The Role of Technology in Green Ship Design

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KEYNOTE PAPER

THE ROLE OF TECHNOLOGY IN GREEN SHIP DESIGN

Spyros Hirdaris[1], Fai Cheng[1]

ABSTRACT

In today's environmentally conscious world maritime innovation is expected to reflect the increasing societal demands to minimise the impact of shipping on the environment. Current and future ship designs are expected to comply against demanding environmental standards, requirements for new equipment and for sustainability within the context of lifecycle performance. This paper discusses the importance of environmental technologies and some of the recent research experiences of Lloyd's Register in this area.

KEY WORDS

Green Ship Design; Strategic Research and Innovation; Technology; Sustainability.

INTRODUCTION

With more than 70% of the planet's surface covered by water, the oceans are at the heart of life on earth. Today, more than 90% of trades are carried out by waterborne transport and we are venturing into more hostile parts of the oceans, in ever greater depths to extract resources and power world economic growth. In the last few decades the maritime industries have continuously endeavoured to mitigate the increasing environmental expectations via the implementation of operational strategies and the development of technologies that may be related with efficient engine design, propulsion systems and optimised ship hull designs. It is true that earlier and current technological efforts facilitated a noteworthy reduction in fuel consumption and resulting CO_2 emissions on a capacity basis (tonne-mile). However, in recent years social interest on global warming issues has grown increasingly and topics related to energy conservation and reduction in CO_2 emissions is becoming omnipresent. In the coming decades, the efforts to develop strategies and technologies which will continue to deliver social and economic benefit without adversely affecting the environment upon which we depend are expected to increase. To succeed, we must continue to improve on infrastructure, knowledge and innovation capability. We should also understand the role of developing, implementing and assuring technology within the context of balancing maritime safety against environmental legislation, economic measures and the demands of the human element.

Lloyd's Register plays an important and well established role within the regulatory framework of the marine industry by helping to assure standards of safety and sustainability through the application of technology resources. Notwithstanding, the diverse and increasing technological demands implied by the environmental expectations raise some questions on the role of technology and regulation versus classification based assurance. In the years to come the so called 'constraint' of Regulation will continue to be driven by conscience and principle (Kent, 2011). However, the increasingly new environmental requirements shall imply that prescriptive requirements for specific features of a ship will sit alongside provisions for alternatives on the basis of risk and equivalence. With the increasing environmental demands and the rapid technology development it may also be expected that the role of Classification to safeguard the assurance and the implementation of technological applications on green ship designs will become increasingly important. Accordingly, enabling sustainable technologies within the context of developing some fundamental understanding of their application at early stage and later on implementing them by means of realistic technical or operational measures may become necessary.

This keynote discusses recent regulatory developments, outlines some technological implementation options as well as some of the recent innovation initiatives of the Society. In this sense it supports the notion that Strategic Research may be an essential milestone in response to the demands of the international community to 'connect and catalyse' some of the foreword looking socioeconomic expectations imposed upon the maritime industry.

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THE REGULATORY LANDSCAPE

Since the 1970s, the answers to the environmental questions facing the maritime world have been spearheaded by the International Maritime Organization (IMO), the body which regulates shipping through international consensus. During this time, the IMO has successfully adopted a number of international treaties, such as the MARPOL Convention with its six Annexes, the 'Anti-fouling Systems Convention' and the 'Ballast Water Management Convention'. The majority of these contribute to the protection of the environment both in water and in air, while others are on a steady course towards ratification. In fact, 21 of the 51 IMO Conventions relate to environmental issues. The Lloyd's Register environmental roadmap outlined in Figure 1 presents a projection of the key existing and forthcoming environmental legislation from the IMO up to the end of 2017, identifying future compliance dates and emerging regulations (Lloyd's Register, 2011).

International efforts to reduce the impact of climate change started in Rio in 1992 where the framework for sustainable development was agreed by more than 150 governments. This was followed by the adoption of the Kyoto protocol in 1997 which bound the Annex I nations to reduce Green House Gas (GHG) emissions to the average of 5.2% below 1990 levels by 2012. Although ships are the most efficient mode of transport the 2nd IMO GHG study 2009 identified a significant potential for further improvements in energy efficiency mainly via the use of existing technologies (IMO, 2009a).

In recent times the IMO has adopted two distinct approaches to developing measures to control CO_2 emissions namely (a) Technical and operational measures, primarily aimed at improving energy efficiency of ships; (b) Market Based Measures (MBM) aimed at stabilisation or overall reduction of GHG emissions from international shipping. This dual approach has been necessary to try to ensure that any technical and operational measures which may be implemented to reduce GHG emissions on a ship by ship basis are not counteracted by increased emissions associated with the predicted future growth in the world fleet and shipping activity. The technical and operational measures are the direct means for improving ship energy efficiency. The former are implemented by improving ship hardware equipment, while the later are implemented by improvements or innovations in the operation of the ship. In contrast, economic instruments are not meant to reduce CO_2 emissions directly; they may be considered as instruments that offer economic incentives to promote implementation of the technical measures or the operational measures. Since the technical and operational measures are technology focused some of their ongoing status is explicitly discussed in the following section. The reference on market based instruments is brief as it is ongoing in development and notion.

Technical and Operational Measures

As CO_2 is formed from the oxidation of carbon in hydrocarbon fuels in order to reduce associated emissions, either less fuel must be burnt or the carbon content of the fuel burnt must be reduced or eliminated. These approaches essentially translate to either the implementation of energy efficiency measures, both technical and operational, the use of alternative low or zero carbon fuels or preferably the implementation of both in ship design and operation. To date, the development of technical and operational measures has been aimed primarily at improving energy efficiency since it is generally accepted that the use of alternative low or no carbon fuels may be implemented over the medium to long term.

At IMO level the package of technical and operational measures was initially intended for trial purposes until the 60th Marine Environmental Pollution Committee (MEPC 60) in March 2010. Subsequently, at MEPC 61 (September/October 2010), all parties requested to circulate proposed amendments to MARPOL Annex VI to make mandatory the use of Technical measures via the Energy Efficiency Design Index (EEDI) for new ships and the Ship Energy Efficiency Management Plan (SEEMP) for all ships in operation. The proposed amendments were adopted by Parties to MARPOL Annex VI during MEPC 62 (IMO MEPC.203 (62), 2011), to make mandatory the EEDI for new ships, and the SEEMP for all ships. The regulations apply to all ships of 400 gross tonnage and above and are expected to enter into force on 1 January 2013. However, under regulation 19, an Administration may waive the requirement for new ships of 400 gross tonnage and above from complying with the EEDI requirements. In the current state of affairs the technical measures are implemented and evaluated by the EEDI which relates to the efforts by the IMO to limit global warming through pollution of the environment by marine engines, allowing for a specific figure for an individual ship design to be calculated by the fairly complex formula outlined in Figures 2,3. The EEDI is expressed in grams of CO_2 per ship's capacity mile and a smaller EEDI value indicates a more energy efficient ship design. The formula may be roughly simplified as: EEDI = CO2 emission/transport work; broadly then, EEDI may be thought of as a ship's CO_2 output divided by its cargo carrying capacity. Implementation of the EEDI will be achieved via the International Energy Efficient Certificate (IEEC).

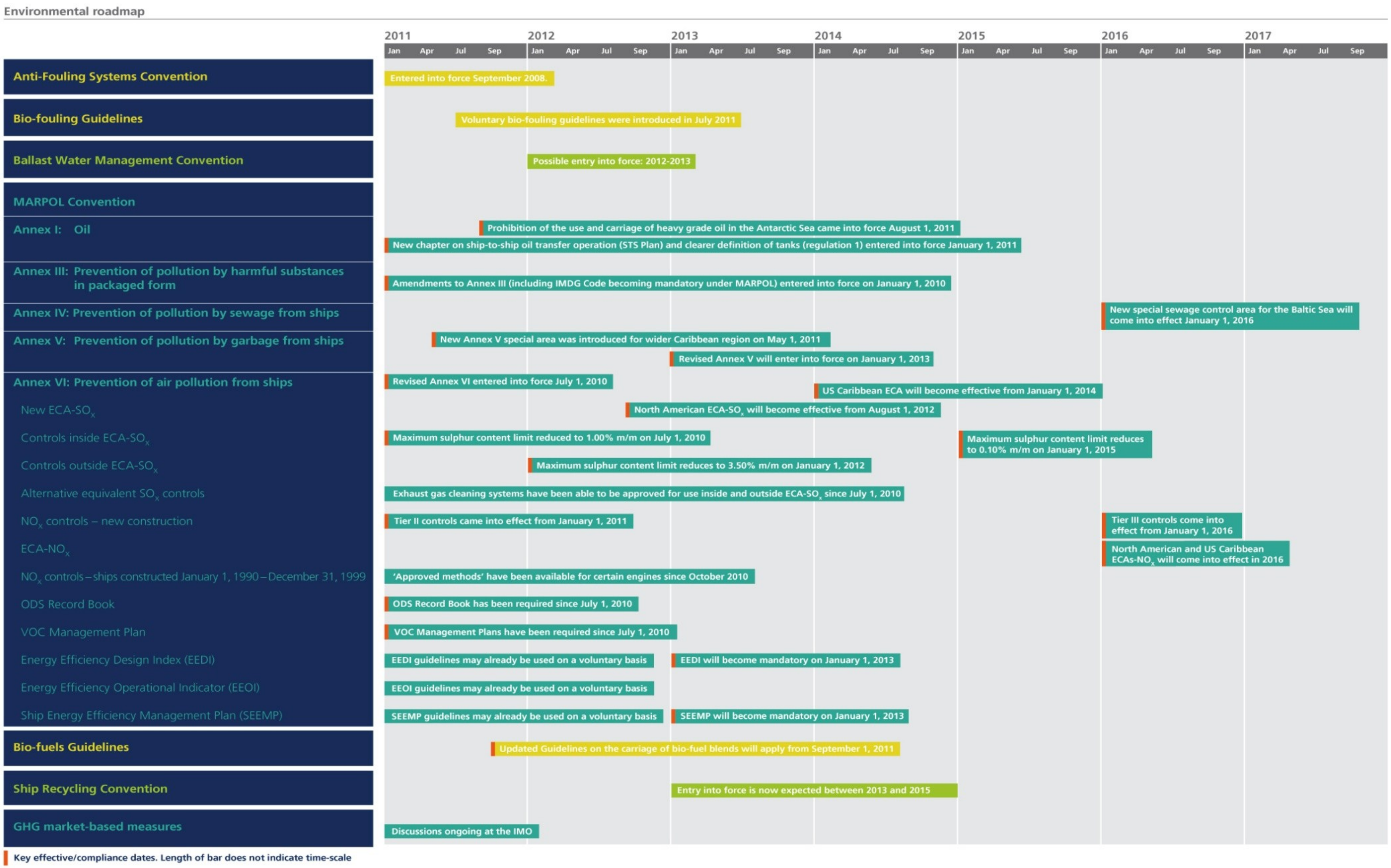

Figure 1: Lloyd's Register Roadmap on Current and Forthcoming Environmental Regulations (Lloyd's Register, 2011)

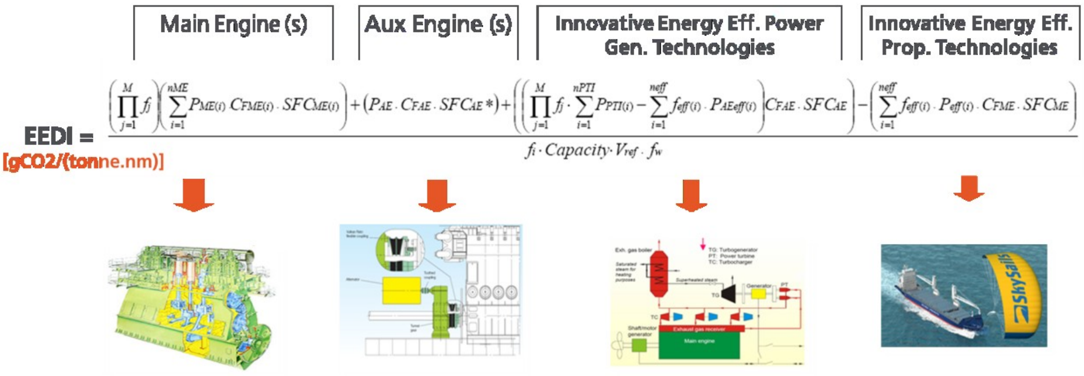

Figure 2: Key Components in EEDI Formulation (Bazari 2011)

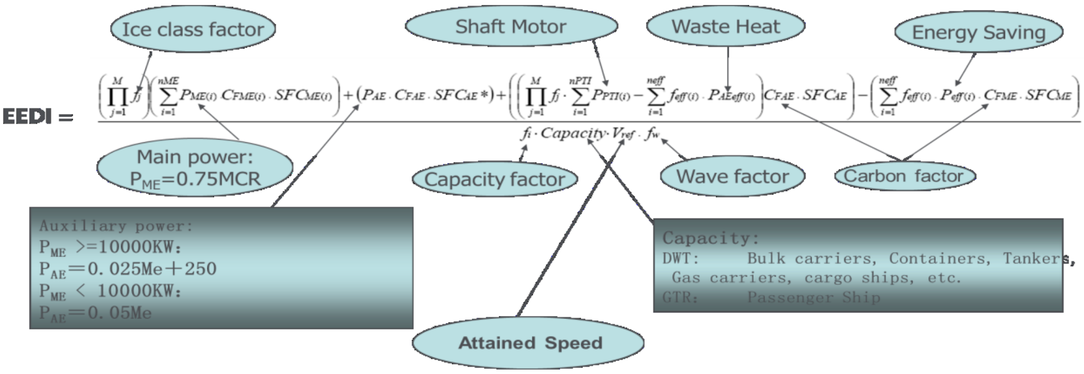

Figure 3: Illustrative Example of Key Components of the EEDI Formulae (Bazari 2011)

SEEMP is an operational measure that establishes a mechanism to assist a shipping company to improve the energy efficiency of its ship operations in a cost-effective manner. It provides an approach for monitoring ship and fleet efficiency performance over time using the so called Energy Efficiency Operational Index (EEOI) as a monitoring tool and serves as a benchmark tool. The guidance on the development of the SEEMP for new and existing ships incorporates best practices for fuel efficient ship operation, as well as guidelines for voluntary use of the EEOI for new and existing ships. The indicator enables operators to measure the fuel efficiency of a ship in operation and to gauge the effect of any changes in operation, e.g. improved voyage planning, more frequent propeller cleaning, or the introduction of technical measures such as waste heat recovery systems or a new propeller. As opposed to the EEDI its calculation is based on the real fuel consumption and cargo load of the vessel as expressed in the equation below:

$$\mathrm{EEOI} = \frac{\text{Total fuel consumption} * \text{Fuel carbon content}}{\text{Mass or cargo unit} * \text{Actual distance travelled}} \frac{\text{gram } CO_2 \text{ emmited}}{\text{tonne cargo transported}} \qquad [1]$$

Contrary to the EEDI the EEOI is changing with time and calculated on a daily basis using non reports. The adoption by IMO of mandatory reduction measures for all ships from 2013 and onwards may lead to significant emission reductions and cost savings. By 2020, up to 200 million tonnes of annual CO_2 reductions are estimated from the introduction of the EEDI for new ships and the SEEMP for all ships in operation, a figure that, by 2030, may increase to 420 million tonnes of CO_2 annually. The annual fuel cost saving estimates states a staggering figure of \$20 to 80 billion by 2020, and even more astonishing \$90 – 310 billion by 2030.

Market Based Measures (MBM)

In addition to the technical and operational measures, overarching market based measures are also under discussion and are expected to start utilising in measurable format over the medium term. Although all discussions at IMO on the matter of CO_2 emission control from international shipping have been hampered by on-going differences of opinion as regards the applicability of the United Nations Framework Convention on Climate Change (UNFCCC) principle of common but differentiated responsibility, it is the discussion of market based measures that has been most severely impacted over the years (Reynolds, 2011). The main problem has been that many developing countries ("non-Annex I" in terms of the Kyoto Protocol) consider that any mandatory regime aimed at reducing GHG emissions from ships should be applicable to the countries listed in Annex I to the UNFCCC only. However, other delegations at IMO consider that the IMO regulatory framework on the GHG issue should be applicable to all ships irrespective of the flags they fly, consistent with other IMO Conventions. In order to progress on the consideration of market based measures, MEPC 60 agreed to establish an Expert Group to undertake a feasibility study and impact assessment of the various proposals submitted for a market based instrument to control CO_2 emissions from international shipping. These proposals included schemes based on a contribution or levy on CO_2 emissions from international shipping, emission trading schemes and schemes based on a ship's efficiency. The proposals were assessed with regard to environmental and cost effectiveness, the potential to provide incentives to technological change and innovation, practicality, economic burden, etc. An intercessional Working Group subsequently met in March 2011 to consider the need and purpose of market based measures as a mechanism to reduce GHG emissions from international shipping and to evaluate further the MBM considered by the Expert Group. Little progress was made in terms of selecting and further developing a MBM for international shipping. Further consideration of a MBM addressing GHG from international shipping is unlikely to take place at IMO until MEPC 63 in 2012 due to the focus on technical and operational measures. In any case the link of MBM to Technical or Operational measures and the provision of additional associated economic incentives on ship design remains a future exercise.

THE CONTEXT OF STRATEGIC RESEARCH

Given the pivotal role of the Classification Societies within the maritime industry and the need to make sure that the regulatory processes do not constrain the take up of innovation other than by providing effective safeguards, any technology development that offers a better insight into the understanding and implementation of environmental technologies and consequent implementation of measures must be important. The later offers the potential to develop products and services which take better account of the technology advances. The approach taken to Strategic Research by Lloyd's Register is well balanced by considering the imperative that the Rules and their supporting knowledge, which form the basis of classification, reflect current technology, design assurance methodologies and analysis methods. The Society is working at arms length from the principles research which sits within academia to the development and implementation spectrum that involves both industry visionaries and in occasion academia (see Figure 4). Whereas the former is primarily associated with the so called bleeding edge low cost/investment initiatives (usually assigned technology readiness levels, TRL: 1–3) the later facilitates the innovation spectrum where decisions are made on which technologies will be adopted and offered to the marine industry for application (TRL: 3–7). Accordingly, the environmental technologies development programme takes knowledge and experience as its inputs and translates these into new or improved products and services (TRL:6–8). The development programme also provides input to the skills and technology base of Lloyd's Register, which maintains the value of the human capital and enhances service delivery (TRL: 2-8).

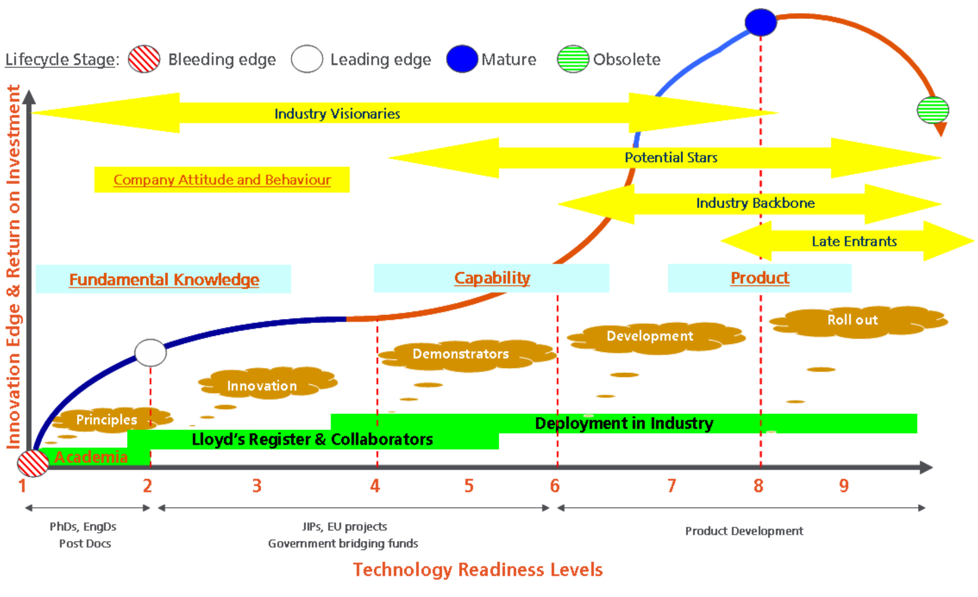

Figure 4: Lloyd's Register Technology Lifecycle and Innovation

The innovation approach is, therefore, quite complex because of the interactions and outputs involved. Firstly, there are projects that underpin the technological knowledge base of Lloyd's Register. These projects will not usually result in the direct development of a specific product or service, but provide the groundwork for further projects that will take the knowledge and use it to develop exploitable applications. These projects tend to focus on the technology sectors that have been identified as those in which Lloyd's Register needs to carry out work. These projects include:

- Evaluation of new technologies in the core implementation areas and assessment of their potential usefulness;
- Monitoring developments in other technology sectors and evaluating their potential for marine application;
- Developing understanding on fundamental concepts and methods that could be used for service provision.

There are also a number of relatively small projects that look forward to develop technology strategy. Those include:

- Tracking of scientific and technological research;
- Developing future technology plans;
- Preparing briefings for the marine industry on technology trends.

A number of activities in this programme of projects are carried out collaboratively with other organisations, primarily representing the industry visionaries. This is quite important as the new chapters of regulation introduced by the IMO clearly imply the need for increased promotion of technical co-operation and transfer of technology relating to the improvement of energy efficiency of ships. There are a number of projects targeted at satisfying the identified business needs of one or more of the ship segments or environmental product lines/services that Lloyd's Register offers, or wishes to offer, to its marine clients. These projects utilise the outcomes of the underpinning technology projects, the knowledge, experience and expertise of the Societies' technical employees and last but not least the knowledge gained from external sources, either from published information or from collaborative ventures. In the environmental arena these projects include:

- Development of revised Rules and survey procedures for Classification for all types of marine vehicles;
- Development of new or revised services for analysis or other processes;
- Preparation and maintenance of guidance documents for customers and surveyors;
- Development of new capabilities for specialist services that form part of the portfolio of services and products.

The development programme comprises a number of projects that help to:

- Ensure that Lloyd's Register retains a sound understanding of current and future technologies;
- Deliver new environmental products to the marketplace that reflect up-to-date knowledge and understanding.

The availability of research funding is increasingly a function of the demonstrable impact of the research outcomes, or at least the impact which is the target at the outset of the programme of work. Consequently, in recent years the competition for funding has resulted in a strong focus on the support from industry through Joint Industry Projects (JIPs), governmental funds (e.g. UK Engineering Research council, Technology Strategy Board etc.) or regional administrations (e.g. EU FP7 Waterborne programme) as an indicator of the value of the research activity, which in turn reflects the impact on wealth generation. So, with a relatively mature subject such as maritime technology the choices made consider: (a) what impact does industry anticipate from the ongoing programmes of research which are being undertaken in universities, research institutes and industry itself, (b) what are the current questions which it is hoped might be answered by the research activity and (c) which will be the value derived from the research outcomes in a world which is increasingly focused on the use of energy and climate change justify the investment of time, talents and money.

In reflecting these considerations, over the last four years Lloyd's Register has embarked on a number of large environmental research programmes working both collaborative with universities, technology providers, shipyards and owners. Whereas the summary presented in Table 1 is not an exhaustive list, it serves as an indication of the extensive works in the area of green ship design technologies and their implementation. The involvement with these programmes provided both the opportunity for original thinking with regards to the socioeconomic trends (see Table 2) that impact on technology as well as helped in identifying some of the fundamental or applied technology research and implementation areas that need to be considered in shaping up a research and product development agenda over the short, medium or long term (see Table 3).

Table 1: A Summary of Research Programmes with Active Participation from Lloyd's Register

Technology Categories	No. of Projects	Key areas of research	Funding sources
Policy research	3	Low carbon shipping, green impact assessment, carbon abatement	UK government, Lloyd's Register funded PhD, EU FP7
Modified hull forms (reduction in resistance and improvement in propulsion)	1	Design optimisation	Lloyd's Register and JIP
Modified propeller (enhanced propulsion efficiency)	2	Propeller design optimisation, novel propellers	JIP and EU
Energy saving appendages on hull	3	Novel propellers, appendages flow design optimisation	JIP, EU FP7

Ship size increases via increase in deadweight capacity	2	Modular ship design concepts, green container ships	Lloyd's Register funded PhD, JIP
Use of energy from exhaust heat recovery	3	Green bulk carrier, containership and tanker	
Use of renewable energies	7	LNG as a fuel, biofuels, fuel cells, algae based fuel, wind assisted propulsion, solar energy, methanol and DME, batteries, nuclear propulsion	Lloyd's Register, JIP, EU, PhD

Table 2: Global Trends That May Affect the Implementation of Environmental Technologies

Trend	2011-2015	2016-2018	2018 -2030
Emissions & efficiency	Public awareness on environmental issues is driving the market		Energy economics drive consumer behaviour
			Market develops the will to pay for efficiency
Energy scarcity & security		Oil Peaks	Transition to an energy and efficiency driven market
	Policy driven by energy and carbon emission issues		Alternative technologies to be used at a cost
Capability	Industry has some segmented capability to innovation		Globally linked R&D driving change and redefining possibilities
	Restructuring and merging of small industry players		Long-term R&D expenditure at levels substantially above OECD
	Expansion into Far East innovation markets and collaboration with domestic markets		
Competition	Growth markets in developing Asian economies, particularly China and India		
	Underutilisation of production capacity		Emerging competition from India, Thailand, Philippines, Vietnam
Technology	Performance based Regulations		Advances in IT and Simulation technologies
			Innovative Ship Designs
			Alternative fuels & Gaseous Storage Techs
	Low cost materials		
Infrastructure			Environmental awards schemes
			Development of fuelling infrastructures

Table 3: Outlook of Fundamental Environmental Technologies

Research Area	Technology	2010-2014	2014-2020	2020-2030
Resistance and Powering	Ship resistance in waves	✓	✓	
	Optimisation	✓	✓	
	Novel Hull forms		✓	✓
Auxiliary propulsion	Novel Propulsors	✓	✓	✓
	Propeller Design methods	✓	✓	
	Propulsor/appendage interactions	✓	✓	
	Retrofit Technology Support	✓	✓	
	Wind Propulsion	✓	✓	
	Propulsor Efficiency Indexing		✓	
Operational Aspects	Operational Optimisation	✓	✓	
	Hull Air Lubrication	✓	✓	✓
	Ice and Cold operations	✓		✓
	Ballast Free operations			✓
Environmental Aspects	Noise & Vibration	✓	✓	✓
	Performance Assessment	✓		
	Acoustic emissions monitoring		✓	✓
Fuels	LNG and CNG as a fuel	✓	✓	✓
	Biofuels, methanol and ethanol		✓	✓
Engineering systems	New diesel engines	✓	✓	
	Heat recovery systems	✓	✓	
	Selective catalytic reduction	✓		
	Fuel water emulsions	✓		
	Exhaust gas recirculation	✓		
	Advanced battery technologies	✓	✓	
	Fuel cells		✓	✓
	Scrubbers	✓	✓	
	Nuclear propulsion			✓
	Tidal stream ships		✓	✓
	wave power propulsion		✓	✓
Corrosions and Coatings	Protective coatings	✓		
	Cathodic Protection Systems	✓	✓	
	Autonomous intelligent systems	✓		
	Antifouling systems	✓	✓	
	Coatings for Ice Class ships	✓	✓	
	Corrosion Monitoring Systems	✓		
	Tank Corrosion Maintenance	✓	✓	
	Coatings Condition Monitoring	✓	✓	
	Effect on high strength steels		✓	
Marine structures	Ship motions and loads	✓	✓	✓
	Climatology	✓	✓	
	Damaged ship structures	✓	✓	
	Crack monitoring	✓	✓	
	Stress monitoring	✓	✓	
	Crack tolerant approaches	✓	✓	✓

IMPLEMENTING STRATEGIC RESEARCH

The technical and operational measures introduced via the IMO current and forthcoming requirements imply the need for investment in Strategic Research with the aim to achieve a significant potential in emission abatement technology implementation. In the current state of affairs a paradigm of shift in the design of ship new building and refits to improve the fuel consumption of ships is emerging. In general terms this may be achieved by:

- Reducing the required power for propulsion via reducing ship resistance and via proper selection of main dimensions and the ship lines and optimum speed;
- Improve propulsion by operating the propeller in optimum efficiency point (better wake), by reducing rotational, frictional or vortex losses or by reducing the required power for equipment on board (e.g. use efficient electronically controlled pumps, ventilation systems, energy saving lighting);
- Improve the use of conventional engine technology by avoiding oversized main or auxiliary systems and adopting sea operational margins to ship type, size and intended operational trade;
- Use fuel energy more efficiently for propulsion and on-board equipment;
- Substitute fuel power (partially) by renewable energies like wind and solar energy;
- Substitute fuel power by alternative sources of energy such as LNG or Nuclear.

The following discussion outlines some examples stipulating the recent experiences of Lloyd's Register. Instead of design issues per se in each example some of the lessons learnt in relation to techno-economic issues, the applicable implementation of design principles and utilisation of technologies is highlighted. This is primarily driven by the fact that the role of Classification is to coordinate industrial expertise and provide, in occasion, advisory services within the context of risk based assurance.

Design Optimisation of a Handysize Bulk Carrier

Concerns about emissions and volatile fuel oil prices are driving the development of new designs capable of operating efficiently at different speeds. Many bulk carriers trading today are not optimised for high energy prices so many owners have been implementing steaming strategies. Rising bunker prices may do more to drive bulk carrier owners and operators to curb emissions from their vessels than any of the shipping industry's voluntary emissions reduction guidelines. One recent example of design optimisation orientated strategic research project using the EEDI as a benchmark measure has been the collaboration between Lloyd's Register and Shanghai Bestway Marine Engineering Design Co. Ltd. The research programme focused on the optimisation of a Handysize Bulk Carrier (Figure 5) with emphasis on:

- Energy saving including hull shape optimisation, rudder/propeller integration, propulsion package optimisation and the use of 2nd generation anti-fouling paints;
- Design optimisation for weight reduction including ballast capacity reduction;
- Machinery and systems optimisation with the aim for maximum energy saving and reduction of emissions and minimising electrical load and maximising heat recovery.

A number of model tests of hull to reduce resistance and simulation for propulsion efficiency were carried out. The new design exceeded targets in a number of key areas after extensive model testing:

- Steel weight reduction of 12% was achieved against a target of 10%;
- Fuel consumption was reduced by 19.5% against a target of 15%;
- 18% EEDI reduction via the combined implementation of the technology measures

It is notable, that these improvements were achieved by using existing technologies which showed what can be achieved by using EEDI as a target for optimisation. In this case the IMO baseline EEDI was 6.56 and an index of 4.95 was achieved for the revised final design. Whereas the project confirmed on the usefulness of the EEDI as an essential yardstick for future ship design within the context of goal based standards; it also highlighted that global implementation of technical assurance measures should be supported by further Strategic Research initiatives. In particular more impact assessment studies that may clarify the interrelationship between technical, operational and market based measures are deemed necessary so that the industry can digest the balance between safety, environment and economic incentives.

L_{BP} = 171.5m

B = 28.4m

Dwt (at design draft) = 31,000MT

Dwt (at scantling draft) = 35,200MT

Trail speed = 15.2 knots (on ballast draft at MCR)

Service speed = 13.8 knots

Fule Cons. = 23.2 tons/day

Endurance = 15,000 sea miles

Figure 5: Design Optimisation of a 35,000dwt Bulk Carrier (A) Ship General Particulars (B) Overall Impression of Bestway Design (C) Resistance and Propulsion Model Tests (D) Hull Model For Design Optimisation

LNG As a Fuel

As IMO regulations become more stringent ship owners are likely to gradually change fuel types and use mitigating factors in order to comply with the regulations. Whereas technical design implementation is always important, future issues are related with the availability of supply, sourcing and most importantly price. Based on 2011 spot prices Marine Gas Oil (MGO) is on average USD 320/tonne more expensive than conventional Heavy Fuel Oil (HFO) of 380 cSt. Whereas existing abatement technologies, such as exhaust gas scrubbers, look more feasible over the short term, it would be possible to assume that the increasingly more stringent IMO regulations over the next 10 years will force owners to change their fuel type consumption. Currently the Lloyd’s Register strategic research efforts focus on three fronts exploring (a) the will of the ship owners to invest and expand the LNG fuelled fleet, (b) techno-economic design issues including the status of bunkering infrastructure, and (c) the implementation of technologies and associated ship design regulations with emphasis on design assurance for energy efficiency and safety.

Results from a recent Lloyd’s Register deep-sea ship owners’ survey (Aagesen, 2011), have shown that LNG fuelled ships may be a viable option in the long-term particularly for Container ships and Cruise ships (see Figure 6). However, there is still some doubt among Tanker owners who are uncertain what mitigating technologies they will use in the future to deal with emission regulations. Existing global bunkering ports are well positioned to supply LNG for ships with nearly all located close to a LNG import or export terminal and along the main trade routes. Whereas some ports, such as Rotterdam and Singapore, already have plans to develop LNG bunkering infrastructure, it may be expected that in the future the driving factors will be LNG supply at the bunkering ports and price, bunker hubs, fuel consumption per route.

On the technological and design implementation front Lloyd’s Register has been working on Strategic Research initiatives with European owners and engine manufacturers as well as shipyards in the Far East on a number of Joint Industry Projects using LNG as a fuel for existing Kamsramax vessels and VLCCs. As most project stakeholders have requested confidentiality the following discussion outlines some of the key issues under consideration with the aim to demonstrate how the extensive experience and knowledge of Classification in this field may assist in mitigating the ship design risks. The programme under development considers aspects of Rule development stipulated under the relevant Lloyd’s Register Rules (Lloyd’s Register, 2012a) and the draft IMO guidelines for Gas Fuelled Ships (IMO, 2011b). Accordingly acceptability for Class is demonstrated by compliance with the prescriptive requirements of the Lloyd’s Register Rules for Gas Fuelled Ships as well as acceptance of alternative arrangements.

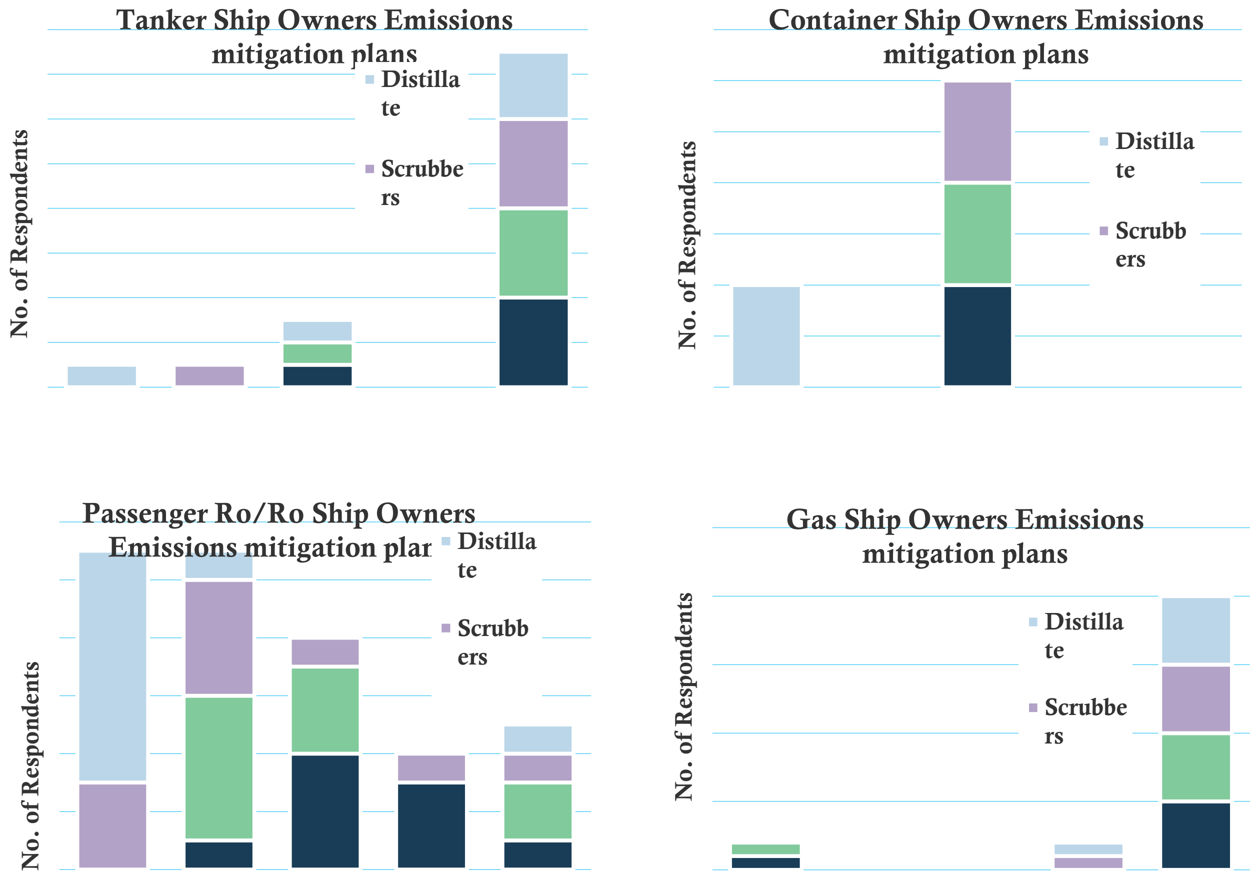

Figure 6: Survey Responses on the Use of LNG as A Fuel (Aagesen, 2011)

Along the lines of prescriptive requirements, the objective of design assurance is to achieve an equivalent level of integrity, as for oil fuelled ships, and this is based on achieving stated functional objectives (e.g. restrict gas dangerous areas). On the other hand, the approach of alternative design and arrangements is based on the notion of engineering safety justification on a case by case basis and along the lines of the Lloyd's Register Rules Part 7 Chapter 15 (Lloyd's Register, 2012b) a high level documented route to achieve safety and reliability is specified by:

- Arrangement and designation of all gas hazardous areas;
- Sources of ignition;
- Availability of gas-fuelled propulsion and auxiliary systems;
- Gas bunkering and storage arrangements;
- Gas piping systems;
- Ventilation systems;
- Control systems for machinery protection and safety;
- Gas detection systems.

This risk based technical justification, or risk assessment, is required to address the consequences of hazardous events including the effect on the ship, the whole machinery system and personnel. To date experience has shown that hazards to consider may include:

- Various failure modes of piping systems leading to leakage;
- Fire/explosion;
- Damage or sparking due to impact;
- Failure of structural integrity of containment systems;
- Mechanical/control/electrical failure;
- Manufacturing defects in equipment/materials;
- Error in material and equipment selection;
- Operator intervention/human error.

Some of the key conclusions may be summarised as follows:

- Low temperature vacuum insulated tanks may be above or below the deck. Arrangements are to be provided for containing any LNG leak. Protection is required for structure not suitable for LNG temperatures;
- LNG storage tanks are to be independent tanks designed in accordance with the IGC code Chapter 4 (IMO 2009b), and should be located in a space designed as a secondary barrier in case of liquid leakage;
- In the case of vacuum insulated tanks the outer shell in combination with a stainless steel box containing all pipe connections may be accepted as the tank room;
- A separate bilge piping system not passing through the machinery spaces is required for the tank room;
- For gas safe machinery spaces Gas fuelled machinery is to be within gas safe machinery spaces. Machinery spaces may be considered gas safe when a suitable ventilation hood is provided over gas fuelled machinery.

Solar Energy for Ships?

Solar energy has always been considered as one option and the solar technologies are rather new. Since the modern solar cell was invented in the 1950s, there has been a long experience in space (e.g. satellite projects) and terrestrial (e.g. lighthouses) applications. There has been limited service experience for the marine transport, mainly restricted to yachts and ferries, expanded to car carries over the last few years. Figure 7 summarises the development of solar energy for marine applications. Notably, the major interest comes from Europe, Japan, and Australia due to their thriving solar energy industries. A recent Strategic Research horizon study focused on reviewing the current development of solar technologies and assessed whether it would be feasible to spread the application of solar energy in ship design applications.

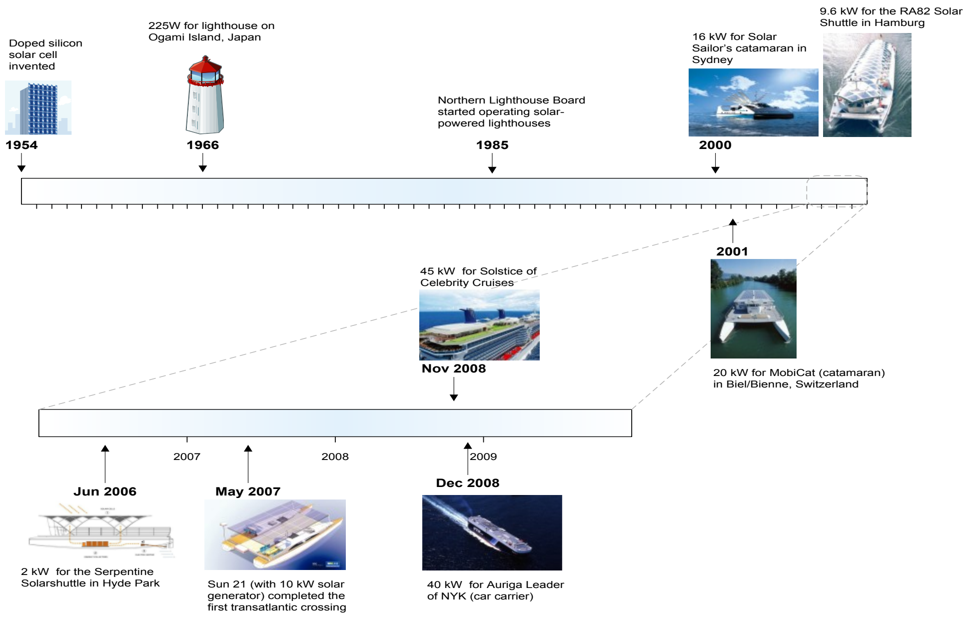

Figure 7: The Development of Solar Energy for Marine Applications (Hirdaris and Fang 2010)

There are different ways of storing solar energy, including the biological approach (such as fossil fuels and biomass from photosynthesis), through atmosphere and ocean (such as wind and ocean current driven by temperature difference) and devices that directly utilise solar energy (solar cells or solar thermal collectors). There are a couple of technologies available for making solar cells on a commercial scale and it would be perhaps acceptable to consider them for ship design applications. The most common solar cells found in the market are the first generation solar cells and are made of non-toxic and abundant silicon. Employing silicon may also benefit greatly from the experience gained in the semiconductor industry, however, the energy-intensive production process raises the manufacturing cost and the energy payback period. Thin-film solar cells, also known as the second generation solar cells, are aimed to reduce the material thickness. This helps to cut down the material usage as well as the cost.

Bulk carriers, tankers, and container ships either have limited available space on deck or harsh loading/unloading procedures that might cause severe damage or soiling to the solar panels. Passenger ships and car carriers may be more suitable for solar panel installation because there could be larger spaces available and a cleaner and simpler working environment on deck. Besides fixing solar panels on a flat surface, there is potential for new flexible designs. Based on the current developments, it is still expensive to have solar panels on low cost ship assets. As an example, recenly NYK invested ¥150 million in installing 328 solar panels that generate 40 kW of power, on its car carrier, Auriga Leader. The initial cost may be reduced in the future by better manufacturing processes, mass production of solar cells, or the commercialisation of new generation solar cells. Solar Sailor suggested that for a ferry operating at Sydney Harbour, it takes one hour to raise the sails via hydro pumps and about one minute to fold them. They further claimed that the panels can harness the sunlight and contribute up to 5% of the ship's electricity requirement. Adding the wind's contribution, the fuel reduction could be up to 20-40%. The total pay-back period is estimated to be four years.

Placing "solar wings" on ships may just be one way, which creates additional surface area for solar energy devices and reduces the space required on board (see Figure 8). However, it should not be underestimated that the solar power systems are electrical supply points and accordingly carry potential risks. Solar modules connected in series would result in larger voltage and may bring about shock hazard. Solar panels, using first generation solar cells in particular, could be regarded as additional weight on the weather decks. Their impact on imposing local stress to the structure, ship flexibility and stability remain unclear and it is difficult to answer all the questions without further data from sea trials.

(a) (b)

Figure 8: Solar Sailor's (A) Concept Design Of A Water Tanker For The Tasmanian Government And (B) Existing Ferry For Sydney Harbour

Wind Assisted Propulsion

There is renewed interest today in harnessing shipping's traditional free and abundant energy source – the wind. A number of applications are commercially available or they are being developed (see Figure 9). In general terms, those apply modern design principles to maximise the efficiency with which the wind is converted to propulsive energy. Wind assisted propulsion involves using rigid or soft sails, kites, or Flettner rotors to convert energy from the wind to thrust forces. Lloyd's Register has been involved with academic and industrial initiatives highlighting the potential of most concepts.

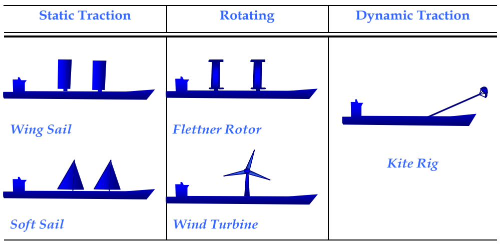

Figure 9: Different Forms of Wind Assisted Propulsion (Chapman 2010)

Kite Assisted ship propulsion

A recent Strategic Research study (Chapman, 2009) focused on quantifying the key benefits of reduced fuel consumption and balance it against the potential safety risks in order to determine the feasibility of kite assisted ship propulsion. Within this study a hazard identification technique has been employed to carry out a formal risk assessment of kite assisted propulsion with the ultimate aim to discuss design aspects in relation with international regulation and classification implications. It was concluded that:

- Whereas various kite propulsion systems are conceivable and have been patented over the years (see Figure 11) traction kite systems are the closest to commercial and operational reality;
- High aspect tethered aerofoil kites have some distinct benefits over more conventional deck mounted rigs. This is because traction kites have advantages in relation with deck space, they are lightweight, they do not suffer from adverse upwind drag effects and facilitate for negligible heel angle at operational level;
- In determining the potential fuel savings of kite assisted propulsion it was concluded that the calculation of fuel saving is much more heavily dependant on the resolution of an accurate longitudinal kite force. Whereas operating at low loads may have a negative effect on specific fuel consumption and safety implications, risk may be reduced via engine modifications. In addition, the fact that the propeller efficiency decreases as the kite power increases highlights the importance of a case by case review of the 'off design conditions', especially where the propeller may operate at a reduced thrust for long periods of time;

- Whereas intermediate results compare relatively well with past studies, for an average wind speed of 15 knots a saving ranging between 16% and 28% may be achievable;
- The sensitivity of kite assisted propulsion to wind velocity means such systems may not be suited to vessels involved in spot trading and careful attention must be paid to the select optimum routes. To optimise this technology the kite power model needs to be further integrated into existing operational procedures;
- Key operational and design for safety findings from the formal risk assessment can be summarised as follows:
  - o Launch and recovery of the system, when the kite is least stable, is likely to be the most hazardous activity. This risk needs to be reduced through safety release system and hardware redundancy;
  - o Formal crew training and navigational codes with respect to kite flying need to be established;
  - o An electronic system is needed to control the interaction between engine power, rudder and kite position to provide the most efficient arrangement for given weather conditions.
- The formal acceptance of kite propulsion by classification bodies and statutory regulators is fundamental in the advancement of such technology. With classification bodies paying particular interest to the structural deck strength at the kite attachment point, the kite control system, emergency release procedures and the influence on main engine performance;
- In the near term future kite assisted propulsion is likely develop in niche markets where there is extra pressure for renewable energy transportation.

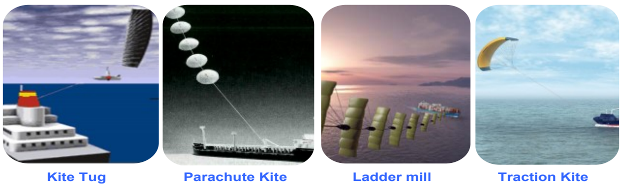

Figure 10: Some Auxiliary Kite Propulsion Systems (Skysails 2009; Duckworth 1985; Winter 1999; Ockels 2007).

Flettner rotors

The Flettner rotors principle is based on the idea that when a cylindrical body is spun in a viscous fluid, it creates around itself a boundary layer. The later induces a circular motion in the fluid in its immediate vicinity (creating a vortex flow). As the body progresses through the fluid the velocity in way of the boundary layer becomes greater than that on the forward-moving side but less than that on the backward-moving side. Applying this to a cylinder rotating in air, it is the pressure differentials which create the thrust. Due to the acceleration of air over the top of the cylinder (and thus increased velocity) a perpendicular component of force is produced. Thus the combined flow has a higher velocity, and a lower pressure, on the top surface, leads to a pressure imbalance and a net upward force (i.e. thrust) on the cylinder, also known as the 'Magnus effect'. Although the idea is not new, over the last three years Lloyd's Register has been following a rather original implementation of the concept in a Joint Industry Initiative lead by the Greenwave environmental charity. The producers have designed a unit which can be shipped (when disassembled) in standard shipping containers. The assembly is a modular approach, and the size of the engine (which may be dependant on the application) can be altered by simply adding or removing sections. The drive behind this design approach is simply ease of retro-fit; a green technology which can be considered for and installed on any new build or existing ship (see Figure 11).

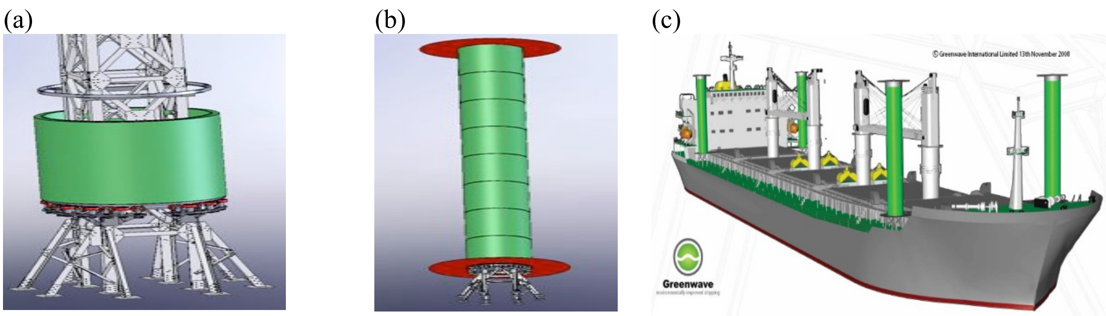

Figure 11 : Artists' Impression Of The Greenwave Flettner Rotor Design (A), (B), Idealisation Of The Flettner Rotor Pylon/Skeleton; (C) The Integrated Greenwave MK1 Rotor Assembly On A Panamax Bulk Carrier).

To date, Lloyd's Register has followed up all technological developments lead by Greenwave and witnessed model and performance/handling tests. The Society has also performed design appraisal of the first version of the Greenwave MK1 system for engineering systems, structures and electrical equipment in accordance with the requirements of the Lloyd's Register Provisional Rules on Sail Assisted Ships (Lloyd's Register, 2012c). Witnessing of technological developments prior to design assurance and implementation has proved particularly valuable in assessing the adequacy of the assurance provision guidelines.

The Greenwave model tests have been conducted successfully for a 1/85th scale model with the purpose to investigate the effects of yaw angle on side force and drag characteristics for a 182m waterline Bulk Carrier. At first instance the model was tested at zero yaw in the full load and light load displacement conditions through a range of speeds to establish the basic drag characteristics and viscous form factors. The second set of tests was conducted at the medium load displacement and with the model at the upright position with the aim to evaluate the effects of the bilge keels and weather board addition. It was concluded that due to the low variation in drag at low yaw angles the drag would be unaffected or even reduced by side force generation. It was also concluded that at the sail assisted mode the side force would not exceed 40% of the vessel's drag and yaw angles would not exceed 1 degree. The primary objective of the performance and handling tests was to investigate the controllability of a Bulk Carrier fitted with wind engines and to ascertain if the ship had a tendency to round up into the wind or produce an unreasonable amount of leeway when it is partially powered by the wind engines. It was concluded that the wind engines were very capable of providing 50% of the required thrust in light winds and 100% of the required thrust in moderate winds. The ship held its course reasonably well although in stronger winds increased rudder angles were required to keep the ship on course. Leeway angles were not excessive and tended to oscillate with wind strength and the wind engines were very capable of acting as air brakes in a fail safe manner. Based on the lessons learnt throughout the concept development the determination of the scope and extends of Classification provision has led to the following conclusions:

- A Bulk Carrier with wind engines may be design approved in accordance with the Lloyd's Register Provisional Rules (Lloyd's Register, 2012c) and if Classified it may be assigned the notation 100A1 Bulk Carrier Sail Assisted;
- Due to the need to integrate the rotor assembly into the deck and below deck structure, design approval in accordance with the Lloyd's Register Rules is required;
- Classification of the design integration of the electrical supply and control circuits into the main ship distribution system is applicable. However, the integration onto the vessels is ship specific should be addressed on a case by case basis;
- When considering the general mechanical design of the rotor Classification is not a requirement. As the rotor is only intended to be used as an assisted sailing method and not allowed by rules to be used as sole or primary propulsion, in principle there would be no safety considerations applicable to its design. However, it wouldn't be prudent to take into account some additional design considerations of the rotor system (e.g. bearing loads, vortex shedding frequency) which will result in safer operation and longevity of the rotor, which is the basis engineering systems performance;
- If the item is classed, the survey procedures manual needs to be updated to reflect in specific the requirements for areas/frequency for inspections.

Could wind turbines become part of modern ship designs?

Despite the numerous projects in the area of wind assisted propulsion the benefits of holistically quantifying the harnessing of wind energy on ships is not well understood. In a recent ongoing study with Zodiac Maritime Agencies and Totem Power a wind monitoring system has been installed on a capsize Bulk Carrier with the aim to collect real life wind data on a regular trading route. This project aims to identify and quantify the potential power capacity from wind power based on the vessels trading pattern and the collected data are envisaged to be used to facilitate the development of simulation models suitable to predict potential energy yields for other ships of similar design, based on the wind speed patterns they may encounter.

(a) (b) (c)

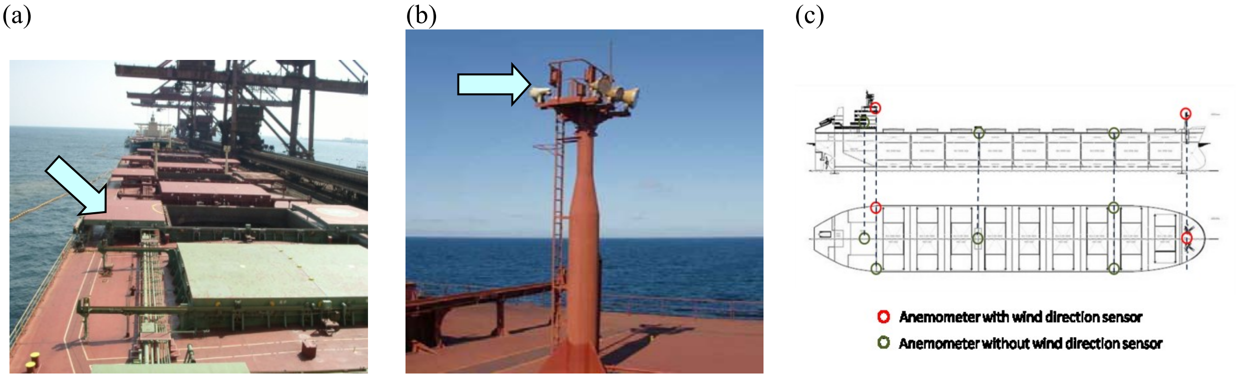

Figure 12: Wind Condition Monitoring Set Up - (A),(B) Typical System Mounting Locations (C) Overall Sensor Positioning

To date a fully autonomous wind monitoring system has been fitted on a Capesize Bulk Carrier and sensors have been installed. The locations identified (see Figure 12c) correspond to the presumed best wind conditions and the most relevant environmental data (wind speed, direction and turbulence) will suggest where real turbines could practically be positioned for energy generation. The stand-alone system setup is made up from two stations with wind direction, acceleration and GPS measurement in addition to the anemometer, and five stations with anemometers only. The upcoming feasibility report as the main deliverable of this project will analyse and discuss the results of the monitoring project, specifically in regard to the energy generation potential using currently available wind turbines, based either on a selection of existing models and their manufacturer data or on generic designs. It will also evaluate the suitability of different types of turbines based on the prevalent wind conditions and practicality of implementation. The report will further analyse and discuss the commercial potential and opportunity, including implementation cost forecasts and modelled paybacks. At the final stages of this investigation issues related with design implementation and approval will be considered.

Small Modular Nuclear Reactors (SMR)

Recent market demands and associated responses have shown that amongst the alternative sources of energy the application of nuclear technology may be inextricably linked to the environmental demands. This is not surprising as nuclear energy presents the opportunity of implementing a technology which is both technologically conservative and alarmingly radical. Naval nuclear propulsion is a well established technology which is 'clean' in many ways over existing power plants, hence its resurgence in favour for land-based electricity generation. Indeed, the naval plants in production currently, used aboard several nations' aircraft carriers and submarines, are of more than ample power capacity to comfortably drive even the largest bulk carrier, container ship or tanker. In addition to this, uranium is actually at a low price point and, though expected to rise over the next few years, is a remarkably cost effective fuel with supplies readily available for those with permission to access them. As successful as nuclear power has been, there has been one aspect of the industry that escaped attention in the commercial sector – the development of Small Nuclear Reactors (SMR) that are compact, modular, safe and proliferation free. The SMR technology is under development, with a thermal power output of over 68 MW and can be treated as a plug-in 'nuclear' battery. The use of an SMR for ship propulsion is an exciting prospect. This ongoing effort in association with BMT Nigel Gee ship designers and Hyperion Power Generation (HPG) aims to:

- Understand the concept of SMR nuclear reactor technology;
- Investigate and understand the implication of SMR as an alternative source of energy for propulsion;
- Design rules and procedures for design, construction, operation, maintenance and eventually disposal of Tanker Ships incorporating SMR; and
- Develop commercially viable concept designs of Tanker Ships, integrating SMR.

As the developments within this programme of work are bound by strict confidentiality agreement in the following sections only the basics of the ongoing developments are discussed with the aim to shed some light in the prospects for technology implementation and design integration or approval.

SMR technology basics

The SMR technology is still under development. In contrast to the case of the typical Pressurized Water Reactors (PWR) for SMR a conventional boiler is replaced with a reactor and a steam generator. The circuit consists of two main circuits including coolant, control, electrotechnical systems as well as component for linkage with power train systems. Upon licensing SMRs are expected to have greater simplicity of design, economy of mass production, and reduced siting costs. Many are also designed for a high level of passive or inherent safety in the event of malfunction. The idea of having an SMR is not limited by reactor type. The main motivator for developing an SMR is that it will be able to supply a dependable power source for small electricity grids often needed in remote areas or for marine applications. The modular design would allow for the majority of construction and assembly to be completed at the factory and then transported to the site as almost complete units. This may result in reducing the capital cost and construction time required to build the nuclear power reactor when compared with conventional PWR designs. In an SMR the core's design and layout features 24 subassemblies which contain the fuel pins. The core includes three independent reactivity shut-down systems, namely (a) shutdown rod system with 6 boron carbide rods (b) a control rod system – 12 boron carbide rods and (c) a reserve shutdown system with a central cavity in which boron carbide balls may be placed. One of the typical SMR designs considered within the current strategic research programme is the Hyperion Power Module (HPM). A single module of this SMR concept provides 70MW of thermal electricity and an electrical output of 20 MW electrical output. With a life time of 8-10 years, a size of the order of 1.5m (width) by 2.5m (height), a sealed core and a weight of the order of 50 tons in principle this reactor offers ideal sizing for installation on ocean going vessels. The coolant used is PbBi and the fuel is stainless clad/uranium nitride with enrichment less than 20%, hence proliferation is not such an issue as with traditional PWR designs (Hirdaris et al, 2011).

Some Concept design considerations

The integration of an advanced nuclear reactor technology onboard a merchant marine vessel is not simplistic and pushes the boundaries of ship design implantation along the notion of risk based assurance. It would be perhaps fair to assume that the most benefit of having a nuclear propulsion system would be for large ships with long endurance. In addition, the requirements of regional authorities (e.g. Port State Control authorities) may impose additional constraints related with loading and unloading of nuclear merchant marine vessels. To satisfy such requirements the concept ship design considered to date for the purposes of this Strategic Research investigation has been a Suez Max VLCC. Such vessels load and unload outside the port; they require also power of the order supplied by a single unit of HPM. To date the concept design studies considered risk based issues associated with classification, regulations, human factors as well as techno-economic aspects. A preliminary Hazard identification analysis (PHA) led by Lloyd's Register facilitated this process and considered issues associated with collision, grounding, cargo tank explosion, structural failure, flooding, human factors, propulsion or steering machinery failures or combination of those. In this preparatory to HAZID process the reactor and steam generating section was treated as a sealed black box as the internal workings requirements would be covered by the National Nuclear Administration (NNA) that would provide licensing. The process recognised that failures within the black box would certainly affect the ship structure and systems surrounding the SMR and vice versa. Since at concept design stage it would not be possible to consider those independently it was concluded that at conceptual level only the principle design consideration of damage to the reactor by external influences may be discussed with reference to: (a) prevention of damage to the box from external factors, (b) precautions in place following damage/malfunction inside the box, (c) precautions following box rupture and (d) ship operation following reactor failure/shutdown. The principal interfaces considered with the 'black box' have been : (a) Feed in / Steam out, (b) Control cabling, (c) Emergency cooling and (d) Compartment surrounding the SMR 'black box' and associated systems. Three possible layouts for the main machinery (SMR forward, amidships and aft) and several machinery configurations have been considered (Dedes et al, 2011). There is no absolute 'show stopper' for any of these arrangements but vulnerability of the SMR forward and fire safety issues for SMR amidships would favour the SMR aft option. Following the PHA it was decided that it would be necessary to define the ship specific requirements for the SMR. These should include ship motion effects and ship structure related issues including heat sink, emergency cooling without external aid etc. as well as human factors issues. Currently and in order to carry out a meaningful HAZID, the chosen arrangement is being developed to the next level of maturity which should include details of the SMR structural protection, SMR vault details and arrangement, and the control/cabling and emergency cooling arrangements.

Provisional Rules for Nuclear Merchant Marine Propulsion

The IMO's Resolution A.491-XII (IMO, 1981) defines specific safety issues and criteria concerned with the protection of people and the environment from possible radiation hazards throughout the vessel's lifecycle (International Maritime Organisation, 1981). It defines requirements concerned with the reactor's shielding, heat removal and core cooling, the vessel's stability, structural integrity, fire and safety features, whilst also defining surveying requirements during construction, sea trials and operation. The main safety objectives of the Code are:

- The protection of people and environment against 'unacceptable' hazards due to intentional or accidental release of radioactive substances and ionizing radiation in both port and sea.
- The safety of the ship as a whole, (i.e. not just nuclear hazards) but also the interaction of the nuclear propulsion plant with the ship, cargo and operating environment.

It would perhaps be appropriate to assume that in the future the prescriptive rule based approach favoured by the marine industry will be: (a) thorough enough for integrating nuclear plant into a ship (b) will satisfy the land based nuclear regulators, and (c) it will give Lloyd's Register sufficient confidence to Classify a vessel. Accordingly, the style of the rules being considered as part of this research programme is based on achieving design goals. A further development to this is that for each design goal there are a series of design principles that need to be satisfied. Underpinning design principles are design details which are either the only way, or one way in which meeting the design principles and goals can be achieved. Figure 13 illustrates the relationship between design goals, principles and details. The design goals identified are related with Engineering and Safety systems (electro-technical, secondary pressure and safety), the ship's structure and radiological protection. In contrast to the current marine industry practise where the builder typically demonstrates, or more often meets prescribed regulatory requirements, it is possible that in the future the nuclear regulators will want to ensure that it is the operator of the nuclear plant that demonstrates their ability to operate the plant, in addition to the plant being designed and built correctly. The Lloyd's Register Provisional Rules (Lloyd's Register, 2010) have introduced the concept of a design authority, which represent the organisations involved in design, construction and operation of the ship. This should ensure that the overall design, construction and operation, as an integrated system are assured. In addition to the Provisional Rules being goal based, a systems engineering approach will have to be taken to ensure the integrity of the reactor plant and ship.

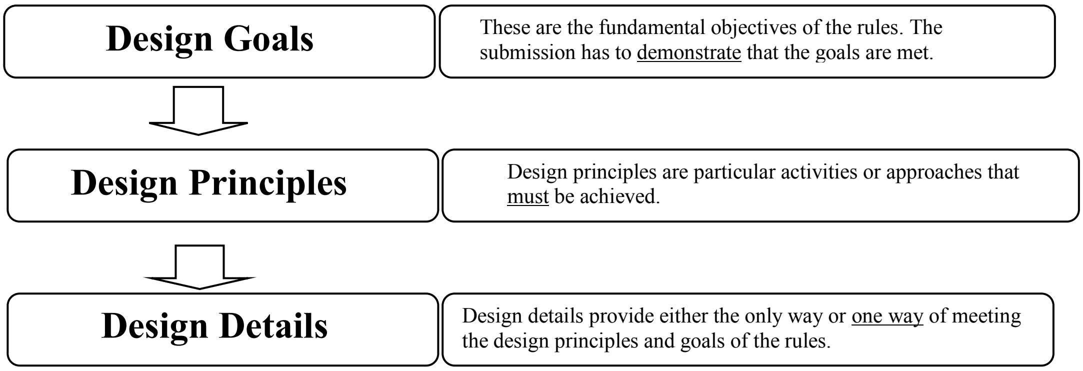

Figure 13: The Philosophy of Lloyd's Register Provisional Goal Based Rules on Nuclear Ship Propulsion (Lloyd's Register 2010)

CONCLUSIONS

The shipping industry is under pressure to reduce CO_2 emissions. This keynote has discussed some of the recent Strategic Research experiences of the Society, all of which have the potential to play some part in the future pathway to low carbon shipping. The need to understand in further technologies and issues associated with their safe and cost efficient development and implementation will be important in the years to come. Whereas individual ship owners and operators will face pressures, both from the anticipated environmental regulations and also from high fuel prices. Their main concern will be to comply with the new rules and to outperform competition. Thus, Classification Societies will have to reflect the demands of the market within the context of assurance provision and risk adverse ship designs. Thus, two issues arise in parallel regarding the climate impacts from shipping namely: (a) the development and implementation of solid technical and operational solutions for cutting emissions on individual ships, and (b) designing appropriate regulations that safeguard the interests of society as a whole. The range of technologies and solutions that are available for reducing GHG emissions from ships creates the need for the development of consistent and rational assurance provision systems and cost-effective infrastructures that may assist with medium to long term decision making. If a reduction in shipping emissions is the target, then a significant boost in Strategic Research and development is necessary in order to overcome barriers and to accelerate the process of bringing novel technologies to the market, and also to discover forthcoming solutions. It is obvious that facilitating new ways of collaboration and innovation must be developed, with clear incentives for all parties to improve operations towards overall emission reduction. In order to develop technological solutions and to implement them in a rather conservative industry such as shipping, large-scale demonstration projects are necessary. Development of tools and methods for assessing radical and novel designs, along with the complex ship systems, should be kept in focus. Improved tools for evaluating the performance of new solutions will ease their introduction into the shipping industry.

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