IRENA
International Renewable Energy Agency

RENEWABLE ENERGY OPTIONS FOR SHIPPING

TECHNOLOGY BRIEF



JANUARY 2015

Copyright © IRENA 2015
Unless otherwise indicated, material in this publication may be used freely, shared or reprinted, so long as IRENA is acknowledged as the source.

ABOUT IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. www.irena.org

ACKNOWLEDGEMENTS

The research for this technology brief was led by Peter Nuttall and Alison Newell of the University of the South Pacific. The brief benefitted from valuable inputs and review from Gavin Allwright (Greenheart Project), Alice Bows-Larkin (Tyndall Centre for Climate Change Research, University of Manchester), Diane Gilpin (B9 Shipping), Christophe Rynikiewicz (University of Sussex), Tristan Smith (The Energy Institute, University College London) and Michael Traut (Tyndall Centre for Climate Change Research, University of Manchester)

Authors:

Linus Mofor (IRENA)
Peter Nuttall and Alison Newell (The University of the South Pacific)

For further information or to provide feedback, please contact: Linus Mofor, IRENA Innovation and Technology Centre.

E-mail: *LMofor@irena.org* or *secretariat@irena.org*.

Disclaimer

While this publication promotes the adoption and use of renewable energy, the International Renewable Energy Agency does not endorse any particular project, product or service provider. The designations employed and the presentation of materials herein do not imply the expression of any opinion whatsoever on the part of the International Renewable Energy Agency concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries.

INSIGHTS FOR POLICY MAKERS

The shipping industry is the backbone of global trade and a lifeline for island communities, transporting approximately 90% of the tonnage of all traded goods, as estimated by the International Chamber of Shipping. According to the United Nations Conference on Trade and Development (UNCTAD), the global shipping tonnage loaded annually increased from 2.6 billion to 9.5 billion tonnes between 1970 and 2013. The demand for shipping is predicted to grow further, owing to the changing configuration of global production, the increasing importance of global supply chains and the expected growth in many economies. Also for the foreseeable future, seagoing ships will continue to carry the bulk of that trade.

The energy source for the propulsion of ships has undergone significant transformations over the last 150 years, starting with sails (renewable energy) through the use of coal to heavy fuel oil (HFO) and marine diesel oil (MDO), now the dominant fuel for this sector. The consumption of these fuels has been increasing over the years in line with rising demand for shipping. The International Maritime Organisation (IMO) estimates that between 2007 and 2012, on average, the world's marine fleet consumed between 250 and 325 million tonnes of fuel annually, accounting for approximately 2.8% of annual global greenhouse gas emissions. However, compared to other modes of transport, shipping produces the lowest emissions of carbon dioxide (CO_2) per tonne per kilometre travelled. Still, emissions are expected to rise with shipping demand and could triple by 2050 if left unchecked.

Emissions from the shipping sector must be curbed in order to reduce air pollution and climate change impacts. The International Convention for the Prevention of Pollution from Ships (MARPOL) has stipulated mandatory technical and operation measures, which require more efficient maritime energy use and, simultaneously, less emissions.. These regulations came into force in 2013. The industry itself has set targets to reduce carbon dioxide emissions by 20% by 2020 and 50% by 2050. Ship operators, therefore, need to consider cleaner fuel and power options, including the use of renewables, to meet these targets. Furthermore, rising bunker fuel prices, amid a globally volatile market, provide another compelling reason to scale up modern shipping solutions based on renewable sources and technologies.

Renewable energy can transform the global shipping fleet at all levels and in varying magnitudes, including: international and domestic transport of goods, people and services; fishing; tourism and other maritime pursuits. Renewable power applications in ships of all sizes include options for primary, hybrid and/or auxiliary propulsion, as well as on-board and shore-side energy use. Potential renewable energy sources for shipping applications include wind (*e.g.* soft sails, fixed wings, rotors, kites and conventional wind turbines), solar photovoltaics, biofuels, wave energy and the use of super capacitors charged with renewables. These clean energy solutions can be integrated through retrofits to the existing fleet or incorporated into new shipbuilding and design, with a small number of new ships striving for l00% renewable energy or zero-emissions technology for primary propulsion.

The transition to a clean energy shipping sector requires a significant shift from fossil fuel-powered transport to energy-efficient designs and renewable energy technologies, starting today. The contribution of renewables to the energy mix of the shipping sector, however, is limited in the near and medium terms—even under optimistic scenarios. Nevertheless, developers are increasingly enhancing ship designs and proof-of-concept pilots demonstrating major savings in some applications. The development of renewable energy solutions for shipping has been hampered by over-supply of fossil fuel-powered shipping in recent years and the related depressed investment market. The main barriers to increased penetration of renewable energy solutions for shipping remain: 1) the lack of commercial viability of such systems; and, indeed, 2) the existence of split incentives between ship owners and operators, resulting in limited motivation for deployment of clean energy solutions in this sector. Ultimately, market forces working within a tightening regulatory regime will govern the speed of uptake of renewable energy technology for shipping, although this will also be tempered by infrastructure lock-in and other non-market factors. Therefore, a set of organisational/structural, behavioural, market and non-market barriers needs to be removed before renewables can make meaningful contributions to the energy needs of the shipping sector**.** Most importantly, the transition from fossil fuels to clean energy for shipping needs to be planned carefully.

Significant efforts and support measures must be applied now to demonstrate and increase the role of renewables in shipping. In particular, support policies and incentives to promote research, innovation and proof-of-concept exam-

ples are crucial in order for renewable energy shipping solutions to achieve commercial viability. For quick-win solutions, support should focus on small ships (less than 10 000 dead weight tonnes), which are more prevalent worldwide, transporting less of the total cargo but emitting more of the greenhouse gases per unit of cargo and distance travelled, compared to larger ships.

This technology brief summarises the current status and applications of renewable energy solutions for shipping, along with the barriers and opportunities for further deployment. It provides recommendations to policy makers to promote realistic renewable energy solutions that can support efficiency and reduced emissions in the important, growing shipping sector.

Abbreviations

DME	Dimethyl ether
dwt	Deadweight tonnage (measure of the vessel's carrying capacity)
ECA	Emissions controlled area
EEDI	Energy Efficiency Design Index
FAME	Fatty acid methyl esters
GHG	Greenhouse gas
gt	Gross tonnage (measure of the vessel's overall internal volume)
HFO	Heavy fuel oil
HVO	Hydrotreated vegetable oil
ICS	International Chamber of Shipping
IEA-AMF	International Energy Agency—Advanced Marine Fuels (Implementing Agreement)
IMO	International Maritime Organisation
LBM	Liquefied biomethane
LNG	Liquefied natural gas
MARPOL	International Convention for the Prevention of Pollution from Ships
MDO	Marine diesel oil
NO_x	Nitrous oxide
OECD	Organisation for Economic Cooperation and Development
R&D	Research and development
SEEMP	Ship Energy Efficiency Management Plan
SIDS	Small Island Developing States
Solar PV	Solar photovoltaic
SO_x	Sulphur oxide
SVO	Straight vegetable oil
TEU	Twenty foot equivalent unit – standard container size
UNCTAD	United Nations Conference on Trade and Development
VLCC	Very large crude carriers – 200,001 dwt – 350,000 dwt

HIGHLIGHTS

Process and Technology Status

Presently, renewable energy (RE) options are being considered for the global shipping fleet at all levels and in varying magnitudes, including: international and domestic transport of goods, people and services; fishing; tourism and other maritime pursuits. Renewable options can be used in ships of all sizes to provide primary, hybrid and/or auxiliary propulsion, as well as on-board and shore-side energy use. These clean energy solutions are being integrated through retrofits to the existing fleet or incorporated into new shipbuilding and design, with most applications deploying renewable energy as part of an integrated package of efficiency measures. The current focus of renewable energy application in shipping is on:

- **wind** energy: for example, using: ***soft-sails***, such as Greenheart's 75 dwt freighter, B9 Shipping's 3000 dwt bulker and Dykstra/Fair Transport's 7000 dwt Ecoliner; ***fixed-sails***, such as in the UT Wind Challenger and the EffShip's project; ***Flettner Rotors***, such as in the Alcyone and Enercon's 12,800 dwt E-Ship 1; ***kite sails***, such as in the MS Beluga Skysails; ***wind turbines*** (no successful prototypes to date); on
- **solar photovoltaics** (mainly in ***hybrid*** models with other energy sources on small ships, such as NYK's Auriga Leader and SolarSailor by OCIUS Technology (formerly Solar Sailor Holdings Ltd); and
- **biofuels**, such as the Meri cargo ship which claims to be the first of its size to use 100% bio-oil).

Hydrogen fuel cells have also been used as a clean energy technology for shipping: for example, in the FCS Alsterwasser, a 100-pax fuel-cell-powered passenger vessel based in Hamburg Port (Germany), as well as a number of other small ferries and river boats. In 2012, as part of the FellowSHIP project, a 330 kW fuel cell was successfully tested on board the offshore supply vessel, Viking Lady, operating for more than 7000 hours. This was the first fuel cell unit to operate on a merchant ship, with the electric efficiency estimated to be 44.5 % (when internal consumption was taken into account), with no NO_x, SO_x and particulate matter (PM) emissions detectable. In 2012, Germanischer Lloyd set out design concepts for a zero-emissions 1500 passenger "Scandlines" ferry and a 1000 TEU (twenty foot equivalent unit) container

feeder vessel with a 15-knot service speed and using hydrogen fuel cells. Other renewable energy propulsion systems include WWL's proposed ambitious "Orcelle" car carrier that will use a series of underwater flaps, modelled on the tail movements of Irrawaddy dolphins, to create propulsion and generate electricity and hydraulic power for the ship.

The enormous variety in global shipping vessel types, usage and routes means that different applications favour the use of different energy sources and technologies. Table 1 below summarises the current state and potential of renewable energy solutions for these different categories of ships.

Performance and Costs

This technology brief does not include a comparison of the actual costs or savings and returns on investment on different technology applications. There are multiple reasons for this omission: i) there are a myriad of types of applications and designs in varying stages of development; ii) the data on final costs and benefits is often insufficient; and iii) the lack of sufficient comparative data on other costs of ship/industry operation externalities makes it difficult to produce meaningful data to support a comprehensive analysis of overall costs and benefits.

Although the role and extent of renewable energy technology adoption by the shipping sector varies depending on the scale, function and operational location of the particular vessel, technology providers contend that research and innovation efforts on the use of renewable energy options, together with efficient designs, are already achieving significant results for immediate and near-term energy savings for a number of selected applications. For example, Enercon reported in 2013 that its prototype E-Ship 1 had achieved 25% savings and OCIUS Technology Ltd reported 5-100% savings depending on application for the SolarSailor, which claims a renewable energy solution cost of 10–15% of the capital cost of the vessel and a return on investment (ROI) of between 2 and 4 years. B9 Shipping and Fair Transport BV predicted additional building and maintenance costs of 10-15% of total asset costs for a projected 60% savings in fuel, as well as significant reductions in main engine and propeller wear. Fuel savings vary from nearly 100% (fuel switching to renewables) for

designs such as *Greenheart* down to only 0.05% main energy and 1% ancillary energy savings of NYK's solar array retrofitted car carrier *Auriga Leader*. The University of Tokyo has predicted that fuel costs could be reduced by as much as one-third with the 60 000 gross tonnage *UT Wind Challenger*. OCIUS Technology contends that by retrofitting opening wing sails to a "motor-sail", without altering the primary propulsion system of a modern tanker or bulker, ship operators can expect 20–25% fuel savings on cross-equator shipping routes and 30–40% on same-hemisphere shipping routes, with a payback period of only 2 years, based on 2013 average fuel prices.

In the case of **rotor technology**, the amount of fuel savings decreases as the ship size increases: Savings of 60% for small ships have already been achieved while savings of up to 19% on Very Large Crude Carriers (VLCC) are being modelled. The *Ulysses Project* has focused on ultra-slow steaming scenarios to demonstrate that the efficiency of the world's fleet of ships can be increased such that an 80% emissions reduction by 2050 against 1990 baselines can be achieved, with ships of the future travelling at speeds as slow as five knots. In such a scenario, renewable energy technologies could play a dominant role.

The development of renewable energy solutions for shipping has been hampered by the over-supply of fossil fuel-powered shipping in recent years and the related depressed investment market. Data and information on the actual deployment costs of the various renewable energy solutions so far been adopted in the shipping sector are very scarce. What is clear though is that there has not yet been sufficient demonstration of commercially viable solutions for the sector to drive deployment and thereby bring down costs. The speed of uptake of renewable energy technology solutions for shipping will ultimately be determined by market forces in a tightening regulatory regime. However, this uptake will also be tempered by the infrastructure lock-in of existing investments and other non-market factors.

Table 1: Summary of renewable energy technology applications and potentials for the shipping industry

Renewable energy type		Retrofit (RF)/ New Build (NB)	Vessel category, application and potential			
			< 400 tonnes e.g., recreation, artisanal/small fishery, tourism, passenger, break, landing craft, barges, research, coastal patrol and security	**400 – <10 000 tonnes** e.g., large landing craft, small-medium fishery, domestic Ro-Ro, break bulk, bulk, container, tanker, tramp	**10 000 – <50 000 tonnes** e.g., Ro-Ro, deep sea fishery, bulk, container, tanker, car carrier, cruise liner	**>50 000 tonnes** e.g., Very Large Crude Carrier (VLCC), Panamax, Aframax, large container ships
Wind	Soft sails	RF	●●●	●●●	●●●	●●
		NB	●●●	●●●	●●●	●●
	Fixed wings	RF	●●	●●	●●	●
		NB	●●	●●●	●●●	●●
	Rotors	RF	●●	●●	●●	●●
		NB	●●●	●●●	●●●	●●
	Kites	RF/NB	●●	●●	●●	●
	Turbines	RF/NB	●	●	●	●
Solar photovoltaics	Main propulsion	RF	N/A	N/A	N/A	N/A
		NB	●	N/A	N/A	N/A
	Auxiliary propulsion	RF	●●	N/A	●	N/A
		NB	●●	N/A	●	N/A
	Ancillary power	RF/NB	●●	N/A	●	N/A

Biofuels	1st Generation	RF	●●	●●	●●	●
		NB	●●	●●	●●	●
	2nd Generation	RF	N/A	N/A	N/A	N/A
		NB	●●●	●●●	●●●	●●
	3rd Generation	RF	N/A	N/A	N/A	N/A
		NB	●●●	●●●	●●●	●●
Wave	Main propulsion	NB	●	N/A	●	N/A
	Auxiliary propulsion	NB	●	N/A	●	N/A

Keys:

Current Application

- In commercial use
- Proven
- Proof-of-concept
- Design
- Concept
- Uncertain

Potential Application

●●●	High potential (Scores well on all three metrics: economic, environmental and social)
●●	Medium potential (Scores on two of the three metrics)
●	Limited I (Scores on only one of the three metrics)
N/A	Not available

Drivers, Potential and Barriers

Global trade and the socio-economic activities of island communities depend heavily on shipping, transporting approximately 90% of the tonnage of all traded goods. The global shipping tonnage loaded annually increased from 2.6 billion to 9.2 billion tonnes between 1970 and 2012, and the demand for shipping is predicted to grow further, owing to the changing configuration of global production, the increasing importance of global supply chains and the expected growth in many economies. As the demand for shipping services continues to grow, research on the use of renewable energy options for the sector—although still relatively immature—is growing fast. Between 2007 and 2012, the world's marine fleet consumed between 250-325 million tonnes of fuel annually, accounting for approximately 2.8% of global annual greenhouse gas emissions (3.1% of CO_2 annual emissions), amidst rising bunker fuel prices in a globally volatile fossil fuel market and increasing requirements to significantly reduce emissions from the sector. The International Convention for the Prevention of Pollution from Ships (MARPOL) has stipulated, among other measures, low sulphur emission control areas in the marine environment, as well as mandatory technical and operational measures requiring ships to be more efficient in energy use and to reduce emissions. The MARPOL regulations make the Energy Efficiency Design Index (EEDI) mandatory for new ships and the Ship Energy Efficiency Management Plan (SEEMP) for all ships. These economic and environmental constraints, therefore, constitute key drivers for adopting the use of renewables in the shipping sector.

The overall contribution of renewable energy technologies to international shipping is unlikely to achieve a dominant or even major role in the near future. Still, it has strong and increasingly proven capacity to make a modest contribution in many sectors over the short- and medium-term. For selected applications, the role of renewables can be significant, even dominant. Of the various renewable energy options, advanced biofuels have a very high potential to transform energy choices of the shipping sector. However, this potential will depend on a number of factors, including the global availability of sustainable feedstock for the production of biofuels. Hydrogen fuel cells as a power source for shipping also hold great potential but the sustainability of the energy source used to produce the hydrogen, as well as lack of cost-effective and reliable low-pressure storage options for the fuel remain as critical issues to be addressed. Overall, the greatest potential lies in using a combination of

renewable energy solutions that maximises the availability and complementarity of energy resources in hybrid modes. In this sense, achieving the full potential of renewables in the shipping sector will require an integrated systems engineering approach that also addresses the barriers to their deployment.

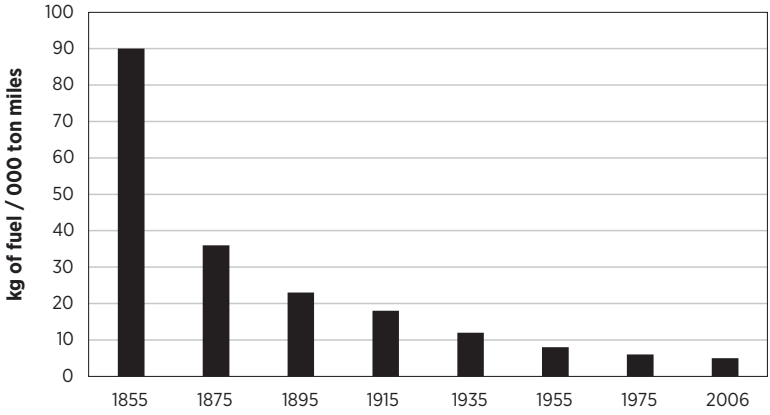
The barriers to the adoption of renewable energy in the shipping sector are complex. These can be categorised under organisational/structural, behavioural, market and non-market factors. This complexity, in part, reflects the unique and international nature of the shipping industry, with underlying constraints and factors that lie beyond the ability of individual states to effect incentives plus the policy and regulatory framework needed to overcome the barriers. With regard to organisational, structural and behavioural barriers, limited R&D financing, particularly for initial proof-of-concept technologies, is a major factor, together with ship owners' concerns over the risk of hidden and additional costs, as well as opportunity costs of renewable energy solutions. This is particularly true since, historically, there has been a lack of reliable information on costs and potential savings of specific operational measures or renewable energy solutions for this sector. Concerning market barriers, the fundamental problem is that of split incentives between ship owners and hirers, limiting the motivation of owners to invest in clean energy solutions for their shipping stock since the benefits do not always accrue to the investing party and hence savings cannot be fully recouped. Another barrier is the risk adversity of investors in the sector, especially following the collapse of the shipping boom in 2006. Furthermore, the shipping sector is seldom visible to the general public, resulting in less societal pressure on the industry to transition to cleaner energy solutions. Of the non-market barriers, the different classes and scales of ships, the markets and trade routes served and the lack of access to capital are some of the key barriers that must be addressed.

PROCESS AND TECHNOLOGY STATUS

During the past 150 years, shipping propulsion underwent a significant transformation from renewable energy (sails) to steam (coal), heavy fuel oil (HFO) and marine diesel oil (MDO), the latter two being high emissions fuels that are now the dominant source of power for propulsion in this sector. Over this period, the performance of merchant ships powered by diesel engines has improved with thermal efficiency approaching 55% for slow speed engines. For example, Figure 1 shows that between the years 1855 and 2006, the increase in efficiency was sharp, plateauing in the last 15 years of that period.

Renewable power applications in ships of all sizes include options for primary, hybrid and/or auxiliary propulsion, as well as on-board and shore-side energy use. Potential renewable energy sources for shipping applications include wind (soft sails, fixed wings, rotors, kites and conventional wind turbines), solar photovoltaics, biofuels, wave energy and the use of super capacitors charged with renewables (see, for example, (DNV, 2014); (Rojon & Dieperink, 2014); (Traut *et al.*, 2014); (EffShip, 2013b); (Royal Academy of Engineering,

Figure 1: Efficiency of merchant ships (1855-2006)



Source: Adapted from Stopford, 2010

2013); (Ecofys, 2012b); (Einemo, 2010); (Oceana, 2010); (UNESCAP, 1984)). These clean energy solutions can be integrated through retrofits to the existing fleet or incorporated into new shipbuilding and design, with a small number of new ships striving for 100% renewable energy or zero-emissions technology for primary propulsion.

Research and development (R&D) in renewable energy shipping has lagged significantly behind investment in other energy user sectors. Traditionally, innovation has been led by Organisation for Economic Cooperation and Development (OECD) countries. However, two transformations are likely to dominate the first half of the 21st century: geopolitical reconfigurations of the global economy and the transition from high- to low-carbon economies. A major research programme at the Institute of Development Studies is looking to provide evidence on whether this global power shift will make the low carbon transformation faster and cheaper[1].

Efforts to decarbonise the shipping sector are becoming increasingly evident as demonstrated by rising interest in green ships in South Korea, the focus of China's shipbuilding industry to strengthen technological innovation and design capability and strategic partnerships between European and Asian companies[2] on the development of innovative green ships (Ecofys, 2012a); (Bruckner-Menchelli, 2010); (Ecofys, 2009). In the EU, the LeaderSHIP initiative is aimed at ensuring the future of European shipbuilding through innovative, green and energy-efficient ship designs and diversified markets[3].

Past renewable energy lessons

The transition from soft sails to fossil fuels that propelled shipping in the late 19th and first half of the 20th century was not smooth but followed a series of energy crises and shipping booms. Renewable energy was revisited during

1 http://www.ids.ac.uk/project/global-power-shift-and-low-carbon-transformation

2 See, for example, the cooperation signed between Denmark and China in April 2014 (http://www.dma.dk/news/Sider/Danish-Chinesecooperationstrengthened.aspx)

3 Further information on the initiative is available at http://ec.europa.eu/enterprise/sectors/maritime/shipbuilding/leadership2015/index_en.htm

each major energy crisis. For example, energy security issues after the First World War led to the development of the Flettner rotor technology whose evolution was in turn curtailed by the Wall Street crash of 1929 and the introduction of cheap diesel fuel and engines in the late 1920s. The relatively short duration of such events meant that renewable energy alternatives did not gain traction, despite proof-of-concept. This lack of market traction was echoed in the 1979 oil crisis when a range of promising trials of renewable energy technologies were cut short after oil prices fell in 1986. Such trials included sail retrofitting on 300 gross tonnage[4] cargo/passenger vessels in Fiji, sail-powered passenger catamarans in Indonesia and auxiliary fixed-wing tankers and bulkers of 600-31000 gross tonnage in Japan. Such experiments were realising fuel savings of between 10-30% but falling oil prices curtailed these endeavours. The "lessons learned" from this period – in addition to confirming that substantive savings were to be made in fuel use, engine and propeller wear, vessel stability and comfort – were that the initial concerns over the ultimate stability of vessels, reduced passage speeds and excessive leeway were shown to be unfounded.

Renewables for shipping: Retrofit or newly built pathways for primary and auxiliary propulsion and ancillary power?

The primary candidates for near future renewable energy maritime use are: wind, solar, biofuel/gas and wave power. The use of renewable energy requires an operational paradigm shift, such as weather and seasonal routing, to maximise exposure to the primary energy sources (in this case, sun, wind and waves). This is essential for efficient performance and new operational processes and systems that will need to be acquired. There are varied opinions on just how large a role renewable energy will play. A range of innovative technological designs have emerged, many of them exploiting mature technologies, with the potential to offer significant fuel savings, depending on ship

4 Gross tonnage is a measure of the ship's entire internal volume, *i.e.* a function of the moulded volume of all enclosed spaces of the ship, expressed as 100 cubic feet to the tonne (see, for example, http://www.imo.org/About/Conventions/ListOfConventions/Pages/International-Convention-on-Tonnage-Measurement-of-Ships.aspx)

type, route and speed. These designs also aim at reducing the need for fossil fuel for auxiliary and ancillary power.

There are two basic ways to introduce renewable energy solutions for shipping: 1) as retrofits for the existing fleet; or 2) through incorporating them into new construction designs. Many new design concepts for ships of all scales include renewable energy options for auxiliary and ancillary energy use while a smaller number are targeting 100% renewable energy or zero-emissions technologies for primary propulsion (*e.g.*, *B9, Ecoliner, Greenheart, Orcelle*). Most applications envisage renewable energy as part of an integrated package of efficiency measures. Renewable energy also has potential application in shore-side infrastructure, primarily for alternative electricity generation.

Renewable energy applications can be primary propulsion (*e.g. Greenheart, B9,* OCIUS), auxiliary propulsion (*e.g. UT Wind Challenger, E Ship 1, SkySails*) or ancillary power substitution (*e.g. Auriga Leader* and shore side electricity generation). When considering the energy efficiency of the shipping industry as a whole, it is important that a holistic approach be taken that calculates the "energy footprint" of each technology from cradle-to-grave over a vessel's lifetime and also considers the primary source of energy used. See, for example, (Smith *et al.*, 2014a); (Royal Academy of Engineering, 2013) and (Smith *et al.*, 2010). For example, there are various concepts and prototypes of electric and hydrogen fuel cell-powered vessels. The "renewable" aspect, needs to consider the primary source of energy being used. For instance, where the electricity being used comes from renewable sources such as hydro, wind or solar, then these can be considered renewable energy applications; not, however, when the energy input into the fuel cells is from non-renewable sources.

Current renewable energy foci for shipping applications: wind, solar, biofuels and wave energy

Wind

Prior to the advent of the steam engine, sails monopolised the high seas, propelling relatively small ships with large crew complements. After all, wind is a readily available, if fluctuating, renewable energy source that is well under-

stood. The major disadvantages are variations in wind force and difficulty in harnessing the full propulsion potential when sailing into or close to the wind. Current initiatives include adoption of a number of different types of renewable energy technologies, targeting a range of ship types from small village-scale ships to large cargo carriers, both as primary and auxiliary propulsion. Wind propulsion can be categorised under soft-sail, fixed-sail, rotor, kite and turbine technologies.

» Soft-sails

Conventional soft-sails attached to yards and masts offer a proven, mature technology capable of directly harnessing the propulsive force of wind. Technological advances in the super yacht and yacht-racing industries can now be incorporated into industrial use. Sails can be deployed as either primary or auxiliary propulsion and can be either retrofitted to some existing assets or incorporated into new construction design. Current market leaders include *Greenheart's* 75 dwt freighter, B9 Shipping's 3000 dwt bulker and Dykstra/Fair Transport's 7000 dwt *Ecoliner* (Figure 2). The latter two designs feature versions of Dyna-Rig systems (proven on the super yacht *Maltese Falcon*) that are operated automatically from the bridge, enabling wind to be harnessed more easily, keeping crew sizes comparable with fossil-fuel powered ships and allowing easy access to hatches for loading and discharging cargoes. *Greenheart*'s freighter will deploy a more conventional jib and mainsail combination. Italian shipping innovation company, Seagate, has patented folding delta wing sails for retrofitting to existing ships, including Ro-Ro, container ships and car

Figure 2: Examples of ship designs deploying soft-sail technology



(a) Greenheart



(b) B9



(c) Ecoliner



(d) Seagate delta wing sail

Printed with permission from Greenheart Project, B9 Shipping, Dykstra Naval Architects and Seagate

Figure 3: Fixed wingsail designs



(a) UT Wind Challenge



(b) Oceanfoil

Printed with permission from the UT Wind Challenger Project, EffShip Project and Oceanfoil

carriers. There are also various rig configurations that can be used on small-scale freighters and catamarans for local use, especially in island communities or as auxiliary power to a wide range of existing small-scale, conventionally powered craft.

» Fixed-sails

Fixed-sails are essentially rigid 'wings' on a rotating mast. Current proposals include use on large ships (*e.g. UT Wind Challenger* and *EffShip's* project[5] which includes using rigid sails capable of reefing down on telescoping masts for heavy weather or in-port situations). Various forms of fixed wings have been proposed since the Japanese experiments in the 1980s. These include the Walker Wingsail, fitted to the 6 500 dwt *Ashington,* in 1986. Trials then did not demonstrate substantive savings and some technological barriers are still to be overcome with this design approach. A UK company, Oceanfoil, has revisited the wingsail and is offering a new patent for a revised and improved design that will be available for retrofitting from the beginning of 2015[6]. Examples of the application of this technology are shown in Figure 3.

Promising new commercial designs adapted from the racing yacht sector are being developed by Propelwind[7]. The Australian company, OCIUS

5 http://www.effship.com/PublicPresentations/Final_Seminar_2013-03-21/06_EffShip-Wind_propulsion-Bjorn_Allenstrom_SSPA.pdf

6 http://oceanfoil.com/technology/

7 http://www.propelwind.com

Figure 4: Ships using rotor sail (Magnus Effect)



(a) Alcyone



(b) E-Ship 1

Printed with permission (a) – by David Merret, CC BY 2.0; (b) – by Carschten, CC BY-SA 3.0 DE

Technology Ltd, uses fixed wings combined with photovoltaic panels to successfully power harbour ferries. OCIUS has recently patented a unique form of fixed sail capable of folding down to complement differing wind conditions. It predicts that the technology will be usable on all sizes of modern vessels. LadeAS's *Vindskip*[8] design concept is a hybrid merchant vessel powered by an LNG-fuelled engine and an aerodynamic hull that functions as a giant sail.

» Rotors

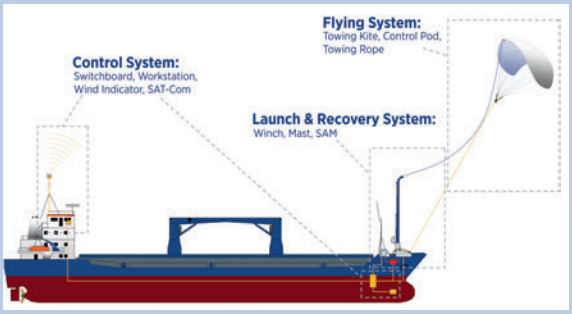
Flettner Rotors harness the Magnus Effect, created when wind passes over an already revolving cylinder, for propulsion. It was first proven in the 1920s on a number of ships, including the 3000 dwt *Barbara*. The technology was largely forgotten until the early 1980s when the oceanographer, Captain Jacques Cousteau, and his team introduced the 'TurboSail', a non-rotating fan-driven design, on his research vessel *Alcyone*[9]. In 1985, the US company, Windship Corporation, released findings from a detailed analysis of 75 wind-powered rigs backed by extensive practical trials, concluding that the rotor had by far the greatest potential.

In 2010 Enercon began trials of the 12 800 dwt *E-Ship 1* with four Flettner rotors powered initially by the exhaust gas from the main conventional turbine

8 http://www.ladeas.no/

9 http://www.cousteau.org/technology/turbosail

Figure 5: Kite-assisted sail



(a)



(b)

Printed with permission from Skysails GmbH

motor. Retrofitting Flettner rotors to bulkers and tankers up to VLCC class is being actively considered although the use of deck space for different ship types is a key consideration. There are now modern concept designs adopting Flettner style rotors[10]. Figure 4 shows examples of ships using rotor technology to assist propulsion.

» Kite sails

Kite sails attached to the bow of the vessel operate at altitude to maximise wind speeds as shown in Figure 5. A small number of innovative companies have been advocating this technology for more than a decade. In 2008 *MS Beluga Skysails* was the world's first commercial container cargo ship partially powered by a 160-square-metre kite[11].

10 See, for example, Wartsila concept designs at http://www.wartsila.com/file/Wartsila/en/1278517253502a1267106724867-Wartsila-SP-A-Tw-2030-b.pdf

11 SkySails GmbH http://www.skysails.info

» Wind turbines

Wind turbines have been mooted over many years for ship propulsion. However, to date there are no successful prototypes of their application. This reflects systemic issues with their ultimate stability and vibration and the inherent inefficiency in energy conversion relative to other technologies. The advantage of the turbine is that it can continue to harness power even when the craft is sailing directly into the wind. There is a case to be made for wind turbines as a producer of ancillary power for ships and as a replacement for shore-side electricity generated from non-renewable sources. Given the enormous advances made in wind turbine technology for electricity generation, it is highly likely there are important lessons to be transferred now to the shipping sector.

Solar photovoltaics and hybrid systems

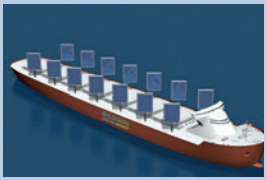
Solar PV applications use electricity generated by photovoltaic (PV) cells. All advances in this fast evolving technology are available for maritime transport use. The primary limitations are the lack of sufficient deployment area for the PV panels and the energy storage required. Recent advances in energy storage technology offer higher potential and better prospects for solar PV-powered propulsion systems for ships in the short term, but full ship propulsion using solar PV requires further technical development and is likely to be confined to relatively small ships (Royal Academy of Engineering, 2013).

The *Greenheart* design for a 220 gross tonnage freighter proposes using solar-charged lead-acid batteries to provide auxiliary propulsion for its primary sail rig. Batteries may offer a potential hybrid solution in conjunction with other modes of propulsion for some small- to medium-sized ships, provided that their recharging does not increase the production of other harmful emissions. OCIUS Technology's SolarSailor[12] design uses hybrid fixed sails in tandem with solar PV arrays, both sail and deck mounted as shown in Figure 6. These have now resulted in commercially competitive harbour ferries in Australia, Hong Kong and Shanghai and show strong promise for deployment on larger ships. Japan-based Eco Marine Power[13] is developing a large solar-sail Aquarius MRE

12 http://www.solarsailor.com

13 http://www.ecomarinepower.com

Figure 6: Fixed wing and solar PV hybrids



(a) Eco Marine Power's Aquarius MRE system



(b) OCIUS Technology's SolarSailor



(c) NYK's Auriga Leader

Printed with permission, courtesy of Econ Marine, OCIUS Technology Ltd and NYK Ltd

(Marine Renewable Energy) system for tankers and bulkers. WWL's proposed *E/S Orcelle* zero-emissions[14] car carrier is proposing a similar set-up with solar panels incorporated into large fixed wing sails that can harness power in sail mode or when deployed horizontally on deck. The *Auriga Leader* project[15] by NYK and Nippon Oil Corporation in 2008/09 saw 328 solar panels fitted to a 60 000 gross tonnage car carrier providing 40 kilowatts, about l0% of the ship's power while stationary in dock. It was also the first ship to direct solar power into the ship's main electrical grid. The solar panels produced 1.4 times more energy on the ship at sea than at port in Tokyo but the overall contributions to propulsive power were minimal.

Solar PV has potential when used to charge shore battery systems supporting rechargeable electric propulsion units for smaller scale car ferries but this is only applicable for extremely short-run shipping. It also has applications in augmenting other electric supplies for most shore-side infrastructure. In order to accrue the greatest benefits, this type of use needs to be coupled with low-carbon and other power saving technologies. Solar (along with wave energy and wind turbines) may have a future role to play in providing initial energy for hydrogen separation from seawater for hydrogen fuel cell technology.

14 http://www.2wglobal.com/sustainability/responsible-logistics/environmental-frontrunner/zero-emission-future/#.VE1vWihdkrh

15 See, for example, http://www.nyk.com/english/release/31/NE_090908.html

Bioenergy

Biofuels are currently the most relevant alternative for replacement or blending with fossil fuels in the transport sector. Yet, experience with their use and the scale of their application in the shipping sector is still very minimal. A comprehensive evaluation of alternative fuels for marine applications, including biofuels, is given in the Annex 41 report of the Advanced Marine Fuels Implementing Agreement of the International Energy Agency ((IEA-AMF, 2013)). Other studies have also assessed the potential use of biofuels in the shipping sector: See, for example, (DNV, 2014); (Lloyds Register and UCL, 2014); (EffShip, 2013b); (Ecofys, 2012b) and (ZERO, 2007). Biofuels can be used in the sector in the form of biodiesel, bioethanol, biomethane, straight vegetable oil (SVO), dimethyl ether (DME), pyrolysis oil, hydrogenated vegetable oil (HVO) or some other derivation. The pathways for producing these fuels from biomass-based feedstock is summarised in Figure 7.

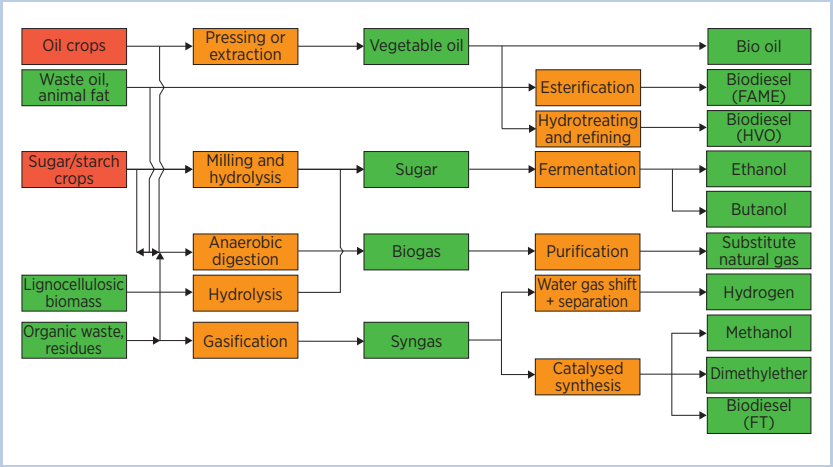
Whichever form of biofuel is used, the application take the form of drop-in fuels (*i.e.* used as direct substitution for current conventional fossil fuels and compatible with existing infrastructure and engine systems) or through new or redesigned infrastructure and systems. Technical problems, such as instability of onboard stored fuel, corrosion and bio-fouling, arising from the use of certain biofuels in shipping are readily surmountable (Ecofys, 2012b).

Although biofuel's share in the shipping sector's energy mix is small and will most likely remain so in the short- to medium-term, over the long run they will have a substantial role to play[16]. Technology learning for the production of advanced – or second and third generation – biofuels[17] is increasing, making

16 See, for example, *http://www.biofuelstp.eu/shipping-biofuels.html*

17 The definition of conventional (first generation) or advanced (second and third generation) biofuels depends on the source of carbon used. The European Biofuels Technology Platform *(http://www.biofuelstp.eu/advancedbiofuels.htm)* gives a good description of these definitions as:
1st Generation: The source of carbon for the biofuel is sugar, lipid or starch directly extracted from a plant. The crop is actually or potentially considered to be in competition with food.
2nd Generation: The biofuel carbon is derived from cellulose, hemicellulose, lignin or pectin. For example this may include agricultural, foresty wastes or residues, or purpose-grown non-food feedstocks (*e.g.* Short Rotation Coppice, Energy Grasses).
3rd Generation: The biofuel carbon is derived from aquatic autotrophic organisms (*e.g.* algae). Light, carbon dioxide and nutrients are used to produce the feedstock "extending" the carbon resource available for biofuel production.

Figure 7: Summary of pathways for conventional and advanced biofuels production



Source: Adapted from Ecofys, 2012b

these fuels the most viable renewable energy option with the highest penetration rate for the shipping sector in the long term. This high potential will depend on various factors, such as the availability of sustainable feedstock for their production, the viability of global trade in biofuels and how their costs compete with other low-emission fuel options.

» Liquid Biofuels

Liquid biofuels can be combusted in a diesel engine and are potentially applicable to all vessel types, with only small modifications of the main engine required. Early trials in 2006 demonstrated the commercial and technical feasibility of the use of biofuels for marine applications. The following examples are elaborated in Appendix D of (Ecofys, 2012b). In 2006-2007, Royal Caribbean Cruises tested biodiesel on selected cruise ships, including the 293m *Jewel of the Seas*, starting out with 5% blends (B5) and eventually culminating with 100% (B100) biodiesel. Between May and October 2006, the Canadian Bioship project ran the 17 850 dwt freighter *Anna Desgagnes* on a B20 blend

of rendered animal fats and cooking oil biodiesel. These trials were followed by Maersk and Lloyd's biofuel feasibility tests in 2010-2011 using batches of biodiesel (FAME) blends on the 88 669 dwt *Maersk Kalmar* container ship. The results were promising but inconclusive as the tests only ran for 160 hours. In 2012, Meriaura Ltd's ship, the *Meri* — a 105 m long, 4 359 dwt multi-purpose vessel — delivered the world's first commercial shipment using 100% biofuel (bio-oil from wood pulp waste) in Finland; the ship was powered by three Wärtsilä generator sets that could use MDO as a back-up fuel[18].

Tests on the use of third generation algal biofuels in shipping have also been progressing. In December 2011, Maersk and the U.S. Navy announced their collaboration to test algae-based biofuel on the container ship *Maersk Kalmar*[19]. The U.S. Navy's Great Green Fleet initiative aims to cut the use of fossil fuels in its fleet by 50% by the year 2020[20] while Maersk aims to reduce its emissions by 25% by the year 2020 compared to 2007. Sustainable, cost- and technically-competitive biofuels would play a significant role in achieving this target[21]. In June 2014 the U.S. Navy put out a tender seeking at least 37 million gallons of drop-in biofuels as part of its F-76 marine diesel and JP-5 shipboard jet fuel supply. Maersk, DONG Energy, Haldor Topsoe, MAN Diesel and Turbo, Novozymes, Technical University of Denmark and the University of Copenhagen are partners on the Bioenergy for the 21st Century (B21st) project that is co-funded by the Danish National Advanced Technology Foundation as a technology platform aimed at developing biomass for marine fuels and chemicals[22]. In February 2013 Maersk signed an agreement with Progression Industry[23] to develop a marine fuel from lignin, CyclOx, that is sustainable, cost-competitive and technically sound and for which Maersk is committed

18 See, for example, http://www.meriaura.fi/en/company/news/first_shipiment_using_100_bio-oil.375.news

19 The press release is available at http://www.maersklinelimited.com/pressreleases/Maersk_Biofuel_Test.pdf

20 See http://greenfleet.dodlive.mil/files/2012/06/20120610-N45-Biofuel-FactSheet.pdf

21 See http://bio4bio.ku.dk/documents/conference2012/sterling_maersk_line_biofuel___biorefinery_conf

22 Further details on the B21st project available at http://b21st.ku.dk/

23 http://www.tue.nl/en/university/departments/mechanical-engineering/news/progression-industry-develops-alternative-marine-fuel-for-maersk/

to buy 50 000 tonnes of the fuel if it meets these conditions[24]. The European Biofuels Technology Platform gives a good summary of other trials of renewable biofuels for shipping[25], including the Lloyds Register and Maersk programme of biodiesel for marine engines, the European Commission TEN-T programme[26] (aimed at supporting the construction and upgrade of transport infrastructure across the European Union) that includes priority projects aimed at alternative fuels for marine transport[27], and the METHAPU project[28] (for the validation of renewable methanol based auxiliary power system for commercial vessels), among others.

» Biogas

Biogas is derived from the anaerobic digestion of organic material. It can be cleaned through removal of impurities, such as moisture, hydrogen sulphide and carbon dioxide to form biomethane which has the same quality as natural gas. Just like natural gas, biomethane can be liquefied to form liquid biomethane (LBM) and used as a transport fuel. The shipping sector favours liquefied natural gas (LNG) as a transitional fuel for a low-carbon/low-emissions future and a suitable bunkering network is rapidly evolving on established transport routes. The case for the shipping sector to adopt LBM as a renewable fuel of choice is strong. Combining LBM with other proven renewable energy solutions; such as wind, as is proposed by B9 Shipping[29], enables 100% renewable energy ships to be operational in the short term. The Rolls-Royce Bergen K gas engine was certified to power the world's first major car and passenger ferries running on LNG and is now used in over 20 vessels[30]. The increased

24 See, for example, http://www.biofuelsdigest.com/bdigest/2013/03/21/maersk-to-develop-two-marine-fuel-projects/

25 http://www.biofuelstp.eu/shipping-biofuels.html

26 http://inea.ec.europa.eu/en/ten-t/

27 Such as the Priority Project 21 aimed at testing the performance of methanol on the passenger ferry, Stena Germanica, operating between the ports of Gothenburg and Kiel (see http://inea.ec.europa.eu/en/ten-t/ten-t_projects/ten-t_projects_by_country/multi_country/2012-eu-21017-s.htm)

28 http://cordis.europa.eu/project/rcn/81512_en.pdf

29 See, for example, http://www.b9energy.co.uk/B9Shipping/FlagshipsoftheFuture/TheIrresistibleBusinessCase/tabid/5071/language/en-GB/Default.aspx

30 See, for example, http://www.rolls-royce.com/sustainability/performance/casestudies/lng_fuelled_engines/

Table 2: Current viability of selected biofuels for the shipping sector

	Engine Applications	
	Drop-in fuel	**Comment**
Diesel cycle	Biodiesel (FAME)	● High availability and variety of feedstock ● Land use and food nexus issues for conventional biodiesel production ● Standard well-understood specifications ● Bio-fouling potential ● Requires anti-corrosion seals and components in engine ● Suitable for low to medium speed propulsion (e.g. small carriers and cargo ships)
	Straight vegetable oil (SVO)	● Up to 100% replacement possible ● Cheap and readily available ● High viscosity requires pre-heating ● Can be used in dual engines ● Suitable for low-speed propulsion of all vessel sizes
	Hydro-treated vegetable oil (HVO)	● Very high quality for shipping ● High energy content ● Land use and food nexus issues depending on feedstock used ● Suitable for medium-speed propulsion of all vessel sizes
	Dimethyl ether (DME)	● High potential ● Challenges with stability and storage ● Limited availability, but can be produced from ethanol using on-board alcohol to ether (OBATE) technology ● Requires fuelling infrastructure and anti-corrosion seals and components in engine ● Takes up cargo space ● Suitable for low-speed propulsion of all types of vessels
	Biomass-based Fischer-Tropsch diesel	● Can use residues for feedstock ● Limited availability, depends largely on gasification ● Not yet commercially viable ● Can be used for medium-speed propulsion of all vessel sizes
	Pyrolysis oil	● Low cost and high availability potential ● Corrosive ● Low heating value and high viscosity ● Difficult to store ● Suitable for low-speed propulsion of all types of vessels

Dual fuel Otto cycle	Liquefied bio-methane (LBM)	● Limited by availability of biomethane ● Infrastructure and storage issues
	Biomethanol	● Multiple pathways for production ● Holds very high potential but is presently limited by technologies for syngas production ● Suitable for high-speed auxiliary engines
	Bioethanol	● Mainly for blending ● Land use and food nexus issues for conventional bioethanol production ● Potential with second generation bioethanol ● Standard specifications and well understood ● Suitable for high-speed main or auxiliary engines

Fuel Replacement	
Marine diesel oil (MDO) / Marine gas oil (MGO)	● Conventional and advanced biodiesel (best option as blended fuel at up to 20% biodiesel – B20) ● Dimethyl ether (DME) ● Biomethanol ● Pyrolysis oil
Heavy fuel oil (HFO)/ Intermediate fuel oil (IFO)	● Straight vegetable oil (SVO), up to 100% ● Hydro-treated vegetable oil (HVO)
Liquefied natural gas (LNG)	● Liquefied biomethane (LBM)/ Biomethanol ● Dimethyl ether (DME)
Electricity	Bio-hydrogen fuel cell

Source: Compiled from European Biofuels Technology Platform[1]; Argonne National Laboratory, 2013; EffShip, 2013b; IEA-AMF, 2013; Royal Academy of Engineering, 2013; Bengtsson et al., 2012; Ecofys, 2012b; Renewable Fuels Association, 2010

1 European Biofuels Technology Platform: Use of biofuels in shipping. http://www.biofuelstp.eu/shipping-biofuels.html

development of LNG storage facilities at ports will help facilitate the use of this technology and bio-methane.

Table 2 summarises the viability of biofuels as drop-in fuels for marine applications in terms of their combustion system types, as well as their direct substitution potential. Table 3 summarises biofuels application and any related issues with regard to marine propulsion in terms of cost potential with respect to engine and fuel system, fuel supply, emissions abatement, safety and indirect costs.

Wave energy

Current wave power plant designs suggest that an entirely new design concept will be needed to be readily applicable to the shipping sector's energy needs. The small number of developers in this field are attempting to learn from biology and mimic the manner in which dolphins and pelagic fish use muscle energy in marine environments. The ambitious E/S *Orcelle* car carrier by Wallenius Wilhelmsen Logistics (WWL) proposes using a series of 12 underwater flaps (fins), modelled on the tail movements of Irrawaddy dolphins, to harness and convert wave energy in the ocean to create propulsion and generate electricity and hydraulic power for ship's systems[31].

Hydrogen fuel cells

Hydrogen was much vaunted in the mid-2000s as the fuel for the future in shipping and is still hoped to provide a long-term solution. The burning of hydrogen as a drop-in fuel in standard marine diesel engines is possible only at low levels of blending without presenting significant risks of engine damage. Hydrogen's potential lies in its use in a fuel cell. The development of hydrogen fuel cell technology has made significant advances and attracted a high level

31 Further information on the WWL's proposed Orcelle ship can be found at *http://www.2wglobal.com/globalassets/environment/orcelle-green-flagship.pdf*

Table 3: Summary of applications and issues for biofuels in shipping

Aspect	Biofuel			
	Biomass to liquid (advanced biofuels – e.g. via Fischer-Tropsch process)	**HVO/ SVO/ FAME**	**Dimethyl ether (DME)**	**Liquid biomethane (LBM)**
Engine and fuels system cost	Drop-in	Drop-in	Storage	Dual fuel cryotanks
Projected fuel cost	Refining	Land use	Infrastruc-ture	Infrastruc-ture
Emissions abatement cost				
Safety-related cost			Ventilation	Pressure / Temperature
Indirect cost		Water, en-ergy, land and food nexus	Cargo space	Cargo space

Feasible solution Significant cost Serious impediment

Adapted from IEA-AMF, 2013

of interest, especially from the offshore supply vessel, passenger and cruise ship markets.

In 2008, the Zemships (Zero Emissions Ships) project developed the *Alster-wasser,* a 100- passenger vessel for inland waterways and a number of other small ferries and river boats have followed suit. The Zemships, which was later called FCS Alsterwasser, was the first fully fuel cell-powered ship to be operated. It was powered by two hydrogen fuel cell units of 48 kW power capacity each. The ship operated in Hamburg until late 2013 when the chal-lenge of economically operating the hydrogen charging infrastructure put it

out of service[32]. In 2012, as part of the FellowSHIP project, a 330 kW fuel cell-powered ship was successfully tested on board the offshore supply vessel, *Viking Lady,* operating for more than 7000 hours. This was the first fuel cell unit to operate on a merchant ship, with the electric efficiency estimated to be 44.5 % (taking internal consumption into account), and no NOx, SOx and PM emissions detectable. When heat recovery was enabled, the overall fuel efficiency increased to 55% with room for improvement[33].

In 2012, Germanischer Lloyd set out design concepts for a zero-emissions 1500 passenger Scandlines ferry and a 1000 TEU container feeder vessel with a 15-knot service speed, using liquid hydrogen as fuel to generate power with a combined fuel cell and battery system[34]. However, the sustainability of hydrogen production is a critical issue, with almost all current commercial production coming from fossil fuels. Potential for renewable energy hydrogen production will come from the electrolysis of seawater using energy sources, such as excess offshore wind farm energy, other land based renewable energy supplies or generators aboard wind-powered vessels.[35] However, reliable, low-pressure storage of hydrogen remains a challenge to development of this energy source for shipping.

Battery-electric propulsion

Examples of battery-powered vessels include the *Zerocat* and the *Ar Vag Tredan*. The Siemens' *Zerocat* 120, which won the 2014 SMM Ship of the Year award, is a newly built lithium battery-powered 120-car ferry with a capacity of up to 360 passengers for short routes (ca. 20 minutes) with the battery needing just ten minutes to be recharged[36]. The vessel will go into service in 2015, operating on the Norwegian west coast where the battery would be re-

32 See, for example, *http://www.abendblatt.de/ratgeber/wissen/article132332343/Das-Hamburger-Wasserstoff-Schiff-liegt-still.html*

33 *http://www.dnv.com/binaries/fuel%20cell%20pospaper%20final_tcm4-525872.pdf*

34 *http://www.interferry.com/2012papers/5-4Interferry_Povel.pdf*

35 h*ttp://segelenergie.de/technologie/*

36 See, for example, *http://uk.reuters.com/article/2014/09/15/corvus-energy-idUKnBw145016a+100+BSW20140915*

charged with 100% renewable electricity from hydropower generation. In September 2013, Lorient Agglomération launched the *Ar Vag Tredan*, (designed by STX France), a 147-passenger zero-emissions, electric passenger ferry, as part of the Ecocrizon research and development programme set up by STX France in 2007[37]. The system is propelled by two thrusters of 70 kW each, powered by super-capacitors used to store the energy needed by the ferry for short roundtrips. The super-capacitors can be recharged portside in just four minutes. However, this can only be considered a renewable energy-powered vessel if the electricity used comes from renewable sources.

37 See, for example, *http://www.stxfrance.com/UK/stxfrance-reference-23-AR%20VAG%20TREDAN.awp*

PERFORMANCE AND COSTS

As noted earlier, the development of renewable energy solutions for shipping has been hampered by over-supply of fossil fuel-powered shipping in recent years and the related depressed investment market. So far there is not yet sufficient demonstration of commercially viable solutions for the sector to drive deployment and thereby bring costs down.

This Technology Brief does not include a comparison of the actual costs or savings and returns on different technology applications. While this is an obvious priority for further research and would be of benefit for policy and decision makers, such a comparison is not attempted here for the following reasons: *first*, there are many different types of applications and designs in various stages of development, trialling and conception; *secondly,* there are insufficient data in many cases on final costs and benefits; *thirdly,* there are very few comparative data on other costs of ship/industry operation externalities that would be needed to produce real meaningful data to support a comprehensive analysis of overall costs and benefits. Cost and benefit figures provided throughout this review are taken from either industry sources or material published on the internet.

The role and extent of renewable energy technology adoption by the shipping sector will vary greatly depending on the scale, function and operational location of the particular vessel. Technology providers in the field contend that research and innovation efforts on the use of renewable energy options, together with efficient designs, are already achieving significant results for immediate- and near-term energy savings for a number of selected applications. Analysis has suggested substantial unrealised abatement potential using options that appear to be cost-negative at current and near-future fuel prices (Rehmatulla *et al.*, 2013).

The small number of validated proof-of-concept vessels and advanced business modelling for leading future contenders show reasonable rates of return of investment for several applications. Across the sector, fossil fuel energy savings owing to the deployment of renewable solutions vary from close to

100% (total fuel switching to renewables) for designs, such as *Greenheart*[38], down to 0.05% (main engine) and 1% (ancillary engine) energy savings of NYK's solar array retrofitted car carrier, the *Auriga Leader*[39]. For soft-sails, B9 Shipping[40] and Fair Transport BV Ecoliner[41] predictions foresee additional construction and maintenance costs of between 10-15% of total asset costs in return for a projected 60% savings in fuel, significant reductions in main engine and propeller wear, cleaner fuel compliance costs and possible future emissions trading levies. Seagate has modelled fuel savings of 9-19% with a payback period of 3-4 years for its delta wing collapsible sails[42].

For fixed wing sails technology, OCIUS Technology Ltd. reported 5-100% fuel savings depending on the application[43]. The company contends that by retrofitting opening wing sails to a "motor-sail", without altering the primary propulsion system of a modern tanker or bulker, ship operators can expect 20-25% fuel savings on cross-equator shipping routes and 30-40% on same-hemisphere shipping routes—representing an estimated return on investment of between one and two years at 2013 fuel prices[44]. Oceanfoil has modelled a fuel saving of 20% and an estimated payback period of 15-18 months for its new wingsail design[45]. The University of Tokyo projected that for its 60 000 gross tonnage *UT Wind Challenger*[46], fuel costs could be reduced by as much as one-third. The EffSail, developed from the EffShip project, has been modelled to show that, under certain conditions, savings in fuel use of up to 40% could be achieved with shorter payback times than kites and rotors based on simplified economic assumptions[47].

38 http://www.greenheartproject.org

39 http://www.nyk.com/english/release/1414/ne_110525.html

40 http://www.b9energy.com/B9Shipping/FlagshipsoftheFuture/TheIrresistibleBusinessCase/tabid/5071/language/en-US/Default.aspx

41 http://www.marin.nl; http://www.fairtransport.com

42 http://seagatesail.com/application-studies/commercial-applications/roro/

43 http://www.solarsailor.com/solar-sails/

44 http://www.solarsailor.com/third-international-symposium-on-marine-propulsors/

45 http://oceanfoil.com/technology/

46 http://www.marinepropulsors.com/proceedings/2013/11B.3.pdf

47 http://www.effship.com/PublicPresentations/Final_Seminar_2013-03-21/09_EffShip-Hand-out.pdf

The use of kite-assisted sailing has also been shown to achieve fuel savings. The MS Beluga Skysails system saved 10-15% of fuel on selected passages. However, annual savings in consumption on most routes is on the order of 5.5%, as determined by the EU-funded Life project WINTECC[48]. Propulsive savings can only be realised with wind coming from the beam to the aft (back) of the ship. Kite-assisted technology is thought to have a higher maintenance and servicing cost compared to other wind technologies. Recent studies under the EffShip programme have modelled savings using fixed-wing, rotor and kite auxiliaries for a Panamax (EffShip, 2013a). (Traut *et al.*, 2014) and comparisons for rotor and kite fitted ships on transatlantic runs.

In the case of rotor technology, the amount of fuel savings decreases as the ship size increases. Savings of up to 60% for small ships have already been achieved while savings of up to 19% on Very Large Crude Carriers (VLCC) are being modelled. For example, Enercon reported in 2013 that their prototype rotor sail ship, the E-Ship 1, had achieved 25% savings after 170 000 sea miles[49].

The Ulysses Project has focused on ultra-slow steaming scenarios to demonstrate that the efficiency of the world fleet of ships can be increased to an 80% emissions reduction by 2050 against 1990 baselines, with future ships travelling at speeds as slow as five knots[50]. In such a scenario, renewable energy technologies could play a dominant role.

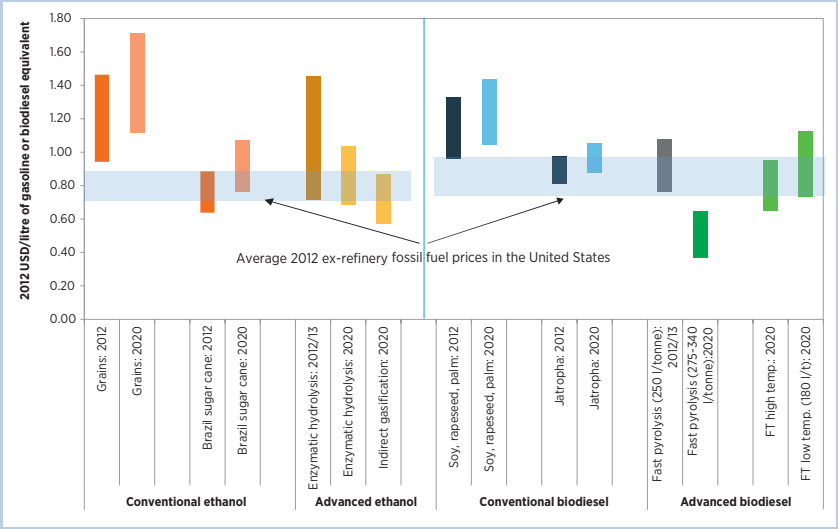
With regard to biofuel options for shipping, there remain limitations associated with the relatively high costs of production and the scale required to meet shipping demands and the competition for the fuel from road, aviation and even rail transport sectors. The production costs of conventional and advanced biofuels as shown in Figure 8 (IRENA, 2013) are generally still high compared to gasoline or diesel, although some pathways are already cost-competitive. The potential for cost reductions to the year 2020 is fairly uncertain owing to the projected rise in food prices, low potential for efficiency gains for first generation biofuel technologies and uncertainties in technology breakthroughs for advanced biofuels.

48 *http://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=search.dspPage&n_proj_id=3074&docType=pdf*

49 See, for example, *http://www.enercon.de/en-en/2224.htm*

50 *http://www.ultraslowships.com/*

Figure 8: Production costs for conventional and advanced biofuels, 2012 and 2020



Source: IRENA, 2013

DRIVERS, POTENTIAL AND BARRIERS

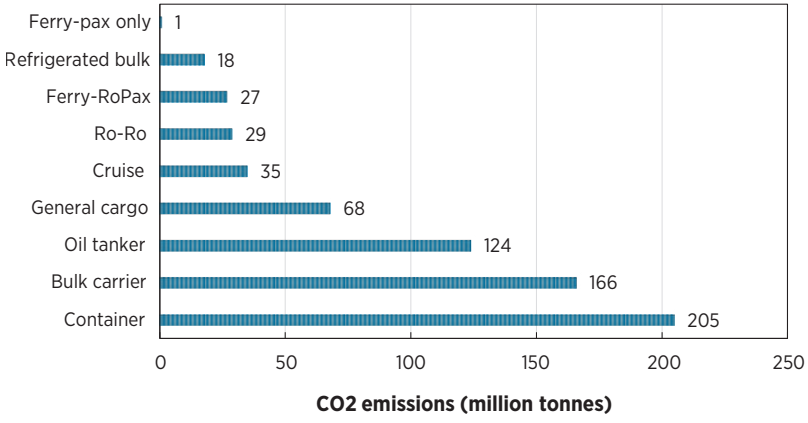
Drivers

Global trade depends heavily on shipping, which accounts for approximately 90% of the tonnage of all trade. See, for example, (ICS, 2013); (Stopford, 2013); (Stopford, 2010)). Shipping is also a lifeline for island communities. The United Nations Conference on Trade and Development (UNCTAD) estimated that the global shipping tonnage loaded annually increased from 2.6 billion to just over 9.5 billion tonnes between 1970 and 2013 (UNCTAD, 2014). This tonnage has little or no alternative means of transportation in the foreseeable future. Indeed, the demand for shipping is predicted to grow further, owing to the changing configuration of global production, the increasing importance of

global supply chains and expected growth in many economies. See, for example, (Danish Ship Finance, 2014); (ICS, 2014); (ICS, 2013); (Stopford, 2013); (UNCTAD, 2014); (IMO, 2012). Along with this predicted growth in shipping, there is an expected increase in energy consumption and greenhouse gas emissions from this sector. At the end of 2012, the total world merchant fleet comprised 86 942 ships, including 11176 oil tankers, 9 512 bulk carriers, 21114 general cargo carriers, 5109 containerships and 40 031 other categories (UNCTAD, 2013). Renewable energy deployment and increased energy efficiency measures provide the means to reduce the energy and emissions intensities of this sector.

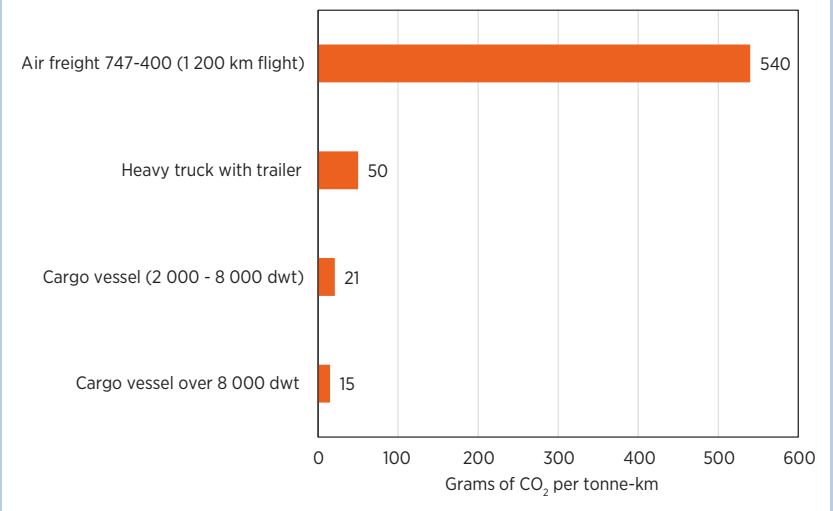
The International Maritime Organisation's Third GHG Study 2014 (Smith *et al.*, 2014b) shows that between 2007 and 2012 the world's marine fleet consumed 250—325 million tonnes of fuel, accounting for approximately 2.8% of annual global greenhouse gas emissions (3.1% of annual CO_2 emissions). Carbon dioxide emissions from selected ship types in 2012 shown in Figure are based on the results from this study. However, as shown in Figure 10, compared to other modes of transport, shipping produces very low emissions of carbon dioxide per tonne carried per kilometre travelled.

Figure 9: CO_2 emissions of selected ship types in 2012



Adapted from the International Maritime Organisation's Third Greenhouse Gas Study 2014 (Smith et al., 2014b)

Figure 10: Comparison of CO_2 Emissions between Modes of Transport



Adapted from NTM as cited by the International Chamber of Shipping (ICS, 2013)

Emissions from the sector are expected to rise in line with shipping demand and could triple by 2050 if left unchecked (Smith *et al.*, 2014b); (IMO, 2012); (Stopford, 2010); (Fuglestvedt *et al.*, 2009). These emissions need to be curbed in order to reduce air pollution and mitigate climate change impacts. The International Convention for the Prevention of Pollution from Ships (MARPOL) has stipulated mandatory technical and operation measures which require ships to be more efficient in their energy use and emissions reduction[51]. These requirements came into force in 2013. The industry itself has targets to reduce carbon dioxide emissions by 20% by 2020 and 50% by 2050 (ICS, 2013). Ship operators, therefore, need to consider cleaner fuel and power options, including the use of renewables, to meet these targets.

51 Annex VI of MARPOL. See http://www.imo.org/About/Conventions/ListOfConventions/Pages/International-Convention-for-the-Prevention-of-Pollution-from-Ships-(MARPOL).aspx

A number of cost-effective technology options for new and existing ships and operators have been identified to improve energy efficiency of ships or lower their energy intensity. These options can be categorised into four option groups, namely: improving energy efficiency (*i.e.* increasing productivity using the same amount of energy); using renewable energy (*e.g.* solar and wind); using fuels with lower carbon content (*e.g.* LNG and biofuels) and using emission reduction technologies (*e.g.* through chemical conversion, capture and storage). Although sea transport is the most efficient transporter of goods per tonne per kilometre (see Figure 10), there are major efficiency gains still to be made with fuel cost, amid a globally volatile market. The shipping industry is introducing efficiency measures at an unprecedented rate in its history.

Therefore, although significant efforts are being made in the design and operation of ships of all scales to enhance energy efficiency, such measures on their own may not be enough to substantially reduce the use of fossil fuels. Renewable energy is one of a range of alternative/additional sources of energy available for application in this sector. Table 4 summarises the drivers influencing the deployment potential of renewable energy solutions in the shipping sector.

Potential

Renewable energy has the potential to transform the global shipping fleet at all levels and scales, including: international and domestic transport of goods, people and services; fishing; tourism and other maritime pursuits. The transition to a clean energy shipping sector requires, *inter alia,* a significant shift from fossil fuel-powered transport to energy-efficient designs and renewable energy technologies. The sooner this shift occurs, the better. The future of a sustainable shipping sector, including options for renewable energy solutions, has been well elaborated. See, for example, (DNV, 2014); (Lloyds Register and UCL, 2014); (Smith *et al.*, 2014a); (EffShip, 2013a); (Royal Academy of Engineering, 2013); (Sustainable Shipping Initiative, 2013); (Ecofys, 2012b); (Forum for the Future, 2011) and (Einemo, 2010). The contribution of renewables to the energy mix of the shipping sector, however, is presently very limited and is likely to remain so in the near term. Still, developers are increasingly introducing designs and proof-of-concept pilots demonstrating major savings in some applications so there is potential for renewables to make a modest contribution in the medium term. For selected applications in this sector, the

Table 4: Summary of drivers for the deployment potential of renewable energy solutions in the shipping sector

Drivers for Clean Energy Solutions in the Shipping Sector			
Environmental	**Technical**	**Economic/ Financial**	**Policy and Regulatory**
• Emissions reduction and pollution control	• Propulsion system	• Fossil fuel price	• Governance
• Climate change	• Engine technology	• Investment cost	• Regulatory framework and enabling environment
• Energy availability	• Fuel properties	• Operational costs	• Energy security
• Sustainability	• Material properties	• Economic growth	• Investment in research and development
• Alternative fuels	• Information technologies	• Global trade	
• Life cycle impact	• Energy storage	• Economic integration	
• Health and safety	• Hybrids and optimisation	• Incentives and market-based mechanisms	
• Societal pressure		• Financing mechanisms	
		• Pricing and returns	
		• Public/private partnerships	

Compiled from EffShip, 2013b and ICF International, 2008

role of renewables can be significant, even dominant. Of the various renewable energy options, advanced biofuels have a very high potential to transform energy choices in the shipping sector from about 2030 onwards. By then, the production of most biofuels, in the presence of supportive policy measures, is expected to be cost-competitive and the share of biofuels should increase substantially as a result of efforts to double the share of renewables in the

global energy mix. See, for example, (IRENA, 2014b); (Lloyds Register and UCL, 2014); (OECD-FAO, 2014); (Ecofys, 2012b) and (IEA, 2011).

However, the potential of biofuels for the shipping sector will depend on a number of factors, including the global availability of sustainable feedstock for its production. Projections covering the global supply and demand for bioenergy has been recently summarised and analysed (IRENA, 2014a). With regard to the availability of biofuel feedstock, first generation technologies, while viable, are unlikely to offer major options for shipping with the exception of communities with high bio-resource surpluses and/or extended supply chains for fossil fuel supply. In terms of carbon emissions reduction potentials, savings over the full life-cycle are very sensitive to a range of parameters, including feedstock type, growing conditions, land use change and the refining process. Second generation biofuels face similar challenges in terms of feedstock, but their potential is far greater, especially for biomethane in tandem with marine LNG infrastructure investment that is already underway or planned. Furthermore, local biomass residues and wastes can also be processed into marine liquid biomethane to make a closed loop system for remote applications in island communities. Third generation algae-derived fuel is perhaps the most promising biofuel for shipping as it could be produced in close proximity to ports and coastal areas and meets the technical and sustainability requirements. When used for shipping, the development of algae-based biofuels requires less refining compared with development for the aviation or automotive sectors since current marine diesel engines are well adapted to burning lower grade HFO fuel. However, the technology of algae-based biofuels is still in development and uncertainties remain with regard to the availability and processing of algae for substantial volumes of biofuel.

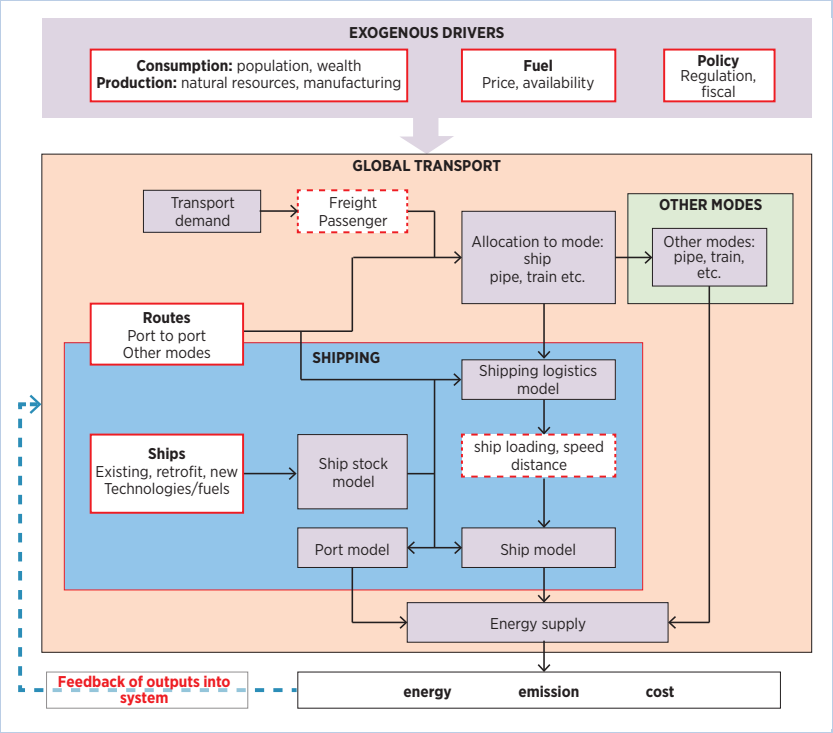
Hydrogen fuel cells as renewable energy pathway for shipping also hold great potential but the sustainability of the energy source used to produce the hydrogen, as well as a lack of cost-effective and reliable low-pressure storage options for the fuel remain critical issues to be addressed. See, for example, (DNV, 2014); (IEA-AMF, 2013) and (Royal Academy of Engineering, 2013). Overall, the greatest potential lies in a combination of renewable energy solutions that maximises the availability of energy resources and the complementarity of those sources in hybrid modes. In this sense, achieving renewables' potential for the shipping sector requires an integrated systems engineering approach that also addresses barriers to its deployment. Such

a systems approach must consider all elements of ship design, marine and control engineering, as well as operational practices and patterns and levels of trade. Effective improvements in efficiency and emissions reduction can thus be readily achieved. The potential for sustainable and resilient shipping is further increased when the systems approach makes a compelling case for renewable energy solutions, including addressing all of the stakeholder requirements while ensuring that the overall emissions profile of the propulsion method and the fuel used are properly assessed through a life-cycle approach. As a result, any reductions in propulsion emissions and energy savings gains would not occur at the cost of increasing harmful emissions in land-based sectors that produce either the propulsion machinery or the fuel.

With the global shipping industry increasingly dominated by larger vessels and ever larger shipping entities, the potential for cost savings and emissions reductions are experiencing constraints. However, there are still opportunities for substantial savings, especially at the small- and medium-sized vessel level. As energy costs for fossil fuel applications increase, the case for renewable energy use for selected applications improves significantly. Computer modelling shows the opportunities and cost effectiveness of varying technologies, especially when combined with efficiency measures, both technological and operational. Figure 11 shows how exogenous drivers of the global transport system can be modelled to identify cost-effective, low emissions solutions for the shipping sector.

The potential for increased penetration of renewable energy solutions in shipping's energy options will increase substantially once their commercial viability is clearly demonstrated and efforts are made to motivate investment and remove deployment barriers. In particular, support policies and incentives to promote research, innovation and proof-of-concept examples are crucial in order for renewable energy shipping solutions to reach commercial viability. While conventional shipping on established and well-travelled routes appears likely to transition to LNG as a stepping stone to longer term fuels such as hydrogen and methane, there is a special case to be made for increased use of renewable energy on routes where alternative fuelling infrastructure may be economically prohibitive. See, for example, (Nuttall *et al.*, 2014). Such routes include those connecting many Small Islands Developing States and other Least Developed Countries. These routes are mainly serviced by smaller (and generally older) assets, which are far less efficient in terms of fuel used to

Figure 11: Exogenous drivers for the global transport sector provide opportunities for deployment of energy efficiency and renewable measures in the shipping sector



Source: Smith et al., 2010

move each tonne and the greatest proportionate emitters of pollutants. With a range of cost-effective technologies available for such services, either as retrofits or new design construction, significant efforts and support measures need to be applied now to demonstrate and increase the role of renewables in shipping. For quick-win solutions, support should focus on small ships (less than 10 000 dead weight tonnes) that are globally prevalent, transporting less of the total cargo but emitting more greenhouse gases per unit of cargo and distance travelled, compared to larger ships.

Barriers

The barriers to the adoption of renewable energy in the shipping sector are complex, but can be categorised under organisational/structural, behavioural, market and non-market factors. See, for example, (Rojon & Dieperink, 2014); (Acciaro *et al.*, 2013); (European Commission, 2013) and (Rehmatulla *et al.*, 2013). These barriers are summarised in Table 5. The complexity of barriers to deployment of renewable energy solutions in the shipping sector, in part, reflects the unique and international nature of the industry, with the underlying constraints and factors lying beyond the scope of individual states to effect incentives along with the policy and regulatory framework needed to overcome said barriers. With regard to organisational, structural and behavioural barriers, limited R&D financing, particularly for initial proof-of-concept' technologies is a major factor, together with ship owners' concerns about the risk of hidden and additional costs, as well as opportunity costs for renewable energy solutions. This is particularly true since, historically, there has been a lack of reliable information on costs and potential savings of specific operational measures or renewable energy solutions for this sector.

Concerning market barriers, the fundamental problem is that of split incentives between ship owners and hirers, where costs and benefits do not always accrue to the investing party and hence savings cannot be fully recouped because of differences in the charter types in specific sectors. This lessens owners' motivation to invest in clean energy solutions. There is no current consensus on whether the responsibility and cost of the change to renewable options for shipping should fall to the ship owner or to the ship operator. In addition to the issue of split incentives, a space (Acciaro *et al.*, 2013) among Norwegian shipping companies on measures for reduction of emissions found that operational measures (*e.g.* reducing speeds, voyage performance, main engine improvements and drag reduction technology) were perceived by ship owners as the most easily implementable solutions. Technical measures, such as the introduction of renewable solutions (*e.g.* fuel cells, wind, liquefied biomethane and solar photovoltaics) were identified as those with the highest implementation barriers.

The Sustainable Shipping Initiative (SSI) has created a *Save As You Sail (SAYS)* financial model, designed to overcome split incentives. Under SAYS; the owner takes out a loan with a finance provider and agrees to a regular fixed SAYS

fee with the time charterer in addition to their charter rates. The additional income for owners represents a share of the cost savings that the charterer makes and, with proven established technologies, this can more than cover the owner's SAYS loan payments, meaning that owners profit during and after the loan period[52]. Another barrier is the risk adversity of investors in the sector, especially following the collapse of the 2006 shipping boom. Furthermore, the shipping sector is a low-visibility sector for the average person, which means that there is less societal pressure on the industry to transition to cleaner energy solutions. Of the non-market barriers, the different classes and scales of ships, the markets and trade routes served and the lack of access to capital are some of the key barriers to be addressed.

With regard to non-market failure barriers, the key issue is the lack of R&D financing, particularly for initial proof-of-concept technologies. There is room for Public Private Partnerships (PPP) in shipping finance but the development of these partnerships is a complex process. Many investment processes in transport projects rely on two main streams of capital flow: public programmes and private investment. Combined, they create the basis for PPPs. Each consists of a variety of financial tools, for instance all EU public programmes allocate resources for projects under different schemes (*e.g.* grants awarded following a call for proposals, grants awarded without a call for proposals and grants awarded by virtue of an 'easy fit' for the specific programmes). Another non-market failure barrier is the lack of effective technology for green shipping technology transfer. The United Nations Secretary-General's recent report "Options for Facilitating the Development, Transfer and Dissemination of Clean and Environmentally Sound Technologies" found that Member States and stakeholders shared the objective of accelerating technology facilitation, but differences existed in the details and approaches[53]. In the maritime sector, the 65th session of the Marine Environment Protection Committee (MEPC) of the IMO adopted a resolution on technical cooperation for energy efficiency measures[54]. The resolution "*requests the Organization, through its various programmes, to provide technical assistance to Member States to enable cooperation in the transfer of energy efficient technologies to developing countries in particular; and further assist in the sourcing of funding*

52 http://ssi2040.org/wp-content/uploads/2012/11/SSI_finance_infograph_130529.pdf

53 See http://www.un.org/ga/search/view_doc.asp?symbol=A/68/310

54 http://www.imo.org/MediaCentre/MeetingSummaries/MEPC/Pages/MEPC-65.aspx

for capacity building and support to States, in particular developing States, which have requested technology transfer." In the long term, the technology transfer arising from such technical cooperation should contribute to green shipping in all sectors and economies.

Table 5: Principal barriers to renewable energy uptake in the shipping sector

Barriers	Examples	Key Actors	Approaches/Solutions
Organisational/ Structural	• North/South power dynamic • Political and legislative structures • Conservative culture • Fragmented and/or incremental approach • Focus on large versus small vessel sectors	• International Maritime Organisation, International Chamber of Shipping • Classification societies • Banks and financial Institutions • National/International governments	• Lobbying for sustainable shipping incentives • Establish a clear, stable legal and regulatory framework • Develop multi-stakeholder technology research and development programmes • Sustainable shipping projects in developing markets
Behavioural	• Perceptions of complexity and cost of solutions • Investment and innovation inertia • Lack of reliable information re true cost of solutions • Lack of awareness of viable solutions and their scope • Limited R&D transparency	• Technology providers • Shipbuilders • Academics • Seafarers • Policy makers	• Demonstration/pilot commercial programmes • Independent research "think tanks" • Training, education programmes

Market Failures	• Principal-agent problem as a result of information asymmetry • Split incentives • Lack of policy and regulatory framework and market incentives • Long investment horizons and vested interests	• Policy makers • Ship owners • Ship operators/ charterers • Technology providers • Investors	• Charter changes/adjustments • Eco-labelling initiatives (industry and consumer) • Increased transparency and investment analysis • Market-based mechanisms and initiatives • Accurate long-term energy needs assessment • Cradle-to-grave analysis
Non-Market Failures	• Technical uncertainty and complexity of solutions • Lack of R&D investment • Safety and reliability issues • Hidden costs • Access to capital • Lack of risk management	• All shipping actors • Ports and logistics owners • Local/national governments • Investors, banks and other financial institutions	• Increasing PPP collaboration • Demonstration projects/ships • Development of innovative financial systems • Sharing risk through multi-stakeholder developments • Promotion of technology transfer

Compiled from Rojon & Dieperink, 2014; Acciaro *et al.*, 2013; European Commission, 2013 and Rehmatulla *et al.*, 2013

Table 6: Summary of benefits of renewable energy applications in the shipping sector

Economic – Direct		Economic – Indirect		Environment/Social	
Significant fuel cost reductions	Further increased with other efficiency measures (*e.g.*, slow steaming, voyage routing, hull design)	Increased resilience	Resilience to climate change, fuel shocks and other externalities when energy costs are reduced and energy security is increased.	Substantially reduced emissions	Lower CO_2 emissions and potential to eliminate SO_x, NO_x, particulate matter
Increased stability and security in energy prices and supply	Forecasting and decreasing investment risks over the medium- to long-term	Potential to revitalise uneconomical routes	Stimulating local/regional growth and increasing trade system access	Less risk of spills	Less fuel and reduced environmental damage from spills (biofuels are biodegradable, etc.)
Reduction in wear and tear, increased stability	Wind energy as an auxiliary to other propulsion significantly reduces engine, transmission and propeller wear and increases vessel stability	Stimulation for new and existing industries	Advanced technology systems (*e.g.* PV, navigation software, design); manufacturing (*e.g.* new engines, shipbuilding); new energy solutions (e.g. biofuel and waste feedstock sector); and trade in general	Decreased marine noise	Use of wind/wind-assist, electric motors
Maintenance of resale and chartering value	Through marine vessel eco-labelling schemes and compliance with future emissions regulations	Shake up/increase of competition in the energy supply chain	Bunkering agents (competition) and ship owners (choice – mix of fuels, various energy investment options)	Health benefits	Contribution to the reduction in shipping emissions-related deaths (approx. 60 000 per year) and ill-health

Potential for reduced port fees and local/ regional levies	Through reduced emissions and energy demand	Reduction of wider economic impact of emissions on health	Workdays lost through shipping emissions-related deaths (approx. 60 000 per year) and ill-health; reduced social and healthcare costs	Health and safety benefits on-board	For both passengers and crew: cleaner environments, lower emissions, less flammable material carried, etc.
		Eligible for market-based mechanisms	Carbon credits and other market-based incentives	Inspiration	Renewable energy technologies bring new challenges to ship designers, engineers and shipping industry in general, helping to attract talent and retain expertise in the sector
		Eco-branding	Marketing opportunities	Aspiration	Renewable energy in shipping feeds into the green-growth agenda, creating opportunities for employment and training, new business and opening up innovation and entrepreneurial space, especially in regions under-serviced by the existing shipping network (*e.g.* Pacific Islands, Least Developed Countries)

Table 7: Summary of renewable energy applications and their potential for shipping

Renewable energy type		Retrofit (RF)/ New Build (NB)	Vessel category, application, examples and potential							
			< 400 tonnes *e.g.*, recreation, artisanal/ small fishery, tourism, passenger, break, landing craft, barges, research, coastal patrol and security		**400 – <10 000 tonnes** *e.g.*, large landing craft, small-medium fishery, domestic Ro-Ro, break bulk, bulk, container, tanker, tramp		**10 000 – <50 000 tonnes** *e.g.*, Ro-Ro, deep sea fishery, bulk, container, tanker, car carrier, cruise liner		**>50 000 tonnes** *e.g.*, Very Large Crude Carriers (VLCCs), Panamax, Aframax, large container ships	
Wind	Soft sails	RF	●●●	*Na Mataisau, Kwai*, Avel Vor	●●●	Seagate deltasail	●●●	Seagate deltasail	●●	Seagate deltasail (up to 100 000 tonne)
		NB	●●●	*Greenheart*	●●●	*B9, Rainbow Warrior 3, Maltese Falcon* (Dynarig), *Maruta Jaya* (Indosail), *Atlantic Clipper*	●●●	*Ecoliner, B9*	●●	*Bulker-1*
	Fixed wings	RF	●●		●●	*Shin Aitoku Maru, Ashington*, Oceanfoil wingsail	●●	*Usuki Pioneer*, Oceanfoil wingsail	●	Oceanfoil wingsail
		NB	●●	OCIUS – short run passenger	●●●	Propelwind	●●●	*UT Challenger*, OCIUS, *Orcelle Ecomarine*	●●	*UT Challenger*, OCIUS, *Ecomarine*
	Rotors	RF	●●	*Tracker*	●●	*Bacau*	●●	Numerous applications	●●	
		NB	●●●	*UniKat*	●●●	*Barbara*	●●●	*E-Ship 1*	●●	Magnuss (telescopic)
	Kites	RF/NB	●●	Beyond the Sea	●●	SkySails, Beyond the Sea, *Beluga*	●●	SkySails, Beyond the Sea	●	Beyond the Sea
	Turbines	RF/NB	●	Ancillary power only	●	Ancillary power only	●	Ancillary power only	●	Ancillary power only
Solar photovoltaics	Main	RF	N/A	Small outboard/inboard, short run	N/A					
		NB	●	Lagoon, tourism	N/A	Theoretical only	N/A		N/A	
	Auxiliary	RF	●●		N/A		●	*Auriga Leader*	N/A	
		NB	●●	OCIUS – short run passenger	N/A		●		N/A	
	Ancillary	RF/NB	●●		N/A		●	*Auriga Leader*	N/A	

Biofuels	1st Generation	RF	●●	High technological feasibility. Cost effectiveness unproven. Environmental sustainability of feedstock issues	●●	High technological feasibility. Cost effectiveness unproven. Environmental sustainability of feedstock issues	●●	*Jewel of the Sea, Anna Desgagnes.* Cost effectiveness unproven. Environmental sustainability of feedstock issues	●	High technological feasibility. Cost effectiveness unproven. Environmental sustainability of feedstock issues
		NB	●●	As above	●●	*Meri.* As above	●●	As above	●	As above
	2nd Generation	RF	N/A		N/A		N/A		N/A	
		NB	●●●	High technological feasibility	●●●	*B9.* High technological feasibility	●●●	High technological feasibility	●●	High technological feasibility
	3rd Generation	RF	N/A		N/A		N/A		N/A	
		NB	●●●	Upcoming technology	●●●	Upcoming technology	●●●	Upcoming technology	●●	Upcoming technology
Wave	Main	NB	●	Unmanned research RCVs	N/A		●	*Orcelle*	N/A	
	Auxiliary	NB	●	Theoretical concept only	N/A		●	*Orcelle*	N/A	
Electric	Supercapacitor	NB	●	Short run – limited geographical range	●	Short run – limited geographical range	N/A		N/A	

Keys:

Current Application

This colour key provides a measure of the market status of each renewable energy technology

	In commercial use
	Proven
	Proof-of-concept
	Design
	Concept
	Uncertain

Potential Application

This black-dot designation provides a crude assessment of overall potential benefits of each renewable energy technology in terms of economics (e.g. Does it offer improved economic performance for the end user? Is it easy to adopt/adapt?), environment (What CO_2 savings are likely? How is embedded CO_2 managed?) and social factors (Is the technology suitable for cultural/societal development? Does it support development or create community resilience?).

●●●	High potential (Scores well on all three metrics: economic, environmental and social)
●●	Medium potential (Scores on two of the three metrics)
●	Limited I (Scores on only one of the three metrics)
N/A	Not available

REFERENCES

Acciaro, M., P.N. Hoffman and M.S. Eide, (2013) The energy efficiency gap in maritime transport. *Journal of Shipping and Ocean Engineering*, 3, pp.1-10.

Argonne National Laboratory. (2013) *Life Cycle Analysis of Conventional and and Alternative Marine Fuels in GREET* [Online]. Available at: https://greet.es.anl.gov/files/marine-fuels-13 [Accessed October 2014].

Bengtsson, S., E. Fridell and K. Andersson, (2012) Environmental assessment of two pathways towards the use of biofuels in shipping. *Energy Policy*, 44, pp. 451–463.

Bruckner-Menchelli, N., (2010). Asia's maritime industry sees benefits of a green revolution. *Bunkerworld*, May/June, p. 24.

Danish Ship Finance. (2014) *Shipping Market Review, May 2014*.

DNV. (2014) *Alternative Fuels for Shipping. DNV Position Paper, 1-2014*.

Ecofys. (2009) *Study on Competitiveness of the European Shipbuilding Industry*.

Ecofys. (2012a) *Green Growth Opportunities in the EU Shipbuilding Sector*.

Ecofys. (2012b) *Potential of Biofuels for Shipping*. Utrecht: Ecofys.

EffShip. (2013a) *EffShip Project Summary and Conclusions*.

EffShip. (2013b) *Work Package 2 Report: Present and Future Maritime Fuels*. EffShip Project.

Einemo, U., (2010). Fuelling the future. *Bunkerworld*, September/October. pp.1-4.

European Commission (2013) *Time for international action on CO_2 emissions from shipping* [Online]. Available at: http://ec.europa.eu/clima/policies/transport/shipping/docs/marine_transport_en.pdf .

Forum for the Future. (2011) *Sustianble Shipping Initiative: the case for action*. Sustainable Shipping Initiative.

Fuglestvedt, J. *et al.* (2009) Shipping Emissions: From Cooling to Warming of Climate – and Reducing Impacts on Health. *Environmental Science and Technology*, 43(24), pp. 9057–9062.

ICF International. (2008) *Long Range Strategic Issues Facing the Transportation Industry, Final Future-focused Research Framework, National Cooperative Highway Research Program, Project 20-80* [Online]. Available at: http://onlinepubs.trb.org/onlinepubs/archive/NotesDocs/NCHRP20-80(2)_FR.pdf [Accessed March 2014].

ICS. (2013) *Shipping, world trade and the reduction of CO_2 emissions* [Online]. Available at: http://www.ics-shipping.org/docs/default-source/resources/environmental-protection/shipping-world-trade-and-the-reduction-of-co2-emissions.pdf?sfvrsn=14 [Accessed June 2014].

ICS. (2014) *2014 Annual Review*. Annual Review. London: ICS International Chamber of Shipping (ICS).

IEA. (2011) *Technology Roadmaps: Biofuels for Transport*. Paris.

IEA-AMF. (2013) *Annex 41 Report: Alternative Fuels for Marine Applications* [Online]. Available at: http://www.iea-amf.org/app/webroot/files/file/Annex%20Reports/AMF_Annex_41.pdf [Accessed October 2014].

IMO. (2012) *International Shipping Facts and Figures – Information Resources on Trade, Safety, Security, Environment* [Online]. Available at: http://www.imo.org/KnowledgeCentre/ShipsAndShippingFactsAndFigures/TheRoleandImportanceofInternationalShipping/Documents/International%20Shipping%20-%20Facts%20and%20Figures.pdf [Accessed May 2014].

IRENA. (2013) *Road Transport: The Cost of Renewable Solutions*. Abu Dhabi: IRENA.

IRENA. (2014a) *Global Bioenergy Supply and Demand Projections: A working paper for REmap 2030*. Abu Dhabi: IRENA.

IRENA. (2014b) *REmap 2030: A Renewable Energy Roadmap*. Abu Dhabi.

Lloyds Register and UCL. (2014) *Global Marine Fuel Trends 2030* [Online]. Available at: http://www.lr.org/en/_images/213-34172_Global_Marine_Fuel_Trends_2030.pdf [Accessed October 2014].

Nuttall, P. *et al.* (2014) A review of sustainable sea-transport for Oceania: Providing context for renewable energy shipping for the Pacific. *Journal of Marine Policy* , 43, pp. 93-105.

Oceana. (2010) *Shipping solutions: technological and operational methods available to reduce* CO_2.

OECD-FAO. (2014) *Agricultural Outlook 2014 – 2023*.

Rehmatulla , N., T. Smith and P. Wrobel, (2013) Implementation Barriers to Low Carbon Shipping. In *Low Carbon Shipping Conference*. London, 2013.

Renewable Fuels Association. (2010) *Ethanol and Marine Use: Frequently Asked Questions* [Online]. Available at: http://ethanolrfa.org/page/-/Ethanol%20and%20Marine%20Use%20FAQs%20Nov2010.pdf?nocdn=1 [Accessed October 2014].

Rojon, I. and C. Dieperink, (2014) Blowin' in the wind? Drivers and barriers for the uptake of wind propulsion in international shipping. *Energy Policy*, 67, pp. 394-402.

Royal Academy of Engineering. (2013) *Future Ship Powering Options: Exploring Alternative Methods of Ship Propulsion*. London: Royal Academy of Engineering.

Smith, T. *et al.* (2010) Low Carbon Shipping – A Systems Approach. In *Ship Design and Operation for Environmental Sustainability*. London, 2010.

Smith, T.W.P. *et al.* (2014a) *Low Carbon Shipping – A Systems Approach*.

Smith, T.W.P. *et al.* (2014b) *Third IMO GHG Study 2014*. London: International Maritime Organisation.

Stopford, M. (2010) *How shipping has changed the world & the social impact of shipping* [Online]. Hamburg Available at: http://ec.europa.eu/competition/consultations/2012_maritime_transport/euda_8_en.pdf [Accessed July 2014].

Stopford, M. (2013) *The Tanker & Dry Cargo Outlook* [Online]. Mareforum, Rome. Available at: http://old.mareforum.com/ROME2013/STOPFORD.pdf [Accessed June 2014].

Sustainable Shipping Initiative. (2013) *Sustainable Shipping Initiative Progress Report: a case for more action*.

Traut, M. *et al.* (2014) Propulsive power contribution of a kite and a Flettner rotor on selected shipping routes. *Applied Energy*, pp. 362–372.

UNCTAD. (2014) *Review of Maritime Transport 2014*. New York and Geneva: United Nations.

UNCTAD. (2013) *Review of Maritime Transport 2013*. New York and Geneva: United Nations.

UNESCAP. (1984) *Wind-powered vessels for coastal and inter-island use in the Asian and Pacific Region*.

ZERO. (2007) *Biofuels in Ships* [Online]. Available at: http://cleantech.cnss.no/wp-content/uploads/2011/05/2007-Opdal-and-Hojem-Biofuels-in-ships.pdf [Accessed October 2014].



P.O. Box 236
Abu Dhabi
United Arab Emirates

IRENA Innovation and
Technology Centre
Robert-Schuman-Platz 3
53175 Bonn
Germany

www.irena.org



www.irena.org

Copyright © IRENA 2014