the water surface in non- displacement mode by aerodynamic forces generated by ground effect.”

Crew members will be required to meet national requirements if remaining on domestic waters, but will have to apply IMO credentialing requirements on international voyages.

Current Design

There are currently several manufacturers in the design process or who have already built operational Wing-in-ground craft. REGENT Craft out of Rhode Island, the Flying Ship Company out of Virginia, Aron Flying Ship Ltd. of South Korea, and Wigetworks out of Singapore. REGENT Craft advertises the carriage of passengers or payload, while Wigetworks is currently advertising the movement of passengers. The Flying ship company out of Virginia has craft that are unmanned, designed for surveillance and possible movement of cargo.

Financial Analysis

Is this mode of transportation economically feasible? It is safe to assume that passengers choosing transportation via WIG will be willing to pay within the same range that they would for a flight or a ferry ride to their final destination. Therefore, the price must be comparable to competing modes of transportation (Taylor, G., 2000). Eurasia Mobility Solutions, seeing a potential market in the Mediterranean ordered 10 Airfish, built by STX Engineering (partner of Wigetworks) to transport tourists (The Economist, 2024). Although the price of the craft is not disclosed on their website, the company does price the Airfish 8 as costing “significantly more” than $500,000 (Wigetworks, 2023). The Airfish 8 holds 8 passengers and two crew. A Cessna Caravan, which holds 10-14 passengers has an approximate price of $400,000.

The Cessna Caravan has a range of around 1,070 nm, while the REGENT Viceroy has a range of 160nm, and the STX Engineering Airfish 8 a range of 300 nm. The REGENT Viceroy can handle the most passengers (12) while the others carry up to 6 passengers. The Cessna Caravan was chosen for comparison due to the passenger carriage limitations being similar to our WIG vessels as well as the ability to act as a sea plane.

Looking at these numbers we can judge that a WIG will be priced accordingly. Logically, transportation on board a WIG craft will be closer to that of a short flight than a fast ferry. If we were to look at a ferry ride from Newcastle UK, to Amsterdam however, we would see that this is around 516nm journey that normally takes 16 hours. A ground-effect vehicle could accomplish this in 3 hours. Granted that the ferry is a RO/RO passenger ferry, but for those who want to get across quick, this would be an excellent alternative to the 280€ one way ferry trip. The REGENT Viceroy would even be able to save a passenger money by not having to pay the emissions tax since the craft is all-electric.

Figure 1. Concept art of the REGENT Viceroy

CONCLUSION

There is much more that can be said about Wing-in-Ground effect craft from an expanded history to design aspects of the airfoils. Variation in design is significant in the variety of applications that these craft can be used for. Both governmental and private organizations are expressing an interest in utilizing WIG craft for passenger and cargo transport. There will be a period of market adjustment as pricing is properly determined, but there is bright outlook for the success of these crafts.

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DISCLOSURE

The views expressed in this paper are those alone of the author. No views or opinions expressed herein represent the views of the U.S. Government, the U.S. Maritime Administration, or the U.S. Merchant Marine Academy. The author fully acknowledges as to having a working relationship with REGENT craft as an independent consultant from time to time, however the materials used for research in this paper are publicly available documents and no financial renumeration was provided for the authorship of this paper.

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