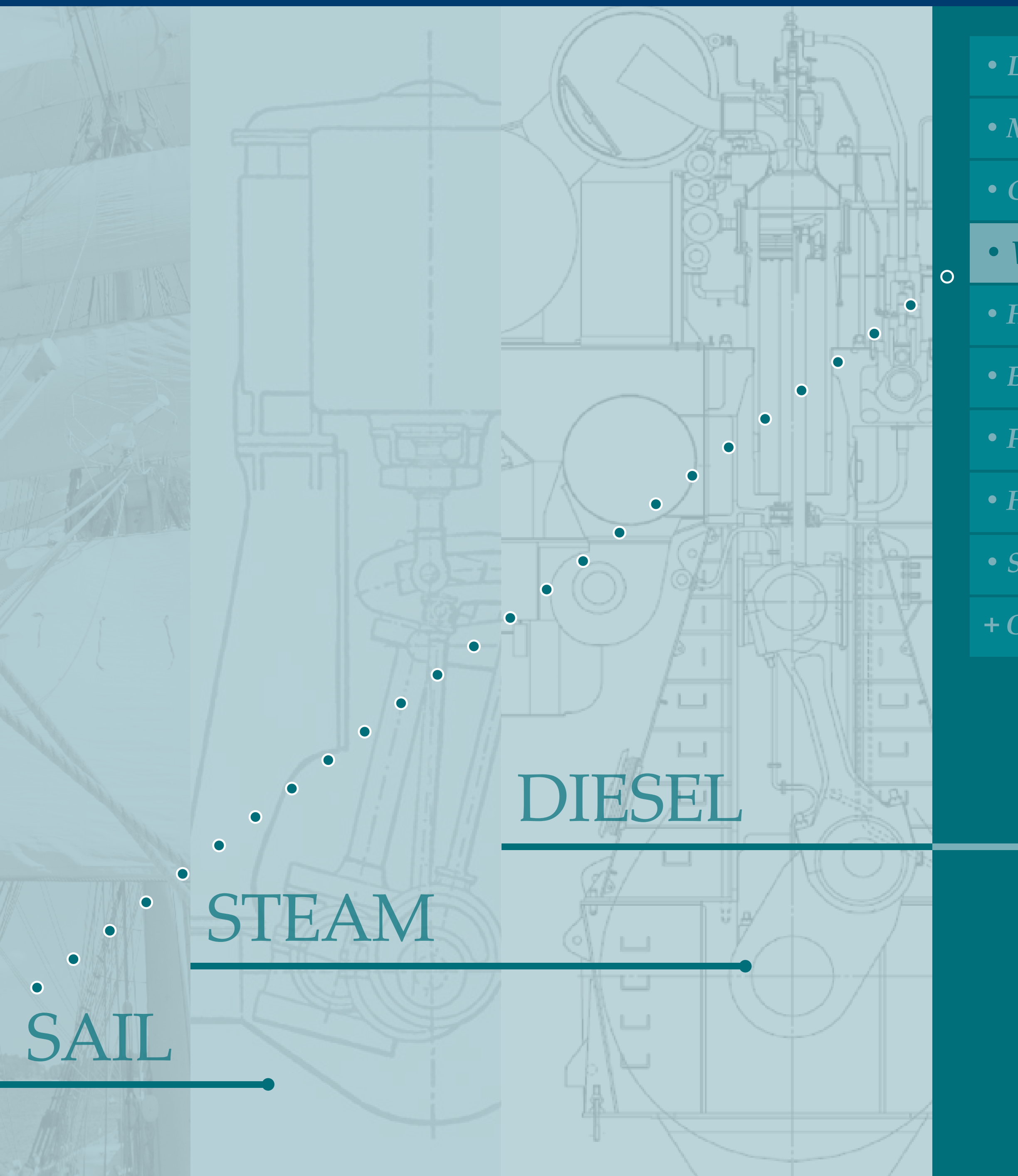
Lloyd's Register Marine

Working together
for a safer world

Wind-powered shipping

A review of the commercial, regulatory and technical factors affecting uptake of wind-assisted propulsion

Understanding technology



- *LNG-as-fuel*
- *Methanol*
- *Gas turbines*
- *Wind power*
- *Hybrid propulsion*
- *Biofuels*
- *Fuel cells*
- *Hydrogen*
- *Solar*

\+ *Other technology*

Contents

Introduction

Commercial and regulatory challenges are driving the development of new technologies and strategies for the design and operation of ships.

To date, most improvements in ship fuel efficiency have been realised through changes in behaviour, such as slow steaming, and reductions in installed power, to meet the Energy Efficiency Design Index (EEDI) requirements. New fuels – mainly LNG – and hybrid technologies have been adopted by North European and North American operators of niche, small or specialised tonnage – such as ferries. Meanwhile, mainstream cargo shipping has yet to make significant technology or operational step changes. And the dramatic decline in the price of oil and ships' bunkers during 2014 has reduced the operators' incentive to reduce energy consumption – for now.

To meet potential demand for lower energy consumption and to reduce carbon emissions, an increased number of energy saving and new technology concepts have been emerging. Many of these concepts are not fundamentally new but benefit significantly from new understanding, materials and methods. One of these old concepts with a new lease of life is wind-assisted propulsion.

Sailing merchant ships reached their technical peak during the 1840s. Clipper ships were superior to early steamships, which were considered inefficient and slow, and sacrificed cargo space for machinery and bunkers. The introduction of the triple expansion engine and, later, the diesel engine, combined with the exponential growth of the merchant fleet (and the need for larger ships), made sailing merchant ships obsolete.

Renewed interest in wind-assisted propulsion in the 1980s was driven, similarly to today, by the oil crisis of the 1970s. But by the time the technology was showing promise, fuel prices had stabilised and put a brake on further development and adoption. It can be argued that, in 2015, wind-assisted propulsion technology faces the same threat – reduced incentive from falling bunker prices – despite its potential double-digit fuel savings. But today, we live in a different world, one where many organisations see additional benefits in reducing their carbon footprint and dependence on fossil fuels – benefits beyond reducing operational costs. In this respect, wind-assisted propulsion offers one of the few realistic options for introducing renewable power into shipping.

While merchant shipping abandoned wind more than a century ago, the technology never stopped developing in the racing yacht sector, to the extent that Americas Cup yachts (the equivalent of Formula One cars) can sail faster than the wind.

For wind-assisted propulsion, the challenge, perhaps, is not developing new technology but taking existing technology in an advanced form and adapting it to merchant shipping. In order to do that, there are commercial, technical and regulatory challenges that need to be addressed, and barriers that need to be overcome.

This report describes and considers these challenges and barriers, and hopefully generates a debate about how wind-assisted propulsion might reach its unfulfilled potential.

1. What is wind-assisted propulsion?

Wind-assisted propulsion is the use of a device, such as a wingsail, soft sail, kite or Flettner rotor, to capture the energy of the wind and generate forward thrust.

The thrust required to propel the ship through the water comes from combining this device with the ship's engine, a process known as 'motorsailing'. This reduces the amount of effective propulsion power needed to achieve a given speed. Wind-assisted propulsion works in one of two[1] ways:

1. It maintains the same ship speed for reduced engine power. This means reduced fuel consumption, costs and CO_2 emissions.
2. It increases ship speed for the same engine power. This means reduced voyage times and, potentially, increased ship profitability.

Wind-assisted propulsion is one of the few ship technologies potentially offering double-digit fuel savings, although the savings claimed by the different wind technologies vary widely, up to the highest claim of 50%. This variation is due not only to the different technology types, but also to the varying options for implementation and the influence of operational factors such as weather conditions and the ship's route.

This report focuses on wind-assisted propulsion technologies that can be highly automated and do not require specialist crew competencies or additional crew numbers. These include:

Wingsails or rigid sails
Similar to aircraft wings, and deployed as single foils or multiple foils attached to a single base. Flaps are often used.

Square rig sail systems ('DynaRig')
Freestanding, rotating spars that carry canvas sails similar to those used by the old square-riggers (clipper ships). The modern version is fully automated and has no rigging on the deck or mast.

Towing kites ('SkySails')
Kites connected to a control pod at the forecastle, deployed at high altitude at sea and recovered to allow passage under structures such as bridges. One or more towing kites can be used.

Flettner rotors
Cylindrical structures mounted on the deck and spun mechanically. The cylinders spin (powered by electrical motors) to use the Magnus effect and generate forward thrust.

Note: this report only examines wind as an auxiliary means of propulsive power. The assumption is that the ship should have sufficient installed power to operate within its intended profile (safely and commercially) without the use of the wind-assisted propulsion device.

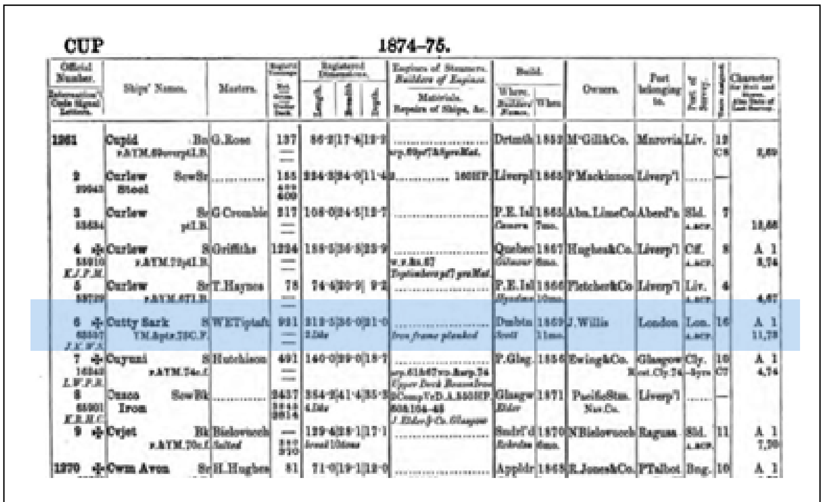
1 Wind generators can also be used to convert mechanical energy to electrical energy. This can be used to reduce the ship's auxiliary power consumption or as an additional energy source in ships with hybrid propulsion systems. In this report, we are focusing on wind as an alternative means of propulsion and we have therefore not examined this concept

2. The history of wind-assisted propulsion

Merchant shipping used wind as the main form of propulsion for centuries, until the arrival of steam and diesel engines. The increased speed and reliability that steam and diesel allowed, and the availability of cheap, high-density energy sources such as coal and oil, made wind propulsion redundant for much of the 20th century (Smith, et al., 2013).

It is now largely forgotten that the last of the famous China clippers (or tea clippers), such as the *Cutty Sark*, could reach peak average speeds of 15 knots[2] under sail alone – faster than much of today's merchant fleet. One of them, the *Flying Cloud*, held the world sailing record for the fastest passage between New York and San Francisco for over 100 years (1854-1989). (Bruzelius, 2003).

The clipper ship, *Flying Cloud*



CUP 1874–75.

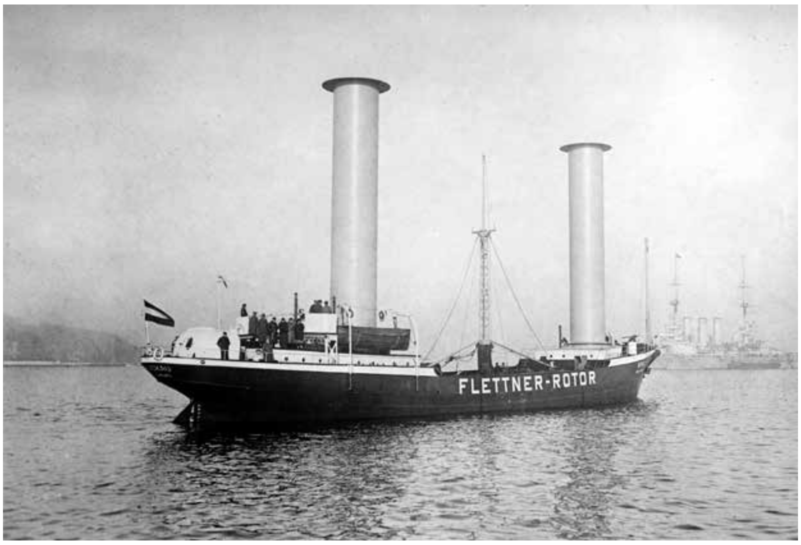
Official Number	Ships' Names	Masters	Tonnage	Length	Breadth	Depth	Engines of Steamers / Materials / Repairs of Ships, &c.	Build: Where	Build: When	Owners	Port belonging to	Port of Survey	Years assigned	Character
1261	Cupid Bn	G.Rose	137	96·2	17·4	12·[illegible]		Drtmth	1852	M'Gill&Co.	Monrovia	Liv.	12 C8	8,69
2 29943	Curlew SowSr Steel	....	155	224·3	24·0	11·4	160HP	Liverpl	1865	P.Mackinnon	Liverp'l	......	—	
3 53484	Curlew Sr	G.Crombie	317	108·0	24·5	12·7		P.E.Isl	1865	Abn.LineCo	Aberd'n	Shl.	7	13,68
4 58910	✠ Curlew S	Griffiths	1234	185·5	36·5	23·9		Quebec	1867	Hughes&Co.	Liverp'l	Cf.	8	A 1 8,74
5 58720	Curlew Sr	T.Haynes	78	74·4	20·9	9·2		P.E.Isl	1866	Fletcher&Co	Liverp'l	Liv.	4	4,67
6 63557	✠ Cutty Sark S	W.E.Tiptaft	921	212·5	36·0	21·0	Iron frame planked	Dmbtn Scott	1869 11mo.	J.Willis	London	Lon.	16	A 1 11,73
7 16849	✠ Cuyuni S	Hutchison	491	140·0	29·0	18·7		P.Glag.	1856	Ewing&Co.	Glasgow	Cly.	10	A 1 4,74
8 65901	Cuzco SowBk Iron	....	3437	384·2	41·4	35·[illegible]	Comp.VrD.A.550HP	Glasgw Elder	1871	PacificStm. Nav.Co.	Liverp'l	......	—	
9	✠ Cvjet Bk	Bielovucich	—	129·4	28·1	17·1		Sndrl'd	1870	N.Bielovucich	Ragusa	Shl.	11	A 1 7,70
1270	✠ Cwm Avon Sr	H.Hughes	81	71·0	19·1	12·0		Appldr	1865	R.Jones&Co.	P.Talbot	Bng.	10	A 1

An extract from the Lloyd's Register of Ships 1874-75 showing *Cutty Sark*, one of the last tea clippers and one of the fastest, before sail gave way to steam

2 The fastest logged speed on the Cutty Sark was 17 knots and the greatest distance recorded over 24 hours was 363 nautical miles (15.1 knots average).

2.1 The development of wind-assisted propulsion

The concept of wind-assisted propulsion emerged in the 1920s, with the construction of two Flettner rotor ships in Germany – *Buckau* and *Barbara*.



Flettner rotor ships in the 1920s – *Buckau* (above left) and *Barbara* (left, under a Creative Commons license)[3]

The high oil prices in the 1970s brought renewed interest in wind-assisted propulsion and incentivised significant research, especially in Japan. This led to some remarkable projects, such as the *Shin Aitoku Maru* (a 70-metre tanker), the *Usuki Pioneer* (a 26k dwt bulk carrier) and the *MV Ashington* (a 6,600 dwt bulk carrier, trialled between 1986 and 1987).

Different versions of rigid sails (wingsails) were used for these vessels ('JAMDA'[4] in Japan and the 'Walker' wingsail in the case of *MV Ashington*). The success of *Shin Aitoku Maru* led to another 17 vessels being built up to 1994 using a similar technology (Schönknecht & Laue, 1987).

3 Buckau image at: http://commons.wikimedia.org/wiki/File:Buckau_Flettner_Rotor_Ship_LOC_37764u.jpg.
Barbara image: Rotor ship "Barbara" by Erich Sidow, licensed under the Creative Commons license "Attribution Share Alike 2.0 Germany"

4 Japanese Marine Machinery Development Association

Wind-assisted propulsion using wingsails in the 1980s. Clockwise from top:

***MV Ashington* with a Walker wingsail (Copyright FotoFlite)**

***Shin Aitoku Maru* with a JAMDA wingsail (under a Creative Commons license[5])**

***Usuki Pioneer* (pictured while named *Swift Wings*) with a JAMDA wingsail. (Copyright Keith Edney).**

5 Image at http://entsyklopeedia.ee/galerii/purjelaev1 and licensed under a Creative Commons Attribution-Noncommercial-Share Alike license

Despite these projects demonstrating significant savings, the interest in wind-assisted propulsion was abandoned when oil prices collapsed in the late 1980s.

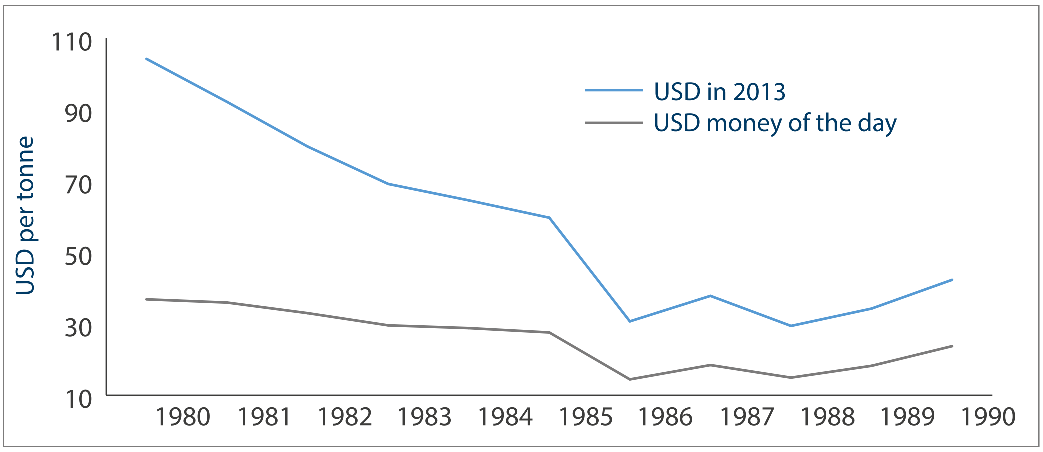


Figure 1: Historical crude oil prices in the 1980s. (BP, 2014)

The following two extracts are quite representative of the changing sentiment towards wind-assisted propulsion during the 1980s as a result of oil prices:

1982
"…the utilisation of wind energy for the propulsion of ships is so obvious and necessary that the utilisation of wind energy will succeed during the next decade. Contrary to the land situation, there will be no alternative energy sources available for shipping in the foreseeable future." (Kurmin & Bernaerts, 1982)

1988
"Our board takes the view that due to the low cost of marine bunkers and limited availability of "useable wind" on our trading routes, the wingsail does not currently satisfy our payback criteria". Extract from the evaluation report of the original Walker wingsail by *MV Ashington*'s owners (Stephenson Clarke Shipping Limited, 1988).

3. The technology today

Today, wind-assisted propulsion concepts combine proven principles with advances in automation, control systems, weather routeing and materials, while advances in computational fluid dynamics (CFD) and wind tunnel testing enable their performance to be predicted and optimised more reliably.

Most of today's technologies have been applied or trialled at full scale in the past or are a modern evolution of an older concept. For example, the wingsails proposed today are an evolution of the Walker wingsail and the JAMDA technology used in the 1980s (see pages 6 and 7).

Another interesting example is the DynaRig, developed by W Prolls in the 1960s and evolved from the original square rig technology used on the Clipper vessels. (Perkinks, et al., 2004).

Some wind technologies are operating on ships today (or have been until very recently). These include the DynaRig on the 88m superyacht *Maltese Falcon*, the Flettner rotor installation on *E-Ship 1* (an 11,000 dwt roll-on/lift-off cargo vessel) and the towing kite on the 474 teu *BBC SkySails*.

Wind-assisted propulsion technologies in operation today, or until very recently. Clockwise from top left:

Flettner rotors on board *E-Ship 1* (under a Creative Commons license[6])

The towing kite on board *BBC SkySails* (Copyright SkySails)

The DynaRig on board *Maltese Falcon* (Copyright COCHLIAS SAM, photograph by Ed Wright).

6 Cargo E-Ship 1, the port of Emden, CN-02 by Carschten, licensed under the Creative Commons license "CC BY-SA 3.0 de"

3.1 The four technologies and their operating principles

The following is a brief overview of each technology and its operating principles:

Wingsails or rigid sails
Unlike traditional sails, which are flexible, these are wing-shaped foils with varied geometry and configurations. They can be deployed as single foils or multiple foils attached to a single base. Flaps are often used. Depending on the size of the vessel, the available deck space and other restrictions, multiple sets can be deployed.

The operating principle is the same as any aerofoil: when moved through a fluid it produces an aerodynamic force consisting of lift and drag. By rotating to the optimum angle of attack, the lift can be maximised. Wingsails can also be used as 'brakes' to slow down the vessel, if needed, instead of using the engine astern.

Square rig sail systems (DynaRig)
These are freestanding, rotating spars that carry canvas sails similar to those used by the old square-riggers (clipper ships). The modern incarnation is fully automated and has no rigging on the deck or mast.

For the Maltese Falcon, high-end carbon composite materials were used (Perkinks, et al., 2004). However, in commercial shipping (where weight and stability are less critical), spars can be manufactured from steel to reduce cost.

While traditional square rigs were limited in how they were positioned to the optimum angle of attack, the DynaRig concept overcomes this by having a rotating spar. Although the lift coefficients may be lower than wingsails, this is compensated for by the larger surface (sail) areas, resulting in large lift forces being generated.

Towing kites
These are kites connected to a control pod at the forecastle, deployed at high altitude at sea and recovered to allow passage under bridges or through other navigational constraints. One or more towing kites can be used. The system comprises a towing kite fabricated from high-strength textile, a towing rope, a launch and recovery system, and a control system for automated operation. (SkySails Marine, 2014)

While wind speed is reduced near the water surface (due to water-air boundary effects), kites fly at higher altitudes and therefore benefit from higher wind speeds. (The TARGETS Consortium, 2014)

Flettner rotors
These are cylindrical structures (fixed, telescopic or collapsible), mounted on the deck and spun mechanically. Using motors powered by the ship's electrical supply, the cylinders spin to use the Magnus effect and generate forward thrust.

When wind passes across a rotating cylinder a lift force is produced. This force has a linear relationship with wind speed and, unlike conventional sails or aerofoils, a true cross-wind relative to the ship will produce a useful forward thrust at any ship speed even when this is greater than the wind speed. However, the vorticity produced by a rotor and its interaction with other rotors or the vessel's superstructure is complex and requires a detailed assessment (using CFD) in order to evaluate the performance of the technology. (Royal Academy of Engineering, 2013)

3.2 Current status of technologies

A number of wind technology projects and concepts are under development. Their maturity level varies from full scale demonstration projects (very few) to research projects, concepts or ideas. A few technologies are commercially available. Due to the rapidly evolving nature of wind-assisted propulsion technology, this report does not directly compare specific systems or even similar technologies. All the technologies have their own merits and their success relies not necessarily on exploiting these merits but on addressing some of the challenges involved in their implementation (discussed in Sections 4 and 6).

Instead, Table 1 details the current status of the four wind-assisted propulsion technologies covered by this report and lists the technology providers, projects and concepts associated with them. Because LR is bound by Non-Disclosure Agreements (NDAs) with a number of technology companies, we only include projects that are in the public domain, i.e., those which have a website.

The list of providers, projects and concepts is validated against information kindly provided by Mr Patrick Englebert (Englebert, 2014), CEO of PROPELWIND and founding member of the International Windship Association (IWSA)[7].

The range of suggested fuel savings in Table 1 is derived by combining upper and lower estimates quoted by the different technology providers, and needs to be considered alongside the factors affecting performance, discussed in Section 4.1. Potential fuel savings are not the only parameter for technology selection.

Technology	Quoted fuel savings	Current status	Technology providers / concepts / projects (with website links)[8]
Wingsails or rigid sails	10% – 40%	A large number of concepts and technologies are presently commercially available or being considered. Some systems have been tested either at model scale (in a wind tunnel) or with CFD. In some instances, structures have been fabricated. No full-scale installation is currently operational.	• **Eco Marine Power Aquarius MRE** • **MOL Power Assist Sail** • **Oceanfoil** • **Ocius Technology** • **PROPELWIND** • **Seagate delta wing sails** • **Turbosail Pte Ltd.** • **University of Tokyo Wind Challenger Project** • **Windship Technology Ltd.**
Square rig sail systems (DynaRig)	Up to 50%	Two new ship concepts are currently considering the use of the DynaRig at the newbuild stage (the B9 Shipping Project and the Ecoliner concept by Dykstra Naval Architects). The technology is not marketed for retrofits. DynaRigs have been operational on the Maltese Falcon since 2006.	• **B9 Shipping** • **Dykstra Naval Architects**
Towing kites	10% – 35%	There are two operational installations, one prototype and at least three projected or currently in production (SkySails Marine, 2014).	• **beyond the sea** • **SkySails Marine**
Flettner rotors	10% – 35%	A number of technologies are commercially available. A single installation on *E-Ship 1* has been operational since 2010. Since December 2014, a trial has been underway on the *M/V Estraden*, a 9,700 dwt ro-ro (Norsepower Oy Ltd, 2014)	• **Magnuss Voss** • **Norsepower Oy Ltd** • **Thiiink** • **Wind Hybrid Coaster (MariTIM project)**

Table 1: Status of wind-assisted propulsion technologies and technology providers (as of November 2014)

7 The IWSA was established in November 2014, with the aim of encouraging, advising and advocating for the use of wind propulsion technologies in the shipping industry. ISWA's website – http://wind-ship.org/ – contains useful resources on wind propulsion.

8 Presented in alphabetical order and validated using information kindly provided by Mr Patrick Englebert of PROPELWIND.

4. Technical considerations

4.1 Performance

The performance of wind-assisted propulsion systems is influenced by a number of technical and operational factors, summarised in Table 2. These factors make it difficult to pinpoint a single percentage figure for estimated fuel savings – a figure which is often the basis for payback period calculations.

Performance factor	Consideration
Type of technology	For example, whether a Flettner rotor, wingsail, DynaRig or towing kite is being used.
Design and implementation	Similar technologies can be designed and applied in different ways; for example, there are a number of different variants of the wingsail/rigid sail concept. Even for the same technology and system, the performance is likely to vary between different installations and as the design becomes more mature.
Efficient operation	The degree of automation and crew interference can influence performance. If a technology is fully automated, the optimum performance will be determined by how 'intelligently' the system is designed. On the other hand, if a certain degree of flexibility is offered, then the master's 'sailing' skills and their ability to interpret the available information (routeing, weather) will affect the savings that can be achieved.
Size and footprint of installation	Factors such as the number of units (e.g., rigs, rotors, kites or wingsails), the sail surface and the mast height will have a significant influence on performance.
Vessel type and size	The number of units that can be installed depends on available deck space, which is affected by ship size and type (for example, a tanker versus a geared bulk carrier). Ship type and size also determine operational speeds, which, in turn, have a large bearing on likely performance gains.
Retrofit or newbuild	Performance can be optimised if the technology is designed together with the ship, for example by optimising the hull form for 'motorsailing' or incorporating appendages (such as retractable keels). The design point of the propeller can also be optimised for wind-assisted propulsion, creating greater performance potential for new designs as opposed to retrofits.
Hull design	The design of the hull and/or the existence of a bulbous bow can affect performance when motorsailing. Further optimisation can be achieved if a hull is designed for a specific route (for example, a hull might be optimised for upwind performance in a route with predominantly head winds).
Performance losses through the system	The effects of aerodynamic drag, additional hydrodynamic drag as a result of heel, and parasitic load for motors (in the case of Flettner rotors) need to be subtracted from any projected performance gains.
Weather conditions	Wind speed and direction and sea state will affect the performance of a technology. In some cases, a technology may no longer be able to be used (for example, over a certain wind speed) and will need to be 'neutralised' for safety reasons. Different technologies will be affected by different conditions: Flettner rotors by beam winds; wingsails by headwinds; and towing kites by winds from the stern.
Vessel's route	Certain routes have more favourable predominant winds than others and this will have a major impact on performance. Given routes can also be optimised for wind-assisted propulsion as opposed to for conventionally-powered vessels, where the preferred route is normally the shortest distance between the origin and the destination (known as the rhumb line). With wind-assisted propulsion, a vessel can choose to deviate from this route to take advantage of favourable winds (in terms of speed and direction). (Smith, et al., 2013)
Vessel's speed profile	Optimum performance is typically found at lower speeds but the optimum speed range will vary with the technology. As vessel speed increases so does the proportion of headwind in the apparent wind. This reduces the lift generated by certain technologies, and some technologies may perform better than others in this respect. Headwind performance is also related to the overall hull design, not just the technology itself.

Table 2: Some of the factors affecting the performance of wind-assisted propulsion technology

Table 2 demonstrates that direct comparisons between technologies can be misleading. Performance can only be assessed credibly on a case-by-case basis, for a specific vessel, route and technology. This can be done at model scale (for example, through wind tunnel tests) or using CFD. Ideally, the desktop assessment should be followed by a full-scale trial.

Of course, such a comprehensive assessment is costly and this is one of the main barriers to the adoption of wind-assisted propulsion.

4.2 Safety

While performance and expected fuel savings are important when considering investing in wind-assisted propulsion, safety is of equal (if not greater) importance to ship operators.

Failure to address safety concerns at an early stage in the design process can act as a deterrent to the adoption of otherwise promising technologies and concepts.

Some wind-assisted propulsion systems are expected to be novel or complex designs, and prescriptive requirements may not fully apply to them or even exist. Some examples are provided in Section 4.3.1.

If wind-assisted propulsion systems are being installed on an LR classed ship, LR needs to be satisfied that they will not adversely affect the safe operation of the ship or the safety of its crew, either during normal operation or following failure. LR therefore requires that the risks to the ship's occupants and to the safe operation of the ship are assessed through a structured risk assessment, which must be reviewed and accepted by LR.

To enable and promote innovation and application of novel technologies, LR has developed a robust methodology, called Assessment of Risk Based Designs (ARBD), which is incorporated into our Rules for Ships. ARBD is fully aligned with the requirements for Alternative Designs and Arrangements contained in the Safety of Life At Sea (SOLAS) Convention (II-1 Reg. 55, II-2 Reg. 17 and III, Reg. 38).

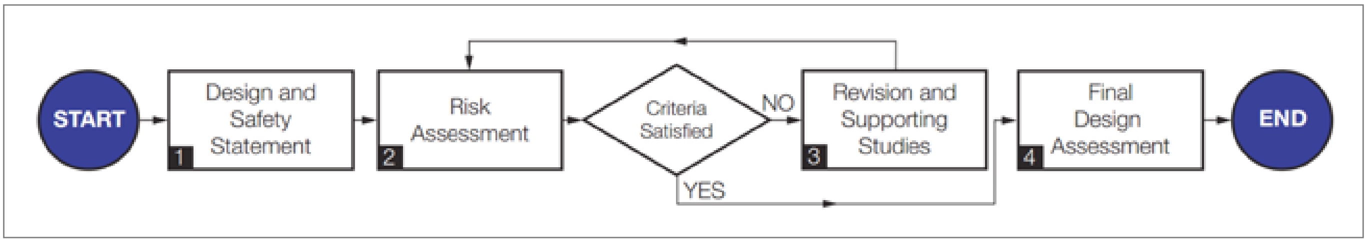


Figure 2: LR's generic process for the Assessment of Risk Based Designs (ARBD)

Each installation will need a specific appraisal to ensure compliance with classification and statutory requirements. As the technology matures and experience is gained, prescriptive Rules and guidance are expected to be developed.

Table 3 details some of the high-level safety aspects that can be considered (Lloyd's Register, 2008).

4.3 Applicability of existing regulations

4.3.1 What happens in cases of non-compliance with statutory requirements

While, in general, risk-based techniques can be applied in order to demonstrate that an equivalent level of safety is achieved, there may be cases where compliance with statutory requirements is challenging. This is because some requirements (for example, SOLAS) have not been designed from the outset with wind-assisted ships in mind.

At this point, it is important to appreciate the dual role that classification societies have in approval and certification of wind-assisted propulsion systems:

Classification role: A classification society which the ship is registered with will need to carry out a design appraisal and certification of the proposed installation. This is in accordance with the classification society's Rules and Regulations.

Recognised organisation (RO) role: Most classification societies act as ROs and are authorised to undertake approvals and certification on behalf of the national authority (flag administration) that the ship is registered with. This is in accordance with international conventions such as SOLAS.

When acting as an RO, a classification society can undertake approvals on behalf of the administration and issue certificates. In the case of LR, this is covered under agreements held with most administrations and it is a 'business as usual' scenario.

However, in cases of potential non-compliance, a classification society cannot make a decision on behalf of the administration. The classification society can provide a technical opinion, but the final decision rests with the administration.

In practice, this means that interested parties, such as technology providers, yards, owners and operators, need to present a proposal to the administration demonstrating how an equivalent level of compliance can be achieved.

Consideration	Details
Stability	The system should satisfy stability requirements (for example, SOLAS) of the national authority (flag) the vessel is registered with.
Visibility and COLREGS[9]	Similarly, compliance with visibility and COLREGS requirements within SOLAS, and any national authority (flag) requirements needs to be satisfied.
Installed engine power	The installed power should be sufficient to ensure adequate manoeuvrability in all conditions, including when the wind-assisted propulsion system is inoperative. It should also be able to operate in all conditions of heel and trim which may result from the operation of the wind-assisted propulsion system.
Control systems	A control system should allow setting and adjustments to be carried out from the bridge, and, once set, to be automatically maintained. It should also provide adequate speed of response to automatically neutralise the sail system in the event of wind conditions which may damage the sail system and endanger the ship.
Fire safety	In the case of ships carrying cargoes or fuels that have a low flash point or are hazardous, the construction material of sail systems, their ancillary and control systems and their location in relation to the hazardous areas should minimise the risk of ignition of flammable vapours or gases.
Masts, posts and supporting structures	These should have adequate strength to resist the highest design loading imposed by the sail systems in normal and emergency working conditions. Design, construction, stiffening and thickness of masts and posts should be adequate to prevent buckling under all conditions of loading.
Integration with the hull structure	In general, it is envisaged that system supporting masts and structures will be carried through the main strength deck and, if required, extended below to a second deck or equivalent structure. The hull structure should be reinforced and stiffened locally to ensure adequate strength and resistance to plate buckling.

Table 3: Some safety considerations for wind-assisted propulsion

4.3.2 Example: bridge visibility

A typical example is compliance with the visibility provisions of SOLAS (Regulation 22, Navigational Bridge Visibility). These stipulate specific requirements for the field of vision and extent of blind sectors from the bridge. For most vessels with the bridge positioned aft, many wind-assisted propulsion systems (wingsails, Flettner rotors, rigs) will inevitably obstruct the field of vision to an extent that makes it challenging or even impossible to meet these requirements. This is especially true in systems with multiple masts and structures.

9 International Regulations for Preventing Collisions at Sea

In cases like these, Regulation 22 does allow for ‘equivalent arrangements’: “On ships of unconventional design which, in the opinion of the Administration, cannot comply with this regulation, arrangements shall be provided to achieve a level of visibility that is as near as practical to that prescribed in this regulation.”

Such an equivalent arrangement could, in theory, be a combination of remote cameras and sensors. But while cameras have been used in the past, this has been to mitigate against lack of visibility from the bridge wing during docking, not necessarily for continuous navigation. The effectiveness of cameras under poor visibility conditions (for example, fog) or during night navigation is also a major concern. So, if cameras are to be employed, they need to provide an adequate degree of redundancy and operate continuously and satisfactorily under a range of environmental and light conditions.

Today’s advances in camera and remote sensing technology may help overcome these challenges. In any case, it is important that technology providers engage in early conversations with administrations and understand their position before investing resources in developing a solution.

In addition, and before even developing a technical solution to deal with a case of non-compliance, all avenues to minimise the extent of non-compliance need to be explored and exhausted. In the case of visibility, this may mean re-positioning or adjusting the dimensions of the sail system. This of course has an impact on performance, so it becomes a multi-dimensional problem to solve.

4.4 Operation

Operating a wind-assisted propulsion system can have safety and performance implications and should be considered in the context of the technical considerations discussed so far. While, under an engineering logic, it is preferable to eliminate risks (safety or performance-related) by design, it is often impossible (or too expensive) to achieve this in practice. A degree of ‘residual’ risk will need to be managed in operation. Operational ‘side effects’ are not always negative, however; sail-systems can be used to improve vessel control and manoeuvrability.

4.4.1 Training, competence and automation

Crew training and competence are vitally important, regardless of the degree of automation or ‘intelligence’ built into a wind-assisted propulsion system. The crew must be able to respond in the event of an emergency, and manually override the system if necessary.

While performance can be optimised automatically under normal operation, the ship’s master may also be able to achieve better performance by applying their ‘sailing skills’ and interpreting routeing and weather information. This is no different than the operation of conventionally-powered ships where, despite the advances in information systems and technology, ship operators often report significant differences in the fuel consumption of sister vessels, which they attribute to masters’ competence.

4.4.2 Air draft and cargo operations

The presence of large structures on deck means that air draft needs to be carefully monitored, especially for systems that are not retractable or that extend beyond the maximum mast height. In some cases, the vessel’s available routes may be restricted (to ports without bridges, for example), making some systems unattractive for vessels trading on a spot market.

Deck structures can also affect cargo loading and discharging operations. Unless the sail system is retractable, it will need to be designed to withstand reasonable contact from cargo cranes. It should also minimise obstruction to cargo holds. For ships designed to serve specific terminals with dedicated cargo gear, some of these issues need to be addressed at the design stage. Again, this may inhibit their ability to trade globally.

Ultimately, there will be a trade-off between operational flexibility and performance (which is strongly linked with the size and positioning of the sail system). An efficient design process should be employed to minimise this trade-off.

4.4.3 Directional stability and manoeuvrability

Directional stability and manoeuvrability are critical operational aspects related to wind-assisted propulsion technology, and are often overlooked when increased emphasis is placed on performance.

With regards to directional stability, Flettner rotors, for example, have been observed to cause difficulty in steering at low ship speeds (around six knots), and may need to be neutralised (i.e., stop rotating). Alternatively, this effect can be compensated by continuous rudder adjustments, although this will increase drag (and reduce efficiency). (Pearson, 2014).

With regards to manoeuvrability, and especially during berthing and unberthing, most ship masters and pilots will testify that large deck structures generate significant wind forces. These forces need to be compensated for in order to balance the ship and control her lateral movement and rate of turn. This is achieved by using tugs or the ship's control devices (rudder, propeller and bow and stern thrusters, if available). Each ship behaves differently in this respect and it is critical that masters and pilots are familiar with the manoeuvring characteristics of sail-assisted ships.

On the other hand, some wind-assisted systems can be adjusted so that they will act as a 'brake' and help maintain control at slow speeds (something that is particularly challenging for larger vessels). This allows the propeller to be operated at a higher speed, increasing the flow to the rudder and making the ship more responsive. This feature can be particularly useful when navigating in restricted waters. In an even more advanced scenario, one could argue that sail systems can be operated in a 'manoeuvring' mode, where, by rotating into certain angles, they can generate lateral forces in the desired direction (to push or lift the bow and stern and therefore assist tugs or even render them obsolete).

As well as undesirable lift forces, large structures on deck will generate undesirable drag. At low speeds and for ships with limited reserves of installed power – for example, ships where installed power has been reduced in order to comply with the Energy Efficiency Design Index (EEDI)[10] – this may compromise manoeuvrability under adverse conditions. Conversely, additional drag can improve vessel control downwind.

4.4.4 Heel, seakeeping and vibration

Some systems may generate undesirable levels of heel, with adverse effects on crew and passenger comfort or cargo safety. The level of heel may be negligible for larger vessels in laden condition but could be significant for smaller vessels or vessels with critical stability issues. Ideally, the effect of wind-assisted propulsion systems on heel and the general sea-keeping performance of the ship should be investigated at the design stage.

The induced vibration from sail systems also needs to be investigated. The effects can be adverse (increased vibration affecting crew and passenger comfort or compromised machinery performance) or positive (reduced vibration). Although the effects will be operational, they will need to be investigated at the design stage.

10 The EEDI is a mandatory requirement for new ships. See Section 5.2 for more details.

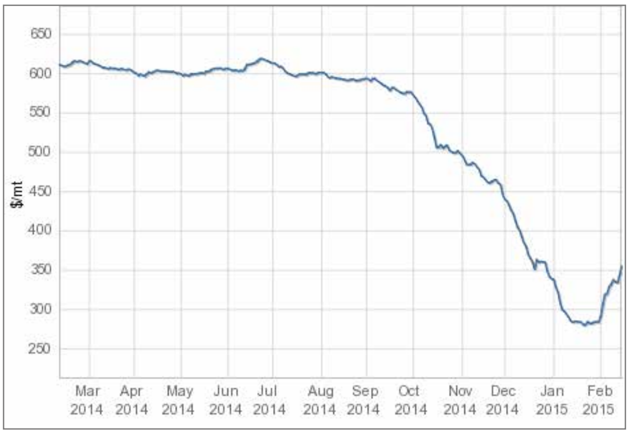
5. Drivers

5.1 Commercial

5.1.1 Bunker prices

The main commercial driver for wind-assisted propulsion is fuel cost, which, at high bunker prices, is a significant proportion of a ship's operational costs. This is the same as for any technology which offers fuel savings in return for a capital investment.

In a resource-constrained world, it may appear safe to assume that marine bunker prices will "always go up". But during 2014, we experienced a drop in the price of bunkers, as demonstrated in Figure 3[11].



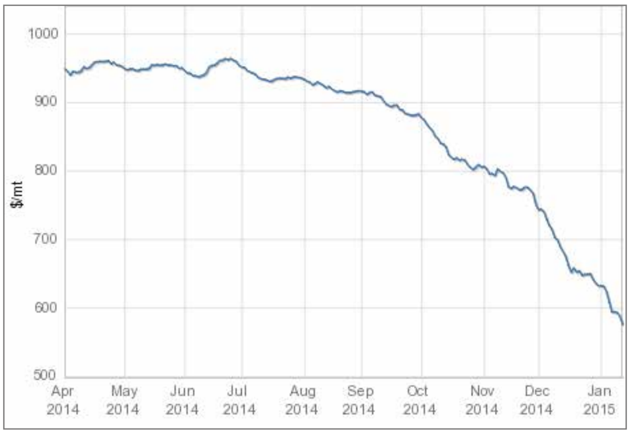


Figure 3: Average bunker prices for heavy fuel oil (left) and low- sulphur fuel oil (right) between March 2014 and February 2015. (Source: www.bunkerworld.com/prices)

Whether this drop is going to be sustained or not is uncertain. Especially for low-sulphur fuel, the upcoming requirement for 0.10% sulphur fuel in emission control areas from January 2015 is likely to lead to an upward spike in prices. If past experience is anything to go by, the sensitivity of the payback period in relation to fuel prices is critical.

In Table 4, we have chosen to represent the payback period as a function of:

Daily fuel consumption: this allows comparison between different vessel types and sizes, or different levels of efficiency and operational profiles.

Capital cost: this reflects the variety of technological options and, crucially, how a business case can be affected by cost overruns.

Expected savings: these are the average annual savings. Again, these reflect the variety of technologies and take into account the performance considerations discussed in Section 4.1.

And we have examined three fuel prices:

600 USD/t: this represents what was considered the typical or 'today's' fuel price, up until August 2014.

200 USD/t: this scenario may have appeared remote in August 2014, but not when looking at the latest trends. It is chosen to demonstrate what it would mean for the technology if fuel prices were to collapse, in a similar way to the collapse in the 1980s. It can also be used to evaluate wind-assisted propulsion in a scenario of abundant (and cheap) LNG for shipping.

1,000 USD/t: this is chosen to represent the future. From 2020 or 2025[12] , all ships will need to operate on 0.50% sulphur fuel, of a type (and price) not dissimilar to 0.10% sulphur marine gas oil (MGO), represented by the second graph in Figure 3.

11 Data showing the Bunkerworld Index (BWI) for heavy fuel oil (IFO 380) and low-sulphur (0.10%) fuel oil used for emission control area (ECA) compliance. The BWI is a weighted daily index made up of 20 key bunkering ports. To obtain a representative geographical spread, the ports were selected by size with reference to their geographical importance.

12 Subject to an IMO decision related to fuel availability, due in 2018

A quick glance at Table 4 indicates, for example, that while most '10%' technologies would be financially unattractive for 200 – 600 USD/t prices, they could become commercially viable at higher fuel prices.

Fuel price	Tonnes per day	Payback period at 10% saving (yrs)			Payback period at 30% saving (yrs)			Payback period at 50% saving (yrs)		
	CAPEX (USD millions)	1	3	5	1	3	5	1	3	5
200 USD/t	10	25.0	75.0	125.0	8.3	25.0	41.7	5.0	15.0	25.0
200 USD/t	30	8.3	25.0	41.7	2.8	8.3	13.9	1.7	5.0	8.3
200 USD/t	50	5.0	15.0	25.0	1.7	5.0	8.3	1.0	3.0	5.0
600 USD/t	10	8.3	25.0	41.7	2.8	8.3	13.9	1.7	5.0	8.3
600 USD/t	30	2.8	8.3	13.9	0.9	2.8	4.6	0.6	1.7	2.8
600 USD/t	50	1.7	5.0	8.3	0.6	1.7	2.8	0.3	1.0	1.7
1,000 USD/t	10	5.0	15.0	25.0	1.7	5.0	8.3	1.0	3.0	5.0
1,000 USD/t	30	1.7	5.0	8.3	0.6	1.7	2.8	0.3	1.0	1.7
1,000 USD/t	50	1.0	3.0	5.0	0.3	1.0	1.7	0.2	0.6	1.0

Table 4: Payback periods as a function of expected average savings, daily consumption, technology CAPEX and fuel price (assuming 200 days a year at sea[13])

5.1.2 Market size for wind-assisted propulsion technology

Different wind-assisted propulsion technologies will be attractive to different target markets. As shown in Section 5.1.1, this is determined by:

– the technology CAPEX
– scalability and technical compatibility (in terms of ship type and size)
– expected fuel savings (related to technology performance)
– annual fuel consumption (as a function of daily consumption and days at sea)
– fuel price.

For example, a technology applied on smaller ships (with low fuel consumption and low expected savings) can still be attractive as long as the CAPEX is low and the fuel price is high.

Table 5 can be used to estimate the potential market size for wind-assisted propulsion for bulk carriers and tankers only. We have excluded container ships due to lack of deck space and cargo loading limitations. For example, looking at Table 4, at USD 600/tonne, a technology which costs USD 1 million and has estimated savings of 10% is only attractive to ships with fuel consumption above 30 tonnes a day (payback period < 2.8 years). Therefore, based on Table 5, the market size is about 6,000 ships.

13 This is the average days per sea across the global fleet in 2012, estimated using AIS data. Source: IMO 3rd GHG Study (International Maritime Organization, 2014). Of course, with more favourable market conditions, this can increase.

Ship type	Size category (dwt)	Number of ships (IHS Fairplay)	Number of active ships (Automatic Identification System)	Average at sea consumption (tonnes per day)
Bulk carrier	0 – 9,999	1,216	670	5.5
	10,000 – 34,999	2,317	2,131	17.6
	35,000 – 59,999	3,065	2,897	23.4
	60,000 – 99,999	2,259	2,145	28.8
	100,000 – 199,999	1,246	1,169	42.3
	200,000 – +	294	274	56.3
Oil tanker	0 – 4,999	3,500	1,498	4.3
	5,000 – 9,999	664	577	7.1
	10,000 – 19,999	190	171	10.8
	20,000 – 59,999	659	624	22.2
	60,000 – 79,999	391	381	31.4
	80,000 – 119,999	917	890	31.5
	120, 000 – 199,999	473	447	39.4
	200,000 – +	601	577	65.2
Total	–	17,792	14,451	–

Table 5: Number of tankers/bulk carriers and their average fuel consumption. Source: IMO 3rd GHG Study (International Maritime Organization, 2014)

5.1.3 Energy security

Dependence on fossil fuel energy sources is a major long-term risk for shipping. Increased dependence leaves ship operators at the mercy of price volatility, driven by fuel supply and demand variations. More importantly, perhaps, current and emerging regulations, and especially future policies on carbon, add a further element of uncertainty and business risk.

The power requirements of merchant ships combined with today's expectations of reliability, redundancy and safety mean that wind cannot be considered as a main propulsion option for large ships in the future. However, replacing a proportion of fossil-fuel dependence with a renewable energy alternative (wind) provides an element of energy security. How significant this element is depends, ultimately, on the long term performance of the technology.

5.1.4 Outlook for the world fleet

Not-withstanding segment-specific tonnage variations (and the opportunities and threats they present), the outlook for the growth of the global fleet is positive towards 2020, with a slightly higher rate than the growth of demand for seaborne trade.

If trade demand and fleet capacity grow in parallel, this will only increase the overcapacity we currently observe. This will create cost pressure for shipowners and, arguably, a non-favourable environment for testing novel concepts such as wind-assisted propulsion.

On the other hand, the competitive situation created by overcapacity could also make fuel-efficient and technologically advanced ships more attractive (as a product) and easier to charter. In this way, the technology would be acting as a differentiator.

5.2 Regulatory

The current energy efficiency regulations for new ships (contained in the EEDI) are non-prescriptive, allowing ships to be built using any combination of technology and design as long as they achieve a certain efficiency level. This can be a combination of proven technologies, such as engine technology or hydrodynamic optimisation and devices, or novel technologies, such as wind-assisted propulsion or hull air lubrication.

Design speed reduction (and the associated decrease in installed power) has so far proved a popular option for 'straightforward' compliance with the EEDI.

The efficiency levels stipulated by the EEDI will incrementally increase between now and 2030, requiring 10%, 20% and 30% more efficient ships in 2015, 2025 and 2025 respectively. While for some ship types, such as containerships, this is easily achievable through market-driven design speed reductions, this is not true for a significant proportion of the tanker/bulk carrier fleet.

Due to the non-prescriptive nature of the EEDI, it is difficult to predict which technology will see the largest uptake and whether shipowners and shipyards or designers will consider wind-assisted propulsion as a means of reducing the EEDI. This will depend on how wind-assisted propulsion compares with other options in terms of cost versus EEDI-reduction potential.

5.3 Environmental and societal

According to the 3rd IMO GHG (greenhouse gas) Study (International Maritime Organization, 2014), the CO_2 emissions from the top five ship types were 618 million tonnes in 2012. As Figure 4 shows, this is comparable to the total emissions from Central Europe and the Baltics (Wikipedia, 2014). A 10% reduction in emissions from these five ship types (61.8 million tonnes) is comparable to the total emissions of Finland.

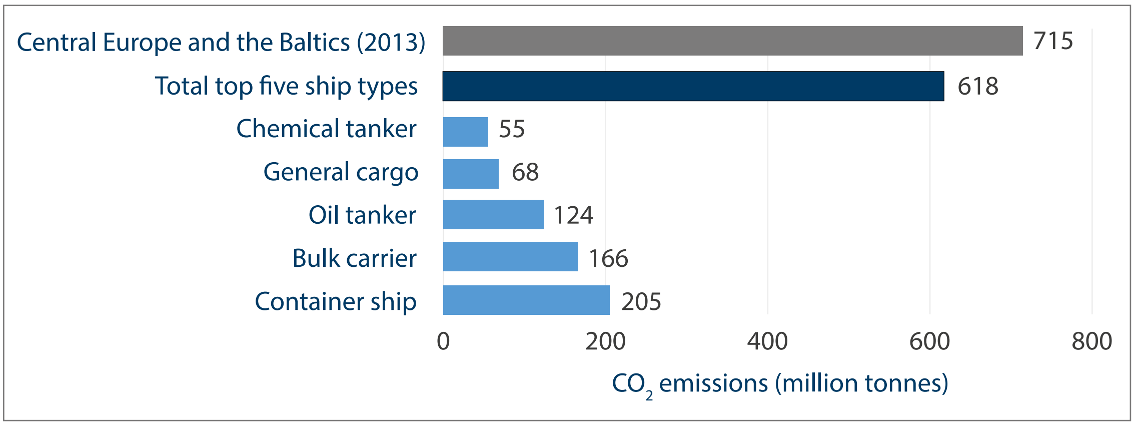


Figure 4: CO_2 emissions by ship type, showing a comparison with land-based emissions.
Source: IMO 3rd GHG Study (International Maritime Organization, 2014)

Increasing public awareness of the environment, and especially climate change, will continue to generate pressure on governments to address these issues through regulatory policy. International shipping is not immune to this pressure. As discussed in Global Marine Fuel Trends 2030 (Lloyd's Register, University College London, 2014), future global carbon policies will have a profound effect on shipping and may even drive the uptake of alternative fuels such as hydrogen from 2025. Although shipping has already responded by adopting a mandatory GHG-reduction mechanism (the EEDI), expected fleet growth indicates that further policies will be required for shipping to align with the 2° C limit on global temperature increase.

It is possible that public awareness and policies combined will create a more favourable environment for the adoption of wind-assisted propulsion.

It can be argued that shipping is an industry which is relatively 'under the radar' considering its size and contribution to the global economy and trade. But with increased public scrutiny of corporations and ever-greater demand for transparency and environmental responsibility, shipping stakeholders are under more pressure to demonstrate their sustainability credentials and transform their promises into action. Wind-assisted propulsion is a technological innovation which can offer significant reputational benefits in this regard.

6. What next for wind-assisted propulsion?

Whether wind-assisted propulsion is adopted more widely in future depends on overcoming the technical, operational and commercial challenges outlined in the previous sections. But in order to fully answer the question of "why a technology offering double-digit savings with short payback is not being adopted" we also need to understand shipping's 'bigger picture'.

Working with Craig Eason of Lloyd's List, we identified seven barriers for the adoption of wind-assisted propulsion in shipping. He concludes that overcoming these barriers will require a "new type of shipowner, one more closely linked to a logistics supply chain". (Eason, 2014)

Barrier 1: Industry structure
The conflict between owners and charterers is well debated (who pays for fuel vs. who pays for investment), and wind-assisted propulsion solutions need high levels of capitalisation. Inability to change charterparty clauses that relate to fuel and speed, or lack of interest in doing so, remains an obstacle.

Barrier 2: Perception
There is a psychological barrier on a potential solution that is so visible and will be associated with a high-profile failure, if things don't go as planned. Shipowners will take market risks, often resulting in ordering too many ships, yet find visible risk-taking such as embracing a novel solution, even on a trial basis, difficult to accept.

Barrier 3: The promises
The large suggested savings from across the board of technology providers are not yet accompanied by substantial reality. It requires more than one or two vessels using solutions to convince the industry that the large investment will deliver a large return.

Barrier 4: Capital intensity for working demonstrators
Technology companies need a significant amount of capital to bring the product to a point where it has been working on full scale for a length of time and can prove its value. Many companies do not have access to unlimited resources. They are rich in intellectual property, but not in capital. This means that other funding/investment options are necessary and some of them (e.g. public funding) have long lead-times.

Barrier 5: Lack of technology transfer
Amazing advancements in the offshore and yacht sectors have not been transferred into commercial shipping. For example, advancements of Formula One racing cars have led to significant advances in ordinary family cars. This development has not occurred in a similar magnitude in commercial shipping.

Barriers 6 and 7: Operational and technical challenges
Operational challenges have been extensively debated in Sections 4.1 and 4.4. In summary, savings from wind-assisted propulsion are route-specific, so the business case is thrown out of the water if the route changes. Vessels on liner trades would be more suited to wind-assisted propulsion, but this, in turn, creates challenges related to air draft and cargo handling. Equally, technical challenges related to performance and safety have been extensively analysed in Sections 4.1, 4.2 and 4.3.

7. Conclusions

Wind-assisted propulsion is one of the few technologies potentially offering double digit fuel savings today.

Although wind cannot be considered a primary means of propulsion for the majority of the merchant fleet, it presents a realistic option for introducing renewable power into shipping by reducing the required propulsion power.

Technological advances in materials, automation and control systems, weather routeing systems, and computational fluid dynamics and wind tunnel testing mean that the industry today is better positioned to overcome some of the challenges presented in the past.

There are strong commercial, societal and environmental drivers favouring the adoption of wind-assisted propulsion, although falling bunker prices reduce potential savings.

Despite the evident drivers, technical challenges related to safety, operation and performance optimisation need to be satisfactorily addressed. Challenges may manifest differently on various technologies.

These challenges, combined with the current structure of the shipping industry, access to capital for working demonstrators and other 'soft' barriers such as perception, have inhibited the adoption of wind-assisted propulsion so far.

Overcoming these challenges and barriers is key to the adoption of wind-assisted propulsion.

Route to market and commercial success may not necessarily be a case of having the 'best' technology 'on paper', but about credibly addressing the challenges described above and managing safety, performance, operational and investment risks.

Lloyd's Register is committed to working closely with technology providers and stakeholders across the supply chain, to overcome these challenges and make wind-assisted propulsion a reality.

8. Recent Lloyd's Register wind-assisted propulsion projects

Lloyd's Register has been working on a number of projects with wind-assisted propulsion technology innovators, especially over the past three years, during which time high fuel prices have incentivised interest in the area.

The majority of these projects are covered by Non-Disclosure Agreements (NDAs)and so the amount of information that can be shared is limited. In many instances, the names of the organisations involved cannot be disclosed. Table 6 contains general descriptions of some of our recent work:

Project	Technology	Details
B9 Shipping	Square rig sail system (DynaRig)	Technical support during the design development and commercialisation of a wind-assisted general cargo ship
Windship Technology Ltd.	Wingsails	Technical support on safety considerations Independent performance assessment of a supramax bulk carrier using CFD tools
Confidential	Wingsails	Technical support on safety considerations to facilitate technology route to market.
Magnuss	Flettner rotors	Review of documents and plans covering the specification, design and components of the VOSS™ system and issuance of a Machinery General Design Approval (MGDA)
Norsepower	Flettner rotors	Plan approval of the pilot installation on board the *M/V Estraden*, a 9,700 dwt ro-ro (LR class) which is currently undertaking trials
Confidential	Flettner rotors	Plan approval of a proposed installation
Confidential	Flettner rotors	Plan approval of a proposed installation
Confidential	Flettner rotors	Plan approval of a proposed installation

Table 6: Lloyd's Register wind-assisted propulsion projects

9. References

1. **BP, 2014. BP Statistical Review of World Energy June 2014. [Online]**
Available at: http://www.bp.com/statisticalreview
[Accessed 17 November, 2014].

2. **Bruzelius, L., 2003. Flying Cloud. [Online]**
Available at: http://www.bruzelius.info/Nautica/Ships/Clippers/Flying_Cloud%281851%29.html
[Accessed 18 November, 2014].

3. **Eason, C., 2014. SMM 2014: seven obstacles to innovation in shipping. [Online]**
Available at: http://www.lloydslist.com/ll/sector/ship-operations/article448092.ece
[Accessed 14 November, 2014].

4. **Englebert, P., 2014. List of wind propulsion projects – November 2014. s.l.:s.n.**

5. **International Maritime Organization, 2014. Third IMO GHG Study 2014 – Final Report (MEPC 67/INF.3), London: International Maritime Organization.**

6. **Kurmin , V. & Bernaerts, A., 1982. Basics for the useage of wind propulsion on sea-going ships, Hamburg, Bremen: Hansa.**

7. **Lloyd's Register, University College London, 2014. Global Marine Fuel Trends 2030, London: s.n.**

8. **Lloyd's Register, 2008. Provisional Rules, Sail Assisted Ships. London: Lloyd's Register.**

9. **Norsepower Oy Ltd, 2014. Press Release: Norsepower starts sea trials of an auxiliary wind propulsion system that maximizes cargo ship fuel efficiency. [Online]**
Available at: http://www.norsepower.com/SiteAssets/news/Norsepower%20Press%20release%202014-12-01%20EN%20SE%20FI.pdf
[Accessed 2 February, 2015].

10. **Norsepower Oy Ltd, 2014. Technology. [Online]**
Available at: http://www.norsepower.com/rotor-sail-solution/technology
[Accessed 11 November, 2014].

11. **Pearson, D. R., 2014. The use of Flettner rotors in efficient ship design. London, The Royal Institute of Naval Architects.**

12. **Perkinks, T., Dijkstra, G., Perini Navi Project Team & Roberts, D., 2004. The Maltese Falcon: the realisation. Delft, The International HISWA Symposium on Yacht Design and Yacht Construction 2004.**

13. **Royal Academy of Engineering, 2013. Future Ship Powering Options, London: Royal Academy of Engineering.**

14. **Schönknecht, R. & Laue, U., 1987. Hochseefrachter der Weltschiffahrt- Band 1. Berlin: Transpress.**

15. **Silvanius, M., 2009. Wind assisted propulsion for pure car and track carriers, Stockholm: KTH Centre for Naval Architecture.**

16. **SkySails Marine, 2014. Skysails propulsion for cargo ships. [Online]**
Available at: http://www.skysails.info/english/skysails-marine/skysails-propulsion-for-cargo-ships/
[Accessed 11 November, 2014].

17. **Smith, T., Paul, N., Graeme, W. & Grech La Rosa, A., 2013. Analysis techniques for evaluating the fuel savings associated with wind assistance. London, Low Carbon Shipping Conference.**

18. **Stephenson Clarke Shipping Limited, 1988. Wingsail Evaluation, Final Report, London: s.n.**

19. **The TARGETS Consortium, 2014. Targeted Advanced Research for Global Efficiency of Transportation Shipping – Technology Report, Hamburg: The TARGETS Consortium**.

20. **Wikipedia, 2014. List of countries by carbon dioxide emissions. [Online]**
Available at: http://en.wikipedia.org/wiki/List_of_countries_by_carbon_dioxide_emissions
[Accessed 2014 November 20].

Lloyd's Register
Marine

For further information please contact:

Dimitris Argyros
Lead Consultant, Environment and Sustainability
Lloyd's Register Group Limited
Southampton, UK

T +44 (0) 330 4140 084
E dimitris.argyros@lr.org
W www.lr.org/windpower

www.lr.org/windpower

February 2015
Cover image: steam engine detail taken from The Marine Steam Engine by Richard Sennett and H. J. Oram