

## MECHANICAL ENGINEERING | REVIEW ARTICLE

# Considerations regarding the use of rigid sails on modern powered ships

Gregory Atkinson, Hung Nguyen and Jonathan Binns

*Cogent Engineering* (2018), 5: 1543564



Received: 13 September 2018  
Accepted: 30 October 2018  
First Published: 03 November 2018

\*Corresponding author: Gregory Atkinson, Eco Marine Power, Japan  
E-mail: [greg.atkinson@ecomarine-power.com](mailto:greg.atkinson@ecomarine-power.com)

Reviewing editor:  
Duc Pham, School of Mechanical Engineering, University of Birmingham, UK

Additional information is available at the end of the article

## MECHANICAL ENGINEERING | REVIEW ARTICLE

# Considerations regarding the use of rigid sails on modern powered ships

Gregory Atkinson<sup>1\*</sup>, Hung Nguyen<sup>2</sup> and Jonathan Binns<sup>2</sup>

**Abstract:** The global shipping fleet is vital to world trade with billions of tonnes of cargo being transported annually by merchant vessels. This activity however results in large volumes of carbon emissions and airborne particulate matter being released into the atmosphere due to the burning of fossil fuels for propulsion and on-board power. Recently, there has been an increasing focus on the need to reduce fossil fuel consumption and airborne emissions across the shipping sector. To facilitate this, a range of technologies have been developed or are currently in the development phase. Rigid sails are one of these technologies, yet despite these being installed on a number of ships in the 1980s they have to date been unable to gain widespread acceptance. This paper will briefly discuss the history of sails on ships and then review a broad range of issues regarding their use encompassing previous research studies, journal articles and operational experiences.

**Subjects:** Ship Operations; Ship Building Technology & Engineering; Sustainable Transport Engineering; Clean Technologies; Novel Technologies; Renewable Energy

## ABOUT THE AUTHORS

Gregory Atkinson is the Chief Technology Officer at Eco Marine Power (EMP). He is a Fellow of the Institute of Marine Engineering, Science and Technology (FIMarEST), a Fellow of the Royal Institution of Naval Architects (FRINA) and currently a part-time student at the Australian Maritime College, University of Tasmania.

Jonathan Binns is an associate professor and is the Associate Dean Research, Australian Maritime College, Director, ARC Research Training Centre for Naval Design and Manufacturing and Principle Senior Research Fellow, Australian Maritime College, University Of Tasmania. His primary expertise is in a variety of model and full scale experiments, as well as potential flow and finite volume flow predictions.

Hung Nguyen is a lecturer and Graduate Research Coordinator at National Centre for Maritime Engineering and Hydrodynamics, Australian Maritime College, University of Tasmania. He obtained his PhD in marine control engineering and MSc degrees in marine transport systems from Tokyo University of Marine Science and Technology, Japan, and BE degree from the Vietnam Maritime University, Vietnam.

## PUBLIC INTEREST STATEMENT

The use of rigid sails on powered ships has the potential to reduce fuel consumption and CO<sub>2</sub>, NO<sub>x</sub> SO<sub>x</sub> emissions from a wide range of ocean going ships. Despite this they are currently not in widespread use even though trials during the 1980s confirmed their effectiveness in lowering fuel consumption. This study briefly reviews the use of sails on powered ships and identifies a range of key areas related to the use of rigid sails on ships today based previous research studies and operational experiences. A number of key barriers regarding their use are also highlighted and discussed.

**Keywords:** sails; ship emissions; rigid sails; shipping; CO<sub>2</sub> emissions; sail assisted shipping; wind propulsion

## 1. Introduction

Approximately, 90% of world trade (by volume) is transported by the global shipping fleet (International Chamber of Shipping (ICS), 2014). Not surprisingly the many thousands of ships that perform this vital task burn vast quantities of marine fuels for propulsion and on-board electrical power. A Pure Car and Truck Carrier (PCTC), for example, may consume between 30 and 60 tonnes of fuel per day depending on its operating speed and weather conditions (Bialystocki & Konovessis, 2016). On a global basis, it is estimated that between 2007 and 2012 ships consumed on average approximately 250 million to 325 million tonnes of fuel per year resulting in approximately 740–795 million tonnes of CO<sub>2</sub> emissions (Smith et al., 2014). Another estimate is that in 2007, CO<sub>2</sub> emissions from 45,620 vessels amounted to 943 million tonnes with the total fuel oil consumption (FOC) being 297 million tonnes (Psaraftis & Kontovas, 2008).

In addition to CO<sub>2</sub> emissions, a range of other substances, including NO<sub>x</sub>, SO<sub>x</sub> and particulate matter (PM) are released into the atmosphere as a result of global shipping activity (European Commission, 2015; Psaraftis & Kontovas, 2008). These substances have an adverse impact on human health with research suggesting that shipping emissions are a contributing factor in approximately 60,000 deaths per year (Corbett et al., 2007). In the top 50 ports alone, approximately 230 million people are directly exposed to emissions from shipping (Merk, 2014). The major contributing factor behind the relatively high level of emissions is the composition of the marine fuels used on ships (Andersen, 2012; Trozzi & Lauretis, 2016), however emissions are also a concern even when liquefied natural gas (LNG) is used as a fuel source (López-Aparicio & Tønnesen, 2015).

In recent years, organizations including the International Maritime Organization (IMO) and European Commission (EC) have taken steps to reduce airborne emissions from the shipping sector via policy initiatives. These include the implementation of Emission Control Areas (ECA's) (European Commission, 2015), the setting of sulphur content limits in marine fuels (International Maritime Organization [IMO], 2014) and the International Convention for the Prevention of Pollution from Ships (MARPOL) (IMO, 2015). These policy initiatives have encouraged the development and adoption of various eco-friendly technologies and measures (Forum for the Future, 2011; Scott, 2014). Examples of these include exhaust scrubbers (Exhaust Scrubbers—What you need to know, 2014), waste heat recovery systems (MAN Diesel & Turbo, 2014), exhaust gas recirculation (EGR) (Wik, 2010), air lubrication systems (Kawabuchi et al., 2011), fuel cells (Marine Engineers Review, 2008a), Propeller Boss Cap Fin (PBCF) (MOL Techno-Trade, 2015), de-rating engines, slow steaming, operational data analysis and optimised voyage route planning (ABS, 2015). Renewable energy technologies have also been identified by classification societies, including Lloyds Register (Lloyd's Register Marine, 2015) and DNV-GL (Det Norske Veritas AS, 2012) as having a role to play in reducing fuel consumption and emissions. These technologies include rigid sail devices, including wing sails (Eco Marine Power, 2018a; Harbor Wing Technologies, 2006–2009; University of Tokyo, 2015) kites (SkySails GmbH (SkySails), 2015), wind power rotors or Flettner rotors (Deutsches Technikmuseum, 2010) and solar power (Atkinson, 2016a; Eco Marine Power, 2015; NYK Line, 2011).

Sails have been used on ships since ancient times and during the golden age of sail, fast clippers crossed the oceans at speeds comparable to modern cargo ships today. Now with an increasing focus on making shipping more environmentally friendly, the use of sail power is again being considered as a possible supplementary or alternative source of propulsive power. But in addition to potential benefits regarding their use there are also a number of factors that to date, appear to have hindered their widespread use on ocean-going powered ships.

## 2. Brief history and overview of sails on ships

Sails were the primary source of propulsion for ships for more than 2,000 years and it could be said that the first hybrid ships were the sail and oar powered triremes of ancient Greece and Rome. During the nineteenth century sailing ships known as a clippers, including the famous Cutty Sark (built 1869) could average speeds of approximately 15 knots (kn) if the winds were favourable (Royal Museums Greenwich, 2015). However, sailing ships depend on the vagaries of the wind and as a result voyage durations could vary significantly. This factor combined with the opening of the Suez Canal in 1869 and the advent of the steamship during the Industrial Revolution led to the gradual decline in the use of sail power as the primary source of propulsion for ocean going ships.

At first sailing ships and steamships performed different roles and did not directly compete with each other. Interestingly, most early steamships had masts and sails in case of engine failure or to use them as a source of propulsion when wind conditions were favourable (Royal Museums Greenwich). During the transition from sails to steam several notable ships that combined a steam engine with sail power were built, including the SS Savannah (ConnecticutHistory.org). In 1819, this was the first steamship to cross the Atlantic Ocean and during the 29 day voyage between Savannah (USA) and Liverpool (Great Britain), the auxiliary steam engine was used for only about 100 h or just 16% of the voyage time (National Museum of American History). The steamship Great Britain took the concept of using sails and steam engines together further. This ships rigging and sails were specifically designed to work efficiently with the primary source of propulsion—a 1,000 horse power engine. At the time it was launched in 1843, it had the largest steam engine that had ever been used at sea (SS Great Britain Trust, 2012). On journeys to Australia, the ship relied more on sail power than the steam engine as this was used mainly when conditions were not favourable.

By the 1920s, sails were no longer in use on the majority of ocean-going ships. However, the development of sails for powered vessels continued (albeit at a slower pace) and in the 1980s, a number of ships including the Shin Aitoku Maru (Yoshimura, 2002) and Usuki Pioneer (Marine Engineers Review, 1985) were fitted with Japan Marine Machinery Development Association (JAMDA) type rigid sails (Hamada, 1985). Rather than being the primary source of propulsion, these sails were fitted to ships as a means to reduce fuel consumption. The use of sails in this manner is known by a number of terms, including sail-assisted shipping and wind-assisted propulsion.

Although JAMDA sails (Figure 1) did lead to reductions in fuel consumption of up to 30% or more (Marine Engineers Review, 1985), the development of this technology effectively ended when oil prices fell (Fujiwara, Hirata, Ueno, & Nimura, 2003). During this period another type of rigid sail known as the Walker WingSail was installed onto a 7,000 DWT bulk carrier—MV Ashington (Figure 2). Fuel savings of up to 30% were claimed during 5 months of evaluation in 1986 (Bonney & Walker, 1986) although another estimate was that on average fuel savings were 8% and up to 15–20% under favourable conditions (GreenPort, 2008). A few years after installation though the Walker WingSail was removed from the ship (Cooke Associates, 2017; Marine Engineers Review, 1991). A summary of the reported fuel savings for the JAMDA sails and Walker Wingsail are shown in Table 1.

Hybrid sail concepts have also been developed in recent decades and these sails incorporate design elements of both soft sails and rigid sails. An example of this type of sail has been proposed by researchers at the National Maritime Research Institute (NMRI) in Tokyo, Japan, and the overall design is shown in Figure 3. Based on wind tunnel experiments and calculations the NMRI hybrid sail performed better in terms of lift and drag than soft and rigid sails (Fujiwara et al., 2003). Although promising, the NMRI hybrid sail has yet to be fitted to any commercial ship.

**Figure 1. JAMDA sail on a ship in Japan in the 1980s.**

Picture courtesy of Teramoto Iron Works (1980)



Another hybrid sail technology is the DynaRig and its design is based on a concept developed by Wilhelm Prölss in the 1960s. This sail type is used today on the yacht—Maltese Falcon (SY Maltese Falcon, 2015) and each sail has a camber of 12% and can be furled into the mast. Although the Maltese Falcon is an impressive example regarding the use of sails, it must be remembered that it reportedly cost US\$150 million to build in 2006 (Elliott, 2012). This is approximately two to three times the cost of some of the largest cargo ships in service today (Stopford, 2009).

Sails (excluding kites) for powered ships can be broadly categorised as either being soft sails, hybrid sails or rigid sails and each type is briefly described in Table 2.

There have been relatively few soft sail equipped ships with a gross register tonnage (GRT) of 500 tonnes or more since the end of the clipper era. Today their use is mainly limited to speciality cruise ships like the Club Med 2 (Vessel details for CLUB MED 2, 2018) and sail training ships. Hybrid sails due to their relative complexity and higher cost, appear suitable mainly for large luxury yachts (SY Maltese Falcon, 2015) or specialised hybrid sail equipped cargo ships (B9 Energy Group, 2015). Rigid sails are not in use on large ships today but as demonstrated by the JAMDA's sails they are able to reduce fuel consumption. Therefore, it seems reasonable to speculate that if their more



**Figure 2. Walker Wingsail installed on MV Ashington.**

Image used with permission from  
 Cooke Associates, Cambridge, UK



**Table 1. Reported fuel savings from JAMDA sails and Walker Wingsail**

Sail Type	Reference Vessels	Reported Fuel Savings	References
JAMDA	Shin Aitoku Maru Usuki Pioneer	10% to over 30%	(Marine Engineers Review, 1985; Ouchi, Uzawa, & Kanai, 2011; Yoshimura, 2002)
Walker WingSail	MV Ashington	Average 8% Up to 15–20% logged	(Bonney & Walker, 1986, Marine Engineers Review, 2008b)

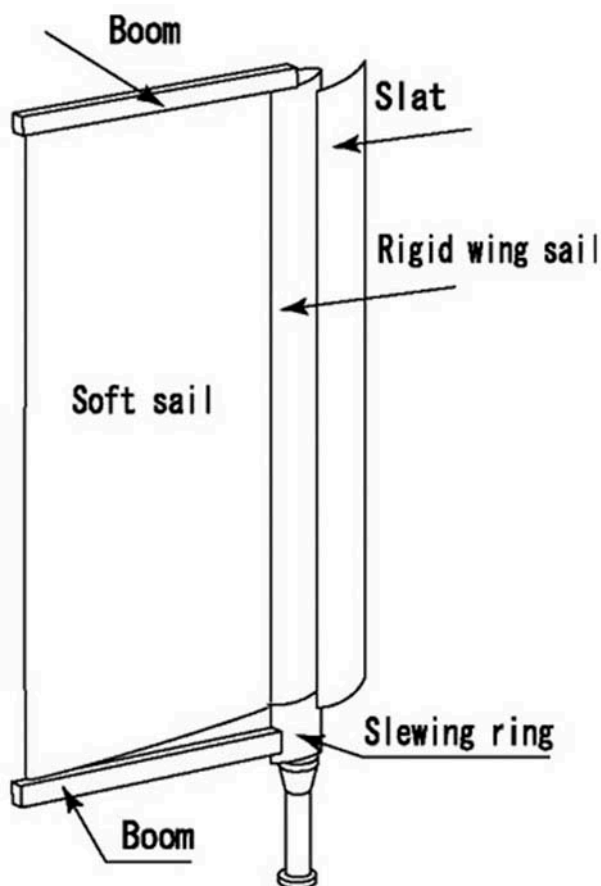
modern equivalents were used again, then these might prove to be an effective means of reducing FOC and emissions. An example of a possible arrangement of 14 rigid sails on an Eco Ship (bulker) is shown in Figure 4. This arrangement includes segment rigid sails (SRS) in a side by side configuration (Atkinson & Binns, 2018a) with a total sail area of 1,400 m<sup>2</sup> (Eco Marine Power, 2018b).

### 3. SWOT analysis: use of rigid sails on powered ships

To better understand the potential benefits and limitations concerning the use of rigid sails, a Strengths, Weaknesses, Opportunities and Threats (SWOT) analytical framework was used to identify key topic areas. These topic areas are outlined in a quadrant format in Table 3 and described more fully in this section. It should be noted that this analysis is focused on the use of rigid sails on powered ships only, and not on the use of sails in general and/or on modern sailing ships or yachts where sails are the primary source of propulsion.

The topic areas identified during the SWOT analysis are related to various phases of the ship design (D), build (B) and operate (O) cycle (Figure 5) and these are indicated next to each section below as applicable.

**Figure 3. Particulars of the NMRI Hybrid Sail.**  
 Reproduced with permission.



**Table 2. Modern sail types for powered ships**

Sail Type	Description	Examples
Soft Sail	A sail made from a lightweight material that deforms, sags and flexes due to the wind forces acting upon it.	Square rigged sail. Sails used on most recreational yachts. All sails used on commercial shipping during the 1800s.
Rigid Sail	A sail that is made from a material which does not deform, sag or flex significantly due to the wind forces acting upon it.	JAMDA sail. Walker WingSail.
Hybrid Sail	A sail that includes characteristics of both a soft sail and a rigid sail.	NMRI hybrid sail. DynaRig.

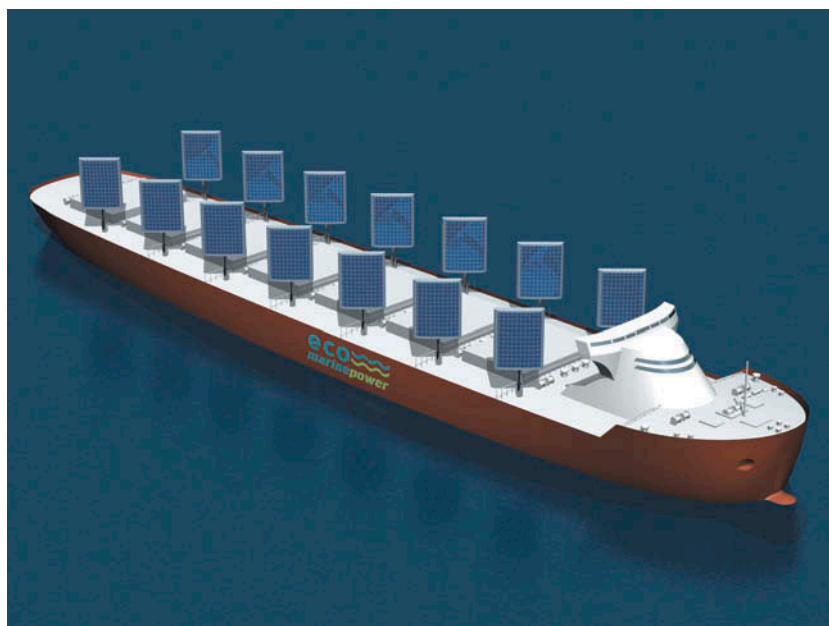
### 3.1. Strengths

#### 3.1.1. Reduction in fuel consumption (O)

Estimates regarding how much fuel can be saved via the use of rigid sails vary widely and are dependent on numerous factors, including the total sail area, the type of rigid sail(s) used and the wind conditions encountered during voyages (Atkinson & Binns, 2018b; Smith, Newton, Winn, & Rosa, 2013; Smulders, 1985; Viola, Sacher, Xu, & Wang, 2015). Possibly the best estimates can be based on the operational experiences from the ships that were fitted with the JAMDA sails (Table 1). The average fuel savings achieved by the Shin Aitoku Maru for example has been stated as being approximately 10% (Ouchi et al., 2011). This fuel consumption reduction is also similar to a calculated estimate of approximately 8% in a study for a ship using similar type sails operating

**Figure 4. Impression of 14 rigid sails on aquarius eco ship concept design.**

Used with permission from Eco Marine Power



**Table 3. Key topic areas identified during rigid sail SWOT analysis**

Strengths	Weaknesses
<ul style="list-style-type: none"> <li>• Reduction in fuel consumption</li> <li>• Reduction in emissions</li> <li>• Reduction in operating costs</li> <li>• Source of emergency propulsion</li> <li>• Improved vessel stability</li> <li>• Less space needed for fuel</li> </ul>	<ul style="list-style-type: none"> <li>• Impact on ship and crew safety</li> <li>• Initial cost</li> <li>• Additional operating costs</li> <li>• Variable performance</li> <li>• Interference with cargo operations</li> <li>• Space and storage requirements</li> <li>• Additional weight</li> <li>• Additional work load for crew</li> <li>• Additional training needed for crew</li> </ul>
Opportunities	Threats
<ul style="list-style-type: none"> <li>• Implementation of environmental regulations</li> <li>• Trend towards lower emission shipping</li> <li>• Higher fuel prices</li> <li>• Desire to enhance brand image</li> <li>• Corporate and consumer pressure</li> <li>• Slow steaming</li> </ul>	<ul style="list-style-type: none"> <li>• Competing technologies</li> <li>• Competing measures</li> <li>• Industry resistance</li> <li>• Lower fuel prices</li> <li>• Alternative lower cost fuels</li> <li>• Over-stated fuel savings not realised</li> <li>• Ships moved to unsuitable route</li> <li>• Sails deemed too complex</li> </ul>

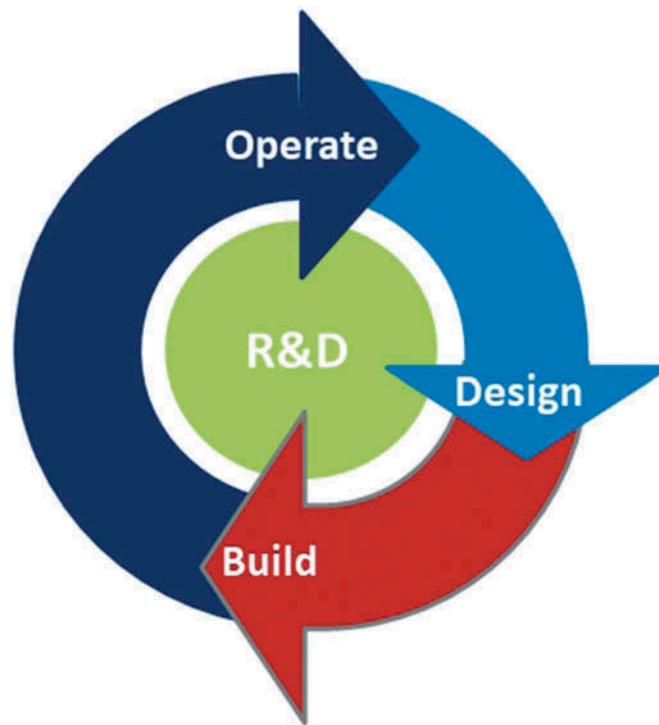
between Mumbai and Durban (Smulders, 1985). In addition, fuel savings for certain voyages undertaken by the Usuki Pioneer were reported as being over 30% (Marine Engineers Review, 1985). Thus we can conclude that based on past operational experiences and supported by recent research, that rigid sails have the potential to reduce fuel consumption by a significant amount.

### 3.1.2. Reduction in emissions (O)

A reduction in fuel consumption due to the use of rigid sails would also result in a reduction in CO<sub>2</sub>, SO<sub>x</sub> and NO<sub>x</sub> emissions. In addition to this having a positive impact on health and the environment



**Figure 5. Overview of a typical ship design, build and operate cycle.**



(Roberts, 2018) wind-assisted propulsion may provide economic benefits as well (Ballini, Ölçer, Brandt, & Neumann, 2017). Regarding CO<sub>2</sub> emissions for example, a Ro-Ro (Roll-on/Roll-off) vessel of 27,000 DWT travelling between Rotterdam and New York operating at 16 kn would generate approximately 77 tonnes of CO<sub>2</sub> emissions per voyage (Laboratory for Maritime Transport, 2013). Assuming that fuel savings of 10% can be achieved this could lead to a reduction of approximately 7.7 tonnes of CO<sub>2</sub> emissions per voyage. Depending on the fuel type, SO<sub>x</sub> and NO<sub>x</sub> emissions would also be significantly reduced.

#### 3.1.3. Reduction in operating costs (O)

Fuel used on board ships (often referred to as bunker fuel) is one of the largest cost items of a ship operating expenses (OPEX) (Bialystocki & Konovessis, 2016). A ship fitted with rigid sails could be expected under favourable conditions to use less fuel since the propulsive power from the sails would supplement power from the main engines (M/E's). This lower fuel consumption would consequently lead to a reduction in operating costs. For reference purposes a summary of FOC cost reduction scenarios are outlined in Table 6.

#### 3.1.4. Source of emergency propulsion (O)

As with steam ships in the 1800s, rigid sails have the potential to provide a source of emergency or back-up propulsion. In 1985, the Usuki Pioneer achieved a speed of 5 kn using two JAMDA sails as the only source of propulsion (Marine Engineers Review, 1985) and it has been estimated that nine large rigid sails with a total sail area of 9,000 m<sup>2</sup> could in favourable wind conditions, generate enough thrust to move a Capesize bulker at a speed of almost 14 kn (Ouchi et al., 2011). Thus, we can suppose it may be possible to propel even large ships using sail power alone in emergency situations.

#### 3.1.5. Improved vessel stability (O)

During the voyage of Usuki Pioneer in the winter of 1984–1985, it was observed that the roll angle was reduced by 30% when the sails were set (Marine Engineers Review, 1985). Further research in

this area is required; however, it does appear that under certain conditions the use of rigid sails on powered ships may result in improved stability.

#### 3.1.6. *Less space needed for fuel* (D B O)

On certain shipping routes, it may be possible to reduce the amount of fuel stored in tanks due to the fuel saving achieved through the use of rigid sails. As a consequence this would reduce the weight of the ship and could lead to further fuel savings. Longer term it may be possible to design sail-assisted ships with less space set aside for fuel storage thereby freeing up space for extra cargo and/or allowing for the overall weight of the ship to be reduced.

### 3.2. *Weaknesses*

#### 3.2.1. *Impact on ship and crew safety* (O)

Sails on modern ships may negatively impact the safety of a ship in several ways. Firstly, the weight of the sails and the wind forces acting upon them (Hu et al., 2015) may cause the ship to heel especially when the vessel is not loaded. Secondly, depending where the sails are located, the view from the wheelhouse or bridge could be obstructed and this may prove to be problematic in terms of navigation and avoiding collisions. Thirdly, the sails may pose less obvious safety hazards, such as obstructing the movement of the crew on the deck during an emergency or in the event of equipment failure, they may present a risk to the ship (and crew) if they cannot be stowed or secured during storms.

#### 3.2.2. *Initial cost* (CAPEX) (D B)

On a large ship, it is likely that more than one rigid sail will be required along with some form of automated or semi-automated control system. This system is likely to require multiple layers of safety in terms operational and system design to prevent accidents that may be caused by human errors or system malfunctions. This initial capital expenditure (CAPEX) along with the associated installation cost may be considered by ship owners as an optional expense since rigid sails are not currently considered as being essential. As a consequence, even though rigid sails may provide economic benefits in terms of reduced fuel costs, some shipping companies may be reluctant (or unable) to allocate additional funds to purchase them either when building new ships or for retrofitting onto existing ships. This additional cost may not be fully recovered by ship owners since for example, only around 40% of the financial savings achieved through energy efficiency measures for Panamax ships may accrue to the vessels' owners for ships under charter (Agnolucci, Smith, & Rehmatulla, 2014). It is also worth noting that rigid sail systems will also need to conform to the applicable classification rules (Hu et al., 2015) plus comply with the International Convention for the Safety of Life at Sea (SOLAS) (ABS, 2015) as applicable. Compliance with these and other regulations may also increase the initial cost of rigid sail installations.

#### 3.2.3. *Additional operating expenses* (OPEX) (O)

Electrical and mechanical equipment installed on ships require regular maintenance especially when exposed to the harsh marine environment. This additional maintenance cost related will need to be factored into OPEX and may deter ship owners from utilising rigid sails. This cost may also become problematic if the sails and associated equipment are unreliable and frequently need to be repaired. In addition, since the M/E's may be operating at times at a lower % of MCR (Maximum Continuous Rating), there could be an increase in engine maintenance costs as has been noted from experiences with slow-steaming (Kowalak, 2013).

#### 3.2.4. *Variable performance* (O)

The performance of any sail is dependent on the wind direction and wind speed and these vary constantly. During a voyage a ship may encounter winds of 30 kn or more and then spend days sailing though light winds of less than 5 kn. Additionally, the direction of the apparent wind may not be suitable for the use of sails and in such cases they may provide little or no propulsive power. Other factors that impact their performance include interaction effects between sails and

interference caused by the superstructure. Interaction losses between sails have been found in one study to reduce the driving force by approximately 24% for multiple rectangular sails (Fujiwara, Hearn, Kitamura, & Ueno, 2005). Thus, the propulsive power from sails cannot be relied upon to be the main or even a significant source of propulsion at all times. On some voyages or routes they may provide little or no useable propulsive power. The nature of this variable performance could be a major issue if the ship was moved from a windy route to one where the winds were less favourable. In such a case, the rigid sails may not be often utilised. In Figure 6, the wind conditions that could be experienced on a route between North America and Europe are shown. In this example a ship sailing across from North America to Europe may encounter several major changes in wind direction with winds speeds varying from calm to 35 kn.

In Figure 6, wind barbs are used to show wind direction and speed. The end mark or tail on each barb indicates the direction the wind is blowing from, with each small barb representing a speed of 5 kn and a large barb representing 10 kn.

### 3.2.5. Interference with cargo operations (O)

A requirement for modern ships is that a sail or sails should not interfere with the loading or unloading of cargo (Bergeson & Greenwald, 1985; Ishihara, Watanabe, Shimizu, Yoshimi, & Namura, 1981; Smulders, 1985) even when folded or lowered. Tall sails and/or masts that cannot be lowered may also prevent a ship from entering certain ports due to the height of bridges, cranes and other infrastructure. If rigid sails obstruct cargo handling in some way then this would most likely be viewed negatively by ship owners and ship charterers. Another issue to consider is that if a very tall sail (e.g. over 20 m in height) was unable to be lowered due to a mechanical failure then this may prevent a ship from berthing and/or unloading cargo. If such failures were common this would undermine their usefulness.

### 3.2.6. Space and storage requirements (D B O)

The inability to store or stow rigid sails could be problematic since the sails might be damaged during storms or interfere with cargo operations (Atkinson, 2016b; Hirayama, 2015). Thus, it is likely that the sails will at times need to be stored in some manner. However, deck areas on ships are often crowded with equipment and fittings or the space is required for passengers and/or cargo. Therefore, if space was set aside to store the sails then this may reduce the amount of cargo that the ship was able to carry. This reduction in cargo would result in less income per voyage being generated for the ship owner and thus undermine the cost effectiveness of using rigid sails. Also the installation of rigid sails may be difficult on container-ships, LNG tankers or vessels where installation or storage space is not readily available.

**Figure 6. Wind conditions across the North Atlantic Ocean in October 2015.**

Source: MarineTraffic.com  
(MarineTraffic.com, 2015).



### 3.2.7. Additional weight (D B O)

One prototype large rigid sail currently being tested in Japan weighs approximately 60 tons (Mitsui O.S.K Lines, 2013). If multiple sails of this type (or similar) were to be used then a significant amount of extra weight would be added to the ship. In situations where the rigid sails could not be used due to poor wind conditions (or other reasons) then the sails effectively would become cargo. Thus, instead of reducing fuel consumption they may to some extent, actually increase fuel use due to this additional weight. Another consequence of the sail weight is that this may adversely impact the stability of the ship (Hu et al., 2015) especially if the ships centre of gravity is impacted. For new ship designs this additional weight could be accounted for during the design process, however in cases where sails might be retro-fitted then this issue would require careful attention.

### 3.2.8. Additional training needed for crew (O)

Even if the control of rigid sails can be fully automated via a computer system, some of the ship's crew including the engine room and deck departments will need to be trained on how to deal with equipment failures and emergency procedures. The requirement for this extra training may be viewed negatively by some shipping companies due to the additional costs involved. Some maintenance training would also likely be required for the engineering department and onshore technical support teams.

### 3.2.9. Additional crew work load for crew (O)

In theory, a fully automated rigid sail system would result in little extra work for the crew (Bergeson & Greenwald, 1985; Eco Marine Power, 2018a). Nonetheless, there would most likely be situations when manual control was required. In addition the operational status of the rigid sails would need to be monitored. This additional workload, even if quite small, is likely to be viewed negatively especially for ship types where the trend is towards reducing crew numbers. Some maintenance would also be required although much of this could be undertaken by onshore technical staff and contractors.

## 3.3. Opportunities

### 3.3.1. Implementation of environmental regulations (D B)

The IMO has outlined a range of policies to reduce air pollution from shipping and further policy initiatives including a tax on carbon emissions are being discussed. Regulations focused on ships' energy efficiency came into force in January 2013 while stricter sulphur requirements regarding the use of marine fuels for specific areas came into force in 2015 and will be applied globally from 2020 (Det Norske Veritas AS, 2012; IMO, 2016). These regulatory initiatives are likely to support the further development of fuel and emission reduction technologies including rigid sails.

### 3.3.2. Shift towards lower emission shipping (D B)

Green shipping, eco shipping, sustainable shipping and low emission shipping are themes that are now frequently discussed at shipping and maritime related events. Many shipping companies have sustainability programs and/or strategies that include plans to reduce emissions and improve energy efficiency (Attica Group, 2015; Stena Bulk, 2012; The Maersk Group, 2015). This growing trend towards lower emission shipping may help sail-based solutions gain acceptance within the shipping industry.

### 3.3.3. Higher fuel prices (D B)

Although IFO380 was below USD \$200 tonne a few years ago, it is expected that over the long term fuel prices for shipping will remain expensive (Det Norske Veritas AS, 2012). This is likely to drive innovation in the field of fuel reduction measures and this in turn should assist the development of rigid sails and other similar technologies. A similar trend for example has been seen in the field of automobile engineering with hybrid and electric cars becoming common in many countries. If the price for low sulphur marine gas oil (LSMGO) was to rise to USD \$800 per tonne then annual fuel saving of \$832,000 might be achieved on a ship fitted rigid sails if these reduced fuel consumption by 10% (Tables 5 and 6). Price charts for IFO380 and LSMGO380 are shown in Figure 8.

### 3.3.4. Desire to enhance brand image (O)

In a recent online survey, approximately 96% of respondents indicated they would have a more favourable impression of a ferry or cruise ship company if their vessels used renewable energy (Table 4) (Ohori Capital Pty. Ltd, 2015). This presents an opportunity for companies to use renewable energy technologies including rigid sails to enhance their brand image. This in turn could generate increased revenue by attracting additional customers especially those focused on making spending choices based on environmental and sustainability issues.

### 3.3.5. Corporate and consumer pressure (O)

Governments and corporations in many countries are taking measures to reduce their carbon footprint as a result of concerns about climate change. This has led to programmes aimed at reducing CO<sub>2</sub> emissions in logistics via initiatives, such as “Green Logistics” (Panasonic Corporation, 2015). Initially many of these programmes were focused on land transport however attention is shifting towards sea transport as well. Shipping companies therefore are likely to experience pressure to meet the demands of their customers in terms of reducing emissions. This along with consumer pressure and public awareness (Lloyd’s Register Marine, 2015) may help facilitate the acceptance of rigid sails across the shipping sector.

### 3.3.6. Slow steaming (O)

Slow steaming is an operational measure implemented by shipping companies to reduce fuel costs by lowering the operating or cruising speed of their vessels (Malonia, Paulb, & Gligor, 2013). Since powered ships operating at lower speeds are generally more suited to the use of sails (Hansen, 2000), this trend could assist the uptake of rigid sails.

**Table 4. Response to Q4 of survey: Renewable Energy On Cruise Ships & Passenger Ferries (Ohori Capital Pty. Ltd, 2015)**

Would you have a more favourable impression of a ferry or cruise ship company if their vessels used renewable energy?		
Yes, very much so.	Yes, to some extent.	My impression would not be changed.
70.9%	25.5%	3.6%

**Table 5. Possible FOC profile for Capesize bulk carrier with 14 rigid sails**

Ship Type	Bulker	FOC (Daily)	40 tonnes
Operating Speed	12–14 knots	FOC (Annually)	10,400 tonnes
Days at Sea	260	Rigid Sail FOC Savings*	10% or 1,040 tonnes per year

\*Estimate based on previous rigid sail trials and studies and not specific to any particular sail type or sail configuration.

**Table 6. Rigid sail ROI scenarios for bulker fitted with a generic rigid sail system**

FOC Savings Scenarios (IFO380)—All amounts in \$USD Rigid Sail System Cost: \$2.5 million			
Cost per tonne	Annual Fuel Cost	Potential FOC Savings	ROI Period
\$1000	\$10.4 million	\$1.4 million	1.8 years
\$800	\$8.32 million	\$832,000	3.0 years
\$600	\$6.24 million	\$624,000	4.0 years
\$400	\$4.16 million	\$416,000	6.0 years
\$200	\$2.08 million	\$208,000	12 years

Annual fuel cost = FOC annually (tonnes) x fuel cost per tonne.



### 3.4. Threats

#### 3.4.1. Competing technologies and measures (B D O)

A number of alternative technologies and measures that will reduce fuel consumption and/or emissions are available or being developed as outlined in the introduction to the paper including air-lubrication systems and slow steaming. These options together with rigid sails will be subjected to a cost-benefits analysis and the results compared. For variety reasons these competing technologies and measures may in certain cases be more suitable or cost effective than rigid sails. Slow steaming requires no additional equipment to be installed, though this measure does result in longer transit times and an increase in pipeline inventory (Malonia et al., 2013). Ship design options include the Semi Spherical Shaped (SSS) bow developed by the Kyokuyo Shipyard Corporation that theoretically can save around 800 tons of fuel and about 2,500 tons of CO<sub>2</sub> emissions annually (Kyokuyo Unveiled Eco-Friendly Ship Design, 2010) (Figure 7).

#### 3.4.2. Industry resistance (B D)

The shipping industry has a reputation for being slow to adopt new technologies (Det Norske Veritas AS, 2012). Consequently, rigid sails may not gain acceptance if shipping companies can meet regulatory requirements via existing technologies or measures even if these are not as effective. In additional organisational barriers may also hinder their acceptance (Rehmatulla, Parker, Smith, Stulgis, & Mitchell, 2015).

**Figure 7. City of Rotterdam with SSS bow.**

Picture courtesy of Paul Whitelaw

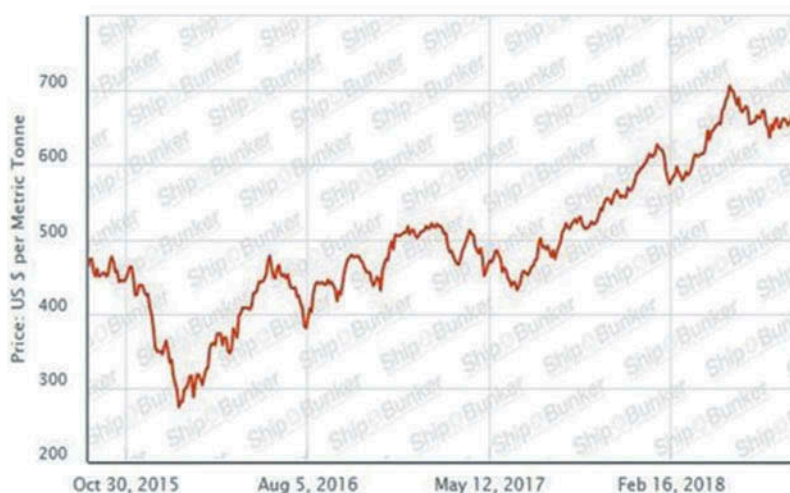


**Figure 8. Price charts for HFO and LSMGO 2015–2018.**

Used with permission from Ship and Bunker (Price charts for HFO and LSMGO 2015–2018, 2018)



Price chart for IFO380 (Singapore)



Price chart for LSMGO380 (Singapore)

Charts courtesy of Ship & Bunker <https://shipandbunker.com/>

### 3.4.3. Lower fuel prices (D B O)

The development of the JAMDA sails and similar technologies (Bergeson & Greenwald, 1985; Conway, 1985) effectively came to an end when the price of oil fell in the 1980s. Lower oil or marine fuel prices effectively extend the return on investment (ROI) time-frame for rigid sails and other fuel saving technologies. This can be illustrated by considering the estimated daily FOC profile of a bulk carrier incorporating a rigid sail system as shown in Figure 4. This configuration comprises of 14 sails with a total sail area of 14,000 m<sup>2</sup>. The profile of this bulk carrier is outlined in Table 5 and various ROI scenarios are presented in Table 6.

For the purpose of estimating potential cost savings it was assumed that on average a ship fitted with rigid sails (JAMDA type or similar) can achieve fuel savings of 10% per annum as per Table 1. To calculate the ROI period, a baseline cost of USD \$2.5 million for a generic rigid sail system is a total sail area of 1,400 m<sup>2</sup> is used. The rigid sail cost estimate is a theoretical figure since accurate figures for a modern rigid sail solution in commercial production are not available.

If the price for IFO380 fell back to USD \$200 per tonne then the ROI pay-back period would be 12 years and this timeframe is unlikely to be attractive to many ship owners. This in turn may negate the necessity to install rigid sails on existing or on planned newbuilding projects.

#### 3.4.4. *Alternative lower cost fuels (O)*

LNG is a relatively cleaner and potentially lower cost fuel that is gaining increasing acceptance across the shipping sector especially since it has virtually no sulphur content (Adamchak & Adede, 2013). Other alternative fuels being studied or considered include methanol, ethanol, biodiesel and hydrogen (Chryssakis, Balland, Tvette, & Brandsate, 2014). If these alternative fuels prove effective in lowering operating costs and emissions then interest in the use of rigid sails and other similar technologies for ships may decline.

#### 3.4.5. *Over-stated fuel savings not realised (O)*

As discussed earlier, the performance of rigid sails are influenced by many factors. It is possible therefore that the theoretical estimated fuel savings outlined in discussion papers, company brochures and presentations at conferences, etc. might be based on overly optimistic assumptions. Subsequently, these estimates may not be replicated during sea trials or observed during normal operations. If this situation was to eventuate then confidence in rigid sails as a fuel saving technology would be diminished.

#### 3.4.6. *Ships moved to unsuitable route (O)*

Many ships operate on a charter basis (United Nations, 2014) and may sail on different routes during their operational life. Some of these routes may be less suitable for the use of rigid sails due to wind and weather conditions. Hence, shipping companies might be reluctant to invest in this technology or similar technologies if their vessels are likely to be moved to routes where these would be less effective.

#### 3.4.7. *Rigid sails deemed too complex (O)*

Even the simplest form of a rigid sail system would typically comprise of a mast, sail structure, electrical and/or hydraulic equipment to position the sail and a computer control system. This combination of system elements might be considered too complicated to manage and operate when compared to other relatively straight forward fuel saving measures, such as slow steaming, regular hull cleaning, innovative bow designs or weather routing.

### 4. Conclusions

Rigid sails have the potential to provide an auxiliary or supplementary source of propulsion on powered ships. This potential has been realized in the past with the use of JAMDA type sails in the 1980s being the most notable example. Ships fitted with these sails reportedly reduced their fuel consumption between 10% to over 30% albeit under favorable conditions. Therefore, it can be concluded that if rigid sails were again fitted to ocean-going powered ships that significant reductions in FOC and airborne emissions could be achieved. In addition they may provide other potential tangible and intangible benefits including improving the health of those living near ports and shipping lanes, being a source of emergency propulsion, improving vessel stability and enhancing the brand image and reputation of shipping companies that utilize them.

However, a number of issues highlighted in the current study require further research. These issues may hinder the use of this promising technology until feasible and cost effective solutions can be found. The most significant of the issues identified are:

- Safety concerns—in terms of protecting personnel and the vessel itself. Areas that need particular focus include ship stability, measures to prevent accidents due to human error or equipment failure and the handling of the sails in poor or extreme weather conditions.

- Design limitations—related to physically installing rigid sails and incorporating rigid sails into new or existing ship designs including meeting classification society requirements.
- Economic and business considerations—including up-front costs, return on investment periods and operating costs. Importantly rigid sails should be competitive with other fuel and emission reduction technologies and/or measures even during periods when fuel prices are relatively low.
- Operational issues—in terms of ongoing maintenance requirements and the performance of rigid sails under varying operational and weather conditions.

#### Nomenclature

B	Build
CAPEX	Capital expenditure
CO <sub>2</sub>	Carbon dioxide
D	Design
DWT	Deadweight tonnage
EC	European Commission
ECA	Emission control area
ECR	Exhaust gas recirculation
FOC	Fuel oil consumption
GRT	Gross register tonnage
HFO	Heavy fuel oil
IFO	Intermediate Fuel Oil
IMO	International Maritime Organization
JAMDA	Japan Marine Machinery Development Association
Kn	Knots
LNG	Liquefied natural gas
LSMGO	Low sulphur marine gas oil
MARPOL	International Convention for the Prevention of Pollution from Ships
MCR	Maximum continuous rating
M/E	Main engine
MEPC	Marine Environmental Protection Committee
MV	Merchant vessel
NO <sub>x</sub>	Nitrogen oxides
NMRI	National Maritime Research Institute (Japan)
O	Operate
OPEX	Operating expenditure
PBCF	Propeller Boss Cap Fin
PM	Particulate matter
PCTC	Pure car and truck carrier
FOC	Fuel oil consumption
Ro-Ro	Roll on—roll off
ROI	Return on investment
SOLAS	International Convention for the Safety of Life at Sea
SO <sub>x</sub>	Sulphur oxides
SRS	Segment rigid sail

SS	Steam ship
SSS	Semi spherical shaped
SWOT	Strengths, weaknesses, opportunities and threats
USD	United States Dollar

#### Funding

The authors received no direct funding for this research.

#### Author details

Gregory Atkinson<sup>1</sup>  
 E-mail: [greg.atkinson@ecomarinepower.com](mailto:greg.atkinson@ecomarinepower.com)  
 ORCID ID: <http://orcid.org/0000-0003-2911-6317>  
 Hung Nguyen<sup>2</sup>  
 E-mail: [h.d.nguyen@utas.edu.au](mailto:h.d.nguyen@utas.edu.au)  
 ORCID ID: <http://orcid.org/0000-0003-0118-8597>  
 Jonathan Binns<sup>2</sup>  
 E-mail: [jonathan.binns@utas.edu.au](mailto:jonathan.binns@utas.edu.au)  
 ORCID ID: <http://orcid.org/0000-0001-6892-0063>

<sup>1</sup> Eco Marine Power, Japan.

<sup>2</sup> Australian Maritime College, University of tasmania, Australia.

#### Citation information

Cite this article as: Considerations regarding the use of rigid sails on modern powered ships, Gregory Atkinson, Hung Nguyen & Jonathan Binns, *Cogent Engineering* (2018), 5: 1543564.

#### References

- ABS. (2015). *Ship energy efficiency measures*. ABS, Editor, Author. Retrieved from [ww2.eagle.org/content/dam/eagle/.../2013/Energy%20Efficiency.pdf](http://ww2.eagle.org/content/dam/eagle/.../2013/Energy%20Efficiency.pdf)
- Adamchak, F., & Adede, A. (2013). *LNG as marine fuel*. Retrieved from [http://www.gastechnology.org/training/documents/lng17-proceedings/7-1-frederick\\_adamchak.pdf](http://www.gastechnology.org/training/documents/lng17-proceedings/7-1-frederick_adamchak.pdf)
- Agnolucci, P., Smith, T., & Rehmatulla, N. (2014). Energy efficiency and time charter rates: Energy efficiency savings recovered by ship owners in the Panamax market. *Transportation Research Part A: Policy and Practice*, 66, 173–184.
- Andersen, I. M. V. (2012). *Emissions from ship machinery*. Technical University of Denmark.
- Atkinson, G. M. (2016a). Analysis of marine solar power trials on blue star delos. *Journal of Marine Engineering & Technology*, 15(3), 115–123. doi:10.1080/20464177.2016.1246907
- Atkinson, G. M. (2016b). *Power module for use in marine vessel, and wind-propelled vessel provided with said power module*. United States: Eco Marine Power Co. Ltd. Retrieved from <https://www.google.com/patents/US9376187>
- Atkinson, G. M., & Binns, J. (2018a). Analysis of drag, air-flow and surface pressure characteristics of a segment rigid sail. *Journal of Marine Engineering & Technology*, 1–10. doi:10.1080/20464177.2018.1494953
- Atkinson, G. M., & Binns, J. (2018b). Power profile for segment rigid sail. *Journal of Marine Engineering & Technology*, 17(02), 99–105. doi:10.1080/20464177.2017.1319997
- Attica Group. (2015). *Press release: 6th corporate social responsibility report 2014*, Athens.
- B9 Energy Group. (2015). B9 shipping. Retrieved from <http://www.b9energy.com/B9Shipping/tabid/4036/language/en-US/Default.aspx>
- Ballini, F., Ölçer, A. I., Brandt, J., & Neumann, D. (2017). Health costs and economic impact of wind assisted ship propulsion. *Ocean Engineering*, 146 (Supplement C), 477–485. doi:10.1016/j.oceaneng.2017.09.014
- Bergeson, L., & Greenwald, C. K. (1985). Sail assist developments 1979–1985. *Journal of Wind Engineering and Industrial Aerodynamics*, 19, 45–114. doi:10.1016/0167-6105(85)90056-X
- Bialystocki, N., & Konovessis, D. (2016). On the estimation of ship's fuel consumption and speed curve: A statistical approach. *Journal of Ocean Engineering and Science*, 1(2), 157–166. doi:10.1016/j.joes.2016.02.001
- Bonney, P., & Walker, J. (1986). Walker wingsail operating experience on the MV Ashington. *Transactions - North East Coast Institution of Engineers & Shipbuilders*, 103 (1), 29–30.
- Chryssakis, C., Balland, O., Tvete, H. A., & Brandsate, A. (2014). *Alternative fuels for shipping*. Hovik: DNV GL. ConnecticutHistory.org. Steaming across the Atlantic. Retrieved 2015, from <http://connecticuthistory.org/steaming-across-the-atlantic/>
- Conway, A. (1985, July). Something's in the wind. *Marine Engineers Review*, 16–18.
- Cooke Associates. (2017). Commercial history | wingsails. Retrieved 2018, from <http://www.cookeassociates.com/sports/commercial.php>
- Corbett, J. J., Winebrake, J. J., Green, E. H., Kashibhatla, P., Eyring, V., & Lauer, A. (2007). Mortality from ship emissions: A global assessment. *Environmental Science and Technology*, 41, 8512–8518.
- Det Norske Veritas AS. (2012). *Shipping 2020*. Høvik: Author.
- Deutsches Technikmuseum. (2010). The flettner rotor – An invention ahead of its time. Retrieved 2015, from <http://www.sdtb.de/Flettner-Rotor.1623.0.html>
- Eco Marine Power. (2015). Aquarius marine solar power. Retrieved from <http://www.ecomarinepower.com/en/aquarius-marine-solar-power>
- Eco Marine Power. (2018a). EnergySail - wind & solar power for low emission shipping. Retrieved from <http://www.ecomarinepower.com/energysail>
- Eco Marine Power. (2018b). Aquarius eco ship. Retrieved from <http://www.ecomarinepower.com/en/aquarius-eco-ship>
- Elliott, H. (2012, October 19). The ultimate billionaire toy: The maltese falcon, forbes. Retrieved from <http://www.forbes.com/sites/hannahelliott/2012/10/19/the-ultimate-billionaire-toy-the-maltese-falcon/>
- European Commission. (2015). Emissions from maritime transport. Retrieved from <http://ec.europa.eu/environment/air/transport/directive.htm>
- Exhaust Scrubbers - What you need to know. (2014). Neuilly-sur-Seine: Bureau Veritas.
- Forum for the Future. (2011). *Sustainable shipping initiative vision 2040*. London: Author. Retrieved from [https://www.forumforthefuture.org/sites/default/files/images/Forum/Projects/Sustainable-Shipping/SSI\\_Vision\\_2040\\_webfinal.pdf](https://www.forumforthefuture.org/sites/default/files/images/Forum/Projects/Sustainable-Shipping/SSI_Vision_2040_webfinal.pdf)
- Fujiwara, T., Hearn, G., Kitamura, F., & Ueno, M. (2005). Sail-sail and sail-hull interaction effects of hybrid-sail assisted bulk carrier. *Journal of Marine Science and Technology*, (10), 82–95. doi:10.1007/s00773-005-0191-4



- Fujiwara, T., Hirata, K., Ueno, M., & Nimura, T. (2003). On development of high performance sails for an ocean going sailing ship. International conference on marine simulation and ship manoeuvrability (MARSIM '03), Kanazawa, National Maritime Research Institute (Japan).
- GreenPort. (2008). Windsail: Energy saving solution? Retrieved 2015, from <http://www.greenport.com/news101/energy-and-technology/windsail-energy-saving-solution>
- Hamada, N. (1985). The development in Japan of modern sail-assisted ships for energy conservation. Regional conference on sail-motor propulsion, Manila.
- Hansen, P. K. E. (2000). Modern windships. Retrieved from [http://www2.mst.dk/common/Udgivramme/Frame.asp?http://www2.mst.dk/udgiv/publications/2000/87-7944-019-3/html/helepubl\\_eng.htm](http://www2.mst.dk/common/Udgivramme/Frame.asp?http://www2.mst.dk/udgiv/publications/2000/87-7944-019-3/html/helepubl_eng.htm)
- Harbor Wing Technologies. (2006–2009). Wingsail. Retrieved 2015, from [http://www.harborwingtech.com/technology\\_wingsail.htm](http://www.harborwingtech.com/technology_wingsail.htm)
- Hirayama, A. (2015). Research and development into the practical applications of power assist sails. *ClassNK Technical Bulletin*, 33, 63–67.
- Hu, Y., He, J., Tang, J., Xu, S., Liu, S., & Wu, Y. (2015). Sail structure design and stability calculation for sail-assisted ships. *Marine Engineering Frontiers (MEF)*, 3. doi:10.14355/mef.2015.03.001
- International Chamber of Shipping (ICS). (2014). *Shipping, world trade and the reduction of CO2 emissions*. London: International Chamber of Shipping.
- International Maritime Organization (IMO). (2014). Sulphur oxides (SOx) – Regulation 14. Retrieved 2015, from <http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Sulphur-oxides-%28SOx%29-%E2%80%93-Regulation-14.aspx>
- International Maritime Organization (IMO). (2015). International convention for the prevention of pollution from ships (MARPOL). Retrieved 2017, from <http://www.imo.org/en/About/Conventions/ListOfConventions/Pages/International-Convention-for-the-Prevention-of-Pollution-from-Ships-%28MARPOL%29.aspx>
- International Maritime Organization (IMO). (2016). IMO sets 2020 date for ships to comply with low sulphur fuel oil requirement. Retrieved October 28, 2016, from <http://www.imo.org/en/mediacentre/pressbriefings/pages/mepc-70-2020sulphur.aspx>
- Ishihara, M., Watanabe, T., Shimizu, K., Yoshimi, K., & Namura, K. (1981). Sail-equipped motorship feasible, in maritime reporter and engineering news, *MarineLink.com*. Retrieved from <http://magazines.marinelink.com/Magazines/MaritimeReporter/19810315/content/sailequipped-motorship-feasible-205712>.
- Kawabuchi, M., Kawakita, C., Mizokami, S., Higasa, S., Kodan, Y., & Takano, S. (2011). CFD predictions of bubbly flow around energy-saving ship with mitsubishi air lubrication system. *Mitsubishi Heavy Industries Technical Review*, 48(1), 55–57.
- Kowalak, P. (2013). Chief engineer's hands-on experience of slow steaming operation. Maritime University of Szczecin.
- Kyokuyo Unveiled Eco-Friendly Ship Design. (2010). Retrieved 2017, from <http://www.kyokuyoshiyard.com/en/01news/112.html>
- Laboratory for Maritime Transport. (2013). Ship emissions calculator. Retrieved 2016, from <http://www.martrans.org/emis/>
- Lloyd's Register Marine. (2015). *Wind-powered shipping*. Southampton. Retrieved from <http://www.lr.org/en/marine/technology-and-innovation/technology/wind-poweredshipping.aspx>
- López-Aparicio, S., & Tønnesen, D. (2015). *Pollutant emissions from LNG fuelled ships*. Kjeller, Norway: Norwegian Institute for Air Research.
- The Maersk Group. (2015). Our sustainability strategy. Retrieved from <http://www.maersk.com/en/the-maersk-group/sustainability>
- Malonia, M., Paulb, J. A., & Gligor, D. M. (2013). Slow steaming impacts on ocean carriers and shippers. *Maritime Economics & Logistics*, 5, 151–171. doi:10.1057/mel.2013.2
- MAN Diesel & Turbo. (2014). *Waste Heat Recovery System (WHRS) for the reduction of fuel consumption, emissions and EEDI*. Copenhagen: Author.
- Marine Engineers Review. (1985, July). *Substantial fuel savings for sail-equipped "Usuki Pioneer"*, p. 15. London: Institute of Marine Engineers
- Marine Engineers Review. (1991, September). *Hybrid rotors for wind propulsion*, pp. 54–55. London: Institute of Marine Engineers
- Marine Engineers Review. (2008a, July/August). DNV looks to the future, *Marine Engineers Review*, pp. 17–18.
- Marine Engineers Review. (2008b, July/August). *Wind power set to sail again*. 19–20. London: Institute of Marine Engineers
- MarineTraffic.com. (2015). *Marine traffic. North Atlantic Ocean winds. October 2015*. Author. Available from <http://www.marinetraffic.com/en/>
- Merk, O. (2014). *Shipping Emissions in Ports*. Paris: International Transport Forum.
- Mitsui O.S.K Lines. (2013). MOL starts new sailing rig onshore demonstration test. Retrieved 2015, from <http://www.mol.co.jp/en/pr/2013/13052.html>
- MOL Techno-Trade. (2015). PBCF energy saving device. Retrieved from <http://www.pbcf.jp/>
- National Museum of American History. *Rigged model, auxiliary steamship Savannah*. Retrieved 2015, from [http://americanhistory.si.edu/onthewater/collection/TR\\_319026.html](http://americanhistory.si.edu/onthewater/collection/TR_319026.html)
- NYK Line. (2011, May 25). World's first solar-power-assisted vessel further developed. Retrieved 2015, from [http://www.nyk.com/english/release/1414/ne\\_110525.html](http://www.nyk.com/english/release/1414/ne_110525.html)
- Ohuri Capital Pty. Ltd. (2015). Survey: Renewable energy on cruise ships & passenger ferries. Retrieved 2016, from <https://www.surveymonkey.com/r/28V6CQ2>
- Ouchi, K., Uzawa, K., & Kanai, A. (2011). *Huge hard wing sails for the propulsor of next generation sailing vessel*. Second International Symposium on Marine Propulsors, Hamburg.
- Panasonic Corporation. (2015). *Environment: Green logistics*. Retrieved from <http://www.panasonic.com/global/corporate/sustainability/eco/co2/logistics.html>
- Price charts for HFO and LSMGO 2015 – 2018. (2018). Ship & Bunker. Retrieved from <https://shipandbunker.com/>
- Psarftis, H. N., & Kontovas, C. A. (2008). *Ship emissions study*. National Technical University of Athens.
- Rehmatulla, N., Parker, S., Smith, T., Stulgis, V., & Mitchell, J. (2015). *Barriers to uptake of wind propulsion technologies*. University College London.
- Roberts, K. B. (2018). Cleaner ship fuels will benefit health, but affect climate too. Retrieved from <http://www.udel.edu/udaily/2018/february/shipping-fuel-health/>
- Royal Museums Greenwich. (2015). *Cutty sark*. Retrieved from <http://www.rmg.co.uk/cutty-sark/history/cutty-sark-construction-facts-figures>
- Royal Museums Greenwich. *Steam power*. Retrieved 2016, from <http://www.rmg.co.uk/explore/sea-and-ships/facts/ships-and-seafarers/steam-power>

- Scott, M. (2014, August 1st). Sustainable shipping is making waves. *The Guardian*. Retrieved from <http://www.theguardian.com/sustainable-business/2014/aug/01/sustainable-shipping-is-making-waves>
- SkySails GmbH (SkySails). (2015). Skysails marine. Retrieved from <http://www.skysails.info/english/skysails-marine/skysails-propulsion-for-cargo-ships/>
- Smith, T., Newton, P., Winn, G., & Rosa, A. L. (2013). *Analysis techniques for evaluating the fuel savings associated with wind assistance*. Low Carbon Shipping Conference, 2013. London.
- Smith, T. W. P., Jalkanen, J. P., Anderson, B. A., Corbett, J. J., Faber, J., Hanayama, S., ... Hoen, M. (2014). *Third IMO Greenhouse gas study 2014*. London: International Maritime Organization (IMO).
- Smulders, F. (1985). *Exposition of calculation methods to analyse wind-propulsion on cargo ships*. International Symposium on Windship Technology (WINDTECH'85). Elsevier Science Publishers B.V, Southampton.
- SS Great Britain Trust. (2012). Brunel's ss Great Britain. Retrieved 2015, from <http://www.ssgreatbritain.org/>
- Stena Bulk. (2012) Our take on sustainability. Retrieved 2015, from <http://www.stenabulk.com/en/sustainability/Pages/our-take-on-sustainability.aspx>
- Stopford, M. (2009). Table 6.1 Economics of scale in bulk shipping (including bunkers), in *maritime economics 3rd edition* (p. 224). London and New York: Routledge.
- SY Maltese Falcon. (2015). The maltese falcon. Retrieved from <https://www.symaltesefalcon.com/index.php>
- Teramoto Iron Works Co. Ltd. (1980). *Foldable JAMDA Sail 1980's*. Author.
- Trozzi, C., & Lauretis, R. D. (2016). *EMEP/EEA air pollutant emission inventory guidebook 2016*. European Environment Agency.
- United Nations. (2014) Review of maritime transport 2014. UNCTAD/RMT/2014; Retrieved from <http://unctad.org/en/pages/PublicationWebflyer.aspx?publicationid=1068>
- University of Tokyo. (2015). Wind challenger project. Retrieved from [http://wind.k.u-tokyo.ac.jp/index\\_en.html](http://wind.k.u-tokyo.ac.jp/index_en.html)
- Vessel details for CLUB MED 2. (2018). Retrieved from [https://www.marinetraffic.com/en/ais/details/ships/shipid:175105/mmsi:227194000/imo:9007491/vessel:CLUB\\_MED\\_2](https://www.marinetraffic.com/en/ais/details/ships/shipid:175105/mmsi:227194000/imo:9007491/vessel:CLUB_MED_2)
- Viola, I. M., Sacher, M., Xu, J., & Wang, F. (2015). A numerical method for the design of ships with wind-assisted propulsion. *Ocean Engineering*, 105, 32–42. doi:10.1016/j.oceaneng.2015.06.009
- Wik, C. (2010). Reducing medium-speed engine emissions. *Journal of Marine Engineering & Technology*, 9(2), 37–44. doi:10.1080/20464177.2010.11020234
- Yoshimura, Y. (2002). *A prospect of sail-assisted fishing boats*. Hakodate, Japan: The Japanese Society of Fisheries Science.



© 2018 The Author(s). This open access article is distributed under a Creative Commons Attribution (CC-BY) 4.0 license.

You are free to:

Share — copy and redistribute the material in any medium or format. Adapt — remix, transform, and build upon the material for any purpose, even commercially.

The licensor cannot revoke these freedoms as long as you follow the license terms.

Under the following terms:

Attribution — You must give appropriate credit, provide a link to the license, and indicate if changes were made.

You may do so in any reasonable manner, but not in any way that suggests the licensor endorses you or your use.

No additional restrictions

You may not apply legal terms or technological measures that legally restrict others from doing anything the license permits.



**Cogent Engineering (ISSN: 2331-1916) is published by Cogent OA, part of Taylor & Francis Group.**

**Publishing with Cogent OA ensures:**

- Immediate, universal access to your article on publication
- High visibility and discoverability via the Cogent OA website as well as Taylor & Francis Online
- Download and citation statistics for your article
- Rapid online publication
- Input from, and dialog with, expert editors and editorial boards
- Retention of full copyright of your article
- Guaranteed legacy preservation of your article
- Discounts and waivers for authors in developing regions

**Submit your manuscript to a Cogent OA journal at [www.CogentOA.com](http://www.CogentOA.com)**

