

Pacific Blue Shipping Partnership – Technical Working Group

Technical Working Paper 3: Pacific domestic shipping emissions abatement measures and technology transition pathways for selected ship types.

1. Purpose of Paper

The Governments of Fiji and Marshall Islands have identified an urgent need for large-scale financial investment to catalyse a multi-country transition to sustainable, resilient, and low carbon shipping, drawing down to zero carbon all domestic shipping in participating Pacific Island Countries by 2050, with a 40% reduction achieved by 2030.

Technical Working Paper 1 gives known participating country summary data, Technical Working Paper 2 summarises potential measures and associated Marginal Abatement Cost Curves (MACCs) being considered internationally. This paper, Technical Working Paper 3, discusses potential abatement measures applicable to Pacific Small Island Developing States' (SIDS) transition and provides indicative initial vessel type transition pathways options.

Understanding which technologies, behavioural changes or fuels are likely to be the most cost-effective in reducing emissions is complex. The most effective approach to reduce shipping emissions is likely to differ based on the type, size, and age of ship – and these vary substantially across the fleet. Furthermore, the cost of the technologies will vary, in part, depending on the scale of the market for those technologies and the time period over which they are developed (if economies of scale are achievable, costs may decline over time as markets grow) and when they are deployed. In addition, a key challenge facing the industry is that to achieve zero emission shipping, determined action is likely to be needed over many decades. This is because, with the life of a vessel often around 25-30 years (or longer) and many markets for low emission technologies still in their infancy, this requires co-ordinated action involving multiple parties such as the shipping industry, the government, technology and fuels industries, other energy providers, end users and other stakeholders coming together to achieve the shared objective over a sustained period.¹

2. Structure of Paper

This paper has been prepared for the Technical Working Group providing advice to a coordinating committee chaired by RMI/Fiji. The TWG Terms of Reference includes a request for delivery of the following outputs:

- Analyses that identify and rank potential measures (operational and technological) available internationally for decarbonisation and the MACCs associated with these.
- Review analyses against a Pacific operating scenario to determine: (i) what are the most effective available measures we can take in the target countries now/very near future (and the MACCs associated with these) and (ii) what are the potential measures for Pacific deployment that require research and development (and the MACCs associated with these).

3. Research on Pacific domestic Abatement Measures to date

No dedicated study has considered the full suite of abatement measures available to Pacific SIDS seeking to decarbonise the maritime sector, although a growing body of knowledge is being assembled. A rapidly growing range of international trials and research effort continues to inform selection of potential measures for Pacific SIDS. These include a number of studies on abatement options for international shipping conducted since the release of the 2nd and 3rd IMO GHG reports from a variety of sources (in particular CE Delft, UCL/UMAS, DNV-GL, Lloyd's Register, ITF-OECD). More recently this effort has included domestic shipping studies for northern European countries.

In the context of Pacific operating scenarios, the literature begins with research findings centred on a range of fuel efficiency trials and proof of concept projects during the 1980's oil crisis². Such projects, implemented by a range of development partners including United Nations agencies, European Commission and the Asian Development Bank at various ship scales from artisanal fishing to government service cargo/pax ferries, focussed heavily on various wind-hybrid approaches, identified at the time as the most likely practical measure for achieving cost-effective energy efficiency savings. There is an incomplete record of these projects and their results and, where they exist, project reports varied from minimal to detailed analysis of both efficiency savings and cost/benefit³. Collectively they clearly identify an achievable range of savings based upon then mature technology for a range of vessel types available to the current debate. With falling international fuel prices in 1986, no further work was done in this field specific to a Pacific SIDS domestic scenario until the USP-hosted Sustainable Sea Transport Talanoa in 2012⁴ and 2014⁵ and the subsequent papers published under the Sustainable Sea Transport Research programme⁶, which include sectoral analysis of various measures such as Flettner rotors, soft sails, biofuels and wing-in ground technologies. A comprehensive review and analysis of all available reference material to 2015 relevant to Pacific decarbonisation transition was prepared for the UNCTAD Sustainable Freight Transition knowledge portal⁷. The German government funded TLCSeaT project in RMI is producing options portfolios for RMI inter-island government and intra-lagoon scale vessels⁸, the Swire/USP Cerulean Project is currently assessing viability for a wind-hybrid 200GT inter-island cargo vessel design⁹. More recently SPC/SPREP, under the IMO GMN programme, have completed trials on retrofitted PV systems for reducing fuel use providing auxiliary power on two vessels in Vanuatu and Samoa as well as work on port side efficiencies' potential with provisional results now available¹⁰.

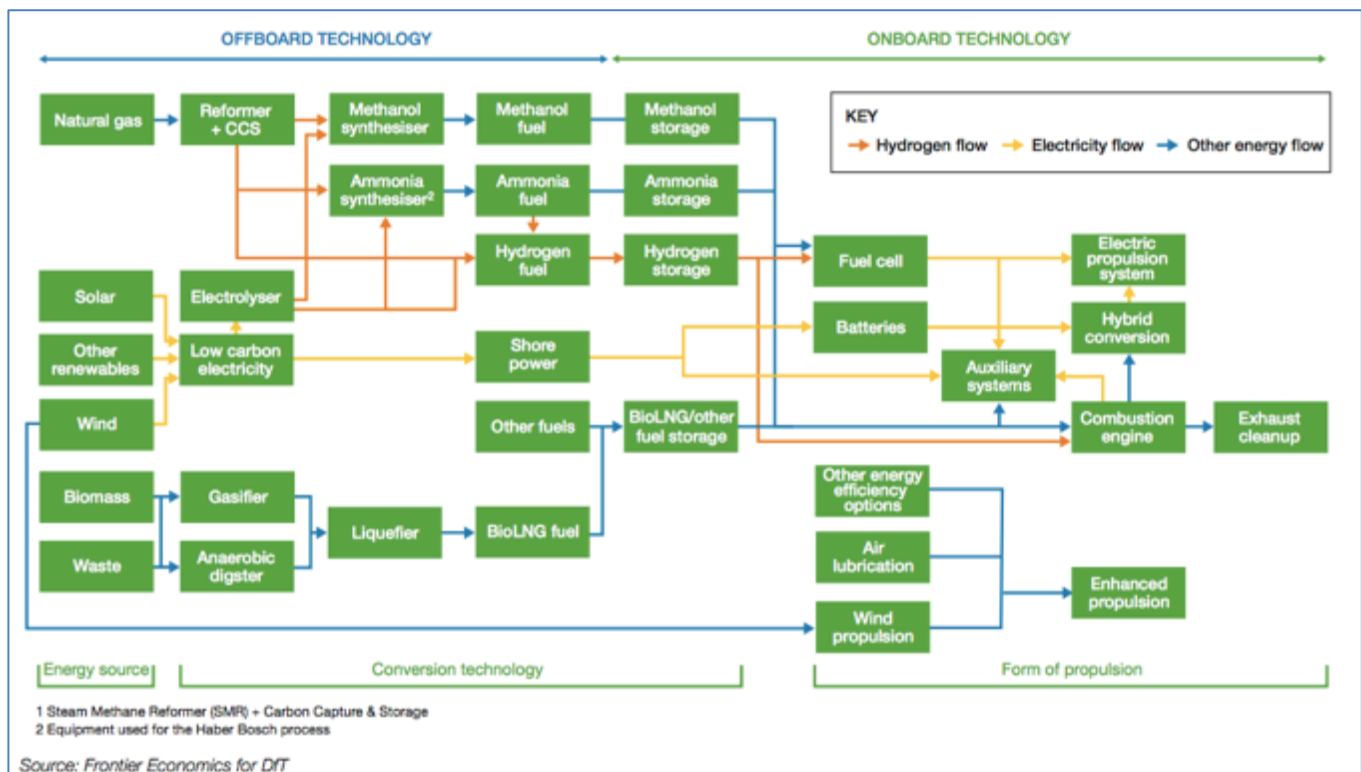
The literature remains incomplete and such data that is available is at different levels of verification. The issues of Pacific domestic shipping data availability and reliability have been identified as an ongoing issue for over a decade¹¹. Almost no detailed reviewed

analysis on cost/benefit, return on investment or MAC curves for any measure is currently available, with the exception of the 1986 Fiji ferry trials¹².

4. Abatement Measures available for consideration by the Pacific

The fast-moving nature of international shipping decarbonisation research means new information and research is rapidly becoming available, albeit almost all effort remains focussed on the economics and technologies to support large/developed economies' shipping. There is considerable consensus amongst international experts that sufficient technology exists in some form to produce low or zero carbon vessels at most scales, but what is essentially missing today are the financial drivers to mature those technologies to market-scale deployment¹³. The key technologies available at global scale for decarbonisation of shipping are summarised in Figure 1.

Figure 1: Technologies and fuels on a pathway to zero-emission shipping.



International studies generally agree on the range of measures available to shipping, although there are different methodologies proposed for grouping and assessing the viability and readiness of such measures. All work to date agrees that existing mature technology and operational measures alone cannot deliver full decarbonisation and, even with new builds incorporating all available advances, ultimately alternative fuel(s) are required with methanol, hydrogen, ammonia and sustainably sourced biofuel among currently identified candidates.

This raises special issues for SIDS and Pacific States in particular, who already struggle with adequate bunkering facilities for fossil fuels. A new alternative domestic fuel source that requires new and additional bunkering infrastructure to that already in place for fossil fuels would likely require greater investment than could be made available to Pacific States in any future development scenario. This is a key supporting assumption in our current analysis that simply scaling down international shipping decarbonisation measures for Pacific deployment is inappropriate and bespoke Pacific SIDS solution pathways are required.

The UMAS UK study¹⁴ provides the current benchmark for international work and considers that the different options for reducing GHG and air pollution from both UK domestic and international shipping are, for the most part, commonly agreed and can be considered in four categories¹⁵. These are used as the starting point for considering Pacific applicability below:

1. Technologies that can increase energy efficiency;
2. Operational or behavioural change that can increase efficiency;
3. Technologies specific to the capture/treatment of exhaust emissions (GHG and air pollutant emissions); and
4. Alternative fuels and energy sources and related machinery.

Of these, Category 3, the GHG reduction savings accruable from technologies specific to the capture/treatment of exhaust emissions, primarily either equipment for removing GHG and sulphur oxides from exhaust gases such as scrubbers or catalytic converters, have been largely shown to have nil to marginal effectiveness. Measures in this category with high abatement potential require on board capture for future sequestration or introduction of methane catalysts, neither measure which is likely

to be used in any future Pacific domestic scenario given vessel scale and cost. Consequently, this category is not considered further here.

Efficiencies and savings are available to the Pacific under the remaining three categories, although there are characteristics of the Pacific domestic scenario that imply that application of measures will not be uniform with either a global or a large economy transition. Of these access and affordability of alternative fuels; access to cost effective, renewably generated electricity; and technology transfer barriers to high tech solutions being the most significant. Lack of appropriate domestic maritime investment finance and insurance underlie all issues.

A number of global studies have considered the applicability and availability of these measures and various toolkits have been developed¹⁶. However, none of these have been constructed specific to a Pacific SIDS domestic scenario lens and all to date are of limited value for determining potential savings or priorities at this scale.

Most international study has also considered the availability of identified measures to the market, either as simple scales of mature to immature or, in the example of the recent UMAS study, in terms of a Technical Readiness Index on a 1-9 scale. Neither of these approaches is particularly useful to a Pacific scenario given its unique characteristics and non-conformity with large-scale, logistics chain operations¹⁷.

Measures need also to be considered in light of whether they are targeted at current fleet retrofits or next generation newbuilds. Given the average age of Pacific domestic fleets, such that vessels commissioned under current regulations and legislation today are as likely to still be in service in 2050 as not, this means full consideration needs to be given to both options. However, as a rule, retrofits will never achieve the same degree of efficiency of new builds where full control can be maintained over all design elements, choice of materials, etc. and, in a life-cycle analysis, will be unlikely to achieve the same investment returns over time. This further implies that the use of climate financing to accelerate a generic fleet replacement policy across the Pacific to new vessels is necessary to meet emissions reductions targets at the speed and scale set by Pacific leaders¹⁸.

Category 1: Technologies that can increase energy efficiency

Abatement Measure		Retrofit	New Build	Savings potential ¹⁹	Applicability to Pacific domestic scenarios and potential savings	Availability to Pacific domestic scenarios
<p>Propulsion devices including modifications to the propeller, propeller boss and adjacent area, (ducts, fins, cowlings), bulbous rudders, etc.</p>		yes	yes	<p>1-25%²⁰. Up to 12% propulsive fuel efficiency claimed²¹ but 2-8% is more realistic.</p> <p>Ducts, fins etc are considered relatively cheap and low technology measures, with costs increasing sharply for high efficiency measures such as contra-rotating propellers. Savings vary considerably dependant on ship type, size and operating speed.</p> <p>New innovation research on Large Area Propellers (LAP) indicates they could use up to 20% less fuel than today, depending on the vessel type, size and operating profile.</p>	<p>High potential in selected applications.</p> <p>There is a wide range of known measures in this category. Most work has been at large ship scale with much less research into ships appropriate to Pacific domestic scale. Innovation need to be very specific to the individual vessel and its operating parameters. For example, Propeller Boss Cap Fins (PBFC) were developed in the 1980s and more than 2,000 installations worldwide, with manufacturer's savings claims of 3-5%²². However, most PBFC's effectiveness is reduced at slower steaming speeds and may be a constraint at operating speeds common to Pacific domestic vessels.</p>	<p>Available.</p> <p>The technologies are generally well known and readily commercially available, primarily at large ship scale.</p> <p>Most new builds internationally now incorporate latest known designs and innovations and could be made mandatory via national policy for appropriate Pacific future builds. Retrofitting during routine drydocking is also readily available.</p> <p>Locally situated research to determine the 'best-fit' of known innovation and technology for local operating scenarios and vessel types is needed.</p> <p>Specialist knowledge required. Some potential for localised componentry manufacture.</p>
<p>Ship design including changes in the hull shape, lightweight construction materials, addition of bulbous bows, etc</p>	Hull design	no	yes	<p>Individual vessel dependant but up to 25% efficiency²³ possible (when combined with other initiatives e.g. new propellers, etc.)</p> <p>The design efficiency of ships has varied significantly over time. All large ship types analysed by Faber et al (2016) witnessed a sharp improvement in the design efficiency of new ships in</p>	<p>High potential if investment is available to re-fleet with new vessels.</p> <p>Most work has been at large ship scale with less research into ships appropriate to Pacific domestic scale.</p> <p>For vessels such as inter-island ferries where many ships are either aged 2nd hand or donated vessels, potential efficiencies under an overall new build fleet replacement strategy are</p>	<p>Available.</p> <p>Limited current Pacific situated ship construction, esp. naval architecture, capacity - requires long-term international partnerships/investment if new hulls are to be Pacific designed/built in whole or part.</p> <p>Essential and high priority if financing available for Pacific re-fleeting with new builds.</p> <p>Opportunity for revitalisation of Fiji shipbuilding capacity and</p>

				<p>the 1980s, gradual deterioration in the 1990s and 2000s, and increasing improvements in recent years via hull and propeller design. Changes in speed and size have contributed less to changes in efficiency.²⁴</p> <p>In general, fuel-efficient hull designs are more expensive to build and can result in reduced carrying capacity over BAU designs, so uptake is a factor of fuel cost, carbon regulation and freight charges.</p>	<p>high if vessel design is tailored to identified transport need.</p>	<p>expansion of existing maintenance capacity.</p>
	Air lubrication	yes, For some types only	yes	<p>10-15% reduction in propulsive fuel possible²⁵, 4-5% savings²⁶ demonstrated in latest large-scale commercial deployment.</p> <p>Some additional energy requirements for pumping Most effective on flat bottom ships. Efficiency gains decline rapidly as sea state increases.</p>	<p>Low future potential. Most work on this measure for merchant shipping has been on large ships with no targeted research at Pacific domestic scale. Current high cost and high technology installation and maintenance costs suggests overall gains will be low and expensive to achieve at smaller scale with low or negative investment cost. Landing craft would be most appropriate if low cost/low tech installation proved.</p>	<p>Not currently available at Pacific domestic scale. Limited future potential. Recommend watching brief and research into Pacific application of low cost/low tech approach for landing craft/flat bottom cargo vessels.</p>
	Bulbous bow	yes, (but not common)	yes	<p>3-7% in fuel savings on large cargo carriers²⁷. Other devices or retrofit to reduce resistance can reduce CO₂ emissions of about 2-5%²⁸.</p>	<p>Not applicable except in specific vessels. Bulbous bows are common for large-scale shipping but can have negative efficiency effect on small-scale shipping.</p>	<p>Available. But not likely to result in uptake as likely very marginal or negative effect on most Pacific scale shipping. May be seen on imported vessels. Retrofits are uncommon and likely not cost effective at Pacific domestic scale.</p>
	Aerodynamics	yes (but of limited application and largely restricted to bow shields)	yes	<p>No reviewed literature figures available. Ship design can reduce windage and enhanced aerodynamic performance. For existing vessels, retrofitted bow shields are available and there are some initial trials at large ship scale. For newbuilds, this design parameter should be included in all new ship design</p>	<p>Low potential. (but should be incorporated in new ship design)</p>	<p>Limited availability.</p>
Main machinery and engine modification (design improvements to the diesel engine, energy from waste heat recovery (WHR), etc)		yes	yes	<p>0.1 -3%²⁹</p> <p>Modern marine diesel motors have nearly reached their maximum design efficiency, although minor design gains can still be expected. The most thermally efficient low-speed marine diesel engine is rated at 50 percent between fuel energy content and crankshaft power. Regularly maintained serviced motors will always be more efficient.</p>	<p>Low, but future potential if increasing new builds are introduced to Pacific domestic scenarios. Regular engine tuning, maintenance and derating are likely most cost effective measures for existing Pacific domestic fleet. Despite up to 50% of fuel energy being lost to heat before it gets to the propeller, almost no work is being done at the scale of vessels used domestically in the Pacific. WHR is high cost</p>	<p>Available. The first priority should be maximising available efficiencies through enhanced regular maintenance and servicing regimes. Smart technologies likely higher relative cost when employed at Pacific scales and remoteness. WHR needs immediate Pacific focussed research. All require, to varying degrees, capacity development across the Pacific domestic logistics chain to effect.</p>

				<p>Electronically controlled engines offer increased precision in terms of fuel injection and exhaust emission control.</p> <p>Turbochargers for both engine and transmissions also offer some potential for future efficiencies.</p> <p>Diesel/electric hybrid drive systems can provide additional efficiency.</p> <p>Waste heat recovery has been identified as having a fuel reduction potential of 0-12% dependant on ship type³⁰.</p> <p>De-rating, especially when combined with permanent slow steaming regimes and wind hybrids, can provide 1-3% additional savings³¹.</p>	<p>for large shipping and probably prohibitive for Pacific scale retrofits but could be considered for new build scenarios.</p> <p>Given high age average of Pacific domestic fleet, new engines will almost certainly automatically increase efficiency considerably. However, as with other measures in this category, this is probably not cost effective for many vessels given ship age for many vessels.</p> <p>Much greater overall savings accrue from investment in new generation vessels rather than retrofitting with new improved main engines.</p>	<p>Cost effectiveness of the more sophisticated measures means it is probably not applicable to older, smaller Pacific vessels.</p>
<p>Auxiliary (energy management and recovery) See also RE sections under Category 4 below</p>	<p>Autopilot upgrades Hotel and secondary machinery systems/ equipment upgrades/ efficiencies Smart controllers and battery buffers</p>	yes	yes	<p>Main engine measures are also viable for auxiliaries. WHR could be diverted to either main or auxiliary assistance.</p> <p>Use of smart controllers and battery buffers, a fast moving field internationally, increases the ability to tailor the auxiliary generation to meet specific power need. More efficient 'smart' motors', and variable frequency drives can be used to upgrade many secondary and hotel systems e.g. pumps, fans, LEDS, etc. Autopilot upgrades.</p> <p>On most international shipping, auxiliaries only use a fraction of the main drive fuel consumption. Likely higher for many Pacific domestic vessels given high port times.</p>	<p>Medium.</p> <p>For many Pacific scenarios, auxiliaries are much larger percentage energy users given often long port times of Pacific domestic shipping. Measures can be considered as low or high tech. Technology transfer barriers exist for high tech given current Pacific capacities. Smart technologies likely higher relative cost while employed at Pacific scales and remoteness.</p> <p>All require, to varying degrees, capacity development across the Pacific domestic logistics chain to effect.</p>	<p>Available.</p> <p>The first priority should be maximising available efficiencies through regular maintenance and servicing.</p> <p>Smart technologies likely higher relative cost when employed at Pacific scales and remoteness and require significant investment in short and long term capacity development.</p> <p>WHR needs immediate Pacific focussed research.</p> <p>Cost effectiveness of the more sophisticated measures means probably not applicable to older and smaller Pacific vessels.</p> <p>Port waiting times imply much greater potential for Pacific savings to accrue with these measures than internationally.</p>

Category 2: Operational or behavioural change that can increase energy efficiency

Abatement Measure		Retrofit	New Build	Savings potential ³²	Applicability to Pacific domestic scenarios and potential savings	Availability to Pacific domestic scenarios
Speed/voyage optimisation related	Slow steaming	yes	yes	<p>0-60% of propulsive fuel use.</p> <p>A speed reduction of 10% translates into engine power reduction of 27%. When adjusted for increased transport work needed due to increased passage time, a 10% speed reduction results in a reduction of 19% total emissions saving³³.</p>	<p>Low to medium applicability.</p> <p>Many domestic ships already employ voluntary slow steaming in periods of high fuel cost in any regard. Faster passage time usually demanded by customers, especially for passenger transport and majority of Pacific vessels are mixed cargo/pax.</p>	<p>Available.</p> <p>Lower speeds are more effective if design speeds of ships are brought down as well.</p>
	Increase ship size/ capacity	no	yes	<p>Up to 30% emissions reduction³⁴</p> <p>Savings need to be considered over full</p>	<p>Low applicability.</p> <p>Would only benefit high volume routes. Many Pacific ports, especially for remote</p>	<p>Available.</p>

				logistics chain as smaller vessels/other modes needed to disperse from main ports. Savings assume vessels operate at capacity	communities are restricted as to vessel size due to passages and harbour restrictions and infrastructure limitations. There is often a high inward/outward loading imbalance. Fewer larger vessels is contrary to most Pacific policy to build outer island economic capacity and resilience.	
	Just-in-time routing Weather routing	yes	yes	Highly variable dependant on ship, route, trade and communication with shoreside ports and operators.	High applicability.	Available.
Condition related (e.g. trim, - hull coating selection, maintenance, etc)	Ballast water trim	yes	yes	0-5-2% main engine fuel use. Using digitised ballast water data and onboard computerised ship sensors, ballast water can be optimised for maximise trim efficiency.	High applicability and potential savings. (for ships using computerised ballast water and ships sensors,). Low potential for older, smaller vessels	Available. But likely only cost effective in high volume traffic routes or new build scenarios. Technology transfer and capacity development barriers
	Cargo	yes	yes	1.5% main engine fuel use. Using digitalisation and computerisation of cargo loading records to optimise trim, Hapag-Lloyd achieved savings of about 1.5% of main engine fuel oil consumption ³⁵ .	High potential savings for ships using computerised cargo data and ships sensors. Medium potential for older, smaller vessels	Available. But computerised solutions likely only cost effective in high volume traffic routes or new build scenarios and there are technology transfer and capacity development barriers. Strong potential for training on all vessels for masters, mates, supercargoes in load management best practices.
	General Maintenance – to ensure best lightship trim	yes	yes	2-8% emissions reduction potential.	High. Given high average age of Pacific domestic and low profit margins, ongoing maintenance upkeep is a longstanding issue for many domestic scenarios. Historic Fiji trials in 1980s showed that basic maintenance of ship bilges, ballast, engines and machinery could achieve 4% savings ³⁶ .	Available. Strong potential for training on all vessels for masters, mates, supercargoes in load management best practices.
	Hull coating/cleaning	yes	yes	1- 5% propulsive fuel savings. Regular cleaning/renewal can have marked improvement. New generation coatings may increase current savings potential by 50%	High potential. Drydock/Haul-out facility capacity for larger vessels is limited outside of Fiji. TCLSeaT research in RMI suggests hard coatings with regular cleaning by dive teams may be more effective than new anti-fouls and result in less lost service time and full burn to drydock in Fiji.	Available. Pacific domestic specific research needed to confirm “best-fit” solutions given lack and cost of haul-out facilities in many locations.
Port related (just in time berthage, etc)	Improved ship-port interface			~1 ³⁷ -5% ³⁸ .of total shipping emissions globally Achieved through auxiliary engines reduced energy consumption. Needs to be integrated with other route optimization tools, weather routing and shore side logistics,	Low current applicability. Many domestic ports/jetties have shoreside infrastructural and transport network challenges and systemic local constraints which present major barriers for shoreside/port efficiency, each which present high	Low Availability and high financial/ institutional investment required. Except in major centres, domestic maritime infrastructure and substandard vessel fleets have always presented a severe challenge to successive Pacific governments. Improved ship/port interface requires upgrades across the

				warehousing and transport regimes. In case of significant speed reductions, there will be more load/unload operations, and a greater need for port efficiency and accurate voyage timing, therefore the need to have an efficient ship-port interface will increase in importance.	cost requirements to resolve. Better collaboration and data exchange would be needed by the different actors that have an influence on ship waiting time, including terminal operators, port authorities and port service providers such as pilotage and towage. Greater digitalization is likely needed throughout the logistics chain to achieve.	whole logistics infrastructure of which this is only one component. Requires integration with overall land use and land transport planning regimes. Major maritime infrastructure strategies and projects are ongoing, in progress or planned for many countries, e.g. Nauru, Solomon Is, Vanuatu Kiribati, RMI and Tuvalu, which provide opportunities for energy efficiency to be built in as a priority. Long term planning capacity needs to be built into education/training regimes.
	Port side energy efficiencies ³⁹			0-100% of emissions from ports Numerous “green port” projects internationally to increase energy efficiency/reduce emissions. Port side emissions are primarily related to building and infrastructure, electricity usage, vehicle and machinery usage.	High applicability. Measures are consistent with other land based decarbonisation pathways and requires minimal additional specialised training to that already been provided for those sectors.	Available. The measures are consistent with existing transition pathways for infrastructure, building, roading, land transport, machinery and electricity. SPC/MTCC has undertaken recent initial studies and pilots in ports in Solomon Islands, Fiji and Vanuatu. The Solomon project provisionally reports energy savings of 8% (15tonne CO ₂) with strong potential for increased savings over time ⁴⁰ .

Category 3: Technology specific to the capture/treatment of exhaust emissions.

As discussed above, the GHG reduction savings accruable from technologies specific to the capture/treatment of exhaust emissions have been largely shown to have nil to marginal effectiveness for reducing GHG emissions. Measures in this category with high GHG abatement potential require on board capture for future sequestration or methane catalysts, neither measure which is likely to be used in any future Pacific domestic scenario given vessel scale and cost. Consequently, this category is not considered further here.

Category 4: Alternative fuels and energy sources and related machinery.

Abatement Measure		Retrofit	New Build	Savings potential ⁴¹	Applicability to Pacific domestic scenarios and potential savings	Availability to Pacific domestic scenarios
Wind propulsion ¹	Soft sail	yes, dependant on deck and equipment layout	yes	10-90% propulsion efficiency depending on scale ⁴² . Fiji 1980’s trials on 274 and 300GT cargo/pax ferries confirmed average fuel savings of 23-30% ⁴³ with greater savings available if a feathering prop was used. SV Kwai has demonstrated fuel savings up to 30% average with a retrofitted soft sail rig ⁴⁴ .	High for retrofit/new build subject to vessel type ⁴⁶ . Historic use of aux-sail vessels in all Pacific country’s domestic fleets. Successful historic Pacific trials in 1980’s at various scales to 300 tonne, newbuild and retrofit. Sail hybrids are currently deployed at various scales in the tourism and recreational maritime sectors in countries	Available. The historic trials of Fiji ferries of 50 (newbuild), 274 and 300 (retrofit) tonne ferries were using all Fijian manufactured and fitted technologies. The 50 tonne <i>Tai Kabara</i> was outer-island built. Soft sail rigs are available at technology levels from high cost/high tech (as in superyacht type applications) to low cost/low tech (as seen in historic trials <i>with Na Mataisau</i>). It is assumed Pacific domestic application will maintain

¹ Wind theoretically can provide 100% of all propulsion (and did for 100s of years) but this is not practical for modern commercial operations, nor consistent with safety standards. Therefore, wind propulsion will always be a hybrid solution requiring a second propulsion system, usually propeller driven, as either main or auxiliary.

Common to all wind-hybrid options (except kite) are verified significant secondary savings in engine wear and drive trains through to propeller, generally increased stability and passenger comfort, greatly increased safety (due to dual propulsion availability) and choice between additional fuel savings and decreased passage time. Wind has additional potential for supplementing auxiliary and hotel power generation.

Wind availability varies regionally meaning savings for this measure are not uniform, with countries such as equatorial Kiribati having lighter average wind to RMI and Fiji which are considered close to ideal^{8, 46}. As a general rule of thumb, higher savings are available at smaller vessel scale.

The EU projects that there could be 10,700 wind installations internationally on tankers and bulkers alone by 2030⁴¹. Overall CO₂ emissions reductions available by wind have been calculated to be up to 32% of fuel use^{20, 2}. Wind hybrid propulsion is agreed by all reviewed literature as having high potential for Pacific domestic application. ADB (1985) concluded, “approximately 25 per cent of a ship’s fuel may be saved by the application of sail assistance without compromising required operational schedules.”⁴¹ Greatest efficiency is achieved when combined with new-build, advanced hull design and auxiliary power measures.

				<p>Noeline has 2x soft-sail diesel/electric hybrids (5000 dwt freighters) under construction with projected operational efficiency savings up to 80-90%⁴⁵.</p> <p>Numerous designs, proof of concept and models exists for vessels at all scales from artisan fishing upward and there are increasing pilot vessels in operation or under construction internationally.</p>	<p>such as Fiji and there already exists mature secondary industry to support commercial scale manufacture and maintenance.</p> <p>All newbuild and retrofit options being undertaken under the Cerulean and TLCSeaT RMI project for inter-island and intra-atoll work include variations of either soft-sail or rotors.</p>	<p>innovation at the lower tech end of the scale.</p> <p>Fijian yards report capacity to build low/medium tech retrofits and new vessels to 30m/200t. Numerous ex-region options also exist to any technology level.</p> <p>Specialist crew and master training is required.</p> <p>Technology is either locally procurable or importable.</p>
Fixed sail	yes, dependant on deck and equipment layout	yes	<p>8-30% propulsion efficiency depending on scale.</p> <p>1980's trials on a variety of Japanese commercial vessels (including tankers, bulkers and general purpose) confirmed average fuel savings of 10 to 32%.⁴⁷ Walker Wingsails trials in 1986 were giving an average of 8% and up to 25% fuel savings⁴⁸</p> <p>Several international projects, including Tokyo University trials for 180k Capesize with trials showing 30% annual energy savings^{49,50}.</p>	<p>Unknown but potentially low for retrofit/new build subject to vessel type.</p> <p>Fixed wing sails have not previously been used or studied for Pacific domestic deployment.</p> <p>International reviews consider that fixed sails have potential but identify outstanding safety concerns, design limitations (including classification society requirements), economic and business considerations and operational issues.⁵¹</p>	<p>Not currently available.</p> <p>Fixed wing sails have not previously been used or studied for Pacific domestic deployment.</p> <p>Pacific specific research needed before considering further.</p>	
Rotor (e.g. Flettner rotors)	yes, dependant on deck and equipment layout	yes	<p>6-50% propulsion efficiency depending on scale, number of rotors and retrofit/new build.</p> <p>Since 2011, commercial trials have been completed on new build (10,500 dwt RoRo – 25% overall efficiency⁵²), retrofits on 62,000 GT tanker (2x rotors, 8.2% savings⁵³), 4,000 GT coaster (1 x rotor, 10-20%), 67k DWT Bulker (4 x rotor, 10%+⁵⁴), 9,700 DWT Ro-Lo carrier (1 x rotor, 5%), 58k GT Cruise liner (1x 24m rotor, 3.6%⁵⁵).</p> <p>Advanced designs and modelling for numerous vessel types exist with savings projected up to 50% for new builds combining advanced hull and other componentry design⁵⁶.</p>	<p>Medium to High.</p> <p>Savings potential increases with decrease in vessel size.</p> <p>Increasing knowledge of application and rotor designs and preliminary modelling on selected Pacific routes⁵⁷ and Fiji and RMI domestic applications.</p> <p>No cost/benefit or ROI available yet for Pacific application. C/B varies with installation prices ranging \$300-800k per rotor.</p> <p>Maersk 2018 trials show savings equivalent to \$200k p.a.⁵⁸ and Vahs et al. have modelled \$150,000 savings from a 2 rotor system costing \$880,000⁵⁹.</p> <p>High potential for cost reductions as market matures. Some componentry could be built in Fiji.</p>	<p>Available.</p> <p>A small number of international commercial designs available and design shops capable of bespoke designs⁶⁰.</p> <p>Advanced modelling available for retrofit application on current RMI government ships.</p> <p>Technology would need to be imported, Fijian yards report capacity for some component fabrication.</p> <p>Limited specialist training needed.</p>	
Kite (e.g. Beluga Sails; Sky Sails)	yes, dependant on deck and equipment layout	yes	<p>10-15% propulsion efficiency on selected passages.</p> <p>However, annual savings in consumption on most routes is on the order of 5.5%, as determined by the EU-funded Life project WINTECC48.</p>	<p>Very low applicability to Pacific scenarios and would only be practical on a very limited number of domestic routes.</p> <p>Internationally, kite development to date has not been able to overcome safety concerns.</p>	<p>Not available.</p> <p>No commercial models available or known current pilots. K Line announced a 20-year deal in 2019 to commence new trials with France-based Airseas⁶¹.</p> <p>Pacific specific research/verification would be required if international trials demonstrate future viability.</p>	

				<p>A limited number of trials and modelling have been undertaken with mixed reviews as to actual saving achieved.</p> <p>Greatest application is likely in larger vessels on long predicable routes</p>	<p>Propulsive savings largely only realised with wind coming from the beam to the aft (back) of the ship so best on long routes with predictable wind patterns</p> <p>Kites were considered during the Tokelau ferry <i>Mataliki</i> design process and found to be unsuitable on cost, safety and technology level grounds despite good wind availability</p> <p>Specialist training required</p>	
	Suction Wings (e.g. Ventifoil, Turbosail)	yes, dependant deck and equipment layout	yes	<p>10 – 30% propulsion efficiency.</p> <p>Championed by Cousteau’s <i>RV Alycone</i> in the 1980’s, the verification of savings has been questioned.</p>	<p>Low.</p> <p>Lack of profile and data means that there is likely greater interest and uptake of other wind propulsion options</p>	<p>Low availability.</p> <p>It is assumed that any future applications would be via bespoke installations. The technology transfer barrier for Pacific uptake is not high as the engineering is not complicated</p>
Wind Turbines	Auxiliary power supply	yes, dependant on deck and equipment layout	yes	<p>Unknown.</p> <p>Dependant on size, type, manufacturer and operating scenario. Requires battery storage, controllers, etc. Most effective when combined with other energy generators. Considered high cost relative to solar, but generally low maintenance and long life (dependant on quality). Low potential for future cost reductions of turbines but likely medium potential of cost reduction in related componentry (e.g. batteries). Given that many Pacific domestic vessels have high port times, fuel use from auxiliary generation are likely higher than global averages. Actual emissions savings need to consider whole of life cycle of all componentry (e.g. batteries, controllers) to ascertain overall savings and costs</p>	<p>Medium – High.</p> <p>Effectiveness dependent on location and routes</p> <p>Combined with solar provides a hybrid RE auxiliary package.</p> <p>Limited specialist training required.</p>	<p>Available.</p> <p>A wide range of maritime models commercially available and deployed worldwide in recreational vessels. These include both rotating blade and helix configurations.</p> <p>Initial modelling available for RMI ship government retrofits.</p> <p>Unlikely to provide full axillary power needs in any transport demand scenario so needs to be combined with additional generation source(s)</p>
Solar	Auxiliary power supply	yes, dependant on deck and equip layout	yes	<p>Minimal to 32% of total fuel use⁶²</p> <p>Requires battery storage, controllers, etc</p> <p>Given that many Pacific domestic vessels have high port times, fuel use from auxiliary generation likely higher than global averages.</p> <p>Medium potential for future cost reductions and likely medium potential of cost reduction in related componentry (e.g. batteries).</p> <p>Actual emissions savings need to consider whole of life cycle of all</p>	<p>High potential.</p> <p>Unlikely to provide full axillary power needs in any transport demand scenario so needs to be combined with additional generation source(s).</p> <p>Constraints of deck and equipment layouts in existing vessels limit cost effective deployment to suitable vessels for retrofit application. Potential for PV’s incorporated into rig/sails for solar/wind hybrids.</p> <p>Some specialist training required.</p>	<p>Available.</p> <p>Wide range of imported commercially available componentry.</p> <p>Increasing deployment of terrestrial solar applications means increasing local capacity to install and service.</p> <p>Current low cost effective Pacific capacity/access to 2nd generation/tertiary battery technology supply and servicing.</p>

				componentry (to ascertain overall savings and costs.		
Electric /Battery	Main engines with diesel gensets Main engines with RE Shaft generator	highly limited	yes	Up to 100% emission reduction potential. Power supply for zero-carbon electric propulsion can come from energy storage systems such as batteries, flywheels or super capacitors, which, compared to batteries, can store and release large amounts of electricity very quickly. Energy storage systems remain a relatively costly technology. Electric motors are assumed to be cheaper than conventional engines, but the cost of batteries per unit of energy and their accommodation on ships makes it a very expensive option. Throughout different scenarios, the electric vessel has been estimated to be the least profitable technology compared to alternative fuel options such as hydrogen, ammonia and biofuels ⁶³	Low except for targeted application. The key limiting factors are range, high CAPEX, high technology transfer needs and access to low carbon electricity sources. Current Scandinavian trials suggest 95km storage limits between charges for larger ferries and Ro-Ro's ⁶⁴ . Greatest potential is in smaller scale and fast inshore ferry applications with dedicated RE onshore charging facilities or (bio)diesel gensets complemented with onboard RE. Along with fuel cells, battery propulsion is the highest cost alternative to fossil fuel ⁶⁵ . This implies, its use will be specialised and restricted to smaller vessel or high return use.	Low except for targeted application where potential is medium/high. Recommended that research, pilot trials be initiated targeting established high value tourism operators in sheltered water scenarios targeting small fast ferries and e-outboard/inboards. Requires close collaboration with electricity supply planning if grid supply envisaged and Pacific locations specific research for off-grid charging options. Predicted to be a fast improving field and international developments in e-motors, batteries and charging options likely to improve availability for Pacific operators in near future.
Fuel cells		no	yes	0-60% emission reduction potential. Directly converts electrochemical energy by transforming into electric power without combustion. Releases both electrical energy and some thermal energy in the process. Hydrogen most frequently used. Can be produced conventionally from methane steam reforming, fossil fuel or biomass gasification, or water electrolysis. Possible alternative fuels are methanol, LNG, liquid organic hydrogen carriers (LOHC) and ammonia. High-temperature fuel cells could become suitable as sources of on-board energy for larger vessels such as cruise ships and container ships. Existing fuel cell solutions favour smaller vessels of short range where storage of compressed hydrogen is more viable.	Low immediate application but medium future potential for small scale if technology transfer and fuel storage/supply solutions can be devised.	Not available. Future availability will be determined by international advances in technology and fuel supply storage solutions.
Shore power (cold ironing)		yes But requires equipment installation for existing vessels	yes	Not considered. Generation source needs to be more carbon neutral than ship auxiliaries to have emissions benefit. Onshore power supply (OPS) facilities OPS in ports cost USD 5-10 million per installation, mainly related	Applicable in highly limited scenarios. No detailed current research is available on Pacific scenarios. Surplus shore power generation capacity and the shore power needs to be renewably sourced or generated and transmitted at higher efficiency than	Not currently available. For limited application at small vessel and high value (e.g. tourism) scale, dedicated RE shore side recharging facilities or limited grid supply arrangement with electrify power supply companies can be envisaged. This scale warrants immediate research priority.

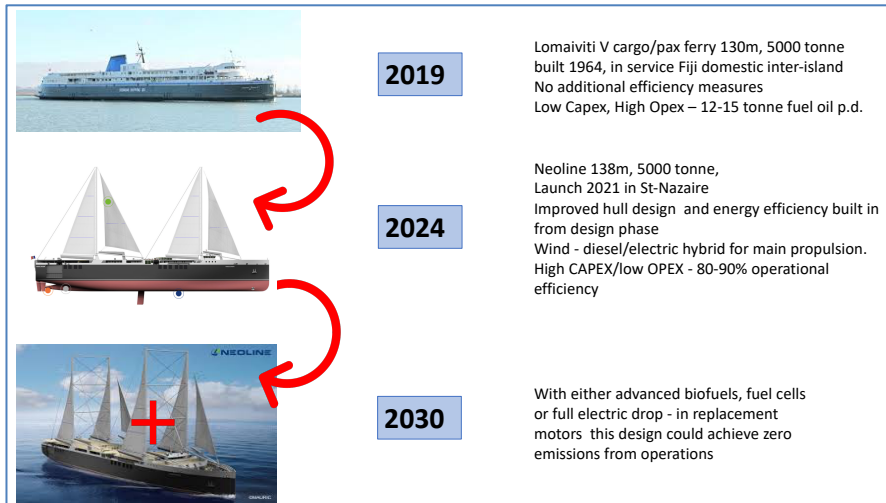
				to extending grid into port ⁶⁶ The total share of a ship's energy demand that can be met through shore power is small ⁶⁷ .	onboard systems. This situation does not exist in Pacific domestic scenarios currently and other electricity users would most likely be afforded higher priority to shore power in the foreseeable future .	Larger scale application will require greatly increased RE energy generation capacity in all Pacific countries
LNG/CNG		no	yes	Not considered. A previous regional study determined that LNG is not viable or appropriate for Pacific domestic deployment given lack of bunkering and high transition and transaction costs ⁶⁸ .	Not applicable. There are competing expert opinion on the use of LNG as an alternative propulsion fuel internationally with some considering it a viable transition fuel and others considering it a 'red herring' and neither appropriate or cost effective for a decarbonation transition pathway fuel.	Not available. A previous regional study determined that LNG is not viable or appropriate for Pacific domestic deployment ⁶⁹ given lack of current bunkering infrastructure, high cost to introduce such infrastructure at scale and high transition and transaction costs.
Biofuels- 1st generation (crop based) Biofuels 2nd generation (waste based) Biofuels 3rd generation (specially engineered crops such as algae)	Achieving deep decarbonisation will require new fuels to be adopted; either bio, electro or synthetic See also notes in next section	yes	yes	25-100% overall emissions reduction available ⁷⁰ . Increasing number of international trials of both crop and waste fuel at large ship scale. Technically feasible to produce marine-grade biofuels compatible with the existing marine engines, pipelines and bunker infrastructure, so adaptation costs are limited. Can be blended with distillates – with an increasing emission penalty relative to % blend. Unresolved issues remain over competition for fuel with other sectors and competition over land use prioritisation for crop sourced. Analysis undertaken for current RMI TLCSeaT project concluded no cost effective biofuel source is available ⁷¹ . Cost effectiveness is projected to improve as carbon taxes or similar MBM are introduced and fossil fuel subsidies reduced.	Not applicable until potential feedstock can be economically sourced. Requires high grade fuel to avoid storage issues. A full decarbonisation pathway will require the Pacific ultimately adopting alternative fuel(s). A key advantage for Biofuels is lower investment needs to modify existing bunkering facilities comparative to some other options. Numerous Pacific trials and blended fuel standards, regulation, testing facilities established in some countries. No successful cost-effective large-scale production solution has been established. No detailed directed research of application to Pacific maritime domestic use yet undertaken. Applicability will be more favourable in high, wet island scenarios. Atolls will require either marine-sourced or imported fuel stocks or imported refined product .	Available but requires trials and research to establish scaled cost effective production. As the primary issue is securing adequate fuel supplies common to other potential end users, maritime specific research should be integrated into wider Pacific fuel replacement research for other sectors.

5. Potential technology transfer pathways

A transition towards low-/zero-carbon shipping requires a whole of sector approach including all elements of the maritime logistic chain, including various scales and types of vessels, portside connectivity and secondary industry. Transition pathways need to be researched and mapped for each.

Some initial potential technology transfer pathways for six representative vessel types are given below for illustrative purposes ⁷²: Collectively, and when combined with available operational efficiencies, they indicate that sufficient energy and emissions savings are available to the PBSM today to achieve the 40% by 2030 reduction committed to by Fiji and RMI governments across a range of vessel types in common usage.

Example 1: Large Ro-ro/ passenger ferries



The largest vessels in the Fijian domestic fleet are private sector owned/operated, aged, second-hand, inter-island ferries of up to 5,000 tonnes, serving the economic routes between the primary ports on the main islands. They can be expected to use about 10-15 tonne of diesel per day with fuel and related costs contributing a large, sometimes majority, share of operating expenditure (OpEx). Bought at low or scrap value on retirement from Canada, NZ and Australia, they illustrate the maritime financing and insurance dilemma facing the Pacific domestic sector and the resultant low capital expenditure (CapEx), high OpEx approach to asset management. Such

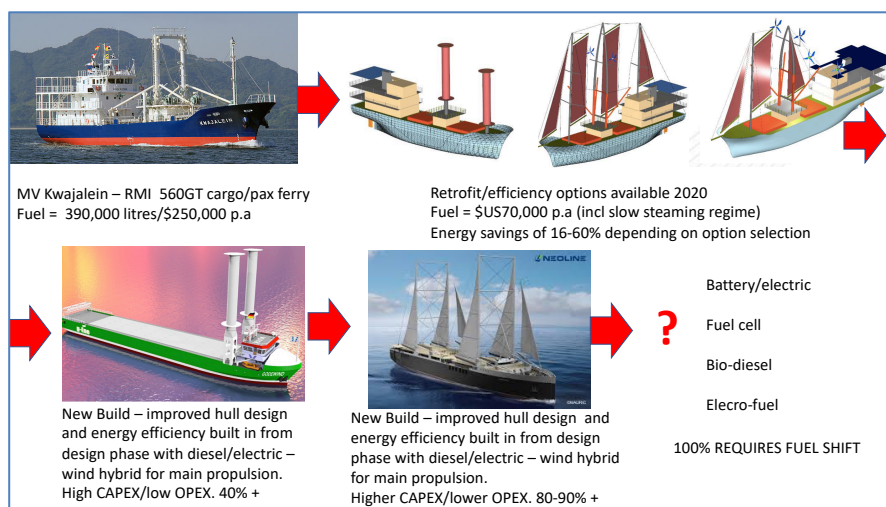
vessels face ever-increasing maintenance and survey costs due to their age and offer minimum opportunity for achieving increased efficiency at economic cost given their age and configuration.

The Neoline 138m craft, with its first two vessels under construction and scheduled for operation in 2021 between France and North America, offers a projected 80-90% operational efficiency improvement, high CapEx - low OpEx, replacement option. The advanced hull design and profile can be reconfigured into ro-ro, ro-lo, general freight or container (240 TEU) modes. The vessels is designed from the outset for maximum energy efficiency in all aspects of design and was selected from 15 portfolios submitted by leading European innovators⁷³. It is offered here as one example. If there were no financing barriers, such innovation is potentially be in Pacific scenarios by 2024 is Alternative designs from other sources are at advanced stage of approval.

In time, the current diesel/electric hybrid may be able to be replaced with either biofuels or full electric, fuel cell or electro-fuel motors for up to 100% carbon neutral energy conversation as these technology options come to market at economic rates. These will be required from 2030 if PBSP targets are to be met.

Example 2: Medium inter-island cargo/pax ferry

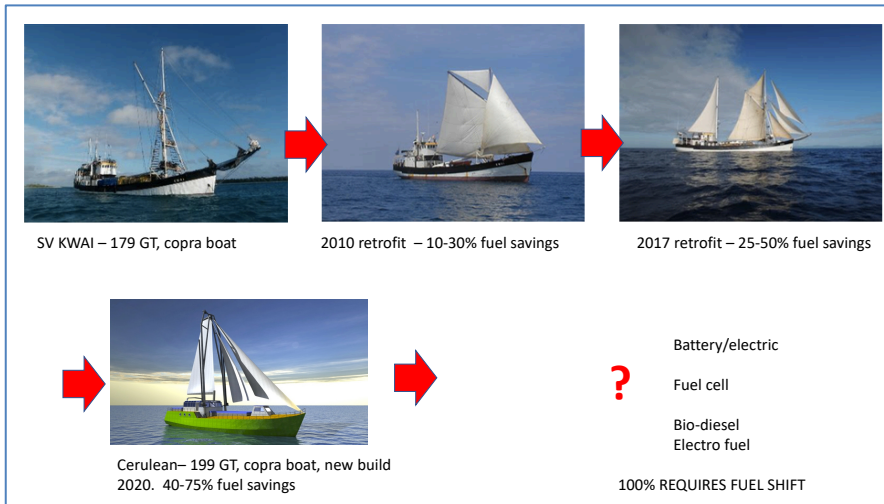
The MV Kwajalein is an exemplar of Pacific vessels in government-owned or operated fleets, providing essential, and often primary, connectivity between urban centres and outer-islands. Current work under the TLCSeaT project in RMI⁷⁴ has identified a design portfolio of retrofittable efficiency options which, in various combinations, can achieve efficiency gains of between 11- 60 % and accrue up to \$140,000 in fuel savings. Maximum savings are achieved though combining high capacity wind/diesel hybrid propulsion and diesel generators supplemented by wind and solar for auxiliary power.



Achieving greater efficiency requires a newbuild approach, which allows efficiency to be built into all aspects of design from the outset. Two different approaches are shown in the vignette above with a lower CapEx, more functional approach with a Flettner rotor hybrid powered cargo hull offering greater than 40% energy saving potential or a higher CapEx, full efficiency sailing hull approach as in the Neoline, projected to achieve greater than 80% savings. There are different trade-offs evident in each option and the designated transport work of the vessel will determine the most effective and economic operational choice.

A transition to full zero-carbon operations would require either option to be upgraded to enable operation on zero-carbon alternative fuels. As discussed above, internationally the leading choices are methanol, ammonia, hydrogen and advanced bio-fuels. None are currently available at scale or affordable cost and all pose significant issues for Pacific deployment. Pending better analysis, on available data advanced bio-fuels appears to offer the most promise but all options will require detailed Pacific specific research and advanced field trialling.

Example 3: Small inter-island cargo freighter



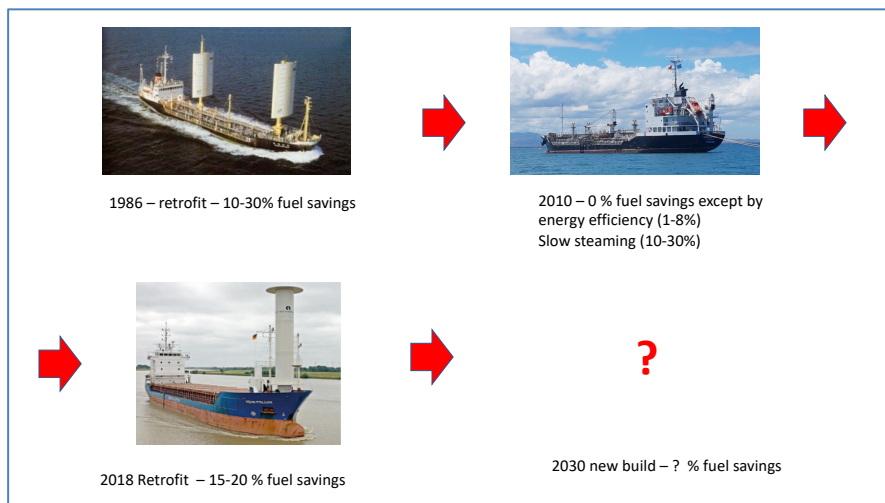
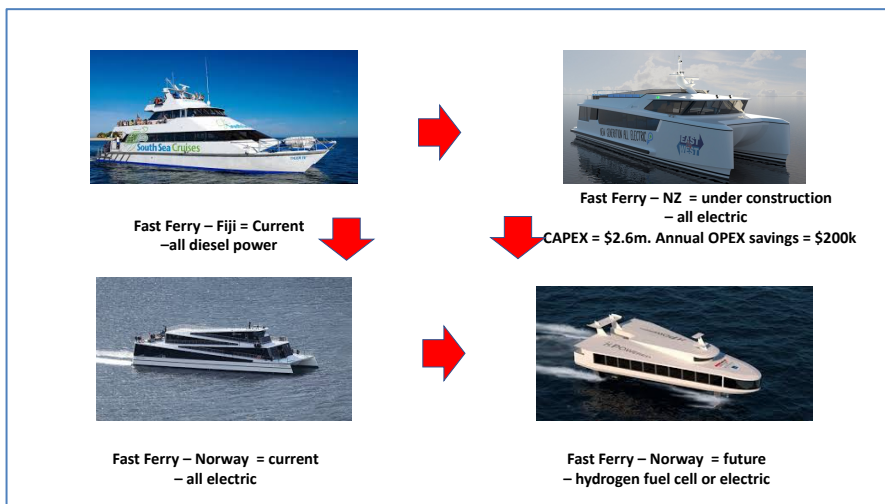
Historic trials in Fiji in 1984-86 saw wind-hybrid retrofits to small general purpose cargo/pax ferries achieve between 23-30% in fuel savings. Between 2006-2019, Island Venture Traders have operated the *SV Kwai*, a 179GT cargo freighter between Hawaii, Kiribati and Cook Islands, serving one of the longest and thinnest shipping routes in the world. The vessels has been progressively retrofitted to a full sail/diesel hybrid rig, with the fuel savings sufficient to make an otherwise uneconomic route profitable. Return cargoes of seaweed and copra maintain the backbone of these communities' economies.

The current Swire Shipping funded Cerulean Project seeks to introduce a new build, lost cost/low tech version of this proven model to demonstrate improved efficiencies, potentially up to 70%. If field proven, this low OpEx/low CapEx model is replicable and scalable in multiple SIDS scale locations. While wind/diesel hybrid propulsion, advanced hull design, low carbon auxiliary power and other measures will achieve a majority of emissions reduction, zero-carbon operation efficiency will require a transition to alternative fuels than those currently at market.

Example 4: Small coastal/inshore fast ferry

Fast ferries are common in high tourism or outer island/coastal resort use in many countries. Fast paced innovation is now demonstrating that this application is available with lower carbon/fuel profiles through all electric models such as the New Zealand and Norwegians examples shown in this vignette. Range is limited by the battery storage for fully electric versions and the carbon footprint of the electricity source used for charging (including full life-cycle accounting) is needed to calculate the total savings accrued. Unless the charging is entirely from renewable or zero carbon energy sources, zero- carbon efficiency for this vessel type will require a further transition to alternative fuels or more advanced fuel cell technology than those currently at market.

Fast ferries are common in high tourism or outer island/coastal resort use in many countries. Fast paced innovation is now demonstrating that this application is available with lower carbon/fuel profiles through all electric models such as the New Zealand and Norwegians examples shown in this vignette. Range is limited by the battery storage for fully electric versions and the carbon footprint of the electricity source used for charging (including full life-cycle accounting) is needed to calculate the total savings accrued. Unless the charging is entirely from renewable or zero carbon energy sources, zero- carbon efficiency for this vessel type will require a further transition to alternative fuels or more advanced fuel cell technology than those currently at market.

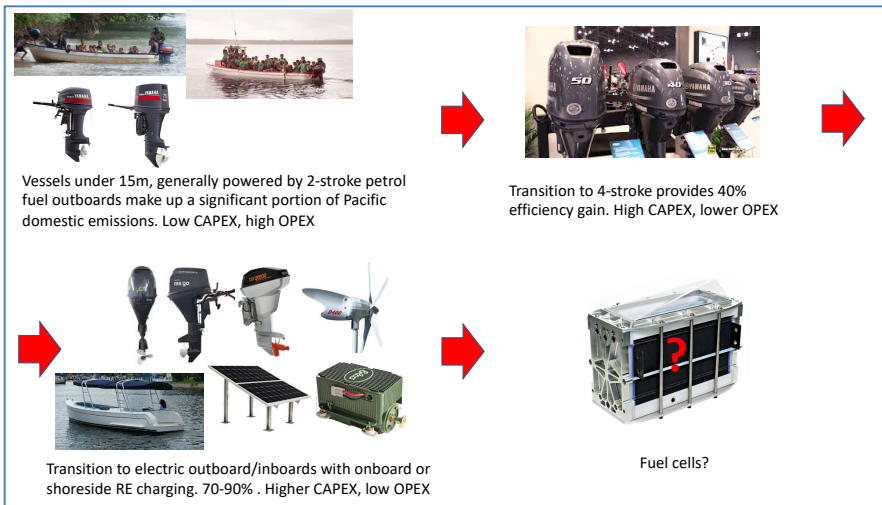


Example 5: Coastal tanker/bulker

Japanese trials in the 1980s oil crisis demonstrated the energy savings accruable to small coastal tankers and bulkers through use of power/wind hybrids, along with associated benefits in increased stability, decreased engine wear and increased overall passage speed. The deck layout of such ships is generally more conducive to mounting wind assist technologies than other vessels. The 2018 4,000 tonne *Fehn Pollux* Flettner rotor retrofit shows that savings of 15-20% are available today to vessels of this type.

Example 6: Vessels under 15m

Vessels under 15m, overwhelmingly powered by petrol 2-stroke outboard motors, make up a significant proportion of all Pacific SIDS maritime emissions⁷⁵. 4-stroke engines are more expensive to purchase, require more regular servicing but are generally more durable, more fuel/emissions efficient and have a much lower oil consumption and hence lower overall OpEx⁷⁶. A transition pathway that included duty and tax instruments with increased capacity in 4-stroke technology maintenance and public education/outreach (particularly at village operator scale) is available, followed with extension to sustainably generated electric power options. The latter will be driven initially via the maritime tourism sector in established locations. Deeper savings may become available in time with fuel cell technology. Further efficiencies for vessels of this scale are also available through improved hull design and wind-hybrid technologies, with multiple options for both measures.



6. Summary

This paper provides an overview of the various options for abatement measures either already available or being developed for international shipping decarbonisation considered through a “Pacific lens” for applicability and availability. Several of the options being used or developed internationally will likely have little short term applicability to the Pacific domestic fleet, such as electric propulsion, shaft generators, cold ironing, except in very specific applications. Others, such as renewable energy use of propulsion (wind) and auxiliary powered supplementation (wind, solar) are already being used in the Pacific and can be replicated, advanced and scaled up. Retrofits of various measures will achieve savings but real reduction will come from fleet replacement with new build vessels.

Six vignettes illustrate potential transition pathways for representative exemplars of common vessels servicing Pacific domestic shipping today, in each case initiating the transition with known mature technologies and designs. These and the applicable measures identified above strongly suggest that emissions reductions of 40% by 2030 are likely available to the PBSP if appropriate financing is made available. Full decarbonation by 2050 will still require additional measures and technological development, including replacement fuels to the diesel and petrol derivatives used almost exclusively today. All available options for alternative fuels, including sustainably produced advanced biofuels, synthetic and electro-fuels pose significant cost and technology transfer barriers for Pacific domestic uptake.

At an international level, there has been noticeable increase in R&D into alternative fuels, new designs, refinement of existing technologies and operational practices as regional and global policies and strategies drive emissions reduction from the shipping sector. The Pacific needs to be aware of the innovations happening globally, and to continue to look at such developments in order to assess whether there is any merit in each for the scale of ships prevalent in the region given the specific operating environments. However, it is assumed that a bespoke Pacific domestic solution is required.

This is a working paper based on best available information available at time of preparation. Additional information and comment is welcomed. This Paper will be reviewed periodically and updated to provide the Pacific Blue Shipping Partnership and other interested stakeholders with a reference to assist in the further development of the Pacific Blue Shipping Partnership initiative.

¹ Smith, T. et al (2019) *Reducing the Maritime Sector's contribution to Climate Change and Air Pollution Scenario Analysis: Take-up of Emissions Reduction Options and their Impacts on Emissions and Costs*. A Report for the Department for Transport, London.

https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/816018/scenario-analysis-take-up-of-emissions-reduction-options-impacts-on-emissions-costs.pdf

² Asian Development Bank (1985) *Proceedings of regional conference on sail-motor propulsion*. ADB, 1985:18–21 November, Manila; Nuttall, P. et al (2013) A review of sustainable sea-transport for Oceania: Providing context for renewable energy shipping for the Pacific. *Mar. Policy*

<http://dx.doi.org/10.1016/j.marpol.2013.06.009>; Newell, A. et al (2016) Turning the Tide: the need for sustainable sea transport in the Pacific, *Mar. Policy* (2016), <http://dx.doi.org/10.1016/j.marpol.2016.01.009>.

³ E.g. Satchwell, C.J. (1985) *Windship technology* in Proceedings of the international symposium on windship technology (Windtech '85). Southampton, U.K.; Clayton, BR. (1987) Wind Assisted Ship Propulsion. *Physics in Technology* 18:53-60. The project portfolio is summarized in Newell, A. et al (2016) *ibid*.

⁴ Sustainable Sea Transport Talanoa (2012) Programme and presentations. <https://www.usp.ac.fj/index.php?id=12461>

⁵ 2nd Sustainable Sea Transport Talanoa (2014) Programme and presentations. <https://www.usp.ac.fj/index.php?id=16753>

⁶ See for example Nuttall, P. (2012) Steering a course for the future with sticks, stones, grass and a little sharkskin *J.Pac.Stud.*32 (2012) 163–175; Prasad, B. et al (2013) Sustainable Sea Transport Research Programme: Toward a Research-based Programme of Investigation for Oceania. *Journal of Pacific Studies* (33), 78–95; Nuttall, P. et al (2014) A review of sustainable sea-transport for Oceania: Providing context for renewable energy shipping for the Pacific. *Journal of Marine Policy* Vol. 43 (Jan 2014), 283-287; Holland, E. et al (2014) Connecting the Dots: Policy Connections between Pacific Island Shipping and Global Carbon Dioxide

- and Pollutant Emission Reduction, *Carbon Management* 5(1) 99-105.; Nuttall, P. et al (2013) *ibid*; Nuttall, P. and Kaitu'u, J. (2016); Newell, A. et al (2016); Goundar, A. et al (2017) etc.
- ⁷ <https://unctadsftportal.org/sftftoolkit/transitioningtolowcarbonshippingmodule/>
- ⁸ Vahs, M. et al (2019) *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*, Hochschule Emden-Leer. https://mcst-rmiusp.org/images/Projects/TLCSeaT_HEL_TechnicalAndOperationalOptionsCatalog.pdf
- ⁹ <https://mcst-rmiusp.org/index.php/projects/current-projects/cerulean-project>
- ¹⁰ SPC (2019) <https://www.spc.int/updates/news/2019/10/reducing-greenhouse-gas-emissions-in-maritime-sector-saving-thousands-for-boat>
- ¹¹ See for example Asian Development Bank (2007) *Oceanic Voyagers: shipping in the Pacific*. ADB, Manila; Moon, JR. (2013) Strengthening Inter-island Shipping in Pacific Island Countries and Territories. Background paper, ESCAP. <http://www.unescap.org/sites/default/files/Background-Paper.pdf>
- ¹² Satchwell CJ. (1986) *Preliminary analysis of log data from the Fiji windship 'Cagidonu'*, Ship Science Reports, University of Southampton, Southampton.
- ¹³ See for example Dr Tristan Smith being interviewed at 2.46min on https://www.youtube.com/watch?v=EZoE_BKizxl; also Merf, et al, (2018). <https://www.itf-oecd.org/sites/default/files/docs/decarbonising-maritime-transport.pdf>
- ¹⁴ Smith, T. et al (2019) *ibid*
- ¹⁵ For more detailed description of each individual category see Smith, T. et al (2019) *ibid*
- ¹⁶ See for example <https://glomeep.imo.org/resources/fleet-and-co2-calculator/>, https://glomeep.imo.org/wp-content/uploads/2019/03/ship_emissions_toolkit-g1-online_New.pdf
- ¹⁷ See TWG Technical Paper 1 and 2 for descriptions of Pacific domestic shipping. Also Moon, JR. (2013) *ibid*; Newell, A. et al (2016) *ibid*.
- ¹⁸ For Fiji and RMI this is 40% reduction by 2030 and 100% decarbonisation by 2050.
- ¹⁹ Assuming a new build will always be higher efficiency and more cost effective over a whole of lifecycle analysis than retrofit of existing vessels.
- ²⁰ Merk et al, (2018) *Decarbonising Maritime Transport: Pathways to zero-carbon shipping by 2035*, ITF/OECD, Paris. <https://www.itf-oecd.org/decarbonising-maritime-transport>.
- ²¹ <https://www.schneekluth.com/en/>
- ²² <https://gcaptain.com/propeller-technology-ship-efficient/>
- ²³ Merk et al (2018) *ibid*. Summarises leading studies to 2017, finding light materials capable of 1-10%; slender hull design 10-15%, bulbous bows 2-7%. (Note: emission reduction potentials are assessed individually. Ranges roughly indicate possible fuel savings depending on varying conditions such as vessel size, segment, operational profile, route, etc., hence limiting the possibilities for comparison. Numbers cannot be cumulated without considering potential interactions between the measures).
- ²⁴ Faber, J. et al (2016) *Historical Trends in Ship Design Efficiency: The Impact of Hull Form on Efficiency*, CE Delft, Delft. https://www.transportenvironment.org/sites/te/files/publications/2016_CE_Delft_Historical_Trends_in_Ship_Design_Efficiency.pdf
- ²⁵ SSPA (2018) <https://www.sspa.se/ship-design-and-hydrodynamics/hull-air-lubrication-future-and-challenges>
- ²⁶ This figure is for a new build LNG carrier with capacity of 173,400 m³ <https://www.rivieramm.com/news-content-hub/first-air-lubricated-lng-carrier-joins-maran-gas-fleet-56931>
- ²⁷ Smith, T. et al (2016) *CO₂ emissions from international shipping: Possible reduction targets and their associated pathways*, prepared by UMAS, London, October 2016.
- ²⁸ Tillig et al. (2015) *Systems modelling for energy-efficient shipping*, Department of Shipping and Marine Technology, Chalmers University of Technology, Göteborg, Sweden.
- ²⁹ Winkel, R. et al (2015) *Study on energy efficiency technologies for ships - CLIMA.B3/ETU/2014/0023r*, ECOFYS Netherlands B.V., Utrecht http://publications.europa.eu/resource/ce/302ae48e-f984-45c3-a1c0-7c82efb92661.0001.01/DOC_1
- ³⁰ Tillig et al (2015) a range between 5 and 10%; Gilbert et al (2014) potential of 0-12% depending on the ship type; Smith, T. et al (2016) maximum 4% of main engine fuel consumption. Reported in Merk et al (2018) <https://www.itf-oecd.org/sites/default/files/docs/decarbonising-maritime-transport.pdf>
- ³¹ Winkel, R. et al *ibid* http://publications.europa.eu/resource/ce/302ae48e-f984-45c3-a1c0-7c82efb92661.0001.01/DOC_1
- ³² Assuming a new build will always be higher efficiency and more cost effective over a whole of lifecycle analysis than retrofit of existing vessels.
- ³³ Faber, J. et al. (2012).
- ³⁴ Lindstad et al. (2012).
- ³⁵ <https://www.hapag-lloyd.com/en/news-insights/insights/2017/03/how-vessel-trim-optimisation-creates-efficiencies.html>
- ³⁶ Satchwell, CJ. (1985) *Applications of Windship Technology in the Design and Operation of Wind-Propelled Ships*, Asian Development Bank, Manila
- ³⁷ If all ship waiting time reduce to zero. Data on this is scarce and fragmented.
- ³⁸ ITF (2014) calculate that 5% of all shipping's CO₂ emissions are currently generated in ports. According to TNO and Port of Rotterdam's 2018 study, this is around 4% (<https://www.portofrotterdam.com/en/news-and-press-releases/just-in-time-sailing-saves-hundreds-of-thousands-of-tonnes-of-co2>)
- ³⁹ Port side emissions and energy use is not part of a national carbon accounting for maritime transport and under IPCC guidelines falls primarily under infrastructure (buildings and roading), land transport, machinery and electricity use sectors.
- ⁴⁰ <https://www.spc.int/updates/news/2018/09/green-pacific-port-initiative-looks-to-improve-port-operations-across-the>
- ⁴¹ Assuming a new build will always be higher efficiency and more cost effective over a whole of lifecycle analysis than retrofit of existing vessels. <https://www.maritime-executive.com/article/flettner-rotor-exceeds-expectations>
- ⁴² Merk et al (2018) quotes the abatement potential of wind technologies estimated to be around 10–60% (Rehmatulla, N. et al 2015) and 1–50% of reduction in CO₂ according to a meta-study of existing estimates (Bouman, et al 2017). The Neoline projection postdates those studies. <https://www.neoline.eu/en/neoline-selects-neopolias-offer-for-the-construction-of-its-first-two-136m-sailing-cargo-ships-in-saint-nazaire/>
- ⁴³ Satchwell, CJ. (1985,1986). Savings resulted from a retrofitted soft sail rig; engine tuning and retrimming ballast, with sail providing the majority of savings.
- ⁴⁴ Held, R, (2017), <http://svkwai.com/typical-fuel-analysis-kwai-voyage/>
- ⁴⁵ <https://www.neoline.eu/en/the-neoline-solution/> Neoline claim their "transport solution will reduce GHG emissions by up to 90% on an ocean crossing, and eliminate SO_x and NO_x emissions". Additional information on how this figure is calculated is not currently publicly available.
- ⁴⁶ There is an increasing body of peer-reviewed science and expert opinion to support the use of wind hybrids in Pacific domestic scenarios; see for example, Couper, AD. (2008); Blinkhorne, P. (2015); Newell, A. et al (2016); Nuttall, P. (2012, 2013), Nuttall et al (2017); Searcy, T. (2017); Vahs, M. et al (2019); Mofor, L. et al (2015) https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2015/IRENA_Tech_Brief_RE_for-Shipping_2015.pdf and presentations in particular by Gilpin, D., Smith, T., Traut, M., Vahs, M. etc. at SSTT 2014 <https://www.usp.ac.fj/index.php?id=16753>.
- ⁴⁷ Mofor, L. et al (2015) *Renewable Energy Options for Shipping: Technology Brief*, IRENA, Bonn, 2015. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2015/IRENA_Tech_Brief_RE_for-Shipping_2015.pdf
- ⁴⁸ Li (2017) A New Type of Collapsible Wing Sail and its Aerodynamic Performance, *36th International Conference on Ocean, Offshore and Arctic Engineering*, Trondheim DOI: [10.1115/OMAE2017-61084](https://doi.org/10.1115/OMAE2017-61084)

- https://www.researchgate.net/publication/318361455_A_New_Type_of_Collapsible_Wing_Sail_and_its_Aerodynamic_Performance; and Aitkinson, G. et al (2018) *Considerations regarding the use of rigid sails on modern powered ships*, Cogent Engineering, 5:1, DOI: [10.1080/23311916.2018.1543564](https://doi.org/10.1080/23311916.2018.1543564)
- <https://www.tandfonline.com/doi/full/10.1080/23311916.2018.1543564>
- http://www.otpe.k.u-tokyo.ac.jp/en/project_details.html?key=1351657954
- ⁴⁹ Aitkinson, G. et al (2018) *ibid*. See also discussion on fixed wing examples in Mofor, L. et al (2015) https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2015/IRENA_Tech_Brief_RE_for-Shipping_2015.pdf
- ⁵⁰ Aitkinson, G. et al (2018) <https://www.tandfonline.com/doi/full/10.1080/23311916.2018.1543564>
- ⁵¹ <http://www.enercon.de/en-en/2224.htm> the newbuild vessel E-Ship-1 combined advanced hull and rudder design, waste heat recovery and rotors to achieve an overall 25% fuel reduction. 15% of this is directly attributable to the rotors.
- ⁵² <https://www.motorship.com/news101/engines-and-propulsion/maersk-tanker-rotor-sails-trial-a-success>
- ⁵³ <https://www.cruiseshipportal.com/news/cruise-news-maritime-news/rotor-sails-greek-dry-bulk-operator-reports-success-with-flettner-rotor-sails-onboard-mv-afros/>
- ⁵⁴ <https://www.norsepower.com/cruise-ferry>
- ⁵⁵ Traut, M. et al (2014) modelled a 5500 DWT cargo ship with 3 x 27m rotors could save up to 50% of main engine power under typical slow steaming conditions. <https://www.sciencedirect.com/science/article/pii/S0306261913005928?via%3Dihub>. Vahs et al (2018) are more conservative with modelling for their new Eco-Flettners at 17-25% depending on size <http://www.eco-flettner-rotor.com>
- ⁵⁶ Traut, M. (2014) <https://www.usp.ac.fj/index.php?id=16753>
- ⁵⁷ <https://www.motorship.com/news101/engines-and-propulsion/maersk-tanker-rotor-sails-trial-a-success>
- ⁵⁸ Vahs, M. and Oltmanns (2017) http://marigreen.eu/wordpress_marigreen/wp-content/uploads/2017/01/Eco-Flettner_description-short_2017.pdf
- ⁵⁹ See for example <https://www.norsepower.com>, <https://www.dnvgl.com/expert-story/maritime-impact/ECO-FLETTNER-rotor-sail-stands-the-test.html>, <https://www.anemoimarine.com/flettner-rotors/>
- ⁶⁰ <https://worldmaritimeneeds.com/archives/278046/k-line-to-cut-ship-emissions-with-automated-power-kites/>
- ⁶¹ The potential CO₂ reduction reported in different international studies range from 0.2–12% according to Bouman et al (2017) meta study. SPC (2019) reports 32% savings of all operational cost is available from retrofitting on a 183 GT Vanuatu landing craft and 10% for a 1000 GT Samoan passenger ferry. <https://www.spc.int/updates/news/2019/10/reducing-greenhouse-gas-emissions-in-maritime-sector-saving-thousands-for-boat>. These figures have yet to be verified but from available data it seems to indicate the landing craft had an annual fuel use of 150 tonne or which 50 tonne is saved through PV's.
- ⁶² Lloyd's Register/UMAS (2018) in www.itf-oecd.org/decarbonising-maritime-transport.
- ⁶³ IRENA (2019) https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Renewable_Shipping_Sep_2019.pdf
- ⁶⁴ Smith, T. et al (2019) https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/816018/scenario-analysis-take-up-of-emissions-reduction-options-impacts-on-emissions-costs.pdf
- ⁶⁵ Merk et al (2018) www.itf-oecd.org/decarbonising-maritime-transport.
- ⁶⁶ Smith, T. et al (2019) *ibid*; ITF (2014) calculated that approximately 5% of all shipping's CO₂ emissions are currently generated in ports.
- ⁶⁷ Morgan & Atkinson (2016) *LPG and Natural Gas as Alternative Energy Sources for the Pacific*, PRIF, Sydney. http://prdrse4all.spc.int/sites/default/files/lpg_and_lng_report.pdf
- ⁶⁸ Morgan & Atkinson (2016) *ibid*.
- ⁶⁹ Merk et al (2018) *ibid*.
- ⁷⁰ Vahs, M. et al (2019) <https://mcst-rmiusp.org/index.php/projects/current-projects/transitioning-to-low-carbon-sea-transport-tlcseat>
- ⁷¹ No full cost/benefit analysis are available for these examples. Full economic options analysis is a critical next step work priority.
- ⁷² <https://www.neoline.eu/en/>
- ⁷³ <https://mcst-rmiusp.org/index.php/projects/current-projects/transitioning-to-low-carbon-sea-transport-tlcseat>
- ⁷⁴ In 2013, Tuvalu estimated this might be as high as 32% of all maritime emissions. The Fiji Low Emission Development Strategy (2018) estimates that vessels under 15m contribute 12% of total national maritime emissions. https://unfccc.int/sites/default/files/resource/Fiji_Low%20Emission%20Development%20Strategy%202018%20-%202050.pdf
- ⁷⁵ Actual savings vary according to make, size, and operation of individual motors but is generally held that 4-strokes are overall 40% more efficient than 2-strokes.