TECHNICAL AND OPERATIONAL OPTIONS CATALOG

Proposal for Technical and Operational Options to reduce Fuel Consumption and Emissions from 'Inter-Atoll Transport' and 'Inside-Lagoon Transport'

In the Project **Transitioning to Low Carbon Sea Transport in the Republic of the Marshall Islands**

Between

Federal Ministry for the Environment, Nature Conservation and Nuclear Safety

Implemented by

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

Partnered by

Published by the University of Applied Sciences Emden-Leer

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Transitioning to Low Carbon Sea Transport

Technical and Operational Options Catalog

Proposal for Technical and Operational Options
to reduce Fuel Consumption and Emissions

from

Inter-Atoll-Transport
and
Inside-Lagoon-Transport

MCST Framework for TLCSeaT


Photo: Karen Earnshaw

This report was prepared within the project 'Transitioning to Low Carbon Sea Transport' in the Republic of the Marshall Islands.

Between:
Republic of the Marshall Islands (RMI)
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU)

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Partnered by:
The University of the South Pacific (USP)
Micronesian Center for Sustainable Transport (MCST)
Marshall Island Shipping Cooperation (MISC)
RMI Ministry of Transportation & Communications
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Published by the University of Applied Sciences Emden/Leer, **August 2019**

The project 'Transitioning to Low Carbon Sea Transport' is funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety within the International Climate Initiative of the German Federal Government 2016.

I. Content

1 Introduction

The cooperation project 'Transitioning to Low Carbon Sea Transport' (TLCSeaT) has been initiated to support the Republic of the Marshall Islands to achieve the NDC in the field of waterborne transportation between the islands and inside the lagoons.

Technical options will be presented for retrofitting one or more ships of the existing MISC fleet. Complementing the fleet by a new built is an additional option, where the approach of designing a tailor-made transport solution without the limitations of adapting to the given designs and technical installations leaves higher fuel saving potentials. Although more challenging for the engineers retrofitting options could create a large potential of existing ships for saving fuel and CO_2 at lower costs than by replacing them. The design of a tailor-made ship for ocean transport between the islands seems to be rather the second step after gaining experience with low carbon ship technology on the base of retrofitting existing ships and evaluating the outcome.

For retrofitting a ship from MISC a long-term plan including all technical details has to be worked out. Further, the company has to arrange a schedule taking into account that the respective vessel is out of service during the works in the shipyard. For efficient conduct of the project, all parties involved shall be enabled to start the planning and preparation phase as early as possible. Therefore, the basic technical options to achieve the set carbon saving goals shall be presented at an early stage to enable an effective decision process. This report outlines a number of selected technical and operational options. It will be presented on the 4^{th} Management and Technical Advisory Committee (MTAC) Meeting in May 2019 to initiate the decision-making process.

A team of marine engineers of Emden/Leer University of Applied Sciences has prepared this report with selected options. The utmost care and diligence have been exercised to include all information and advice from the local experts. However, for the sake of not overloading the report, the selection of options had to be limited. To eliminate the risk of not including important options or overseeing any demands this paper shall be seen as a draft report. There will be a period for reviewing the draft report and proposing enhancements and changes. All parties involved are invited to hand-in their comments and specific interests. It is the intention of the project to suit local demands in the best possible way for the objective of transitioning to low carbon transportation.

Basic Concept

The main objective of the TLCSeaT project is to demonstrate ways for the transition to low carbon sea transport with special regard to the conditions and needs of the Marshall Islands. The outcomes of the project should give workable technical and operational solutions as a base to achieve the goals of the Nationally Determined Contributions (NDC). At the same time, an energy efficient islands supply fleet shall strengthen the resilience against crisis caused by natural or economic reasons.

From the baseline study, it becomes obvious that optimized operational procedures, such as routing/logistics, engine maintenance, and hull cleaning do not comprise sufficient fuel and emission saving potential to reach the short and mid-term NDC`s (2025, 2030) of the national climate strategy.

The estimated potential by operational improvements (-17 % to -27 %) is significantly smaller than the NDC 2025 (-32%), respectively the NDC 2030 (-45%)

Therefore, the project needs to include the transition to low carbon ship propulsion for higher saving potentials meeting the climate targets. From the wider range of technical options, the transition to alternative fuels such as LNG (Liquefied Natural Gas) requires new infrastructure and will lead to high fuel costs. This may raise economic risks. Even the level of technical maturity in the use of new fuels in combustion engines has to be seen as critical as increased wear and tear may present typical risks. A workable solution is the use of renewable energy for ship propulsion and auxiliary electricity to take over a significant load from the main engine and diesel generators.

The combination of operational measures to raise the ship's efficiency and the use of renewable energy has the potential to reach the short and mid-term NDC. The project should demonstrate the potential of fuel and emission savings of 50% for one or more ships of the MISC fleet on the base of retrofitting.

When looking at the potentials of renewable energy the available atmospheric energy density of the sea area and the achievable efficiency for the conversion into thrust or electricity will drive the decisions for technical options. From performance potential analysis of different technologies in regard to the prevailing weather and environmental conditions following recommendations can be clearly pointed out.

- wind/sail technology has by far the highest potential for ship propulsion
- wind and solar technologies are both suitable for the supply of electricity to auxiliary systems

From this basic analysis of the boundary conditions, technical and operational measures described in this report have been developed.

Structure of the Report

This report is a catalog of options to reduce the carbon footprint of shipping. Technical and logistical concepts for emission reduction were developed. This includes proven techniques to improve ship efficiency, as well as innovative new technologies such as wind propulsion systems, both for Inter-Atoll, as well as Inside-Lagoon shipping.

The report is structured in 3 main parts:

- A case study for Inter-Atoll transport, describing integrated technical and operational measures to achieve high saving potentials in relation to the expenses (chapter 2)
- Detailed feasible technical and operational options for Inter-Atoll transport (chapter 3)
- Detailed feasible technical and operational options for Inside-Lagoon transport (chapter 4);

In order to achieve the most sustainable and long-lasting improvements, this report is composed with an open structure, providing the possibility to share knowledge, technology and experiences between Inter-Atoll and Inside-Lagoon shipping.

The options for in this report provide the possibility to significantly lower the carbon footprint of the entire fleet. The operational measures discussed include slow steaming, weather routing and voyage optimization, logistics and cargo hold efficiency, navigation, hull cleaning and training of the crew. The technical measures considered include wind assisted propulsion, auxiliary and main engine systems. Considerations and possibilities for a new built vessel are discussed as well.

The options for lagoon transport follow a structure of less complexity. A number of different boat designs have been evaluated and approved by WAM in the first project phase. During the second phase, any one of the designs may be built, tested and evaluated. Details of the designs are included in this report in chapters 3 and 4 without any limitations to changes that may be found necessary in the upcoming process.

1.1 Background

This report is taking into account the inputs from the political framework in regard to the climate strategy and preceding surveys and studies that have been conducted recently. Further, the role of cultural heritage is pointed out as an important factor and potential driving force.

1.1.1 RMI Climate Strategy

The Government of the Marshall Islands has presented the '2050 Climate Strategy - Lighting the way' to set a clear framework for progressing towards net zero greenhouse gas emissions by 2050, as well as transitioning to an economy and society that is resilient and can adapt to the inevitable impacts of climate change[1].

Following details are reproduced from the climate strategy.

RMI produced its NDC in 2015. The key GHG provisions of the NDC state that:

- RMI commits to a quantified economy-wide target to reduce its emissions of GHGs to **32% below 2010 levels by 2025**;
- RMI communicates, as an indicative target, its intention to reduce its emissions of GHGs to **45% below 2010 levels by 2030**;
- These targets put RMI on a trajectory to nearly halve GHG emissions between 2010 and 2030, with a view to achieving net zero GHG emissions by 2050, or earlier if possible.

RMI's 2050 Strategy also includes three illustrative Scenarios for RMI's GHG emissions:

- A 'Moderate' enhanced ambition Scenario, reflecting technically and economically feasible targets;
- An intermediate 'Significant' enhanced ambition Scenario, which is equivalent to the Lighthouse Scenario, but is delayed by 15 years due to presumed lack of funding; and
- A 'Lighthouse' enhanced ambition Scenario, which is technically feasible but more expensive.

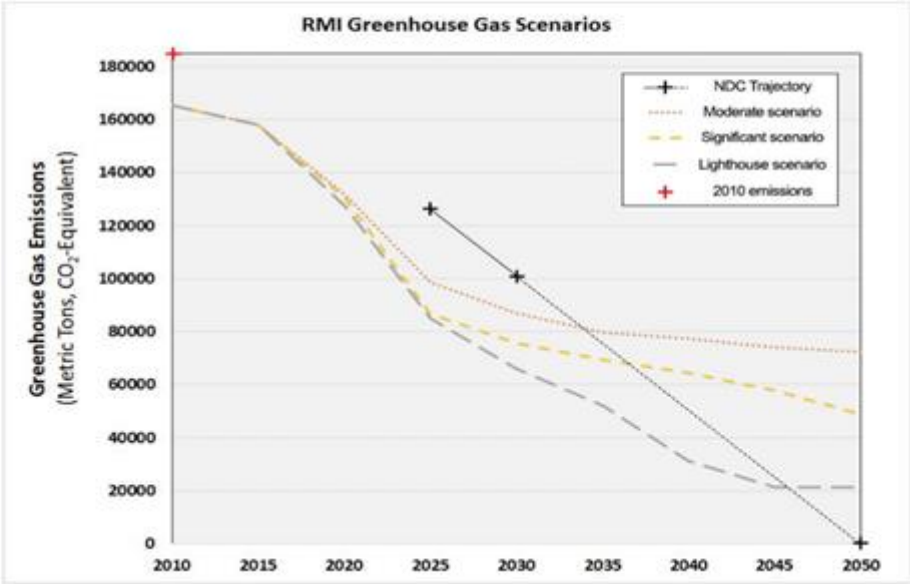

Figure 1: RMI Greenhouse Gas Emissions Reductions – NDC Trajectory and Scenarios[1]

Specifically for the domestic Ocean based transportation there are following Headline Recommendations[2]:

- Improve data collection to better illustrate what proportion of imported fossil fuels are used by domestic sea-based transport
- Explore options to reduce GHG emissions from domestic ocean-based transport, including by using the results of the GIZ/University of the South Pacific (USP) Low Carbon Sea Transport Transition Project (TLCSeaT); and
- Consider institutional reforms that will allow the Ministry of Transport and Communication (MTC) to exercise more effective regulatory control over the operational aspects of domestic sea transport in addition to managing the infrastructure.

Further reference is made to the different options of reducing fuel consumption, e.g., through improved ship design for new builds, low carbon propulsion technology, ship operational fuel saving measures and improved port logistics. The structured collection of ship efficiency data is found to be a prerequisite giving a better overview of the actual fuel consumption in waterborne transportation.

[1] Government of the Republic of the Marshall Islands, TTE Committee (2018), '2050 CLIMATE STRATEGY - Lighting the way', Foreword by the President, Majuro
[2] Government of the Republic of the Marshall Islands, TTE Committee (2018), '2050 CLIMATE STRATEGY - Lighting the way', Foreword by the President, Majuro, page 10

1.1.2 Fleet Survey and Baseline Study

There have been first efforts to provide for a database in domestic ocean transportation including guidance for the approach to reduce fuel consumption and emissions. Both, a fleet survey[3] and a baseline study[4] conclude that there are different technical and operational fields with significant potentials to reduce fuel consumption and raise transport efficiency.

Major recommendations are:

- Collection and analysis of ship performance data to gain understanding and competence in ship efficiency
- Voyage optimization, e.g., through
  - Alternative routes and scheduling
  - Slow steaming
  - Just in time arrival
  - Improved cargo logistics
- Increased effort in ship maintenance
  - Main engine and auxiliary machinery
  - Hull and propeller cleaning
- Use of wind and solar power for
  - Ship propulsion
  - Ship's electricity demand

The baseline study by Oxley estimates a potential in cost reductions of up to US$ 400 k p.a. through fuel savings in the range of 17 % to 27 % by improved operational practices. CO_2 emission reductions can amount to about 900 tons. New technical approaches were not included in this estimation. There are references towards the use of wind and solar power for ship propulsion and auxiliary electric systems. However, a detailed analysis is beyond the scope of the report. The model for the implementation of Flettner rotors cannot be validated for the lack of details. Figures given are not matching results from published research and trial cases.

1.1.3 Cultural Heritage

For centuries, Ri Majol, the people of the Marshall Islands, were known for their superior boat building and sailing skills. The lagoons of their low-lying coral atolls were crowded by sails of smaller outrigger canoe designs for rapid inside lagoon transportation, food gathering, and fishing. They traveled frequently between their atolls (for trade and war) on big offshore canoes called 'Walap' (some of them 100ft long).[5]

Today the traditional outrigger canoe designs are not any longer in use for inter-atoll voyages in RMI. None of the traditional inter-atoll canoes (Walap) survived. The smaller lagoon designs got under

[3] Held, R. (2018), 'Transitioning to Low Carbon Shipping - A Survey on the Fleet within the Inter-Island Shipping in the Republic of the Marshall Islands with Special Regard to CO2 Emissions and their Reduction Potential', Bachelor Thesis in Ship Operations Engineering, University of Applied Sciences Flensburg

4 Oxley, M. (2018), 'Establishing Baseline Data to Support Sustainable Maritime Transport Services-FINAL REPORT', TA-8345 REG: Establishment of the Pacific Region Infrastructure Facility Coordination Office (PRIF)

[5] https://www.canoesmarshallislands.com/

pressure of the spreading western lifestyle and growing boat imports and finally died out in numerous atolls. During the late ’80s, only very few canoes were built. Up from 1989, with the documentation project Waan Aelõñ Kein, and later the Waan Aelõñ in Majel training program the interest in traditional canoes experienced a revival.

Even though the art of traditional canoe building has been almost extinct in RMI for several reasons in the past, the sophistication behind those vessels has inspired many boat and yacht designers all over the world. This fascination led to several interesting sailing boat designs, mainly on the pursuit of maximizing vessel speed.

Traditional canoe racing in RMI:

- Annual regatta for traditional canoe racing.
- The small and medium sized boats were used in the past, for fishing and inside-lagoon transport.
- Every atoll had its own designs, adapted to local conditions and the needs of the people.

Figure 2: Traditional canoe racing in RMI[6]

Traditional Marshallese ‘Walap’

- Traditional voyaging canoes beached in the lagoon of Majuro at the end of the 19th century.
- For Centuries, cargo and passenger transport was accomplished by highly specialized vessels, moving at high speeds between the atolls of RMI and beyond.
- Powered by the wind and built from renewable resources, these vessels were climate neutral and sustainable solutions for inter-atoll transport.

Figure 3: Marshall Islands Proa[7]

From a technical point of view, it is no wonder that the idea of the Pacific Proa was taken up primarily for high-speed sailing. Due to the extreme slenderness, the hull is able to pierce its own bow wave and the wave resistance is no longer a speed barrier. The total weight of the vessel is a good 30% lower than that of a comparable catamaran, as only one main hull is required, while its sail

[6] Source: WAM
[7] http://www.pacificproa.com/micronesia/marshall_isles_proas.html

carrying capacity is higher than that of most mono hull vessels due to the long lever to the flying weight of the cantilever hull.

1.2 Vision

The first project phase, in the studies and reports by Oxley[8] and Held[9], has revealed that there is a high motivation to rebuild the shipping sector and reconnect to their own maritime heritage at the same time. It is not only a strong mindset towards sustainable and low carbon transportation at sea but also the desire to recover maritime knowledge and competencies. A revival of Marshallese maritime culture fulfilling nowadays islanders' needs and meeting all requirements for a small carbon footprint with low impact on the environment seems to be a good vision to guide this project and further developments into the future.

It is a matter of drawing up a realistic picture of the future maritime sector from today's situation, based on experience and knowledge as well as the determined national climate targets. Even though new technologies provide the possibilities to achieve those targets, it is well worth taking a look back at the history of the Marshall Islands. It gives a very good example of a functioning zero-emission maritime trading network encompassing both inside-lagoon traffic and inter-atoll trade.

About 150 years ago, the Marshallese sea transport and trading network was based on large canoes with capacities for several tons of freight and up to 50 passengers. These canoes were perfectly adapted to the local weather conditions and operated at almost twice the speed of today's vessels when using favorable wind patterns. They were built from natural and locally available resources.

Hence, the transportation system at that time was exactly in line with the Nationally Determined Contribution to climate targets of 2050. However, within recent decades of development, the needs for transportation services have changed tremendously. Modern lifestyle has created higher consumptions and the need for quick delivery of goods and short travel times. Nevertheless, the question should be raised whether it is possible and reasonable to include traditional boat designs of the Marshall Islands in the development of a new futuristic concept of island traffic.

Many questions of how cargo and passenger transportation between the atolls can be handled in the future need to be discussed and examined in detail, for it seems that today's vessels may not be optimally suited for future transportation tasks and their changing boundary conditions. High connectivity to the outer islands at low cost and low environmental impact is the ultimate vision. Looking at economic and social trends it becomes obvious that people are moving towards the cities and metropoles leaving the remote and rural areas behind. One of the driving factors is the lack of job opportunities and connectivity for both economic and social reasons. On Pacific Island Countries, highly efficient sea transportation for goods and passengers will be a key factor for sustainable development of intact communities on remote atolls and islands.

Coming back to the technical issues of this project it becomes obvious that 'Transitioning to Low Carbon Sea Transport' is interconnected with many other issues and objectives. The transitioning

[8] Oxley, M. (2018), 'Establishing Baseline Data to Support Sustainable Maritime Transport Services-FINAL REPORT', TA-8345 REG: Establishment of the Pacific Region Infrastructure Facility Coordination Office (PRIF)

[9] Held, R. (2018), 'Transitioning to Low Carbon Shipping - A Survey on the Fleet within the Inter-Island Shipping in the Republic of the Marshall Islands with Special Regard to CO2 Emissions and their Reduction Potential', Bachelor Thesis in Ship Operations Engineering, University of Applied Sciences Flensburg

process has to be seen as a long-term operation of well-tuned consecutive steps. In this regard, it seems to be more important to identify and adopt a variety of future technologies and designs well suited for the Marshall Islands rather than focusing on the design of a single ship.

There are many challenging questions on the road ahead, e.g.,

- What are the most suitable low carbon ship technologies?
- Will we see a revival of wind propulsion? Based on conventional sails or modern adaptions such as the Flettner rotors?
- Will there be a larger number of smaller vessels sailing more often for better connectivity of the outer islands? Or few bigger ships with large capacity?
- Will we see new designs based on traditional Pacific concepts with multi-hulls rather than nowadays standard mono-hull ships?

Most probably there will be no single answer to these questions. This report can be understood as a starting point with a variety of possible options. The knowledge and experience of all parties involved will grow with the ongoing work on the subjects. High motivation and effort may lead to a new era of low carbon shipping in the Pacific Ocean region connected to hundreds of years' zero-emission sailing experience of the past.

With this vision in mind, the technical and operational measures developed in this report provide a starting point and guideline towards a sustainable future.

2 Inter-Atoll Transport: A Case Study for MV Kwajalein

There are numerous options to reduce fuel consumption and thereby emissions of a vessel. Most options will influence each other in some way. For MV Kwajalein a case study has been carried out to demonstrate the effect and interaction of different possible measures on vessel conversion variants.

The case study is based on MV Kwajalein and gives a short overview of the options described in this report. Since MV Aemman, as well as the new ship currently under construction in China, is of a similar type, most of these options will have a similar effect on those other vessels. Detailed information on the different measures is provided in chapter 3.

Slow steaming has the greatest potential to cut fuel consumption towards a reasonable level if the time schedule of the vessels in question allows the resulting prolonged traveling times. On the road towards the low-emission vessel, slow steaming, however, is only the first step. For further emission reductions, the greatest saving potential lies in direct thrust reduction through the use of wind propulsion technologies in combination with weather routing and voyage optimization.

Further operational measures like increased cargo hold efficiency, logistics, and navigation technologies will help to support the above mentioned measures, expand the scope of possibilities, increase vessel safety and offer time-saving potential.

2.1 Slow Steaming

*Details in Chapter: 3.4 '*Slow Steaming*'*

Of all thinkable measures for fuel and emission savings, slow steaming is the most effective and simplest option to drastically reduce fuel consumption. Following figure based on engine test records, which were carried out at the time of building in 2013 for MV Kwajalein, as well as on basis from resistance calculations for typical wind and weather conditions on the Eastern Route, illustrate this simple truth.

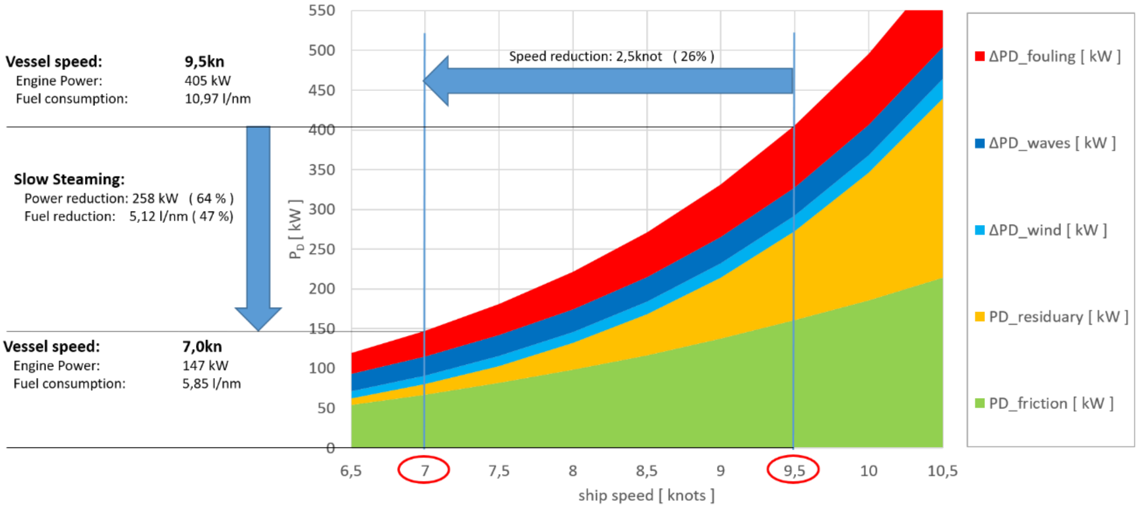

Figure 4: Relationship between resistance, power, and speed for MV Kwajalein in normal service condition[10]

Fuel consumption, as well as emission savings, result directly from reduced main engine power demand. A speed reduction as demonstrated above will lead to approximate 47% fuel and emission savings per nautical mile. Figure 5 displays fuel consumption per nautical mile in dependency on vessel speed.

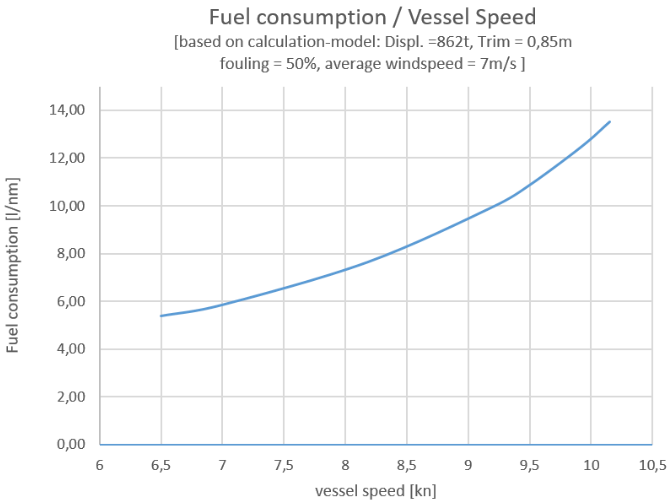

Figure 5: Fuel consumption per nautical mile

However, the time needed for the passages between the atolls will increase by 26 % (following the above-proposed example).

2.2 Coating and Regular in Water Hull Cleaning

Details in Chapter: 3.8 'Hull Coating and Cleaning'

Also displayed in Figure 4 is the effect of added resistance due to fouling. The effect of fouling increases ship resistance by adding to frictional resistance. Added resistance from fouling should be avoided by

[10] Diagram based on simplified formula for residuary resistance calculation. Possible error in total resistance in low speed range of 2-6 %.

appropriate measures. A good option to deal with this problem is regular in-water cleaning in combination with a special coating.

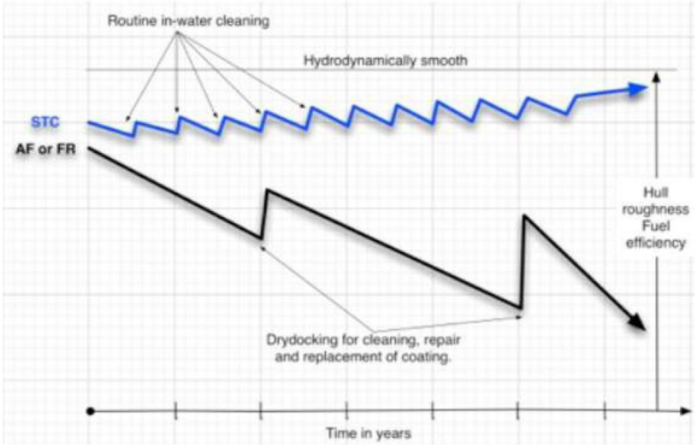

Figure 6: Comparison of hull roughness over time between coating types (AF=anti-fouling, FR=foul-release) due to long term paint degradation[11]

For the MISC fleet, the combination of a Surface-Treated Composite (STC) coating with a cavitation in-water cleaning system is recommended. This combination provides for a smooth hull, the regular cleanings even increase the efficiency of the vessel and dry-docking intervals are no longer crucial for fouling control. The necessary divers to provide the under-water cleaning operations will provide employment at the larger lagoons and the cleaning tools are relatively inexpensive.

2.3 Wind Propulsion Retrofit Variants

Details in Chapter: 3.9 'Wind Assisted Ship Propulsion (WASP)'

Six different retrofit options for wind propulsion technologies have been analyzed in greater detail. The retrofit with one system can be carried out on a minimum basis (Flettner-Min, IndoSail-Min, Conventional-Min) with minimal vessel conversion effort. The other option is a vessel conversion towards a full sailing vessel (Flettner-Max, IndoSail-Max, Conventional-Max). Those second – maximum - refit options can lead to major fuel and emission savings, especially if the full potential of the retrofit options is exploited by voyage optimization, considering typical wind conditions and by the use of weather routing technologies.

[11] van Rompay, B. (2011). Hydrex White Paper No. 5 Underwater ship hull cleaning: cost effective, non-toxic fouling control. white paper, The Hydrex Group, Antwerp, Belgium.

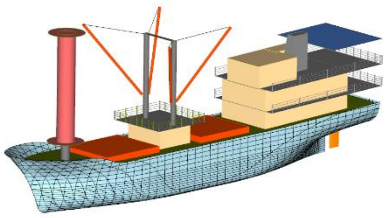

Figure 7: Variant Flettner-Min

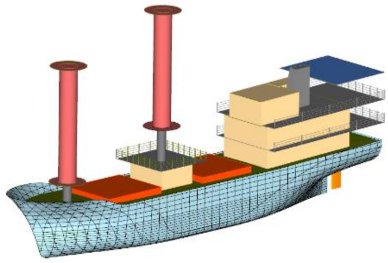

Figure 8: Variant Flettner-Max

The Flettner rotors are fully automatic high-tech solutions, which can be operated from the ship's bridge alone, without any further intervention by the crew. Recently several applications have been successfully tested in the commercial shipping industry.

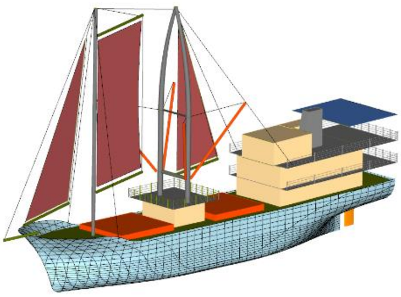

Figure 9: Variant IndoSail-Min

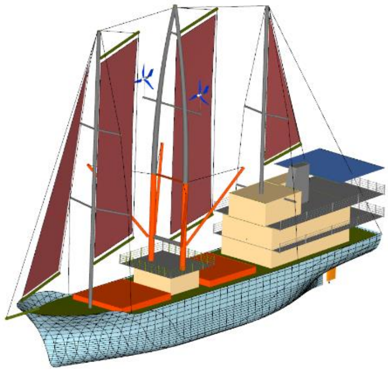

Figure 10: Variant IndoSail-Max

The IndoSail system is a proven, powerful and functional system which has been specially developed for use on small cargo vessels. It can be operated fully automatically as well as manually.

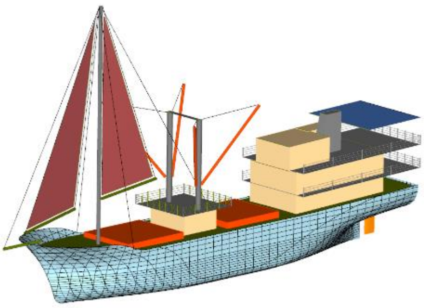

Figure 11: Variant Conventional Rig-Min

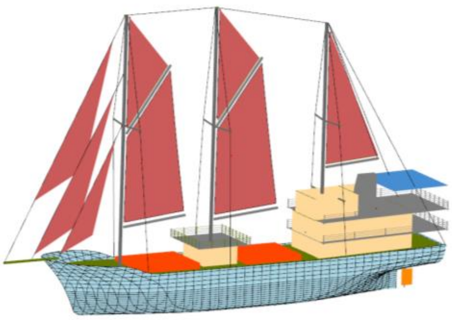

Figure 12: Variant Conventional Rig-Max

The conventional minimal variant is the simplest retrofit variant, but offers only small savings potential, while the traditional gaff sail variant is a system that does not require complex technology, but must be operated completely manually.

The quantification of costs for the above-proposed solutions depends on the specific layout and size of the systems, the grade of automation and many other factors. But from the large variety of wind propulsion technologies, those selected technologies represent most likely the most economical solutions in terms of economic efficiency compared to initial and maintenance costs.

2.4 Saving Potential from Wind Propulsion Technologies

*Details in Chapter: 3.9.7 '*Predicting Saving Potential from WASP'

The expected savings potential for four conversion options with different wind propulsion technologies is shown in the following figure for two different service speeds.

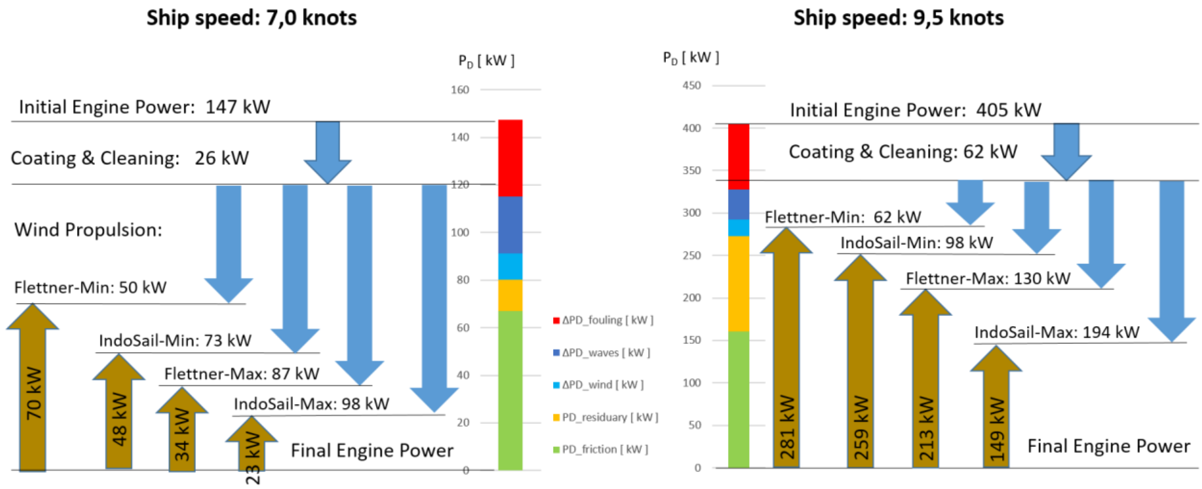

Figure 13: Saving potential from wind propulsion technologies and regular hull cleaning

Currently, MV Kwajalein travels at approximately 9.5 knots. A reduction of the cruise speed to 7 knots would be conceivable, based on the utilization of the vessel.

To give an example for the cost saving potential, one of the above displayed variants has been calculated. In FY 2017 the MV Kwajalein consumed abt. 85,800 gallons/year of diesel oil[12], leading to costs of 250,000 $/year (2.93 $/gallon). The average fuel consumption per nautical mile has been 11 l/nm. By application of slow steaming (7 kn), coating and regular hull cleaning, as well as retrofit to wind propulsion technologies (for this example the IndoSail-Min variant) the average fuel consumption per nautical mile will drop to 3 l/nm, leading to diesel oil costs of abt. 70,000 $/year. The annual financial savings are therefore in the order of 180,000 $/year, a substantial saving. [13]

The power saving potential that is displayed above (Figure 13: Saving potential from wind propulsion technologies and regular hull cleaning) assumes that the vessel is sailing in all directions towards the true wind direction equally often. Since every sail system produces different power depending on wind force and especially wind direction, the full potential of wind propulsion technologies can only be harnessed when the routes of the ships are adapted to the local wind conditions. Saving potential from wind propulsion technologies can be maximized if the vessel is operating in favorable conditions.

[12] Oxley, M. (2018), 'Establishing Baseline Data to Support Sustainable Maritime Transport Services-FINAL REPORT', TA-8345 REG: Establishment of the Pacific Region Infrastructure Facility Coordination Office (PRIF)
[13] Numbers are approximations and subject to changes in the oil price development and dependent on vessel specifics

2.5 Weather Routing and Voyage Optimization

Details in Chapter: 3.5 'Voyage Optimization and Weather Routing'

The saving potential from wind propulsion can be further increased by the application of weather routing as well as voyage optimization based on prevailing wind conditions. Alternative voyage planning and weather routing have the potential to further increase the savings from wind propulsion technologies to more than 90%, in dependency on the installed system and the chosen route.

The graphs in Figure 14 and Figure 15 display the saving potential for the Flettner-Min variant as well as the IndoSail-Max variant in combination with slow steaming (7 knots) in dependency on the course sailed towards the true wind direction (Beaufort 4, ca. 7.6m/s).

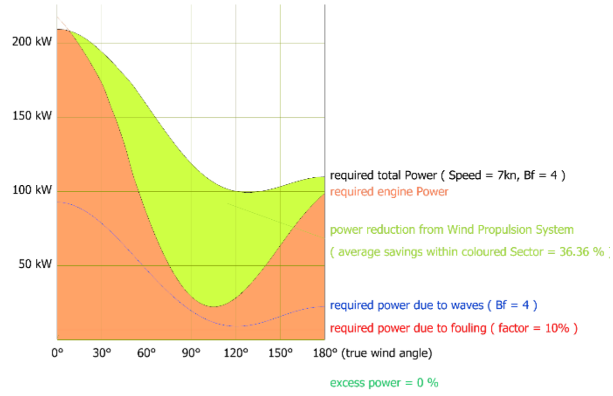

Figure 14: Saving potential Flettner-Min

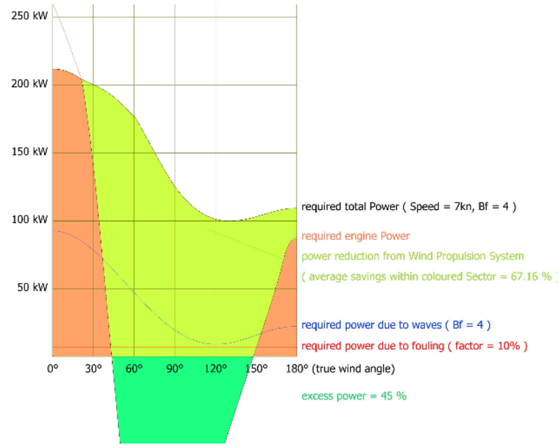

Figure 15: Saving potential IndoSail-Max

The figures show the required total power, resulting from the different resistance components, as well as the power reduction (green areas) that the wind propulsion system is capable to generate in dependency on the course towards the true wind direction. The orange sector displays remaining engine power to maintain a service speed of 7 knots.

For routes perpendicular towards the true wind direction, the saving potential becomes largest. In case of the maximum variants, more than 100% of the required power can be delivered by the wind propulsion system on the selected routes. Excessive power either leads to faster traveling speeds (up to 11 knots and more in favorable conditions) or the power can be transformed to electrical power if the vessel is equipped with the necessary systems.

Figure 16 shows the eastern sector route (orange arrows) with typical wind conditions from Majuro to Kwajalein and back to Majuro. Average wind speed is 7m/s, and most probable true wind direction is E-NE.

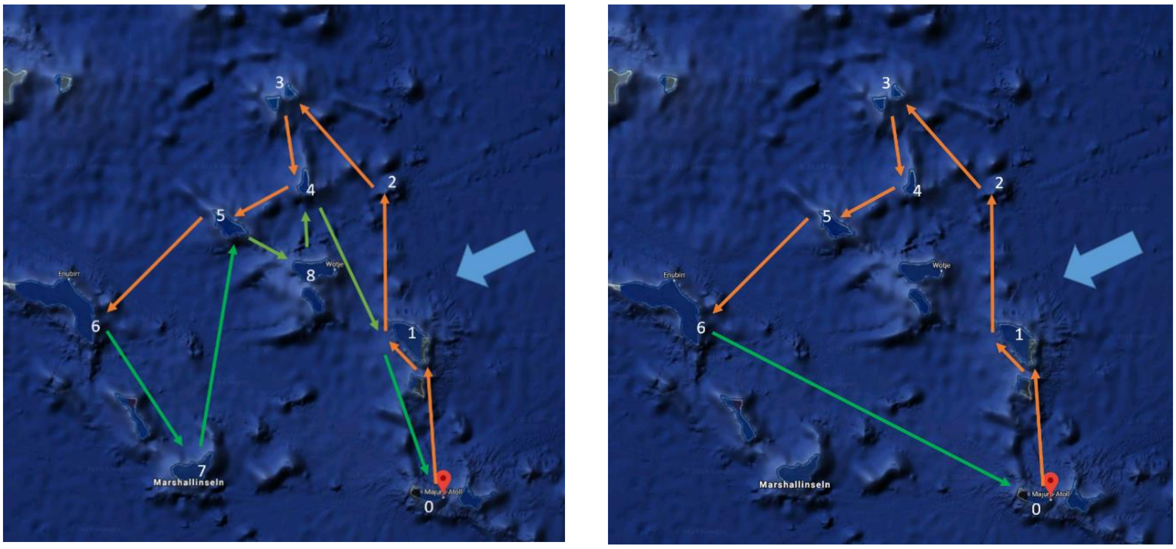

Figure 16: Current and alternative legs of the eastern sector route

The green arrows show a fictive alternative route back to Majuro and are just one demonstration example of how wind propulsion technologies in combination with voyage optimization and weather routing will lead to considerable fuel savings.

The standard route (0-1-2-3-4-5-6 and 6-5-4-3-2-1-0) will lead to a course close to the wind (0% savings from wind propulsion) between 6 and 4 on the return leg (about 15% of the voyage).

If the voyage planning is done by considering wind directions, like on the examples (green arrows), courses against the wind are less likely, leading to additional fuel and emission savings by increased wind propulsion efficiency. In addition, this alternative return route would improve connectivity between the atolls, whereby life quality can be improved. Good voyage optimization in combination with wind propulsion systems and weather routing will minimize fuel consumption.

While good voyage optimization ensures that the probability of favorable wind conditions and thus maximum savings potential of the WASP technologies is available, weather-routing based on current wind forecasts ensures that current weather conditions are used as well as possible on each leg of the voyage.

2.6 Main Engine Drive Train Concepts

Details in Chapter: 3.11 ' Main Engine and Drive Train'

Besides an engine overhaul restoring engine performance as intended from the design stage, there are further options thinkable. The savings that can be achieved by optimizing the main engine drive train result from the following:

- Improved drive train efficiency
- Reduced specific fuel oil consumption of the main engine under part load conditions
- Storage of excessive power (resulting from wind propulsion technologies)
- Biofuels

An analysis of the drive train has been done for MV Kwajalein. First findings and possible refit options are presented below.

2.6.1 Adapt Propeller-Layout to Slow Steaming

For MV Kwajalein it turned out that the existing propeller can be kept for new vessel speed resulting from slow steaming since propulsive efficiency is improved under new working conditions. Propeller load reduction from the utilization of WASP technologies will improve propulsive efficiency by additionally 5 %.

2.6.2 Upgrade to Diesel Electric Drive Train for Increased Efficiency

Reducing the specific fuel oil consumption under very low load conditions can be realized by the utilization of the 80 kW auxiliary generator in combination with a new Electric-Unit (PTI/PTO) installed between the gear and the main engine. Following figures illustrate the saving potential for low load conditions.

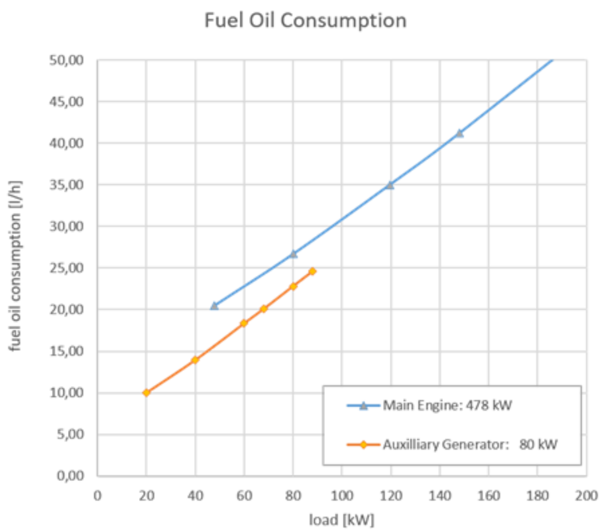

Figure 17: Fuel consumption main engine and auxiliary generator units[14]

Additional costs result mainly from the additional electric engine as well as the necessary changes (rearrangement of machinery) for installation. All existing machinery will be integrated into the concept. Nevertheless, the fuel and emission savings depend on the efficiency of the installed electric engine. Below 90% efficiency, the gains for improved part load efficiency are lost through electric conversion.

However, due to the relatively low efficiency of the auxiliary engines, not much can be gained here. Better results would be achieved by more modern generators (see chapter 3.10.2 Diesel Generators with Variable Engine Speed)

[14] Data from engine tests on test stand

2.6.3 Upgrade Potential to Hybrid-Drive Solution

The diesel-electric layout can be upgraded to a full diesel-electric-hybrid concept by the utilization of a battery bank for storing excess energy. This allows running all participating engines under ideal conditions independently of changing power requirements for propulsive needs. If the battery bank is fully charged, diesel engines can be turned off, using previously stored energy for propulsion needs (electric mode).

Since the costs for an appropriate battery system are very high and changes to adapt the electrical system of the vessels to work in conjunction with the diesel-electric-hybrid-drive-train would raise further technical effort, the total costs will likely exceed the expected benefits. Furthermore, the diesel-electric-hybrid concept demands special skills. Local specialists could hardly carry out maintenance work and monitoring of the systems at regular intervals. Flying in specialized personnel for maintenance work would further increase costs.

However, manufacturing companies claim high saving potential compared to conventional drive-train layouts and reasonable amortization timespans. Another point that speaks for this system is the high diesel-fuel cost in RMI since the amortization timespan depends on fuel-cost savings.

2.6.4 Use of biofuels

The use of biofuels (coconut/algae) would perfectly fit into the concept for final emission reduction. Nevertheless, all other measures should be applied first to minimize fuel consumption. Production cost for biofuel is high and upscale potential is limited, due to high fuel demand as well as the fact that not every engine can be run by biofuels.

2.7 Auxiliary Energy System

Details in Chapter: 3.10 'Auxiliary Energy System'

The analysis of the auxiliary system on MV Kwajalein has shown, that the existing electricity generation is very inefficient for various reasons and accounts for a high proportion (30 to 50 percent) of the total fuel consumption.

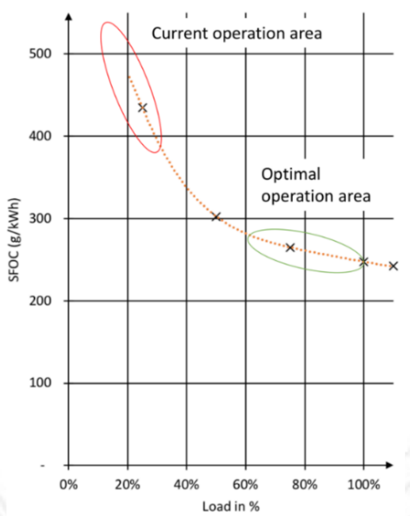

Figure 18: Specific fuel oil consumption of a Diesel Generator

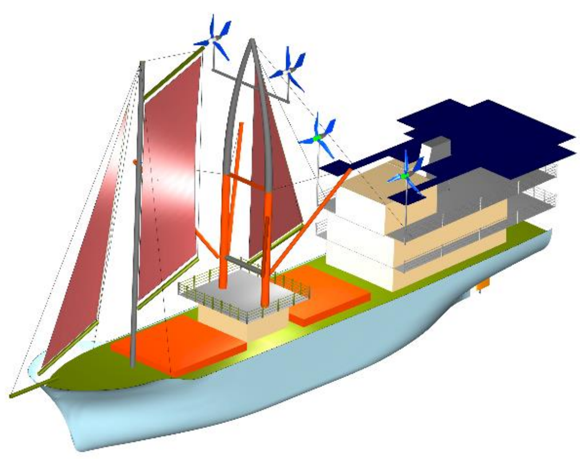

Figure 19: PV and Wind-Generators for MV Kwajalein

The efficiency of the system can be increased significantly by installing an additional Diesel Generator (DG) for low load operating states e.g., navigation and idle states. For further planning and possible implementation, the measurement of surge currents of the individual motors, as well as the preparation of load profiles and peak demands during the different operating conditions are required.

Besides, the integration of renewable energies can reduce fuel consumption. Photovoltaics should primarily be considered here, as it offers the most significant cost-benefit ratio. Wind turbines could also be considered. They are more expensive and more complex than photovoltaic but therefore offer better availability.

The use of photovoltaics and wind turbines requires a higher battery capacity to store unused energy. Combined, the measures for the auxiliary machinery (new smaller generator, photovoltaics and wind turbine) will result in auxiliary fuel consumption savings of about 50%.

The system that is created for auxiliary power generation is also perfectly suited as a charging station for small electric drive systems that could be used on board the small boats for cargo delivery and the collection of copra. See chapter 3.10 for further details.

2.8 Navigation

Details in Chapter: 3.7 'Navigation'

Safe navigation is a critical part of ship operations and the precision level of the navigation has a significant impact on the overall efficiency of the fleet. The vessels in the MISC fleet have different levels of navigation systems on board, with not all the equipment being operational. It is therefore recommended to repair or replace the equipment that is out of order, or install new systems where none is on board at the moment to ensure at least the following standard on each MISC vessel:

Table 1: Recommended navigation equipment

System	Purpose	Recommended model
Satellite Compass	• Provide position • Provide heading for autopilot • Provide roll and pitch data for data analysis	Furuno
Wind sensor	• Provide wind data for fleet analysis	Furuno
Autopilot	• Enable precise navigation on long sea passages to save fuel	Tokimek / Simrad

ECS (Electronic Chart System)	• Display and use current nautical charts in route planning and for safe passage of dangerous areas • Display survey data gathered in the future	Furuno TimeZero
Satellite communication system, e.g., INMARSAT-C	• Receive weather updates for weather routing • Enable ships to be in contact with head office	Furuno

Precise navigation can only be as good as the survey data it is based on. It is therefore recommended to establish a low-cost survey system that is able to improve chart data along dangerous areas and narrow channels. This will enable vessels to sail in these waters even during not optimal conditions (i.e. during hours of darkness), which will improve flexibility and passage times between destinations.

2.9 Cargo Operations, Hold Efficiency and Logistics

Details in Chapter: 3.6 'Cargo Operation, Hold Efficiency'

Operation of cargo is performed by a traditional four boom loading gear for access to the two main cargo holds. If the vessel is to be retrofitted with wind propulsion technologies, depending on the system in question the operating procedure must be altered towards a system that allows the utilization of the specific WP-Technologies. Several alternatives are thinkable that could come to application:

- State of the art - hydraulic crane system
- Integration of the WP-System into the cargo operation by using the WP-System booms
- Alter the existing loading gear to adapt to WP-System
- Choose new positions for loading gear, to not interfere with WP-System

In dependency of the installed WP-System the best working solution will be realized.

The necessity of separate stowage for copra and all other types of cargo is - according to our understanding - the main reason for planning the return trip calling the same atolls as the outward trip. On the way to Kwajalein general goods are brought to the atolls, while on the return journey the copra is collected from these atolls.

Better use of the cargo space capacities (tween-decks), improved storage facilities (stowage boxes) and improved logistics (planning and monitoring) would make it possible to use the different cargo holds of MV Kwajalein in such a way that the proposed round trip would be possible without copra coming into contact with other cargo.

2.10 Cargo and Passenger Operation with tender boats – Parallels towards Inside-Lagoon Transport

Details in Chapter: 4.3 'Electrical and hybrid propulsion'

For all destinations, except the ports of Majuro and Kwajalein, small tender boats carried on deck of the ships are needed for cargo and passenger operations. The operational profile of those boats is similar towards the requirements on the inside-lagoon boats (WAM). They must be capable to carry small amounts of cargo as well as passengers. The boats should be stable in the water and ideally they should be powered by renewable energies.

Electric Hybrid Drive and WP Solutions for MISC tender boats

Since these boats always return to the large vessels after a short trip to the shore, they represent the ideal platform for experimenting with electric-hybrid propulsion technologies. The needed electric energy can be produced on board the MISC vessel by means of efficient generators, photovoltaic and wind-turbines.

Additionally, these boats can be powered by small wind propulsion systems for further reduced energy demand. Herby, different systems can come to application. Measurements on performance and practicality of these systems under real working conditions can be analyzed in the course of this project and will add valuable data to the proceedings of inside-lagoon transport.

2.11 Training Concepts

Details in Chapter: 3.13 'Training Concepts'

In order to help the crews onboard and personnel ashore to implement the chosen measures, it is vital to develop and implement a comprehensive training program. Crew training is best achieved onboard a ship with the new technologies on board, so it is recommended to build up training capacities on the retrofitted vessel. Training onboard this `trial and training vessel' can include modules like basics, operational efficiency, specific technology training and the use of wind propulsion. New technologies can be added and tried in several successive steps, and experiences and knowledge gained can be transferred to the other vessels and will help to ensure long-term sustainability.

3 Detailed Operational and Technical Options for Inter-Atoll Transport

This chapter deals with various operational and technical measures that can be applied to achieve the objective of reducing emissions from MISC ships in particular and similar ships in general. It is our goal to mediate an understanding towards the underlying physical principle of each operational and technical measure that can be taken for improving efficiency and reduce fuel consumption and emissions.

3.1 Description and Assessment Scheme of the Proposed Measures

The description and assessment of the proposed measures are based on the scheme described below:

- Description of the technology based on the technical and scientific background with the aim of presenting the starting point of the measure described as comprehensible as possible.
- Discussion on the interaction of the different measures. Positive as well as negative effects, which could result from an implementation of the measure are presented.
- Consideration of the specific boundary conditions within the Marshall Islands as well as on board the MISC vessels, which could be of particular importance for the implementation of the measure.
- Estimated calculations with regard to performance, costs and the expected fuel/emission savings potential of the proposed measures.

The essential aspects for the selection of technology for in-depth consideration in this catalog are:

- Degree of technological development
- Efficiency and economy

Technical proposals will, therefore, focus on solutions that have been well documented and analyzed by scientific research or previous implementations in a similar context.

Efficiency in terms of expected fuel/emission savings compared to production/installation costs and maintenance and operating costs must be the most important factor in selecting appropriate technologies. Cost and efficiency of the proposed solutions have to be considered. The geographical situation and aspects related to the availability of qualified staff have to be taken into account.

3.2 Considerations on Achievable Savings Potential

Quantifying the savings potential of the proposed measures is a very complex matter since the savings potential of any operational or technical measure depends on many influencing factors. Each implementation of a technical or operational measure changes the initial situation for subsequent measures. In addition, measures that are particularly beneficial for one ship may not be applicable to another ship or may offer only limited savings potential in this context, as different conditions exist for this second application.

The achievable savings potentials are therefore not universally valid but must be re-evaluated for each application. The aim of this catalog, however, is to assess the potential of these measures as well as possible and to identify the influencing factors, which have a positive or negative effect on the corresponding measure.

A mathematical model based on empirical-analytical formulae was used for all calculations of resistance, power requirements and savings potential. The different coefficients used in these formulas were selected to the best of our knowledge. The mathematical model was calibrated on the basis of the test results from the speed trial performed by Mark Oxley with the MV Kwajalein in the lagoon of Majuro in 2018.

However, these calculated values are only a good estimate of the actual ship performance as some parameters were kept constant (displacement, trim) and other assumptions had to be made in lack of detailed information. In reality, displacement and trim of the vessels in question will, of course, vary from voyage to voyage, resulting in different power requirements and savings potential.

The available data will provide a good overview of the possibilities of the proposed measures and should convey a deeper understanding of the underlying technical principles.

The simultaneous implementation of various measures will lead to the overall result of the measures taken within a test period (e.g., one year) becoming visible in the form of time savings as well as bunker costs and emission savings. However, it will be difficult to quantify the specific benefits of individual measures. In order to quantify the savings potential of each individual measure, a step-by-step implementation would be advantageous. In this way, a scientific evaluation of the efficiency of the measures taken could be determined by appropriate measurement techniques. This measurable data on the efficiency of each individual technical and operational measure would be of great value for decision making in terms of scalability towards additional vessels and other regions.

3.3 Fuel- and CO_2-Monitoring

To develop low carbon sea transport in a structured way a monitoring system for fuel consumption and CO_2 emissions needs to be established as a basic tool for evaluation, continuous optimization, and decision-making. The development of such a system requires operational procedures, measurement devices and the recording and processing of data, e.g.:

- measuring and recording the ship’s and boat’s fuel consumption
- measuring ship performance data: speed, distances, engine power, cargo quantity
- documenting cargo flow and cargo handling operations
- evaluating all data and presenting relevant information and statistics
- using relevant information and statistics for continuous optimization, benchmarking, planning and decision-making

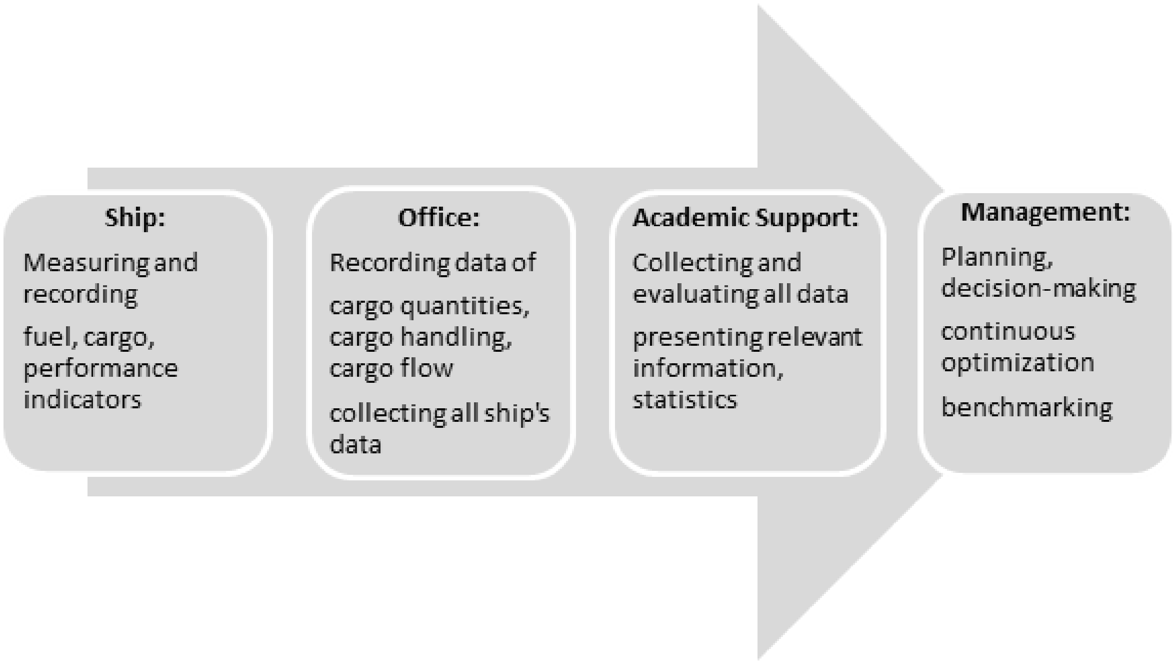

Figure 20: Fuel- and CO_2-Monitoring System – flow chart presenting basic procedures

Building up a monitoring system requires an integrated approach comprising all parts of the chain of sea transport, even better including interfaces with other modes of transport. It can be assumed that all required data is available but needs to be put into a new monitoring process. Onboard the ships effective methods to measure and record fuel consumption and ship performance data need to be introduced. First proposals for automatic recording of ship performance data have been presented and trialed on MV Aemman in February 2019 by Emden/Leer University of Applied Sciences. The objective is to design a simple and low-cost measuring and data collecting system fulfilling the specific requirements of fuel- and performance monitoring. The basic approach is the design of an open source system where local institutions can participate and further develop the system e.g., by adding new components.

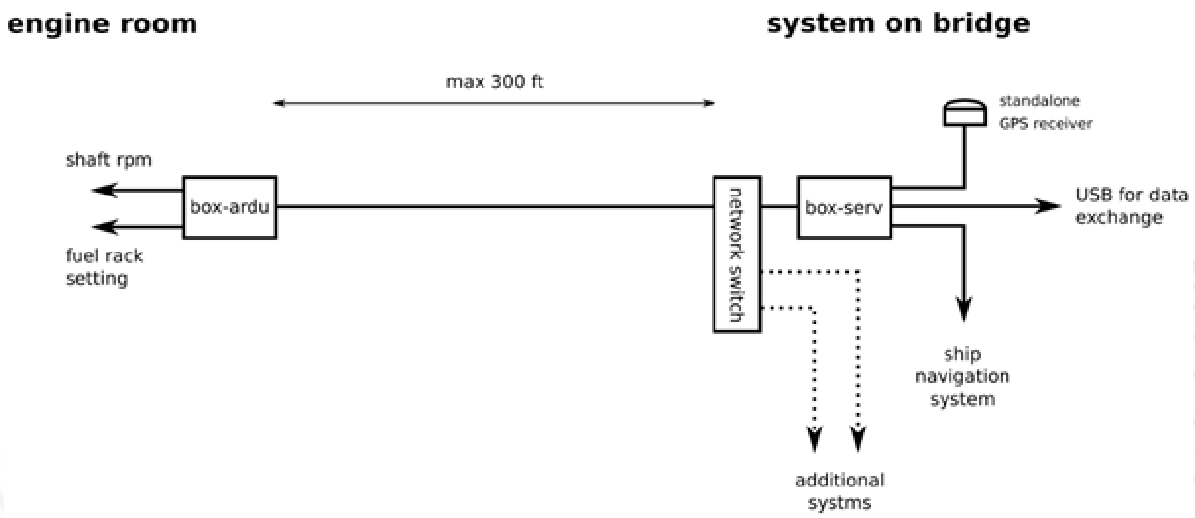

Figure 21: Basic measuring system trialed on MV Aemman in February 2019[15]

[15] University of Applied Sciences Emden/Leer

The installation of measuring and data collecting devices could be arranged as a part of upgrading the navigation system as described in chapter 3.7. The build-up of processing, evaluating and using information as an input for optimization and ongoing improvement can be arranged as a set of training modules for all participating parties. The University of the South Pacific in cooperation with its own Micronesian Center for Sustainable Transport could take over coordination of this process and develop special competencies in this field. Emden/Leer University of Applied Sciences could support through technical and operational inputs.

Fuel- and CO2-monitoring will not directly contribute to savings, thus saving potentials of this option cannot be numbered. However, a monitoring system seems to be an essential part of the whole process serving as a basis of knowledge and steering instrument.

3.4 Slow Steaming

Slow Steaming is the most effective fuel and emission reduction measure for any ship powered by a conventional powertrain consisting of the main engine and its propeller.

The first and most effective response by ship owners after the 2008 economic crisis was the introduction of "Slow Steaming". Later on in this crisis, even "Super Slow Steaming" had been introduced for some vessels.

The second step in adapting ships to these new conditions has been to adapt the ship's drivetrain to the new speed, which had lost its optimum operating point with the introduction of slow steaming. In this sense, the propellers were first replaced and later the bow bulges (which are always optimized for a certain cruising speed) were rebuilt.

The trigger for those measures has been the drastic decrease in cargo volume, which resulted in long lay times and thus increased costs. As response, to the urgent need to reduce costs slow steaming has been introduced as a first measure to ensure the continuous utilization of ships and bunker cost reduction.

Regardless of the further measures (adaptation of the drive train), a reduced speed will always lead to a better fuel/emission value per nautical mile sailed. On the other hand, there is, of course, an economic reason for the need for higher ship speed, as the annual freight capacity decreases the slower the ship travels.

Slow Steaming is the optimization to economically acceptable sailing speeds in relation to the transport task of the ship or the fleet.

3.4.1 Considerations on the Physics of Hull Resistance

Every ship is exposed to different forces of resistance. The resistance of a ship can be divided into different parts, which have different causes. The two main components are:

- Frictional resistance
- Residual resistance

The frictional resistance of all wetted parts of the hull depends on the surface finish and condition of the hull and the degree of fouling on the hull and propeller.

Residual resistance includes wave resistance and vortex resistance. The wave resistance refers to the loss of energy caused by waves generated by the ship's motion through the water, while the vortex resistance refers to the loss caused by the separation of currents, in particular at the aft end of the ship.

Additional important resistance components that will influence the power demand of the vessel are:

- Added resistance due to fouling
- Added resistance due to wind
- Added resistance due to waves

For a deeper understanding of the different resistance components, calculations were carried out for the MV Kwajalein, based on the measurements performed by Mark Oxley and Raffael Held in the lagoon of Majuro[16]. The calculation model was calibrated by the different measurements performed for varying engine load (MCR 50%, MCR 75%, and MCR 85%). Prior to the speed-trial, the hull had been recently cleaned. The value for added frictional resistance is therefore assumed with a low value of 10% (5% difference towards the perfectly/hydraulic smooth surface and another 5% for the first level of fouling: forming of slime on hull surface). The calibration of the calculation model indicated that the total efficiency of the powertrain lies at a low level of about 42%. The real value for the 'total propulsive efficiency' can only be determined with certainty after the installation of a shaft power measurement device.

Theoretical background for the calculation model is based on the works from B. Wagner[17], P. Schenzle[18], B. Blendermann[19], P. Blume, U. Keil [20], and M. Khiatani[21].

The following graph shows the calculated value for the required delivered Power (P_D) in dependency of vessel speed ranging from 7 to 10 knots, for MV Kwajalein. The required delivered power is subdivided, based on the different resistance components, displayed in different colors:

- green for frictional resistance
- yellow for residuary resistance (in dependency of hull form)
- blue for added resistance from wind and waves (Bft 3, wind direction 90° from the port side)
- red for added frictional resistance resulting from surface condition (fouling)

[16] Oxley, M. (2018), 'Establishing Baseline Data to Support Sustainable Maritime Transport Services-FINAL REPORT', Appendum 1, TA-8345 REG: Establishment of the Pacific Region Infrastructure Facility Coordination Office (PRIF)

[17] Wagner, Windkräfte an Überwasserschiffen, 1967

[18] Schenzle, Technik und Strömungsmechanik von Segelschiffen, 2014

[19] Blendermann, Schiffsform und Windlast Korrelations- und Regressionsanalyse von Windkanalmessungen am Modell, 1993

[20] P. Blume, U. Keil, P. Schenzle, Rechnerische Bestimmung der Widerstandserhöhung eines Schiffes in regelmäßigen Wellen und Vergleich mit entsprechenden Modellversuchen, 1973

[21] Khiatani, Der Einfluß des Zusatzwiderstandes durch Seegang und Wind auf den Schiffsentwurf, 1985

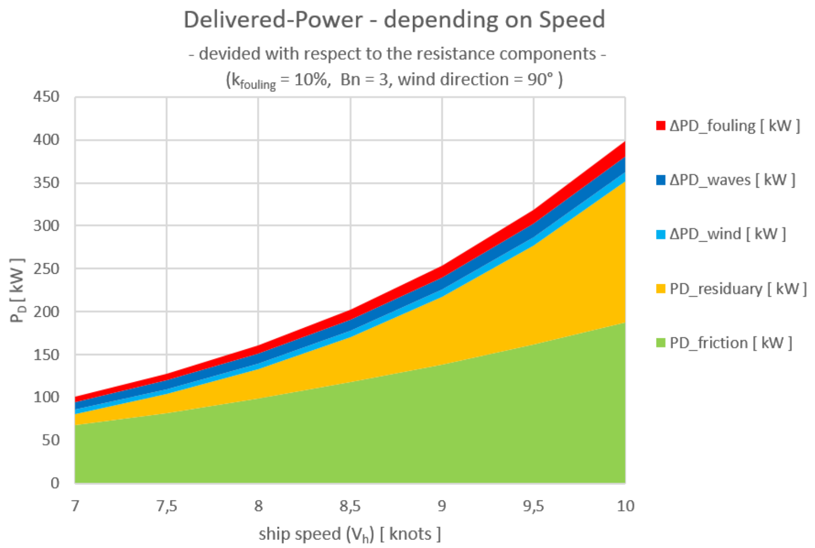

Figure 22: Speed-Power curve for MV Kwajalein

It can be seen, that residuary resistance resulting from hull form (shown in yellow) grows with the 3rd power of vessel speed and becomes more dominant at higher speeds.

Besides significant power reduction, slow steaming therefore leads to a shift in the share of resistance components on total resistance. This will have an influence on added frictional resistance caused by fouling since the percentage of frictional resistance increases the slower the vessel is sailing.

3.4.2 Saving Potential from Slow Steaming

A first approximation of the expected fuel saving is done for MV Kwajalein. Detailed documentation of the installed main engine, sea trials, fuel consumption, etc. is available, which allows the approximation of savings through the application of the proposed measures. From the speed trial we have the following table for engine load and corresponding vessel speed:

Table 2: Fuel consumption in various engine load conditions (MV Kwajalein) based on speed trial

Nominal Load		50%	75%	85%
RPM	min^{-1}	1189	1362	1420
Speed	kn	8.63	9.59	9.93
Fuel consumption	lt/hr	55.7	83.3	94.7
	lt/nm	6.46	8.69	9.54

The following graph shows an approximation of fuel consumption per nautical mile in dependency of vessel speed, ranging from 6.5 knots to 10.2 knots for MV Kwajalein in typical operational conditions. The figure was created on the basis of the calculation model for vessel resistance as well as main engine test record file[22] concerning fuel consumption for different engine loads.

[22] Shipyard documentation files provided for MV Kwajalein, 2013

The huge potentials of slow steaming can be seen in the graph, neglecting the influence of engine load-dependent changes in the specific fuel oil consumption (SFOC). These aspects will be considered in chapter 3.11 on main engine and drive train performance.

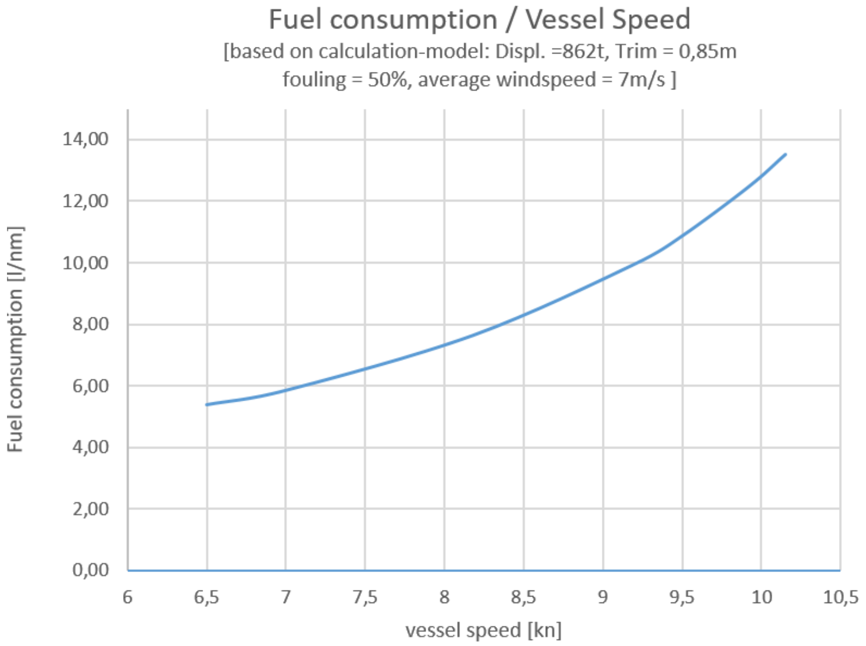

Figure 23: Fuel consumption based on the calculation model and main engine test record

A reduction of vessel speed by 26% will lead to fuel and emission savings of about 47%.

3.4.3 Interaction with other Technical or Operational Measures

While at higher vessel speeds frictional and added frictional resistance (fouling) is responsible for about 40% to 50% of total resistance, this value increases significantly the slower a vessel is sailing. Thus, all measures that have a positive influence on frictional resistance will yield better results if slow steaming is introduced as well. Since total power requirement decreases to less than one-third of the original power (speed reduction to 7knots for MV Kwajalein), all measures that lead to direct thrust reduction will significantly benefit from the introduction of slow steaming as well.

Speed reduction (slow steaming) reveals a high potential for fuel/emissions savings. It has to be seen that the voyage duration will be affected by this measure. As long as the effect of longer voyage duration is not critical for economic or other reasons slow steaming could be an effective part of the concept. However, the loss of time can be partly or fully compensated by other measures, such as weather routing, improved navigation methods, and voyage logistics. Furthermore, the use of wind propulsion technologies (Chapter 3.9) allows faster traveling speeds again, if wind conditions are favorable.

As already mentioned in the introduction to this chapter, slow steaming is only the first and simplest part of this measure. Further savings will result from the complete adaption of the drive train to this new speed. Starting with the adaptation of the propeller to the new load conditions and ending by an optimized main engine concept and bow bulb shape.

3.4.4 Potential of slow steaming for MISC fleet

The Baseline study revealed that all four vessels were utilized only about 40% (Ribuuk Ae) to 70% (Aemman) of time during the year in 2016. Just about 70 days during this year has each vessel actually been on voyage at sea. This data indicates that slow steaming even at low speeds of 7 knots would be a very good option to significantly reduce operating costs and thus emissions of the fleet.

Even if the option proposed in the baseline report of withdrawing the Ribuuk Ae from service (compensation for these voyages with MV Aemman and MV Kwajalein) is implemented, more than enough time remains for a speed reduction of 26% or more for the remaining fleet.

3.5 Voyage Optimization and Weather Routing

Optimizing the routes and the trading patterns of ships in the area will yield further savings potential. Voyage optimization comprises all long term options that can be applied for finding the optimal sequence for the approach of different destinations during one voyage, by regarding typical weather conditions depending on seasonal changes. Prefer of traveling routes along the leeward sides of atolls and islands (expected lowest sea state conditions), will lead to minimizing additional resistance from waves. Weather routing at the other hand is the art of making the most out of short term weather conditions by finding and continuously optimizing the route towards the next destination on one voyage.

3.5.1 Resistance and Power Requirements in Wind and Waves

Figure 24 shows the influence of wind and waves on the required P_D (power delivered) to maintain a constant vessel speed. P_D is plotted against the course sailed towards the true wind direction (angle from 0° to 180°, Beaufort 4). The diagram shows the different parts that sum up to the total required power P_D to maintain this speed. It can be seen, that there is a significant increase in resistance when sailing against the wind due to waves and wind.

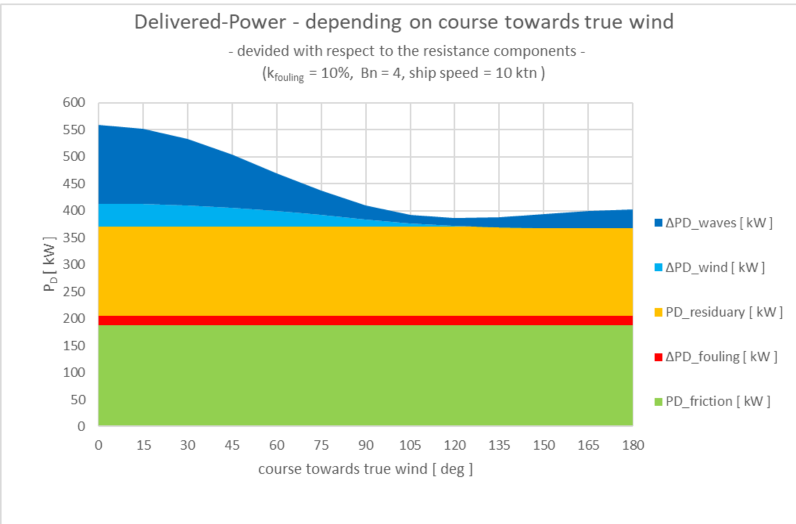

Figure 24: Delivered power depending on true wind angle

The added resistance from wind and waves varies with true wind angle. The diagram shows the total resistance with wind from starboard-side. Values for wind from port-side can be mirrored.

The total required power to maintain constant vessel speed in different wind conditions is displayed in the following two diagrams for the MV Kwajalein with a speed of 7 and 10 knots.

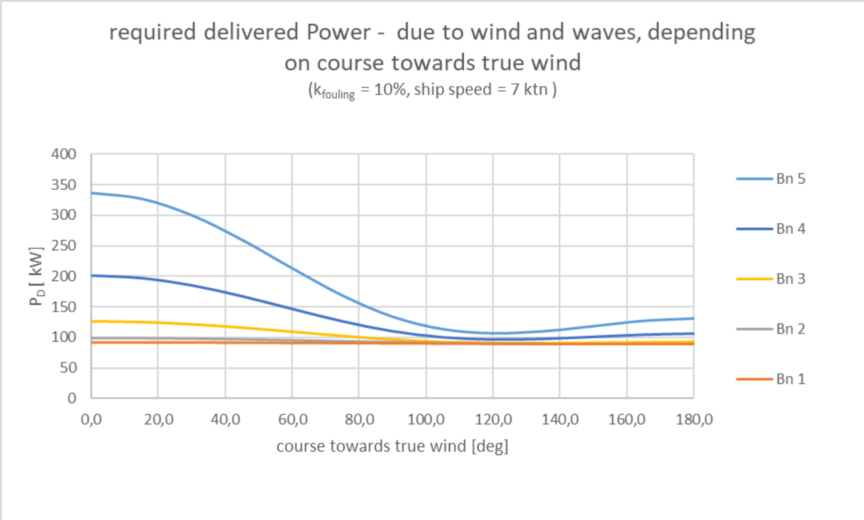

Figure 25: Required power depending on true wind angle (speed 7 kn)

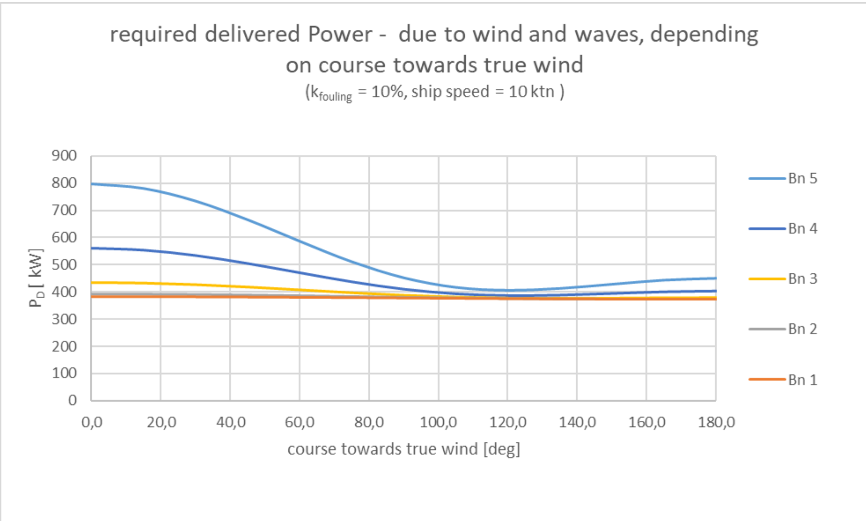

Figure 26: Required power depending on true wind angle (speed 10 kn)

Wind and waves have a significant influence, even in moderate weather conditions of 4 to 5 Beaufort (average value for RMI). For low vessel speeds, the importance of weather routing is more pronounced than for high vessel speeds. Considering a course against the wind at 4 Bft, around 30% - 60% (depending on vessel speed) of required engine power is needed to overcome wind and wave resistance. Avoiding these conditions can reduce the fuel consumption of the vessel. An additional advantage is the possibility to avoid large waves to increase cargo safety and passenger happiness.

A Route Optimization System (ROS) can take advantage of the different power requirements and changing weather conditions to find the optimal route with the lowest fuel consumption from origin to destination.

The necessary inputs for this optimization are:

- The point of departure and destination
- The time frame (arrival time, departure time, or time window)
- A model of the ship's resistance in all weather conditions
- Current high-resolution weather forecast for the area

Based on this data, an algorithm in the routing program can calculate and compare different feasible routes and output the path of least fuel consumption that meets the defined constraints, i.e. arrival time. The suggested route may not be the shortest route, but it will be the most fuel efficient, considering the additional resistance in certain conditions, and the additional thrust from an installed wind assisted propulsion system.

As this route is calculated on the basis of weather predictions with increasing uncertainty attached, the further they reach in the future, there is a need for re-calculation as often as once per day. This brings the need to update the forecast data while underway, so a communication system capable of downloading new forecast data at least once per day is needed. This is discussed in chapter 3.7 Navigation equipment. An optimized route might also be suggested to depart later than planned, which could lead to significant fuel savings if this is feasible from a logistical standpoint.

3.5.2 Weather Routing - Conditions in the RMI

The RMI is located in the trade wind zone, which gives very stable wind conditions from November to May, and variable wind conditions from June to October. Weather routing takes advantage of changing weather conditions to find the path of lowest fuel consumption, so this measure is particularly effective during the summer months when conditions vary. The best route is likely to change on a daily basis, which makes frequent recalculation with current forecast data sensible and necessary.

During the winter months, when stable conditions are prevailing, frequent weather routing has a lower savings potential. In this period, it is sensible to perform a deep analysis of all trade patterns of the fleet and optimize the port rotation based on the lowest fuel consumption.

3.5.3 Voyage Optimization

For the climatic/seasonal optimization of the sailing routes, it is advisable to invest some research towards the optimal seasonal time frames for sailing certain routes between the atolls. This can be done by detailed analysis of stored digital weather data from the last decades. At the same time, this is a good opportunity to make use of cultural knowledge, as this is exactly what happened during several hundreds of years of trial and error. People found the most economic connections and seasonal time-frames with perfect weather conditions for the needed tasks.

Changing the voyage schemes and port rotation is a major change for all shipping parties who are used to the current trading patterns, and the MCST is already working on this topic in relation to cultural heritage and effects. The voyage optimization is recommended to take any approved WASP retrofit options into account.

3.5.4 Interaction with other Measures

Voyage optimization based on weather can lead to fuel consumption reductions on its own, but in combination with installed wind propulsion systems, the importance of this technology is amplified, as not only the resistance from wind and waves is minimized, but also additional thrust is generated in favorable conditions. Therefore, with more installed wind power, the importance of optimized routes rises to gain full advantages of these systems. For further details on the potential savings of weather routing in combination with wind propulsion systems refer to chapter 0 of this report.

3.6 Cargo Operation, Hold Efficiency and Logistics

The main goal for the proposals that are presented in the following is to enhance efficiency by more efficient cargo operation methods, changing the concept for cargo handling logistics as well as better use of available cargo hold capacities. Also the adaptation of wind propulsion technologies requires in some cases different solutions for the handling of the cargo at the quayside.

Savings in GHG emissions result from reduced waiting times, shorter loading times at the quayside, which leads to reduced use of auxiliary power as well as fewer journeys through maximizing the efficiency of available freight capacities.

An important part in the process of cargo operation relies on the delivery boats carried on deck of MISC vessels for the handling of cargo and passengers at destinations where the vessels have to anchor inside the lagoons. Since this is the case for almost all destinations, the efficiency of those boats offers a considerable portion for overall savings potential.

Changes in the schedules, port rotation or time available in each port will significantly affect other aspects connected to the operation of the vessels. Such aspects are connectivity between atolls, the time required to do business along the route and so on. To avoid disruption and to include all parties affected by those changes, it is suggested to continue an in-depth discussion. The measures suggested in this report are intended to start this discussion and provide inspiration for solutions suitable to everyone’s needs.

3.6.1 Cargo Operation Equipment

Cargo operation on board most MISC vessels is performed by the use of two cargo booms for each cargo hold. A well proven system that comes to application for many general cargo vessels.

Today, more advanced systems are available that allow quicker handling of the cargo and require less man power for operation. Also the introduction of wind propulsion technologies sometimes requires other systems for the handling of the cargo, since the existing large cargo gear would interfere with the newly installed WP-technologies.

In the following different alternative options for the handling of cargo are described:

Rotating Crane

If no other systems obscure the use of a rotating crane, this can be a good solution for efficient cargo handling. The setting allows the access of all cargo holds with only one rotating crane, positioned between the cargo holds. A Trolley underneath the boom, enables the operator to place the load, independently from the length of the boom.

A system of this kind, could come to application if a Flettner-Rotor is installed in mid ship position between the two cargo holds. In this case the crane would rotate around the base pipe of the Flettner-Rotor, without interfering or the possibility of damaging the WP-System during cargo operations.

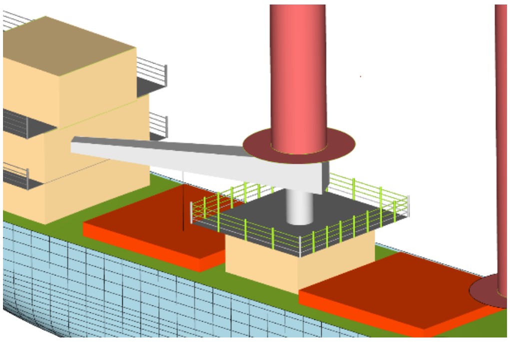

Figure 27: crane rotating around axis of Flettner-Rotor

A system like this will allow the access of both cargo holds towards both sides of the vessel. If the rotating crane is positioned at one side of the hull (use of a finished product) the service for the two cargo holds can still be accomplished by just one crane system, but only to one side (port- or starboard-side) of the vessel.

Hydraulic Equipment

Hydraulic equipment is todays standard wherever large forces are needed. A hydraulic crane would enhance cargo handling tremendously. Besides of faster operation, it is likely that energy demand as well as required man power will be reduced. Since heavy loads are quite common for marine applications there are many manufacturers specialized in the production of hydraulic cranes for marine applications. The variety of available options ranges from very small units to huge heavy duty applications.

For the application aboard MISC vessels the crane should be positioned in a way that ideally all cargo holds can be accessed by one unit. If the same model comes to application on all MISC vessels, maintenance as well as availability of spare parts could easily be managed.

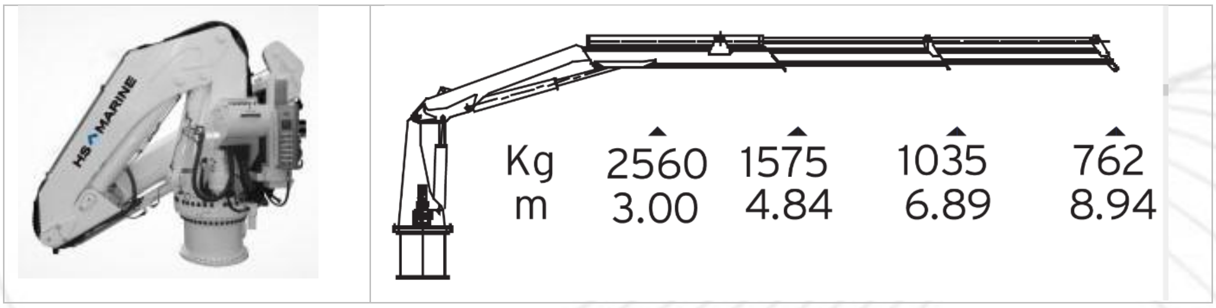

Figure 28: hydraulic crane system from HS-Marine[23], Model: AK 10 NE2

A hydraulic system like above, can be installed between the two cargo holds at one side of the vessel with access to both cargo holds.

[23] http://www.hsmarine.net/images/pdf/HSMARINE_products-ak.pdf

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Use the boom of WP-System

Depending on the Wind-Propulsion system that comes to application, the handling of cargo can be accomplished by utilizing the booms of the WP-System. If this option is anticipated, the design and construction of the booms must allow the operational mode for cargo operation. Details of how this can be accomplished depend very much on the specific design of the WP-System and the layout of the vessel in question.

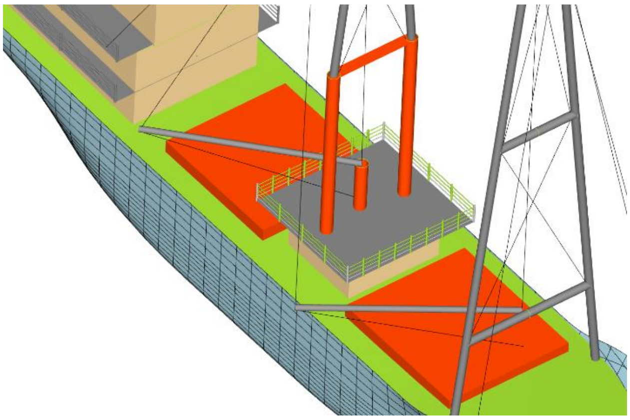

Figure 29: using the boom for cargo operation

A trolley underneath the boom can serve for the positioning of the cargo. The resulting system would be similar to the option of a rotating crane, limited in this case to the cargo hold underneath the boom, but offers the possibility to operate towards both sides of the vessel.

3.6.2 Optimizing efficiency of Cargo/Passenger delivery boats

Basically the same principles that have been identified for the large MISC vessels also account for small inside lagoon boats as well as the tender boats for cargo and passenger operation. Measures for reduced emissions are:

- Speed reduction (slow steaming)
- Reduced hull resistance by maximized freight capacity (clever vessel design)
- Reduced engine power demand -> use of WP-Technologies
- Use of renewable energies for thrust generation (E-Propulsion)

Since the operational profile of the tender boats is very similar to the requirements on inside-lagoon transport vessels, the experience gained in the course of prototyping and testing for inside-lagoon transport can be adopted in the development towards efficient tender boats for MISC-Vessels. Details on hull design and WP-Technologies are subject of the inside lagoon experimenting with new vessel designs and wind propulsion systems (refer to chapter 4.2 'Prototype Development' for inside-lagoon boats). Vessel design for inside lagoon can serve as guideline, but must of course be adapted to the specific demands for the tender boat service in the framework of MISC.

E-Propulsion for Tender Boats

Additionally, to the proceedings accomplished by WAM prototype development, the experimenting with electric hybrid drive solutions, would perfectly fit for the propulsion needs of MISC delivery boats. All experience gained with electric propulsion will also advance the transition to renewable energies in the sector for inside-lagoon transport.

In combination with renewable energies for auxiliary power generation through the implementation of PV and wind turbines integrated into the auxiliary energy system of MISC vessels, the systems can serve for the charging of the batteries of the delivery boats, by providing energy from renewable resources.

Different e-propulsion technologies can be tested during cargo/passenger operation in real service conditions. Valuable experience in the handling and management of these systems will be made, which enables fast transition to those technologies also in the inside-lagoon transport context, once the needed shore based electricity grid is ready for the task of charging the batteries for inside-lagoon boating. Experience gained with those technologies will be valuable for all inside lagoon transport vessels but also for future large scale applications for advanced main drive train concepts for propulsion of MISC vessels.

For details on E-Propulsion technologies refer to chapter 4.3 on ‘Electrical and hybrid propulsion’ in the inside lagoon transport section.

3.6.3 Optimizing Cargo Hold Efficiency

The cargo hold of most MISC vessels is not fully used during most voyages. The main reason for this is the lack of a tween deck that would make use of the available cargo hold height of more than four meters (MS Kwajalein). Other measures like more efficient stowing of pallet freight can additionally increase the efficiency of available space.

Options for increased cargo hold efficiency are:

- tween deck, for increased freight capacity,
- Storage boxes etc. for better preparation of cargo beforehand as well as easier and quicker handling of cargo,
- Foldable top frames, instead of standardized boxes.

The efficiency of the ships can be raised by improved utilization of the hold capacities, as well as the introduction of a suitable and standardized freight box system. Opportunities are also opened up for the organization of the routes, as improved utilization of the available space would allow, for example, parallel transport of food/consumer goods and Cobra in separate cargo holds.

Reactivating tween decks

For better utilization of the available space, a tween deck can be used to improve the loading capacity and accessibility of the cargo, reducing the need to stack cargo. This can be seen in the following cargo hold drawing of MV Kwajalein (red line in Figure 30).

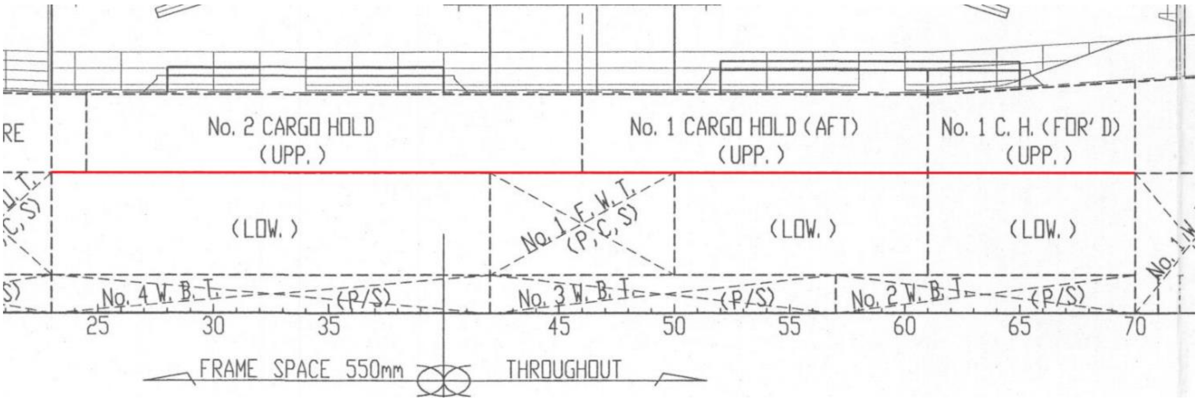

Figure 30: Position of tween-decks aboard MV Kwajalein[24]

The tween-deck can be designed in various ways. On the one hand, a fixed tween deck with access hatches to the lower hold would be conceivable. On the other hand, a movable/foldable tween-deck presents an option. This could lead to better cargo handling during loading and unloading.

Storage boxes for pallet freight

The use of storage boxes would lead to a uniform and standardized dimension, which could improve the handling of the goods as well as the organization and logistics.

Figure 31: Foldable stacking frames for euro-pallets[25]

Since empty storage boxes must also be carried, a foldable system is an obvious solution. Empty boxes can be stowed easily and space-saving.

[24] Yard drawings of MV Kwajalein
[25] http://www.bassum.com/en/pallets-overview-1/collars-wooden-stacking-frame/

3.6.4 Cargo Logistics

There are several aspects that can be optimized regarding the logistics of cargo and passenger transport. Even though the fleet fulfills the task of transporting goods and people between the islands, there is room for further improvements. Some areas for optimization are:

- Reducing waiting times for collection of copra at the islands, for example by using a collecting station
- Packing and handling cargo in standardized boxes or simple containers
- Using modern equipment for handling of cargo at the quayside
- Planning logistics in advance, e.g., by digital applications, leading to weight optimization and improved accessibility for efficient unloading at the point of destination
- Separating cargo-holds for carrying copra at the same time as general goods

3.7 Navigation

Navigating ships to the port of destination is one of the core tasks of the bridge crew of any ship. Proper navigation ensures the vessel will sail in safe conditions and therefore, deliver the ship including cargo and/or passengers to the destination without damage or undue delay. To perform this task even in sub-optimal conditions (adverse weather, dangers to navigation), the crew must be able to rely on navigational equipment and aids to navigation that is in working condition and able to provide reliable, accurate and reproducible data and information.

There are two parts to this system. The first is the equipment on board each individual ship. It has to provide information such as position, route data, and information on other ships in the area. This information is closely related to the individual ship and the current voyage.

Navigation infrastructure as the second part is the foundation of the onboard systems, such as updated charts, accurate surveys and properly maintained aids to navigation.

In combination, these factors can ensure safe navigation for all ships in the area and in the fleet, which will enable operation of the ships even during the night or adverse weather. This can increase the efficiency of the ships, the possible cargo capacity between lagoons and the frequency of connections in the area.

3.7.1 Background on the Role of Navigation Equipment Onboard Ships

The Navigation equipment on board serves the primary purpose to enable safe and reliable operation of the ship along the intended route. This includes several processes from route planning over measuring the progress along that route to collision avoidance.

There are several basic instruments that are needed for safe and precise navigation:

- GPS, providing position, COG, SOG
- RADAR providing secondary position and collision avoidance
- Satellite compass providing heading, roll, pitch, and GPS data

- Autopilot enabling accurate navigation on longer sea passages
- Optional: Gyrocompass providing heading information for the autopilot
- Satellite communication unit

The most basic combination of systems for modern electronic navigation is a GPS receiver, providing position, speed over ground (SOG) and course over ground (COG), combined with an electronic chart system (ECS) that is able to display a chart, route and the current position of the vessel. This basic system will work in good conditions; as visual confirmation of the position is needed during coastal navigation. In order to also operate during the hours of darkness or in poor visibility, a second position referencing system such as RADAR has to be installed. This allows the crew to double-check the position and track of the ship, i.e. using parallel indexing techniques, and therefore navigate narrow channels even in adverse conditions. This makes it possible to enter the lagoons even at night, which will provide greater flexibility in planning the logistics. Additionally, it enables the vessel to ensure collision avoidance even in those adverse conditions.

Looking at the operational factors influencing the fuel consumption of a ship during the sea passage, the steering accuracy has a large impact on the overall efficiency of the vessel. If the ship is allowed to deviate off course by a large margin, large rudder angles are necessary to correct these deviations. The rudder resistance is highly dependent on the rudder angle, so it is important to keep the rudder angle low whenever possible. Steering the ship during long sea passages, human helmsmen are prawn to be distracted and let the heading deviate too far, which makes large corrective rudder angles necessary. Therefore, an autopilot is an important tool to ensure operational efficiency during sea passages. The autopilot can keep the rudder angle under a critical limit and will reliably keep the ship on course along the intended route for optimum fuel efficiency. In order to operate an autopilot system, the ship's heading is needed as an input value, provided by a gyro compass. It is a well-tested and reliable system, independent of external factors or connections.

In order to further improve operational efficiency, the route can be planned and optimized according to the current weather forecast. As conditions change, the route optimization system (ROS) can calculate the path of least resistance to the required destination, also taking possible wind propulsion systems into account; refer to chapter 3.5 for further details. The ROS relies on current and accurate weather data, and performance can be enhanced by frequent forecast updates. This is especially true on longer passages. Therefore, a satellite communication system is required to ensure the transfer of the current forecast data. The file sizes are rather limited, so no high bandwidth installation is needed, but a reliable and easy-to-use system is of advantage. This system can also help connect the ships to the operations center on a more reliable basis throughout the voyage.

3.7.2 Status and Improvements Onboard the MISC Fleet

In the context of the project TLCSeaT, the operational profile of the MISC ships is to be further studied and analyzed in depth. Much of the needed data can be provided by the above-mentioned sensors and equipment. But there are also additional sensors, that can record valuable data on the conditions the ships are operating under. This data is needed to make the simulation and analysis performed in the project as close to reality, and therefore as useful as possible. The additional measuring equipment is not strictly necessary on board of every ship but will provide useful additional information to the crew on board and can act as a backup to the primary systems used for navigation on board.

There are several additional systems that are needed for data collection:

- Satellite compass providing heading, pitch, roll, and heave
- Wind sensor providing apparent and true wind speed and direction

The advantage of a satellite compass over a gyro compass is the low cost and additional data that can be measured by it, such as roll, pitch and heave motions of the ship. This data can be recorded and help to analyze and improve the behavior of the ship in different weather and sea conditions. It can also be easily retrofitted. The same is valid for a wind sensor, which provides insight in the conditions a ship is operating in, is very useful to evaluate forecast models and is especially important if any wind propulsion system is installed or planned to be installed onboard.

3.7.3 Choosing a manufacturer

There are several manufacturers that offer the equipment range described above. When choosing a manufacturer in practice, there are several factors to take into account. When considering a refit, it is sensible to expand the existing system, that is to minimize equipment from different manufacturers on the ship. This will reduce potential problems, as the individual components of the navigation system are integrated and need to communicate with each other. The same holds true for newbuilds, with the addition that it is also advisable to limit the number of different manufacturers across the fleet. This will make it easier for crews to switch between vessels, troubleshoot problems and reduce the organizational effort put in maintenance, ordering spare parts and crew familiarization.

It is also important to make sure that there is proper support and service for any equipment installed onboard the MISC ships from the manufacturer side. If the need for manufacturer support should arise, it is beneficial to have this support as close by as possible to minimize spare part delivery times and have technical staff on site to assist with the repairs. When installing equipment for the first time, it is advantageous to have a dealership close to the shipyard that is usually called at for regular repairs, as especially in the installation phase, there is a need for support from the manufacturer and dealer for the shipyard.

The shipyard used for the vessels in the MISC fleet is located in Suva, Fiji Islands. At the time of writing, there is only one dealership for navigation equipment in the area, that is Furuno dealer Tecair Ltd., also located in Suva. The majority of the MISC fleet is equipped with Furuno navigation equipment. So due to the above-mentioned considerations, it is recommended to choose the Furuno product range for installation on the MISC vessels.

The need for new equipment is reduced, as most of the vessels are equipped with the basic navigation equipment, although some repairs and maintenance might be needed. In order to be able to optimize the data collection and fuel monitoring onboard the ships, it is only desirable to install a satellite compass and a wind sensor onboard the ships. This, in addition to the equipment already on board, will enable the collection of valuable data about the operation of the ships, and the conditions that are encountered along the traveled routes.

3.7.4 Surveys, Charts, and Aids to Navigation

For even the most basic navigational tools to work, there is a need for detailed and accurate nautical information about the surroundings. The most important information in this regard is the depth of the water, which is presented in navigation charts. These charts can be printed on paper or used in electronic format. But in order to create the charts, a detailed survey must be carried out, and the collected soundings data be transferred to a readable file to be used for navigation. The accuracy of the surveys should follow the risk of groundings in that specific area. This risk has two factors associated to it, which is the depth of the water in relation to the draft of the ship, as well as the nature of the ground, which will influence the damage to the ship in case of grounding.

In the waters of the RMI, the open ocean is usually very deep and is therefore not a danger to ships navigating on the surface. The area inside the lagoons is typically shallower and can be a threat to certain ships in specific areas. But the highest risk is associated with entering and leaving the lagoons when crossing the reefs to enter or exit the lagoon. Here, the waters are shallow, and the hard and sharp coral can indeed damage a ship's hull in case of grounding.

Due to the inherent nature of these narrow channels, many ships do not attempt to cross them during the hours of darkness, but instead, choose to drift outside in open water to wait for daylight and safer conditions to enter the lagoons. This limitation reduces the operational efficiency of the ships and elongates the duration of the voyage.

This situation can be improved by increasing the precision of navigation. The improvements on the vessel side have been discussed above, but the foundation of precise navigation is accurate charts, based on accurate survey data. Gathering this data usually requires specialized survey ships, experts to operate them and to analyze and process the data. But advances in the fishing industry have made the multi-beam echo sounder technology available at a cheaper price and modern software is able to process the data without extensive knowledge in the area from the user. The multi-beam technology makes it possible to map the ocean floor in critical areas and make this information available for all ships in the area.

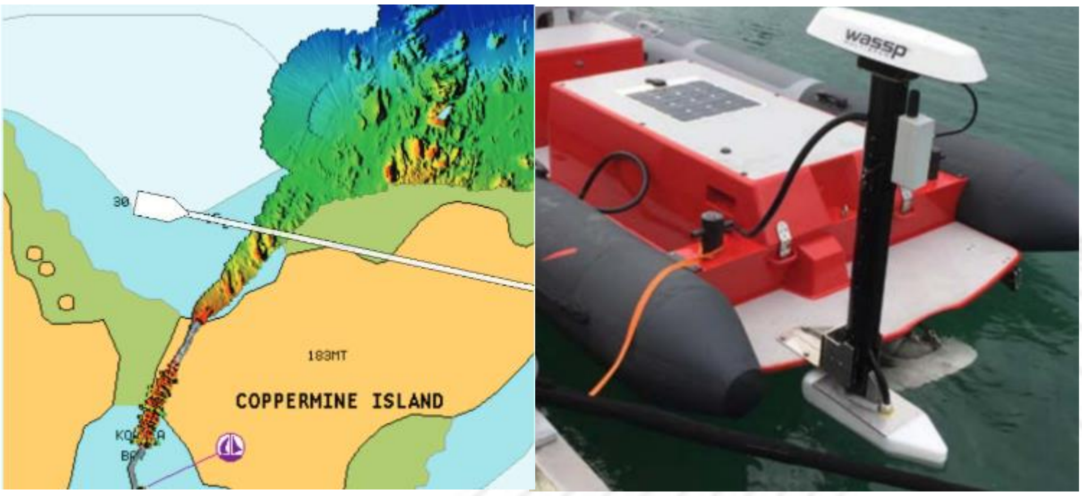

Figure 32: Survey data overlay (left) and WASSP S3 example installation on a RIB (right)[26]

[26] Furuno WASSP brochures
http://www.furuno.de/Downloads/Wassp%20S3/Produktbl%C3%A4tter/WASSP%20Wirless%20Navy%20brochure.pdf and http://www.furuno.de/Downloads/Wassp%20S3/Produktbl%C3%A4tter/WASSP%20S3%20brochure.pdf

Recent advances in this technology make it available also to a lower tech market as well. The WASSP S3 system consists of a compact transceiver unit and a black-box for data processing. The collected data can be viewed directly in an ECS on board or ashore. This will not create a new official electronic navigational chart but will be displayed as a chart overlay on top of the official charts, that can be switched on or off as required. This data can then be shared with other vessels in the area, who can display the survey data as a chart overlay as well.

A sensible solution is possible due to the compact size of the WASSP S3 system: The installation of the entire system on a small tender or a coastguard vessel, which is able to do the surveys of the critical areas one by one, processing the data and making it available to the fleet. This reduces the investment in the system and makes the training of the few operators possible. With the proper training and guidance in the beginning, over time it is possible to map all the critical entrances and other dangerous areas.

In combination with the above-mentioned navigation systems onboard the ships, this system may enable crews to sail their vessels through these channels more safely with fewer limitations. It will add flexibility and efficiency to the schedules and reduce the travel time between certain destinations.

3.7.5 Recommendations

Safe navigation is a critical part of ship operations and the precision level of the navigation has a significant impact on the overall efficiency of the fleet. The vessels in the MISC fleet have different levels of navigation systems on board, with not all the equipment being operational. It is therefore recommended to repair or replace the equipment that is out of order, or install new systems where none is on board at the moment to ensure at least the following standard on each MISC vessel:

Table 3: Recommended navigation equipment

System	Purpose	Recommended model
Satellite Compass	• Provide position • Provide heading for autopilot • Provide roll and pitch data for data analysis	Furuno
Wind Sensor	• Provide wind data for fleet analysis	Furuno
Autopilot	• Enable precise navigation on long sea passages to save fuel	Tokimek / Simrad
ECS (Electronic Chart System)	• Display and use current nautical charts in route planning and for safe passage of dangerous areas • Display survey data gathered in the future	Furuno TimeZero
Satellite Communication System, e.g., INMARSAT-C	• Receive weather updates for weather routing • Enable ships to be in contact with head office	Furuno

Precise navigation can only be as good as the survey data it is based on. It is therefore recommended to establish a low-cost survey system that is able to improve chart data in dangerous areas and narrow channels. This will enable vessels to sail in these waters even during not optimal conditions (i.e. during hours of darkness), which will improve flexibility and passage times between destinations.

3.8 Hull Coating and Cleaning

Fouling on ship's hulls is a problem the maritime industry faces from the earliest days, but in the last decades, the strategy of most ship owners has not changed much. In this chapter, the effect of fouling is analyzed taking MV Kwajalein as an example, and strategies to achieve fuel and emission reductions through cleaner hulls are discussed.

As discussed in chapter 3.4 (slow steaming), the frictional resistance is a large part of the total resistance of any vessel, and surface roughness is the main influence on that. The surface roughness of a vessel at any time comprises two factors: the quality and condition of the hull and coating, and the state of bio-fouling adhering to the hull, which is the dominant factor after some time in the water. Fouling leads to a significant increase in frictional resistance and therefore increases fuel consumption and emissions.

The growth rate of marine organisms depends on the following factors[27]:

- The conditions on site, i.e. water temperature and salinity
- Trading pattern and sailing speeds
- The effectiveness of the anti-fouling treatment of the hull

The RMI is located in the marine growth zone 1 and 2 out of 10, indicating very high marine growth rates, mainly supported by high water temperatures. MISC ships have long idle periods and sail at relatively slow speeds, both increasing fouling. Special care should be taken in order to restrict this growth and minimize the impact on fleet performance.

3.8.1 Effect of Surface Roughness and Fouling on Hull Resistance

The following diagram shows the curve for required PD, as it was introduced in chapter 3.4, with increased added resistance due to fouling (typical values for small to medium calcareous fouling or weed[28]). Looking at low vessel speeds of 7 knots, frictional resistance (friction plus added friction from fouling) make up almost 80% of total resistance.

[27] Meenken, E. (2018). Coordinating coating systems and cleaning processes to increase ship performance – A concept development as a contribution to the project 'Transitioning to low carbon sea transport

[28] United States Naval Academy. (n.d.). Effects of coating roughness and biofouling on ship resistance and powering

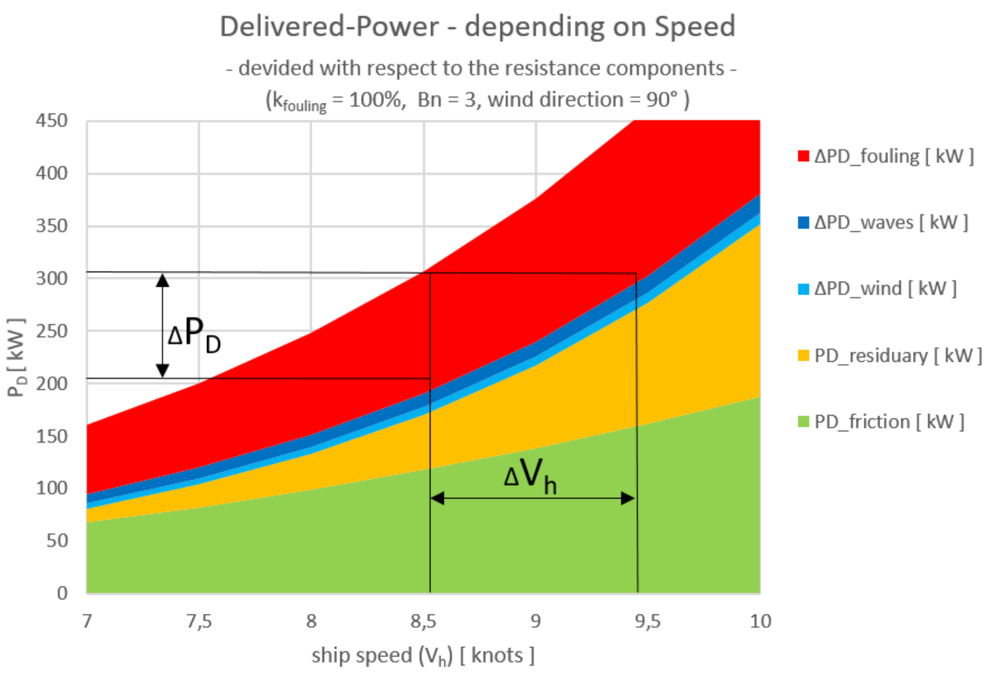

Figure 33: MV Kwajalein – required power depending on fouling

The diagram reveals the importance of clean hulls for MISC vessels since the major resistance component results from hull friction. Fouling thus has a significant influence on the total power requirements of the vessels. Furthermore, the high potential of slow steaming for reducing fuel consumption and emissions is illustrated again.

After dry dockings, vessels usually have a freshly cleaned and painted hull. But the forming of a biofilm, the first stage of fouling, begins already within the first hours of immersion in the water. A clean hull can only be achieved and maintained between dry dockings by a well-chosen combination of hull coatings and regular cleanings of the hull. The cleaning system must be compatible with the applied coating so that regular cleanings will not compromise the integrity of the coating.

The cleaning could be performed by divers within the idle periods of the vessels, either at anchor or while berthed. This ensures a continued low frictional resistance and thus lower fuel consumption and GHG emissions by the fleet.

3.8.2 Strategies for Dealing with Fouling

There will inevitably be an accumulation of slime and fouling on the hull of any vessel in the fleet of RMI due to the geographical location and operating profile. This will lead to a significant rise in fuel consumption of the vessels, depending on the degree of fouling. There are different strategies for dealing with this issue.[29]

1. **Ignore and clean at dry dock**

   The developing slime and fouling is ignored and will be removed at the regular dry-docking intervals of the vessel. After removal of the fouling, the anti-fouling coating is reapplied. The

[29] Hydrex, The Slime Factor. http://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=home.showFile&rep=file&fil=ECOTEC_The_Slime_Factor.pdf

speed and consumption penalty is accepted. This has been the most common strategy of ship owners worldwide and is the current MISC strategy.

2. **Frequent dry docking and cleaning**

   Drydocking intervals are reduced drastically, allowing the hull to be cleaned on a more regular basis. This strategy can solve the fouling problem, but is very expensive and results in long off-hire times. Therefore, this strategy is not practicable and cannot be recommended.

3. **In-water cleaning**

   Cleaning of the hull while the ship is in water, on a regular basis, to minimize dry-dockings and still maintain a smooth hull. The coating system used has a major influence when choosing this strategy. A robust coating that can withstand the mechanical stresses of regular cleaning is needed. Depending on the chosen cleaning interval, this strategy can ensure a clean hull while still minimizing cost and time spent in dry dock, as well as sailing to and from the dry dock.

3.8.3 Coating Options

An important criterion for the selection of a coating system is that it makes a smooth surface which can be maintained in its smooth state. It must be applied properly, monitored and maintained in good condition. There are different anti-fouling systems available on the market. The most common systems are described and evaluated here.[30]

Controlled Depletion Polymer (CDP)

These coatings are releasing biocides over time by the gradual dissolution of the water-soluble part in the coating. This forms a layer of leeched material, which slows down the release of biocides over time, and requires cleaning or moving water to restart the releasing process. Since the MISC ships experience long idle times, this is a disadvantage. The typical lifetime is 3 years, making recoating necessary. If recoating is delayed beyond the lifetime of the coating, the performance is reduced drastically.

Self-polishing Polymer (SPC)

This is a biocide releasing coating as well, but the rate of dissolution of the coating is better controlled, and there is no build-up of leeched material or residual ‘skeleton’ left over. This means, that there is no movement of water or cleaning necessary to restart the releasing process. The release is more uniform over time and has an expected effective lifespan of 5 years.

Foul-release Coating

This coating does not contain any biocides but instead uses non-stick properties to control and shed fouling instead. This requires movement of the vessel through the water of over 15 knots to be effective, which makes it uninteresting for the MISC and most other vessels operating in the RMI. Long idle times also decrease the effectiveness of the system. The effectiveness of the coating relies on the very smooth surface, which is quite sensitive to mechanical damage, i.e. during berthing or from other boats coming alongside. Damaged areas are not protected against fouling anymore, which makes these coatings not suited for operations in RMI waters.

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[30] Meenken, E. (2018). Coordinating coating systems and cleaning processes to increase ship performance – A concept development as a contribution to the project ‘Transitioning to low carbon sea transport

Surface Treated Composite coating (STC)

This system achieves a very smooth and hard surface by embedding tiny glass particles in the coating. There are no biocides contained in the coating, so frequent cleaning is necessary to maintain a smooth hull. But in comparison to the foul release coating, STC produces a very durable surface that can be cleaned in short intervals and will last the lifetime of the ship. This makes reapplying the anti-fouling coating in dry-dock unnecessary, with usually only minor touch-up needed. Due to polishing effects, the smoothness of the coating even increases with every cleaning, increasing the efficiency over time, while also avoiding increased hull roughness caused by re-painting the entire hull during dry-docking (see Figure 34). It is however vital, that regular cleaning intervals are maintained to avoid the buildup of fouling.

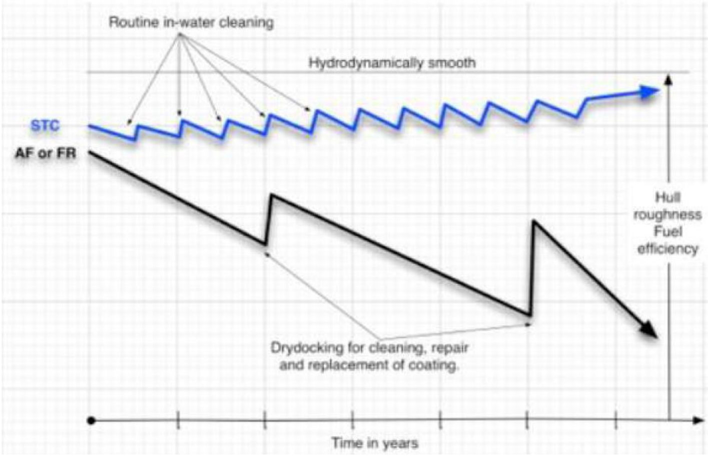

Figure 34: Comparison of hull roughness over time between coating types (AF=anti-fouling, FR=foul-release) due to long-term paint degradation.[31]

3.8.4 Cleaning Options

The cleaning system put in place must be chosen in combination with the coating applied to the vessels in the fleet since not all coatings can be cleaned by the same systems. Traditionally, the underwater hulls of ships are cleaned while out of the water either on the slipway or in dry dock. Since these options do not exist on the RMI and the voyage to the next shipyard is long, the cleaning intervals are quite long as well. In order to reduce these intervals and profit from the benefits of a smooth hull to fuel consumption and emissions, it must be possible to clean the vessels on site, preferably in Majuro during existing idle periods.

Figure 35: Different operating tools for Caviblaster model 1222[32]

This makes an in-water cleaning system necessary. There is a variety of systems available for in-water cleaning. To choose an appropriate cleaning system, there are several factors to take into account. The

[31] van Rompay, B. (2011). Hydrex White Paper No. 5 Underwater ship hull cleaning: cost effective, non-toxic fouling control. white paper, The Hydrex Group, Antwerp, Belgium.
[32] http://www.geaco.eu/images/units_range.jpg.

system must be effective, affordable and easy to use. In-water cleaning requires either cleaning by a robot, which is expensive, or by the diver. This means that divers from the RMI have to be trained to operate the cleaning systems, which can create job opportunities on site.

An extensive assessment of available technologies and products has been carried out by Meenken, E. (2018), resulting in the recommendation of a cavitation cleaning system, which is operated by a diver and can be powered from the ship while at anchor or from shore. There are different operating tools available, optimized either for larger areas or small and hard-to-reach spots.[33]

3.8.5 Interaction with other Measures

The proportion of friction in the total resistance increases with decreasing speed. Implementing a slow steaming concept will result in a percentage increase of the fuel savings potential of maintaining a smooth and clean underwater hull surface.

3.8.6 Recommendations

For the MISC fleet, the combination of a Surface-Treated Composite (STC) coating with a cavitation in-water cleaning system is recommended. This combination provides for a smooth hull, the regular cleanings even increase the efficiency of the vessel and dry-docking intervals are no longer crucial for fouling control. The necessary divers to provide the under-water cleaning operations will provide employment opportunities at the larger lagoons and the cleaning tools are relatively inexpensive.

3.9 Wind Assisted Ship Propulsion (WASP)

The following chapters provide an overview of how wind propulsion can reduce fuel consumption and thus emissions from an engine-powered ship. As a technical measure to directly and significantly reduce the required thrust, wind propulsion technologies can be seen as the most important technically feasible option on the demanding road to emission-free maritime transport.

There is currently no other option available that meets the requirements for zero-emission maritime transport. The only conceivable alternative solutions that could be ready in the near future are electric hybrid drives (today energy storage is the main cost driver), the use of biofuels (currently still too expensive in production costs) and fuel cell technology (requires hydrogen storage or similar variants). However, these alternative solutions do not contradict the use of wind propulsion but are a very good complement if they develop into efficient alternatives from an economic point of view.

Before possible conversion variants based on different wind propulsion systems are presented, the following chapters will discuss the wind as an energy source for ship propulsion, possible wind propulsion technologies as well as various aspects relating to the ship to be converted.

[33] Meenken, E. (2018). Coordinating coating systems and cleaning processes to increase ship performance – A concept development as a contribution to the project 'Transitioning to low carbon sea transport

3.9.1 Wind Conditions in RMI

Looking at wind statistics from the Marshall Islands makes clear that the atmospheric conditions are close to ideal for the use of wind power and the application of wind propulsion on ships. The area between the intertropical convergence zone (ITC) and the subtropical high-pressure belt yields high availability of steady winds from northeasterly directions averaging wind speeds of 14 to 16 knots. Sailing on SE'ly or NW'ly courses along the two island chains (Railik chain and Ratak chain) create ideal beam wind conditions for a maximum of efficiency for wind assisted ships.

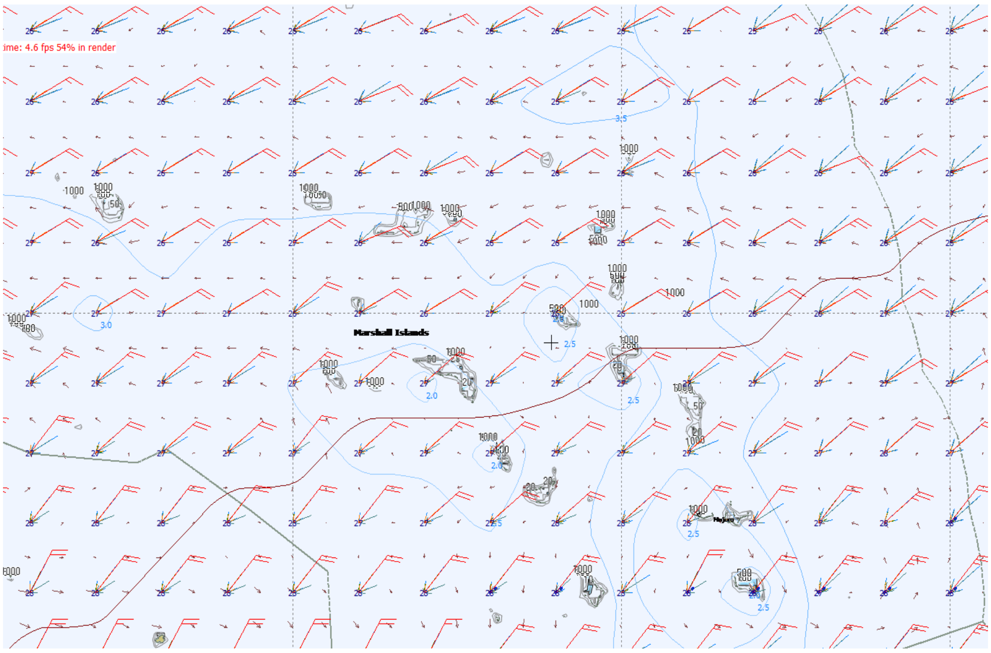

Figure 36: The wind conditions on the Marshall Islands create high efficiency for wind propulsion

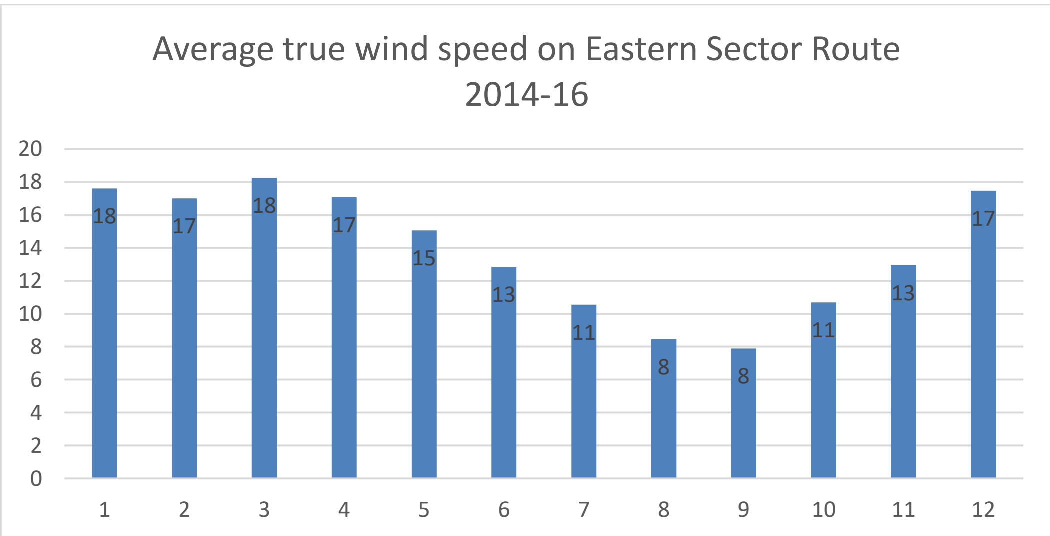

Figure 37: Average monthly true wind speed in knots on the eastern sector route[34]

[34] Analysis data from GFS-model along eastern sector route from years 2014 - 16

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The average wind direction encountered on the eastern sector route is 68°, which is east-northeasterly wind.[34]

3.9.2 Suitability of WASP Concept for MISC Fleet

Traditional, as well as high-performance options, are well suited for retrofit on the Kwajalein/Aemman type of ship. For the decision on the most suitable solution, advantages and disadvantages have to be thoroughly assessed and weighed. Some criteria are the following:

- Aerodynamic performance, saving potentials
- Safe and easy handling (with impact on operating hours and savings)
- No safety issues (maneuvering, stability, crew/passengers)
- Robust technology, simple maintenance concept
- Cost efficiency, e.g., cost per 1 kW installed wind power and maintenance costs
- Upscale potential for the region

From the experiences of different projects, it can be assumed that both options, conventional sails and high-performance wind propulsion are suitable solutions. A decision will be more either towards simple technology but more work and effort by the crew (conventional) or towards more advanced technology easy and safe to use but with a higher level of technology and its requirements. However, the project plan and budget may enable to select both sail technologies on two trial ships. A thorough test program may reveal valuable technical and operational know-how. The test results could support future decisions on the choice of technology for the whole region transitioning to low carbon sea transport. The TLCSeaT project could provide for special competence and high upscaling potential. Other regional projects that are in an early planning phase (e.g., Cerulean/Swire, Sea Mercy) could profit directly from the outcomes.

3.9.3 Wind Assisted Propulsion or Engine Assisted Sailing

The definition of 'wind-assisted' shipping, accounts for engine driven vessels that are assisted by a wind propulsion system. The main thrust is still generated by the main engine of the vessel, while the additional wind propulsion technology will reduce the required power that is needed to sail at a certain speed.

There are different operation modes possible for wind assisted shipping:

- sailing at constant ship speed, resulting from the combined thrust of wind- and engine power. Engine thrust can be reduced, the larger the resulting driving power from the wind propulsion system will get. This operation mode often leads towards situations, where the main engine of the vessel (originally designed for optimum performance at a specific engine speed) will operate in a low-efficiency range. That is why a diesel-electric powertrain is preferred when designing such vessels.
- operate the engine at optimum efficiency, while additional driving power from the supporting wind propulsion system will increase vessel speed. Through the continuous high engine thrust, the hydrodynamic system of the wind-assisted vessel is altered towards a high-performance system (high value for the ratio between

longitudinal and transversal forces). Depending on the prevailing strength of the wind in the sea area, as well as the speed of the vessel, this operation mode implies the installation of a high performance wind propulsion system, since the vessel will operate most of the time in a condition with relatively small apparent wind angles, as a result of relatively high initial vessel speed.

- optimize fuel consumption through clever weather-routing and power-management systems, that optimize engine thrust in combination with wind assistance in relation to arrival times or any other optimization aim. As shown for the operation variant of constant vessel speed, this operational mode requires adaptive power from the main engine, which again leads to the preference of a diesel-electric power train.

At the other hand, there is the option to design or refit the vessel in question, for 'engine assisted' sailing. In this case, the wind propulsion system will be used for the generation of the main propulsion power, using the main engine only for harbor operations, in case of emergency, in case of calms (and time pressure), or if a course against/close to the wind becomes necessary for other reasons.

This second refitting option will surely promise a maximum in fuel and emission savings. But this also implies higher skills from the operating crew and ideally the support of efficient weather-routing technology in order to be able to meet schedules. Wind propulsion systems that come to the application need good overall performance characteristics as well as the ability to work effectively for a large range of weather conditions. Since we would need maximum propulsion power even for low wind speeds, the installed systems must be large enough to deliver the required power, but there must be a simple way of reefing the systems (reduce driving power) in stronger wind conditions.

3.9.4 Ship Design Aspects

Conventional vessels are designed for a specific design speed, which implies that the shape of the hull, the engine layout, as well as the layout of the propeller and rudder are optimized for this service speed. The process of retrofitting existing vessels with wind propulsion systems has to consider many aspects that will influence the performance and safe handling of the vessel.

Balancing Aero- and Hydrodynamic Forces.

Every wind propulsion system generates not only a force in a longitudinal direction but also a lateral force. This cross force has to be balanced by the hydrodynamic layout of the vessel. Furthermore, the hydrodynamic capabilities of the vessel should have similar characteristics than the wind propulsion system, for both systems to work efficiently. An oversized hydrodynamic layout will induce too much additional drag, while a too weak system will not be able to deal with the lateral forces induced by the wind propulsion system and therefore lead to excessive drift angles and poor upwind performance.

The initial situation of most conventional trading vessels is that the hydrodynamic pressure point lies near to the bow of the vessel (vessel on even keel). If we are to install a wind propulsion system, the hydrodynamic pressure point must coincide with the aerodynamic pressure point in order to reach a balanced condition. If this is not the case, the resulting yawing momentum must be compensated by the rudder. This at the other hand can lead to overloading of the rudder, poor steering performance and high rudder drag.

There are several options to deal with this problem.

- The first option is to design the wind propulsion system in a way that its resulting aerodynamic pressure point coincides with the natural hydrodynamic pressure point of the hull near to the bow.
- Another solution is to move the position of the hydrodynamic pressure point aft, by changing the swimming position of the vessel through aft trim. Either through additional fixed ballast or through the use of existing water ballast tanks.
- If the vessels capabilities for dealing with large lateral forces are generally too weak, additional keels or dagger blades can come to application in order to improve this quality. Those can be positioned in a way that yawing momentums resulting from the wind propulsion system, are compensated.

The hydrodynamic calculations used in the performance calculations for MV Kwajalein are based on ‘slender body theory’. Main parameters that influence the hydrodynamic quality of the hull towards its ability to compensate large lateral forces resulting from the wind propulsion system, is the effective draft of the hull, the lateral area and the longitudinal position of the hydrodynamic center of effort (CE_{hull}).

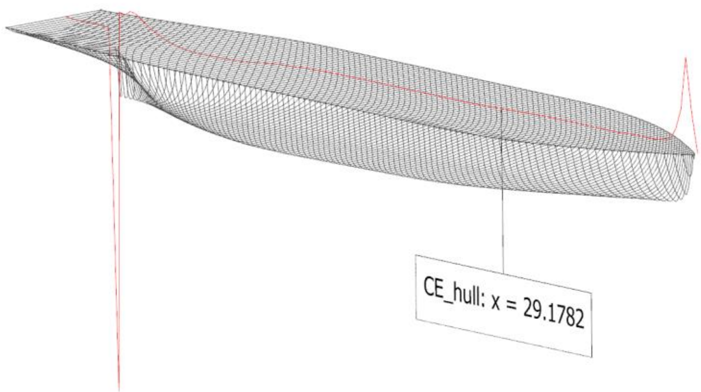


Figure 38: MV Kwajalein Sectional view, submerged part of the hull

The hydrodynamic center of effort (CE_{hull}) moves further aft, if aft trim becomes larger (changing cargo conditions or additional ballast), it will move forwards if aft trim becomes less. The large deckhouse at the aft of MISC-vessels is responsible for a relatively large initial aft trim in light ship condition.

Because of the nearly flat bottom, heeling will additionally increase the effective draft and thus having a positive influence on the hydrodynamic capabilities of the vessel.

Increase Rudder Efficiency:

An important characteristic that needs to be considered is the efficiency of the rudder. The design of the rudder is based on the design speed of the vessel, taking into account the jet effect of the propeller. The propeller thrust increases the efficiency of the rudder by increasing flow velocity around the rudder profile. If the propeller thrust is now reduced by WASP-technologies, the rudder efficiency is also reduced. To compensate for these losses, while sailing with WASP-technologies, the rudder layout should be adapted to the new requirements.

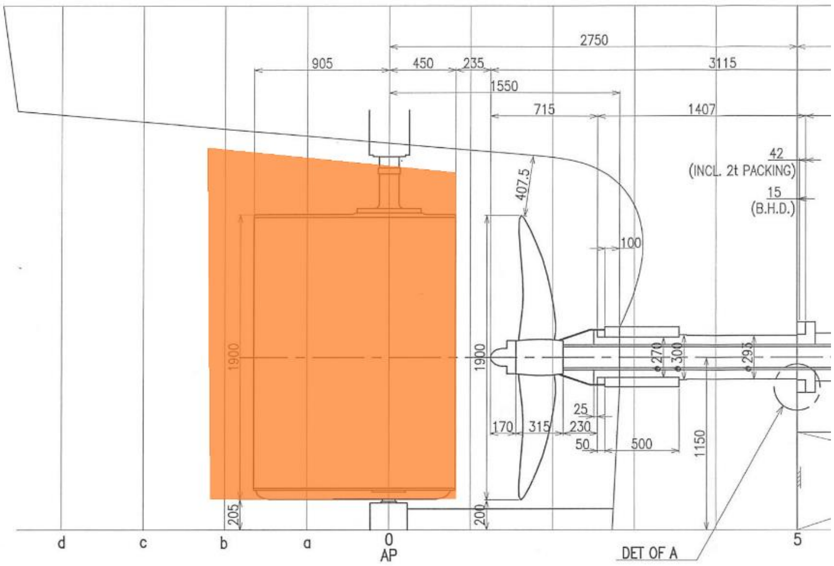


Figure 39: Increased rudder area[35]

The following means are available to increase rudder efficiency:

- Closing the gap between hull and rudder
- Increasing the rudder area by at least 30 %
- Using more efficient profiles for rudder sections

If this aspect is neglected, this can lead to the fact that even with good wind conditions, the main engine must run along to ensure good helm response of the vessel, even if the required propulsion power is completely provided by the wind propulsion system.

Further Aspects to be Considered

Further important ship design- and operational aspects to be considered in the layout of the wind propulsion system, are listed in the following:

- Required space on deck
- Influence /obstruction of view from the bridge
- Compatibility with cargo loading equipment
- Need for additional electrical power (automated systems)
- Need for additional men power (traditional/manual systems)
- Motivation of crew to use the available options despite higher work load

[35] Shipyard drawings of MV Kwajalein

3.9.5 Sail System Design Aspects

There are different options for wind assisted ship propulsion (WASP). They can be subdivided into three main categories.

1. Conventional/traditional sails that are operated manually
2. High-performance soft sail solutions in combination with automation technologies
3. High-performance and fully automated rotors or air-foil technologies

In the field of high-performance technologies, two systems were selected for a deeper analysis. Flettner Rotors and the IndoSail system. There are numerous alternative technologies in development for commercial shipping or already in use for yachting and high-speed sailing. However, most of these systems are based on disproportionately expensive materials and technologies. Therefore, the vast majority of these systems are not a real alternative in this project.

3.9.5.1 Traditional Sails

Many different rigs and sails have been developed over the centuries, mainly depending on the type of ship and the trading sea area and its environmental conditions. E.g., for coastal and island navigation on shorter voyages the schooner rig has been a common solution for better maneuverability and upwind performance in comparison to square rigs which have been found as a suitable solution in long distance trades using large wind pattern for mainly downwind sailing. The Bermuda/Sloop rig has similar characteristics and is mainly used in yachting.

Figure 40: Sail cargo ship Kwai with a ketch type traditional rig, tripod mast, (left)[36]*; Sail cargo ship Avontuur, schooner type traditional rig (right)*[37]

The strength of traditional systems is based on the continuously developed and proven detail solutions of these manually operated systems. Today, the decisive difference to the modern high-tech variants that can be automated lies above all in the underlying philosophy of the system. While modern systems focus on safety, automation and maximized efficiency, the decision for a traditional system is based more on aspects such as: Team spirit, social interaction, training and employment.

[36] www.marinetraffic.com
[37] www.timbercoast.com

Retrofit towards traditional WP-System

The SV Kwai is the perfect example for a successful low budget vessel retrofit towards wind propulsion technologies. Originally built as a typical engine driven fishing vessel, the SV Kwai had been retrofitted in several consecutive steps towards a full wind powered vessel.

3.9.5.2 High-Performance Soft Sail Solutions

There have been some clever developments to enhance aerodynamic performance, safety and handling of conventional gaff sails. E.g., the so-called IndoSail has been developed and successfully tested on a sail cargo ship in Indonesian waters in the 1990s. The system can be operated **manually as well as fully automated.** It, therefore, represents a hybrid solution between the traditional and the modern, high-performance solutions. After the development of the system, there have been several applications of the IndoSail system aboard different vessels which led to further improvement of the techniques.

Figure 41: 'Rainbow Warrior' (left)[38] and Indonesian sail cargo ship 'Maruta Jaya' (right)[39] with IndoSail rig

Technical Aspects: IndoSail-System

The IndoSail system has been designed for maximized efficiency in terms of costs per square meter of sail area. Based on economic efficiency this system seems to be very well suited for the intended task of emission reduction for RMI with good upscale potential for application on similar vessels in neighboring countries.

[38] http://ernestoippolito.blogspot.com/2011/09/

[39] https://www.mainewindjammercruises.com/connect/newsletter/January-2005---Special/Capt--Ray-Builds-Momentum-for-Aid-Ship-Project/

Schematic operation system:

- Stationary frame, controlled via two sheets at boom and gaff
- Both sheets are controlled by one winch (see illustration).
- Rod-roller Sail is positioned within this frame
- Continuously variable reefing of the sails is possible.
- The high aspect ratio for reefed sail leads to good performance in strong winds.
- Control of leech tension independently from sail angle.
- Construction of rig and sail is based on simple techniques.

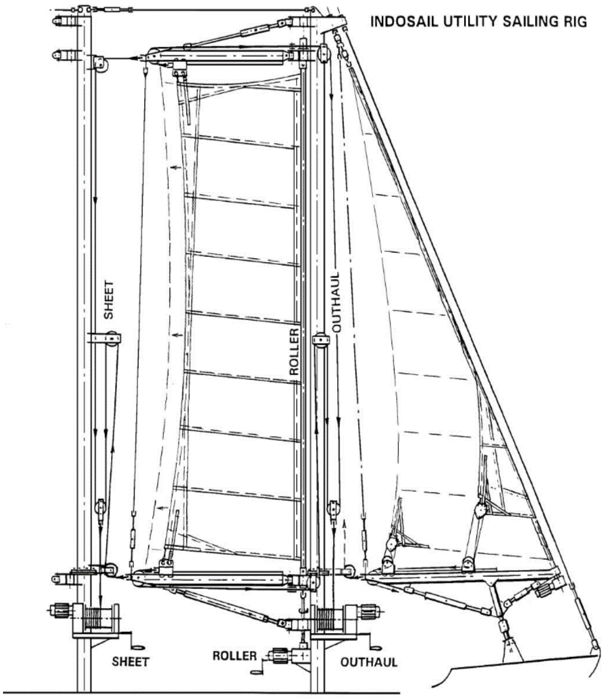


Figure 42: Schematic operation of the IndoSail system

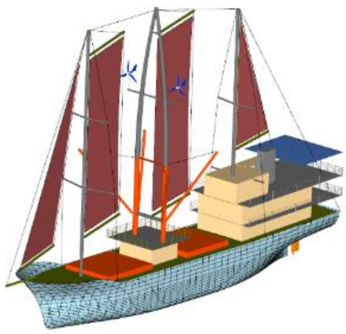


Figure 43: Sail area 100%

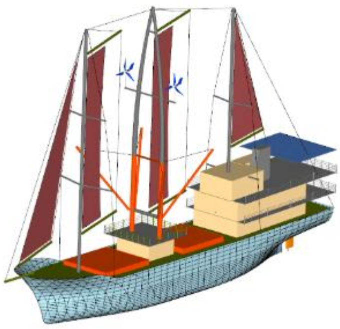


Figure 44: Sail area 70%

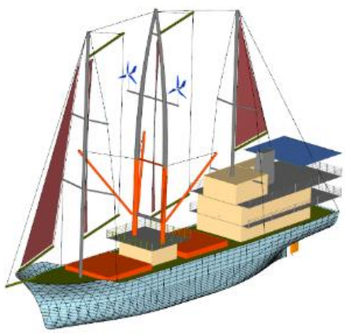


Figure 45: Sail area 30%

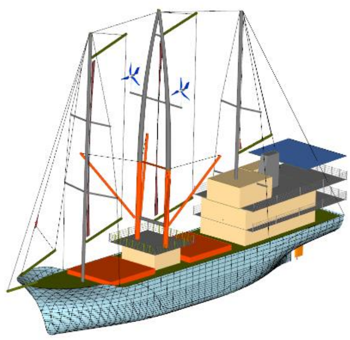


Figure 46: Reefed Sail

Different technical options for the handling of the running rigging (sheet, reefing lines, etc.):

- Low tech variant like on traditional vessels. Pulling sheets and reefing lines etc. by hand power.
- Yachting-technique winches either manual or supported by an electric engine.
- Fixed winch drum allow automated operation of sheets and reefing system, as well as manual operation.

The system can be extended towards a fully automated, system. Different automation grades for the operation of the System (winch drum):

- Manually operation at the base of the mast
- Locally operation of the electrical winch at the mast base
- Remote operation of the sails from the ship's bridge
- Semi-automatic: Computer displays optimal sail angle based on measured weather information.
- Fully automatic operation: sail angle and course controlled by a computer based on measured and predicted wind data as well as weather routing optimization.

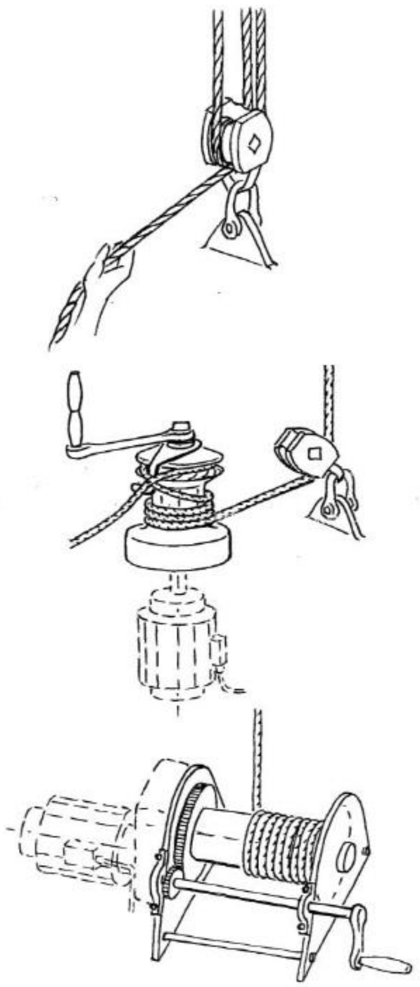


Figure 47: Winch types for IndoSail

Safety in surprising gusts of wind can be achieved by slip clutches, which automatically open the sheets when the sail pressure is too high.
Since the construction of the system, compared to other high-performance wind propulsion solutions, is quite simple, it is likely that even smaller shipyards in the Pacific region could build up the capacity to perform all required refitting tasks that are needed.

3.9.5.3 High-Performance Automated Rotor Technology (Flettner-Rotor)

Shipping's demand for fuel saving and carbon-neutral wind propulsion has initiated more advanced technological developments in recent years. The main advantages of modern wind propulsion are high aerodynamic performance and safe/easy handling through automatic control systems. However, there are few systems that are market ready and proven in their performance such as Flettner-Rotors.

Figure 48: Cargo ship Fehn Pollux with Flettner rotor installation[40]

This type of drive uses the wind to create additional thrust for ship propulsion: A Flettner rotor is a high cylinder that stands vertically on a ship and rotates on its own axis. It is driven by an electric motor. The optimum rotational speed depends on the wind speed and direction, like a regular sail.

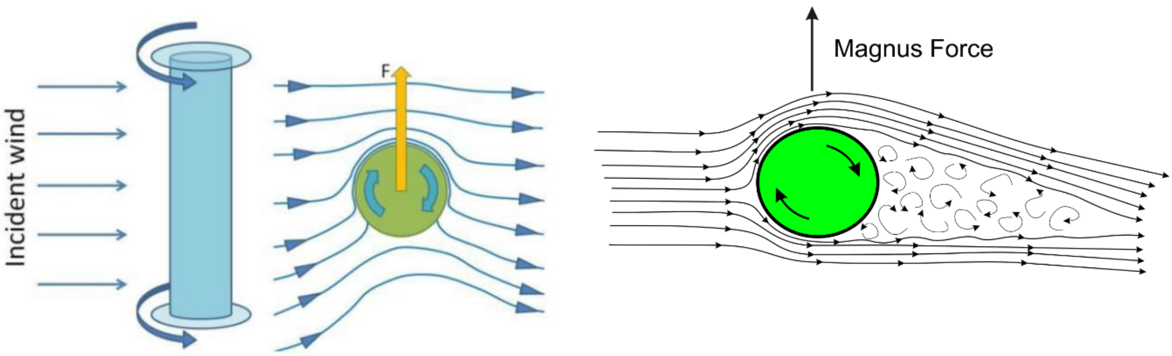


Figure 49: Working principle of Flettner Rotor and Magnus effect[41]

This technology uses the Magnus effect to accelerate and redirect the airflow, which produces an additional thrust force (Magnus Force).

The interaction between the rotor surface and wind flow creates a lift force so that the ship receives additional thrust. The rotors were already developed in the 1920s but did not succeed commercially at that time due to the low oil price. However, greater environmental awareness and rising fuel prices have made this type of wind engine interesting again in recent years.

[40] Mariko GmbH
[41] https://en.wikipedia.org/wiki/Magnus_effect

3.9.6 Stability Requirements and Safety Aspects

Each conversion variant will affect the stability characteristics of the ship. The compliance with all relevant stability criteria already belongs to the work of the performing engineer in the design phase of the conversion option.

The stability properties of the ship can be corrected to the desired level by appropriate design measures, such as additional ballast in the bilge, modified design of the sail rig, for example by choosing different construction techniques. In this way, the ship will meet all legal requirements after a conversion.

In addition to complying with legal requirements, stability can also be taken into account when designing the rig so as not to unnecessarily stress the comfort of the passengers, for example, by excessively inclining the ship when sailing.

When using cloth sails, safety slipping clutches can be used which, depending on a predefined sail pressure, release the sheets to avoid excessive heeling in a wind gust. With rotor technologies, this can be done, for example, by automated rotor control settings.

On the other hand, WASP technologies offer an additional safety benefit, especially in heavy weather situations, as the sail systems have dampening properties which prevent the ship from roll motions in heavy seas. Safety, as well as crew and passenger comfort, will be increased.

Since well implemented WASP technologies can be operated even without the main engine, additional safety through redundant propulsion comes along with the use of this technology. In the case of a main engine breakdown, the vessel will still be controllable.

3.9.7 Predicting Saving Potential from WASP

The savings that can be achieved by the use of wind propulsion systems are directly linked to the savings in fuel consumption. These savings, accumulated for a certain amortization timespan (for example 10 years), give us an indication of how much money we can spend for the retrofitting of the vessel and the maintenance work during this period of time. For commercial vessels, this is the most important financial parameter that has to be considered when thinking about retrofitting options.

For commercial vessels, we have to find the most efficient system in terms of propulsion force compared to maintenance and investment costs.

3.9.7.1 Estimating the Saving Potential for Wind Assisted Shipping

For the relatively simple case of engine thrust reduction by supporting wind propulsion at constant ship speed, it is possible to determine the power reduction due to the sail system using a "power equivalent value per square meter sail area".

For the calculation of this value, the characteristic properties of the sail system (i.e. characteristic values of the sail’s polar diagrams), the average wind conditions as well as the cruising speed of the ship and the efficiency of the drive train are required.

The following table gives the calculated values for different wind propulsion systems. The average wind speed for this example is 15kn. Ship speed varies from 7kn to 10kn.

Table 4: WASP options: power equivalent value per projected sail area

Speed [kn]	**Traditional Gaff** [kW/m²]	**IndoSail-3R** [kW/m²]	**Flettner-Rotor HEL** [kW/m²]
7	0,2	0,28	1,92
8	0,22	0,31	2,10
9	0,24	0,35	2,29
10	0,26	0,38	2,48

From this list, it can be seen that these values differ significantly depending on the propulsion system in question. Another tendency is the increasing efficiency for higher ship speeds. This is related to the increased apparent wind speed when the ship is moving.

The high values for the Flettner rotor result from the small projected area of the rotor compared to a conventional rig. For more details on the actual power saving potential of the different technologies refer to chapter 3.9.8 on different retrofit variants.

For an initial estimation of the average savings potential of a particular sail system, this value can be multiplied by the sail area of the sail design.

3.9.7.2 Calculation of Detailed Saving Potential for WASP Technologies

Velocity prediction programs can be used for more detailed calculations. Based on detailed information about the ship geometry and the characteristics of the sail systems known from wind tunnel tests, it is possible to predict relatively accurately the performance potential of the sail system in combination with the ship to be retrofitted. Particularly details about the sailing behavior on different courses to the wind as well as at varying wind force and different sea state conditions become apparent with a calculation according to these methods.

Based on this detailed information, further savings potentials can be estimated by travel optimization and weather routing techniques. The potential performance of a wind propulsion system is well above the average for courses with particularly favorable weather conditions. Details on the course dependent savings are further explained in chapter 3.5 on weather routing.

For all proposed refit options (chapter 3.9.8) the velocity prediction calculations were performed for two different operational modes.

Wind assistance:

The vessel is assumed to travel with constant speed. The engine is supported by the wind propulsion system. In this scenario, we can calculate the relative saving potential with respect to vessel speed, wind force, direction and corresponding sea state. The savings are presented as a fraction from the total required power that the vessel will need, to follow a course towards a specific angle towards the true wind. As has been shown in chapter 3.5 on weather routing, the total required engine power varies depending on the course towards wind and waves even if no wind propulsion system is utilized.

Sailing without engine support:

The vessel is purely driven by the wind propulsion system. The main engine is switched off. Needed electrical power is supplied by auxiliary energy systems. Depending on the size and efficiency of the wind propulsion system, as well as wind speed and direction, the resulting curves display the performance capabilities of the analyzed vessel.

The results of the calculations are presented in the form of figures and diagrams for the retrofit proposals for MV Kwajalein. The theoretical background for the calculation model is based on the works from B. Wagner[42] [43] [44], P. Schenzle[45], B. Blendermann[46], P. Blume, U. Keil [47], and M. Khiatani[48].

3.9.8 WASP Refit Proposals

For a first approach there have been two retrofitting options defined:

- **Minimum Retrofit**. This option will leave the proposed ships (Aemman, Kwajalein or Newbuild) in their general layout without major changes in the cargo gear. The sail device will be used to depower the main engine.
- **Maximum Retrofit**. This option is aiming at high ambitious fuel savings through wind propulsion. The ship can be operated mainly under sails in adequate wind conditions. Additional measures have to be taken care of:

- Adapt cargo loading equipment to the wind propulsion system
- Adapt steering capacity to a large wind propulsion system
- Adapt energy supply to the requirements of the installed system

[42] Wagner, Windkräfte an Überwasserschiffen, 1967
[43] Wagner, Schriftenreihe Schiffbau: Praktische Durchführung der Berechnung der Fahrtgeschwindigkeit von Segelschiffen, 1962
[44] Wagner, Fahrtgeschwindigkeitsberechnung für Segelschiffe, 1967
[45] Schenzle, Technik und Strömungsmechanik von Segelschiffen, 2014
[46] Blendermann, Schiffsform und Windlast Korrelations- und Regressionsanalyse von Windkanalmessungen am Modell, 1993
[47]P. Blume, U. Keil, P. Schenzle, Rechnerische Bestimmung der Widerstandserhöhung eines Schiffes in regelmäßigen Wellen und Vergleich mit entsprechenden Modellversuchen, 1973
[48] Khiatani, Der Einfluß des Zusatzwiderstandes durch Seegang und Wind auf den Schiffsentwurf, 1985

Three different wind propulsion technologies are proposed:

- Flettner-Rotors, as a future, directed technology. The system is operated automatically and can be controlled from the bridge, e.g., for emergency stop function.
- The IndoSail concept, as a hybrid solution between traditional and high-tech. The system is capable to be operated manually as well as fully automated if the required equipment comes to application.
- Conventional/traditional textile sails as an option on a lower technical level needing a higher effort in manual handling by the crew. Sloop rigs or gaff sails are possible options, both having similar performance characteristics.

A thorough discussion and evaluation could lead to a decision for 'one' choice. However, retrofitting two options on two ships could reveal valuable data, knowledge, and competence for comparing different WASP.

The average savings that are presented in the tables below assume an average wind speed of 15 knots and courses sailed equally frequent in all directions towards the wind. The achieved savings are furthermore dependent on vessel speed. If the vessel is moving slower, then a larger proportion of the required power can be achieved by the wind propulsion system.

More detailed information on the potential savings that can be achieved is displayed in the velocity prediction figures attached to each refit proposal.

3.9.8.1 Retrofit Option 1: Flettner-Rotor-One (Minimal Configuration)

A relatively easy retrofit option is the installation of one medium sized Flettner-Rotor' at the forecastle of the vessel.

Flettner-Min	
Type:	Flettner-Rotor
Number of Rotors:	1
Height:	12 m
Diameter:	2 m
Diameter-endplate:	4 m
Projected Area (PA):	24 m²
Surface Area (SA:	75,4 m²
AR (rel. to PA):	6:1
Total Rotor Area (PA):	24 m²
CE_{sail}:	x = 39,0 m

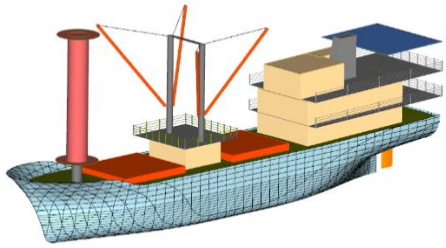


Figure 50: Retrofit option 'Flettner-Min'

The minimum refit with one Flettner-Rotor at the bow of the vessel requires only minor changes to the existing vessel layout.

- Reinforcement of rotor foundation
- Alternative positions for all installed equipment on removed forward mast or moving the complete mast
- Installation of Rotor control unit on the bridge
- Adapt an auxiliary power supply system for Flettner-Rotor power demand

Following table and figures give an overview on the saving potential for minimum refit variant with one Flettner-Rotor of 12m height.

Table 5: Power savings for a refit of one Flettner-rotor (Flettner Min)

Ship Speed [kn]	Average Power reduction [kW]	Fuel / Emission savings per nm [%]
7,00	~ 50 kW	~ 27 %
9,50	~ 62 kW	~ 16 %

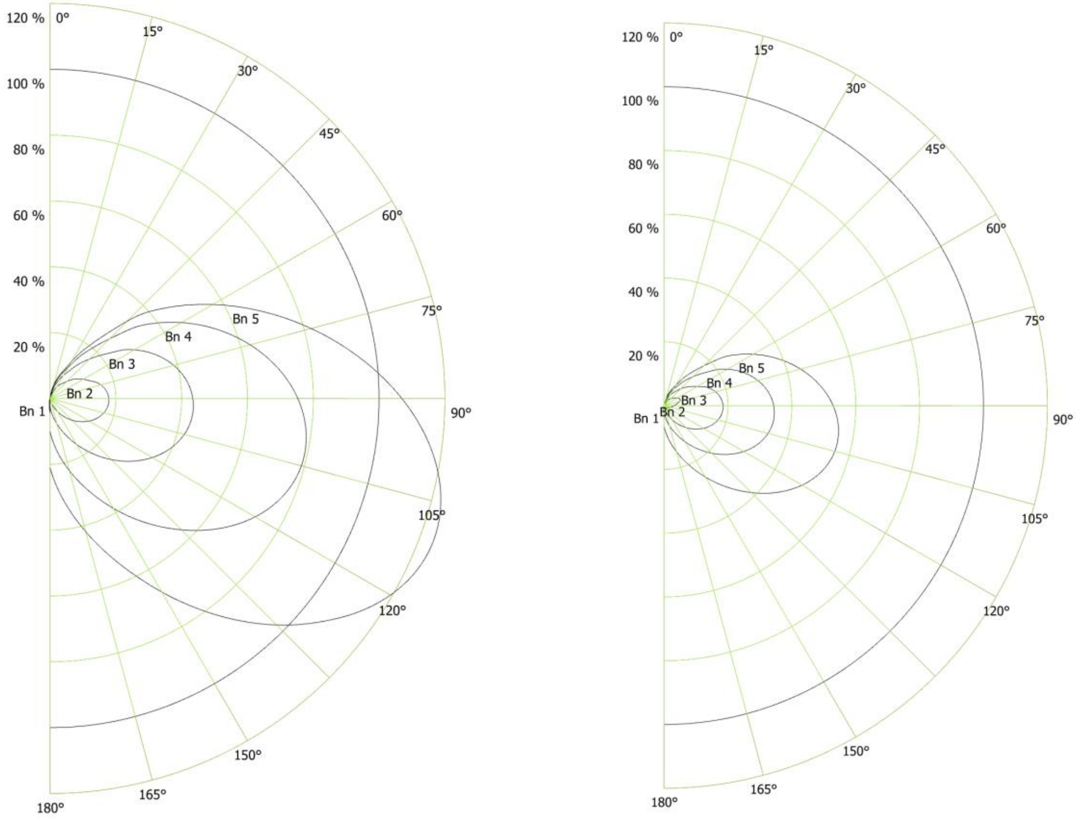


Figure 51:power saving potential for a constant speed of 7kn (left) and 9.5 kn (right) at different weather conditions

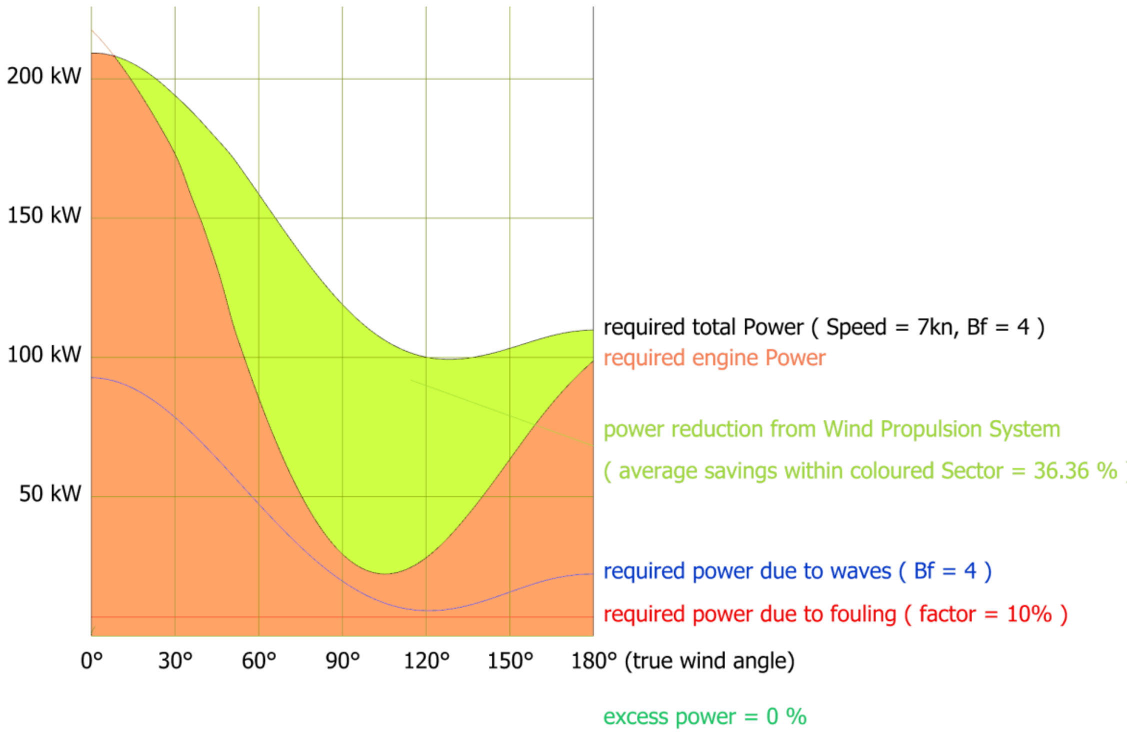


Figure 52: Power saving potential for option 'Flettner-Min' (Speed: 7 kn, Wind: 4 Bft)

3.9.8.2 Retrofit Option 2: Flettner-Rotor-Two (Maximum Configuration)

Flettner-Max	
Type:	Flettner-Rotor
Number of Rotors:	2
Height:	12 m
Diameter:	2 m
Diameter-Endplate:	4 m
Projected Area (P_A):	24 m²
AR (rel. to P_A):	6:1
Total Rotor Area (P_A):	48 m²
Total Surface Area (S_A):	*150,8m²*
CE_{sail}:	x = 32,15 m

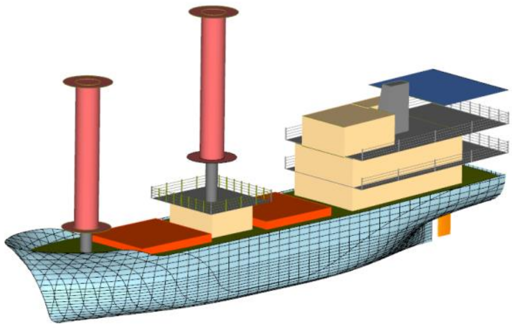


Figure 53: Retrofit option 'Flettner-Max'

Required changes in vessel layout for the maximum refit variant with two Flettner-Rotors at the bow and at the position of the cargo loading equipment.

- Reinforcement of Rotor foundation at bow position
- Alternative positions for all installed equipment on removed forward mast or moving the complete mast
- Reinforcement of Rotor foundation at midship position
- An alternative solution for cargo loading equipment
- Installation of Rotor control unit on the bridge
- Adapt the auxiliary power supply system for Flettner-Rotors
- Enlargement of existing rudder to improve steering capabilities
- Additional rudders, or side keel systems, if improved upwind performance is anticipated

Following table and figures give an overview of the saving potential for maximum refit variant with two Flettner-Rotors of 12m height.

Table 6: Average power savings for refit with two Flettner-rotors (Flettner-Max)

Ship Speed [kn]	Average Power reduction [kW]	Fuel / Emission savings per nm [%]
7,00	~ 105 kW [Excess power: 18 kW]	~ 45 %
9,50	~ 130, kW	~ 31 %

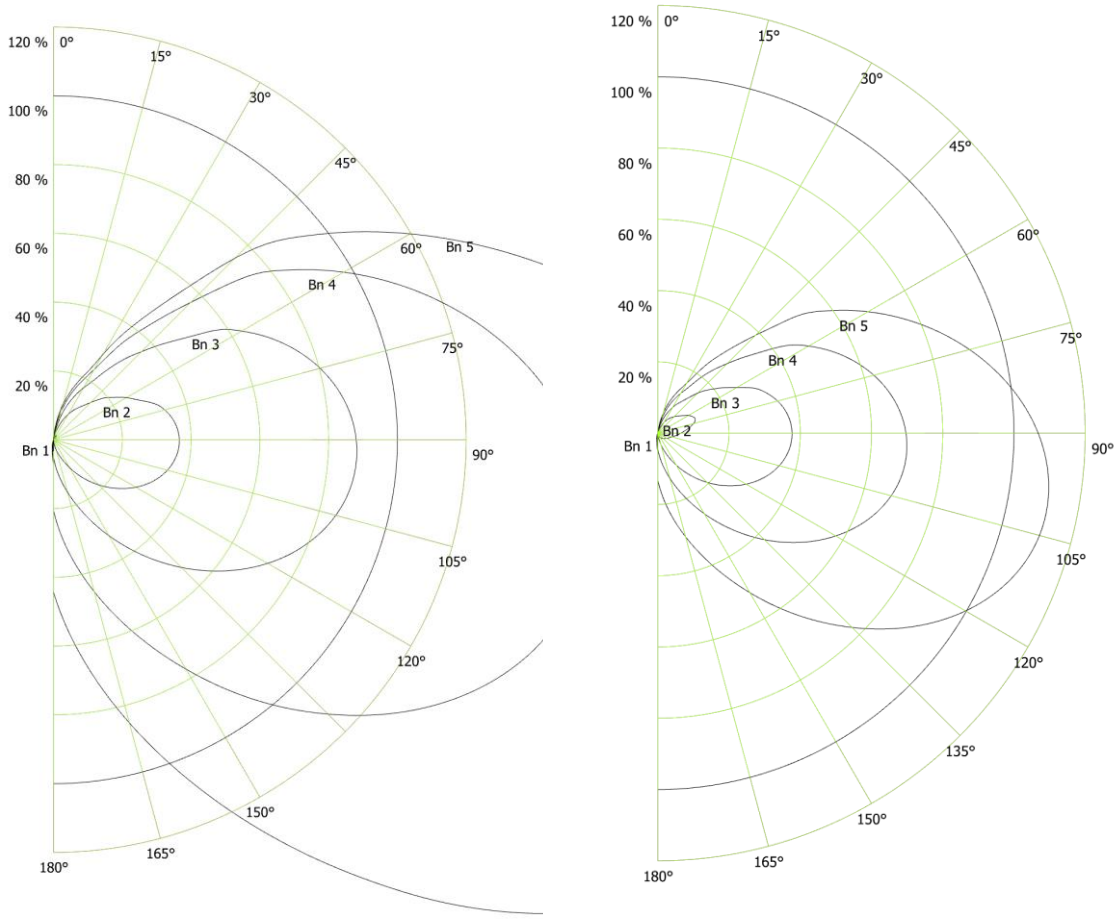


Figure 54: Power saving potential for constant speed of 7 kn (left) and 9.5 kn (right) in different weather conditions.

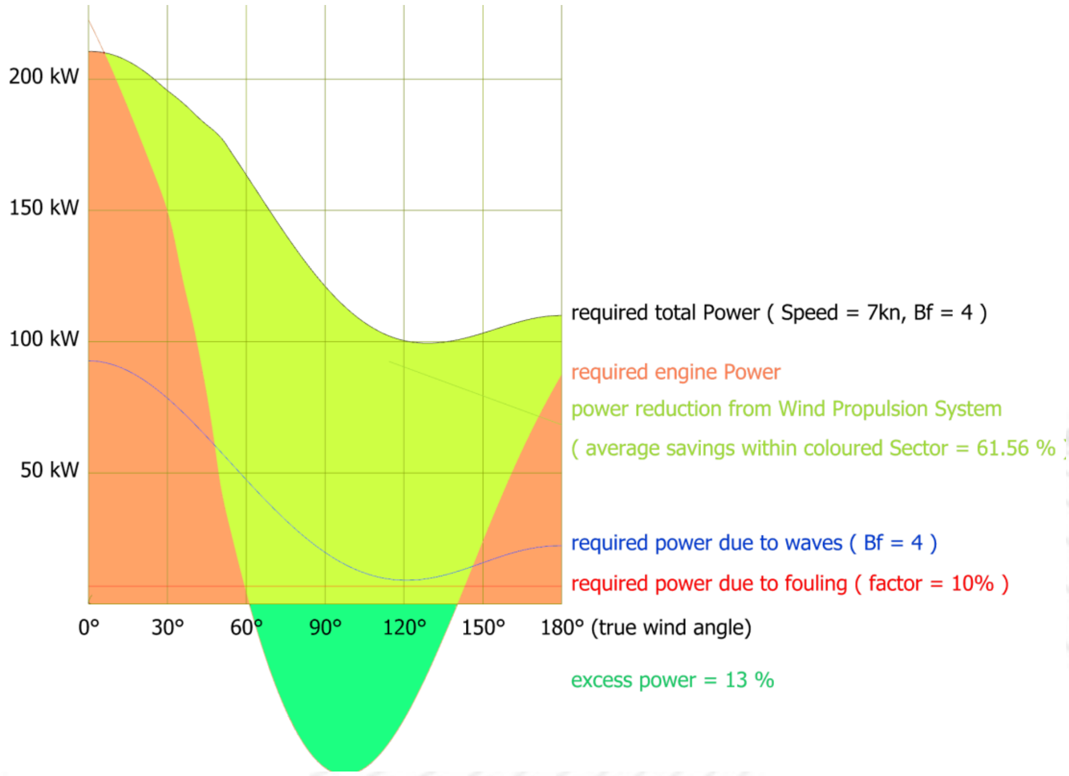


Figure 55: Power saving potential for option 'Flettner-Max' (Speed: 7kn, Wind: 4bn)

3.9.8.3 Retrofit Option 3: IndoSail-2-Mast (Minimal Configuration)

IndoSail-Min

Type:	IndoSail-2R Rig
Sail area:	
Jib:	85,7m²
Main:	147,4m²
Mizzen:	66,8m²
Total:	300m²
CE_{sail}:	x = 31,2m

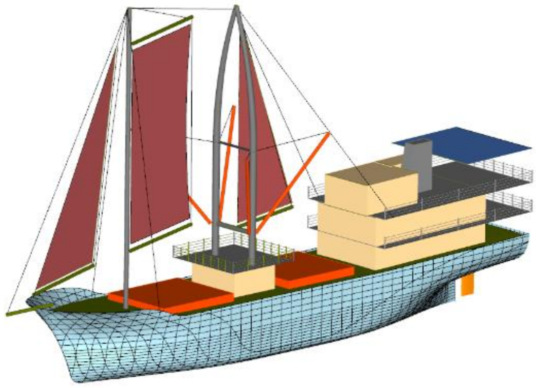


Figure 56: Retrofit option IndoSail 2-masts (IndoSail Min)

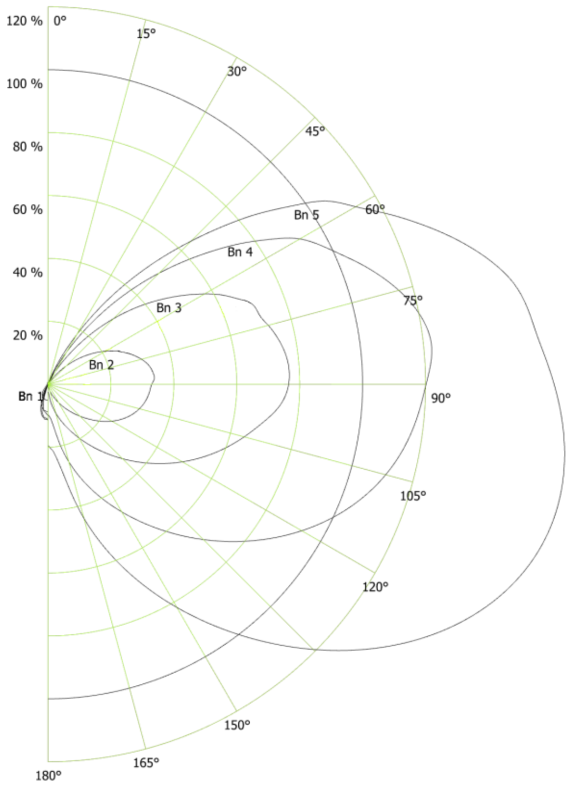
The minimal conversion with a small IndoSail system requires minor changes to the existing ship layout. In addition, the existing cargo gear must be rearranged for dual purpose, cargo handling, and wind propulsion.

- Reinforcement of forward mast foundation
- Alternative positions for all installed equipment on the removed forward equipment mast
- Enlargement of cargo masts for use as aft wind propulsion mast
- Installation of IndoSail automatic furling and sheeting winches/system
- Installation of IndoSail control unit
- Power supply system for sail winches and reefing system

Following table and figures give an overview of the saving potential:

Table 7: Power savings for a refit of IndoSail 2-masts (IndoSail-Min)

Ship Speed [kn]	Average Power reduction [kW]	Fuel / Emission savings per nm [%]
7,00	~ 78 kW [Excess power: 4.5 kW]	~ 38 %
9,50	~ 98 kW	~ 24 %



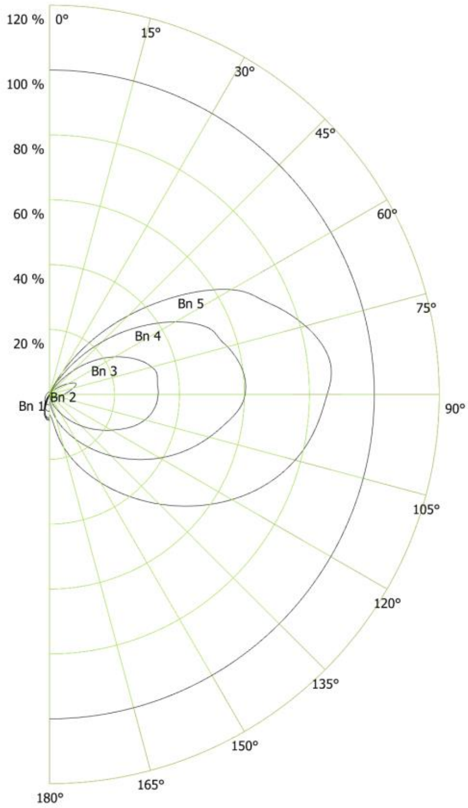


Figure 57: Power saving potential for constant speed of 7 kn (left) and 9.5 kn (right) in different weather conditions.

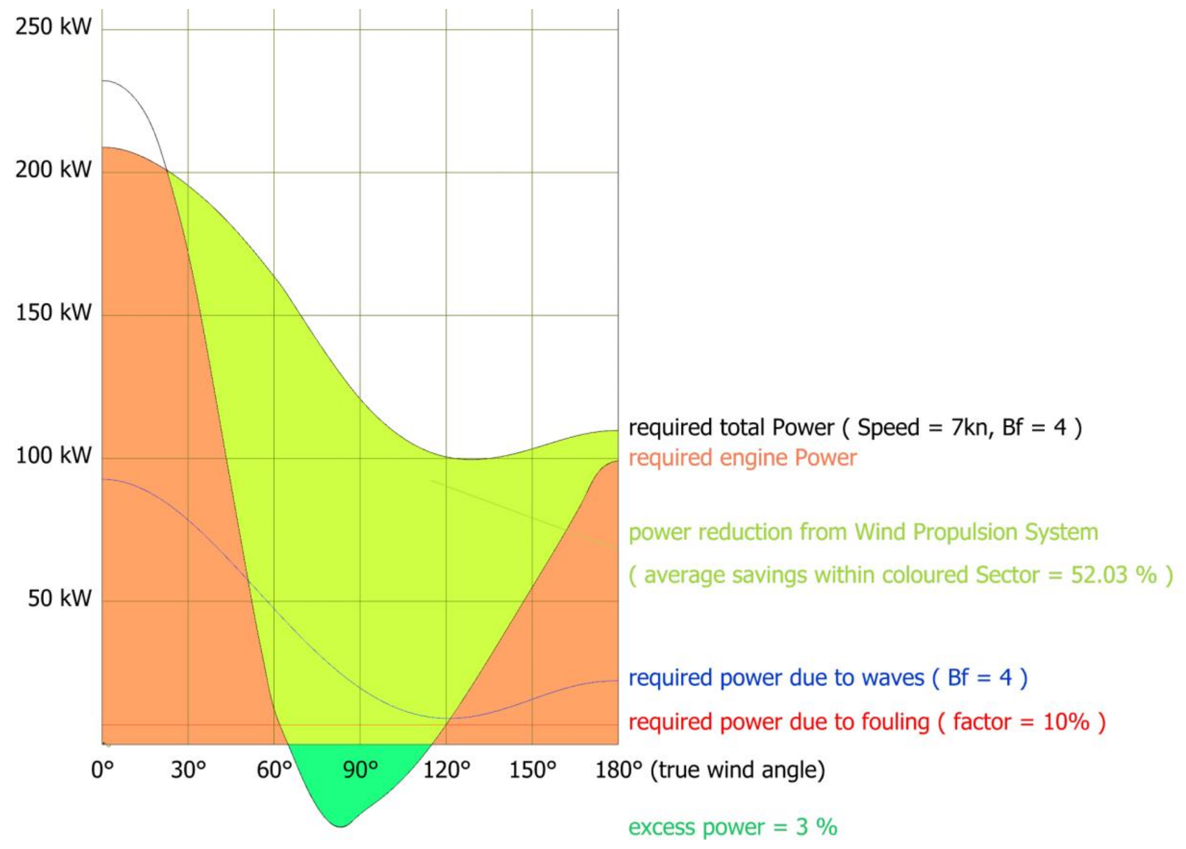


Figure 58: Power saving potential for option 'IndoSail-Min' (Speed: 7kn, Wind: 4bn)

3.9.8.4 Retrofit Option 4: IndoSail-3-Mast (Maximum Configuration)

IndoSail-Max

Type:	IndoSail-3R- Rig
Sail area:	
Jib:	109,2 m²
Main 01:	193,8 m²
Main 02:	193,8 m²
Mizzen:	62,8 m²
Total:	559,5 m²
CE_{sail}:	x = 28,8 m

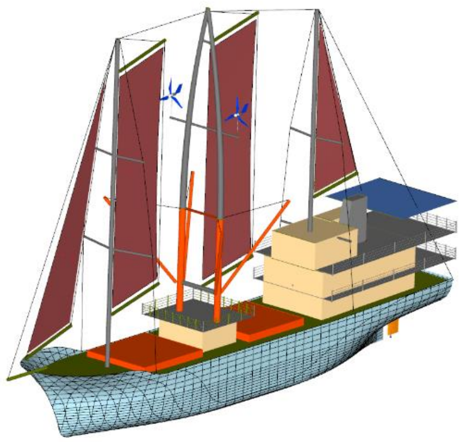


Figure 59: Retrofit option IndoSail 3-masts (IndoSail-Max)

Required changes in vessel layout for the maximum refit variant with large IndoSail system. In addition, the existing cargo gear must be rearranged for dual purpose, cargo handling, and wind propulsion.

- Reinforcement of forward mast foundation
- Alternative positions for all installed equipment on the removed forward equipment mast
- Enlargement of cargo masts for use as aft wind propulsion mast
- Installation of IndoSail automatic furling and sheeting winches/system
- Installation of IndoSail control unit
- Power supply system for sail winches and reefing system
- Enlargement of existing rudder to improve steering capabilities
- Additional rudders, or side keel systems, if improved upwind performance is anticipated

Following table and figures give an overview of the saving potential:

Table 8: Power savings for refit of IndoSail 3-mast (IndoSail-Max)

Ship Speed [kn]	Average Power reduction [kW]	Fuel / Emission savings per nm [%]
7,00	~ 97 kW [Excess power: 67 kW]	~ 50 %
9,50	~ 195 kW [Excess power: 11 kW]	~ 46 %

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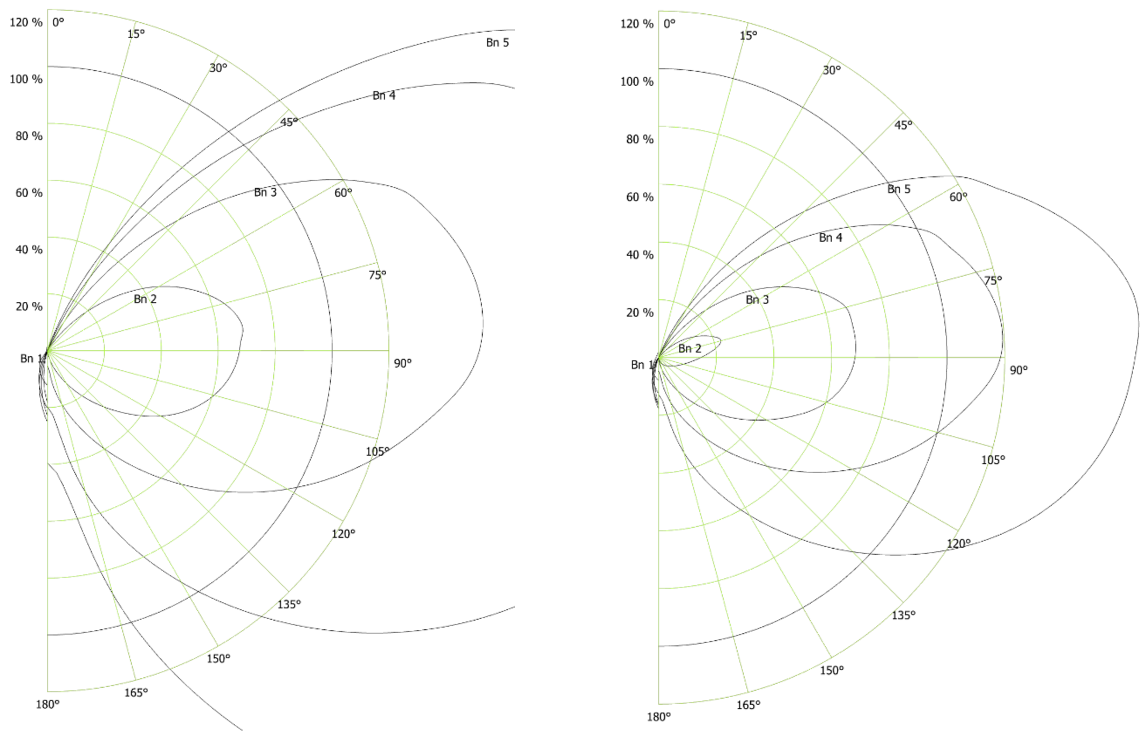

Figure 60: Power saving potential for constant speed of 7 kn (left) and 9.5 kn (right) in different weather conditions.

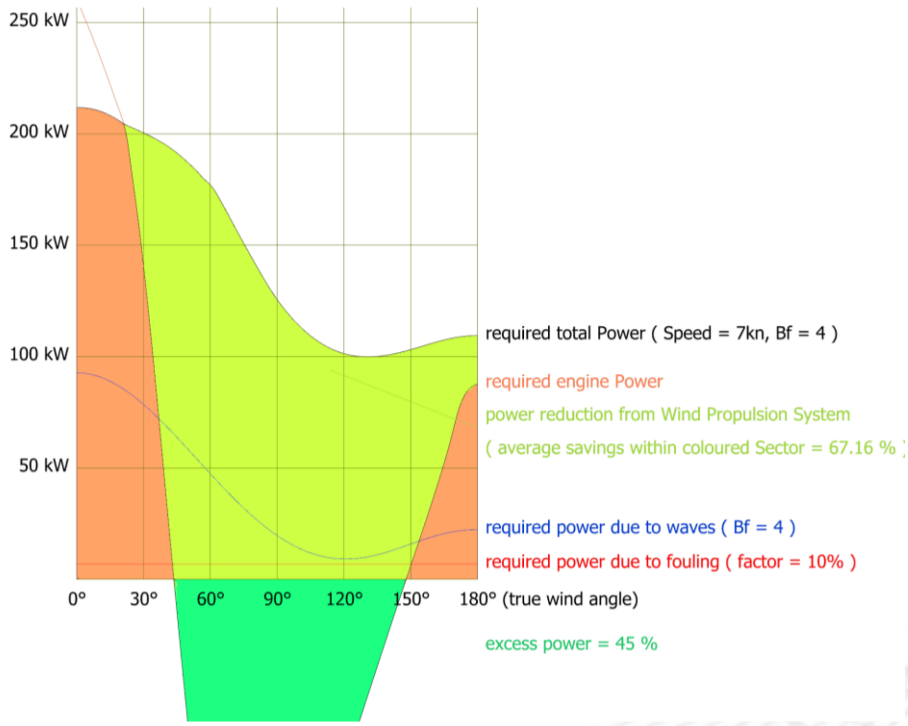

Figure 61: Power saving potential for option 'IndoSail-Max' (Speed: 7kn, Wind: 4bn)

3.9.8.5 Retrofit Option 5: Small Conventional Rig (Minimal Configuration)

Conventional-Min

Type:	sloop rig
Sail area:	
Jib:	99 m^2
Main:	87 m^2
Total:	186 m^2
CE_{sail}:	x = 37 m

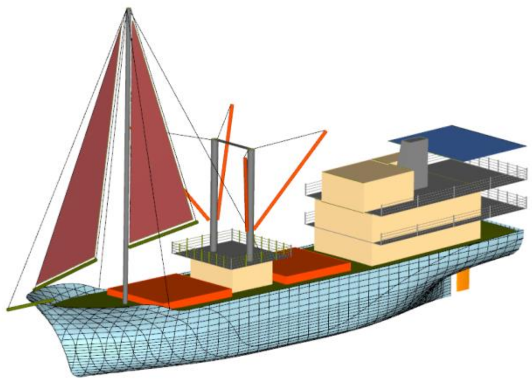

Figure 62: Retrofit option Bermuda Min

The Conventional-Min variant requires only minimal changes to the ship layout. For a conversion only the equipment mast of the foredeck has to be replaced by the mast for the sail system. The simple system is based on proven yacht technology but offers only limited savings potential. Nevertheless, the system can be a good introduction to wind propulsion technology.

Following table gives an overview of the saving potential:

Table 9: Power savings for refit of Bermuda Min

Ship Speed [kn]	Average Power reduction [kW]	Fuel / Emission savings per nm [%]
7,00	~ 36 kW	~ 20 %
9,50	~ 46 kW	~11 %

3.9.8.6 Retrofit Option 6: Large Traditional Rig (Maximal Configuration)

Conventional-Max

Type:	traditional gaff
Sail area:	
Jib 1:	72 m²
Jib 2:	63 m²
Jib 3:	35 m²
Main 1:	115 m²
Topsail 1:	45 m²
Main 2:	115 m²
Topsail 2:	45 m²
Total:	550 m²
CE_{sail}:	x ≈ 28 m

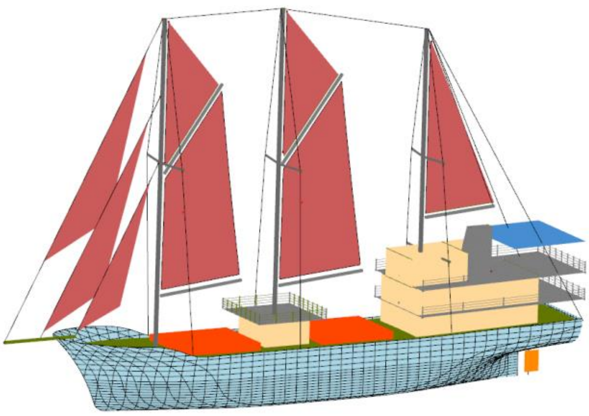

Figure 63: Retrofit option Traditional-Max

The Conventional-Max variant is based on the traditional gaff vessels of the last century. The effort for retrofitting is relatively high, but many detailed solutions do without complex technology, which should enable good maintenance by local employees. The need for manual operation of the sail systems can be seen as an opportunity for training and employment.

Following table gives an overview of the saving potential:

Table 10: Power savings for refit of Traditional-Max

Ship Speed [kn]	Average Power reduction [kW]	Fuel / Emission savings per nm [%]
7,00	~ 95 kW [excess power: 13 kW]	~ 49 %
9,50	~ 136 kW	~ 33 %

3.9.9 Saving Potential in Combination with Weather Routing and Slow Steaming

For the example of retrofit option "Flettner-Min" the potential savings, related to the course sailed towards the true wind, is displayed in Figure 64 and Figure 65 for vessel speeds of 7 and 9.5 knots. The figures show the percentage of required power P_D that can be saved by wind propulsion, depending on wind force and direction.

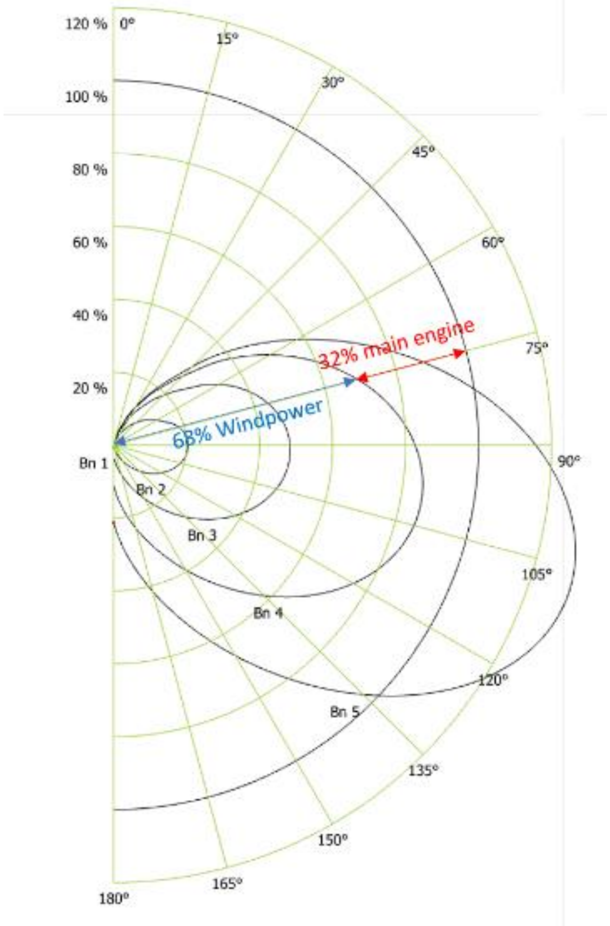

Figure 64: Percentage of wind power from total required power for vessel speed of 7 knots

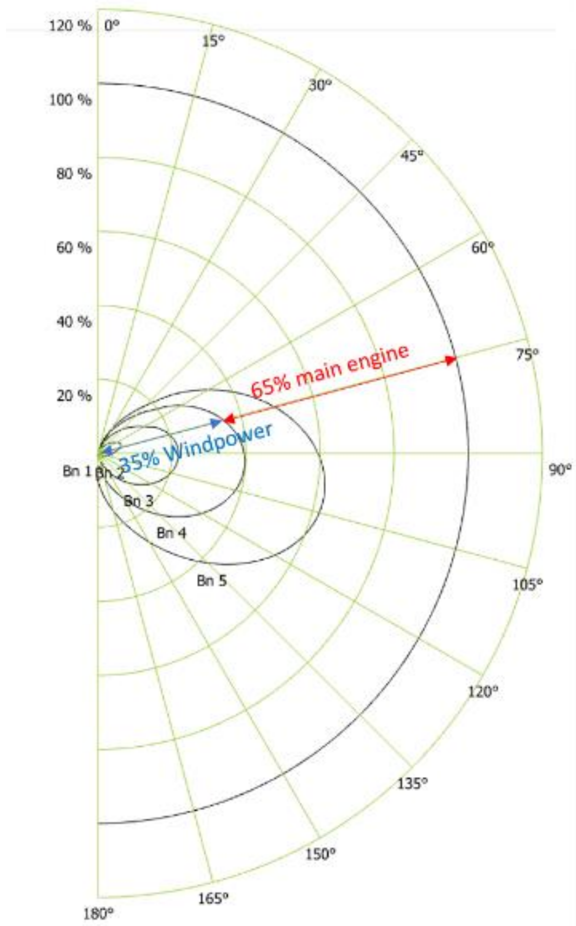

Figure 65: percentage of wind power from total required power for vessel speed of 9.5 knots

As the main trading routes along the island chains are perpendicular to the main wind direction, the most common operating profile can be assumed with true wind angles from 60° to 120°.

The following two figures display the percentage of engine power savings that can be achieved if the vessel is operating in a sector of favorable wind conditions (crosswinds).

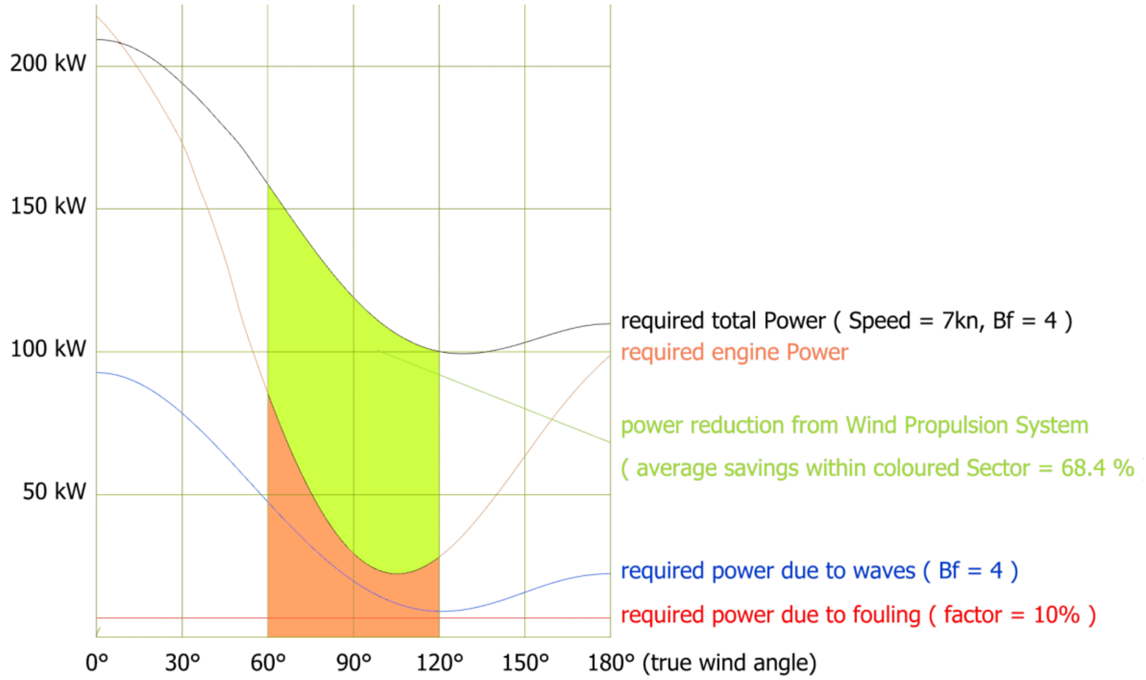

Figure 66: Savings from one installed Flettner Rotor in beam winds

Savings from a Flettner rotor can reach a high value of 68% assuming that the main legs of the routes lie perpendicular to the most probable wind direction (compared to 36% savings for equally distributed courses for all wind directions). For further information refer to chapter 3.9.1.

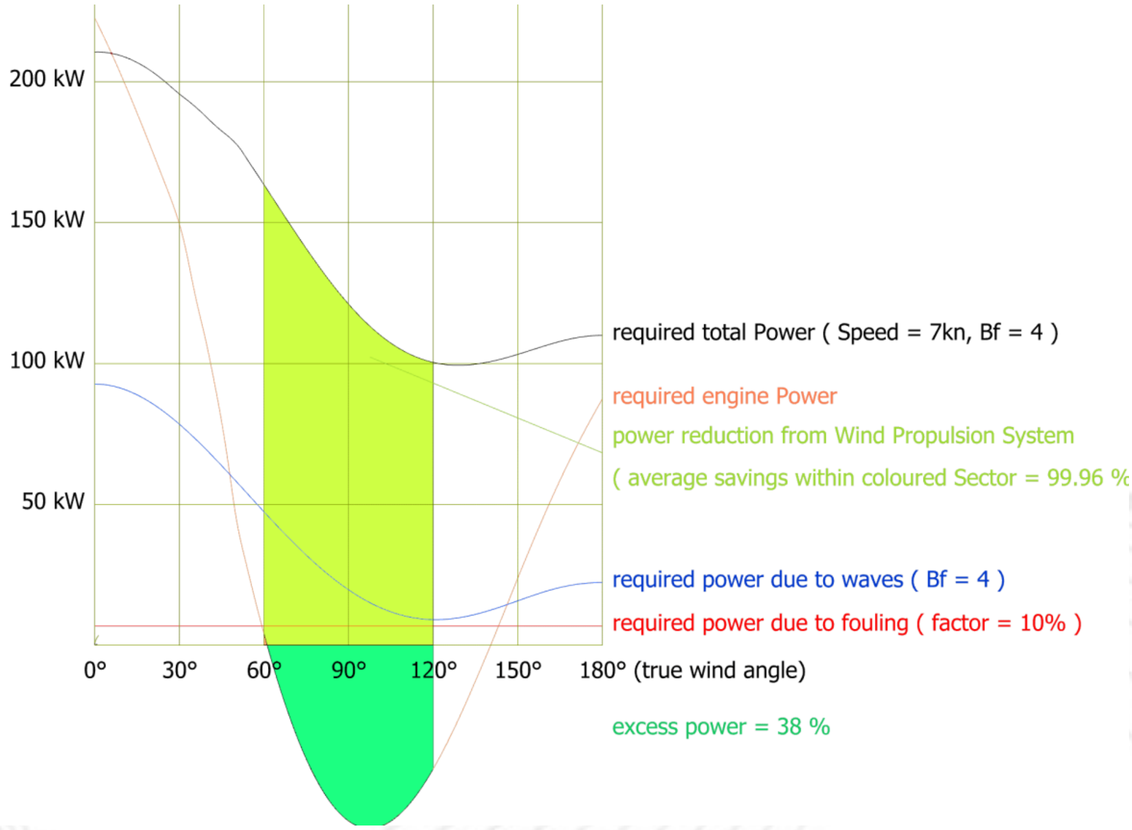

Figure 67: Power Saving-Potential from Flettner-Max in beam winds

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For the maximum refit with two installed Flettner-Rotors (or other large wind propulsion systems), the vessels can sail in beam wind conditions using wind propulsion only.

The calculated power even exceeds the required power for a service speed of 7 knots. The zero-emission status can be achieved if enough excess energy is converted into electrical power to provide for auxiliary systems.

In case of the Flettner Rotors, additional driving power for the operation of the rotors is needed (estimated by 15-20% of the rotor power, supplied by auxiliary engines). If the system is configured like above, this excess power can be used for the operation of the rotors.

3.9.10 Compensation for Slow Steaming through Wind Propulsion and Weather Routing

Figure 68 and Figure 69 below present the calculated vessel speed if the ship was sailing without support from the main engine, relating to wind force and direction.

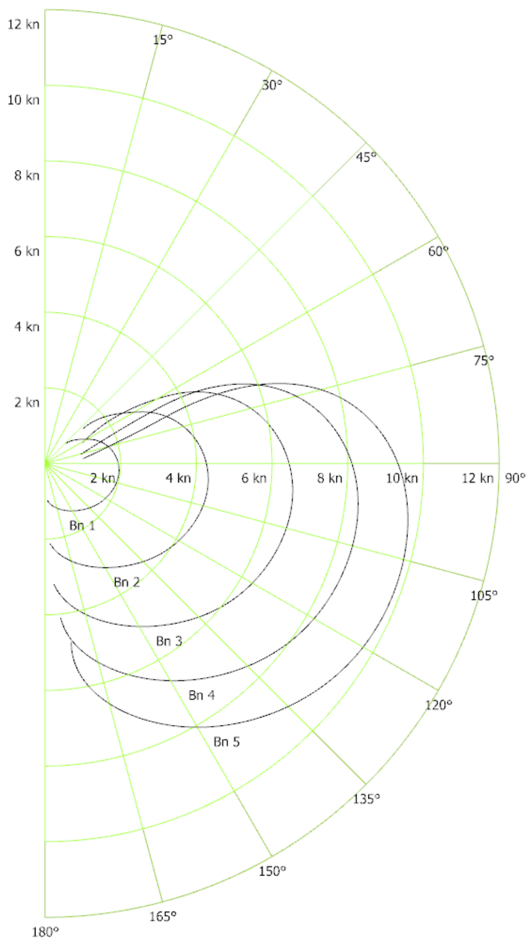

Figure 68: VPP – Flettner-Max variant

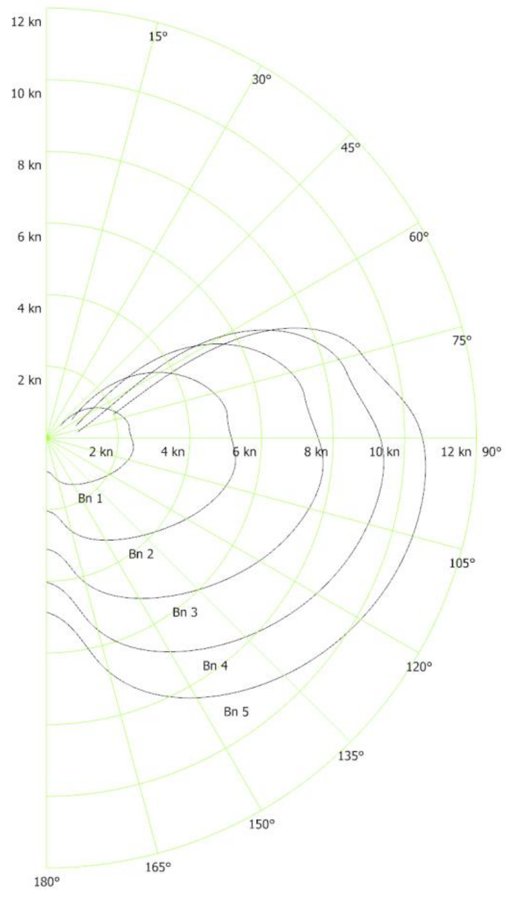

Figure 69: VPP – 3-mast IndoSail variant

Displayed are the corresponding vessel speeds from Beaufort 1 to 5 (Bn 1 to Bn 5). Best performance is reached for a course towards true wind of 90° to 100°. The performance calculations indicate that for prevailing wind force and directions (beam wind), vessel speeds of 8 to 10 knots can be achieved by using the wind propulsion system without engine support.

The following two figures display achieved engine power savings if the vessels were operating at a relatively high speed of 9.5 knots but within the sector of favorable wind conditions.

Figure 70: Power saving potential of Flettner-Max configuration assuming beam winds

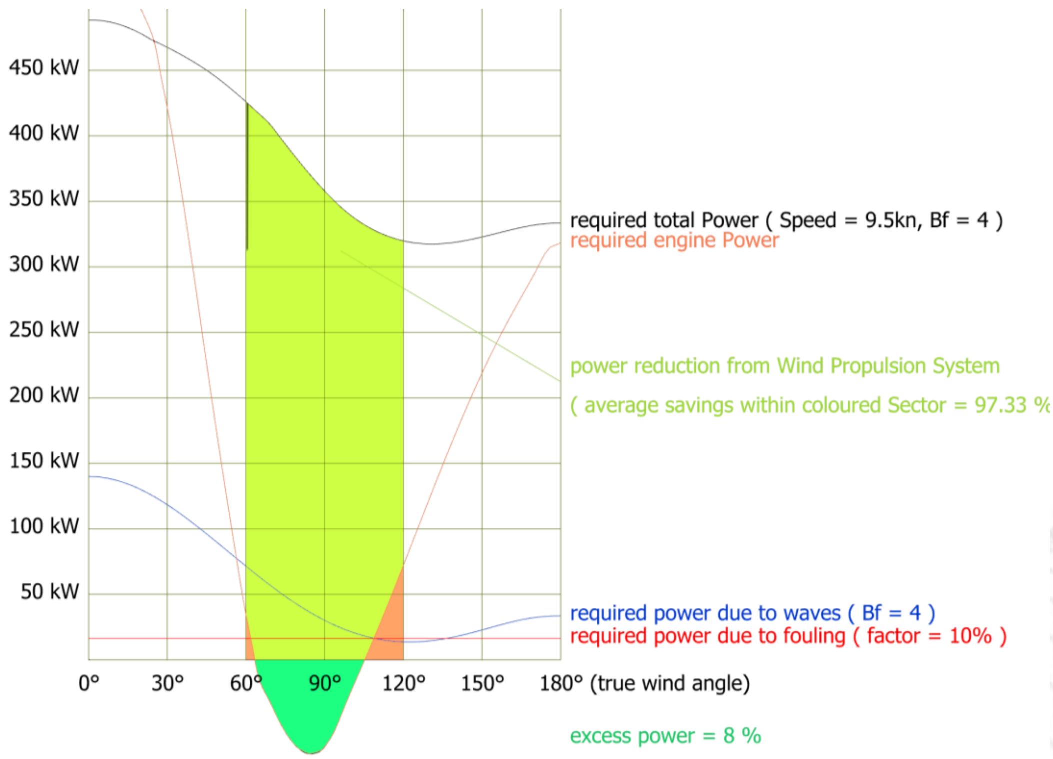

Figure 71: Power saving potential of IndoSail-Max configuration assuming beam winds

3.9.11 Further Improvement of Upwind Performance

To further increase the performance of the hull, the use of additional keels, side blades/boards or additional rudders can be considered.

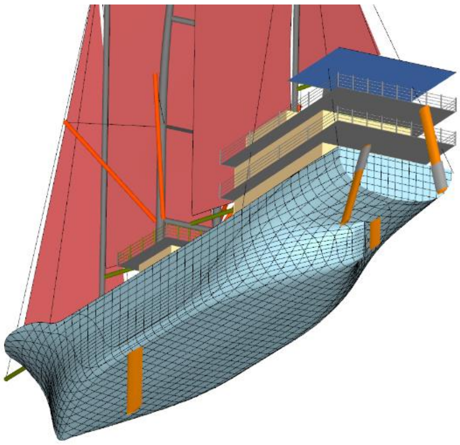

Figure 72: Improvements to hydrodynamic efficiency

- The effective area of the existing rudder can be increased (minimizing the gap between rudder and hull)
- To improve steering and maneuvering capabilities, in conditions with low engine thrust (low rudder efficiency due to lack of accelerated flow through the propeller), additional rudder(s) at the transom of the vessel can be installed.
- The use of side keels/swords will improve upwind performance by around 10 % (Heading angles of 50° to 55° towards the true wind direction can be achieved**).**

It is possible to convert MISC vessels to full and reasonably good performing wind-powered sailing vessels. Nevertheless, the gain in upwind performance comes at relatively high costs. It has to be analyzed, which of the above mentioned additional measures for increased vessel performance are economically reasonable. If vessels are operating mainly in crosswind conditions, it will be much easier to simply use the main engine, to make good for poor upwind performance.

3.10 Auxiliary Energy System

Safe and comfortable ship operation requires numerous electrical powered aggregates. On most ships, electric power is generated from fuel by a combined set of an auxiliary diesel engine and a generator.

In the following, the ship MV Kwajalein is used to present various options to reduce the fuel consumption of the auxiliary energy system. Similar measures and results are achievable on the other MISC ships, which have comparable systems installed.

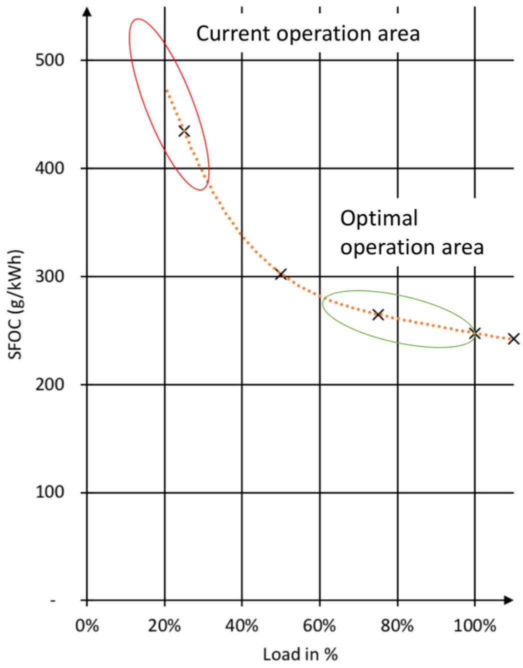

Figure 73: SFOC of diesel-generator-set MV Kwajalein [49]

In general, the most efficient operation area of Diesel generators (DG) is above 60% of their maximum continuous power rating. Load conditions below that usually have significantly higher specific fuel oil consumption (SFOC). Load conditions below 30% should be avoided completely due to high wear and high SFOC. Figure 73 shows the SFOC graph in grams per kWh electricity of MV Kwajalein's DG. The actual load depends on the energy demand on the ship and in particular on the operating state of the vessel (navigation, cargo handling, port (idle), etc.).

Table 11: Load vs. operating states

	Unit	*Navigation*	*Cargo handling*	*Port/Idle*	*Remarks*
avg. load	kW	18	27	17	Fieldtrip October 2018
avg. utilization	%	22%	34%	21%	

Table 11 shows the observed average load of the DG in different operation states during a field trip in 2018. Due to various circumstances, the DGs hardly operate beyond 40% of maximum load. The main reason lies in the generators being oversized for the current use-case in the RMI. The ship was originally

[49] Test record of auxiliary engine MV Kwajalein

designed to perform more cargo handling and therefore needed ample power. In the current use-case, these situations are rare, and the remainder of the time there is a loss in efficiency.

The low-level limit of 30% is exceeded only for cargo handling. During navigation and idle state, the DGs are running in very unfavorable low conditions up to 21% load leading to high SFOC and high wear out.

The following calculations for fuel consumption are based on the operating times from the baseline study by Oxley[50]. Figure 74 shows the operating states in 2017. It indicates the share of the different operating states. Based on times and average loads, the fuel oil consumption can be estimated. It must be noted that during layups in the Majuro Lagoon the DGs are turned off to decrease operating costs. These lay-up times make up to 39% of the total time. Since the ship's share of navigation time where the main engine is running is not very high during the year, the percentage of fuel consumption used for the auxiliaries is high. Over 25% of the total fuel consumption is used to run the auxiliary system. Due to the low effectiveness of the existing system, measures in the auxiliary engine domain offer high savings potential as presented below.

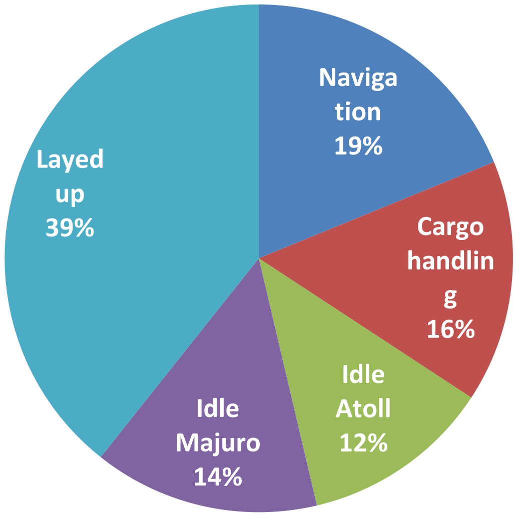

Figure 74: Pie chart of different operating shares [50]

3.10.1 Installation of an Additional Diesel Generator

The most obvious measure to improve the efficiency of the auxiliary system is the installation of DGs that are better suited to the ship's operational profile. The compact integration of the existing DGs in the engine room makes modifications elaborate and expensive. However, a third additional diesel generator can be integrated, which could be especially designed for the low load conditions and thus work in its optimum operating range.

For the operation with a smaller DG, further interventions in the electrical system are likely to be necessary. The lower spinning reserve due to the lower capacity of the DGs has to be addressed. Spinning reserve is required in order to provide high starting currents for electric motors. However, technical upgrades for the electrical system such as star/delta connections or soft starter control will achieve a reduction of surge currents. The existing DGs can be used as a backup or for large loads required during excessive cargo handling, e.g., unloading copra.

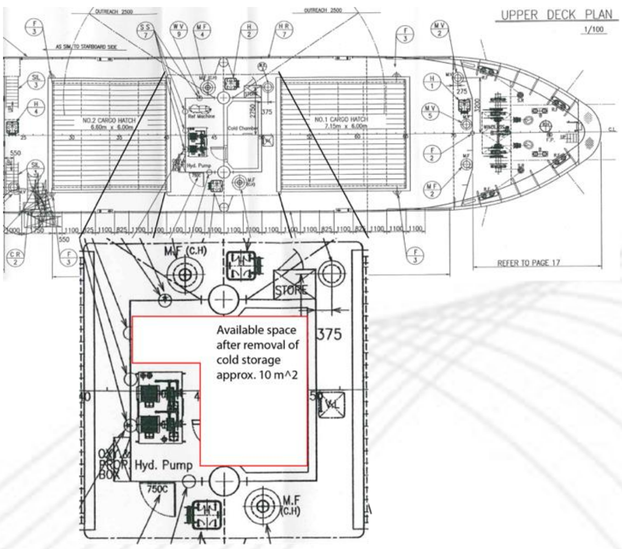

Figure 75: Possible space for installation of a hybrid auxiliary system. Excerpt from general arrangement plan

The engine room most likely does not provide enough space for the installation of an

[50] PRIF Report Mark Oxley - Table 17 page 34 - Results for MISC Ships Operation, FY2017

additional aggregate. A potential installation site for the system could be the cold storage room in the deckhouse between the hatches, which is currently not in use. The removal of the cold storage and the refrigerant machine would offer approximately 10 m^2 (107.7 ft^2), (see figure 3). On the ship MV Aemman a similar installation was undertaken. After the failure of one DG a replacement had to be installed, in the deckhouse. This measure could be implemented smoothly without major conversion measures and pays for itself within few years.

3.10.2 Diesel Generators with Variable Engine Speed

Conventional diesel generators are operating with constant engine speeds. e.g., 1800 RPM for a 60Hz frequency of the electrical grid. The disadvantage of constant engine speed is, that an efficient working range is limited to the range around rated power. With the developments in power electronics and frequency converter technologies, variable speed operation of the Diesel engine is possible today. This offers the advantage that the engine can adjust the speed depending on the electrical load and thus work in better operating points. This offers significant saving potential compared to the DG with constant speed.

The engine manufacturer Wärtsilä[51] states that savings up to 5-10% are possible. Due to a high share of low load conditions in the MISC fleet, savings are estimated to be significantly higher. Because of the high fuel price in RMI, it is definitely advisable to take a closer look at these DGs despite their higher complexity and price. Figure 76 shows a comparison of a fixed and variable speed Diesel engine.

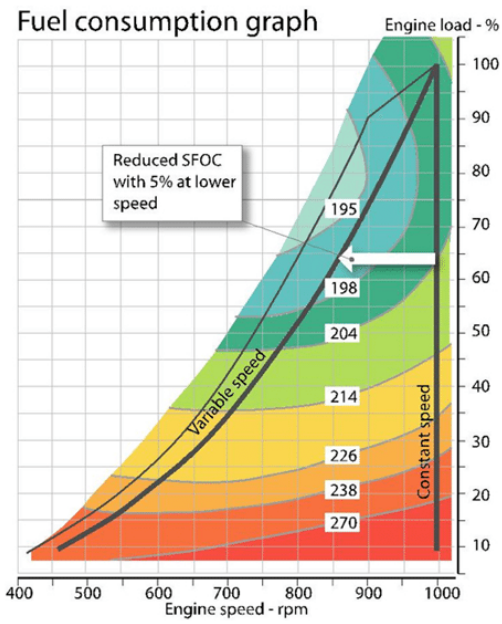

Figure 76: Comparison of SFOC between constant and adjust- able speed power generation

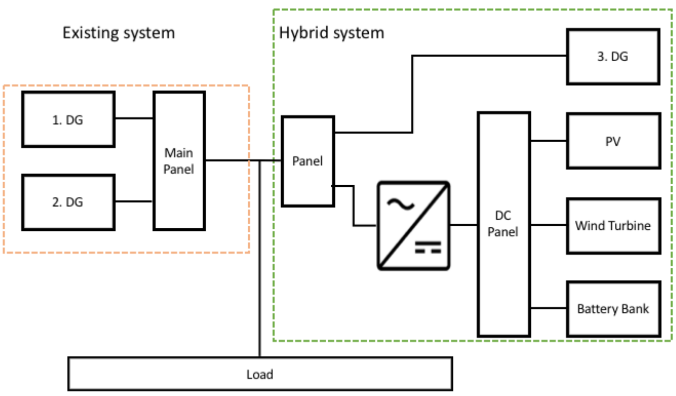

Figure 77: Schematic of an example hybrid auxiliary system

[51] https://gcaptain.com/part-marine-engineering-technology/

3.10.3 Hybrid Electricity Generation

The combination of different energy sources is called hybrid electricity generation. Various options are possible, e.g., combinations of Diesel generator and battery storages or additional renewable sources. Due to the high cost and maintenance of battery systems, the size should be as small as possible. Renewable sources such as Wind and Solar are highly available in RMI. However, the possibilities on a ship are limited, e.g., by installation space as well as the unreliable availability. In combination with diesel generators as a hybrid source, renewables are an excellent option to reduce load from the diesel engine. This combination makes only sense if the DGs are running in reasonable operation ranges. Therefore, a smaller diesel generator must be installed before renewables are considered.

3.10.4 Battery Bank

The high volatility and non-permanent availability of renewable energies require the use of batteries as intermediate storage. These buffers absorb the fluctuations that occur, for example, in PV with short-term cloud cover see Figure 78[52]. In RMI, a clear day is rare; the yield is subject to permanent fluctuations.

The storage system is also suitable for temporarily storing excess regenerative energy and then retrieving it later. This occurs, for example, during lay-up, when the energy requirement is very low and the wind turbine supplies the power. A battery system should be designed with a sense of proportion due to high costs and the limited number of charging cycles. A reference point for the dimensioning can be the yield of a possible wind turbine or PV plant during a day in which the ship is in lay-up condition.

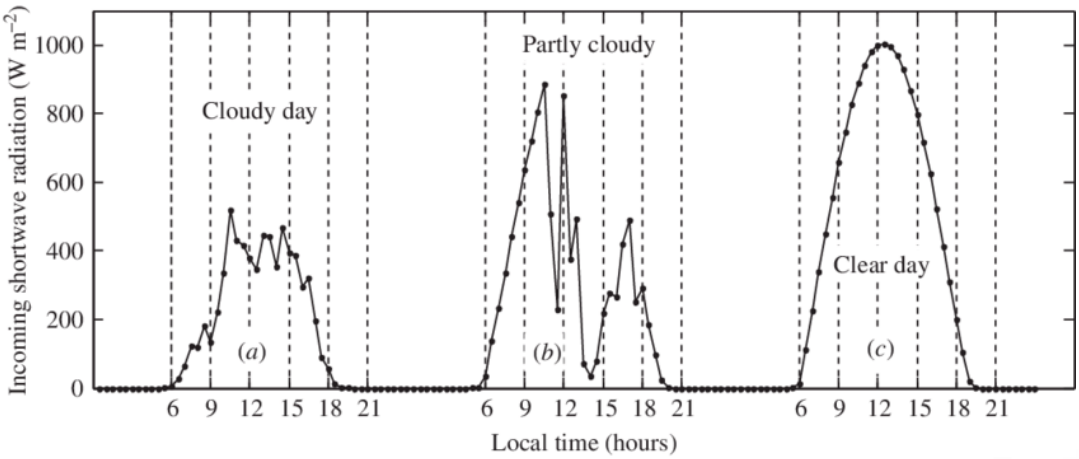

Figure 78: Daily cycle of incoming shortwave radiation on cloudy, partly cloudy, and clear days

3.10.5 Wind Turbines

As stated in chapter 3.9 (wind propulsion), the atmospheric conditions are close to ideal for the use of wind power. This potential is also usable as a source of electricity generation.

[52] https://www.researchgate.net/figure/Daily-cycle-of-incoming-shortwave-radiation-on-cloudy-partly-cloudy-and-clear-days_fig4_260631629

3.10.5.1 Requirements for the Turbines

Due to the highly corrosive environment, only marine grade turbines are considerable. These can be turbines from the yacht sector as well as offshore classified turbines. On the market for small wind turbines, some suppliers are specialized on turbines for extreme operating conditions in remote locations such as Antarctica or unmanned offshore platforms. These turbines seem to be suitable for RMI.

Figure 79: 3kW Wind turbines on an unmanned gas platform[53]

Figure 80: 1.25kW wind turbine[54]

3.10.5.2 Installation Sites

The positions for wind turbines depend on other retrofitting measures, e.g., wind propulsion system. Therefore, different setups are possible. Table 12 shows some of them. For installations that are difficult to access, e.g., an installation on the cargo mast or in the rig of an IndoSail, only small and handy turbines are considered. Turbines bigger than 1kW usually are hydraulically foldable for maintenance.

Table 12: Maximal turbine installation for the different retrofit versions

Measure	*# of 1.25kW*	*# of 3kW*	*# of 6kW*	*Total capacity in kW*
No WASP	2	2	1	14,5
Flettner-Max	0	2	-	6
Flettner Min	2	2	-	8,5
3 Mast IndoSail	2	2	-	8,5
2 Mast IndoSail	2	2	-	8,5
Conventional-Min	2	2	-	8,5

[53] SD Wind Energy Limited
[54] Superwind GmbH

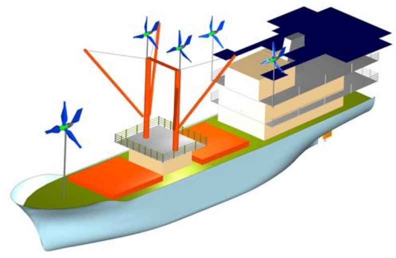

Figure 81: Setup no WASP 2x 1kW & 2x 3kW & 6kW

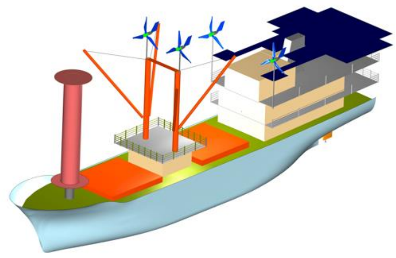

Figure 82: Setup Flettner min with 2x 1kW & 2x 3kW

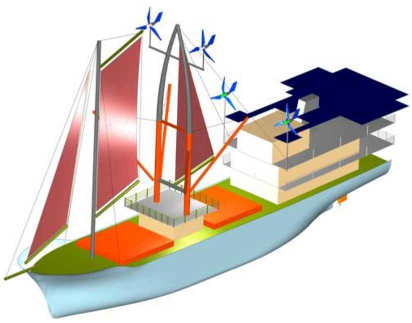

Figure 83: Setup IndoSail min with 2x 1kW & 2x 3kW

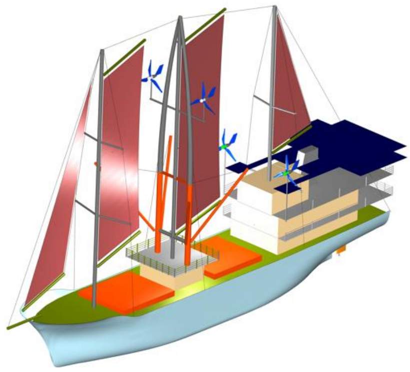

Figure 84: Setup IndoSail-Max 2x 1kW & 2x 3kW

3.10.5.3 Electrical Output

The electrical energy output of a wind turbine depends on the wind speed. Since the ship is mostly in the lagoon of Majuro, the calculations are based on the wind conditions there.

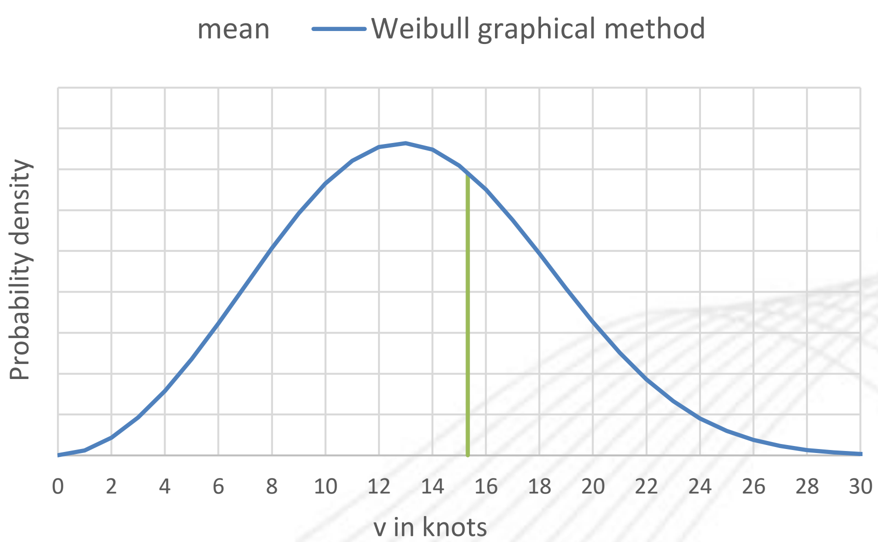

Figure 85: Distribution of wind speeds in at Majuro Atoll Data (2014-2016)[55]

[55] Data retrieved from SPOS, MeteoGroup

During navigation, rotors can be fixed to minimize wind resistance. Additionally, some correction factors were introduced, e.g., air density, turbulence, capacity factor - leading to a conservative estimate of the following annual electric yield which is shown in Table 13.

Table 13: Estimated annual electrical yield

Measure	*Estimated annual electric output in kWh*
no WASP	~29252
Flettner min (max)	~16652 (~11701)
IndoSail	~16539

3.10.5.4 Battery Storage for Wind Energy

During the lay-up periods in the lagoon, the ship is in an electric dead state. At this time, only the emergency lighting of the ship needs electricity. At present, this is ensured by a battery storage unit. However, this is designed just for emergencies for intervals up to 12 hours. A wind turbine can provide the energy which is needed for position lighting of the ship and increase the safety significantly. Besides, the excess energy can be stored in an additional battery and used when the vessel is put back into regular operation. During regular ship operation, the energy generated by the turbines can be used directly for utilities, reducing the load of the DG accordingly. Due to the high initial capital costs of wind turbines, it is recommended to install turbines only at locations with the best cost-benefit factor.

3.10.6 PV - System

The proximity to the equator ensures very high average solar irradiance in RMI. For this reason, Photovoltaic (PV) is ideally suited for the generation of electricity in this region. The disadvantage of PV of being available during the daytime hours only does not play a role for the long idle times in the Majuro lagoon. During idle times high electricity demand is only in daytime. This makes photovoltaic an excellent alternative additional power source on the ship to relieve the diesel generator and save fuel.

3.10.6.1 Installation Sites

Figure 86 shows some options for the most promising PV (blue area) installation sites on the ship. The best area for installation is at the rear of the vessel, avoiding shading as far as possible and locating the modules outside of the working area of the cranes. The existing roof of the passenger area can be used for installation. In addition, an extension of the roof to the front of the bridge is possible, but it is important to note that recess for the Life rafts is provided. Another possibility is to install folding side roofs, which offer an additional large area for PV, as well as protection from sunlight and rain in the passenger area. In strong winds or when mooring together with another ship, these extensions can be folded into a vertical position.

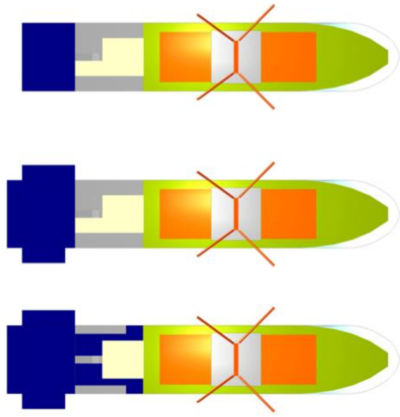

Figure 86: Different options for PV

3.10.6.2 Electrical Output

For the electrical output, the solar irradiation is the decisive factor, the location is of an important element, as in the estimation of the yield of a wind turbine, the values for the Majuro lagoon are used in the following. With an area utilization factor of 7 m^2/kW_p and an annual yield of approximate 1340 kWh/kW_p for a small residential horizontal installation, the following yearly yields can be achieved.

Table 14: Estimated electrical output for PV installations

Site	*Area m2 (ft2)*	*PV installation kWp*	*Electrical output kWh/year*	*remarks*
Passenger Roof	58 (624)	8.25	~11055	
Foldaway Side Roof	43 (463)	6	~8040	2m extension
Roof Extension Bridge	20 (215)	2.75	~3685	
Sum	*121 (1302)*	*17*	*~22780*	

3.10.7 Economical- and GHG Saving Potential

For the calculation of saving potentials, following values are used:

Table 15: Basis values for calculations

Density Diesel (15°C)	0.835	kg/l
CO_2-e	3.206	kg_{CO2}/kg_{diesel}
Fuel Price (Mobil 2018)	0.85 (3,22)	USD/l (USD/gallon)

3.10.7.1 Saving potential for Optimized Additional Diesel Generator

An additional diesel generator with a rated capacity of around 40 kVA (60% capacity reduction) shifts the load in the favorable operating range under the current load conditions. Based on the operation share of FY2017, the estimated fuel/emission savings are shown in Table 16.

Table 16: Savings low load DG

Measure	additional Diesel Generator
Retrofit Options	all
Liter (gallons)	~19044 (5031)
Annual savings in USD	~16122
Annual savings in tons CO2	~51
The annual saving in %	~35%
Estimated amortization time in years	<5
Saving of total fuel consumption	~8.9%

3.10.7.2 Saving Potential for the Penetration with Renewables

With the general assumption that a smaller DG is running in an operation point of MCR of 75% with a SFOC of 265 g/kWh$_e$ the following savings can be achieved.

Table 17: Savings due to additional feed-in of Wind and PV

	Wind turbines			PV	
Retrofit Options	no WASP	Flettner-Min	IndoSail-Min	all exclusive IndoSail-max	IndoSail-max
Annual Yield [kWh]	~29252	~16652	~16539	~22780	~15946
Annual Fuel Savings [liter] (gallons)	~9284 (2453)	~5285 (1396)	~5249 (1387)	~7230 (1910)	~5061 (1337)
Annual Savings [USD]	~7891	~4492	~4462	~6145	~4302
Annual CO_2 Savings [tons]	~24.9	~14.1	~14.1	~19.4	~13.5
Saving [%]	~29	~16	~16	~23	~16
Estimated Amortization Time [Years]	>10	>10	>10	<10	<10
Total Fuel Consumption Savings [%]	~4.3	~2.5	~2.4	~3.4	~2.4

3.10.8 Conclusion and Recommendation

The consideration of the auxiliary operating system on the Kwajalein has shown that the existing electricity generating system is very inefficient for various reasons and accounts for a high proportion of the total fuel consumption.

The efficiency of the system can be increased significantly by installing an additional DG for low load operating states. For the further planning and possible implementation, the measurement of surge currents of the individual motors, as well as the preparation of load profiles and peak demands during the different operating conditions are required. In addition, it would be interesting to have more accurate information about the total fuel consumption of the ship and the auxiliaries in order to make estimates that are more accurate.

Besides, the integration of renewable energies can reduce fuel consumption. PV should primarily be considered here, as it offers the most significant cost-benefit ratio. Wind turbines could also be considered. They are more expensive and more complex than PV but therefore offer better availability.

All measures in combination could reduce the fuel consumption by over 50%, which represents a reduction of the total fuel consumption by approximately 15 %.

3.11 Main Engine and Drive Train

When retrofitting an existing vessel with additional propulsion sources, a major problem is that the originally installed engine often operates at an inefficient operating point in partial load condition. The emission reduction concepts proposed above, however, unfold their savings potential by reducing the main engine power demand. In partial load, specific fuel consumption increases, partially offsetting the emission savings achieved through the above proposed operational and technical measures.

An alternative drive concept for the main engine, which enables a higher degree of efficiency in partial load operation, is therefore desirable. In the following, three different concepts are presented and analyzed with regard to their applicability and within the framework of the project.

The concepts to be considered are:

- Father & Son main engine concept
- Diesel-electric drive train
- Diesel-electric-hybrid drive train

Regardless of the main engine drive train concept, biofuels obtained from regenerative sources can be considered, either for the generators of a diesel-electric drive train, the main engine itself or for use in auxiliary generators.

3.11.1 Father & Son Concept

A promising solution for dealing with partial load conditions is the use of the father and son main engine concept. The basic idea is to use two engines of different sizes (father and son) which are connected to the propeller by a gearbox.

The concept is used wherever different load conditions are to be expected. A typical application is on board inland waterway vessels to meet the different power requirements when sailing with or against the current.

The concept allows optimal efficiency for three different load conditions:

- 1/3 power, when only the small engine (son) is running.
- 2/3 power, when only the big engine (father) is used.
- 1/1 full load, when both engines are running.

The power selection of the two engines can be optimized for any typical engine load condition resulting from the careful study of the ship's operating profile.

In order to switch a motor on and off under load, the transmission from the engine to the gearbox must be realized by means of a clutch. There are different options available:

- Hydraulic clutch
- Mechanical clutch

An alternative transmission concept is to use an electric engine on the propeller shaft, while the two main engines (father & son) are configured as generators. The concept of the diesel-electric drive train is further explained in the next chapter.

As a retrofit measure, this concept is relatively difficult to implement as it requires the replacement of the complete main engine as well as the associated gearbox by two smaller engines with a common gearbox. The accessibility of the engine room as well as the redesign of the foundations etc. would lead to high additional costs.

For new building projects, this variant is very attractive, as the additional costs compared to a classic drive train with a single large engine, remain relatively manageable.

3.11.2 Diesel-Electric Propulsion

The concept of diesel-electric propulsion makes it possible to maximize the efficiency of the main engine drive train even at partial load operation. The underlying concept is to operate the diesel generator(s) at peak efficiency, minimizing specific fuel oil consumption, instead of operating the main engine inefficiently in partial load conditions. The required power is transmitted to the propeller shaft via an electric motor.

Maximum power is provided when all available generators are in operation. In partial load operation, some of the generators can be shut down while the remaining generators continue to run under ideal full load conditions. There are two solutions for the design of the concept:

- The use of several generators of equal value or
- The use of generators of different sizes - the ‘father & son’ concept with electrical transmission

During a retrofit, the existing main engine can be supplemented by further generators, whereby the original maximum power is maintained, while the generators take over the partial load operation.

The advantage of this drive train design is, that no large and expensive battery bank is needed, while the system can still be optimized for two or more very different load conditions. The extra expenditure for the additional electric engine is relatively low compared to the expected benefits. Compared to the direct attached father and son concept as proposed above, this concept has the disadvantage of losses resulting from mechanical to electric power conversion and vice versa.

3.11.3 Diesel-Electric Hybrid Drive-Train

The diesel-electric layout can be upgraded to a full diesel-electric-hybrid concept by the utilization of a battery bank for storing excess energy. This allows to run all participating engines under ideal conditions, storing excess energy to the battery bank. If the battery bank is fully charged, engines can be turned off, using previously stored energy for propulsion needs.

Improved environmental balance is achieved through the use of energy based on renewable sources that can easily be added to the system. Those energy sources include

- Photovoltaics
- Wind power
- Shaft generators (excess energy generated during sailing in ideal wind conditions)
- Charging the batteries from shore-based renewable energy sources

Since the costs for an appropriate battery system are very high and changes to adapt the electrical system of the vessels to work in conjunction with the diesel-electric-hybrid-drive-train would raise further technical effort, the total costs will likely exceed the expected benefits. Furthermore, the diesel-electric-hybrid concept demands special skills. Local specialists could hardly carry out maintenance work and monitoring of the systems at regular intervals. Flying in specialized personnel for maintenance work would further increase costs.

However, manufacturing companies claim high saving potential compared to conventional drive-train layouts. Another point that speaks for this system is the high diesel-fuel costs in RMI since the amortization timespan depends on fuel-cost savings.

3.11.4 Refit options at the example of MV Kwajalein

For the MV Kwajalein, the machinery arrangement and layout has been analyzed in order to identify possible refit options that meet the new power requirements resulting from other technical and operational measures for emission/power reduction, as proposed above.

The highest impact on main engine power requirement results from slow steaming as well as the constantly changing power demand while sailing with WASP concepts.

The new average power requirement is therefore around 100kW to 200kW instead of the installed capacity of 480kW. A detailed analysis of the drive train of the main engine shows whether the engine concept has to be adapted to the new working conditions and whether savings can be achieved with an alternative drive train concept.

The main challenge for the powertrain conversion is the limited accessibility of the engine room. Since the engine room is located below the deckhouse, the replacement of the existing main engine is only possible at considerable cost and effort.

After a short analysis of specific fuel oil consumption and propeller efficiency, in the following, some possibilities are presented which could be feasible under these circumstances.

3.11.4.1 Fuel Oil Consumption in Partial Load Conditions

All savings that can be achieved in the main powertrain area are related to improved efficiency. Figure 87 shows typical SFOC values (specific fuel oil consumption) as a function of engine load for the main engine and auxiliary generators of MV Kwajalein.

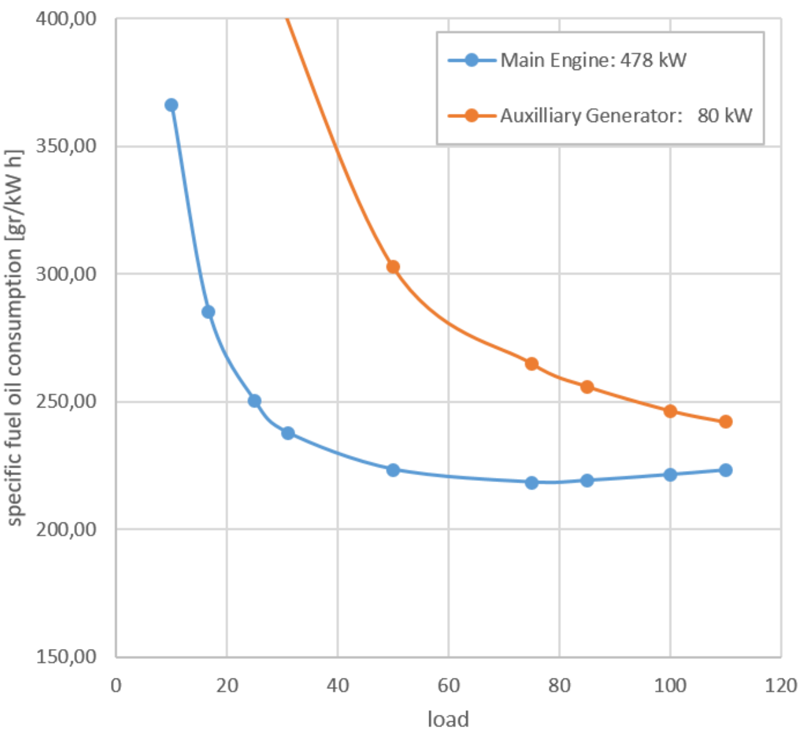

Figure 87: Specific fuel oil consumption of the main engine and auxiliary generator – MV Kwajalein[56]

The main engines aboard MISC Vessels are medium and high speed diesel engines (blue curve in Figure 87) equipped with turbocharger systems. The orange curve displays the auxiliary generators. Below values of 50% engine load, specific fuel consumption starts to increase for the main engine and drastically for auxiliary engines. For very low load conditions alternative main-engine concepts like father and son concepts or diesel-electric propulsion can lead to significant fuel and emission savings.

The comparison of the two engines types aboard MV Kwajalein indicates that saving potential exists for the very low load conditions. The use of one auxiliary generator for propulsion in those conditions is the general approach for the retrofit concept.

[56] MISC – Test record of main engine and auxiliary engine

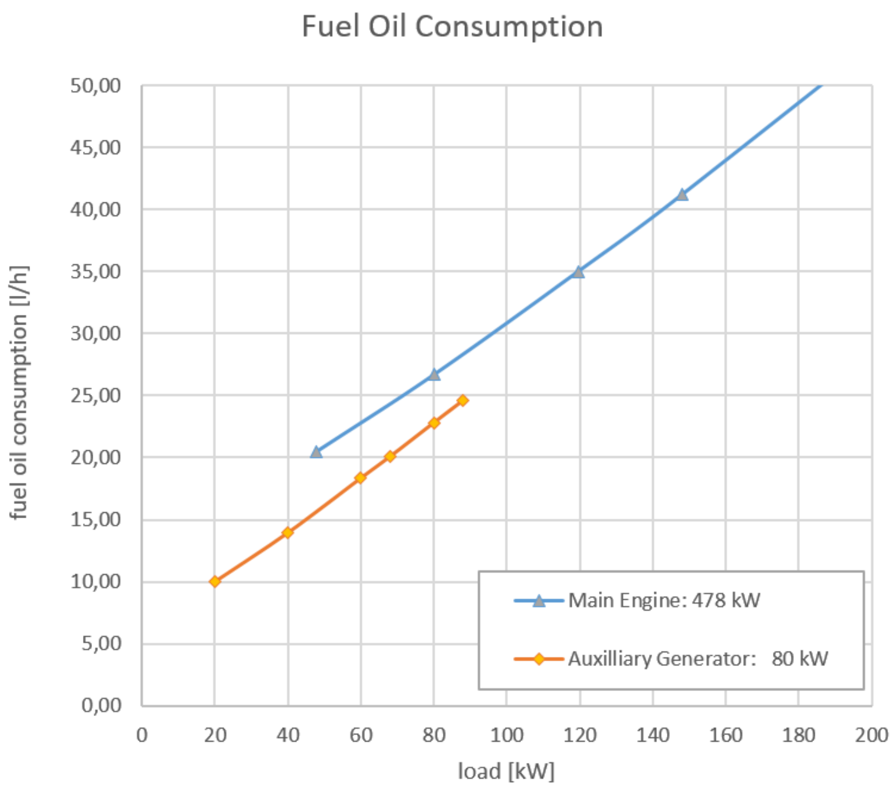

Figure 88: Fuel oil consumption of the main engine and auxiliary generators

The following table gives the savings potential that can be realized by the utilization of one of the existing auxiliary engines. Final savings depend on the efficiency of the electric unit that comes to application. The efficiency losses for electric power transformation can be estimated by around 5 to 10 %.

Table 18: Fuel consumption and potential savings

Load (kW)	Fuel consumption (l/h) Main engine	Fuel consumption (l/h) Auxiliary engine	Fuel / Emission savings (%)
80	26,7	22,8	14,6
60	23,0	18,4	20,0
40	19,0	14,0	26,3
20	16,0	10,0	37,5

Table 18 indicates that for very low load conditions (operations inside lagoon where no speed is required or engine support for sailing in moderate wind conditions) fuel/emission savings potential is at a high level. Better results would be achieved by more efficient generators (see also chapter 3.10.2 on auxiliary engine efficiency).

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3.11.4.2 Analyzing propeller and drive train efficiency in slow steaming condition and due to WASP technologies

Based on resistance prediction calculations and information on the installed propeller, an efficiency estimate was made for the propeller at reduced ship speed as well as for reduced engine load due to WASP technologies. The efficiency of the installed propeller can be estimated from the Wageningen B-Series propeller diagrams. Figure 89 shows the efficiency curve of the installed propeller (red highlighted curve for ratio P/D = 0.7) as well as four ship-side load curves for 10.5 knots (design speed), 9.5 knots (current cruising speed), 7 knots (slow steaming) and for 7 knots sailing with WASP support (IndoSail-Min with average power reduction value).

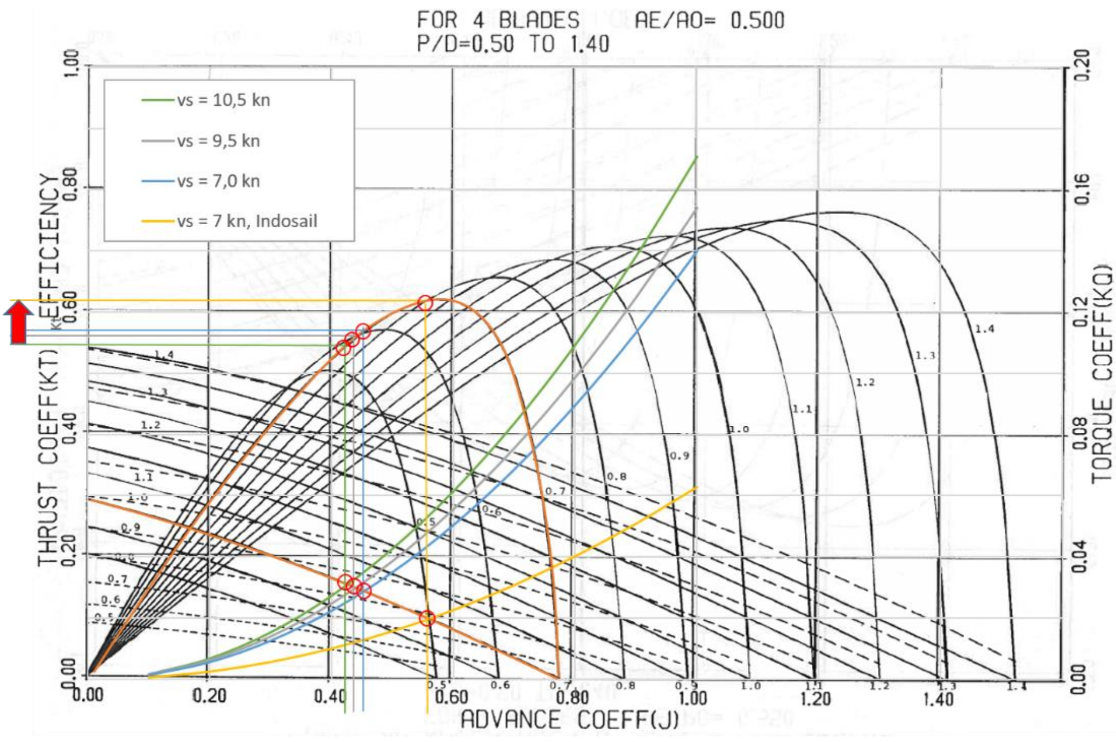


Figure 89: Wageningen B-Series: propeller efficiency chart[57]

Since the original operating point (10.5 knots, green curve in the diagram) of the propeller is clearly to the left of the point of maximum efficiency, the efficiency of the propeller increases with decreasing ship speed and reduced load (relief through WASP technology) by almost 7%. The behavior favors both the proposed slow steaming measure and the use of WASP technologies.

Additional benefit can be expected by a reduction of the wake-number. For normal engine operation, this number can be estimated by 0.2 for this kind of vessel. As the wake-number is the result of accelerated flow due to the propeller thrust, it will drop to zero if the vessel is propelled entirely by WASP technologies. For partial load conditions the reduced wake-number will have an effect as the efficiency of the drive train improves.

3.11.4.3 Retrofit Option 1: Engine Overhaul

As suggested by Oxley in the PRIF baseline study[58], the minimum effort to improve engine efficiency should be to have all main engines and generators on board MISC vessels overhauled by an expert

[57] M.M. Bernitas et al. (1981). KT, KQ and Efficiency Curves for the Wageningen B-Series Propellers
[58] M. Oxley, 'Establishing Baseline Data to Support Sustainable Maritime Transport Services-FINAL REPORT,' Establishment of the Pacific Region Infrastructure Facility Coordination Office (PRIF), 2018.

from the manufacturer. Since almost all installed engines on the MISC vessels were manufactured by "Yanmar", the effort and cost of flying in a specialist would definitely be worth it. Extending this to a training program for MISC engine staff seems to be another interesting option.

3.11.4.4 Retrofit Option 2: Conversion to Diesel-Electric Drive Train

A promising solution that requires only minimum rearrangement effort and makes use of existing machinery equipment is the conversion towards a diesel-electric drive train. An electric unit is installed between the gearbox and the main engine.

Installed machinery:

- 478 kW main engine (Yanmar, type: 6RY17W)
- Marine gear (Hitachi, type: MGN91BL), gear ratio: 5:1
- 2x 80 kW auxiliary generators (engine: Yanmar, type: 4HAL2-TN1, generator: TWY 28DS-4)

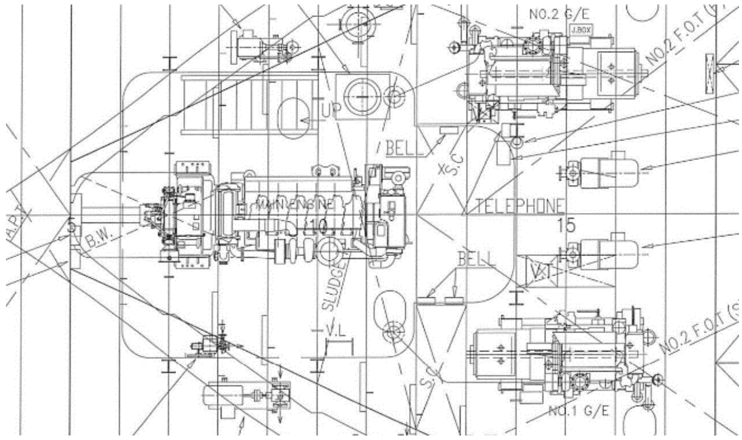


Figure 90: Original main engine setup (top view)[59]

Shafting plan and drive train:

- Propeller layout optimized for vessel design speed of 10.5 kn.
- Reverse marine Gear (transmission: 1:5)
- If slow steaming comes to application, the propeller efficiency must be analyzed.

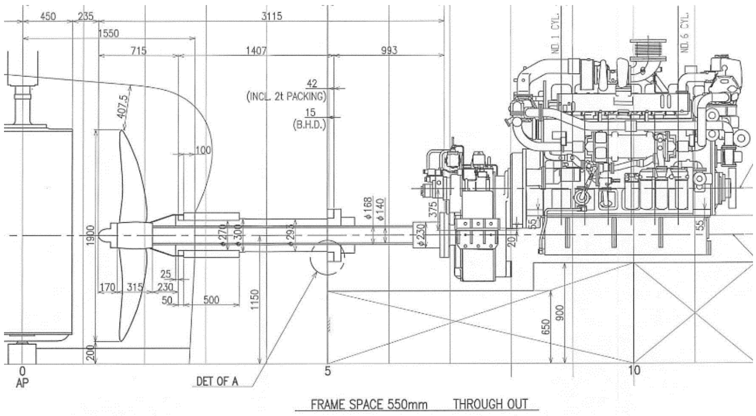


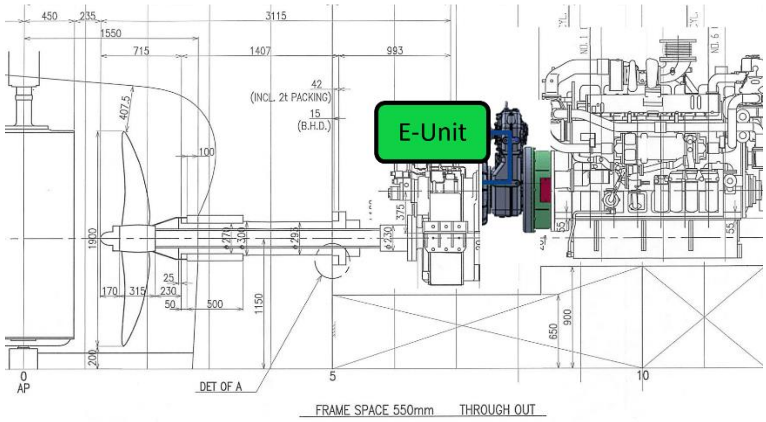
Figure 91: Original main engine setup (side view)[59]

One retrofit option to place an electric unit between an existing gear and the main engine is the application of a parallel-hybrid-transmission. The setting makes it possible to upgrade an existing drive train towards a diesel-electric system. The electric engine can be used in combination with one of the auxiliary generators for low load conditions, while the original engine power is maintained and ready to take over if full main engine power is required (emergency situation).

[59] Yard drawings of MV Kwajalein

Installation of an E-Unit

- For the realization of this retrofit option, the marine gear and/or the main engine has to be rearranged to provide space for the added transmission.
- Attached is an electric engine, powered by one or more generators.



The E-Unit works in both directions, power take-in and power take-off (PTI / PTO).

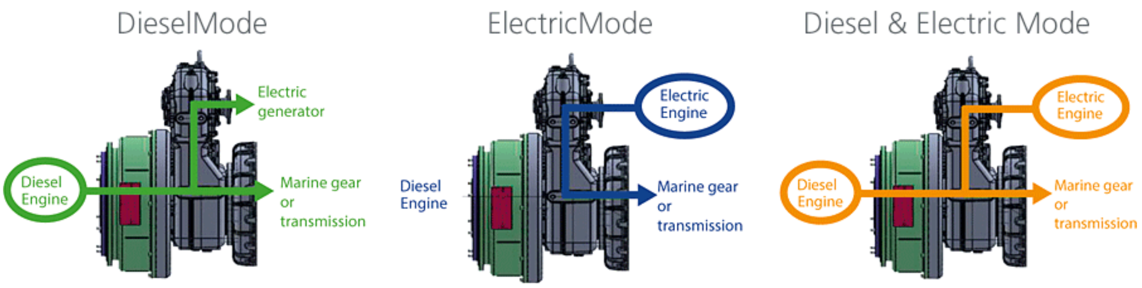


Figure 92: Refit options for connecting an electric unit between the main engine and the marine gear[60]

The setup allows the following operational modes:

- Diesel-Mode: Run the main engine as usual. The E-Unit (PTO-Mode) can be used to generate the required electrical power for all other services. In this way, auxiliary engines can be switched off for fuel/emission savings, by making use of the higher efficiency of the main engine run under full load.
- Electric-Mode: In partial load conditions, the main engine is decoupled and switched off. The E-Unit (PTI-Mode) is powered by one of the generators (80kW), making use of the higher efficiency of the generator compared to the main engine in partial load condition.
- reversed Electric-Mode: If the vessel is powered by sails alone (ideal wind conditions), the main engine is decoupled, while the E-Unit (PTO) is used to generate necessary electrical power for all other service or for charging of batteries (if available).
- Diesel-Electric-Mode: Combined power (diesel engine plus generators) for maximized engine thrust. This option can play a role in emergency situations if the layout of the main engine is chosen on a lower power level (for example: Wind-Propulsion assisting engine)

[60] https://www.esco-drives.com/EN/mechanical-drive-technology/view.php?id=158

The diesel-electric concept of using one of the existing 80kW generator in combination with a retrofitted E-Unit, between the main engine and the gearbox, appears to be relatively economical and practical for adapting to very low load conditions. Additional costs result mainly from the additional electric unit as well as the necessary changes for installation (prepare the foundation, parallel hybrid transmission). All existing machinery can be integrated into the concept. If further increase of performance is needed, the auxiliary engines can be replaced by a more efficient unit (refer to the section on auxiliary energy systems).

Further calculations are necessary to confirm costs and feasibility on the vessels in question. The diesel-electric arrangement allows the vessel to be ready for future upgrades to electric-hybrid technologies.

3.11.5 Alternative Fuels

Despite intensive research into fuel production based on renewable resources such as coconut oil, rapeseed, and algae, the commercial use of these biological fuels in the transport sector is not expected in the near future. The costs per liter currently exceed the price of fossil fuels many times. Nevertheless, the use of biofuels can play a part in emission reduction.

For RMI, however, high fossil fuel costs make this option more attractive. As total fuel consumption is currently too high to be covered by locally produced coconut oil, blending biofuels with conventional diesel oil could be an option. If the engines on MV Kwajalein and other MISC vessels are compatible with biofuels, their use could help further reduce fleet emissions. However, the use of biofuels should be further investigated to avoid damage to the machinery.

Besides the production of coconut oil, an interesting idea for RMI could be the biofuel production from algae. RMI has very little land area, while protected areas at sea within the lagoons are almost unlimited. The conditions for optimal algae growth are at a very high level, which favors economical algae cultivation for potential future biofuel production.

The main goal should be the reduction of fuel consumption. If the overall demand for fuel comes down to a much lower level in course of other measures taken, it could be possible to make use of biofuels or blends with biofuels for covering the remaining reduced demand in the future.

3.12 Considerations on Future New Built Projects

Considering the transformation of MISC vessels towards low carbon shipping, newbuilds can play a role for future investments - the strategy of retrofitting existing vessels has in our opinion more potential, as it is applicable to a larger number of vessels, achieving higher scalability. However, for future investments towards low carbon shipping solutions, the following section will provide considerations to be taken in this case.

3.12.1 Identifying and defining the demand

When discussing new vessels for RMI, all cargo and passenger transportation needs within the RMI should be considered. The entire MISC-fleet has to be transferred into a zero-emission fleet, step by step. The most important task for starting the design of a new vessel is to identify the actual transportation task and to define the demands on the new-build vessels:

Demands on new-build vessels are:

- Zero emission ready: Layout of the new vessel should include easy conversion options to zero emission transport since a vessel build today will still be in service by 2050
- Increase atoll connectivity for improved life quality on outer atolls
- Make use of wind propulsion technology, since boundary conditions for wind propulsion are very good in RMI. The wind is for free compared to very high fossil fuel costs
- Maintenance of the vessels should be possible within RMI or in neighboring countries
- Safety of the vessels should meet international standards
- Cargo handling at the atolls via small cargo barges (carried on deck), since no landside-infrastructures can be used. Ideally, electric engines should run those boats
- Make use of renewable energy as much as possible
- Create working opportunities for Marshallese people

This is only a first start for the list of requirements that a new vessel design should meet. Further analysis and discussions are needed to tighten the framework as much as possible before the design process is started.

3.12.2 Aspects towards the appropriate vessel design

In the following, some aspects of vessel design and requirements will be discussed. This list has to be continued and refined as the process of defining the requirements proceeds.

Vessel Size:

A reduction in the size of the vessels compared to today's MISC vessels seems necessary, as both the utilization time of the vessels and the available cargo capacities are not being reached today. In order to improve the connection between the remote atolls to the cultural center in Majuro, the frequency of atoll calls should be increased, resulting again in smaller vessel sizes (decreased cargo capacity for the single vessel).

Vessel Speed:

Maximizing vessel speed by minimal fuel consumption suggests either modern mono-hull forms or a design on basis of a multihull concept. The later of the two seems more suited if speed is anticipated, since fast mono-hull designs depend on lightweight construction in order to overcome the speed limit set by residuary resistance for displacement vessels. But lightweight construction is not an option for cargo transportation. Multihulls at the other hand are displacement vessels of great length to hull-beam ratio. Large length to beam ratios enable the vessel to pierce through its own bow wave, whereby the speed limit set by hull length is overcome.

Cargo Handling and Passenger Transport:

Today cargo and passengers are transported on the same vessels. For future projects it has to be analyzed in detail if this solution is the best option since vessel requirements for transportation of the two are quite different. The demands for the handling of cargo and towards the cargo-hold are governed mainly by the overall design of the vessel and the type of cargo that is transported.

Besides the transportation of passengers, the typical cargo type for MISC vessels is pallet freight as well as copra. The two types of cargo must be stored in different cargo holds. Requirements on the cargo handling gear are relatively low concerning weight capacity, since no extraordinary heavy goods have to be managed. At the other hand large quantities have to be managed in a reasonable time.

Today special cargo requirements are handled by MV Majuro, a landing craft type of ship.

Passenger Comfort:

Passenger comfort can be considered relatively important, since the connection between the atolls relies on the transfer by ship. Besides of service and accommodation, ship motion in seas and heeling angle while sailing are the main influencing factors on passenger comfort.

While reasonably designed displacement vessels show good motion behavior in heavy seas, multihull designs show their strength in minimal heeling angle when sailing.

Main Engine Drive Train Concept:

Since partial load conditions are to be expected when using wind propulsion as the main energy source, the most economical solution for new-build concepts in combination with WASPs technologies is most likely the father and son concept in combination with an electric engine for main propulsion.

Partial load conditions can be met by switching off one or more generators. Safe peak powers in extreme situations can be met by the use of all existing machinery. In addition, the partition of main engine power into several independent units leads to redundancy of the main engine system and therefore to increased vessel safety.

The main engine drive train concept is thus ready for a further upgrade to hybrid solutions when the time for an economic upgrade to a hybrid drive train solution arrives.

Safety:

Legal safety requirements have to be met, independently of the type, size or purpose of the vessel. The distinction on necessary safety requirements is based on the type of sea area the vessels are operating in.

3.12.3 Type of Vessel

There are several options on different types of vessels. Each vessel type favors other qualities and will have advantages in one field of requirements but also disadvantages concerning other demanding qualities. There is no perfect design, but only the best suited solution for a given task. In the following some interesting designs of different vessel type are mentioned.

Large Cargo Mono-Hulls:

Economy of scale is the keyword for designing large cargo vessels. The costs per ton of transported cargo decreases with increased vessel size. This simple truth applies to some degree also to sailing vessels. But the optimum will be quite different for sailing vessels compared to conventional, large scale shipping, since the use of wind-propulsion technologies reduces bunker costs to a minimum. The costs per ton of freight stands against production, maintenance and personnel costs. Those costs are very much dependent on the specific design of the vessel and chosen WASP technology. Examples for in our context large mono-hull designs are:

Figure 93 IndoSail-Project: Maruta Jaya[39]

Figure 94 SailCargo: Ceiba[61]

Figure 95 HEL: Wind-Hybrid-Coaster[62]

Figure 96 Enercon: E-Ship-One[63]

Small Multipurpose Mono-Hulls:

The basic idea of the following designs is to create a vessel that is capable to reach places that cannot be accessed by large vessels. They should be capable to deliver goods even if no landside infrastructure is available. The flexibility should be as large as possible to be of use for standard trading as well as for

[61] *https://www.sailcargo.org/*

[62] https://www.mariko-leer.de/wp-content/uploads/2016/11/Brosch%C3%BCre-WHC_final.pdf

[63] https://de.wikipedia.org/wiki/E-Ship_1

disaster relief and special purpose delivery. The following design examples represent good alternatives for the multipurpose landing craft MV Majuro:

Figure 97 Greenheart-Project[64]

Figure 98 Dykstra-Naval Architects[65]: Sea Bridge

Multihull Cargo Vessels:

The philosophy behind those designs is, to make good for reduced capacity by increased vessel speed and minimized fuel consumption. Due to simple and easy construction as well as the high vessel speed, the costs per transported ton of cargo remain in a reasonable range.

Figure 99 Rob Denney: Cargo Ferry Concept[66]

Figure 100 Fair Winds Trading Company: Cargo-Proa-Design[67]

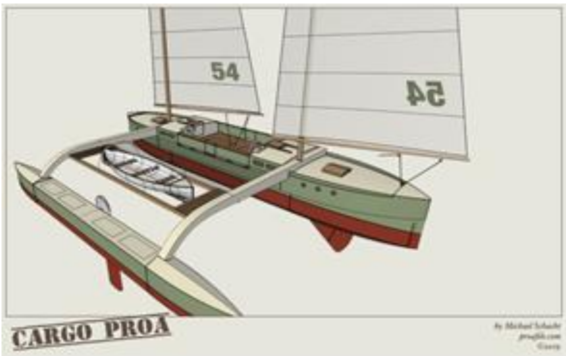


Figure 101 Michael Schacht: 'The Camel of the Sea', Cargo Proa-Design[68]

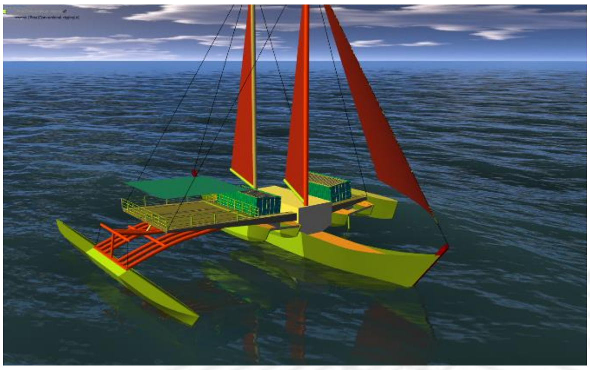


Figure 102 Siegfried Wagner: Barge Carrier – Proa Concept Design

From all multihull concepts, the 'proa' seems to be the best suited option for cargo transportation. Structural strength, performance as well as seakeeping abilities are superior to catamaran or trimaran

[64] http://greenheartproject.org/en/ship/
[65] http://www.seamercy.org/seabridge
[66] http://www.harryproa.com
[67] http://www.fairwindstradingcompany.org/
[68] http://schachtmarine.com/#portfolio

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concepts. The flexibility of those vessels can be similar to the previously described multipurpose mono hull vessels.

Some of the different designs (large mono hull, multipurpose vessel and multihull) presented above, have been built and proven in the past, others are still in development or mere design studies. But all of them are inspiring examples on the diversity of possible solutions for the development of future low emission vessels for the RMI.

3.13 Training Concepts

The success of new concepts for low carbon sea transport highly depends on the training programs going along with technical and operational measures. To unfold the full potential technical equipment and operational concepts need to be run in the correct manner including a continuous loop of improvement.

In this early stage, the description of training activities may be rather conceptual, looking more at the general training objectives and how to organize the whole process. The availability of qualified trainers will be one of the major tasks ahead.

The general lack of trainers in remote island communities may require new cooperation with regional providers of maritime training services. With the University of the South Pacific and Emden/Leer University of Applied Sciences, there are two partner institutions with expertise in setting up training programs. WAM has gathered a lot of experience in vocational training. Close cooperation of the above institutions may create an ideal platform for building up training capacity.

The analysis of the current situation and intended improvements lead to the following objectives:

- Plan and conduct training activities for all technical and operational measures in the project.
- Initiate a structured approach to build up capacity for the maritime transport sector.

This 2-step approach will require the design of short-term training on specific technical and operational topics accompanying the measures that will be chosen for implementation. This will include training of the makers and providers of technical installations, e.g., solar and wind technology. To cover long-term demand for qualified personnel in the maritime sector, a broader initiative including new cooperation with strategic partners can be explored. E.g., the **Maritime Training Centre in Tarawa, Kiribati** and the **Fiji Maritime Academy** in Suva have successfully built up maritime training programs for national and international shipping, thus being potential cooperation partners. Further, the **Maritime Technology Cooperation Centre** run by The Pacific Community (SPC) at Suva is a potential partner for technical development and training in this field.

To promote the participation of Marshallese students in maritime training programs of the above institutions is a general objective for capacity building. Long-term job opportunities and growth of the maritime sector may result from this. To support cooperation with strategic partners in maritime training and education short programs based on the project works and developments could be set up. Ideally, a dynamic process for the transition to low carbon sea transport can be initiated.

Following topics could be targeted by cooperation with strategic partners, e.g., for the conduct of training courses.

- Energy Efficiency and Low Carbon Technologies
- Fuel and CO_2 Monitoring
- Sail Technology and Wind Assisted Propulsion
- Ship and Machinery Maintenance
- Navigation and Routing
- Cargo Handling and Logistics

A good example for the contents of an energy efficiency course can be found in the report 'Fuel and financial savings for operators of small fishing vessels'[69] by the Food and Agriculture Organization (FAO).

[69] Wilson, J.D.K., FAO - Food and Agriculture Organization of the United Nations, 'Fuel and financial savings for operators of small fishing vessels', FAO FISHERIES TECHICAL PAPER 383, http://www.fao.org/3/x0487e/x0487e00.htm#TopOfPage

4 Detailed Options for Inside-Lagoon Transport

Ri Majol, the people of the Marshall Islands were for centuries known for their superior boat building and sailing skills. They traveled frequently between their atolls (for trade and war) on big offshore canoes called ‘Walap’ (some of them 100ft long). The lagoons of their low-lying coral atolls were crowded by the sails of smaller outrigger canoe designs for rapid inside lagoon transportation, food gathering, and fishing. Today the traditional outrigger canoe designs are not any longer in use for inter-atoll voyages in RMI. The traditional inter-atoll voyages stopped with the appearance of foreign colonizers. None of the traditional inter-atoll canoes (Walap) survived.

The way of inside lagoon traffic and artisanal fishing today differs from atoll to atoll in the Marshall Islands. Major influence factors are the shape of the atoll, the density and concentration of its population as well as the existence of canoe building skills. Most of the island communities were not able to maintain their canoe building skills in the past and depend now on motorized and fuel consuming boats for fishing and transportation. Aside from the greenhouse gas emissions by the lagoon shipping sector, the use of combustion-powered boats causes various problems for Marshallese living on the outer islands:[71]

- Reduced availability of transportation and fishing means due to expensive fuel (if available at all) led to
    - Reduced availability of local seafood, and
    - Hindrance for the development of local the economy;

- Compromised security of food supply, low self-esteem and no perspective for the young generation due to an import-dependent lifestyle;

The TLCSeaT measures for lagoon shipping aim at reviving traditional maritime competencies as well as complementing them with modern measures adapted to modern standards. In addition to intensive training programs, the construction of exemplary prototypes will be used to teach how to use modern boatbuilding techniques and technologies. The vision is that the ‘Train the Trainer’ program will bring back maritime skills to the atolls and integrate them into people's daily lives. By the use of modern technologies as well as the revival of sailing canoe culture, the fossil fuel emissions of the lagoon shipping sector can be reduced.

4.1 Training Concept

The TLCSeaT project aims to tackle the challenges by supporting greenhouse gas neutral lagoon crafts.

After analyzing the local conditions and requirements as well as similar past and current projects around the Pacific, a comprehensive project guideline, including a detailed list of requirements for lagoon craft, was prepared in close collaboration with the local NGO and project partner Waan Aelõñ in Majel (WAM).

To achieve a significant reduction of GHG emissions in the lagoon shipping sector the aim of the collaboration between WAM and TLCSeaT is the revitalization of former marine capabilities of the

Marshallese island communities. Therefore, a program comprising canoe building, knowledge transfer, education, and training will be implemented at WAM. The revitalization program will use newly developed sustainable lagoon vessel designs as flagship together with traditional canoes as the backbone of future lagoon shipping.[70]

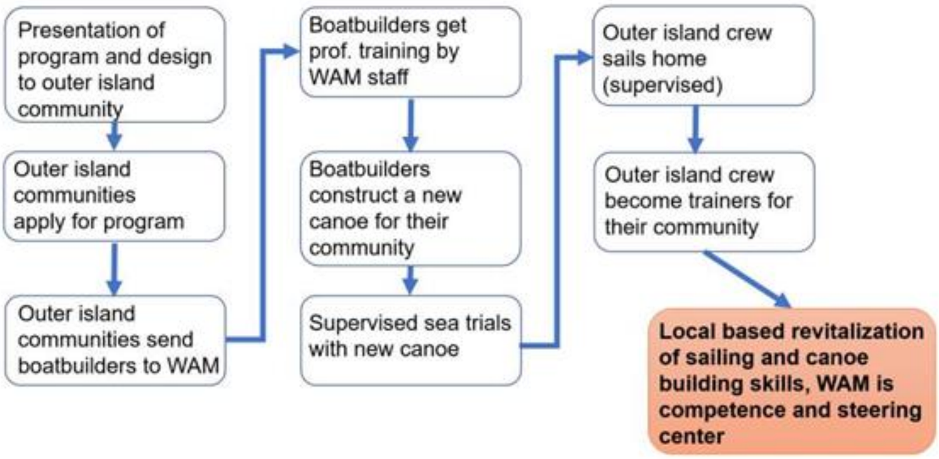

Figure 103: Scheme of the construction and training program[71]

By teaching small delegations of outer islanders to be trainers for their community (tot - training of trainers), even a small program with limited resources can create a momentum with big impact by multiplication. The outer islanders who can be trained by WAM learn the traditional way of Marshallese canoe building as well as a contemporary way. In combination with training on the water (sailing, fishing, safety), the outer island communities will get a group of skilled boat people and a sustainable canoe at the end of their participation. For a comparably low investment (compared to the expenses of motor boats, fuel and resulting expenses), the communities may get the chance to reestablish their former boat-building and seafaring capabilities as well as the independency on fuel, more food security and a boost for the local economy.[71]

4.2 Prototype Development

A comprehensive list of requirements for lagoon craft in RMI was developed after intensive research and design work in close collaboration with Waan Aelõñ in Majel (WAM), the University of the South Pacific (USP) and University of Applied Sciences (HEL):

[70] Richter-Alten, H. (2018). TLCSeaT Lagoon Shipping Report (Draft), Waan Aelõñ in Majel, Majuro
[71] Richter-Alten, H. (2018) ‘TLCSeaT Lagoon Shipping Report (Draft),’ Waan Aelõñ in Majel, Majuro.

	Number	Requirement:	Priority	Comment
1. Basic Characteristics	1.1	Length of waterline: 6m	1	
	1.2	Loading capacity: ~1000kg	5	
	1.3	Empty weight: <600kg	4	
	1.4	Green technology - no fossile fuel - sustainable materials - sustainable construction at WAM - sustainable maintenance on outer islands	5	
	1.5	Consideration of marshallese traditions	3	
2. Construction Technology	2.1	No special Marshallese skills/knowledge needed	4	Outer islanders will build at WAM
	2.2	Use of local materials (timber) whenever possible and sustainable (replantation), reduced use of plastic	5	
	2.3	Use of rope lashings (traditional) instead of conventional hardware	4	
	2.4	No need for power tools	5	
	2.5	A simple roofed space must be sufficient for all construction works	5	
3. Maintenance	3.1	All basic repairs must be possible on outer islands with local resources	5	
	3.2	No use of metal fastenings	3	
	3.3	Easy to beach	4	For maintenance (painting) on land or protection from heavy weather
	3.4	A simple roofed space must be sufficient for all maintnance works	5	
	3.5	All components should be protected from aging influences (20 years service life)	4	
4. Operation	4.1	Main propulsion by wind power	5	
	4.2	Easy handling on the water in all conditions	5	
	4.3	Singlehand sailing	5	
	4.4	Fast and easy maneuvers (tack, jibe)	4	
	4.5	Easy to beach	5	For docking
	4.6	Easy loading and unloading of freight	3	
	4.7	Sufficient upwind performance	4	
	4.8	Sufficient speed for every day use	4	
	4.9	Seaworthy for occasionally inter island trips	3	
	4.10	Economical reasonable (price)	3	competition to conventional boats
5. Safety	5.1	Sealed compartments with reserve buoynancy	5	
	5.2	Crash compartments in bow and stern	4	
	5.3	Singlehand sailing possible	4	
	5.4	Capability for short offshore distances	4	

Figure 104: List of requirements for lagoon craft in RMI[71]

A specific rating according to the overall design goal is proposed for each requirement. Priorities are measured by numbers between 1 (low priority, nice to have) and 5 (high priority, must have). Existing designs and future design options can be rated by multiplying the priority rating and the grade of fulfillment. The fulfillment of a requirement is rated by numbers between 0 (no fulfillment) and 5 (100% fulfillment). The sum of the multiplication of priority and fulfillment number of every requirement expresses the suitability of the rated design in accordance with the design goals. The rating number facilitates comparing the suitability of different designs and permits the best decision for future design options.[71]

4.2.1 Lagoon Shipping Design Options

In the following chapters, various boat concepts for prototype construction are presented. The intention behind these designs is to create understanding for different possible modern boat types and to enable training in different construction techniques. In collaboration with the newly trained experts (locals), final designs will be developed for use in the lagoons of the RMI.

The different available options for lagoon shipping and transport are listed and described in this chapter. The options are compared in the following chapter.

4.2.1.1 Option 1: The Ailuk Catamaran

Built by WAM in 2004, based on a design provided by FAO

- In Service on Ailuk atoll until 2014
- Made by glass fiber and Epoxy in female mold (still at WAM)

- Recycling issues not resolved yet
- Expensive import of materials
- Specific skills in building technologies required

- Decent payload and stable platform
- Very heavy, difficult to handle on the beach
- Limited sailing performance (especially upwind)
- Mold and existing components could be recycled in an improved design

Table 19: Main particulars of the Ailuk Catamaran[71]

Ailuk Catamaran Data	
Building Method:	GRP in mold
Length Overall:	7,50 m
Waterline length:	5.64 m
Beam Overall:	4.20 m (guess)
Draft:	0.20 m (guess)
Weight:	900 kg (guess)
Loading capacity:	1500 kg
Sail Area:	18.00 m^2 (guess)

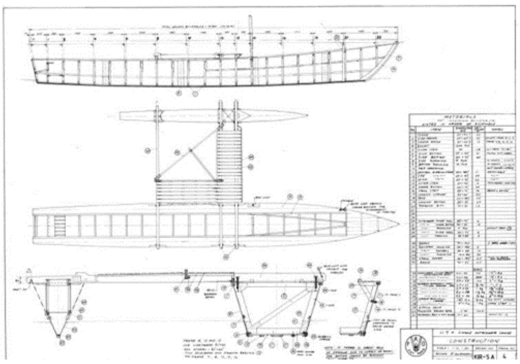

Figure 105: Original drawing[72]

Figure 106: Refit on Ailuk around 2011[73]

[72] by Gulbrandsen, FAO

Figure 107: Construction of the catamaran in 2004 by WAM[73]

Figure 108: Catamaran after launching in 2004 by WAM[73]

Figure 109: Catamaran after launching in 2004 by WAM[73]

Figure 110: Catamaran maiden sail after launching in 2004 by WAM [73]

[73] Photo by WAM

4.2.1.2 Option 2: The WAM Catamaran Design

Table 20: Main particulars of the WAM catamaran design [71]

Prototype 2 Details	
Building Method:	Ply/Glass/Epoxy, Stitch and Glue
Length Overall:	6.50 m
Waterline length:	5.70 m
Beam Overall:	3.70 m
Beam hull:	1.10 m
Weight:	550 kg
Max. Loading capacity:	1000 kg
Loading capacity CWL:	730 kg
Beam hull CWL:	0.57 m
Beam hull max. capacity:	0.65 m
Draft CWL:	0.40 m
Draft max. capacity:	0.45 m
Sail area:	25 m^2

- Combination of 2 traditional hulls to a catamaran
- Concept proofed by similar designs since decades
- Made by plywood and local timber, reinforced and preserved with GRP /epoxy

- Minimized use of expensive and non-sustainable materials
- Strong and durable construction
- Natural waste reduction by degradation at the end of the lifetime

- Decent payload and stable platform
- Light enough to handle on the beach by a small crew
- Average sailing performance
- Different sizes possible
- Easy locally manufactured and maintained on outer islands

Figure 111: WAM catamaran, side view sketc[71]

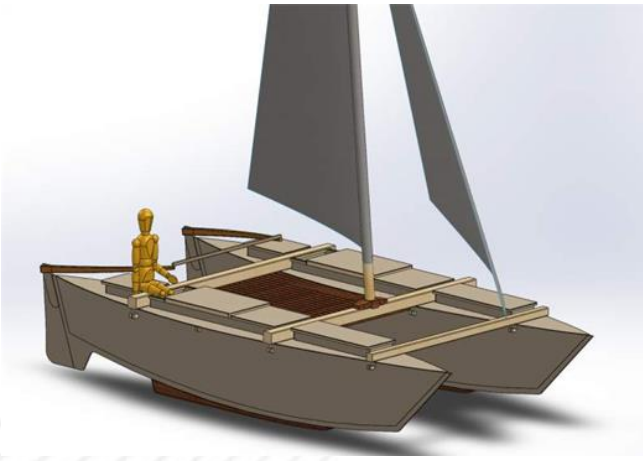

Figure 112: WAM catamaran, sketch from starboard side [71]

4.2.1.3 Option 3: Lagoon Harry-Proa

Table 21: Main particulars of the Lagoon Harry-Proa[74]

Prototype 3 Details	
Building Method:	Ply/Glass/Epoxy, Intelligent Infusion
Length Overall:	9.60 m
Waterline length:	9.60 m
Beam Overall:	3.70 m
Beam hull:	0.60 m
Weight:	490 kg
Max. Loading capacity:	1700 kg
Loading capacity CWL (draft 200mm):	1070 kg
Beam hull CWL:	0.60 m
Beam hull max. capacity:	0.60 m
Draft CWL:	0.20 m
Draft max. capacity:	0.30 m
Sail area:	30 m^2

  - Close to local tradition (outrigger canoe design)
  - Made by plywood and local timber, reinforced and preserved with GRP/epoxy

- Minimized use of expensive and non-sustainable materials (epoxy)
- Strong and durable construction
- Natural waste reduction by degradation at the end of a lifetime

  - Decent payload and stable platform
  - Light enough to handle on the beach by a small crew
  - Good sailing performance, the weight of cargo has limited impact on the performance
  - Different sizes and configurations possible by modular design

- Hulls consist of 2 bow tips (one design) and variable middle sections with constant diameter shape
- Different hull lengths
- Outrigger canoe (one hull, one floater), Drua (a bigger and a smaller hull) or catamaran setup possible

  - Very simple and fast construction due to the box shape
  - No cutoff material due to a design in accordance with the standard ply-sheet dimensions
  - Easy locally manufactured and maintained on outer islands
  - Use of traditional oceanic lateen sail

[74] J.D.K.Wilson, 'Fuel and financial savings for operators of small fishing vessels (FAO technical Paper 383),' FAO - Food and Agriculture Organization, Maputo, Mozambique, 1999.

Figure 113: Lagoon Harry-Proa, side view[75]

Figure 114: Lagoon Harry-Proa, stern view[75]

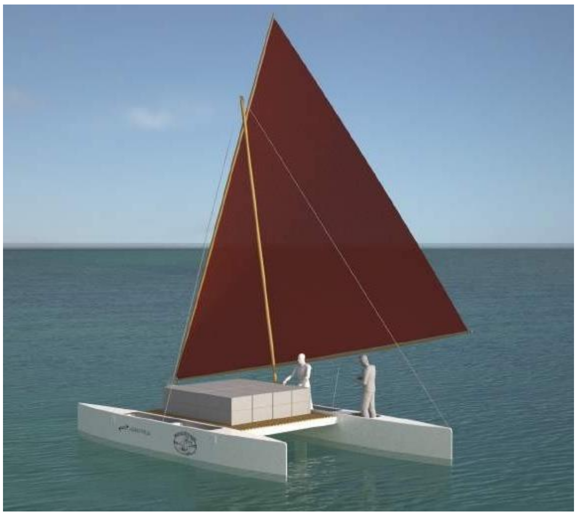

Figure 115: Lagoon Harry-Proa, loaded with cargo[75]

Figure 116: Lagoon Harry-Proa, top view[75]

[75] www.harryproa.com

4.2.2 Comparison of Design Options

The following table shows the rating of a traditional Marshallese Tipnol outrigger canoe and the proposed options 1, 2 and 3 according to the List of Requirements (LoR), calculated as explained above:[76]

Table 22: Comparison of prototype options[71]

Design option 1: Ailuk Catamaran	1.1	1	3	3	308
	1.2	5	5	25	
	1.3	4	2	8	
	1.4	5	2	10	
	1.5	3	1	3	
	2.1	4	3	12	
	2.2	5	1	5	
	2.3	4	4	16	
	2.4	5	4	20	
	2.5	5	4	20	
	3.1	5	3	15	
	3.2	4	3	12	
	3.3	5	1	5	
	3.4	4	4	16	
	3.5	5	3	15	
	4.1	5	3	15	
	4.2	5	3	15	
	4.3	5	3	15	
	4.4	4	2	8	
	4.5	5	1	5	
	4.6	3	2	6	
	4.7	4	2	8	
	4.8	4	1	4	
	4.9	3	5	15	
	4.10	3	0	0	
	5.1	5	0	0	
	5.2	4	0	0	
	5.3	4	3	12	
	5.4	4	5	20	

Traditional marshallese canoe (Tipnol)	1.1	1	5	5	463
	1.2	5	1	5	
	1.3	4	5	20	
	1.4	5	5	25	
	1.5	3	5	15	
	2.1	4	4	16	
	2.2	5	5	25	
	2.3	4	5	20	
	2.4	5	5	25	
	2.5	5	5	25	
	3.1	5	5	25	
	3.2	4	5	20	
	3.3	5	5	25	
	3.4	4	5	20	
	3.5	5	2	10	
	4.1	5	5	25	
	4.2	5	3	15	
	4.3	5	2	10	
	4.4	4	3	12	
	4.5	5	5	25	
	4.6	3	3	9	
	4.7	4	4	16	
	4.8	4	4	16	
	4.9	3	1	3	
	4.10	3	5	15	
	5.1	5	4	20	
	5.2	4	2	8	
	5.3	4	1	4	
	5.4	4	1	4	

Design option 2: WAM Catamaran	1.1	1	5	5	547
	1.2	5	4	20	
	1.3	4	5	20	
	1.4	5	5	25	
	1.5	3	3	9	
	2.1	4	4	16	
	2.2	5	4	20	
	2.3	4	5	20	
	2.4	5	4	20	
	2.5	5	5	25	
	3.1	5	5	25	
	3.2	3	5	15	
	3.3	4	5	20	
	3.4	5	5	25	
	3.5	4	5	20	
	4.1	5	5	25	
	4.2	5	4	20	
	4.3	5	5	25	
	4.4	4	4	16	
	4.5	5	5	25	
	4.6	3	5	15	
	4.7	4	3	12	
	4.8	4	3	12	
	4.9	3	5	15	
	4.10	3	4	12	
	5.1	5	5	25	
	5.2	4	5	20	
	5.3	4	5	20	
	5.4	4	5	20	

Design option 3: Mini Cargo Proa	1.1	1	2	2	569
	1.2	5	5	25	
	1.3	4	5	20	
	1.4	5	5	25	
	1.5	3	4	12	
	2.1	4	5	20	
	2.2	5	4	20	
	2.3	4	5	20	
	2.4	5	4	20	
	2.5	5	5	25	
	3.1	5	5	25	
	3.2	3	5	15	
	3.3	4	5	20	
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	4.5	5	5	25	
	4.6	3	5	15	
	4.7	4	5	20	
	4.8	4	5	20	
	4.9	3	4	12	
	4.10	3	4	12	
	5.1	5	5	25	
	5.2	4	5	20	
	5.3	4	5	20	
	5.4	4	4	16	

[76] The rating result does not intend or insinuate any superiority of one design above another in general. The rating result is specific to the List of Requirements only

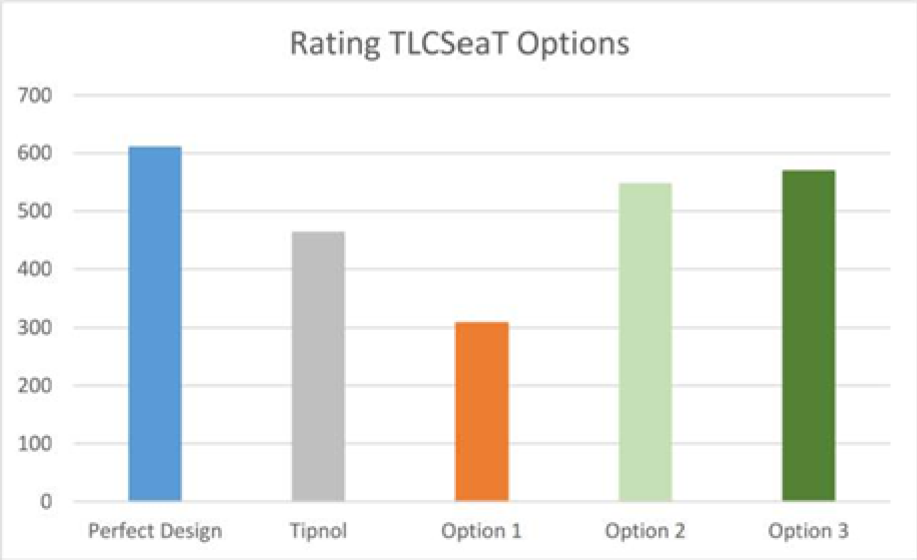

Figure 117: Comparative rating of design options[71]

Figure 117 presents the comparison of ratings of the TLCSeaT prototype design options acc. to the List of Requirements as an addition to traditional canoes. The Tipnol and the 'perfect design' (highest possible number) are shown as a reference.

4.2.3 Recommendations for the Next Project Phase

The traditional Marshallese canoe designs are without any doubt the most sustainable and best suited low carbon lagoon craft for RMI. For a successful transitioning to low carbon lagoon transport and fishing, it is essential to support the art of Marshallese canoe sailing and building culture as WAM has done since 1989. Without a substantial focus on traditional canoes (training and knowledge conservation). TLCSeaT's impact will remain very limited. The proposed low carbon lagoon craft prototype design options do not intend to replace canoes but to serve as additional transport and education means (see List of Requirements).

WAM has done a similar step before with the construction of the Ailuk Catamaran (option 1) in 2004. It served the Ailuk community reliable as sustainable transport craft for the past 14 years. Unfortunately, the catamaran is beyond its lifetime and requires a major refit, which will be close to construction from scratch. Because of issues about the sustainability and economy of glass fiber reinforced plastics, it is recommended to use plywood, if a new construction of the Ailuk Catamaran design would be considered. Instead of a refit, the old, damaged glass fiber hulls could be converted to a floating dock with limited effort. This would offer valuable service for WAM as the boatyard can only enter the lagoon at high tide.

The proposed second and third prototype options are based on the data and experiences WAM collected successfully with the Ailuk Catamaran, as well as previous research done by HEL. Both canoe types are specifically designed to meet the requirements on a sustainable low carbon vessel in RMI as pointed out in the previous section.

Compared to the WAM Catamaran (Option 2) with deep V hulls and decreasing performance if heavy loaded, a Proa design (Option 3) offers a by far better overall performance, almost independent of the displacement. Aside of that, option 3 allows to be flexible in size, configuration (from outrigger to catamaran) and rig (traditional or modern). By its flexibility, the chance of a successful adaptation of the local requirements on islands all around the Pacific is high. The construction of the box shape hulls is very simple and efficient. This makes it a perfect educational project for boat building trainees and a good demonstrator for a possible way of using the full potential of available materials and tools in RMI. The WAM Catamaran combines the local way of canoe hull construction with smart and well-proofed features. The required knowledge, tools and materials are already in place, as the only major difference to a traditional Marshallese outrigger canoe is the second big hull instead of a small outrigger floater. By its concept the performance will be lower and the required building time higher, compared to option 3.

Because of its potential overall superiority (see rating) compared to option 2, the Proa (option 3) should be preferred in the next project steps. In addition, option 2 should be built as a second prototype for conjoint sea trials with option 3, option 1 and traditional outrigger canoes to cover a wide range of different designs and collect comprehensive data. Both design options are favorable designs to be used in canoe building classes.

With option 1, 2 and 3 all constructed, the projects and WAM's technology repertoire contains a wide spectrum of different design features and covers numerous promising combinations of them:

- Catamaran vs. Proa vs. outrigger canoe
- Shunting vs. tacking
- Traditional sail vs. modern wing sail
- Deep V hull vs. box-shape

It is possible and intended to eventually blend design option 1, 2 and 3 (e.g., a Proa with deep V main hull and box-shape outrigger with traditional sail, etc.) without major modifications. Therefore, option 1, 2 and 3 contain all key design features to cover everything between traditional canoes and innovative modern design as well as options for electric propulsion.

4.3 Electrical and hybrid propulsion

The implementation of electric propulsion systems into lagoon and coastal shipping offers another wide field of options in addition to the wind-powered TLCSeaT lagoon crafts.

4.3.1 Considerations on E-Propulsion for inside-lagoon transport

Theoretically, conventional outboard engines, as they are common in RMI, could simply be replaced by electric outboard engines and battery packs to cut down their operating GHG emissions by 100%. The same engines could also be used as an upgrade for the TLCSeaT prototype options, either as auxiliary propulsion, hybrid (sail + electric) or pure electric propulsion. A small electric auxiliary engine would help to make reef passages safer and support in low wind conditions, as they are found in the southern atolls from June to November. More powerful engines could be used, especially on prototype option 1 and 2, to power the lagoon crafts in combination with sails or solely.

However, to gain real benefit out of the new technology, the batteries of the boats need to be charged by green energy. Today, RMI's energy sector relies on conventional diesel generation for the public grids with a small share of renewables (solar) only. The overall emissions of electric boats will increase significantly compared to conventional propulsion if they are charged by the public grid. A useful (ecological and economical) implementation of electric boats requires a change of the Marshallese energy sector from conventional to renewable energy sources. Today, the initial investment in electric engines and batteries is high, compared to conventional outboard motors. A significant cost factor is not the engine itself but the battery packs. Unfortunately, batteries are limited in their lifetime and need to be replaced on a regular base, adding an additional cost. RMI's waste management system is not yet prepared to deal with used batteries.

Regarding the obstructions above some time will pass until RMI is ready for electric propulsion (sea and land) on a big scale. Nevertheless, it is recommended to invest in the future now and integrate the test of electric boat propulsion units and renewable powered charging stations on a small scale into the TLCSeaT program. It is proposed to equip WAM with a modular and mobile set of engines, batteries, and solar chargers to demonstrate the capabilities of the technology in RMI and gain real-life experience and data. On top, among other upgrades of the WAM facilities, a solar power plant on the roof and shore infrastructure to charge boats should be included. The collected data and experience will help RMI for future decisions. Regarding the development of the past decades, the cost for renewable energies, electric boat engines, and batteries can be expected to decrease significantly in the future.

4.3.2 E-Propulsion Technologies for small boats

HEL recently configured a complete propulsion system with various engines, batteries, sensors and further utensils from the market leader 'Torqeedo' to equip a research and test boat. The system installed in the Green-Water-Taxi at HEL is the Torquedo Deep-Blue System. This system is a powerful high performance system for medium sized vessels. In the context of inside-lagoon boating this system is oversized for most applications. For E-Propulsion needs for WAM-vessels and MISC delivery boats the same manufacturer offers smaller e-propulsion sets (outboard engines from the 'cruise' series)[77].

The system consists of the outbord engine (available in different sizes and configurations), a 24v Battery as well as additional electrical equipment for controlling monitoring and charging.

Figure 118: Torquedo: Outbord-Engine and 24v high performance battery

It is recommended to use a system of the same manufacturer for TLCSeaT:

- By using similar equipment at HEL and WAM, HEL would be able to troubleshoot if something doesn't work.
- Test and experiments could be easily prepared and supported

[77] https://www.torqeedo.com/en/products/outboards/cruise

- A professional evaluation of required measurements all around the propulsion system. Sufficient measurement systems are not available on the market. HEL already put much effort in the development of a measurement and data bus system based on Torqeedo technology. The same measurement system could be used at WAM. Another engine system would require an expensive, newly developed system. Without professional monitoring, the benefit of the test engine system will remain very limited for future decisions.
- A full set by Torqeedo is very easy to set up and user-friendly, suitable for an introduction into electric propulsion.

The same system that is suitable for Inside-Lagoon boats, can also serve for the propulsion needs of MISC delivering boats carried on deck of the large vessels.

4.3.3 Floating Energy Production Platforms with E-Drive Charging Station

Since overall conditions for renewable energies are close to ideal, the concept of e-propulsion should be pursued for all atolls in addition to a return to wind propulsion technologies. The first step towards e-propulsion is the transition of the energy sector towards renewable energies.

One option that is relatively independent from the energy production at shore, is the setup of floating E-Drive charging stations that can be used for inside lagoon transport needs. The renewable energy systems that come to application on these stations are comparable to the proposed auxiliary energy systems on board MISC vessels. Koornstra[78] and Lampe[79] analyzed solutions to provide remote locations in RMI with energy. Koornstra's thesis analyses the general potential of renewable energy in RMI, while Lampe's work concentrates on the idea of floating energy pontoons that can be utilized as a charging station for electric powered lagoon vessels.

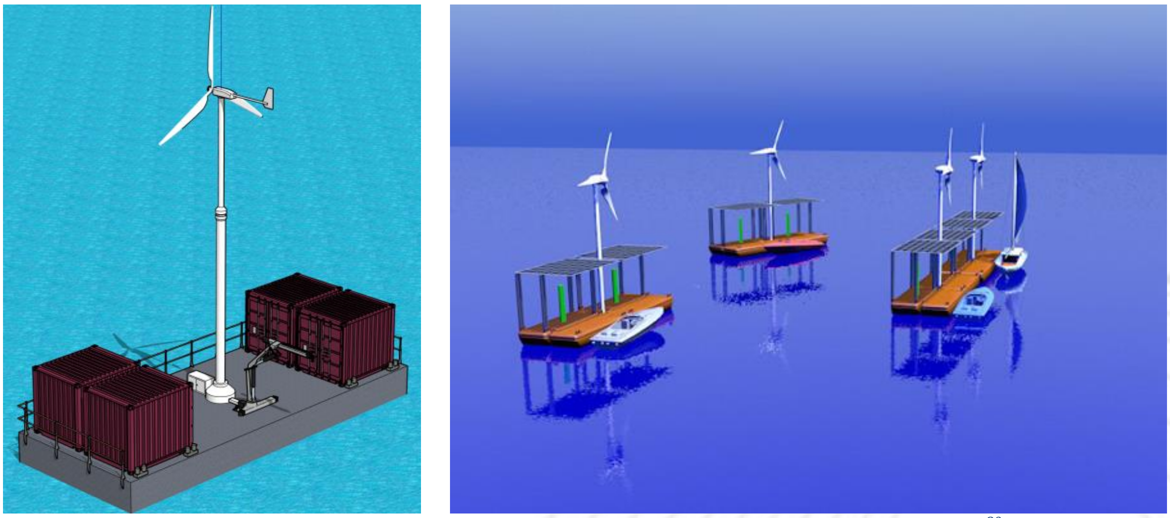

Figure 119: Design study of floating electric energy generation and charging station[80]

[78] Koornstra, J. (2018). Conceptual Design of an Integrated Transport System Based on Electromobility and Renewable Energies for Island States Using Marshall Islands as an Example. Bachelor Thesis at University of Applied Sciences Emden/Leer

[79] Lampe, M. (2018). Conceptual Design of a Small Wind Turbine Installed on a Floating Pontoon for Independent Energy Supply in Remote Maritime Regions. Bachelor Thesis at University of Applied Sciences Emden/Leer

The concept proposes to use wind and sun to charge large batteries, serving as energy storage. Those large batteries remain on the floating platform (pontoon). From this energy storage, smaller high-performance batteries can be charged for use in small (sailing) boats equipped with electric drives. The concept proposes to use a standardized battery system on all boats so that empty batteries can quickly be exchanged at the charging stations.

The stations can further be used as a rallying point for copra collection, whereby the efficiency of MISC vessels can be increased.

This concept for lagoon boat operation with renewable energies is almost identical with the proposed solutions for MISC tender boat operation. On board the MISC vessels the auxiliary energy system, upgraded to: photovoltaic, wind turbines and battery storage, will serve as a charging station for the electric outboard engines of the tender boats, during lagoon cargo and passenger operations (refer to chapter 3.6.2 'Optimizing efficiency of Cargo/Passenger delivery boats' and 3.10 'Auxiliary Energy System').

4.4 Facility Upgrades: Space for Possibilities

In a first step prior to the official launching of the training program, WAM will need major upgrades of its facilities. These are necessary to enable WAM to serve as center of competence, steering the efforts towards professional training for low carbon lagoon shipping.

- New work shed to build low carbon lagoon craft. The existing workshops are not sufficient for the projected development of WAM.
- Slipway to access the lagoon with boats. RMI suffers from sea level rise which causes erosion on its shoreline. The shoreline at WAM is partly paved by concrete, but very steep. It is difficult to access the lagoon with boats or canoes.
- Renovation of the electrical installation.

- Run the new workshop
- Prevent accidents caused by old wiring
- Prepare WAM for electrical propulsion (charging station)

- Installation of a solar power plant on top of the main building's roof

- Run the new workshop with green power
- Make WAM independent from the unreliable conventional power supply
- Stabilize the local grid
- Power the charging station by green energy

- Extension of the wash- and locker rooms for future employees and students
- Enlargement of the water catchment to deal with extended dry seasons due to climate change

It is intended to create an open working environment for canoe and boat building at WAM. The open workshop will be accessible for all Marshallese and support all construction projects, guide them professionally and offer room for experimentation and future development.

4.5 Economic Potential

Compared to the use of conventional combustion powered boats, green and efficient transport and fishing craft mean to offer a big potential for the local economy and GHG savings for RMI. The specifications of a typical motorboat as it is used all around the Pacific are listed in Table 23, compared to a traditional Marshallese canoe design and the newly developed prototype options.

Table 23: Comparison of sail and combustion powered boats[71]

	Traditional Canoe (Tipnol)	TLCSeaT low carbon lagoon craft (prototype options)	Typical Motorboat; fiberglass; 5.5m; 25HP ("Bumbum")
Lenght:	5,50 m	6,50 m	5,50 m
Beam:	3,50 m	3,50 m	1,60 m
Wheight:	200 kg	350 kg	400 kg
Carrying capacity:	600 kg	1000 kg	1000 kg
Fuel consumption	-	-	0,55 l/h/HP
Travel speed	18 km/h	15 km/h	25 km/h
Cost hull:	1000 USD	2000 USD	5000 USD
Cost engine:	Windpowered	Windpowered	3000 USD
Total cost:	**1000 USD**	**2000 USD**	**8000 USD**

Main operation fields for lagoon shipping in RMI are transport and coastal fishing. In the following, typical cases for both fields are shown for the atoll of Ailuk as an example case for all atolls in RMI.

Figure 120: The atoll of Ailuk and typical operation cases of lagoon shipping

4.5.1 Typical Operation Cases

Two typical operation cases are described below.

Lagoon Transportation

The main village of Ailuk is located on the most southern island of the atoll. The other islets are not permanently settled, but often visited for food gathering and copra harvest. The production of copra on the western island chain requires boat trips for copra bag transportation up and down the atoll, including numerous stops on bypassed islands (see red line in Figure 120). A one-way trip on direct course along the reef belt is approx. 27 km (both ways 54km).

Coastal Fishing

Artesian fishing is practiced all around the atoll, in- and outside the lagoon at various fishing grounds. The yellow line in Figure 120 shows an example of countless possible routes within the shorelines of the atoll. A fishing trip differs from a single transportation task by special requirements on the vessels speed. It is characterized by travel speed to and from the fishing grounds and the actual fishing process at the fish grounds at a somewhat slower speed. For the example of Figure 120, it is assumed, that the fishermen start the fishing process at their village on Ailuk-Ailuk and continue at a fishing speed of approx. 10 km/h following the reef belt as long as they get enough fish to change course and return home (see turn close to the western tip of Ailuk atoll). The trip back to Ailuk-Ailuk is at average travel speed and a common transport task. Despite very varying numbers, caused by different influences, 30 to 50 kg fish are assumed to be caught on a fishing trip.

4.5.2 Acquisition and Maintenance

With about 8,000 USD, a common size motorboat incl. engine cost about 4 to 8 times more than alternative transport means. Boats are major investments to island communities: Considered that the average income of an Outer-Islander is around 1 USD per day, it would take 8,000 days (or 22 years) for an individual to save for a motorboat (leaving away all other expenses of daily living). Therefore, boats are usually subject to community or family investments. Traditional canoes and the TLCSeaT prototype design options allow cutting the initial investment by up to 87.5 % (ignoring local labor).[81]

Despite the expensive acquisition itself, the maintenance of engines is difficult and expensive on remote islands. Consumables like lubrication oil, seals, spark plugs, etc. are expensive imported goods. Engines do not operate if they are not properly maintained.

Traditional canoes or the TLCSeaT crafts do not require imported or expensive spare parts for their operation. Repair and maintenance can be done locally, in most cases even using local resources.

4.5.3 Fuel Consumption

The specifications of the common type of open fiberglass motorboats with 25 HP 2-stroke outboard engine are listed in Table 23. The fuel consumption of 2-stroke outboard engines can be roughly assumed to 0.55 l/h per HP[82]. This results in a consumption of 13.75 l/h in this example; however, the

[81] Richter-Alten, (2018). TLCSeaT Lagoon Shipping Report (Draft)

[82] Wilson, J.D.K. Fuel and financial savings for operators of small fishing vessels

real fuel consumption is subject to many factors such as engine type, hull shape, maintenance, currents, wind, wave conditions and more.

Following the numbers above, the motorboat would consume 29.7 l (7.84 gal) gasoline on the full copra transport trip, traveling at a speed of 25 km/h. For an average price of 2.38 USD per liter (9 USD per gal) a full transport trip as shown in Figure 120 cost 70.69 USD. Considering the average income of an Outer-Islander, it would take 71 days for an individual to save for the gas of the trip (ignoring all other expenses of daily living).

Using traditional canoes or the newly developed sustainable lagoon crafts, the fuel cost can be cut down by 100% as they are wind-powered only. While the motorboat operates at a travel speed of 25 km/h (or even faster), the traditional canoe and the TLCSeaT prototype will travel at 18, respective 15 km/h if the trade winds blow at 15 kn. For the full trip, this results in 3 resp. 3.6 h of sailing. Overall, the motorboat would be approx. 1 – 1.5 h faster, traveling at 25 km/h. Compared to around 70 USD of fuel cost, expenses for 1 to 1.5 h more labor are a feasible tradeoff, even if RMI's average wages are applied to the boat operators.

The special requirement of a fishing trip, compared to a single transport task, is a speed of approx. 10 km/h for the fishing process. In the 31 km example fishing trip of Figure 120, 17 km are sailed on fishing speed and 14 km on travel speed.

A motorboat would consume about 23.4 l on fishing speed and 7.7 l for the way back home at travel speed. It is important to note for this specific case, that the fuel consumption per nm at low speeds (displacement mode) can be higher than for travel speed (planing mode) due to different factors such as the hull shape, resistance, engine efficiency and more.

The total consumption of the fishing trip would be 31.1 l (8.2 gal) gasoline, resulting in expenses of 73.85 USD. If 40 kg of fish is caught at the trip, it would cost 1.85 USD per kg for fuel only. An average islander with an income (1 USD per day) can afford to pay for 540g of unprocessed fish (including bones, skin, intestines) a day if the entire income is spent. This is not enough to feed an adult, neither a family.

Compared to that, fish caught by using a canoe or TLCSeaT craft is almost for free; only labor cost of the fishermen needs to be applied. Taking the average income into account as labor time, even this is almost negligible compared to the expenses for fuel.

Assuming a fishing canoe sails out once a week to catch fish, 1,617 l (428 gal) of fuel, equivalent to 3,852 USD, could be saved per year. A community with ten canoes could save 38,520 USD on fuel alone.

4.5.4 Further Effects on Local Economy

Using canoes or the TLCSeaT craft, the money which would have been spent for expensive hulls, engines, maintenance, and fuel otherwise stays within the island community and could be spent for something else. Overall, the wealth of the island communities could grow significantly. The increased purchasing power of the Islanders on one hand and the cheaper boats, on the other hand, make sea transport more affordable to small groups or individuals. Increased wealth, creation of value in place and growing demand boosts the local economy and creates additional jobs.

Aside from direct benefit, a local economy based on wind power is more reliable compared to an import-dependent business model. Canoes can always go out fishing, motorboats without fuel or a missing spare part not.

4.6 GHG Emission Savings Potential

The PRIF study by Mark Oxley[83] estimates a contribution of lagoon craft to the overall GHG emissions of RMI's shipping sector by 40 percent. He further estimates a total consumption of 1,277,000 liters of gasoline, equivalent to 3,038 tons CO_2 in 2017.

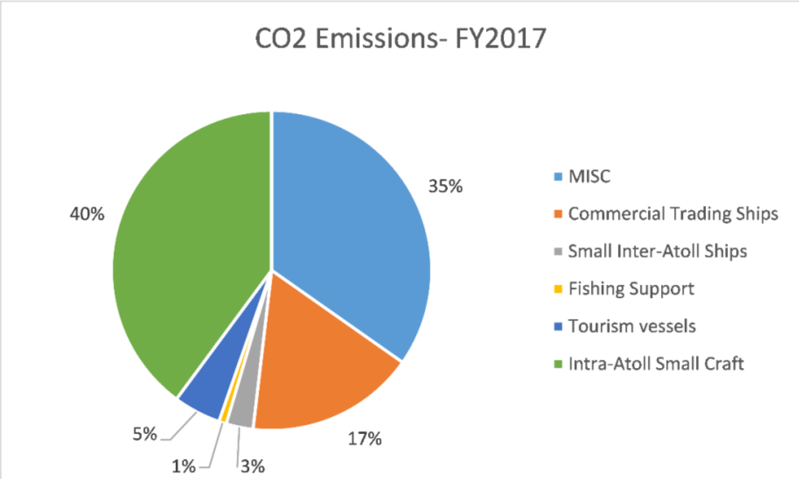

Figure 121: Share of CO_2 emissions 2017 in RMI acc. to PRIF study by Mark Oxley[83]

After comprehensive research, including extended field trips in place, it seems feasible to replace 80% of all small, engine-powered lagoon vessels by carbon neutral craft in the next decades (assuming a successful and sustainable implementation of TLCSeaT and its upscaling). This would result in a CO_2 saving potential of approximately 2,400 tons per year, which represents 32% of RMI's overall emissions in the shipping sector. As midterm contribution, inside-lagoon shipping should meet the indicative target to reduce its emissions of GHGs to 45% below 2010 levels by 2030.

Regarding the examples above, the GHG saving potentials of the proposed measures is 100%. Applying the commonly used emission factor for gasoline of 2.36 kg CO_2 equivalent per liter of fuel, 70 kg CO_2 for the transport task and 73.4 kg CO_2 for the fishing case could be saved.

A single canoe, which sails once a week for fishing or transport, would save approx. 3,500kg CO_2 per year.

[83] Oxley, M., 'Establishing Baseline Data to Support Sustainable Maritime Transport Services-FINAL REPORT,' Establishment of the Pacific Region Infrastructure Facility Coordination Office (PRIF), 2018.

5 Outlook and Next Steps

This report is intended as a presentation of the technical and operational options to reduce fuel consumption and emissions for both the lagoon and ocean transport in the RMI. In order to ensure the project progress over the next months, the next steps to be taken on the basis of this report are:

- Narrowing down the options laid out in this report to decide on the measures that will be implemented within the project scope
- Development of an implementation strategy in cooperation with all project partners
- Research of available manufacturers, suppliers and service partners in the region
- Research of technical feasibility of the measures with the resources and partners in the region
- Investigation of the costs for the final options and measures
- Realization of the technical options and implementation of the operational measures in the fleet

The options laid out in this report can be an important step towards the project goal, reducing the carbon footprint of sea transport in the RMI, and enabling the fleet to achieve zero emission shipping in the future.

II. List of Figures

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III. List of Tables

IV. References

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