SEVENTH FRAMEWORK PROGRAMME
THEME 7: Transport (including Aeronautics)

Energy Efficiency – Technologies and clustered Research Projects

Maritime Europe Strategy Action

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State of the art report

Contents

1. Executive Summary

Contents

The present report summarises the findings of MESA – TTG 1 / Energy Efficiency on the state of the art and technology gaps for Energy Efficiency Technologies in European shipbuilding and global maritime transport.

Contractual Basis

The work described in this document corresponds to Task 1.1 in the contractual Description of Work (DoW) of MESA. The description of MESA Task 1.1 is also quoted at the front page of this report. The structure of the document has been harmonised with the other Technical Groups (TTG) as far as possible.

Scope of the SotA Analysis and Interfaces to other MESA TTGs:

The present State-of-the-Art analysis covers the most important elements and (ship- / maritime asset) functions having an impact on the energy efficiency of vessels. For this a dedicated structure has been developed including 7 main items which form the subgroups in TTG 1:

1. Ship resistance
2. Ship propulsion
3. Prime mover
4. Auxiliary energy (conversion) (solar, wind (not for propulsion), seaway energy)
5. Other on-board energy consumers
6. Energy Management Systems
7. Ship operations

In each of the subgroups the present state-of-the-art has been compiled on the basis of past and on-going research from a variety of sources.

Approach

The present SotA analysis provides a comprehensive overview of EU and nationally funded research projects, (from FP6 for EU projects), for both current and completed projects. It is based on a structure of important topics, an Energy Efficiency Thesaurus, which had been elaborated in a first step in Task 1.1. This was based on the achievements in the MARPOS project and the developments in on-going FP 7 projects. In order to activate and/or improve the network of experts, the main companies, research institutions, single experts, users that are the main actors in the area of Energy Efficiency were involved in the work. The structure or breakdown of technologies relevant for Energy Efficiency has been developed in a first step. This structure is used for the main body of the present report in chapter 3.

The involved partners and contributors, on the basis of the comprehensive knowledge of the project results, both achieved and under development, of the various research projects have populated the structure using all available information stemming from a variety of sources which include EU research projects as well as national and international projects and developments. A comprehensive list of sources used for the present report is given in the appendix. The internal structure of the analysis is based on the following three main steps:

- Identification of relevant European (from FP6 onwards), national, regional and other RDI projects in the area of energy efficiency as well as their main actors – Network of Projects;
- Analysis of the content and results of those projects as well as of the general state of the art in Europe and globally, including other sectors where relevant and possible – State of the Art;
- Proposals for cooperation and information exchange in the network - Cooperation Potentials.

Main Conclusions form the State-of-the-Art Analysis in Task 1.1

The seven sub-groups have been individually structured and were broken down into relevant sub-topics using descriptors. Projects and results have been collected together with known state-of-the-art technologies and descriptions. This has led to the following key findings related to Energy Efficiency Research and Development:

- It appears that past EU research has addressed a large number of energy efficiency related topics in the previous framework programmes FP 5 to FP 7. Based on the available information from these projects it is anticipated that substantial progress has been achieved in a number of individual areas, e.g. in the first three areas of ship resistance and propulsion and engine technology. Here, European makers and suppliers are clearly among world market leaders and it can be reasonably concluded that at least part of these successes are due to the work performed in European research projects. The developments and resulting products typically address individual solutions which already, considered as stand-alone solutions, promise substantial improvements. However, most projects fall short to unleash the full potential of the technologies as often the integration of all advanced tools and concepts into a holistic energy saving approach is missing.
- This holds in particular for Energy management systems where considerable work has been spent during FP 7 and in the early phase of H2020. Although some of these projects have not been finished yet and final results will become available only in the future, it must be noted that results lag behind expectations. Meanwhile a number of commercial solutions have appeared during recent years, though a number of these cannot be tracked down to earlier developments performed in EU research. Although there is constant improvement in these, a general assessment is however that they all lack generality. Each of them addresses parts of the energy management problem, but there is hardly any complete solution available today.
- The present analysis concludes that many individual developments which benefitted from EU research funding have helped to move the state-of-the-art in energy efficiency technologies forward. The improvements achieved have helped to considerably reduce energy consumption for a given transport task or other maritime operation. This leads to the general conclusion that the overall European maritime transport research initiative has been successful.
- The present analysis captures the situation in 2015. Following present trends and up-to-date information in the maritime industry it becomes evident that especially the market for energy efficiency improvement technologies is extremely dynamic with new products or solutions available almost every week. At the same time it is similarly evident that for many of these even a proper proof of concept is missing and must be provided before major market uptake can be diagnosed. This is particularly important at the time of writing as the

global energy price situation is rather volatile. Given the low oil and other fuel prices in 2015, a large number of – costly – energy saving solutions lose their previous competitive edge. Today, the motivation for implementing such technologies needs to come mainly from i) a long term perspective, as latest OPEC news forecast rising oil prices again for the next years and ii) the inherent fact that each fuel saving technology implicitly goes along with emission reductions and hence helps to comply with the further increased requirements to control and limit ship borne emissions.

- These considerations lead to the final conclusion that the exercise performed in MESA's task 1.1 which resulted in the present report should be taken up by the industry and continued on a regular basis to assure that up-to-date information will be available also in the years to come.

Main technology trends in strategic fields

During the work on the present SotA report the following technology trends have been found most relevant for maintaining technological and commercial competitiveness and leadership for the European Maritime industry. In relation to the structure of the approach initially chosen for the SotA analysis these are:

- ***Hydrodynamics, Resistance & Propulsion***: Whilst a lot has been achieved particularly during the last decade to improve hull forms and propulsive efficiency, not least due to recent numerical (CFD) developments originating from earlier framework research, further improvements of frictional resistance (mainly on ship hulls) through the use of advanced coatings, air lubrication techniques and boundary layer control methods, all considered in a life-cycle context, are required. In the present operational context this appears to be the most important element to further reduce energy consumption of maritime transportation.
  In addition, full scale validation of prediction methods, further aspects of operational resistances – including wind and waves – and dedicated developments for advanced propulsors will form the basis of anticipated future developments.
- ***Powering***: Improved engine design for operation in "off-design" conditions with a special focus on advanced control strategies. Mechanically new and advanced cooling systems and the use of new engine components and materials for improved corrosion, fatigue, fouling and high load performance will be required plus novel concepts for engine room design to work for integrated retro-fit concepts.
  The use of alternative fuels in the context of multi-fuel engines opens a complete new field. While LNG has been widely adopted in Europe as well as internationally, the next big step will be the adoption of even more alternative fuel concepts to be run in a single engine. This is associated with developments addressing technology as well as logistics with a special focus on life-cycle cost and impact assessment.
- ***Emissions***: Emission reductions, though not strictly in the context of Energy Efficiency or savings, will play an important role in the future. Post treatment technologies like 2nd generation scrubbers will receive more attention; modelling and more technical developments will be required. Here again, life-cycle considerations will play an important role.
- ***Energy Efficiency governance / EEDI***: The presently (IMO) adopted approach to the formulation of the Energy Efficiency Design Index (EEDI) will need to be revisited in the future. A number of issues associated with the present formulation, including e.g. the minimum power requirement

and conceptual rule driven designs need an adaptation of the design index, especially in view of the overall transport work / performance adding transportation time into the equation.

- ***Big Data / Ship Analytics***: “Big Data” is one of the buzz words in shipping terminology at the moment. Technological advances (IT) and advanced regulations (e.g. MRV guidelines) allow and require capturing a much larger amount of data relevant for the assessment of Energy Efficiency of a vessel. Whilst it will soon be possible to accumulate a large amount of information on fuel consumption, performance of individual components and the overall energy household of a ship, together with operational and environmental conditions, the processing of such data will remain a challenge. A proper analysis and decision making support tools will remain the main task for future development.

Further and more detailed information on the general trends and development needs can be found the subsequent chapter 2.2.

Relation to other MESA Deliverables:

This present document forms the basis for Deliverables D 1.4 (Innovation Show Cases) in which successful outcomes of research projects and their implementation in industry are presented and D 1.2 (Proposal for an R&D Roadmap) in which a sequence of future research topics will be derived to fill the gaps identified in this document. Finally, the document will provide input to D 6.2 (Updated Strategic Research and Innovation Agenda) across all Technical Groups (TTGs) represented in MESA.

2. Strategic Analysis

Increased competition in a global market, the need to develop cost efficient and customer-specific ships as well as new rules and regulations require permanent improvements in all technical areas. The further improvement of the Energy efficiency of products plays a key role in both, shipbuilding and the ever more important offshore markets. While a wide variety of research results are available on company, regional, national and European as well as international levels, the cooperation between projects and a complete overview on available technologies and results is largely missing. MESA set out to address these deficiencies in TTG 1 for the area of Energy Efficiency (as other TTGs do for safety, production and e-maritime).

2.1 Steps performed and outlook to future deliverables

Methodology

The present report compiles the contributions of European projects to improved energy efficiency of ships and puts them into context of the overall state-of-the-art in Energy Efficiency which is constituted from a wide range of national as well as international initiatives. The compilation comprises contributions from a variety of different sectors all influencing fuel / energy consumption on board a ship. It follows an analysis concept agreed in the working group how to gather and structure relevant information. The basic steps for this are:

- Definition of “system boundaries”
- Collection of contributions to all relevant sectors / areas affecting and influencing the energy efficiency of ships and maritime structures:
    - from EU projects,
    - from other sources.
- Definition of a Catalogue of EE related elements.
- Definition of global assessment criteria to evaluate the influence / impact of relevant technologies.

Having defined the system boundaries the present document is based on the catalogue of energy efficiency related technologies and projects. This constitutes a flexible structure which can be maintained and further amended in the future with additional releases of the present report which represents the “as is” situation in the year 2015.

Based on the collection and analysis of past contributions to energy efficiency a set of technology gaps has been identified. These result from technical considerations mainly, related to an optimal functionality of a given product, technology or service and are related to past and on-going work. In a second step it will be necessary to compare these technology gaps with external requirements resulting from either public demand, e.g. new rules and legislation, or from private industrial or trade requirements to provide the basis for an evaluation which shall form a later description of the future maritime research needs in the form of an updated R&D roadmap. This will be performed in MESA workpackage 6 together with the partners from workpackage 5.

Information sources

The present document has been prepared with the support from a large number of experts who have contributed information and their views on past and present research in the detailed analysis in chapter 3. The starting point for information collection were initial tables which were individually compiled on the basis of personal information which covered a wide range of different projects, funding schemes and national as well as EU projects. Further work involved dedicated CORDIS and TRIP research which resulted in a total of 114 projects which were collected, arranged according to the agreed structure and analysed. The following figures give an overview on the origins of the projects considered. The first figure indicates the number of projects receiving DG – Research funding over the past 4 framework programmes. A total of 48 projects were considered, more than 50% of which were from the last framework programme. This clearly indicates the increased interest in Energy Efficiency related developments over time.

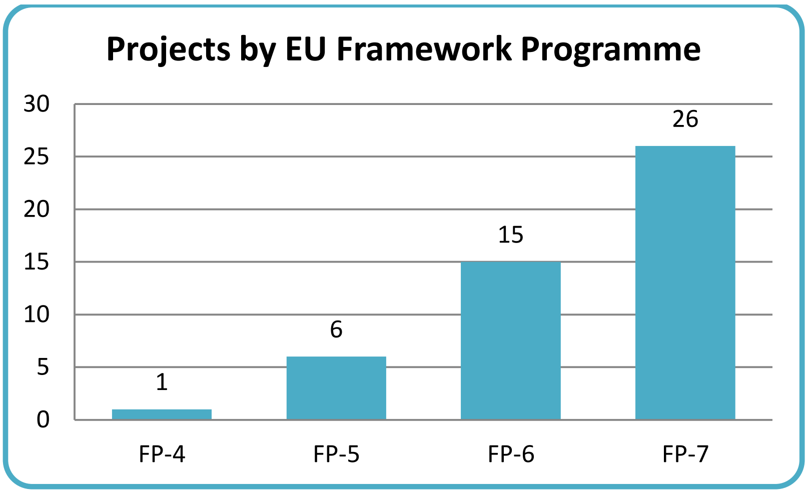


Fig. 1: "Evolution of EU (DG-RTD) Research on Energy Efficiency"

In addition to these projects a variety of inputs were received also from national or other sources. The following figure indicates the breakdown of all 114 projects considered in the present study into different funding sources. Whilst general EU funding is by far the largest source several projects which were considered also received funding from different national sources. The total of 79 for the European projects considered results from the fact that here a number of other funding schemes were taken into account too: the analysis also includes a number of TEN-T projects whilst joint research such as the MARTEC scheme are listed as “others”.

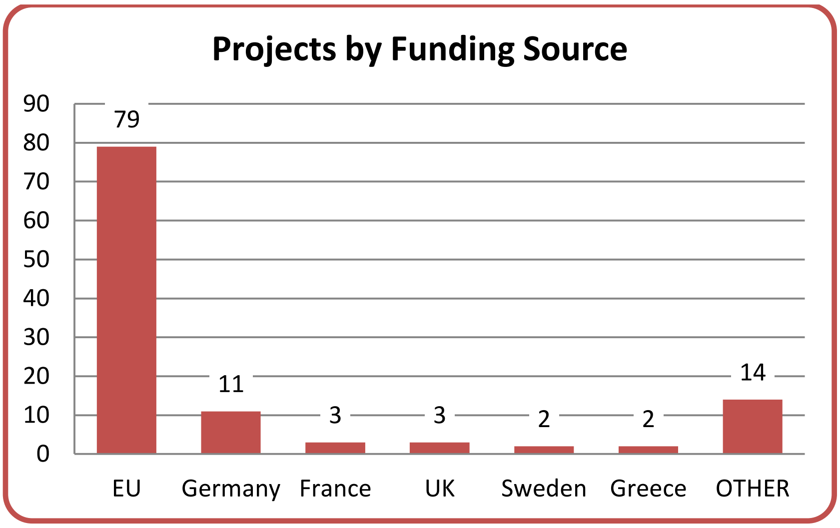


Fig. 2: "Energy Efficiency Projects by funding source"

The visibility of project has been significantly increased over time too. This is mainly due to the fact that the majority of them possesses own web sites as the main means of public dissemination. A complete overview of the projects considered can be found in Appendix 1.

State of the Art Analysis

The state-of-the-art analysis was conducted bottom-up in the seven Sub groups forming the basic structure of the SotA analysis in TTG 1. A comprehensive list of detailed results is presented in chapter 3 below. While this provides a good basis for an assessment of the State-of-the-Art in Energy Efficiency technologies in shipbuilding, it is too fragmented to draw strategic conclusions and identify the "big picture". To overcome, the main conclusions on the State-of-the-Art in technology fields found most relevant for the European maritime industry are summarized in form of a Strategic Analysis in Chapter 2.2 with a special focus on technology gaps identified already in the process of the State-of-the-art analysis.

Outlook to follow-up Deliverables:

The present report D 1.1 is the first deliverable of TTG-1 (WP-1) forming the baseline for

- D 1.2 – Proposal of an RTD Roadmap for Energy Efficiency technologies;
- D 1.4 – Innovation Show Cases for Energy Efficiency.

The outcome of workshops conducted throughout the work in WP 1 will be reported in D 1.3 – Workshops.

Finally, the outcome of the work in TTG-1 will be consolidated in a joint exercise of the thematic technology groups and the members of WP 5 on project level in Deliverable D 6.2 – Up-dated Strategic Research and Innovation Agenda.

2.2 State-of-the-art and Main directions of further technology developments

The Following section summarises the main findings of the work in MESA TTG 1 related to the state-of-the-art analysis and links them to the research needs which were identified in TTG 1 on the basis of technical considerations. To clarify the basis of the analysis and how the results were classified, a short description of the "System boundaries" which specify the range of the analysis is given at the start of the section.

2.2.1 System boundaries

Within the overall context and scope of the MESA analysis it is necessary to limit the extent of investigations performed in the EE – Group. Therefore a clear definition of what belongs to EE technologies and what not is required. Energy efficiency is an operative parameter which means that the subsequent studies will focus mainly on operational performance of ships. On the other hand, the basics for efficient operation are determined during the design of a ship. Consequently both areas need to be considered in the following.

There is a prevailing impression that "greening technologies" are often synonymous with energy efficiency. This is not always the case as certain "greening technologies" do require additional energy to perform. One such example in the context of shipbuilding are scrubbers. On the other hand, we can anticipate that all – real – energy efficiency technologies will have a positive (i.e. reducing) influence on the consumption of primary energy (fuel) on board a ship.

It was decided to limit the study to those aspects which clearly lead to reduced – primary – energy consumption during operation. If certain positive measures require substantial use of energy during production, e.g. the replacement of a component, main engine or similar, these effects need to considered too, where possible. In view of the importance of overall greening related legislation further developments for other emission reduction options, independently of their efficiency, have been considered also for future research.

2.2.2 SotA and Development needs for selected areas of prime interest

Based on the initial structure of the work in task 1.1, i.e. the 7 sub-groups mentioned in chapter 1 and described in detail in the main body of the report chapter 3 the working group on Energy Efficiency has identified 5 main areas of prime importance. Here further research and development will be necessary in the future to sustain and expand the position of Europe's maritime industry. The following tables summarise the present achievements and needs for further work, research and development.

Hydrodynamics, Resistance & Propulsion	
Importance	For the vast majority of merchant vessels, hydrodynamic effects are the prime cause of energy consumption. This holds almost entirely for cargo vessels which typically use up to 85% of all practically available energy to overcome the resistance and for propulsion. Although this picture changes completely when looking at passenger ships or other complex vessels, it must be noted that the first category of cargo vessels constitutes more than 90% of the world fleet. This makes them the prime element to further reduce energy consumption of

	maritime transportation.
SotA	Ship resistance is made up from two principal components, the form related pressure resistance and the viscous drag due to friction forces acting on the hull surface. During the last decade a lot has been achieved particularly to improve the pressure resistance with better hull forms, not least due to recent numerical (CFD) developments originating from earlier framework research, to the extent that today less than 20% of the overall resistance of a "good ship design" can be attributed to pressure forces. Similarly improved propulsors, either as stand-alone solutions or as multi-stage propulsors using specifically tailored energy saving devices have been shown to offer substantial increases in propulsive efficiency. Friction or viscous resistance can be influenced by surface quality and properties. Coatings are the number one element used to improve frictional resistance. After the ban of TBT paints in 2003 new coatings have been developed offering a much better environmental compatibility, though the long term surface quality has not been reached yet. Another popular means to reduce surface friction is air lubrication which has been investigated to some extent. There are different competing technological concepts around for which a full validation and proof or efficiency gains still remains open.
Gaps	Further improvements of frictional resistance (mainly on ship hulls) through the use of advanced coatings, air lubrication techniques and boundary layer control methods, all considered in a life-cycle context, are required. Full scale validation of prediction methods is considered to be of prime importance for future developments towards a complete, simulation based (hydrodynamic) design concept for all maritime vessels. Operational resistances and performance – including wind and waves – are more important to evaluate the life-cycle performance of a vessel. These are presently only roughly considered and the quality of their assessment needs to be further improved to allow for considering these aspects in next generation optimisation systems. While a number of dedicated developments for advanced propulsors have taken place already, a full validation of concepts has not been done yet. This shortcoming will hamper future developments and it should be supported by large demonstrators.

Powering	
Importance	Vessel powering is the most important (ship) function determining cost, efficiency and safety of ship operation. The by far largest share of the prime energy consumption is governed by the prime mover for more than 95% of all ships

	operating worldwide. The amount and choice of fuels determines the emissions and environmental footprint of these vessels.
SotA	Diesel propelled machinery is the principal and main technology used in marine propulsion today. Past research has led to High efficiency engines with optimised internal losses (friction) and increased thermal efficiency through better combustion processes and improved turbocharging. Environmental legislation further resulted in reduced emissions, either stemming from adapted internal combustion processes or external cleaning techniques like selective catalytic reduction or scrubbers. Using alternative fuels (instead of HFO) also resulted in considerable improvements in terms of emissions. The use of LNG is now widely adopted and an adequate supply infrastructure is now being established. Fuel cells which offer in principle cleaner technology have been researched to some extent. High cost and limited power output make it difficult today to apply the technology to shipping at a large scale. Gas turbines or nuclear propulsion either have a lower efficiency or are associated with high cost and limited public acceptance. These technologies can only be found in naval vessels today where high speeds and very high power outputs are required. Renewable energy propulsion mainly relates to wind propulsion. Several attempts have been made to re-establish sailing vessels on a small scale during the past years. A general acceptance of the technology, mainly due to its effect on scheduled services, is not apparent at the moment.
Gaps	Improved engine design for operation in “off-design” conditions with a special focus on advanced control strategies. Mechanically new and advanced cooling systems and the use of new engine components and materials for improved corrosion, fatigue, fouling and high load performance will be required plus novel concepts for engine room design to work for integrated retro-fit concepts. The use of alternative fuels in the context of multi-fuel engines opens a complete new field. While LNG has been widely adopted in Europe as well as international, the next big step will be the adoption of even more alternative fuel concepts to be run in a single engine. This is associated with developments addressing technology as well as logistics with a special focus on life-cycle cost and impact assessment

Emissions	
Importance	The reduction of ship emissions plays and will play an important role in the future of maritime transport. Although this is strictly speaking not an Energy Efficiency issue and hence has not been covered in the detailed analysis in chapter 3 of the present report, there are close relations with other Energy Efficiency technologies which make it appear sensible to list this part too. Despite the fact that shipping is the most efficient transport mode in terms of energy consumption the sheer

	size of transport work and the use of HFO call for larger effort to reduce emissions from seaborne transportation.
SotA	Emission reduction technologies and methods can be grouped into two: Primary methods are measures aimed at reducing the amount of NOX formed during combustion by optimising engine combustion parameters, Secondary methods are on the other hand designed to remove NOX from the exhaust gas by downstream cleaning techniques. For primary methods work has focused on improving combustion process, cylinder lubrication system and turbocharging; employing Exhaust Gas Recirculation (EGR) and introducing water injection. Secondary methods include the use of selective catalytic reduction (SCR), scrubbing methods (using open/closed loop, wet/dry scrubbers), non-thermal plasma (NTP) reactors, smoke/diesel particulate filters (DPF), on-board chemical CO2 capture or pre-turbine oxidation catalysts. Fuel is of course decisive for the amount and quality of emissions. The use of low-sulphur diesel fuels or LNG results in significantly reduced SOX emissions. This approach is widely used today in form of dual fuel engines operating on both HFO and one of the alternative, cleaner fuels in ports and ECAs.
Gaps	Post treatment technologies like 2nd generation scrubbers will receive more attention, Modelling and more technical developments will be required. Here again, life-cycle considerations will play an important role.

Energy Management	
Importance	A complete management of the entire energy household on board ships is one of the main development areas promising substantial gains for the future. This is caused by the fact that the complexity of ship machinery is increasing, partly caused by the ever increasing complexity of the operational profile of many ships which need to perform efficiently under a large variety of operational conditions.
SotA	Energy management on-board ships has found significant interest over the past years, either in form of research projects or industrial developments. Several EU research projects have developed concepts and applications with often varying focus during the past 5 years. Still, a holistic solution is still missing.
Gaps	With “Big Data” being one of the buzz words in present shipping terminology, technological advances (IT) and advanced regulations (e.g. MRV guidelines) allow and require capturing a much larger amount of data relevant for the assessment and management of Energy consumption of a vessel. Whilst it will soon be possible to accumulate a large amount of information on fuel consumption, performance of individual components and the overall energy

	household of a ship, together with operational and environmental conditions, the processing of such data will remain a challenge. A proper analysis and decision making support tools will remain the main task for future development. The inclusion of auxiliary propulsion, e.g. wind or other, must be considered in future energy management systems to allow for optimised consumption under varying environmental and operational conditions. Together with new technological developments in the respective areas, advanced solutions for energy generation (conversion), storage and distribution need to be sought to attain an optimised consumption profile.

Energy Efficiency governance	
Importance	Monitoring and control of energy efficiency standards is a vital instrument to assure the implementations of standards. The Energy Efficiency Design Index (EEDI) was made mandatory for new ships at MEPC 62 (July 2011) with the adoption of amendments to MARPOL Annex VI.
SotA	The EEDI for new ships is the most important technical measure and aims at promoting the use of more energy efficient (less polluting) equipment and engines. The EEDI requires a minimum energy efficiency level per capacity mile (e.g. tonne mile) for different ship type and size segments. The EEDI provides a specific figure for an individual ship design, expressed in grams of carbon dioxide (CO_2) per ship's capacity-mile (the smaller the EEDI the more energy efficient ship design) and is calculated by a formula based on the technical design parameters for a given ship.
Gaps	The presently (IMO) adopted approach to the formulation of the Energy Efficiency Design Index (EEDI) will need to be revisited in the future in the light of new technical developments assuring a higher energy efficiency. A number of issues associated with the present formulation, including e.g. the minimum power requirement for a safe return to port and conceptual rule driven designs need an adaptation of the design index, especially in view of the overall transport work / performance adding transportation time into the equation.

2.3 Recommendations for cooperation and implementation

The following chapter describes observations and experiences made during the collection of the state-of-the-art material. These relate mainly to the availability of documentation from public funded projects, both in the EU and on a national scale.

Documentation and Dissemination of Project Outcomes

Although the general visibility of research projects has improved over time – this is mainly due to the fact that most projects do have their own web site for information and dissemination – it is felt that the dimension of information, especially on useful results as well as failures during a project is rather limited. Especially for European project where clear rules exist to provide public (summary) reports at the end of the project, these are often difficult or impossible to access. It is disappointing to notice that the amount of information that can be accessed through official portals, e.g. CORDIS is rather limited in most cases. Other databases such as TRIP or MARPOS which had been funded during their development also do not provide complete and consistent overviews. Links with projects funded by different sources, e.g. national grants etc. are not available. All this holds particularly for post-project information on the technology uptake and implementation.

Recommendation

(EU) Projects should be obliged to submit the public reports to CORDIS as a central place for storing all framework project information and results.
Projects should be asked to provide follow-up information on the use of results after the duration of the project. This could be supported by a special – small – grant scheme.
It would be beneficial if a single point of contact for technology research could be established, including also non-EU funded research. The MARTEC network could be an opportunity to establish outside contacts.

Cooperation between Projects and Researchers

A general exchange between different projects working in similar or adjacent technological areas appears to be difficult. Past experience indicated that this was only possible when driven by individual initiatives. In the field of Energy Efficiency one such attempt was made during FP 7 when trying to assemble the Green Ship Energy Efficiency Network which finally assembled some 10 projects a subset of which organised a joint workshop during the GST 2013 conference. The main difficulties encountered here relate to small budgets for exchange and extra work to organise communication and dissemination events on one hand and IPR and non-disclosure issues on the other.

Recommendation

Collaboration in technical areas in a pre-competitive or pre-project phase appears to be possible and desirable. Experiences made in early Thematic Networks dating back into the 4th framework programme were universally positive. This concept should be revived for the future.

Take-Up and implementation of project results

A number of Energy Efficiency Projects in the past have been hugely successful and resulted in products or technologies which have been taken up by project partners quickly to be transferred into products and services after the end of the respective projects. However, references are rarely given and an – external – assessment of the success and implementation of project results is very often difficult as the link between the development work (project) and the final product is often missing. Here more effort in post-project documentation (see also above) would be favourable.

Recommendation

In the context of project evaluation it might be helpful to consider a range of conferences, possibly parallel to the TRA conference, in which commercial success stories and results obtained in EU projects are presented to the wider public. For transport this could be organised by sectors.

International Cooperation (outside Europe)

Many of the European maritime actors are active worldwide. These are individual initiatives, projects and co-operations which are in most cases not part of EU projects. An overview of the international work is difficult to obtain other than in long term established umbrella groups such as the International Towing Tank Conference (ITTC) in the field of maritime hydrodynamics or the International Ship and Offshore Structures Congress (ISSC). Even their results and information are however only available to individual members. More overview on international developments on a broader scale would be required for the future.

Recommendation

A dedicated monitoring mechanism on international technical developments should be established jointly by the Industry, e.g. via the Technology Platform and EC.

3. Detailed Analysis of Clustered Projects - State of the art technology

The following section provides a first breakdown of energy efficiency technologies available in maritime transportation. This covers a review of accomplished and on-going research at European and national level and considers also technologies available at international level. Information has been collected from a large variety of sources which include the European project databases at CORDIS and TRIP as well as the ec.europa.eu/research/transport site. Numerous individual web sites have been investigated and external sources such as fathom's Ship Efficiency Guide

General Energy Breakdown

For the vast majority of merchant vessels, hydrodynamic effects are the prime cause of energy consumption. This holds almost entirely for cargo vessels which typically use up to 85% of all practically available energy to overcome the resistance and for propulsion. Of course, this does exclude all internal losses in a combustion engine which are not part of the present considerations. The following figure from IMO's GHG study illustrates the fact that more than 50% of the potential energy included in the bunker fuel is lost in the conversion process in the engine and only 43% of the bunker energy is available for practical purposes. Out of this fraction more than 85% is used to counteract hydrodynamic forces on the hull during sail.

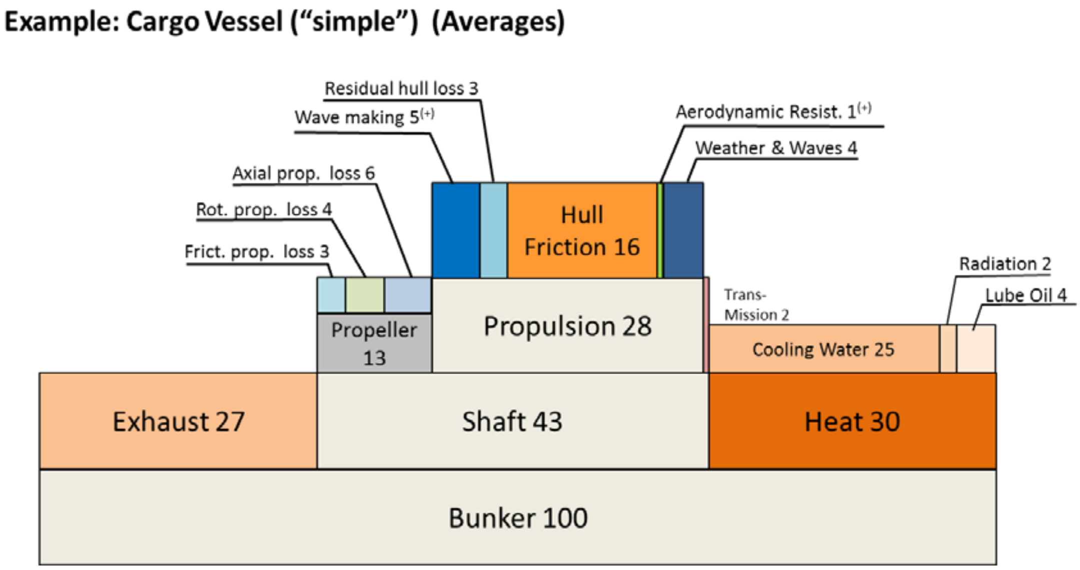


Fig. 3: Use of primary energy on board a small cargo ship, (IMO, 2009)

This picture changes completely when looking at passenger ships or other complex vessels. Large cruise liners are practically floating hotels which need to provide services and amenities for a large number of passengers. Here the hotel loads determine the energy consumption to a large extent: lighting, air conditioning, heating and cooling, refrigeration and cooking as well as fresh water supply become important factors for the energy household of such vessels. The following figure is based on limited information available on the total energy balance of a large PAX vessel.

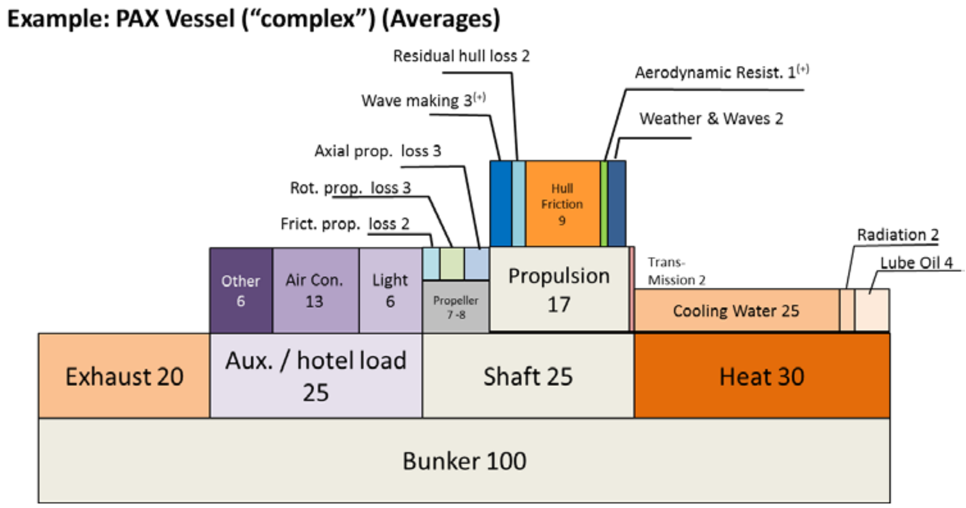


Fig. 4 Use of primary energy on board a large PAX vessel

System boundaries

Within the overall context and scope of the MESA analysis it is necessary to limit the extent of investigations performed in the EE – Group. Therefore a clear definition of what belongs to EE technologies and what not is required. Energy efficiency is an operative parameter which means that the subsequent studies will focus mainly on operational performance of ships. On the other hand, the basics for efficient operation are determined during the design of a ship. Consequently both areas need to be considered in the following.

There is a prevailing impression that "greening technologies" are often synonymous with energy efficiency. This is not always the case as certain "greening technologies" do require additional energy to perform. One such example in the context of shipbuilding are scrubbers. On the other hand, we can anticipate that all – real – energy efficiency technologies will have a positive (i.e. reducing) influence on the consumption of primary energy (fuel) on board a ship.

It was decided to limit the study to those aspects which clearly lead to reduced – primary – energy consumption during operation. If certain positive measures require substantial use of energy during production, e.g. the replacement of a component, main engine or similar, these effects need to considered too, where possible. In view of the importance of overall greening related legislation further developments for other emission reduction options, independently of their efficiency, have been considered also for future research.

3.1 Ship resistance

Focussing on minimising energy consumption, the quest for low drag and improved propulsive efficiency promises the largest gains. The individual aspects considered in the present approach include:

- Ship resistance including all its pertinent components.
- Ship propulsion.

Together these elements form the main contribution of the ship design to achieve the most economic and energy efficient operation. Adapting the operational profile to environmental influences, e.g. ship speed *vs*. sea state and wind conditions will further help to achieve a global optimum in terms of energy consumption.

Ship resistance is comprised from different components: (i) the pressure or form related wave resistance, (ii) the viscous drag, and (iii) the added resistance due to wind and waves. These are responsible for up to 70% of the power required on board a merchant vessel. Due to the different causes of the resistance components, either related to (hull) pressure or (surface) friction, they need to be considered at different stages of the vessel's life cycle. Pressure related components depending on the hullform are a design feature while viscous resistance largely hinges on the surface quality, which is initially determined by production quality and the hull coating and maintenance. Especially the latter is clearly related to the operational stage of the vessel. The same holds for added resistance due to wind and waves which can be influenced through weather routing.

The following figure indicates the decomposition of ship resistance used e.g. in the TARGETS project to integrate resistance into the overall dynamic energy model (DEM) developed in that project.

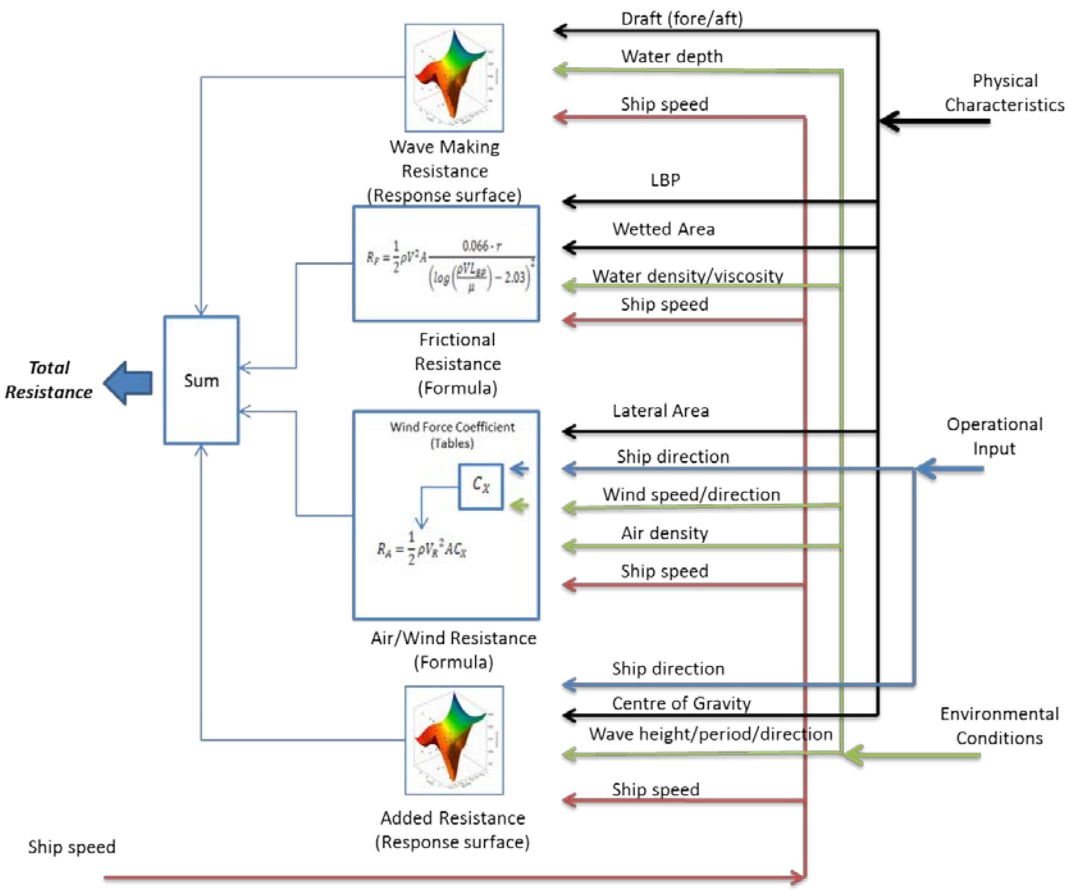


Fig.5: Decomposition of ship resistance

With different physical laws ruling individual aspects of ship resistance, e.g. gravity and viscosity of the fluid, there is no single means to predict operational ship resistance as a total. Although modern state-of-the-art RANS codes offer the potential to compute the total resistance of a ship, this is typically limited to clearly defined, standard conditions, e.g. a new vessel during trial conditions. Further factors imposed during operation over the life cycle of a vessel, e.g. hull fouling, added resistance in a seaway, etc., still need to be superimposed on the basis of empirical methods often.

3.1.1 Form resistance – Assessment technologies

A ship moving through water generates waves which are caused by the pressure distribution imposed by the hull on the water surrounding the hull. A primary wave system, the bow and the stern wave are independent of the individual hullform and relate only to the speed of the ship. The particular form of the hull however can influence the secondary wave system, generated – in general terms - at the forward and aft shoulder of the hull. These can, dependent on speed, be used to influence the primary system through interference effects.

In practice ship designers will attempt to generate smooth shapes which have less pronounced individual and clear wave “generators” such as pronounced shoulders. Still the buoyancy distribution along the length of the hull will lead to a number of waves being generated at speed. These can be influenced, still as a function of speed, by adapting the frame area section curve appropriately and by choosing different bow and particular bulb shapes.

3.1.1.1 Model testing

State of the art technology	***Reference Projects***
Ship model testing has been introduced in the 19th century and since then successively refined. Today, this is a widely established, state of the art technology which does not require any further development when considering resistance testing. Model testing with comparatively large scale models (model (ship) length abt. 10 m) forms today’s standard. They are used for • confirmation / validation • required for EEDI verification	Applied in various projects, no specific reference.

3.1.1.2 Empirical Statistical Methods

State of the art technology	***Reference Projects***
Wide range of existing, standard methods starting from the Admiralty formula and including Series 60, BSRC, Holtrop Mennen, Guldhammer Harvald, …, special methods for dedicated ship types, e.g. fishing vessels. Methods often provide good starting points for initial design. There has been no specific development for statistical methods during the past 3 to 4 decades. This appears to be considered unnecessary.	Used in various projects, no specific reference.
Proprietary correlation methods, e.g. at model basins. In-house know-how, not publically available	

3.1.1.3 Theoretical prediction methods

A number of resistance prediction methods have been developed over time. The most important ones used in ship design are listed below.

3.1.1.3.1 Analytical Methods

State of the art technology	***Reference Projects***
Mitchell, thin ship theory: generic analytical method which can be sensibly applied only to a very limited range of (slender) hullforms. No practical relevance.	./.

3.1.1.3.2 Potential flow codes

State of the art technology	***Reference Projects***
Potential flow codes evolved in the 1980ies, improving rapidly during the past decades due to functional improvements and vastly improved computational power. Today, Hess-Smith / Dawson methods are widely used in the industry and often applied with(in) optimisation environments which are often integrated in maritime CAE packages	CALYPSO, FANTASTIC, VIRTUE, …

3.1.1.3.3 RANS codes with and w/o free surface effects

State of the art technology	***Reference Projects***
RANS codes, with and w/o free surface effects have been developed since the 1980ies- Stemming from other areas of application the first maritime applications have been noted in the 1990ies. For typical maritime free surface applications the use of 2 phase flows (water, air) using either VoF or level set techniques have become an accepted standard. The methods have significantly improved especially during the past decade, not least due to the work done in projects such as VIRTUE which contributed a high level of improved accuracy and computational efficiency. Methods and tools have reached a level of trust which allows using them in the development of new and advanced ships and structures. Still a high level of computational effort is required to run accurate predictions which require fine resolution grids. Hence RANS codes are typically run as stand-alone applications, often used for verification of designs which have been previously optimised using simpler methods (e.g. potential flow codes). Only few uses of RANS directly in optimisation are known.	EFFORT, VIRTUE, STREAMLINE, TARGETS, GRIP, …
The move of applications to even more complex dynamic simulations, e.g. for the transient behaviour during seakeeping or manoeuvring poses additional challenges, specifically with respect to computational effort / speed and data management. This will remain a research topic in the future.	

3.1.1.3.4 Adjoint methods

State of the art technology	***Reference Projects***
integrated prediction of sensitivities w.r.t. a given objective function, development stage, free surface effects not yet included;	TARGETS, VIRTUE (attempts)
Computationally intensive, though more efficient than conventional, search based optimisation methods.	Form-Pro, NoWelle (D)

3.1.1.4 (CFD based) Optimisation

State of the art technology	***Reference Projects***
Explicit optimisation has been developed and applied in a number of projects. The concept uses a given geometrical shape which is analysed and ranked according to a pre-defined set of objective or cost functions. In this way a larger number of analyses will be performed and the optimisation engine applies a search strategy to relate the objective functions to a number of equally pre-defined form parameters which influence the geometry. The main elements used in this form of optimisation are in general terms: • Geometry definition and modification tools; • Analysis – CFD tools; • Optimisation tools; • Post-Processing and visualisation tools; For all of these groups a number of different options are available. Geometry is typically created and manipulated in a CAD system. While for the generation of an initial hullform arbitrary CAD packages can be used, tools are sought which allow for automated modification of hullforms, preferably based on easy-to-control parameters for application in an optimisation process. Today, a number of CAD packages provide either parametric or free form deformation functionality which can be applied in automated optimisation processes. The FANTASTIC project (Maisonneuve et. al.) has demonstrated the use of parametric hullform modelling based on various tools such as the Friendship framework or NAPA integrated into such an automatic optimisation environment. Free form deformation tools can also be applied directly on the computational grid and thus avoid the permanent interaction with an underlying CAD geometry which helps to save time and can avoid problems arising from meshing a complex geometry.	FANTASTIC, (VIRTUE), STREAMLINE, TARGETS

3.1.2 Viscous / frictional resistance

Friction forces are exhibited on each body moving through water. In a real fluid such as water, water particles adhere to the surface of e.g. a ship due to their physical properties, i.e. the viscosity of the fluid and hence generate a boundary layer which under goes shear forces at different rates until reaching the – undisturbed – outer flow field. This causes a significant drag / resistance due to shear forces which in many cases is higher than the pressure or form related forces discussed in chapter 2.1.1.

3.1.2.1 General Prediction Methods

Naval Architecture has since long worked on the definition of appropriate prediction methods for friction resistance. This effort has yielded a number of different formulae which are typically addressed as "friction lines". Based on the analysis work and statistical evaluations of the members, the ITTC has issued a standard formula already in 1957 which is still widely applied.

3.1.2.1.1 ITTC 57 line

State of the art technology	***Reference Projects***
standard friction line based on correlation based on old data, on-going discussion to replace	TARGETS

3.1.2.1.2 Alternative friction lines

State of the art technology	***Reference Projects***
A variety of alternative friction lines exists, e.g. scientific (flat plate) lines, or other correlation lines, e.g. Grigson discussion in TARGETS deliverable D 1.3	VIRTUE TARGETS

3.1.2.1.3 Numerical prediction

State of the art technology	***Reference Projects***
Implemented in RANS codes, function of turbulence model used.	VIRTUE, TARGETS
	All RANS codes / commercial as well as research

3.1.2.2 Surface roughness

Besides the physical properties of the fluid, the characteristics of the surface being pushed through the fluid determine the extent to which friction forces act on the hull. The quality and the smoothness of the surface have a significant effect which can lead to substantial increases of the viscous resistance of a vessel. While all previous considerations assumed hydraulically smooth surfaces, a ship hull will never be completely smooth. Even when launched into the water for the first time production imperfections will mean an increase of the resistance from the ideal, hydraulically smooth surface. This will rapidly grow over time due to fouling effects.

3.1.2.2.1 Measurement techniques

State of the art technology	***Reference Projects***
e.g. BMT Hull Roughness Analyser	./.
TNO Friction Disk Machine	CRS ECONSHIPS

3.1.2.2.2 Computational approach

State of the art technology	***Reference Projects***
Several of the empirical methods mentioned in 2.1.2.1 have additional roughness corrections.	
roughness model implemented in RANS codes / turbulence models	VIRTUE, TARGETS, CRS ECONSHIPS

3.1.2.2.3 Fouling

State of the art technology	***Reference Projects***
Biofouling is known as the attachment of unwanted micro-organisms, animals and plants including diatoms and bacteria (slime) on immersed surfaces. There are more than 4000 species of fouling currently identified which makes the development of new environmentally benign antifouling systems a very challenging task. The TARGETS project has researched the biofouling problem also describing in depth the main antifouling technologies used today. The estimation of roughness effects in the performance of ships are also explained with a view on the current shipbuilding practice. Considering the weaknesses of all those models a new technique that relies on Granville theory and the boundary layer similarity is presented that is utilised to extrapolate laboratory data to full scale change in frictional resistance predictions due to coating roughness and biofouling. Besides these, a number of EU projects dealt with antifouling coatings addressing production and processing techniques, the focus however was less	TARGETS, CRS ECONSHIPS

on energy savings.	

3.1.2.3 Technologies to influence frictional resistance

3.1.2.3.1 Coatings / Antifoulings

State of the art technology	***Reference Projects***
Foul release Coating (FRC), Tin free self polishing Copolymers (SPC), Tin fee controlled depletion paints (CDP) The effects of different antifouling coatings based on a number of different concepts have been investigated in the TARGETS project and their effect on friction resistance has been assessed. This was also investigated in the ECONSHIPS project of the Cooperative Ship Research (CRS)	TARGETS, CRS ECONSHIPS
Riblets / patterned surfaces A comprehensive analysis of the effect of patterned surfaces such as riblets, dimples etc. has been performed in the TARGETS project. These surfaces promise resistance reductions and have been applied on other vessels, aircraft, trains and high performance sailing vessels in the past. The options to apply them on sea going ships however appear to be limited.	TARGETS
Documentation of effect of silicone paints	GREENSHIP project (DK) http://www.greenship.org/projekter/operations/15189.html

3.1.2.4 Air lubrication

Air lubrication systems intend to reduce ship's drag by blowing air bubbles below the hull of the ship thus reducing the friction forces acting between the ship hull and seawater.

3.1.2.4.1 Air film

State of the art technology	*Reference Projects*
Technology development and demonstrator (inland vessel).	SMOOTH, PELS (dutch project)

3.1.2.4.2 Air cavity

State of the art technology	*Reference Projects*
Sota review, technology study, application examples	TARGETS, SMOOTH

3.1.2.4.3 Micro bubble

State of the art technology	*Reference Projects*
Sota review, technology study Industrial technology development, promising but no publically funded R&D	SMOOTH, Industrial Projects (DK-Group / Silverstream)

3.1.2.5 Boundary layer stabilisation

3.1.2.5.1 active / passive control of boundary layer flow, transition delay

State of the art technology	*Reference Projects*
Research on compliant coatings to delay laminar-turbulent transition on a ship hull / fundamental research, project to start in 2014.	FLIPPER (MARTEC project)

3.1.3 Added resistance in Seaways

A natural seaway exhibits additional pressure forces on a ship hull during sailing compared with a standard testing or trial condition in calm water. This part of the resistance is usually referred to as "additional resistance" in waves.

General considerations, naval architecture good practice

3.1.3.1 Model testing

State of the art technology	*Reference Projects*
industry good practice	Used in different projects

3.1.3.2 Seakeeping codes

Parallel to calm water prediction methods described in 2.1.1.3 Naval architects have started to devise computational methods for the prediction of seakeeping behaviour already very early in the 20th century. Besides motion behaviour, the added resistance of a ship in a natural seaway has been one of the objectives of these developments.

3.1.3.2.1 Methods based on (non-linear) strip theory

State of the art technology	*Reference Projects*
Fast methods with limitations, predictions in frequency domain	SHOPERA PerSEE (D)

3.1.3.2.2 3-d panel codes

State of the art technology	*Reference Projects*
Fast methods with limitations, predictions in frequency domain	SHOPERA NEWDRIFT (NTUA-SDL)
Time domain simulation by hybrid method	SHOPERA HYBRID (NTUA-SDL)

3.1.3.2.3 Nonlinear unsteady 3-d panel codes

State of the art technology	***Reference Projects***
Accuracy and computational effort between 3-d frequency domain panel codes and RANS codes.	http://publications.lib.chalmers.se/publication/180980-fully-nonlinear-unsteady-three-dimensional-boundary-element-method-for-ship-motions-in-waves

3.1.3.2.4 RANS codes

State of the art technology	***Reference Projects***
Typically time-domain simulations, expensive, often no spectrum possible.	SHOPERA, PerSEE, TUG Design (D)

3.1.3.3 Form optimisation for resistance in seaways

State of the art technology	***Reference Projects***
research / development stage, little known projects	VRSHIPS-ROPAX2000 (NTUA-SDL)

3.1.3.4 Additional resistance from yawing in a seaway

State of the art technology	***Reference Projects***
Difference with a purely seakeeping approach is that the yaw motion is affected by the steering and that one depends on the control law.	SHOPERA
A mathematical model for ship manoeuvring in waves must be used and the steering strategy optimisation must be considered.	

3.1.3.5 Manoeuvring effects

Ship manoeuvring typically increases resistance, not only in a seaway but already in calm water conditions. Manoeuvring devices (rudder, thrusters) present additional resistance and any yaw angle will add induced drag.

State of the art technology	***Reference Projects***
Drag forces of a manoeuvring ship have been addressed already in the VIRTUE project and first estimates of the effects of bow (and stern) thrusters on ship resistance have been made in the TARGETS project. It is expected that SHOPERA will provide more details on the resistance of a manoeuvring ship and its devices.	VIRTUE TARGETS SHOPERA

3.1.4 Wind resistance

Aerodynamic forces acting on a ship superstructure are often neglected, despite the fact that they can assume up to 7 – 8 % of the total resistance in adverse conditions.

Technologies to predict and improve aerodynamic resistance

3.1.4.1.1 Model tests

State of the art technology	***Reference Projects***
State of the art technology typically performed using (smaller) scale models in a boundary layer wind tunnel.	
Reduction of air resistance of ships "The following steps are included in the project: • Wind Tunnel test of existing design • Superstructure optimization (eg. Crane, forecastle, accommodation rounded shapes, elimination of recirculation zones etc.) • The future bulk carrier where all traditions are reconsidered."	GREENSHIP project (DK) http://www.greenship.org/projekter/propulsion/24891.html

3.1.4.1.2 Statistical methods

State of the art technology	***Reference Projects***
usually based on systematic model tests, e.g. Blendermann, use of characteristic coefficients to be adapted to actual geometry	Blendermann, (pub.). Hamburg, 2013
Improvements required for fast capturing of relevant geometrical features and grid generation.	

3.1.4.1.3 Computational methods

State of the art technology	***Reference Projects***
Typically RANS based relatively expensive due to high modelling effort.	TARGETS

3.1.4.1.4 Reducing aerodynamic resistance

State of the art technology	***Reference Projects***
Aerodynamic appliances, e.g. spoilers, fairings etc. have not been popular for a long time due to higher production costs. Some attempts have been seen in	./.

the 1990ies but not on a wider basis.	
The use of spoilers has been investigated in the TARGETS project theoretically. This indicates some potential for improvements, however no further practical application followed so far. The Danish Green Ship Project investigated the use of aerodynamic appliances also in wind tunnel tests.	TARGETS http://www.greenship.org

3.2 Propulsion

As expressed in chapter 2.1, Ship Propulsion is by far the largest consumer of energy on board a cargo vessel since the introduction of steam engines in the 19th century. Today, by far the largest portion of seagoing ships uses screw propellers for propulsion. They have an inherent limited efficiency which however is still superior to most other mechanical propulsion concepts developed so far.

3.2.1 Screw Propellers

A propeller as a work machine is a device that transmits power by converting rotational motion into thrust. A pressure difference is produced between the forward and rear surfaces of the wing shaped blade, and water is accelerated behind the blade. Propeller dynamics can be modelled by both Bernoulli's principle and Newton's third law. A marine propeller is often referred to as a screw propeller.

3.2.1.1 Design and Prediction methods

A variety of prediction and analysis methods has been developed over time.

3.2.1.1.1 Propeller Series

State of the art technology	***Reference Projects***
Classic propeller series e.g. B-Series, … traditional, naval architecture good practice	Various projects TARGETS
Advanced propeller series updated Meridian Series, standard systematic series, new CFD generated propeller series.	TARGETS

3.2.1.1.2 Propeller panel codes

State of the art technology	*Reference Projects*
often in-house developments, European model basins and others, The coupling of panel methods with RANS methods is now common practice.	VIRTUE, STREAMLINE

3.2.1.1.3 RANS methods

State of the art technology	*Reference Projects*
improved RANS predictions, quality and accuracy	VIRTUE, STREAMLINE, GRIP
functional developments: • sliding interfaces, moving grid, overlapping grid	STREAMLINE

3.2.1.2 Propeller applications and optimisations

3.2.1.2.1 Cavitation

State of the art technology	*Reference Projects*
Cavitation erosion: The detrimental effects of propeller erosion on performance are significant. First attempts to model the effect have been made in the EROCAV project.	EROCAV,
General effects of cavitation: After several decades of basic cavitation research the national (D) KONKAV project summarises the past developments and adds new concepts to cavitation modelling, experimental testing and in particular also to erosion modelling.	KONKAV (I - III)

3.2.1.2.2 Kappel Propellers

State of the art technology	*Reference Projects*
The Kappel Propeller is a special design using winglets. The unique feature of the KAPPEL propeller is that the theory of non-planar wings and winglets has been transformed to marine propellers and applied to a propeller concept where the propeller blade and "winglet" are designed as one integral curved blade to reduce the energy losses inevitably present at the ends or tips of airfoil devices.	KAPRICCIO

3.2.1.2.3 Large area propeller (behind ship)

State of the art technology	*Reference Projects*
RR development: Moving propeller outside conventional constraints behind transom.	STREAMLINE
Potential savings 13.5 at design speed, 17% at full power for a reference ship (8000 DWT Tanker) A realistic alternative for many ship types where the LOA is not restricted and propeller and rudder extending below the base line can be accepted. The wave profile and propeller submersion must be investigated for a number of off-design conditions (risk of ventilation)	

3.2.1.3 POD propulsion

State of the art technology	*Reference Projects*
Fast Ship Applications of Podded Drives	FASTPOD
Optimal Design and Implementation of Azimything Pods for a Safe and Efficient Propulsion Ships	OPTIPOD
Safety and Reliability of Podded Propulsors under Service Conditions	PODs
TRIple Energy Saving by Use of CRP, CLT and PODded Propulsion	TRIPOD

3.2.1.4 Propulsion Improvement Devices

Propulsion Improvement Devices (PID) are often also referred to as "Energy saving devices (ESD)".

3.2.1.4.1 Pre-Swirl devices

State of the art technology	***Reference Projects***
pre-swirl fins • The Pre-Swirl fins is a set of fins installed right before the propeller with the intension of introducing certain pre-swirl for the propeller. The pre-swirl fins are normally fitted to a ship with high block coefficient either for new-building or retrofitting project. Generally it is expected that a power gain of 5% on average with a 2% uncertainty range can be achieved by such an energy saving device. The full scale in GRIP project has proven the power gain of the pre-swirl fins (with three fins on port side) has reached up to 7% in this specific case. • The largely accepted working principle of the pre-swirl fins is to modify the tangential propeller inflow to improve the asymmetric tangential wake due to ship, which makes the propeller working more homogeneously and heavier loaded on port side. That is why the most pre-swirl fins are installed on port side of the ship. By installing pre-swirl fins, the rotational energy losses of the propeller slipstream can be reduced. The side effect of it is that the required rotational rate of the propeller will be reduced by ca. 5%, this should be considered before installation of the pre-swirl fins. • The hydrodynamic design of the pre-swirl fins is still a challenging task and needs individual adaptation for each ship. One of the first attempts to design pre-swirl fins by CFD method in full scale has been realized for a bulk carrier and proven to be successful and confirmed by the full scale trials in GRIP project. There are many deign parameters involved in designing such a device, such as hydrofoil section, chord, span, camber and the angular positions of the fins etc. Current design works are still very much dependent on the experience of the engineers. Often there is no time left for the engineer to do parameter studies involving more parameters, which may influence/improve the performance of the device. More automatic design optimisation process is needed here to allow CFD engineer to find the global optimum of geometry of the pre-swirl fins. The automatic design optimisation process will involve different tools in the design loop: the parametric modeller, the grid generation tool, the RANS-BEM coupling tool for propulsion computation and the newly developed adjoint RANS solver to give the direction of the geometry changes. Such a design process exists today, but not yet fully automatic and mature for industry applications.	GRIP, STREAMLINE, TARGETS,

• The design scenarios of the pre-swirl fins can be defined differently from case to case. Normally, engine and propeller have been carefully matched during the initial design of the ship. It is likely that the safety specifications and engine restrictions has prevented the propeller designer to obtain a higher propeller efficiency. When a ship is equipped with pre-swirl fins, these engine restrictions must still be met if we want to make a fair comparison with the original design. Due to the influence of the pre-swirl fins on the propeller demand curve, without a modification on propeller or engine, the delivered power might be limited by the torque limit of the engine. Therefore it is sometimes meaningful to change the propeller geometry or the engine settings when a ship is equipped with the pre-swirl fins. In principle, there are four design scenarios: Case1. When the propeller geometry remains unchanged, the resulting new engine loading must be accepted; Case 2. When the engine loading must be remained, small modification on propeller geometry will at least be needed to match the engine; Case 3. When the engine loading must be remained and the propeller can be replaced, a new and better propeller geometry can be derived; Case 4. When both propeller geometry and engine loading can be changed, a completely new optimised design of Propeller-PSS-Engine can be obtained. • The propeller cavitation phenomenon seems to be not affected much by installation of the pre-swirl fins if they are properly designed. One other positive effect observed both in the CFD and in full scale trial is that the hub vertex coming from the propeller can be diminished by the pre-swirl fins due to modifying the propeller inflow in lower radius region. This indicates that a combination of the pre-swirl fins with boss cup fins or other post-swirl devices seems to be not meaningful. • The effect of the pre-swirl fins on the manoeuvring behaviour of the ship is yet unknown and needs to be investigated in the future. Also the hydrodynamic loads in heavy seaway conditions seem to be critical for the structural design of such a device. So far, no Class Society has issued a rule on the structural design of such devices.	
vortex generators Numerical tests have been performed in the STREAMLINE project. These indicated less satisfactory improvements compared with other “pre swirl” inducing devices.	STREAMLINE

3.2.1.4.2 Pre-ducts

State of the art technology	***Reference Projects***
Schneekluth ducts The Schneekluth duct is a commercial product developed already several decades ago. It is widely applied, especially for blunt ships e.g. bulk carriers and tankers. Today there is no novel research on improvements, the GRIP project included the Schneekluth nozzle in the list of energy saving devices which can be accessed through the GRIP Early Assessment Tool.	http://www.schneekluth.com GRIP
Mewis duct Although newer than the Schneekluth duct, the Mewis duct is another commercial product which is widely established in maritime industry. Similarly this device has been included in GRIP Early Assessment Tool.	www.becker-marine-systems.com/03_products/products_mewis.html GRIP

3.2.1.4.3 Post devices

State of the art technology	***Reference Projects***
boss cap fins • The propeller boss cap fins consist of small fixed fins attached to the propeller hub. These fins can reduce or eliminate the propeller hub vortex, hence improving the overall propulsion efficiency. • Fuel saving ratios of the boss cap fins are about 2.7% on average with a 2.2% standard deviation. This result comes from the literature review performed in GRIP project. Therefore the uncertainty on this device seems to be relatively high. • There are no specific Class Rules for boss cup fins, so that only their connection to the propeller boss needs to be approved by Class. Boss cup fins are usually bolted directly on the propeller boss. • The boss cup fins can be installed on a new building or retrofitted, possibly afloat. The clearance with the rudder should be sufficient, keeping in mind that a rudder too close to the boss cup fins might also reduce the efficiency of the device. • There are no apparent limitations to the type of ship / propeller on which the boss cup fins can be installed, even CP propellers can be fitted with boss cup fins. RPM is only slightly changed, even if the propeller torque can be slightly reduced. The influence of the boss cup fins on the neighbourhood of hull fittings has been qualitatively evaluated in GRIP	GRIP

project and considered to be small. But so far, no quantitative evaluation has been done on this topic. • In GRIP, RANS open water analysis has been performed for the combination of propeller and boss cup fins. By comparison between model test and CFD results, it seems that the efficiency gain of about 1-2% at different propeller loading in model tests cannot be found by the CFD analysis, which predicts about 0-0.5%, far lower than the model test results. In general, the gains of the boss cup fins are of such a magnitude that it is difficult for both experiments and CFD to accurately resolve them. Also the trend indicated by model test and CFD is different: efficiency gain of the boss cap fins in model test seems to be independent on the advance number J; whereas the CFD indicate a higher gain in low J values, where the propeller is heavier loaded. This situation also applies when the propeller is placed behind a ship. Therefore, larger gains of the boss cup fins may be expected for such a condition. But to confirm this, more research work in this area needs to be done.	
Rudder fins • Rudder fins are a number of relatively small fins fitted on the sides of the rudder (more near the leading edge of the rudder), either horizontally or with certain angular angle positions. • The figures about the saving potential of the rudder fins are rather diverse, from 0% to 5%. • The large variation in energy saving potential indicates that the hydrodynamic design of rudder fins is a rather challenging task. The working principles of rudder fins are not completely understood yet. There are basically two objectives: one is to recover part of the rotational energy losses of the propeller slipstream in addition to the rudder; the other is to generate thrust on the fins, which reduces the need for propeller thrust to achieve a desired speed. To combine these two objectives is not an easy task. Several attempts have been tried in GRIP project; however none of them was successful so far. Further research in this area is therefore needed. • Rudder fins are not compatible with other measures reducing the rotational losses: PSS, Mewis Duct, Contra Rotating Propeller. However, it is meaningful to combine the rudder fins with the rudder bulb. • The hydrodynamic loads and the bending moment on the rudder fins can be very high due to its position in propeller slipstream. Therefore the a combination of rudder fins with rudder bulb is also beneficial from the structural point of view.	GRIP

Rudder bulb • The "original" rudder transition bulb is the "Costa" bulb. The "Costa" bulb is a bulb attached to the rudder directly behind the propeller boss. The bulb reduces the hub vortex losses. Often the bulb is integrated into a rudder and sometimes also connected to the propeller boss with a very small gap. The properly designed rudder bulb can reduce the power needs by about 3% with a 0.3% standard deviation. This indicates that this device is working rather stable. In addition this device can be relatively easy designed and constructed in the shipyard, rudder bulbs are therefore widely accepted in the industry. • The saving potential of a rudder bulb depends on the existing propeller and rudder: extent of the hub vortex and effect of the hub vortex on the rudder. During the GRIP project, an idea appeared that an asymmetric rudder bulb might have higher potential in recovering the hub vertex losses due to the asymmetric nature of the single-screw propulsion system. At right-handed propeller for example, it is often seem that the hub vertex appears more dominant to the port side of the ship due to the asymmetric loading of the propeller. This concept has been initially proven by CFD analysis using the adjoint solver technology in GRIP project, however more investigations involving more parameters need to be done in the future.	GRIP

3.2.1.5 Contra-Rotating Devices

State of the art technology	***Reference Projects***
contra rotating propellers: state of the art technology, industrial application (where feasible)	. / .
Tandem Propellers Acknowledged concept, used in practical / industrial cases.	EPROSYS-HF
Grim / Vane wheel Fundamental research performed in Germany in the 1970ies and -80ies. Significant performance gains were achieved; however material and durability problems at the time hampered further market success. No on-going Research.	. / .

3.2.2 Materials

State of the art technology	*Reference Projects*
Conventional bronze propellers (no material research)	. / .
Composite propellers Composite propellers have been developed since the 1990ies, Voith Turbo AIR produces composite propellers, very few are actually in operation.	. / .

3.2.3 Waterjets

State of the art technology	*Reference Projects*
Streamline objective: increase efficiency at low speed with auxiliary channel. Problem efficiency loss at high speed.	STREAMLINE

3.2.4 Alternative hydro propulsion systems

Although the vast majority of ships is propelled using either conventional screw propellers or waterjets (for fast vessels) a number of rather different technical concepts exist and are either applied on special vessels or are being researched at present.

3.2.4.1 Magnetically geared propulsion motor

State of the art technology	*Reference Projects*
Magnetically geared motor (MGM) direct drive systems (DDS) have shown significant potential as an alternative drive solution which offers a combination of the benefits of regular direct drive machines and traditional high speed, mechanically geared machines.	Mainly U.S. military project.

3.2.4.2 Voith Schneider Propellers

State of the art technology	***Reference Projects***
The Voith Schneider propeller (VSP), also known as a cycloidal drive is a specialized marine propulsion system (MPS). It is highly manoeuvrable, being able to change the direction of its thrust almost instantaneously. It is widely used on tugs and ferries. The fully commercial product is marketed by Voith Marine Technology. There is little research on the VSP as such; R&D focus is on application and the use on-board different ship types (offshore supply vessels).	Tug-Design (D)

3.2.4.3 Paddle Wheels

State of the art technology	***Reference Projects***
The first successful mechanical propulsion concept (Fulton's Clermont), Today only niche applications exist for paddle wheels, no research.	. / .

3.2.4.4 Walvisstart

State of the art technology	***Reference Projects***
rotating horizontal blades, to be applied to inland vessels mainly.	STREAMLINE

3.2.5 Aerodynamic propulsion

For more than three thousand years sail propulsion has been the dominant technology for seaborne transportation worldwide. Apart from few exceptions such as human powered rowing boats / vessels and small river vessels towed by animals, sails provided the main propulsive power on the oceans until the middle of the 19th century when first steam engine and later turbines and combustion engines took over. These offered higher reliability and sailing to a schedule, however at a cost: coal and later oil soon became an important factor determining the efficiency of a ship and hence overall transport cost. However, compared with today's levels, fuel cost remained very reasonable for a period of more than 100 years. Things started to change in the early 1970ies when the world saw the first oil crisis. And although advanced sail propulsion concepts such as the Dyna rig ship were developed already (see below) a major renaissance of the freight carrying sailing ship was not possible at the time. A pure (oil) price driven development apparently was not sufficient to stimulate the interest in alternative, sail driven propulsion for ships. It is only now that additional environmental considerations make shipping operators think about alternative propulsion as a means of saving energy and reducing emissions, more or less with a side effect of saving cost too.

In the past, the advantages of engine driven ships, reliability and fixed schedules, were apparently valued much higher than increased operating cost due to high fuel prices.

Bearing these facts in mind it is evident that under present constraints a pure sailing vessel relying exclusively on wind power for propulsion is not very likely to become a commercial success. If so, it must become part of a more sophisticated and flexible transport/logistics chain that is able to adapt, to reschedule and to provide optimal sailing routes through on-line weather data transmission and much improved routing. Given today's environmental developments and (expected future) ruling the issue of seaborne transportation will be mainly reliability and scheduling of a passage and less so sheer speed.

3.2.5.1 Prediction methods

3.2.5.1.1 Wind tunnel tests

State of the art technology	***Reference Projects***
Wind tunnel testing forms the present state-of-the-art for the assessment of the performance of sails and other wind propulsion devices. The technology is fairly accomplished and applied in all relevant cases. No research on wind tunnel testing technology.	

3.2.5.1.2 Numerical predictions

State of the art technology	***Reference Projects***
Numerical predictions of sails are typically performed using RANS methods. Significant progress has been made in computations in the context of high profile sailing events such as the America's Cup receiving substantial private funding from competitors.	Different AC-campaigns
Initial numerical investigations of sails for cargo vessels have been performed in the TARGETS project. These indicate a very high complexity of the simulations which make them extremely costly for commercial applications. Exploration of wind propulsion for ultra slow speed vessels in ULYSSEES project.	TARGETS ULYSSEES

3.2.5.1.3 VPP

State of the art technology	Reference Projects
Velocity Prediction Programs (VPP) are used to determine the theoretical performance of a sailing vessel in various wind conditions by balancing hull and sail forces. Originating from yacht racing, VPPs are typically used by designers, boat builders, model testers, sailors and sailmakers, to predict the performance of a sailboat before it has been built. The concept is applicable also to larger commercial vessels and is likely to be applied for commercial sailing vessels in the future.	. / .

3.2.5.2 Fixed wing / profile

3.2.5.2.1 Dyna Rig

State of the art technology	Reference Projects
Fixed profile rig, developed in Germany by Hamburg based engineer Wilhelm Pröls in the 1960s, who suggested a largely simplified rig that uses an elliptical profile for the mast and fixed profile sails which can be trimmed automatically. The entire rig is self-supporting, no stays and shrouds are necessary. Initial concept designs presented 1967 concentrated on a bulk carrier of 17000 ts dwt, a vessel type for which only moderate speeds were required. At IfS / University of Hamburg, a comprehensive wind tunnel study was performed for this vessel and, with a further optimised sail plan, superior performance data were found. [18] In the follow-up period several attempts were made to build prototypes, 1st actual ship: Maltese Falcon (yacht) in 2006	Hamburg wind tunnel tests
concept study in:	TARGETS
The UK project B9 investigates the use of fixed profile Dyna rigs for specialised cargo transport in a commercial context. No demonstrator could be built yet.	B9Shipping

3.2.5.2.2 JAMDA rig

State of the art technology	Reference Projects
The JAMDA type wing sail was developed during the 1970s oil crisis by the Japan Machinery Development Association (JAMDA) and Nippon Kokan (N.K.K). It consists of two elements which can be folded about vertical axes	TARGETS

for stowing. The entire rig can again be rotated about a vertical axis for trimming. The JAMDA rig was installed on various vessels, the first being the experimental installation on Mini Daigo (83BRT), later on various commercially operated vessel, e.g.: • Shin Aitoku Maru (600BRT, 200m²), small tanker (series of 17 vessels) • Usuku pioneer (15721BRT, 640m²), bulk carrier • Aqua City (18597BRT), bulk carrier On all of these vessels two JAMDA sails were installed, a reduction of fuel oil consumption of 10 to 30% was reported.	

3.2.5.3 Sails

Conventional sails made from cloth or fabrics are a cheaper but often lesser performing alternative to modern fixed profile wing sails.

3.2.5.3.1 IndoSail

State of the art technology	***Reference Projects***
The IndoSail rig was developed at HSVA by Peter Schenzle during the 1980s within the scope of a development aid project for Indonesia. The vessels developed during this project were intended for short distance coastal traffic in light monsoon wind conditions. Extensive wind tunnel and free sailing tests took place. In the first three phases of the joint Indonesian - German R+D - Project INDOSAIL for the development of cargo sailing vessels for the Indonesian inter-island trade preliminary studies and the design of a prototype vessel have been carried out. 1. An evaluation of the boundary conditions revealed: The weather in the Indonesian waters is governed by light but steady monsoon winds. The rapidly expanding inter-island transport is a typical coastal trade with short sea turns and a relatively high percentage of port time. 2. The selection of technical alternatives for the rigs of a modular series of 3-, 4- and 5-masted coastal sailing vessels between 900 and 2000 t DWT led to the concept of a mechanized roller-reefing gaff-rig with integrated loading gear, which was successfully tested on large free-sailing models. 3. A half size Test-rig has been installed on a 20 m vessel and the design of a 50 m, 900 t DWT Prototype-hull has been completed. The design of the 3-masted, 1100 m2 Prototype-rig can be finished as soon as the current structural and handling trials with the Test-rig have been completed. In the fourth phase of production the working drawings for the Prototype were prepared on the shipyard in Surabaya.	IndoSail Project (D)

The TARGETS project has compared the (theoretical) performance of the IndoSail rig with other concepts such as the Dyna rig and Flettner Rotors.	TARGETS

3.2.5.4 Kites – Skysails

State of the art technology	***Reference Projects***
The German company Sky-Sails was the first one to develop kite solutions for auxiliary propulsion of general cargo vessels. Although the technology appears attractive at first sight – minimal space requirements, no interference with deck cargo or loading gear – the overall performance of the system remains questionable. First sea trials performed with operator Beluga on 2 different vessels yielded unconvincing results and the "inventor" of the technology has meanwhile moved into different areas.	Verbundprojekt: Klimaschutz: Windkraftantrieb für Frachtschiffe (BMBF – D) ULYSSES

3.2.5.5 Flettner Rotor

The physical effect of fast rotating bodies generating lift was discovered by Newton in 1672 and correctly described by Magnus in 1852. The German engineer Anton Flettner was the first to utilise the Magnus effect to propel a ship in 1924. Flettner's spinning bodies were vertical cylinders; the basic idea was to use the Magnus effect. The idea worked, but the propulsion force generated was less than the motor would have generated if it had been connected to a standard marine propeller. These types of propulsion cylinders are now commonly called Flettner rotors. Later two vessels, "Buckau" and "Barbara" were built to an improved concept using direct drives. For this arrangement a maximum velocity of 8.5kts was claimed at a fuel saving of 80% compared to using the auxiliary engine.

The Flettner Rotor concept was not followed for a long period and only in 2007 the German wind turbine manufacturer Enercon started to develop a new ship for waterborne transport of their wind turbines. The 'E-Ship 1' evolved into a showcase design for energy efficiency technologies, sampling the most promising propulsion technologies combined with a fully optimised hullform developed from numerical and experimental analyses. As a prominent feature, the E-Ship 1 sports 4 Flettner Rotors mounted behind the forward superstructure and at the stern of the vessel.

State of the art technology	***Reference Projects***
The TARGETS and ULYSSES projects assessed the theoretical performance of the Flettner Rotor concept and put it in context with other wind propulsion solutions.	TARGETS ULYSSES

Enercon E-Ship The E-Ship 1 has been in use since 2010 (with an interruption in 2013), detailed analysis of the performance and fuel consumption data performed by the owners/operators indicates fuel savings of 25% compared with equivalent vessels of the same size.	Industrial project: ENERCON
Greenwave Commercial provider of Flettner rotor solutions	www.greenwave.org.uk
WindAgain Commercial provider of Flettner rotor solutions	www.windagain.com
Norsepower Oy A new provider of Flettner rotor technology, only one reference installation at the time of print.	www.norsepower.com

3.3 Prime Mover

Background

The European maritime and shipping industry is heavily concerned with the sustainability of current ship propulsion technologies, mainly due to the generally rising costs of marine fuels which heavily determines ship operational costs and also the introduction of environmental regulations intended to reduce greenhouse gas emissions from the shipping sector. To achieve effective improvements in energy efficiency, the ship has to be considered as an integrated system, considering different elements of naval, marine and control engineering alongside operation practices. This part of the report evaluates different state-of-the-art options and improvements that can be made for a ships primary source of propulsion, prime-movers in producing, converting and outputting energy efficiently. Many European projects, whether funded by the EU Commission or nationally have contributed significantly to the current state of technology and will continue to do so to drive us towards a brighter and cleaner future within the shipping industry.

State-of-the-art achieved today

State of technology	*Reference project*
Reciprocating internal combustion engines – Improving efficiency • Diesel propelled machinery is the principal and main technology used in marine propulsion today as their operation is simple, robust and economical. A large focus of most diesel engine research has been driven by the Maritime industry to improve its fuel efficiency and hence lower ships operational costs. • A large portion of the engine produced through expansion of hot gas in the combustion cylinders is used to overcome friction forces between piston and cylinder and also bearings or connecting rod. Today, engine mechanical efficiency can be improved by reducing these friction losses, by using new lubricating oil, state of the art lubrication system, low-friction component technology, improved cylinder coating and by understanding and optimising cylindrical tribology through computer modelling and simulations. • Improving engine thermal efficiency is also crucial to convert more heat from fuel combustion into useful energy output. The four main methods currently researched to accomplish this goal are: <u>Improve combustion process</u> (through innovative combustion chamber designs, handling of fuel, variable inlet valve timing to control charge air, fuel injection systems and computer-aided combustion optimisation); <u>improve turbocharging process</u> (through multistage and sequential turbocharging, variable geometry turbochargers, hybrid turbocharging with power take-in/out, improved component designs and intelligent control); <u>employ intelligent and adaptive engine control</u>;	HERCULES A, B, C Green Ship of the Future (GSF) MARINECFD TEFLES HELIOS CLEEN-FCEP ULYSSES BESST INOMANS2HIP REFRESH CLEANENGINE* JOULES ADEC* POSSEIDON

and <u>implementing waste heat recovery systems</u> (Combined cycle with Steam or Organic Rankine Cycle, or using Adsorption/Absorption chillers). • Engine overall efficiency looks at the entire prime-mover system from the initial input that does not necessarily have to be thermal, to the final output. This can be achieved through different engine arrangements, holistic control & operating strategies for whole ship operations and efficient mechanical-electrical energy conversion.	ENGINE EFFICIENCY* 2020 INTERFACE* EFFSHIP NOx-Reduction SCHE-dual ** = Non Marine Specific projects*
Reciprocating internal combustion engines – Reducing emissions • Another push in diesel engine research comes from environmental legislation like IMO, to reduce emissions (like NO_X, SO_X etc) and make shipping operations more environmental friendly. • To reduce emissions, various technologies and methods can be grouped into two: Primary methods are measures aimed at reducing the amount of NO_X formed during combustion by optimising engine combustion parameters, Secondary methods are on the other hand designed to remove NO_X from the exhaust gas by downstream cleaning techniques. • Primary methods include: improving combustion process, cylindrical lubrication system and turbocharging; employing Exhaust Gas Recirculation (EGR) and introducing water into the process (through inlet air humidification, direct water injection or water-fuel emulsion). • Secondary methods use any of the following: selective catalytic reduction (SCR), scrubbing methods (using open/closed loop, wet/dry scrubbers), non-thermal plasma (NTP) reactors, smoke/diesel particulate filters (DPF), on-board chemical CO_2 capture or pre-turbine oxidation catalysts. • Another way to reduce emissions is to use low-sulphur diesel fuels or to even replace diesel with an alternative fuel of different properties, like liquefied or compressed natural gas (LNG or CNG), bio-fuel/gas, methanol or glycerol fuel (Glycerine) • Intelligent engine operation helps reduce emissions through speed optimisation (slow speed/temporarily de-rating of engine), flexible and adaptive control according to load requirements, and reduction of 'in-port' scenario emissions (by using 'shore power', 'High voltage shore connection (HSVC)' and 'cold ironing' to allow the generators to be switched off).	HERCULES A, B, C Green Ship of the Future (GSF) BunGas Gas-Pax BIOCLEAN MARINECFD DEECON TEFLES HELIOS CLEEN-FCEP BESST METHAPU POSE2IDON REFRESH TEN-T Priority 21 CREATING PLUG CLEANENGINE JOULES NGSHIP NG^2SHIPI/F EFFSHIP GLEAMS SPIRETH MARITIME CCS NOx-Reduction NADiP PCEET (PBCT)

Fuel Cells • Fuel cells are efficient, combustion-less, virtually pollution-free power sources where electricity is formed from electrochemical processes. The maritime industry is currently only looking at three types of fuel cells for propulsion as others are deemed not viable due to different reasons. • Solid-Oxide Fuel Cells (SOFCs) use solid oxide electrolytes (such as zirconium oxide stabilised with yttrium oxide) for the conduction of O_2 ions across the electrodes. The ions will combine with hydrogen ions to form water and CO_2. The operating temperature for this technology is between 700 and 900°C and possible power ranges between 500W and 2MW. • Proton Exchange Membrane Fuel Cells (PEMFCs) use a water-based, proton conducting membrane that conducts hydrogen ions (protons) generated from the H_2 at anode to the cathode side to form water molecules with O_2. A platinum catalyst is used to split the hydrogen molecule. They operate at relatively low temperatures (below 100°C) and hence require pure hydrogen to avoid CO poisoning. The pure hydrogen required is supplied by bottles/tanks or is made locally using a fuel processor/reformer. The fuel processor is a series of chemical reactor and heat exchangers in which the primary fuel is converted in several steps to the suitable gas mixture. PEM fuel cells have power levels ranging from 100W up to 1MW. High temperature-PEMs (HTPEM) use a mineral acid-based membrane and are able to operate at higher temperatures (160 - 200°C). They are hence more tolerant from CO poisoning (1-3%). • Molten Carbone Fuel Cells (MCFCs) use high temperature compounds of salt carbonate as electrolyte to conduct CO_3^{-2} ions between the electrodes. Due to the corrosive nature of the molten salt used, reliability/endurance is limited. However, they can operate without fuel processing, at temperatures higher than 650°C and also at high power levels ranging from 100kW up to 3MW. • Energy Management & Control enables the control of the DC electricity produced by fuel cells for ships and is crucial for the functionality and application of this technology. That typically includes an energy management system, power electronic drives and protection systems.	FELICITAS FellowSHIP e4ships Sailboat Zero CO2 Zemships PURE METHAPU MC-WAP MARIPEM HYMAR JOULES
Hybrid/Full Electric Systems • Diesel-electric propulsion is increasingly popular as an indirect drive. New power electronic drive technology has widened the potential of electric propulsion. For example, power converters allow propulsion to	TEFLES CLEEN-FCEP

be flexibly driven in forward and reverse modes. • Energy storage could serve a number of purposes on different types of ships, including reducing load variation, improving transient performance, increase system efficiency through regeneration, reducing diesel wear, enabling system redundancy and allowing for 'zero emissions' mode of operation. The different state-of-the-art energy storage technologies today include battery systems, ultra-capacitor systems and Flywheel Energy Storage systems. • An energy management method is usually implemented to integrate systems like energy storage, renewable energy and diesel generators and implement smart control for efficient usage of produced or recovered energy. • Power electronics drives enable efficient conversion and smart control of electrical power flow into either electric motor which in turn produces the required torque, or ship electrical grids for ship applications or storing. Development in these technologies today include: new electric machines design, high temperature superconducting (HTS) cables and new converter topologies.	BESST BB-GREEN Sailboat Zero CO2 HYMAR Rensea INOMANS2HIP POSE2IDON TEN-T Priority 21 JOULES Vessel Efficiency Hybrid Ferries
Gas Turbines • Gas turbines for marine propulsion are mainly found in naval applications. It has high power density and is relatively easy to start and stop, giving the high operational flexibility needed by warships. Massive investments are made in aerospace and industrial gas turbine research and benefits are also being reaped in marine applications as we see an increasing range of gas turbines designed for the marine market. However, this is not seen to be as a very promising replacement of the diesel engines in the shipping industry mainly because of the running cost. Fuel for gas turbines is expensive compared to conventional marine fuel and are less thermally efficient for similar power diesel engines.	Many non-marine specific gas turbine research projects
Nuclear Propulsion • Nuclear ship propulsion has clear advantages in reducing pollution and emissions caused by the shipping industry. However, considerable difficulty and cost can be expected from a number of aspects such as design execution and planning, operation, crew and shore staff training, regulation, security, public perception, disposal and etc.	Many non-marine specific nuclear research projects
Renewable Energy Propulsion • Wind propulsion: Several alternatives are available to use wind energy for ship propulsion, using textile sails, non-textile sails and Flettner	WINTECC

rotors. (see section 2.2.5) • Textile sails are like kites (SkySails) or DynaRig. SkySails are made of a large foil kite controlled by a computer. DynaRigs are made with carbon fibre masts supporting several sails each and when they are not needed for propulsion, each sail retracts back into its boom. • Non-textile sails include suction sails (Turbosail), flap sails, and fixed sails (Effsail). The Turbosail idea uses a fixed cylinder that looked like a smokestack and functioned like an airplane wing with a movable shutter and system of fan-drawn aspiration. Fans moved by engines are placed at the top of the Turbosail to accelerate flow around wingmasts and increase life to produce driving force forward. • Flettner rotors use the Magnus effect for propulsion. The spinning bodies of the cylinders are vertical. The Magnus effect is force acting on a spinning body in a moving airstream that acts perpendicularly to the direction of the airstream. • Wave propulsion: Wave energy can be harnessed by converting the movements of the floats in the waves into hydraulic pressure and then into electric power. This was the concept used for Pelamis, a stationary wave power converter. "Eco-Trimaran" uses the same principle except its floats lie side by side and not in a row. There is however no real practical solution seen for this concept for ships for now. • Solar propulsion: Solar energy can be harnessed and converted into electricity that can be used to propel a ship. It is a widely researched topic and the technology is already implemented in many different industries. However, for conventional ships, amount of solar energy possible to produce is less than a few percent of the energy needed for propulsion.	E-Ship 1 EFFSHIP Vessel Efficiency ULYSSES Many non-marine specific solar energy research projects

3.4 Auxiliary Energy

The following part focuses on the possible technologies for the delivery of auxiliary energy on-board, using alternative sources of energy (i.e. non-fossil) and in particular from renewable sources. Auxiliary energy refers to energy that is not used for main propulsion. The main forms of auxiliary energy needed on-board are electrical and thermal energy. A motivation to use renewable energy for this purpose starts to grow today because of a general environmental concern, the development of environmental regulations (international, national and local, e.g. in ports) and the increase in fuel price. Additionally, the relatively reduced amount of required auxiliary energy, compared to that required by ship propulsion for instance, makes alternative sources of energy possible candidates.

However, it should be noted that the use on-board of multiple and intermittent energy sources will require a suitable power management system.

3.4.1 Solar energy

3.4.1.1 Electricity production

State of the art technology	***Reference Projects***
• As explained in the 2nd IMO GHG study, current photovoltaic cells have an efficiency of around 15%, where best cells can achieve around 20 to 30%. This gives average power, accounting for reflection, of 30 to 70 W/m². For large ships, this means that only a fraction of auxiliary power can be delivered by PV cells. • Energy production from PV cells is intermittent because of variations of solar irradiance with latitude, season, weather conditions and time of the day, and also because of ship motions and course changes. In addition, the influence of sea environment on the PV cells (e.g. fouling of cells surface) must be accounted for. • Flexible PV cells today exist, which allow an easier integration, hence over larger surfaces, of PV cells on curved surfaces. • Some small electric or hybrid ferries already using PV cells are in operation today.	• EU BESST / WP12 • PlanetSolar • French project "navire démonstrateur Océan Vital" • GREEN FLAGSHIP Wallenius Wilhelmsen • Eco Marine Power

Figure 1 Solar Albatross (Hong Kong)

3.4.1.2 Heat production

State of the art technology	*Reference Projects*
• Although free thermal power can generally be recovered on-board (e.g. through engines cooling network and/or exhaust gas), solar economizers could be a complementary way to pre-heat water, either for hot sanitary water or for fresh water production.	No reference found

3.4.2 Wind energy

State of the art technology	*Reference Projects*
• Small wind turbines have been used on sailing ships for many years to provide electrical energy. However, the application of wind turbine on larger, commercial ships is new and scarce. • Actually, the installation of wind turbines on the Stena Jutlandica is the only example found during the literature review. Two 7m tall vertical axis wind turbines are installed on the deck of this ferry. According to Stena, they are expected to produce 23 000 kWh per year. Among other things, the produced electricity will power the lighting on the car deck. In addition, Stena claims a reduction of the ship aerodynamic resistance resulting to a reduction of fuel consumption at sea in the order of 80-90 tons per year. • The feasibility of installing wind turbines on a bulk carrier seems to be investigated by a consortium composed of Lloyd's Register Totempower Energy Systems and Zodiac maritime Agencies, with a wind monitoring campaign already performed on the ship.	• No EU project found • Stena Jutlandica • Technico-economical feasibility study performed by Lloyd's Register, Totempower Energy Systems and Zodiac maritime Agencies of installing wind turbines on the Cape Flamingo bulk carrier

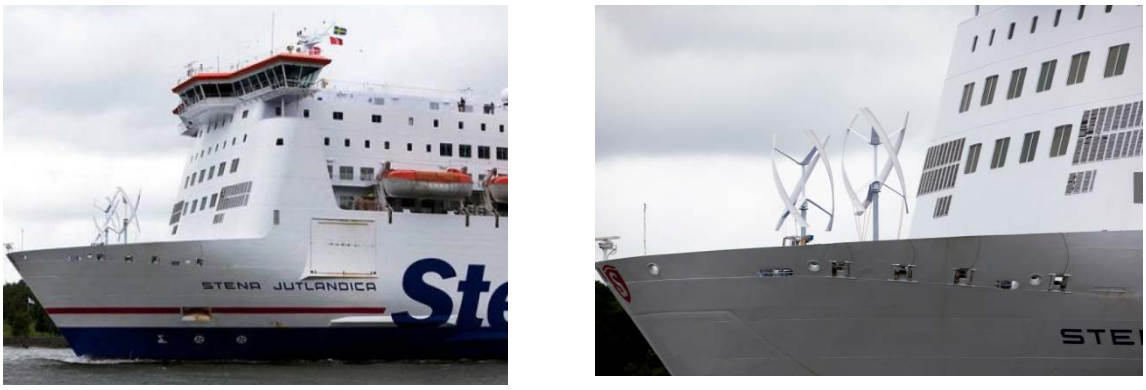


Figure 2 – Wind turbine on Stena Jutlandica passenger ferry.

3.4.3 Energy from seaway

3.4.3.1 Electrical generation from water flow

State of the art technology	***Reference Projects***
• Hydrogenerators are used today on sailing ships to convert mechanical work, provided by a flow of water, into electricity. The flow of water is generated by the ship forward speed, so it is globally a transformation from wind energy to electricity. • The use of such systems on-board commercial ships does not seem to be relevant if conventional propulsion is used (it would be more efficient to produce electricity directly from the main engine). However a few studies have been found of using hydrogenerator, or tunnel turbine, on-board ships with wind aided propulsion.	• No EU project found • Some papers found in the literature

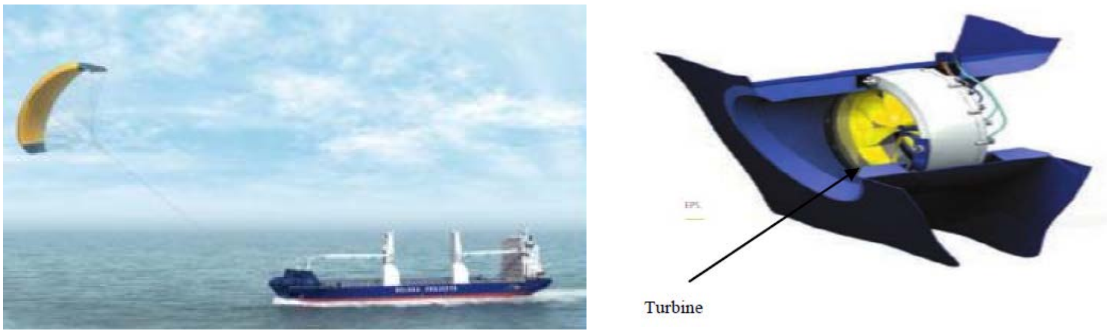


Figure 3 – A study on green ship concept using renewable energy onboard ships with kites and tunnel pipes / turbines, A.S Perumal, AIJRSTEM 13-111 2013.

3.4.3.2 Electrical generation from ship motions

State of the art technology	***Reference Projects***
• Researches on the way to recover kinetic energy of the ship moving on waves have been found in the literature. Two main recovery principles are investigated from gyroscopic effect and from oscillators excited by ship motions. All the references found concern theoretical, numerical or model scale investigations. • It should be noted that since energy is extracted from ship motions, the latter will be influenced by the system, with probably reduced amplitudes since lower kinetic energy. However, if such "damping" effect can be beneficial from comfort or cargo point of view, its influence on ship resistance and propulsion in waves is not obvious and should be investigated to assess the global ship energy balance.	• EU SEAKERS • Whatever Input to Torsion Transfer (WITT) device, A&P Group, Plymouth Marine laboratory & University of Exeter • Energy Harvesting utilising the gyroscopic effect study of the University of Southampton

3.4.3.3 Electrical generation from relative ship motions

State of the art technology	*Reference Projects*
• The objective here is to recover energy from the relative motion between the ship and water. • A first category of devices found in the literature are movable fins or foils. The work of the loads exerted on fins mounted on ship hull when the ship moves on waves is converted into electricity. Sometimes, these devices can be used alternately as propulsion devices or energy recovery devices. All references to such devices found in the literature are for research studies or concept studies. No information concerning the amount of energy that can be recovered has been found. • A second category of system concerns the use of articulated parts of the ship which are moving separately on waves. The energy is recovered from the work of the internal forces between the moveable parts. Here again, only small scale demonstrators or concept ideas/studies have been found in the literature. • Similarly to the energy recovery from ship motions, energy recovery from relative ship motions will influence the ship motions on waves and this influence should be investigated.	• No EU project found • GREEN FLAGSHIP Wallenius Wilhelmsen

Figure 4 – Energy recovery from fins; GREEN FLAGSHIP Wallenius Wilhelmsen.

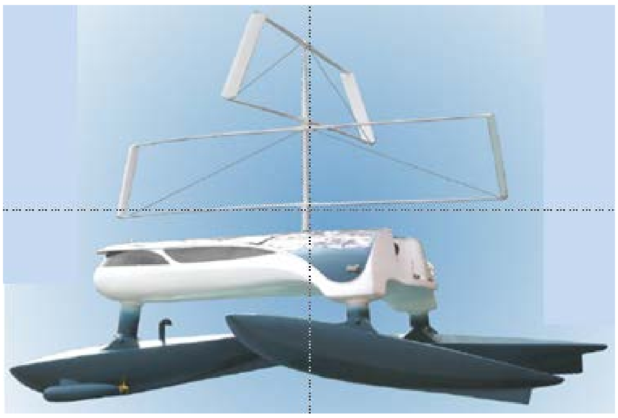


Figure 5 – Eco-trimaran; J. Sommer.

3.4.4 Energy from waste

State of the art technology	*Reference Projects*
• Passenger ships produce a large amount of waste every day. Similarly to what is already experimented on land, the possibility to produce, onboard, synthetic gas from waste has been investigated. • The main physical principles used are pyrolysis followed by gasification or wet oxidation. • Heat can be directly recovered from the process. In addition, the synthetic gas can be burnt in an auxiliary engine to produce electricity. • The main encountered difficulties are firstly technological, for the control of the lower heat value of the waste to be processed, and the quality of the gas that is produced (tar, LHV). Safety issues are also of concern since various hazardous gases are produced in the process (CO, NOx, H_2, CH_4…)	• No EU project found • French project IWEST • French project "navire démonstrateur Océan Vital" • Technologies used on land • HMS OCEAN Technology

•	Development Programme

Figure 6 – HMS Ocean Technology Development Programme
– Small Scale Pyrolysis Unit from QinetiQ

3.4.5 Energy storage

The alternative energy sources considered above, as (complement to) auxiliary energy, are intermittent and it is difficult to adapt the energy production to the demand. Consequently, an energy storage system is necessary for peak shaving, for improving the dynamic response when needed, and also to avoid wasting energy in case the production would exceed the demand.

Most of the technologies identified in the previous paragraphs deliver electrical energy that can be stored on-board in various ways.

State of the art technology	***Reference Projects***
• **Batteries and super-capacitors:** • Many different types of batteries exist today, from mature and well know technologies, such as Lead Acid, Nickel-Cadmium, Nickel-metal-hydride, to more modern, and also more promising in terms of power and energy densities, technologies such as the Lithium-ion family. The latter however needs protection circuit for safety. • A super-capacitor is a capacitor with very high capacitance. A capacitor stores energy by means of a static charge as opposed to an electrochemical reaction. The modern super capacitor crosses the boundary with battery technology by using special electrodes and electrolyte.	• EU JOULES • EU POSE²IDON • EU BESST (WP13) • French passenger ship 'Ar Vag Tredan'

• **Flywheel Energy Storage (FES):** • Flywheels have the ability to store kinetic energy in a regenerative way. They are capable to withstand high and frequent load and unload torques enabling high charge and discharge powers and long life time, respectively cycle life. In addition to the wheel itself, that stores energy, the flywheel contains a power transmission (mechanical / hydrostatic / electrical / power split) for charging and discharging the wheel, a controller for safe and smart energy management and auxiliaries for good system functioning (e.g. bearing, cooling system,…). Flywheel technology is already applied in many domains, although few standards exist. Current flywheels use steel wheels. The next generation will use larger speed flywheels and also high speed carbon wheels for which reliability and safety will be important issues to address.	• EU JOULES • BESST(WP13)

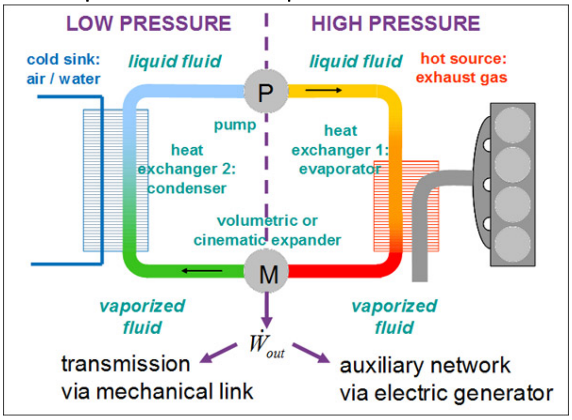
• **Hydrogen:**
• Hydrogen is an energy carrier. It can be produced from renewable energy on-land (marine renewables, wind turbines) or on-board and stored on-board and then used in fuel cells or in generators to produce electricity. The storage and use of hydrogen on-board lead mainly to safety and regulatory issues. Hydrogen can be stored in different ways:
  • Compressed gas, with pressure up to 700 bars,
  • Liquid cryogenic gas
  • Metal hydride
  • Sodium borohydride
• Safety issues are mainly related to gas dispersion, ignition and explosion, due to equipment failure or external effect (e.g. fire, collision).
• Risk control measures involve appropriate tank location, pressure release valves, ventilation, leak detection, system monitoring, emergency venting and shutdown.
	• *Note: projects related to fuel cells are considered in the Prime Mover section*
	• EU BESST (WP13)
	• Fuel cells and Hydrogen Joint Undertaking
	• 'Zemship' passenger ship (Hamburg)
	• Amsterdam fuel cell boat
	• GREEN FLAGSHIP Wallenius Wilhelmsen

3.5 Other on-board consumers

3.5.1 Ship services

3.5.1.1 Waste Heat Recovery (WHR)

<table>
<tr><th>State of the art technology</th><th>Reference Projects</th></tr>
<tr><td>

• **WHR from exhaust gas**
=> Based on Organic Rankin Cycle: To generate electricity
The process to capture the waste heat and generate electrical power is:
1. Hot exhaust gases are passed through the heat exchanger.
2. In the exchanger, heat is transferred from the hot exhaust gases to a liquid such as pressurized water/glycol or thermal oil.
3. This hot liquid is pumped to the heat recovery evaporator in the Organic Rankin Cycle (ORC) system.
4. The refrigerant is boiled in the ORC evaporator and fed to an expander turbine, which drives the electrical generator.
5. The turbine generator generates electrical power, which is fed to the plant distribution network.
6. The exhaust refrigerant is condensed, using plant water as a heat sink and pumped back to the evaporator to repeat the cycle.
7. The master controller monitors system variables such as flow, pressure, temperature, and electrical power and controls the variable speed pumps for optimum thermal performance.


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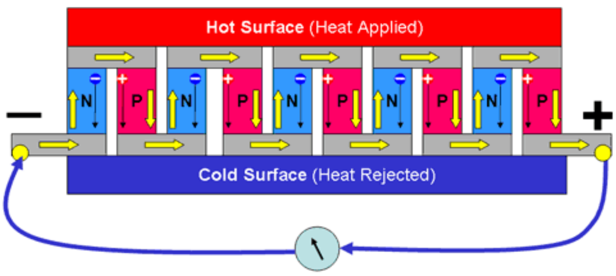
• TRENERGY by Alstom, Enogia and Arts et metiers Paris Tech
• H.REII DEMO
• Life+ EfficientShip
</td></tr>
<tr><td>

=> thermoelectricity: To generate electricity
The system is installed between two heat exchangers, one in the cold side and one in the hot side. Thanks to thermoelectric material and this thermal difference, electricity is made.


Thermoelectric Generator (TEG)
</td><td>

• POWERDRIVER by TGEN
• Rolls Royce PLC make research in marine application for diesel motor
• HeatReCar
• Renoter
• W2PHeat by Cornet
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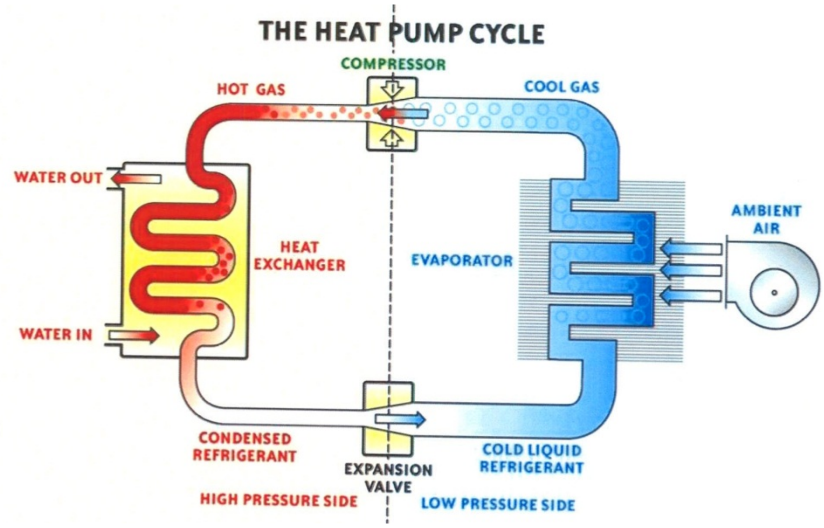
- **WHR system from air or gas**

With a heat pump, energy which is in the air or in the gas can be extracted to heat or to cold.



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<td>

- From gas:

LIFE Eco-HeatOx
LIFE HEART

- From air :

Ticket to Kyoto by RATP

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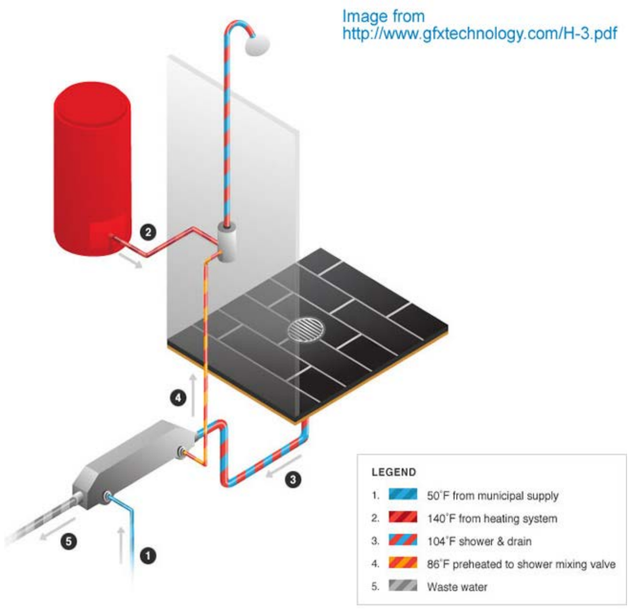
- **Wastewater heat recovery system**

Heat pump or heat exchanger, allows to recover heating contain in the water.



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<td>

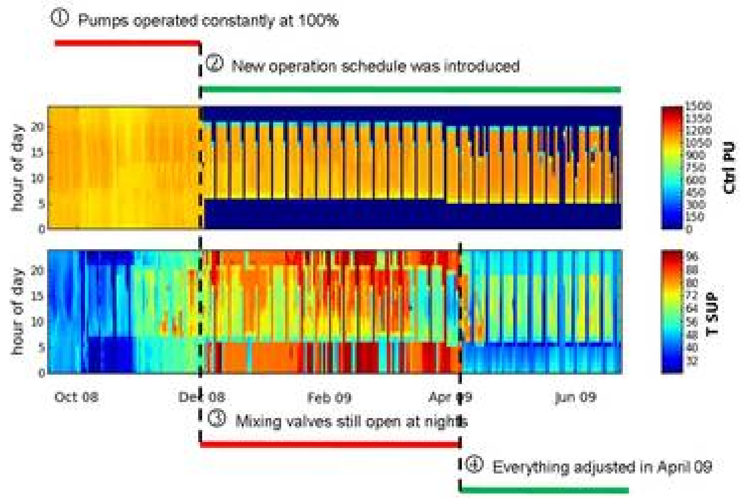
- Lauterecken project by Thermeco
- CELSIUS
- LOW-HEAT project
- SLUDGE2ENERGY
- LIFE MEMORY - anaerobic technology
- LIFE Necovery – With biosorption

</td>
</tr>
</table>

3.5.1.2 *Heating, ventilation, air conditioning*

<table>
<tr><th>State of the art technology</th><th>Reference Projects</th></tr>
<tr><td>

- Energy networks management system
  - Control heating
  - Speed variator on ventilation and air conditioning: Adjust the air flow rate to the needs, allow saving energy.
  - Smart grid
  - ISO 50001



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- LIFE OPERE
- Cascade project

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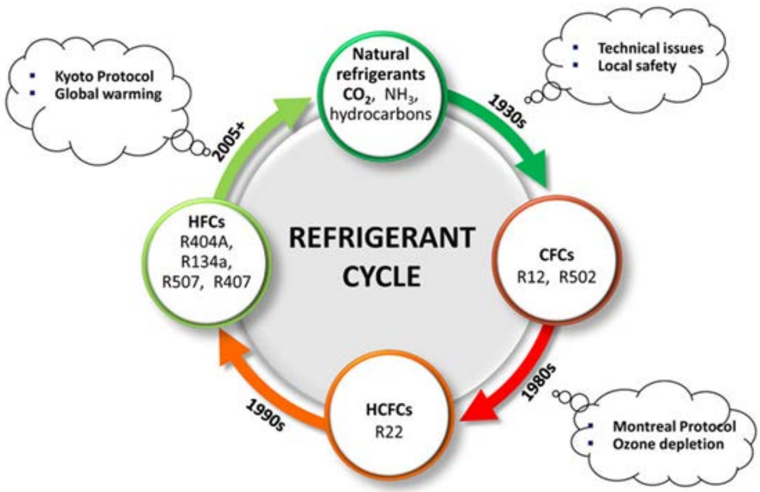
- CO_2 as refrigerant (R744)

Other principal benefits of CO_2 are that it is a natural substance; it is cheap, readily available, not poisonous in any common concentration, and non-inflammable.

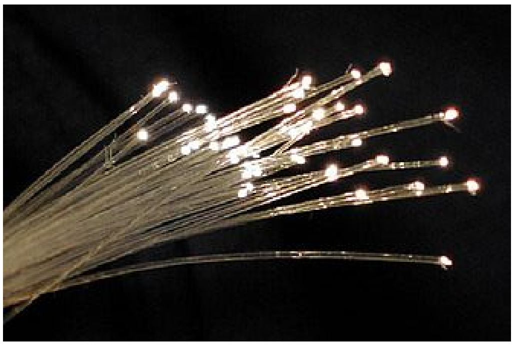


</td><td>

- SHECCO
- B-COOL
- CO2REF

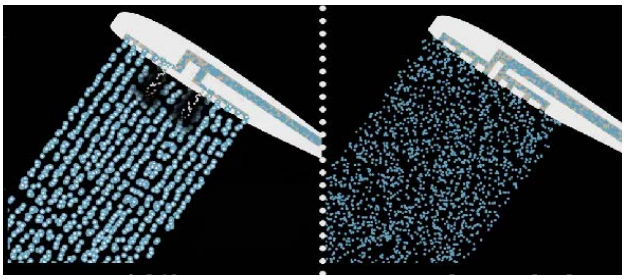
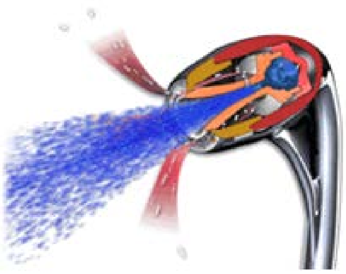
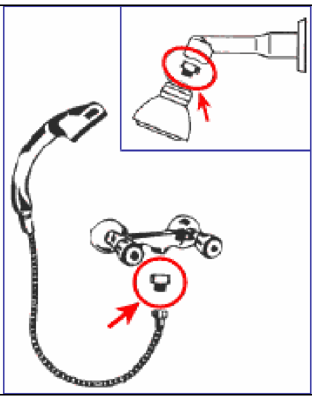
</td></tr>
</table>

3.5.1.3 Lighting system

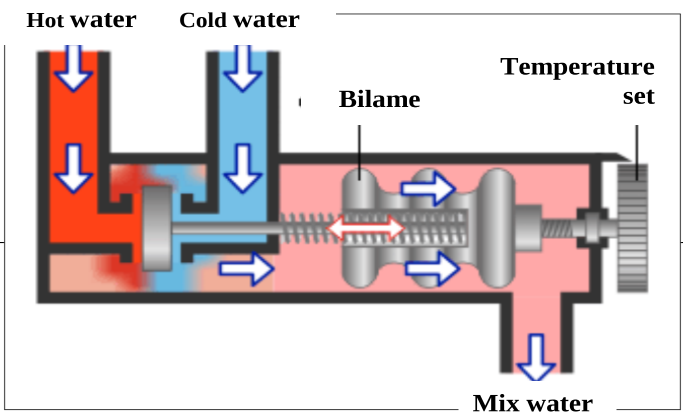
State of the art technology	***Reference Projects***
• Led light A light-emitting diode (LED) is a two-lead semiconductor light source. It looks like a basic pin-junction diode, which emits light when it's activated. When a fitting voltage is applied to the leads, electrons are able to recombine with electron holes within the device, releasing energy in the form of photons. This effect is called electroluminescence, and the light colour (corresponding to the energy of the photon) is determined by the energy band gap of the semiconductor. 	• The EnLight project • Solid-State Lighting project (US project)
• optic lighting An optical fibre is a flexible, transparent fibre made of extruded glass (silica) or plastic, slightly thicker than a human hair. It can function as a waveguide, or "light pipe", to transmit light between the two ends of the fibre. 	• NEXPRESSO - Network for EXchange and PRototype Evaluation of photonicS componentS and Optical systems • EUROPIC - EUROpean manufacturing platform for Photonic Integrated Circuit • LIFT - Leadership In Fiber Technology • MONA - Merging Optics and Nanotechnologies • OPERA - Optics and Photonics in the European Research Area

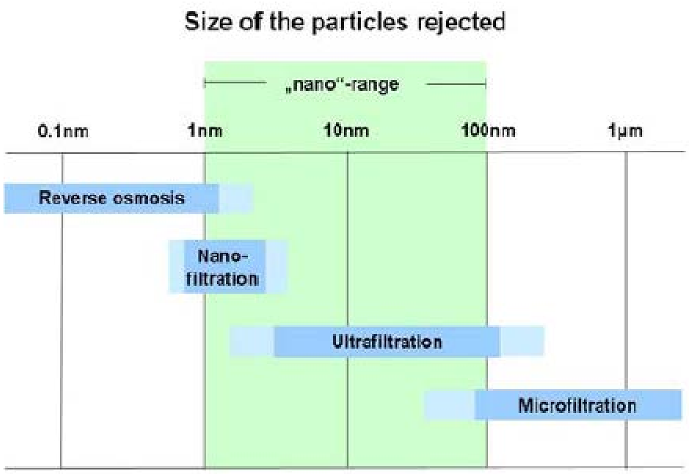
3.5.2 Hotel loads

3.5.2.1 Shower/Tap

State of the art technology	***Reference Projects***
• Shower pulsation Water travels along the shower handle at full pressure to a compartment in the shower head where it is deflected backwards into an expansion chamber. This action causes pressure to build and when it reaches a certain level, the water bounces back out of the chamber. The resulting pulsation occurs between 30 and 40 times per second and manipulates the surface tension of the water to ensure that the pressure is as high as possible in every single drop. Rather than creating an illusion of more water by filling the flow of water with air, this technology maximise the propulsion and impact of fuller drops of water while consuming less energy.  **Shower pulsation** **Classic shower**	• No EU project
• Shower at water restriction  Provide 6L/min of water instead of 12 L/min for a classic shower. Thank to the Venturi effect, the pression is increased but flow of water is reduced.	• No EU project
• Flow regulator The system adapts the flow at the network pressure. 	• No EU project

• Thermostatically controlled shower The system adapts the flow at the network pressure and temperature. The gain is about 5% of energy saving. A thermostatic mixing valve (TMV) is a valve that blends hot water with cold water to ensure constant, safe shower and bath outlet temperatures, preventing scalding. The storage of water at high temperature removes one possible breeding ground for Legionella; the use of a thermostat, rather than a static mixing valve, provides increased safety against scalding, and increased user comfort, because the hot-water temperature remains constant.	• No EU project



• Water recycling Wastewater can be reused after a treatment like ultra-filtration (UF), carbon nano-structured material (CNM) or reverse osmosis (RO) to achieve the desired water quality efficiently. Ultrafiltration: It's used for the separation of suspended solids, colloids, bacteria and viruses. This technology utilizes membranes with pores having a size of 1 to 100nm. Nanofiltration : Pressure-driven membrane based separation process in which particles and dissolved macromolecules smaller than 2 nm are rejected. Reverse osmosis: Liquid-phase pressure driven separation process in which applied transmembrane pressure causes selective movement of solvent against its osmotic pressure difference.  	• LIFE WaterReuse • aWare

3.5.2.2 Washing machine without water

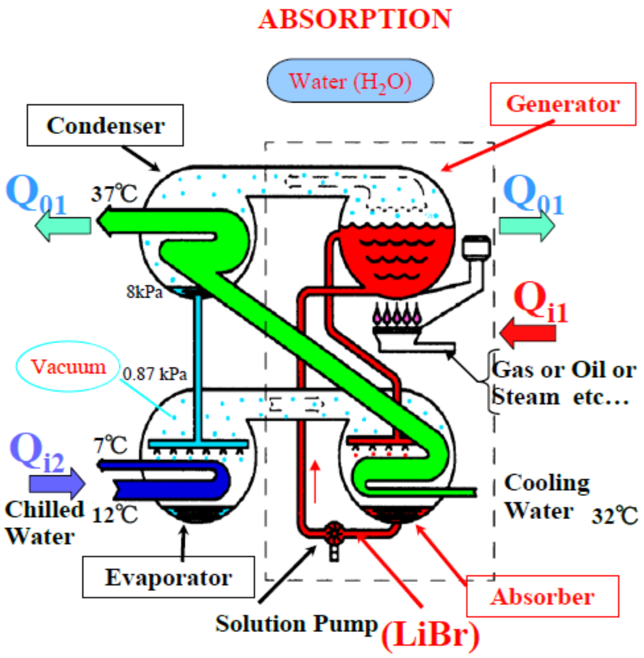
80% of electric consumption of household electrical devices serves for warming water.

State of the art technology	*Reference Projects*
• Washing machine without water This washing machine use only about a cup of water per load, substituting liquid for a handful of nylon polymer beads. The machine is 80% more water efficient than a conventional machine, and uses half the energy. Once added to the wash, the beads become polarized, either absorbing dirt inside their structure, or attracting it to their surface. Other prototype spends too much energy. 	• Nimbus

3.5.2.3 Dishwasher without water

State of the art technology	*Reference Projects*
• Dishwasher without water 1- A powerful jet cleans the surface of the dishes 2- A steam degreases the dishes 3- A UV ray sterilizes the dishes 	• No EU project

3.5.3 Cargo (handling, refrigeration …)

State of the art technology	*Reference Projects*
• Marine absorption chiller A system to recover waste heat for chilling. 1- Evaporation: A liquid refrigerant evaporates in a low partial pressure environment, thus extracting heat from its surroundings (e.g. the refrigerator's compartment). Due to the low pressure, the temperature needed for evaporation is also lower. 2- Absorption: The now gaseous refrigerant is absorbed by another liquid (e.g. a salt solution), reducing its partial pressure in the evaporator and allowing more refrigerant to evaporate. 3- Regeneration: The refrigerant-saturated liquid is heated, causing the refrigerant to evaporate out. This happens at a significantly higher pressure. The refrigerant is then condensed through a heat exchanger to replenish the supply of liquid refrigerant in the evaporator. 	• Eoseas Concept Cruise Ship

3.6 Energy managements and system operation

An efficient energy management system requires taking into account a number of aspects, which can sometimes be conflicting. An integrated approach is then necessary to address this issue.

Holistic models of all ship energy systems and their interaction are still in their infancy and very limited research output is available in this area.

Most identified EU or national projects dealing with aspects of energy management in a holistic manner are still on-going and only preliminary results are available. In most cases, details of the mathematical models are not publically available.

State of the art technology	***Reference Projects***
Energy system modelling and integration Mathematical models of shipboard systems are available for individual systems but holistic models that integrate all ship's systems and their interaction are only starting to emerge.	TARGETS (EU), REFRESH (EU), INOMANS2HIP (EU)
Systems optimisation	TEFLES (EU)
Pumps control Study to develop control algorithms for optimal use of pumps.	Green ship of the future (Danish PPP)
Enhanced power management Automated system to monitor overall power demand and ensure optimal generator loads.	Green ship of the future (Danish PPP)
Methods for optimised use and management of novel on-board energy production, storage and distribution technologies.	INOMANS2HIP (EU)
Design for operation / energy efficiency Study of operational profiles to derive new systems configurations applicable mainly to cruise ships, ro-pax ferries and mega-yachts.	BESST (EU)
Integration of energy saving technologies in early design stage, using advanced simulation models. The aim is to identify optimum combination (s) of energy consumers to improve overall energy efficiency.	JOULES (EU)
Data collection The maritime industry is starting to utilise collected data as a means to improving ship efficiency. Although not a new approach, "Big data" is a terminology that is starting to be used more often in the maritime field. Big data challenges current statistical analysis methods and there is a need to develop new algorithms and methods to manage this volume of data. Research in this area has already started outside the maritime field and one project in particular is looking at the new theory has been identified. One of its objectives is to improve safety and efficiency of marine transport.	Stochastics for big data and big systems (Swedish funding)

3.7 Ship operations

Ship operation has attracted more attention than the holistic energy management of shipboard systems and a number of solutions have been researched. In addition, a number of commercial products are also available.

State of the art technology	*Reference Projects*
Decision Support Systems for ship and fleet management Definition of Key Performance Indicators (KPI) against which ship performance is compared to improve efficiency.	
Decision support tool for the operation of ships to reduce energy consumption and atmospheric emissions. This considers actual measurements in different operational configurations and integrates the operational practices of the crew. Real-time optimisation of emissions is also offered.	EONAV (French)
Route planning Reliance on the accuracy of weather forecast models (for weather routing) and ship performance prediction models.	
Tool development using a precise mathematical model of the propulsion plant in order to estimate resistance components of a ship at sea. This is to determine the most fuel efficient route in combination with data from sea current, shallow water and weather. The tool recalculates the remaining part of the route and provides crew with instant guidance to the required speed.	SeaPlanner - efficient route planning application (Danish PPP)
Development of a prototype of a route planning system with improved reliability for weather forecasts and better models for fuel consumption and emission reduction. An integrated platform is provided on-board to collect real-time performance parameters. The computationally intensive optimisation algorithms are run in a control centre on-shore.	NAVTRONIC (EU)
Trim optimisation Combination of model test data and data monitoring on-board to predict optimal trim. On-going research to understand physics of trim (model tests and CFD analysis).	Performance monitoring and trim optimisation (Danish PPP) TARGETS (EU)
Dynamic trim optimisation Machine learning method applied to data collected through multiple sensors over a period of time to predict engine fuel consumption.	Dynamic Trim optimisation with GreenSteam (Danish PPP)
Crew training For a successful implementation of any energy efficiency measure, crew awareness and training is essential. Only one project was found that identified the need to develop courses for crew.	Low Carbon Shipping (UK-EPSRC)

3.7.1 Commercial products

This subsection covers the previous two items, i.e. energy management and ship operation. Some commercial products/ tools offer a software suite that deals with both aspects and others only cover one.

The information reported here is based upon our understanding of the data provided by the product/tool developers on their websites. General descriptions of the mathematical models are also reported if they have been made available on these websites.

The list of the products/tools in this section is by no means exhaustive and no endorsement is made of any product.

A distinction is made here between on-board systems (expert systems for real-time advice and monitoring) and tools used to assess designs or offer recommendations for ship operation.

On-board systems

- NAPA-DSME Power includes voyage optimisation (using NAPA 3D model with real-time optimisation during the voyage with updated weather, wind, waves and current data, which are automatically acquired by the software), trim optimisation (based on model test or CFD calculations static and dynamic), real-time monitoring of emissions and fuel consumption, and analysis of hull condition and overall technical performance of the monitored fleet.

- Marorka Onboard offers energy system monitoring, electronic measurement logging, simulation-based decision support and extensive energy analysis to optimise fuel consumption. The software has a number of applications: propulsion optimisation (avoiding inefficient use of the propulsion system, providing recommendations on optimal trim and monitoring the efficiency of the hull); navigation optimisation (identification of optimal speed profiles, departure and arrival times by simulations based on weather and sea state forecasts and adjustment of the speed during sea passage for maximum energy efficiency); machinery optimisation(monitoring the efficiency of electricity production and consumption and the overall efficiency of the electrical installation, managing generator loads and reducing unnecessary use of electricity); fuel management (tracking and reporting of fuel consumption and an up-to-date electronic record of ROB inventories); report management; data management.

  A fleet performance option is also available.

- BMT SMART^SERVICES is a software suite which collects and records data from on-board sensors automatically. It provides a fuel monitoring service; trim and environmental data filtering, which incorporates metocean data with recorded vessel data for analysis of vessel performance at different load conditions in different operating environments; hull, propeller, engine and fuel trending, based on developed performance coefficients ("Power Coefficient" to measure increased power absorption, "Hull Coefficient" providing a measure of changes to the hulls condition due to fouling, "Propeller Coefficient" isolating the performance of the propeller and indicates the propulsive efficiency of the propeller, "SFOC (Specific Fuel Oil Consumption) Coefficient" as a measure of engine efficiency, "FOC (Fuel Oil Consumption)

Coefficient" as an indication of total vessel performance), Key Performance Indicators (using traffic light colour coding) and vessel and fleet performance.

Eniram has a number of products, which are based on their Vessel Platform (EVP), which is a real-time data collection platform that measures vessel performance and fuel consumption on large commercial and passenger vessels. EVP collects data from bridge and automation systems in addition to their own attitude sensors. The data is then stored to a data bank for future reference, further analysis and more complex modelling. The following are available Eniram products.

The Dynamic Trimming Assistant (DTA) is a system for monitoring and optimising dynamic trim in real-time. The optimal trim is calculated taking into account the vessel-specific model. The model is generated using mathematical algorithms to identify the effect of different factors, also referred to as "Propulsion Power Decomposition". This allows the DTA to identify the amount of fuel consumed due to incorrect trim and to display the optimal trim at all times. The model is generated based on data collected during actual operation of the vessel.

The Optimum Speed Assistant (OSA) is a system for optimising speed and fuel efficiency in real-time. The system automatically receives route information from navigation systems. Once the desired route and ETA are selected, the system calculates an optimum RPM profile to reach destination 'just-in-time' with the optimum amount of fuel. The profile is then updated several times a minute to keep the guidance up to date with changing wind, weather etc. It also takes into account the optimal engine combination as well as any speed and emission restrictions (e.g. ECA zones) to calculate and display the optimal speed profile. OSA applies a combination of statistical modelling, forecast data, historical data and real-time data monitoring.

The Vessel Performance Manager (VPM) is integrated with other on-board systems (such as the bridge and automation systems) to collect real-time performance data using sensor network technology. VPM monitors and offers guidance on energy management in real-time. All relevant energy flow parameters are collected and visualized in VPM. The cumulative data is collected to enable later reviews and all parameters can be monitored in real-time.

Eniram also offers fleet performance management as part of their products.

- EMMA Advisory by ABB is an integrated suite, which looks at the vessel as a whole. It has a number of functions. Trim optimisation uses an algorithm based on machine learning methods and real-time sensor fusion algorithms of full scale measurements. It includes prior information of propeller properties and some key variables that affect the vessel's resistance and propulsion power loss. The "Power Plant Optimiser" deals with energy management and waste recovery. It uses a physical model adjusted using statistical data from real measurements. The system also offers a tool to address "the towing angle of the Azipods" if fitted and a hull and propeller condition maintenance planning aid.

- Eco-Assistant by DNV-GL and OptiTrim by BV/HydrOcean are trim optimisation software packages. They use a comprehensive database of ship-specific resistance and power demand data calculated for numerous possible operating conditions. The data is generated using computational fluid dynamics (CFD) tools and a fully automated simulation process. The systems search the database to provide the optimal dynamic trim angle for a set of input consisting of vessel's speed, displacement and water depth. The systems also provide the optimal static trim for the vessel to help with the loading of the ship.

- VVOS by Jeppesen is a part of the Jeppesen Integrated Maritime Suite (IMS). The software "automatically generates a full range of optimised routes for the best trade-offs between ETA and fuel consumption".

  The software utilises "advanced routing algorithms to accurately and comprehensively optimise each route for on-time arrival while minimising fuel consumption, maintaining seakeeping limits and avoiding heavy weather".

  "Using sophisticated hydrodynamic modelling, optimisation algorithms and high-resolution ocean forecasts", the VVOS guidance system "recommends speed and heading changes to manage ship motions and help minimise heavy weather damage".

  VVOS includes a detailed, ship-specific model of ship motion as well as engine and propeller characteristics. "The ship model computes the speed made good under forecast wind, wave and ocean current conditions at a given engine power and propeller RPM, as well as ship motion limitations".

  Passage plans can be updated and re-optimised during sea passage when new weather forecasts become available or operational requirements change.

- Fleet Monitoring system (FMOS) by INTECS. Based on the available information, this product seems to be more at a concept stage rather than fully functional. The system has a Voyage Efficiency Analyser (VEA) using data automatically collected. The data recorded on-board can be supplemented with data from the shipping company's database. The VEA consists of a number of modules:

  <u>The Trim Optimisation Module</u> based on the ship hull model, calculates and recommends trim/list to decrease hull resistance. A hydrodynamic mathematical model is used to take into account all factors influencing ship hull resistance.

  <u>The Optimal Speed Module</u> based on individual mathematical models taking into account propulsion characteristics and meteorological conditions. The module calculates and recommends (in real-time) optimal values for propulsion for either a specified ETA or optimal speed (with minimised fuel consumption). "The module parses the real-time working parameters of the main engine at prevailing external conditions affecting its operation. By analysing pressures, torque, RPM and fuel consumption it defines main engine load curves". These curves (with certain assumptions) are then used to provide recommendations for speed.

  <u>The Optimal Route/Schedule Module</u> calculates fuel consumption along the planned route and monitors (in real-time mode) all the factors used to plan a route. It includes a combination of several components:

- Ship mathematical model taking into account hydrodynamic, propeller and propulsion characteristics.
- Fuel consumption model. Except for the input data source, this is the same model as is used in the Optimal Speed Module. The input data for the optimal speed module comes from on-board sensors, whilst for route planning the input is forecast data or data from previous voyages.
- Weather forecasts (meteorological data and currents database).
- Chart component for plotting the route, schedule/fuel consumption calculation and data exchange, as well as sea depth data (from navigation charts).

FMOS also offers emission monitoring and engine diagnostics module as well as fuel consumption monitoring.

Tools for recommendations and advisory services

- SEECAT by BV is holistic modelling of energy flows on-board a ship (energy balance of the entire ship). It is based on physics equations with reasonable complexity (uses Modelica, a non-proprietary object-oriented, equation based language to model complex physical systems). The tool predicts fuel consumption and emissions for realistic (time domain) operating profiles accounting for the coupling between energy systems. It carries out detailed modelling of specific systems (electrical plant /power management system, waste heat recovery, variable speed pumps / fans, propeller (fixed or controllable pitch), speed reduction, accommodation load reduction) using a library of components. The tool is used for design, operation or ship management.

- COSMOSS by DNV-GL is also based on a library of components. The software allows for the analysis of complex phenomena at both the system and individual component levels. This is to “optimise the design and operation of integrated systems, concurrently satisfying often conflicting constraints”. The tool follows the Model-Based Systems Engineering (MBSE) approach, which is based on the mathematical modelling of the steady state and dynamic thermo-fluid behaviour of marine energy system components. The entire system is modelled by connecting individual component models where each model contains the mathematical description of the dynamic behaviour of the component. The models are implemented in the gPROMS process modelling environment (a commercial product). The tool is mainly used to provide advisory services for emissions reduction, efficiency optimisation, considering innovative system concepts, evaluating design configurations and assessing the performance of ships in operation.

4 (Technology) Gap analysis

Concept

Based on the state-of-the-art technology analysis performed in the first step during the preparation of the report (chapter 2) a technology gap analysis has been performed. To put this on an even broader basis, additional work from other groups has been considered and the results of the ESSF (European Sustainable Shipping Forum) Research and Innovation group as well as the work of the relevant Vessels for the Future – VftF Assoc. – working groups has been considered.

In addition a number of external technology and foresight analyses have been considered to compare and balance the findings of the MESA group. Main sources include Lloyd's Registers' Global Marine Technology Trends 2030 Study /2/, ABS' report on Ship Energy Efficiency Measures /7/, Det Norske Veritas' Technology outlook 2020 /12/ and relevant IMO publications /8/, /9/ and /10/. A complete list of literature can be found in the appendix 5.2.

While in some areas technology gaps can be attributed directly to the technologies described in chapter 2, this is not always possible. It was therefore decided to group technology gaps according to an application oriented structure which addresses main areas affecting the energy efficiency of ships and thus provides global lines of research in the future. These are:

1. **Hydrodynamics, Resistance & Propulsion**
2. **Powering**
3. **Emissions**
4. **energy efficiency governance / EEDI**
5. **Big data / ship analytics**

The following chapters list a number of identified technology gaps, some of which have been addressed already either in on-going research or plans for upcoming work programmes. References to these are indicated in blue font. Missing work to bridge the technology gaps is indicated in black.

4.1 Hydrodynamics: Resistance and Propulsion

- [2.1.2] Viscous resistance
    - [2.1.2.3.1] Coatings
        - Systematic investigation of hydrodynamic properties of advanced coating systems.
        - Long term full scale analysis is required to provide reliable data for future optimised life-cycle predictions.

      These aspects are partly addressed in the work programme 2016/17, MG 2.1; further research will be required to assure a proper and publically available data basis.
    - [2.1.2.4] Air lubrication:
        - Air chambers location;
        - Filling methods of air chambers;

        - Prediction of bubbles dynamics (micro bubbles);
        - Effect of air lubrication on propeller performance;
        - Influence of seaway on the efficiency of air lubrication.
        - Numerical models and validation.

    Some development has been made in the past (FP7 – SMOOTH and other national projects), however several fundamental aspects (see above list) are still missing.

    - [2.1.2.5] Boundary layer control
        - Active / passive stabilisation of ship boundary layer;
        - Full scale testing of innovative concepts

    These aspects are partly addressed in the work programme 2016/17, MG 2.1, further research will be required to attain a higher Technology Readiness Level. .

- [2.1.1.3] Full scale validation of CFD predictions.
    - Verification and Validation of CFD for non-standard conditions.
- [2.1.3] Added resistance / ships in operation
    - Practical prediction methods and validation; partly addressed in projects like SHOPERA [FP 7-Transport) and SYNCHRO-NET – EU project, logistics, MG 6.2, 1st call H2020, 2014.
    - [2.1.3.2] Advanced simulation methods for reliable predictions of non-linear behaviour, validation.
    - [2.1.4] Optimisation of Aerodynamic resistance during operation.
- [2.2.1] Advanced propulsors:
    - Enhanced design methods for marine propulsors;
    - Systematic comparisons of alternative configurations;
    - Assessing bio-mechanical propulsion.

  Some development has been made in the past (FP7 – STREAMLINE and other national projects), however several fundamental aspects (see above list) are still missing

- [2.2.1.3] POD: - electric drive train.
- [2.2.1.3] PIDs: comprehensive analysis of performance under all operational conditions.

4.2 Powering

- [2.3] Engines
    - Design for off-design conditions
    - Engine control:
        - (1) adaptive and learning engine Control Strategies,
        - (2) Closed loop controls for engines and integrated solutions,
        - (3) Predictive and model based controls,
        - (4) Engine controls, user experience and human-machine interfaces
    - Cooling:
        - (5) Cooling system and lubrication system control, adaptive to fuel type and engine operating conditions,
        - (6) New cooling concepts (liner, piston, cover) and cooling system arrangements. Numerical modelling of heat transfer, acid formation and acid condensation, including effects on cylinder lubrication conditions,

        - (7) Waste energy utilisation in marine power plants. Intelligent utilisation of excess energy on Tier III engines (Smart WHR, including ORC),
        - (8) Hybrid installations, multi-engine optimisation electrical machines integration, energy transfer and conversion, energy storage utilisation.
    - New engine components materials and their properties
        - Corrosion, fatigue and fouling
        - High temperature materials and corrosion material. Materials for high load.
        - Activities would include thermal-mechanical fatigue of cast iron, resistance against hot corrosion for components in contact with exhaust gas/cooled EGR, fatigue properties and fracture mechanisms in materials used in highly loaded engine components, fatigue fretting phenomena in engine components, fatigue in welded materials, suitability of new material and coatings for engine components
    - Engine (room) design
        - Vessels engine room: Eco-retrofitting, Integrated approach to eco-retrofit

- **[2.3] Alternative fuels**: (in compliance with the new Commission agenda)
    - Engine technology: Impact on Engines and Components.
    - Fuels Benchmarking
    - Distribution & storage:
        - Multi-fuel fuel supply systems including material performance over life cycle, aging, fatigue and vibration issues may need analysing from point of view machinery systems ship safety
        - Multi-fuel fuel supply systems behaviour in possible fire scenarios
    - LCA environmental impact (safety)

- [2.3] New systems & technologies:
    - Assessment of (complex) ship engine / machinery systems and methods. Innovative systems-level modelling, simulation and optimisation tools to assess performance, design, retrofit solutions. (-> MG 4.3, 2nd Call), Validation of models [],
    - demonstrating further hybrid electric, solar, wind and other radical alternative powering technologies for shipping (p 10 ff.) incl. energy harvest and storage technologies
    - LCA of New technologies with respect to energy efficiency, emissions, safety, costs
    - Emission / efficiency measurement / (condition based) monitoring (predictive) maintenance
        - Develop capability to monitoring the vessel and its environment as well as on-board electrical, mechanical and thermal energy systems with distributed affordable novel sensors sometimes operating in harsh environments. Sensors could benefit from wireless and self-powered capabilities and should support intelligent and predictive decision and monitoring support systems with real time data.
        - Develop capability of storing the collected data in a searchable and data secure environment. Develop capability such that the data can be analysed with novel and predictive data process algorithms and shared with intelligent and predictive

support and visualisation systems, both on-board and on-shore. Integration with ship control room systems could be considered as well as transferring and storing data on-shore. Focus should be the facilitation of data usage on predictive maintenance and energy management, prediction and optimisation.

Develop capability to enable real time condition based predictive data driven maintenance. This requires development of vessel system and equipment intelligence through analytical modelling, experimental work and model based approach to enable novel processing and decision support systems. Prediction of future state of the machinery and structure is essential for safe and economical operation. Predictive maintenance should also cover apart from main engine and machinery the hull/propeller cleaning and dry-dock period optimisation. Impact on legislation and technical rules should be considered. Development of a demonstration platform.

FP7 transport projects RISPECT and INCASS include predictive maintenance and data collection aspects.

4.3 Emissions

- [2.3] Emission reduction technologies / scrubber

  Post Treatment Technologies -2nd Generation Scrubbers to reduce PM, application to Medium and High Speed Engine Technologies

  - Modelling tool, Calculation Method, Sensors and Control, Urea and Ammonia Cycles, Test Rig. Cost/Benefit analysis Risk assessment and Decision support tools
  - Definition of size, content, characteristic of PM, Measurement Standards, Engine process, Combustion and lubrication optimisation.
  - Compact WHR, Control system integration at engine system level, increased peak cylinder pressure, materials challenge.
  - Reliability of engines equipped with next generation of SCR, particularly integrated with engines should not decrease ship safety to a standard worse than we have now with current generation of the marine internal combustion engines.

4.4 Energy Efficiency Governance / EEDI

- Minimum power requirement (SHOPERA in FP 7-5)
- Conceptual analysis of EEDI driven design e.g. BMT proposal of long, narrow vessels, in the context of the overall transport system (handling at sea, in ports, during passage, …)
- Alternative formulation of EEDI (does not account for transportation time); introduce a transportation coefficient that accounts for time (-> performance).

4.5 "Big data" / Ship Analytics

The "Stochastics for big data and big systems" project (see page 56) aims at developing "general mathematics and statistics for understanding and modelling complex structures in time, space and networks". Further research appears to be needed to address the wide range of problems that management of such vast data poses. There are possible over-arching applications for this research in the design and operation of vessels.

- [2.6] Energy management Systems
    - Defining tools, index and procedures for managing the energy and fuel consumption and decreasing the energy waste;
    - Speed reduction, ultra-slow speed vessels: manoeuvrability and collision avoidance, reliability of equipment, piracy, and safety.
    - Augmented propulsion utilizing wind and wave: ship motions, manoeuvrability (in particular in congested areas) and collision, handling in all operation phases (including launching, recovery and emergency situations), necessary minimum complementary power onboard, power management between wind propulsors and other propulsion sources, control systems reliability.
    - Solutions for the modulation of prime movers (and their energy consumption) according to their effective load (inverters for the electric motors and/or other solutions)for different services (fans, heat exchangers, etc.); this is a key element into the operation profile of each vessel ;
    - Optimisation of multiple engine power systems to minimise energy consumption in all modes of vessel operation
    - Optimization of energy distribution, Storage and Peak-smoothing
    - Efficient adoption of renewable energies e g. solar and wave, on board vessels, including safety related aspects
    - Monitoring, control and automation devices, procedures and solution for the optimisation of energy use, power load distribution and the elimination of energy waste during the maritime operations of the different ship types in different operational conditions.

    Trim optimisation, route planning and real time monitoring are already offered by various commercial solutions described at section 2 of this document. Research has also been carried out to improve the predictive power and reliability of mathematical models (NAVTRONIC and SeaPlanner projects, for example). More research is needed on the effect of wind and waves on delivered power (i.e. on the operation of the propeller and its interaction with the hull in such conditions). More research is also required in terms of the modelling and validation of holistic ship models.

    - Design of new energy storage system and distribution onboard, improvement of existing systems and architecture for the storage e.g. chemical & thermal
    - Improved energy efficiency through the use of superconducting machine, distribution and energy storage technology

5 Summary and Conclusions

State-of-the-Art – Clustered Research Projects

The present document constitutes the intended catalogue of Energy Efficiency measures which can be taken into account to improve the energy performance and efficiency of ships. It is based on material collected by the MESA Thematic Technology Group I from a variety of sources, covering EU project research as well as open sources from both, member state based and further international research.

The catalogue developed comprises inputs from a large variety of technical areas and elements which affect the energy efficiency of ships and other maritime structures. These elements constitute the 7 main pillars of energy efficiency, namely:

1. Ship resistance.
2. Ship propulsion.
3. Prime mover.
4. Auxiliary energy (conversion) including solar, wind and seaway / motion energy).
5. Other on-board energy consumers.
6. Energy Management Systems.
7. Ship operations.

The seven sub-groups have been individually structured and were broken down into relevant sub-topics using descriptors. Projects and results have been collected together with known state-of-the-art technologies and descriptions.

It appears that past EU research has addressed a large number of energy efficiency related topics in the previous framework programmes FP 5 to FP 7. Based on the available information from these projects it is anticipated that substantial progress has been achieved in a number of individual areas, e.g. in the first three areas of ship resistance and propulsion and engine technology. Here, European makers and suppliers are clearly among world market leaders and it can be reasonably concluded that at least part of these successes are due to the work performed in European research projects. The developments and resulting products typically address individual solutions which already, considered as stand-alone solutions, promise substantial improvements. However, most projects fall short to unleash the full potential of the technologies as often the integration of all advanced tools and concepts into a holistic energy saving approach is missing.

This holds in particular for Energy management systems where considerable work has been spent during FP 7 and in the early phase of H2020. Although some of these projects have not been finished yet and final results will become available only in the future, it must be noted that results lag behind expectations. Meanwhile a number of commercial solutions have appeared during recent years. Although there is constant improvement in these, a general assessment is however that they all lack generality. Each of them addresses parts of the energy management problem, but there is hardly any complete solution available.

The present analysis concludes that many individual developments which benefitted from EU research funding have helped to move the state-of-the-art in energy efficiency technologies forward. The improvements achieved have helped to considerably reduce energy consumption for a given transport task or other maritime operation. This leads to the general conclusion that the overall European maritime transport research initiative has been successful.

The present analysis captures the situation in 2015. Following present trends and up-to-date information in the maritime industry it becomes evident that especially the market for energy efficiency improvement technologies is extremely dynamic with new products or solutions available almost every week. At the same time it is similarly evident that for many of these even a proper proof of concept is missing and must be provided before major market uptake can be diagnosed. This is particularly important at the time of writing as the global energy price situation is rather volatile. Given the low oil and other fuel prices in 2015, a large number of – costly – energy saving solutions lose their previous competitive edge. Today, the motivation for implementing such technologies needs to come mainly from i) a long term perspective, as latest OPEC news forecast rising oil prices again for the next years and ii) the inherent fact that each fuel saving technology implicitly goes along with emission reductions and hence helps to comply with the further increased requirements to control and limit ship borne emissions.

These considerations lead to the final conclusion that the exercise performed in MESA's task 1.1 which resulted in the present report should be taken up by the industry and continued on a regular basis to assure that up-to-date information will be available also in the years to come.

Technology Gaps

As described in the previous chapter, worldwide research and development has led to substantial improvements of the energy efficiency of seaborne operations. The improved State-of-the-Art and the successive industrial implementation of research results and new developments however do not mean that past work has covered the entire ground. The analysis performed in MESA TTG 1 revealed that there are a number of technology gaps which can be identified. These can be grouped into three main categories:

1. Individual technology gaps;
2. Lack of integration work;
3. No radically new powering technologies

The first group comprises mainly technologies which have been addressed as a whole and where research results indicated that still gaps exist to either explain phenomena in sufficient detail to exploit the positive effects to the max (an example is the air lubrication technology) or that technologies have been developed but a complete and comprehensive assessment is still missing to assure a shift to a higher technology readiness level and a sound transfer into industrial practice. Safety with respect to the introduction of new powering and fuel technology can serve as an example here.

The second group relates to the apparent lack of fully integrated energy efficiency solutions which were mentioned already in the previous chapter. While individual elements are already in place a full exploitation through integrated energy management solutions with a life-cycle perspective is still lagging behind and it is felt that a considerable additional potential can be unleashed when bringing the elements together in a consistent way. This relates largely to software techniques and the processing of large amounts of information in the context of "Big Data".

All relevant developments which have a wider impact on the global maritime sector so far appear to be more or less incremental improvements of existing technology. A renunciation of existing “standard technology”, e.g. for the propulsion of ships, has not been addressed in past research in much detail. Such radical ideas constitute the third group of technology gaps found in the analysis. The need for such type of long term strategic research has to be carefully balanced against more short term research needs, however the introduction of ECAs, the new European MRV rules and other emission related regulations aiming at limiting CO_2 and other emissions call for more stringent solutions. The most recent IMO Greenhouse Gas Study offers a number of different scenarios for the expected growth rates in international shipping. Even the most conservative assumptions indicate that the emission increases from shipping due to the increased traffic cannot be counterweighted by traditional means and the expected improvements which can be achieved by means of evolutionary developments and optimisations seen in the past years. Seen from this perspective it seems to be necessary to look into more radical, zero emission transport solutions for the future too and thus lay the foundations for a truly sustainable seaborne transport system in Europe and worldwide.

Synthesis and Future Work

The Gaps identified in the present study relate to technical challenges and shortcomings as identified by the MESA working group in TTG 1. They are based either on engineering considerations or general trends indicated in official public communication such as in /9/. These gaps do not constitute a catalogue or roadmap for future maritime research and development as they need to be balanced i) with the inputs from other TTGs 2 to 4 and ii) need to be aligned with global and maritime market trends and societal needs as analysed in MESA WP 5. This will be done in the next step in MESA’s integration group (WP 6) during the coming months.

6 Appendix 1:

6.1 Project References:

#		FP	YEAR (start)	Project reference / Acronym	Project Title	MESA reference(s)	Web Site
1	EU	FP-7	2009	2020 INTERFACE	2020 Interface	3.3	http://www.2020interface.eu/
2	EU	FP-7	2013	ADEC	Advanced Low Friction Engine Coating	3.3	http://cordis.europa.eu/project/rcn/106828_en.html
3	EU	FP-6	2005	^^	ADVANCED DECISION SUPPORT SYSTEM FOR SHIP DESIGN, OPERATION AND TRAINING		http://cordis.europa.eu/project/rcn/75816_en.html
							http://adopt.rtdproject.net/
4	EUREKA			BALTECOLOGICAL SHIP	E! 2772 BALTECOLOGICALSHIP		http://www.eurekanetwork.org/content/e-2772-baltecologicalship
5	EU	FP-7	2012	BB-GREEN	Battery-powered Boats, providing Greening, Resistance reduction, Electric, Efficiency and Novelty	3.3	http://www.bbgreen.info/
6	EU	FP-7	2009	BEAUTY	Bio-Ethanol engine for Advanced Urban Transport by Light Commercial Vehicle & Heavy DutY		http://cordis.europa.eu/project/rcn/89974_en.html
7	EU	FP-7	2007	BESST	Breakthrough in European Ship and Shipbuilding Technologies	3.3, 3.4, 3.6	http://www.besst.it/BESST/target.xhtml

#		FP	YEAR (start)	Project reference / Acronym	Project Title	MESA reference(s)	Web Site
8	EU	FP-7	2012	BIOCLEAN	New BIOtechnologiCaL approaches for biodegrading and promoting the environmEntal biotrAnsformation of syNthetic polymeric materials	3.3	*www.**bioclean**project.eu/*
9	Private			BMT Defence Services Ltd, UK	BMT Hull Roughness Analyser		http://media.bmt.org/bmt_media/bmt_services/28/200703_HullRoughnessAnalyser.pdf
10	EU	FP-4		CALYPSO		3.1	
							http://cordis.europa.eu/result/rcn/47370_en.html
11	EU	FP-6	2007	CLEANENGINE	Advanced technologies for highly efficient Clean Engines working with alternative fuels and lubes	3.3	http://ec.europa.eu/research/transport/projects/items/cleanengine_en.htm http://cordis.europa.eu/result/rcn/47370_en.html
12	Joint Industry	FCEP	2010	CLEEN-FCEP	Future Combustion Engine Power Plant	3.3	https://research.it.abo.fi/projects/CLEEN
13	EUROSTARS		2010	CONNORESS	Combined NOx-noise reduction system in ships		https://www.eurostars-eureka.eu/eureka-projects?search_api_views_fulltext=&field_project_date_value=&field_project_date_value2=&field_project_type=&&&&&page=2&f[0]=field_shared_countries%3A26&f[1]=field_project_type%3Aeurostars
14	EU	FP-6	2004	CREATING	Concepts to reduce environmental impact and attain optimal transport performance by inland navigation	3.3	http://cordis.europa.eu/project/rcn/73954_en.html

#		FP	YEAR (start)	Project reference / Acronym	Project Title	MESA reference(s)	Web Site
15	EU	FP-7	2011	DEECON	Innovative After-Treatment System for Marine Diesel Engine Emission Control	3.3	http://www.esf.org/coordinating-research/eurocores/completed-programmes/eurodeep/projects/deecon.html
							www.deecon.eu (official websiteacc. to cordis)
							http://cordis.europa.eu/result/rcn/165766_en.html
16	German BMVBS		2009	e4ships	Brennstoffzellen im maritimen Einsatz	3.3	http://www.e4ships.de/
17	EU	FP-7	2011	ECO-REFITEC	Eco innovative refitting technologies and processes for shipbuilding industry promoted by European Repair Shipyards		http://cordis.europa.eu/project/rcn/97672_en.html
18	EU	FP-5	2002	EFFORT,	European fullscale flow research and technology	3.1	http://www.marin.nl/web/JIPs-Networks/Archived-JIPs-Public/Effort.htm
							http://cordis.europa.eu/project/rcn/63402_en.html
19	National Swedish Shipbuilding Institute SSPA		2009	EFFSHIP	Efficient Shipping with low emissions	3.3	http://www.effship.com/index.htm
20	EU	FP-6	2007	ENGINE EFFICIENCY	Fluid Interactions for Engine Efficiency		http://cordis.europa.eu/result/rcn/52367_en.html
21	F		2009	EONAV	Optimized operation of ships	3.7	http://en.polemermediterranee.com/Ship-and-nautical-industry/Ships-of-the-future/EONAV
22	D		2007	EPROSYS-HF	Entwurf von propellerbasierten Propulsionssystemen für große Hochgeschwindigkeitsfähren	3.2	https://beluga.sub.uni-hamburg.de/vufind/Record/565334336
							(HSVA Report 1662)

#		FP	YEAR (start)	Project reference / Acronym	Project Title	MESA reference(s)	Web Site
23	EU	FP-5	2001	EROCAV,	Erosion on ship propellers and rudders - the influence of cavitation on material damages	3.2	http://cordis.europa.eu/project/rcn/53092_en.html
24	Deutsche Bundesstiftung Umwelt (DBU)		2010	E-Ship 1			www.enercon.de/p/downloads/PM_E-Ship1_Ergebnisse_DBU.pdf (In German)
25	EU	FP-5	2000	FANTASTIC	Functional design and optimisation of ship hull forms	3.1	http://cordis.europa.eu/project/rcn/52821_en.html
26	EU	FP-5	2002	FASTPOD	Fast ship applications for pod drives	3.2	http://cordis.europa.eu/project/rcn/64095_en.html
27	EU	FP-6	2005	FELICITAS		3.3	http://www.felicitas-fuel-cells.info/project-description.html
28	EUREKA (Norway & German Gov)			FellowSHIP		3.3	http://www.eurekanetwork.org/content/e-3636-fellowship
29	FIN			Finnish Fuel Cell programme			http://www.tekes.fi/en/programmes-and-services/tekes-programmes/fuel-cell/
30	F - D		2015	FLIPPER (MARTEC)	Flow improvement through compliant hullcoating for better ship performance	3.1	http://www.flipper-martec.com/
31	D		2009	Form-Pro	Ship hullform optimisation with active propulsion based on an adjoint equation approach	3.1	http://www.hsva.de/our-research/research-energy-efficiency.html#formpro

#		FP	YEAR (start)	Project reference / Acronym	Project Title	MESA reference(s)	Web Site
32	Joint Research Project with wellknown German Shipyards			Gas-Pax	development of three gas-fuelled ship types	3.3	http://www.research-in-germany.org/en/research-areas-a-z/maritime-technologies/Research-Projects/GasPax-Project.html
33	UK TSB & TSDL			GLEAMS	Glycerine Fuel for Engines and Marine Sustainability	3.3	http://groupspaces.com/GLEAMSInterestGroup/
34	Joint initiative (Danish Maritime Cluster)		2008	GSF / GREENSHIP	Green Ship of the Future	3.1	http://www.greenship.org/
35	EU	FP-7	2011	GRIP	Green Retrofitting through Improved Propulsion	3.2	www.grip-project.eu
36	Involves ETN	FP-7	2009	H2IGCC	Low Emission Gas Turbine Technology for Hydrogen-rich Syngas		http://www.h2-igcc.eu/default.aspx
37	D		2009	HAI-TECH			http://www.hsva.de/files/faz_19102010.pdf(in German)
							http://www.hsva.de/files/newswave2010_2.pdf (newswave article)
38	EU	FP-6	2007	HANDLING WAVES	Decision support system for ship operation in rough weather		http://www.mar.ist.utl.pt/handlingwaves/
							http://cordis.europa.eu/result/rcn/52955_en.html
39	EU	FP-7	2010	HELIOS	High Pressure Electronically controlled gas injection for marine two-stroke diesel	3.3	http://cordis.europa.eu/result/rcn/53708_en.html

#		FP	YEAR (start)	Project reference / Acronym	Project Title	MESA reference(s)	Web Site
					engines		
40	EU	FP-6	2004	HERCULES A	High Efficiency Engine R&D on Combustion with Ultra Low Emissions for Ship	3.3	http://tra2014.traconference.eu/papers/pdfs/TRA2014_Fpaper_18017.pdf
41	EU	FP-6	2008	HERCULES B	Higher-efficiency engine with ultra-low emissions for ships	3.3	http://www.hercules-b.com/
42	EU	FP-6	2012	HERCULES C	Higher efficiency, reduced emissions, increased reliability and lifetime, engines for ships	3.3	http://www.hercules-c.com/
43	GR			HYBRID (NTUA-SDL) (CFD Code, no Project)		3.1	Shukui Liu:
							Time Domain Simulation of Nonlinear Ship Motions Using an Impulsive Responsive Function Method
							2nd International Conference on Maritime Technology ICMT2014, Glasgow; 07/2014
44	Scottish Govt. with ERDF		2011	Hybrid Ferries			http://www.cmassets.co.uk/project/hybrid-ferries-project/
45	EU	FP-7	2009	HYMAR	Hybrid marine power for all	3.3	http://hymar.org
46	EU	FP-7	2011	INOMANS2HIP	INOvative energy MANagement System for cargo SHIP	3.3,3.6,4.5	http://inomanship.eu/
47	F			IWEST		3.4	
48	EU	FP-7	2013	JOULES	Joint Operation for Ultra Low Emission Shipping	3.3,3.4,3.6,4.5	http://www.joules-project.eu/Joules/index.xhtml
49	EU			KAPRICCIO		3.2	Via: www.hsva.de

#		FP	YEAR (start)	Project reference / Acronym	Project Title	MESA reference(s)	Web Site
50	D		2009	KONKAV (I - III)	Correlation of Cavitation Effects under Consideration of the Water Quality	3.2	www.tuhh.de/fds/research/current-projects/konkav-simulation-of-water-quality-effects-for-cavitating-flows.html
							http://www.hsva.de/our-research/research-energy-efficiency.html#konkavone
51	TSB		2010	LCS	Low Carbon Shipping - A Systems Approach		http://www.lowcarbonshipping.co.uk/index.php?option=com_content&view=featured&Itemid=101
52	EU	FP-7	2008	MARINECFD	Development of CFD Tools for Large Marine Diesel Engine Applications	3.3	CORDIS project reference: 207232
							http://cordis.europa.eu/project/rcn/89604_en.html
53	EUROSTARS		2009	MARIPEM		3.3	https://www.era-learn.eu/network-information/networks/eurostars/eurostars-cut-off-2/auxiliary-power-generator-based-on-pem-fuel-cell-for-nautic-applications
54	EUREKA & TSB		2009	MARITIME CCS	Carbon Capture and Storage	3.3	https://www.eurostars-eureka.eu/project/id/4804
55	EU	FP-6	2005	MC-WAP	Molten-carbonate fuel Cells for Waterborne APplication	3.3	CORDIS project reference: 19973
							http://cordis.europa.eu/project/rcn/78585_en.html
56	EU	FP-6	2006	METHAPU	Validation of renewable methanol based auxiliary power systems for commercial vessels	3.3	www.methapu.com (bad link)
							CORDIS project reference: 31414
							http://cordis.europa.de/project/rcn/81512_en.html
57	F			Navire démonstrateur Océan Vital		3.4	www.fondationoceanvital.com/les-Applications/Applications-Oceanographiques

#		FP	YEAR (start)	Project reference / Acronym	Project Title	MESA reference(s)	Web Site
58	EU	FP-7	2009	NAVTRONIC	Navigation System for Efficient Maritime Transport	3.7,4.5	http://www.navtronic-project.eu/mainmenu/home.html
59	GR			NEWDRIFT (NTUA-SDL)	National Technical University of Athens - Ship Design Laboratory	3.1	http://www.naval.ntua.gr/sdl
60	EU	FP-6	2003	NG^2SHIPI/F	New generation natural gas ship interfaces	3.3	CORDIS project reference: 506154
							http://cordis.europa.eu/project/rcn/73952_en.html
61	D		2013	NoWelle	Numerical Optimisation of ships with high wave resistance	3.1	www.hsva.de/our-research/research-energy-efficiency.html#nowelle
62	D		2012	PerSEE	Performance of ships in seaway	3.1	www.hsva.de/our-research/research-ship-dynamics.html#persee
63	EU	FP-6	2006	PLUG	Power generation during loading and unloading	3.3	CORDIS project reference: 31477
							http://cordis.europa.eu/project/rcn/81518_en.html
64	EU	FP-7	2009	POSE2IDON	Power Optimized Ship for Environment with Electric Innovative Designs Onboard	3.3	http://www.poseidon-ip.eu/
65	FCH-JU	FP-7	2013	PURE	auxuliary power unit for recreational yachts	3.3	www.pure-project.eu
66	EU	FP-7	2012	REFRESH	Green Retrofitting of Existing Ships	3.3,3.6	http://www.refreshproject.eu/
67			2012	Rensea	Regenerative Hybrid-Electric Propulsion	3.3	http://newenergy.is/en/projects/research_and_demonstration_projects/rensea

#		FP	YEAR (start)	Project reference / Acronym	Project Title	MESA reference(s)	Web Site
68	Lloyd's Register, Enterprises Shipping and Trading, Hyperion Power Generation and BMT			Research Consortium			
69	EU	FP-7	2011	RETROFIT	Retrofitting ships with new technologies for improved overall environmental footprint		http://www.retrofit-project.eu/
70				Sailboat Zero CO2		3.3	http://www.zeroco2sailing.com/en
71	EU	FP-7	2011	SEAKERS (for yachts)	SEA Kinetic Energy Recovery System	3.4	CORDIS project reference: 262591
							http://cordis.europa.eu/project/rcn/99157_en.html
72	EU	FP-5	2001	SEAROUTES	advanced decision support for shiprouting based on full-scale ship-specific responses as well as improved sea and weather forecasts including synoptic, high precision and realtime satellite data		CORDIS project reference: G3RD-CT-2000-00309
							http://cordis.europa.eu/project/rcn/53104_en.html
73			2011	SEKTE	Smoke Emission Abatement System for Fast Passenger Ships Maneuvering in Island Harbours		www.lme.ntua.gr:8080/research-1/recent-research/sekte

#		FP	YEAR (start)	Project reference / Acronym	Project Title	MESA reference(s)	Web Site
74	EU	FP-7	2013	SHOPERA	Energy Efficient Safe SHip OPERAtion	3.1,4.4	http://shopera.org
75	EU		2007	SMART-H2			http://newenergy.is/en/projects/research_and_demonstration_projects/smarth2
76	EU	FP-6	2006	SMOOTH	Sustainable Methods for Optimal design and Operation of ships with air lubricaTed Hulls	3.1	www.smooth.ships.eu
77	S		2012	SPIRETH		3.3	Swedish Energy Agency, the Baltic Sea Action Plan Facility Fund (Nordic Investment Bank), the Nordic Council of Ministers' Energy & Transport
78	EU	FP-7	2010	STREAMLINE	Strategic Research For Innovative Marine Propulsion Concepts	3.1,3.2,4.1	www.streamline-project.eu
79	EU	FP-7	2011	TARGETS	Targeted Advanced Research for Global Efficiency of Transportation Shipping	3.1,3.2,3.6,3.7	www.targets-project.eu
80	EU	FP-7	2011	TEFLES	Technologies and Scenarios for Low Emissions Shipping	3.3,3.6,4.5	http://tefles.eu/
81	EU		2004	TEN-T Priority 21		3.3	http://Ec.europa.eu/transport/themes/infrastructure/ten-t-policy/priority-projects/index_en.htm
82	D		2011	TUG Design	Seakeeping Behaviour of Offshore Workboats	3.1	http://www.hsva.de/our-research/research-ship-dynamics.html#tugdesign
83	EU	FP-7	2011	ULYSSES	Ultra-Slow Ships	3.2,3.3	http://cordis.europa.eu/result/rcn/54131_en.html
84	UK TSB			Vessel Efficiency I			
85	EU	FP-6	2005	VIRTUE	The Virtual Towing Tank Utility in Europe	3.1,3.2	www.virtualbasin.org
86	EU	FP-5	2001	VRSHIPS-ROPAX2000	Virtual Reality Ship Systems	3.1	www.vrsproject.com

#		FP	YEAR (start)	Project reference / Acronym	Project Title	MESA reference(s)	Web Site
				(NTUA-SDL)			
87	LIFE		2006	WINTECC	Demonstration of an innovative wind propulsion technology for cargo vessels	3.3	http://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=home.createPage&s_ref=LIFE06 ENV/D/000479
88	LIFE		2006	Zemships	Zero Emission Ships	3.3	http://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=home.createPage&s_ref=LIFE06 ENV/D/000465
89	TEN-T		2012	BLUE CHANGE	Blue Corridors enHance through the Application of Natural Gas Energy	LNG	https://ec.europa.eu/inea/en/ten-t/ten-t-projects/projects-by-country/spain/2011-es-92138-s
90	TEN-T		2012	GREENCRANES	Green technologies and eco-efficient alternatives for cranes & operations at port container terminals	LNG	https://ec.europa.eu/inea/en/ten-t/ten-t-projects/projects-by-country/multi-country/2011-eu-92151-s
91	TEN-T		2012	Make a Difference	Make a Difference	LNG	https://ec.europa.eu/inea/en/ten-t/ten-t-projects/projects-by-country/multi-country/2011-eu-92079-s
92	TEN-T		2012		Technical and design studies concerning the implementation of a LNG bunkering station at the port of Dunkirk	LNG	https://ec.europa.eu/inea/en/ten-t/ten-t-projects/projects-by-country/france/2011-fr-92026-s
93	TEN-T		2012	Fjalir	Fjalir project	LNG	https://ec.europa.eu/inea/en/ten-t/ten-t-projects/projects-by-country/sweden/2011-se-92148-p
94	TEN-T		2013		Flexible LNG bunkering value chain in the Spanish Mediterranean Coast	LNG	https://ec.europa.eu/inea/en/ten-t/ten-t-projects/projects-by-country/spain/2012-es-92034-s

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95	TEN-T		2013		LNG hub in the northwestern Iberian Peninsula	LNG	https://ec.europa.eu/inea/en/ten-t/ten-t-projects/projects-by-country/spain/2012-es-92068-s
96	TEN-T		2014		Innovative LNG-powered hopper barge deployed under real-life conditions in the ports of Bremen and Bremerhaven	LNG	https://ec.europa.eu/inea/en/ten-t/ten-t-projects/projects-by-country/germany/2013-de-92041-s
97	TEN-T		2014		Realizing, real-life demonstration and market introduction of a scalable, multi-modal LNG-terminal in the seaport of Bremen for the reliable supply of LNG as alternative fuel to all transport modes	LNG	https://ec.europa.eu/inea/en/ten-t/ten-t-projects/projects-by-country/germany/2013-de-92056-s
98	TEN-T		2014		Pilot deployment of a LNG propulsion system for combined passenger and freight transportation for the year-round provision to the peripheral and island region of Helgoland	LNG	https://ec.europa.eu/inea/en/ten-t/ten-t-projects/projects-by-country/germany/2013-de-92079-s
99	TEN-T		2014		Pilot Project to promote the use of LNG fuel: Installation of 200 tons LNG tank and filling facility at the port of Hirtshals, Denmark for fuelling of passenger/cargo	LNG	https://ec.europa.eu/inea/en/ten-t/ten-t-projects/projects-by-country/denmark/2013-dk-92060-s

#		FP	YEAR (start)	Project reference / Acronym	Project Title	MESA reference(s)	Web Site
					vessels with a view to later establishment of a a larger tank at the port		
100	TEN-T		2014		LNG Feeders, a Solution for Archipelagos far from LNG Storage Plants	LNG	https://ec.europa.eu/inea/en/ten-t/ten-t-projects/projects-by-country/spain/2013-es-92006-s
101	TEN-T		2014		LNG uptake in the UK: a real-life trial with the first small scale bunkering infrastructure in Teesport and innovative LNG vessels	LNG	https://ec.europa.eu/inea/en/ten-t/ten-t-projects/projects-by-country/multi-country/2013-eu-92045-s
102	TEN-T		2013		LNG Masterplan for Rhine-Main-Danube	LNG	https://ec.europa.eu/inea/en/ten-t/ten-t-projects/projects-by-country/multi-country/2012-eu-18067-s
103	TEN-T		2010		LNG infrastructure of filling stations and deployment in ships	LNG	https://ec.europa.eu/inea/en/ten-t/ten-t-projects/projects-by-country/multi-country/2010-eu-21112-s
104	TEN-T		2012		LNG in Baltic Sea Ports	LNG	https://ec.europa.eu/inea/en/ten-t/ten-t-projects/projects-by-country/multi-country/2011-eu-21005-s
105	TEN-T		2012	COSTA	developing a global strategy for the promotion of LNG (liquefied natural gas) as marine fuel	LNG	https://ec.europa.eu/inea/en/ten-t/ten-t-projects/projects-by-country/multi-country/2011-eu-21007-s
106	TEN-T		2012		LNG Rotterdam Gothenburg	LNG	https://ec.europa.eu/inea/en/ten-t/ten-t-projects/projects-by-country/multi-country/2012-eu-21003-p

#		FP	YEAR (start)	Project reference / Acronym	Project Title	MESA reference(s)	Web Site
107	TEN-T		2012	WINMOS	Winter Navigation Motorways of the Sea	LNG	https://ec.europa.eu/inea/en/ten-t/ten-t-projects/projects-by-country/multi-country/2012-eu-21008-m
108	TEN-T		2012	SEAGAS	SEAGAS	LNG	https://ec.europa.eu/inea/en/ten-t/ten-t-projects/projects-by-country/multi-country/2012-eu-21006-s
109	TEN-T		2013		LNG Bunkering Infrastructure Solution and Pilot actions for Ships operating on the Motorway of the Baltic Sea	LNG	https://ec.europa.eu/inea/en/ten-t/ten-t-projects/projects-by-country/multi-country/2012-eu-21009-m
110	TEN-T		2013		Into the future - Baltic So2lution	LNG	https://ec.europa.eu/inea/en/ten-t/ten-t-projects/projects-by-country/multi-country/2013-eu-21003-s
111	TEN-T		2014		LNG in Baltic Sea Ports II	LNG	https://ec.europa.eu/inea/en/ten-t/ten-t-projects/projects-by-country/multi-country/2013-eu-21007-s
112	TEN-T		2013		Channel LNG	LNG	https://ec.europa.eu/inea/en/ten-t/ten-t-projects/projects-by-country/multi-country/2013-eu-21005-p
113	TEN-T		2013		Pilot Implementation of a LNG-Propulsion System on a MoS Test Track in the Environmental Model Region 'Wadden Sea'	LNG	https://ec.europa.eu/inea/en/ten-t/ten-t-projects/projects-by-country/multi-country/2013-eu-21018-s
114	TEN-T		2013	Costa II East - Poseidon Med	Costa II East - Poseidon Med	LNG	https://ec.europa.eu/inea/en/ten-t/ten-t-projects/projects-by-country/multi-country/2013-eu-21019-s

7 Appendix 2:

7.1 Literature:

/1/ Ship Efficiency: The Guide, www.fathomshipping.com
/2/ Global Marine Technology Trends 2030, 2015 Lloyd's Register, QinetiQ and University of Southampton
/3/ Effizienter und zuverlässiger Schiffsbetrieb mit Antriebs- und Energiesystemen von Siemens, 2015, Siemens AG (www.siemens.com/press/PR2015090325PDDE)
/4/ Historical trends in ship design efficiency, Jasper Faber, Maarten 't Hoen, Delft 2015
/5/ Green Ship Technology Book, EMEC, emec.eu/green
/6/ SMM green Shipping Guide, SMM 2010
/7/ Ship Energy Efficiency Measures, ABS 2014
/8/ Second IMO GHG Study 2009, IMO
/9/ Third IMO Greenhouse Gas Study 2014, IMO
/10/ REDUCTION OF GHG EMISSIONS FROM SHIPS, Report of the Working Group on Energy Efficiency Measures for Ships, MEPC 61, 2010, IMO
/11/ 4th International conference Ship Efficiency, Hamburg, 2013, STG
/12/ Technology outlook 2020, published by Det Norske Veritas, 2013
/13/ Ship Efficiency – Slow Steaming, Lloyd's Register, 2014
/14/ Before and after data convincing for container ship nose replacement, Maritime Propulsion, 2013
/15/ The economic and environmental impact of slow steaming, Kontovas, C. and Psaraftis, H. DTU Transport, 2014.
/16/ Fuel Savings Expected From New ISO Standard For Hulls, Propellers, in http://fathom-ctech.com, 2014
/17/ Hull Coatings for Vessel Performance, in: Fathom Focus, 2013
/18/ Marine Propeller Roughness Penalties, Mosaad, M. A., Newcastle, 1986
/19/ How Will the Shipping Industry Evolve in the 21st Century?, 2013, www.enav-international.com
/20/ World Ocean Review 1, Chapter 8 – Das Meer – der weltumspannende Transportweg (in German), http://worldoceanreview.com/wor-1/