EXPLORING OPTIONS TO REDUCE FUEL CONSUMPTION

J Knott[1] and **J Buckingham**[2]

[1]BMT TITRON (UK) Limited, UK
[2]BMT Defence Services Limited, UK, JBuckingham@bmtdsl.co.uk

ABSTRACT
For any tanker, reduced fuel consumption at sea leads to reduced fuel purchase costs; reduce the logistic cost of fuel acquisition; reduced emissions. Increasingly the benefits of reduced engine emissions both for climate change and pollution legislation reasons are also a strong influence. With the continuing upward trend of fuel costs, all those means by which fuel consumption can be reduced needs consideration. This paper presents a range of energy saving technologies in the context of BMT's own Product Tanker design. The study seeks to show, from an independent viewpoint, how they might be applied to achieve the real financial and environmental benefits. The consequences for machinery performance are identified along with consideration of the parasitic loads such features can require. The estimated acquisition and implementation costs are compared with the benefits to the ship's resultant in-service costs to show how the choice of an energy saving solution needs to be considered in conjunction with the ship's overall design, its machinery and its operating role. The opinions expressed in this paper are those of the authors and are not those of BMT or other third parties. The authors acknowledge the opportunity provided by BMT to present this work. The contribution from the several companies who have assisted with the study work behind this paper is acknowledged with thanks.
Keywords: product tanker, fuel consumption, cost, energy savings

1. INTRODUCTION

1.1 SCOPE

Since the widespread use of propeller driven steel ships in the past 100 years, there has been a sustained but sometimes unsteady effort to identify technologies which offer to improve the energy efficiency of marine propulsion. As each ship is different and each technology has a specific design point, clearly not all technologies will suit each ship.

The current emerging requirement for improved energy efficiency has three main drivers: the increasing cost of energy, its impact on the environment and to a lesser extent, energy security. The paper presents an assessment of a set of relevant emerged and emerging technologies in the context of a product tanker.

1.2 CONTEXT

Since 1999, BMT has conducted a series of studies for a wide range of clients in the field of propulsion efficiency and energy conservation. BMT maintains a database of over 100 technologies of varying degree of maturity. For each project, these are applied to a given platform and its operating profile to identify those which have the most merit, i.e. those with the greatest savings in terms of fuel and emissions.

For shipping as a whole, the price of fuel and its usage is likely to continue to rise due to the triple pressures of:

a. Public and regulatory pressure on environmental emissions

b. Peak oil is/will lead to higher fuel prices

c. Rising world demand for energy.

With the world's known available fossil fuel reserves apparently dwindling, future prices will rise in real terms due to the anticipated future growth in real demand. However, rising fuel prices are nothing new: Figure 1 shows the situation in the 1970's which underlines how events such as wars and natural disasters can affect the prices of commodities.

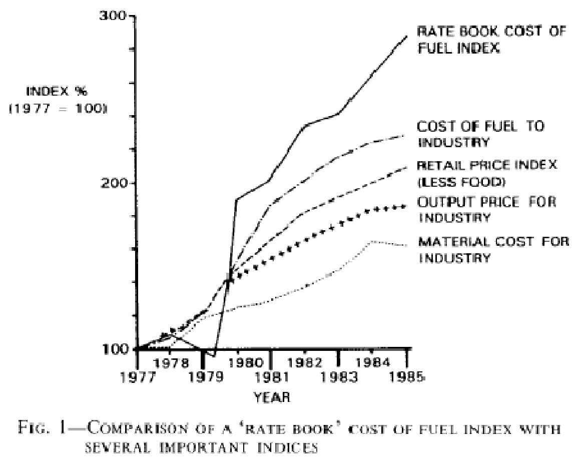

Figure 1: Past Fuel Price Increases

2. ENERGY DEMANDS

The UK has set itself a carbon reduction target which it has been struggling to meet, see Figure 2. Closure of coal-fired power stations has removed large contributors but as the accountable emissions are identified and reduced, shipping will come under greater scrutiny and pressure.

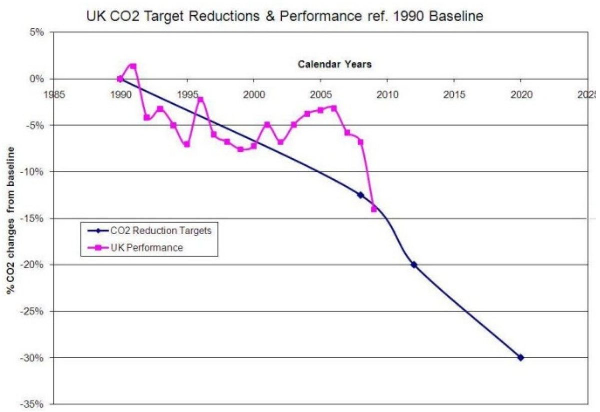

Figure 2: UK CO_2 Target Reductions & Performance (EIA, 1990)

Alternative fuels may be much discussed, but liquid fuel and specifically oil will still be the most important fuel in 2020 especially in transport due to the limited substitution options.

2.1 IMO

The International Maritime Organisation (IMO) is currently debating what measures could be introduced to limit or reduce shipping's emissions of CO_2. The IMO has laid out design guidance to enable designers to reduce marine-based GHG (MEPC 58) which employs the concepts of:

- Energy Efficiency Design Index;
- Energy Efficiency Operational Index.

The EEDI seeks to simplify the machinery arrangements onboard a ship and uses a relatively simple equation to generate the tonnes of CO_2 emitted per tonne.nm travelled.

The EEOI uses actual data from ship operations to identify the same metric. The latter index is clearly more accurate and as there are so many new ships due to the large production of the past ten years it is these which may benefit most from retro-fitting opportunities. The EEDI continues to be a disputed index for designers: it is contested that it cannot form the basis of a legally binding design objective as it does not consider the commercial aspects of ship operations.

Although sea shipping is relatively "climate friendly" compared to other modes of transport when measured in g. CO_2/tonne-nm, in absolute consumption terms, it is a considerable consumer of poor quality fuel and a significant source of air pollutants of all types.

In Europe, GHG emissions from land-based sources have decreased in the last 20 years, but emissions of GHG from sea shipping have been rising due to the increase in the global trading of goods. With unchanged legislation, it has been claimed fuel usage and emissions from international shipping will “more than double by 2020” within the European Union. Even if this is not so and the fleet stays the same, its fractional contribution will grow as other forms of transport become more efficient.

2.2 CARBON DIOXIDE EMISSIONS

In 2007, worldwide shipping CO_2 emissions were estimated to be of the order of 3.3% of the total with 2.7% of this being international shipping (IMO, 2009).

The shipping industry is increasingly expected to share in the burden of reducing global emissions of CO_2. Therefore, the shipping community needs to act now to take responsibility for their share of the GHG burden.

2.3 SHIPBOARD

Fuel and product tankers due to their large size, all consume significant quantities of fuel and so a product tanker design is used in this study as a basis for exploring energy conserving technologies.

2.4 MACHINERY

Improvements to inboard machinery may offer the following benefits:

- Reduced Fuel Usage;
- Increased endurance between refuelling;
- Reduced machinery maintenance burden;
- Potential for reduced heat stress in the machinery spaces;
- Actual cost savings if the efficiencies outweigh the price increases;
- Helps save the environment.

However to use the source energy more efficiently, extra and/or more complex machinery is often required. There is therefore a real ship and upfront financial impact with a more efficient plant. With regard to the ship, the basic impacts are footprint, insertion and removal routes, maintenance access as well as the added complexity: interfaces, controls and interfaces to the ships control systems.

The new plant may also place additional demands on the ships services and a need for better heat management. Thus these demands may detract from the full benefits of the original energy saving measure.

Specifically additional weight from the machinery and its supporting structure increases displacement and hence resistance, unless the bunker fuel is reduced accordingly. There may also be stability aspects due to the location and the weight of the plant.

The opportunity for changes to existing ships is also a challenge as scheduled refits are planned to be short for economic reasons. The changes to the baseline machinery also lead to:

- Operating and support (upkeep) changes
- An increase in the manning and training burden.

All these issues affect the cost-benefit balance and so many of these financial impacts need to be factored into the assessment.

2.5 MAKING IT PAY

The cost of change and its impact on the return on investment is always an issue when decisions on whether to proceed with the introduction of an energy conservation technology. The size of the benefit needs to be significant therefore to make the effort worthwhile although unfortunately the need for a low-risk short-payback period often dominates the decision making assessment. The increased cost of fuel is making these payback periods shorter than ever.

Cost assessments of manning and training needs are complex but the main financial benefit is reduced fuel consumption. The efforts to simply reduce emissions measures do allow for a green image to be presented and until carbon taxes are enforced, it is fuel reduction that saves the money and allows for the savings to recover the outlay costs. The main criterion used in the study was the balance of through life fuel savings to the estimated changes to the acquisition costs.

3. CANDIDATE SHIP

3.1 DESCRIPTION

The study ship is the BMT TITRON product tanker of 40,000 tonnes deadweight [Ref. 1]. It has a trial speed of 14.69 knots at 6,225kW (70% MCR approx) and is driven by single slow speed diesel engine of 8,893kW MCR (87% R1 Rating) which drives a fixed pitch propeller.

There are three Diesel Generating sets (DG sets) to supply the ships electrical power demand of 600kWe seagoing, and in port discharging 2,000kW (max discharge rate).

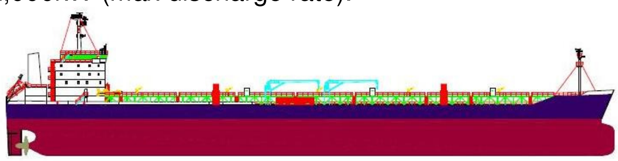

Figure 3: BMT Product Tanker

A parent efficient hullform from the BMT archive (as shown in Figure 3) was selected as the basis for development of the new improved hullform. The basis hull was constructed at the Model Test facility at CTO in Gdansk, Poland and extensively model tested to confirm the historical data available for that hull. After testing the form was then subject to CFD analysis to identify areas of improvement and ensure optimum efficiency over a range of drafts from light ballast to fully loaded.

3.2 BASIS HULLFORM MODEL TEST

The results of the basis ship model tests, covering resistance, self-propulsion; 3D wake and streamlines were carried out with the use of hull model M738 at one design draught. During the self propulsion tests the model was equipped with a stock propeller model No. P565 and with stock rudder R738.

The speed predictions for the delivered power of 6,225 kW are given in the table below.

Table 1: Operating Conditions

Conditions	**V_S [kn]**
Trials	14,43
Service	13,85

Compared with the performance of similar ships the results of the tests were not satisfactory, therefore a modification of the ship shape was necessary. The main objective of the modifications was to decrease resistance and improve the flow to the propeller:

- with reference to the bow, a bulb modification was proposed by adding volume in upper bulb part (in order to direct water down) and to open a channel downwards;
- with reference to aft end: in order to improve inflow to the propeller, the following modification was proposed: changing the run of the aft tunnel by shifting volume from bottom area towards design waterline (this should also improve ship performance at the ballast draught).

3.3 CFD ANALYSIS

The modified hullform was then subject to CFD computations of four versions of the Bulk Carrier:

- Baseline version (Version 0) – used as a point of reference.
- First modified version (Version 1).
- Second modified version (Version 2).
- Third modified version (Version 3).

The purpose of the computations was to assess the influence of the modifications on the vessel resistance and the propeller inflow, at one draught and one speed.

3.4 RESULTS

No major difference in the wave pattern between subsequent versions was identified. However, a slightly better bow wave appeared for version. 1, compared to other versions– this was due to a smaller area of water elevation at the bow and a fairer wave hollow at the shoulder leading to a reduction of wave resistance.

An improvement of the pressure distribution on the fore part compared to the initial basis version is visible only for version 1 – the area of high pressure is reduced, which indicates lower resistance. For versions 1 and 3, the pressure distribution on the aft part is a little more favourable than for version 0 and 2 due to larger area of high pressure.

The wake field on version 1 can be considered better than for version 0 due to reduced intensity of the vortex and higher mean value of the axial velocity.

3.5 CFD CONCLUSIONS

The computations revealed a noticeable reduction of the resistance for only version 1. This version is also the most advantageous in respect of the propeller inflow and consequently, this version was adopted as the final hullform.

On completion of the CFD analysis, the model was updated to reflect the findings and subsequently further tests were carried out to validate the changes. Once it was apparent that the hullform itself was optimised attention then turned to the propulsion system and rudder arrangement.

3.6 MODEL TEST HULLFORM M738-A

The hullform was modified in accordance with the findings of the CFD Analysis and tested for resistance, self propulsion, wake and streamlines at a range of draughts between light ballast, heavy ballast and loaded conditions. The results of these are described below.

The resistance, self-propulsion, 3D wake and streamlines model tests for the BMT 36000 bulk carrier were carried out with hull model M738-A. The hullform was modified by the Ship Hydromechanics Division of CTO.

The self propulsion tests were carried out at design and light ballast draughts. Two rudder models were used: a conventional stock rudder R738 featuring the NACA0019 profile in test 14856 and a rudder model delivered by Becker Marine Systems in the remaining self propulsion tests. At the design draughts both rudders were tested, but the conventional one in a limited speed range only. Additionally a preliminary self propulsion test was also carried out with the Becker rudder without the stock fairwater (bare rudder stock above the rudder blade). At the heavy ballast draught only the Becker rudder was used.

Due to a high value of wake coefficient and relatively low value of thrust coefficient the hull efficiency reach a high level. The speed predictions for the delivered power of 6,225 kW are given in the table below.

Table 2: Speeds Achieved

Conditions	V*s* [kn]			
	design draught			light ballast draught
	stock rudder	Becker rudder without fairwater	Becker rudder with fairwater	Becker rudder with fairwater
Trials	14.80	14.78	14.86	15.20
Service	14.21	14.21	14.27	14.62

The wake measurement was made at design and light ballast draughts. The result of both tests is similar. In general the wake field (inflow to the propeller disc) is slow however slightly better inflow in comparison to previous hull version has been obtained. Areas of flow deceleration has been reduced although still can be observed right below the propeller hub and also beside the hub around 90-100/260-270$^{o.}$ The axial velocities tend to be somewhat higher around 20-60/300-340^{0} position.

The streamlines test was carried out at design draught. The flow pattern around the hull is quite regular. The flow in the stern area is poorly visualised due to slow velocities obtained there. Compared with the performance of previous hull version the results of the tests are satisfactory. The gain in speed for design draught is ~3% and follows the expectations discussed during the modification phase of the project.

Following extensive research it was determined that the best option for improved propulsive efficiency lay with the incorporation of a Wartsila Energopac solution. Extensive investigations were undertaken in conjunction with Wartsila and Becker Rudders to determine the optimum arrangement and propeller size (This was partly restricted as a result of CSR Rules on full immersion at Light Ballast Draft).

3.7 MODEL TESTS HULLFORM M738-A FINAL PROPELLER AND RUDDER

The results of open water and self-propulsion model tests for the BMT 36000 bulk carrier carried out with the use of hull model M738-A. The hullform was optimised by the Ship Hydromechanics Division of CTO at earlier stage of the project.

For the purpose of tests, models of the final propeller (denominated as P575) and rudder (denominated as B-R738-f) with headbox were used. Geometry was delivered by Wartsila and Becker respectively. Model manufacture was provided by CTO.

The self propulsion tests were carried out at design, heavy ballast and light ballast draughts. The speed predictions for the delivered power of 6,225 kW are given in the table below.

Table 3: Speed Predictions

conditions	Vs [kn]		
	design draught	heavy ballast	light ballast
trials	14,96	15,30	15,34
service	14,36	14,65	14,74

The tested configuration shows satisfactory performance: the overall propulsive efficiency increased by ~2.5% resulting ~1% increase of the speed comparing with tests carried out with stock propeller and rudder. The propeller operational point seems to be well selected showing good compromise between efficiency in trial conditions and margin for operation in worse weather conditions.

Further runs were carried out individually with the new propeller and rudder arrangements to assess the improvements in efficiency for each element. Finally the fully assembled configuration was modelled resulting in improvement in hull efficiency and corresponding fuel efficiency of 15% and 25% respectively when compared to the norm for the class of vessels concerned.

The modified profile of the vessel is shown below in Figure 4.

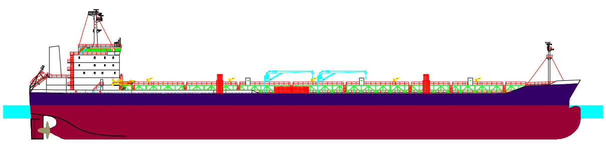

Figure 4**:** BMT TITRON Product Tanker Modified Profile

4. CAVITATION ASSESSMENT

4.1 CAVITATION TESTING

Following completion of the Model Tests the propeller and rudder model were subject to cavitation tests as described below.

The results of the cavitation tests of the design propeller for 36000 bulk carrier in design and ballast conditions. Initially the cavitation visualisation and pressure measurements were scheduled but due to ambiguous results in ballast condition the test scope was extended for cavitation limits. Furthermore on the request of Client's representative, additional runs were undertaken for decreased pressure, increased thrust loading and increased inflow speed in order to give an overview of cavitation margin in ballast condition.

Tests were performed in simulated wake field using the propeller and rudder models manufactured in CTO according to geometry provided by Wartsila and Becker respectively.

4.2 CAVITATION CONCLUSIONS

- The propeller model P575 is free from face cavitation in all tested conditions.
- The propeller model P575 is free from back cavitation in the design condition.
- Limiting back cavitation in form of very slight sheet cavitation and cavitation tip vortex may appear in ballast condition. The point of operation in a ballast condition lies on the boundary of back cavitation inception.
- During the limits cavitation test, it was not possible to determine the face cavitation boundary nevertheless large margin to face cavitation was confirmed.
- The observed types of cavitation should not cause erosion.
- The propeller induced pressure pulses on the after body are low in all tests conditions (also in terms of overloading) and should not induce any significant vibration of ship's hull structure, assuming no resonances.
- In order to reduce the cavitation in the thrust overload condition, it is proposed to decrease tip loading (pitch off-loading).
- The cavitations observed should not impose erosion on the rudder.

5. ENGINE SELECTION

Following completion of the model tests the subject of engine selection and optimised fuel consumption was addressed. An electronic engine ensures better specific fuel consumption figures than a mechanically timed engine so this was adopted.. The rating was chosen such than the engine is running at the efficient part of the fuel curve, i.e. around 60-70% MCR, where specific fuel consumption rates are comparatively steady. The additional benefit of operating the vessel in these conditions means that, if necessary, there is adequate reserve power to counteract the effects of weather and fouling over the life of the vessel.

6. OPERATING PROFILE

The assumed ship's operating profile is 85% at 14 knots, 10% at 15 knots and 5% at 5 knots. This therefore considers the principal operating speed but also the small time spent entering and leaving harbour is also recognised as is the occasional time at slightly faster speeds.

7. TECHNOLOGIES

7.1 WHOLE SET

A set of over 100 technologies were analysed to identify a sub-set which were most applicable to the ship under study. The benefits for each technology were identified using first principles energy-based assessments together with a consideration of the ship impact and increases in the upkeep burden.

The Product Tanker was used to assess the benefits of the technologies identified in Table 4.

Table 4: Product Tanker Merit Set

Drag Reduction	**Drives & Power Sources**
Micro-bubbles	Exhaust Gas Waste Heat Economiser
Skysails	Organic Rankine Cycle
Wing-sails	Wind Turbines
Flettner Rotor	Photo-voltaic solar panels
Mewis Duct	

A number of these technologies are described in detail below.

7.2 MICROBUBBLE DRAG REDUCTION

Microbubble Drag Reduction involves the injection of very small air bubbles into the boundary layer of ships to reduce friction drag. Since 1973 extensive studies on drag reduction using micro-bubbles have allowed their effectiveness to be assessed (McCormick & Bhattacharyya, 1973, Fontaine et al 1992). The detailed research and methods used were addressed in a previous BMT paper (Buckingham J E. 2009). Also known as an Air Lubrication System (ALS) it has been fitted to ships from MHI and Maersk have their own WingedAir Induction Pipe (WAIP) system which has limited success (RINA 2011).

Figure 5 shows how the resistance varies with speed after microbubbles have been introduced. The rate of air supply is proportional to the ship's speed and the application area by a factor 1e-4 in accordance with the guidance of Kodama (Kodama et al. 2005).

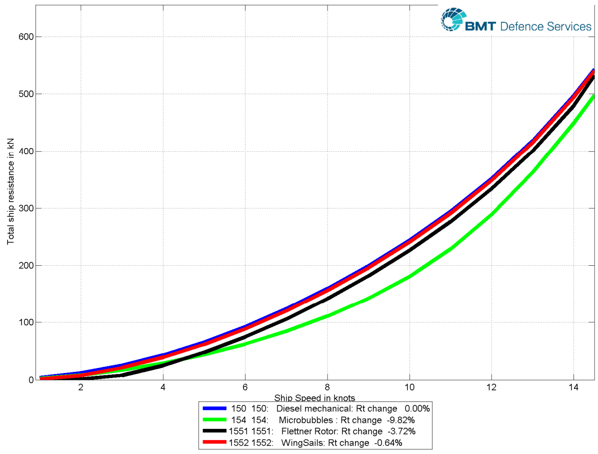

Figure 5: Resistance Reduction

Figure 5 shows the benefit of microbubbles for an air supply provided at a pressure of ~1 barg. The power for the air compressor would go some way to offset resistance power saving. Therefore a microbubble solution is best suited to a ship which has a surplus of compressed air.

7.2 FLETTNER ROTORS

Flettner rotors use the Magnus effect to provide a lateral thrust from a spinning vertical cylinder placed in a moving air stream. The effect was first used in the 1920's to propel a ship (Seybold, 2011). WindAgain Ltd of Singapore now offers modern versions. BMT designed three cylinders, 15m tall, 1.1m diameter to act as Flettner rotors. Their performance calculated from first principles for a range of wind speeds to make an estimate of their effect. The wind spectra and full azimuth of wind directions was considered for each ship speed.

7.3 PHOTO-VOLTAIC SOLAR PANELS

Photo-voltaic solar panels have already been fitted to ships to provide auxiliary power. This is an area of fast-moving technical development with the latest efficiency figures exceeding 13%. A 10% efficiency figure with a pessimistic annual solar radiation of 900kWh/sq.m/year has been used to derive the average power supply from the onboard installation using 90% of the free weather deck area: in practice the super-structure roof could also be covered.

7.4 WIND TURBINES

To quantify the scope for harvesting useful energy from the wind that strikes the port and starboard sides, a 2m by 2m wind turbine design was developed. The unit provides a modest average power of 0.5kW when wind speed variations and ship's heading factors have been factored in. This is considered to be a conservative yield with plenty of scope for further efficiency improvements. Sixty units are located each side.

7.5 SKY SAILS

Sky Sails from the German company of the same name are simple, light and relatively low expense. Real benefits have already been realised but the performance is clearly dependent on the ship's heading relative to the wind and for ship's operating fixed routes this compromises the benefits.

At 15 knots with the wind aft the savings can be as much as 10%. For faster vessels the ship speed may exceed the wind speed and the benefits will be much lower. A 400m^2 design with a 300m tether has been modelled using weather data for the North Atlantic.

7.6 WING SAILS

The current Wing Sails market offering is from Shadotec/WingSail PLC. BMT has used their own variant of a wing-sail for this study: it comprises 3 blades each 15m high. A model of this has identified the kind of performance that might be achieved with North Atlantic wind spectra for a range of ship speeds and the whole circle of headings. The wind speed and ship heading was used to identify the average thrust from the wing-sails for each ship speed. Installation capability is limited by the necessary clearance height between the bridge top and the lowest bridge it has to pass under.

7.8 EXHAUST GAS WASTE HEAT RECOVERY

Exhaust gas waste heat recovery (EGWHR), is an energy recovery method whereby the heat in the engine exhaust is used to create steam which can then be used for:

- Space heating;
- A feed to a steam turbine generator to produce electrical power.
- A feed to an absorption chiller to reduce the load on the chilled water plant.

An EGWHR can allow for the effective use of fuel into the engine to be increased by 12% or so. This technology is widely used in ships such as the Queen Mary 2 and in offshore applications. As of the order of 35% of the engine's waste heat is in the exhaust gas this is an obvious source of recoverable energy.

The MAN Thermo Efficiency System (MAN, 2005) is one example of a modern means of saving energy from a two-stroke design. A fraction of the exhaust gas is bypassed from the turbochargers and fed directly to a turbine driving an alternator. This turbine is combined on a shaft with the steam turbine with a reduction gear and over-speed clutch between the high speed exhaust gas turbine and the slower steam turbine. Energy savings have been estimated using first principles and considering the effectiveness of heat exchangers and the efficiency of the Rankine cycle.

The engine exhaust gas temperature and the exhaust mass flow are both low at slow ship speeds and the operation of the steam generator facility may not be feasible or indeed viable. As the ship's speed increases, the increasing load on the engines allows more heat to be available for steam and hence electrical power generation. The power generated is a bonus even though the Rankine cycle is only about 30% efficient.

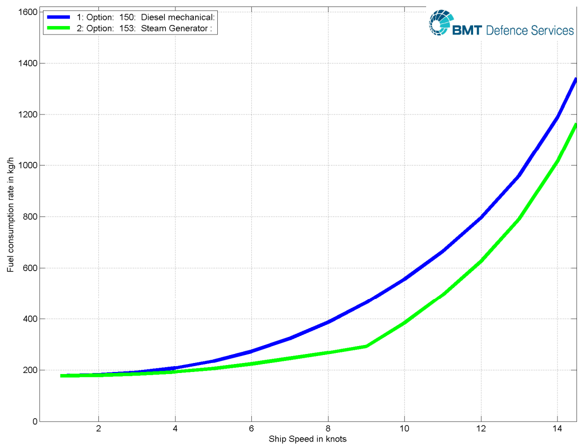

Figure 6: Steam Generator Fuel Benefit

The steam turbo-genset provides a steady stream of savings over the ship's speed. As shown in Figure 6, the useful return on capital must be tempered by the need to provide support and upkeep for the steam and main feed water systems.

7.9 ORGANIC RANKINE CYCLE

An Organic Rankine Cycle (ORC) driven by the exhaust gases may allow for higher efficiencies depending on the design parameters. The heat transfer to the ORC system could be via thermal oil.
Of course such energy extraction is only used for ships electrical systems unless there is a surfeit in which case this could also be used to supplement the main engine with a motor Mounted on the free-end of the crankshaft.

Figure 7 shows how the steam generator with turbo-genset offer significant fuel savings with the SkySails and Microbubble features also offering a tangible benefit.

If these features are all added as a composite design then it is estimated that over 30% fuel savings can be achieved.

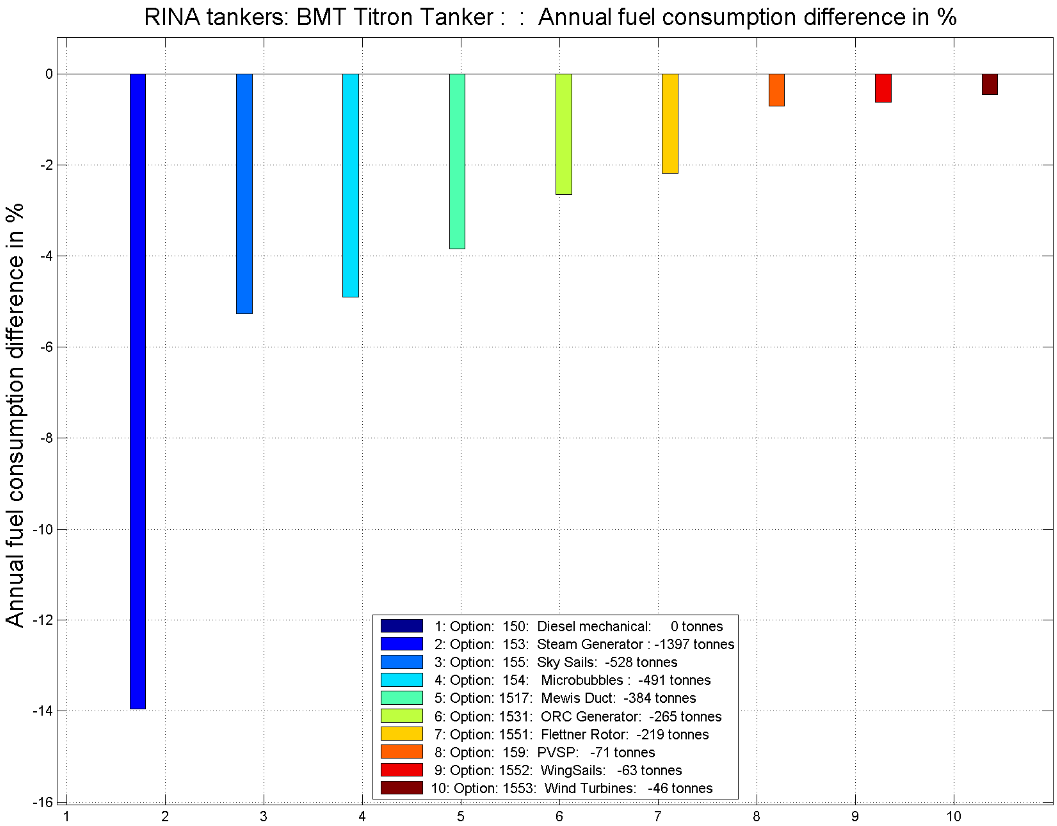

Figure 7: Annual Fuel Consumption Benefits

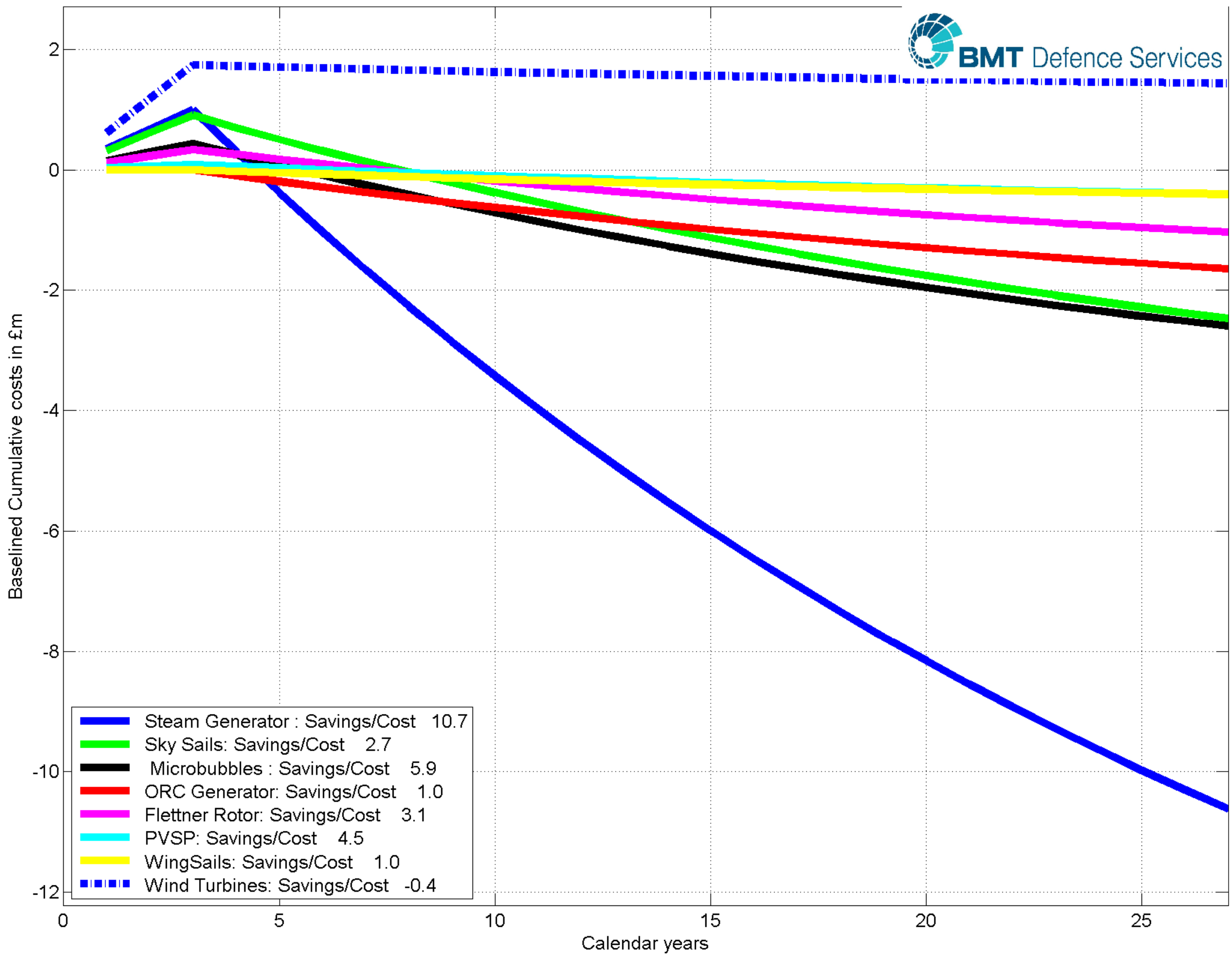

Figure 8: Baselined Whole Life Costs

Figure 8. Shows the estimated balance between the cost of acquiring and inserting the new technologies versus the accrued financial benefits through life. The large fuel saving of steam turbo-genset make it attractive despite it high initial costs which are recovered within a few years assuming no change in the fuel price.

Microbubbles and the photo-voltaic solar panels are also cost-effective whilst the wind turbines as costed by BMT do not make a financial case.

8. CONCLUSIONS

The greatest scope for fuel saving onboard a ship is usually with the Power and Propulsion system: here there is more scope to render the main engine and the propellers more efficient to yield significant fuel savings.

The adoption of an exhaust gas waste heat recovery steam generator together with SkySails and Microbubbles offers scope for significant fuel savings and a much reduced carbon footprint. However each candidate technology needs to be considered with the operating profile of the ship and the method used by BMT allows changes of ships loads and usage to be assessed quickly to yield information on the comparative benefits.

ACKNOWLEDGEMENTS

It is BMT's intention to include copyright with the submitted paper. However BMT acknowledge LCS's request for permission to publish the paper with their proceedings.

The collaboration, assistance and co-operation of Wartsila, Becker Marine Systems and the CTO in Gdansk, Poland are acknowledged with thanks. The kind permission and time granted to the authors by BMT is acknowledged with thanks. All ideas, opinions and errors herein are those of the authors.

REFERENCES

Buckingham J E. (2009). 'Energy Conservation: Matching Technologies to the Platform', MAST September, Stockholm.

Fontaine, A.A., et al (1992). 'The Influence of the Type of Gas on the Reduction of Skin Friction Drag by Microbubble Injection', Experiments in Fluids, Springer-Verlag, Vol. 13, No. 2/3, pp. 128-136.

IMO, (2009). 'Second IMO GHG Study 2009'. International Maritime Organization (IMO), London, UK.

Kodama, Y. et al. (2005). 'Practical application of microbubbles to ships - large scale model experiments and a new full scale experiment', 6th International Symposium on Smart Control of Turbulence, Tokyo.

MAN (2005). 'Diesels: Thermo Efficiency System (TES) for reduction of Fuel Consumption and CO2 emissions', http://www.manbw.com/files/news/filesof5055/P3339161.pdf

McCormick, M.E., & Bhattacharyya, R., (1973). 'Drag Reduction of a Submersible Hull by Electrolysis', Naval Engineers Journal, Vol. 85, No.2, pp. 11-16.

RINA (2011). 'Maersk's Bubble Bursts, The Naval Architect, April.

Seybold, G.B. (2011). 'A Sailing Ship Without Sails: New Wonder of the Seas', Popular Science Monthly (February 1925). http://www.rexresearch.com/flettner/flettner.htm