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# Pacific island domestic shipping emissions abatement measures and technology transition pathways for selected ship types

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ABSTRACT

This paper reports on initial assessments of applicability and availability of potential abatement measures for Pacific domestic shipping scenarios that are being considered for emissions abatement for common Pacific Island vessel types. The studies have been undertaken to inform the Pacific Blue Shipping Partnership (PSBP), an initiative led by Fiji and Republic of Marshall Islands (RMI) to catalyse a multi-country transition to sustainable, resilient, and low-carbon shipping, drawing down to zero-carbon domestic shipping in participating Pacific Island Countries (PICs) by 2050, with a 40% reduction achieved by 2030. The PBSP, in turn, is a product of an action research discourse and theory of change project underway since 2012, and involving academies from the region and international counterparts. The studies add evidence to the assumptions that decarbonisation pathways for Pacific domestic shipping are sufficiently unique to require a bespoke and tailored solution for PICs; and the required transition is best led by a country-driven coordinated programme of work with a significant blended finance investment. A sufficient range of options exists with known measures to assume the initial target set by Fiji and RMI of 40% overall emissions reduction by 2030 is technically attainable and exceed-able, dependent on financial and capacity availability (which is not considered further in this paper). If demonstrable at Pacific domestic scenario scale, lessons learnt will have direct relevance to a number of other island, archipelagic, and coastal locales globally. Findings are preliminary only, reflecting the immature state of knowledge in this field and for this target, and are expected to be updated periodically as the science evolves.

## 1. Abatement measures potential for Pacific domestic shipping

Pacific Islands Countries (PICs) have made several national, regional and international commitments to decarbonise their shipping sector. In particular, the Republic of the Marshall Islands (RMI) has included hard targets for domestic shipping emissions reduction of 40% by 2030 and 100% by 2050 in their updated NDC submitted December 2020 [1]. This raises the important questions of what technology options are available to reduce emissions and their deployment prospects in PICs in the short and longer term.

There is no dedicated study currently available to inform identification or prioritisation of potential candidate abatement measure applicability for reducing fossil fuel burn and related emission from Pacific domestic shipping. This study seeks to: identify the range of technology options available for reducing emissions of GHGs from ships operating in PICs; and present a preliminary assessment of their deployment prospects in PICs in the short and long term, in light of commercial availability and prevailing capacity constraints (broadly defined). It assumes that bespoke and geographically specific solutions will be required, more than a simple downscale and uptake of international or large state measures.

Lack of preceding or island-scale specific contextual analysis means we cannot be more specific at this time as to how we rate or assess deployment prospects of each option. The paper is therefore offered as a preliminary starting point for future informed debate. Without being able to better define selection criteria, we have relied on structured informed expert opinion supported by the existing published relevant literature.

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## 2. Pacific Islands shipping context

The International Maritime Organization (IMO) considers that the Pacific Islands region is composed of 16 States, 14 of which are IMO Member States, and 11 Territories. 14 PICs are Small Island Developing States (SIDS) and four are Least Developed Countries (LDCs) [2]. The Pacific Ocean is the world's largest and less than 2% is land. Collectively these States control large exclusive economic zones (EEZs) with associated fishery and other marine resources. The IMO reports that.

> *[a]chieving economies of scale in the provision of transport services to Pacific Island Countries and Territories (PICTs) is complicated by their small size, their geographical dispersion and the nature of their terrain, … inter-island shipping services play a crucial role in providing the fundamental means of transportation. Most international trade and commerce are conducted by sea and most goods reach regional and national markets by sea transport. …Maritime transport also plays a critical role in sustainable development and poverty alleviation in the region* [2].

This paper considers specifically abatement measures for domestic shipping which we define as ships operating internally servicing a country's domestic routes, as opposed to international shipping services working between countries in the region and transporting goods into and out of the region. The international transport service is generally described as "adequate" in the literature, whereas the domestic situation is agreed to present the greatest challenge [3–6]. In terms of international routes, the region is serviced by a number of competitive liner services, all owned and operated externally to the region, e.g. Swire and Matson. Ships providing these services are generally less than 10 years old and well-maintained vessels. The cost of international shipping is disproportionately high. PICs are thought to have amongst the highest shipping costs per capita per transport mile in the world (the real cost of a TEU shipped to Fiji from Singapore can increase by 830% when transshipped to Kiribati [7]).

In contrast to the international routes where the cost of transport is high but the shipping is relatively energy efficient, the domestic scenario is characterised by often micro communities positioned at the end of long maritime routes with imbalanced inward/outward loadings. This is further complicated by financing barriers, high operational risk, and high infrastructural costs, often resulting in a vicious cycle of poor commercial returns resulting in old vessels being replaced by additional old or benevolently donated vessels. This operational context poses marked inefficiencies at the domestic (local and national) levels [6]. These unique characteristics present a greater challenge than for most other countries and regions, and have been well documented [4,5, 8–10].

Pacific domestic scenarios display strong diversity, ranging from single island countries, such as Nauru or Niue, through high island archipelagos with blue water outer island routes of several hundred nautical miles, for example Solomon, Vanuatu and Fiji islands, to atoll nations with communities scattered over thousands of miles of ocean such as Kiribati and composite nations with high islands and atolls, such as the Cook Islands. National populations range from a few hundred people (Niue, Tokelau) to closer to one million (Fiji, Solomon Islands).

Domestic fleet profiles vary from country to country in the region reflecting population and economy but generally comprise a number of vessel types with small vessels predominating, very few vessels over 5000 GT and the vast majority under 500 GT. For general passenger and cargo movements between islands in an archipelago, vessels are often end of life Ro-Ro of varying size between a few hundred and a few thousand tonnes or donated multi-purpose passenger/cargo vessels. There are a range of tugs and barges, landing craft or varying sizes, old fishing vessels converted to passenger cargo work and specialised vessels of various sizes. Small vessels under 15 m with outboard motor propulsion tend to make up a large portion of the overall domestic fleets and emissions profiles. Rounding out the fleet are a range of fishing vessels from village artisanal scale to long-liners and small trawlers.

## 3. Pacific domestic maritime decarbonisation ambition

We have previously reported the unique challenges faced by Pacific SIDS as described above highlight the need for an urgent transition to low-carbon transport futures. Failure to achieve such a transition in the coming years will mean continued, or increased, imported fuel dependency and the associated vulnerability to global oil price shocks, higher transport costs, increasing economic penalties from continued reliance on outmoded technologies, and future technology slip in an already marginal sector [6].

The governments of Fiji and RMI have identified an urgent need for an initial large-scale blended finance investment to catalyse a multi-country transition to sustainable, resilient, and low-carbon shipping, drawing down to zero-carbon domestic shipping in participating Pacific Island Countries by 2050, with a 40% reduction achieved by 2030 [11]. The rationale for the resultant Pacific Blue Shipping Partnership (PBSP) [12] and the background research accumulated in the Oceania region since 2012 is reported in a growing library, see for example [5,10, 13–15]. Investment in decarbonisation of Pacific domestic shipping has lagged behind other energy sectors, with less than USD20 million committed thus far across the region, compared with some USD2 billion in renewable electricity generation since 2012.[1]

An initial PBSP concept note, in the name of both countries, was launched at the 3rd Climate Action Pacific Partnership Conference held in Suva in May 2019, and is being supported by a number of Pacific governments and related bilateral and agency partners [12]. An ad hoc Technical Working Group has been formed and an international network of academy-based expertise has offered support to develop a range of technical and financial analyses to the Partnership, including the subject of this paper. Earlier technical working papers give known participating country summary data and summarise potential measures and associated Marginal Abatement Cost (MAC) curves being considered internationally [16,17]. A separate process is developing financial and governance options and analyses for the Partnership.

The initiative is bold and ambitious by Pacific scale and reflects the historical lack of priority and investment for this sector to date. There are marked signals of progress at large-scale shipping/country scenarios that an international transition is now in progress, and the Pacific should act now to plan its own decarbonisation path or be left increasingly behind international progress with potentially increasing fuel and carbon cost penalties and on-going dependence on stranded diesel technologies. Insufficient work and analysis of results has been done to date to provide a more comprehensive discussion at this time. It is hoped that this paper will invite additional discourse, data options, and analysis.

The literature remains incomplete and data currently available is at varying levels of verification. Pacific domestic shipping data availability and reliability have been identified as on-going issues for over a decade [18,19]. Almost no detailed reviewed analysis on cost/benefit, return on investment, or MAC curves for any Pacific islands' domestic-based measures is currently available, with the exception of the 1986 Fiji ferry sail retrofit trials [20].

## 4. Historical research on Pacific domestic abatement measures to date

No dedicated study has considered the full suite of abatement

[1] Between 2012 and 2019 we have identified $17 million of funding specifically targeting shipping decarbonisation in the Pacific, and whilst this is likely not all of the funding allocated to such projects, it is likely to be most. Over $2 billion of funding is estimated to have been allocated to renewable energy electricity generation in the region https://www.mfat.govt.nz/en/aid-and-development/our-aid-partnerships-in-the-pacific/regional-initiatives/.

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 Island states. These include a number of studies on abatement options for international shipping conducted since the release of the Second [21] and Third [22] IMO GHG reports from a variety of sources (in particular, work led by CE Delft, UCL/UMAS, DNV-GL, Lloyd's Register, International Transport Forum-OECD). More recently this effort has included domestic shipping studies for northern European countries [23–25].

In the context of domestic Pacific Island 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 crisis [10,12,26]. Such projects, implemented by a range of development partners including United Nations agencies, the European Commission, and the Asian Development Bank. At various ship scales from artisanal fishing to government service cargo/pax ferries, these projects 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/benefit [10,27,28]. Collectively, they clearly identify an achievable range of savings based upon then-mature technology for a range of vessel types available to address issues raised in the current debate.

With falling international fuel prices in 1986, no further work was done in this field specific to a Pacific Islands domestic scenario until the University of the South Pacific (USP)-hosted Sustainable Sea Transport Talanoa in 2012 [29] and 2014 [30] and the related Sustainable Sea Transport Research programme, which includes sectoral analysis of various measures such as Flettner rotors, soft sails, biofuels and wing-in ground technologies [5,10,12–14,31–33]. 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 portal [34]. The German government funded Transitioning to Low Carbon Sea Transport (TLCSeaT) project in RMI is now producing options portfolios for RMI inter-island government and intra-lagoon scale vessels [35], and the Swire/USP Cerulean Project is currently assessing viability for a wind-hybrid 200GT inter-island cargo vessel design [36]. More recently the Pacific Community (SPC)/South Pacific Regional Environment Programme (SPREP) hosted Pacific Maritime Technology Cooperation Centre (MTCC) [37], under the IMO Global Maritime Network (GMN) programme [38], has completed trials of retrofitted solar 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 available [39].

## 5. Abatement measures available for consideration by the Pacific

New information and research on international shipping decarbonisation is rapidly becoming available, albeit almost all effort remains focussed on the economics and technologies to support large-scale shipping servicing large/developed economies. 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 commercial applications of existing technologies to enable market-scale deployment [40] and [41]. The key technologies available at global scale for decarbonisation of shipping are summarised in Fig. 1.

International studies generally agree on the range of measures available to shipping, for example Bouman et al. [42] review around 150 studies to provide a comprehensive overview of $CO_2$ emissions reduction potentials and measures published in literature, 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 low- and zero-carbon fuels 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, as these nations already struggle with adequate domestic bunkering facilities for fossil fuels. A new alternative domestic fuel source that requires new and additional bunkering infrastructure to existing facilities already in place for fossil fuels would require greater investment which may not be available to Pacific States in future development scenarios. 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.

Smith et al. [43] provide the current benchmark for international work and considers the different options for reducing GHG and air pollution from both UK domestic and international shipping. Despite the diametric differences in their shipping scenarios, the caveats given to understanding the UK analysis have parallels and relevance to PIC scenarios and are quoted in full:

> "*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 in the case of Pacific domestic fleets] 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, international shipping representatives and others all coming together to achieve the shared objective over a sustained period.*" [43]

## 6. Abatement measures by category

Smith et al. consider the abatement options for shipping are, for the most part, commonly agreed and can be considered in four categories.[2] 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.

A number of global studies have considered the applicably and availability of these measures and various toolkits have been developed [43,44]. However, none of these have been constructed under a lens specific to a Pacific SIDS domestic scenario and all to date are of limited value for determining potential savings or priorities at this scale.

Efficiencies and savings are available to the Pacific under at least three of these categories, although there are characteristics of the Pacific domestic scenario that imply application of measures will not be uniform with either a global or a large economy transition. Of these access

[2] See [43] for more detailed description.

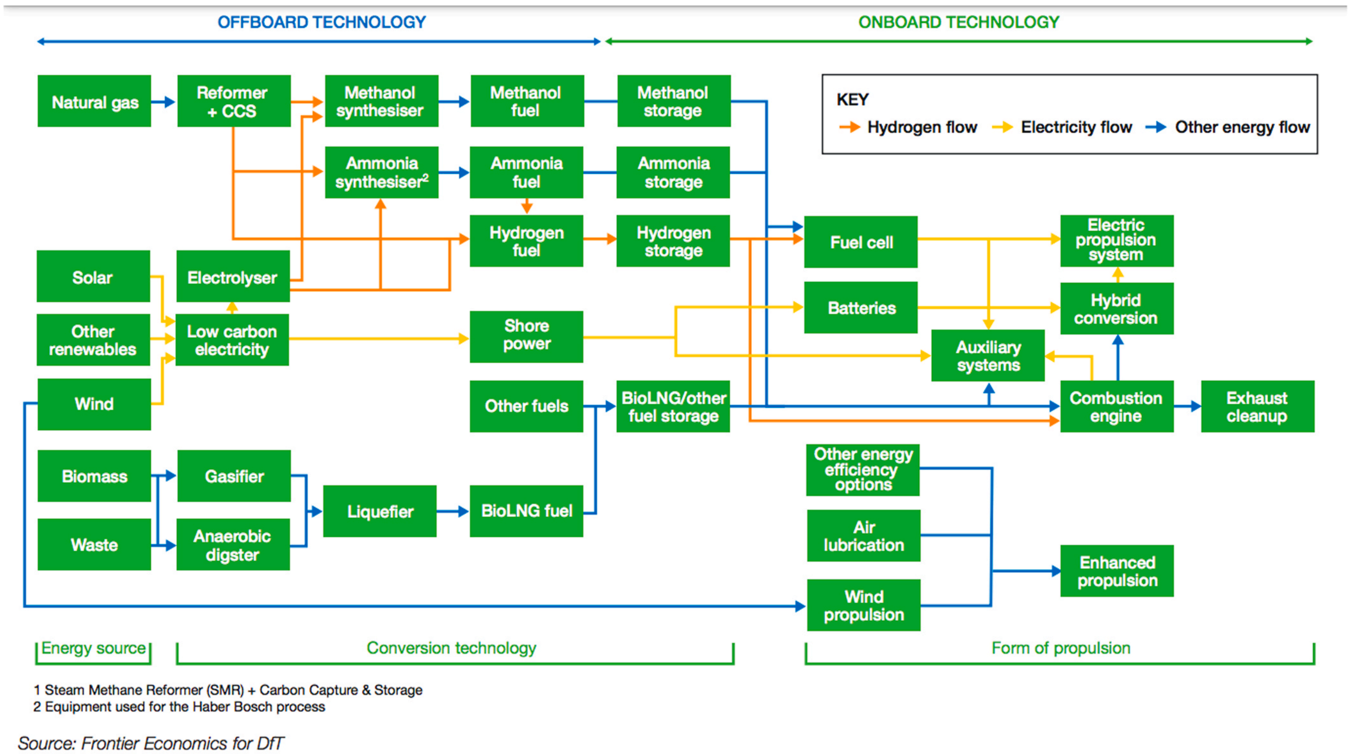


**Fig. 1.** Technologies and fuels on a pathway to zero-emission shipping [24].

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 instruments underlie all issues.

Each of the measures identified has been considered for its applicability and availability within a Pacific Islands domestic maritime context as summarised in the tables in the Appendix, organised under the same four category headings used in Smith et al. [43]. An overview of each measure is given below.

Most international study has also considered the availably of identified measures to the market, either as simple scales of mature to immature or, in the example of Smith et al., in terms of a Technical Readiness Index on a 1–9 scale [43]. Neither of these approaches is particularly useful to a Pacific scenario given its unique characteristics and non-conformity with large-scale, logistics chain operations [15,16]. A lack of verifiable data and reporting makes assessment extremely difficult at this scale.

In addition, there is inconsistency in what is actually being measured in terms of the efficiency or savings potential referred to in the various studies, with some referring to vessel fuel saving potential, others to emissions savings, others to overall efficiency savings, and uncertainty exists as to whether this includes all vessel emissions or just voyage-related, as an example of methodological variables. In any regard, the specificity of individual vessels means there can be marked variance of savings or efficiencies between ships.

Measures need also to be considered in light of whether they are targeted at current fleet retrofits or next generation new-builds. 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.[3] Without a significant and dedicated new fleet replacement programme, with associated commitment of the necessary financial investment to make this happen, retrofitting of existing vessels will be essential. However, as a general 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 leaders.[4]

From the analysis of available measures at Pacific scale, available technology is not the primary barrier to meeting an initial target of 40% reduction, rather establishing and bedding in new finance policy to facilitate new vessel purchase. This said, even if the new finance facility is successful, and quickly, it will still be some time before vessels built after 2020 will predominate in the Pacific fleet. In this case, the majority of the Pacific fleet will continue to be either existing vessels, second-hand/end-of-life imports from outside the region or donated vessels through bi-lateral arrangements. With the latter vessels, there is often little opportunity for the recipient country to negotiate the donated technologies, which are supplied without consideration to their lifetime operational costs or efficiency profiles. This means retrofit programming for some of the existing fleet is pivotal over the next two decades, given the likely slow pace of new vessel introduction.

Sections 5.1–5.4 below summarise the abatement measures according to the four categories used by Smith et al. [43] from the detailed tables and accompanying explanatory notes provided in the Appendix to this paper. Measures are coarsely ranked as low, medium, high as distilled from international references and known Pacific capacities.

### 6.1. *Category 1: technologies that can increase energy efficiency*

Abatement measures in this category cover propulsion devices,

[3] SPC calculate from available national ship registries for Kiribati, Vanuatu, Fiji, Solomon Islands, Samoa and Marshall Islands 59% of Pacific domestic vessels are over 20 years old, 38% over 30 years [46].

[4] For Fiji and RMI this is 40% reduction by 2030 and 100% decarbonisation by 2050 [1].

(including modifications to the propeller, propeller boss and adjacent area, bulbous rudders, etc.) ship design (including changes in the hull shape, lightweight construction materials, addition of bulbous bows, etc.), main machinery and engine modification (design improvements to the diesel engine, waste heat recovery, etc.) and efficiencies from auxiliary power generation (energy management and recovery). While some savings are available under this category, measures need to be tailored to individual cases. For all, Pacific situated research is needed. Measures such as new hull designs have strong potential for savings and could have related benefits to sustaining maritime industrial capacity development. This level of savings and transition is only possible if underlying issues of ship financing and underwriting are resolved and investment capital is available.

| Options | GHG abatement | Commercial availability | Future cost reduction potential[a] | Applicable to Pacific domestic shipping | Available to Pacific domestic shipping | Retrofit applicable |
|---|---|---|---|---|---|---|
| **Propulsion devices** including modifications to the propeller, propeller boss and adjacent area, (ducts, fins, cowlings), bulbous rudders, etc. | Low | Currently available | Low | High potential in specific applications. | Available. Locally situated research needed. Specialist knowledge required. Some potential for localised manufacture. | Yes, depending suitability of device based on scale of vessel. |
| **Ship design** including changes in the hull shape, lightweight construction materials, addition of bulbous bows, etc. | Medium | Currently available | Medium | High if investment available to re-fleet. Low for retrofits. | Available. Limited current capacity – requires long-term international partnerships/investment. Opportunity for revitalisation Fiji shipbuilding. | Some options can be retrofitted but not all. |
| **Main machinery and engine modification** (design improvements to the diesel engine, energy from waste heat recovery (WHR), etc. | Low | Currently available, expected to increase over next 10 years. | Medium | Low, but future potential if new builds. WHR needs immediate Pacific focussed research. | Available. First priority maximising available efficiencies through maintenance. Smart technologies likely higher relative cost for Pacific. All require capacity development. | Yes, all engine types may be optimized in some manner. |
| **Auxiliary** (energy management and recovery) See also RE sections under Category 4 below | Low | Currently available | Medium | Medium to low dependant on level /cost of technology. | Available. Cost, technology transfer and capacity barriers. | Yes, for all sizes of vessels. |

[a] Smith et al. [43] reference the potential for various abatement measures and technologies to reduce in unit cost with advances in technology and production and economies of scale as mass deployment expands.

### *6.2. Category 2: operational or behavioural change that can increase energy efficiency*

| Options | GHG abatement | Commercial availability | Future cost reduction potential | Applicable to Pacific domestic shipping | Available to Pacific domestic shipping | Retrofit applicable |
|---|---|---|---|---|---|---|
| Speed/voyage optimisation related | Medium | Currently available | Low | - Medium to low for slow-steaming<br>- Low for ship size/ capacity increases<br>- High for just-in-time and weather routing | Available. Just-in-time efficiencies assume synergies available with port/shoreside logistics chain componentry. Already widely practiced as operational cost saving measure on many Pacific routes. | Some. Slow steaming, may require engine derating. |
| **Condition related** (e.g. trim, – hull coating selection, maintenance, etc.) | Medium | Currently available | Low | High. Some measures less applicable to older, smaller vessels. | Available. Some measures likely only cost effective in high volume traffic routes or new build scenarios. Strong potential for training crew in load management best practices. | Yes, this entails system and maintenance optimization. |
| **Port related** (just-in-time berthage, etc.) | Low | Currently available | Low | - Low for improved ship-port interface<br>- High for port side energy efficiencies | Low for ship-port interface improvements. High financial / institutional investments required. Port side efficiencies are available. | N/A |

### *6.3. Category 3: technology specific to the capture/treatment of exhaust emissions*

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, of which neither measure is likely to be used in any future Pacific domestic scenario given vessel scale and cost. Consequently, this category is not considered further here.

### *6.4. Category 4: alternative fuels and energy sources and related machinery*

| Options | GHG abatement | Commercial availability | Future cost reduction potential | Applicable to Pacific domestic shipping | Available to Pacific domestic shipping | Retrofit applicable |
|---|---|---|---|---|---|---|
| **Wind propulsion** (soft and fixed sails, rotors, kites, suction wings) | Medium | Available now and expected to increase rapidly in next 5 years. | High | Can be high, dependent on technology, ship type/size/age and route. | Soft sails and rotors available. Availability of other technologies currently limited. Specialist crew and master training is required. Pacific specific research already conducted for some technologies, others will require more research before being considered further. | Yes, dependent on deck space and equipment layout. |
| **Wind turbines** for auxiliary power supply | Unknown | Currently available | Low | Medium to high, dependent on location and route. To satisfy aux power demand, would likely need to be combined with additional generation source(s). | Available. | Yes, dependent on deck space and equipment layout. |
| **Solar** for auxiliary power supply | Low | Currently available | Medium | High. To satisfy aux power demand, would likely need to be combined with additional generation source(s). | Available. Increasing deployment of terrestrial solar applications means increasing local capacity to install and service. Current cost effective Pacific capacity/access to battery technology supply and servicing. | Yes, dependent on deck space and equipment layout. |
| **Electric/Battery** | Low to full, dependent on route length and battery application | Currently available | High | Low except for targeted application (e.g. small vessels or high value scale). Key limiting factors: range, high CapEx, high technology transfer needs and access to low-carbon electricity sources. | Low except for targeted application where potential is medium/high. R&D recommended for high value tourism operators in sheltered water scenarios. Requires close collaboration with electricity supply planning. Predicted to be fast improving field, so availability for Pacific operators likely to improve in near future. | Yes, but limited by integration into the existing systems. |
| **Fuel cells** | High | No | Unknown | Low | Not currently available, current research at small scale ongoing. | No, due to entire fuel system overhauls required. May be possible in specific Situations. |
| **Shore power** (cold ironing) | Low | Currently available | Low | Applicable in highly limited scenarios. No detailed current research is available on Pacific scenarios. Application at scale will require greatly increased RE generation capacity in all PICs. | Not currently available. Limited application at small vessel and high value (e.g. tourism) scale can be envisaged. This scale warrants immediate research priority. | Yes, but requires equipment installation for existing vessels. |
| **LNG/CNG** | Low to medium | Currently available | Low | Not applicable | Not available. Lack of bunkering infrastructure, high cost to introduce infrastructure at scale, high transition and transaction costs. | No, due to entire fuel system overhauls required. |
| **Biofuels** 1st generation (crop based) Biofuels 2nd generation (waste based) Biofuels 3rd generation (specially engineered crops such as algae) | Full | 1st gen biofuels currently available, 2nd and 3rd expected in next 5 years | Low (1st gen) to medium (2nd and 3rd gen) | Not applicable until potential feedstock can be economically sourced. Lower investment needs to modify existing bunkering facilities compared to other low/zero-carbon fuels. Applicability more favourable in high, wet island scenarios. | Available. R&D and trials needed to establish scaled cost-effective production. Maritime specific research should be integrated into wider Pacific fuel replacement research for other sectors. | Yes, depending on drop-in compatibility of fuel type. |
| **Electro-fuels** (including hydrogen, ammonia, and methanol) | Full | Expected in next 5 years | High | Low, major issues related to bunkering and supply infrastructure | Not available | Yes, depending on fuel type and existing fuel system, methanol is a possible retrofit option. |

## 7. Discussion

The coarse analysis summarised above represents only a first 'best-attempt' to consider the assessment of international abatement measures with greatest applicability for Pacific transition pathways. It is obvious that at international scale, shipping is now embarked on its greatest revolution since the adoption of fossil fuel powered screw propulsion and that this revolution will accelerate exponentially over the next decade. If we are correct in the assumptions that a. the Pacific will be further disadvantaged if it cannot match step with this transition and b. the unique aspects of its domestic maritime scenarios demand bespoke Pacific-facing pathways, then we need to clearly identify the available options early.

Such analysis is hampered by both Pacific specific data and a lack of international analysis at island economy scale, with almost all effort currently focussed at large and developed economy industry need. Such work specific to Pacific domestic scenarios is still a work in progress and significant data gaps remain, both in terms of domestic fleet profiling and analytical comparison with other Pacific geographies and economies.

Sufficient knowledge is available to identify where initial effort needs to be focussed. While it is accepted that ultimately next generation fuels are required for full decarbonisation, PICs will inevitably face greater barriers to implementing a re-bunkering regime than most other economies. However, largely due to the small-scale of Pacific domestic vessels, existing technologies have strong potential to achieve the initial target of 40% by 2030 set by Fiji and RMI, especially when used in combination with new build vessels. Even if sufficient financial modalities cannot achieve a full re-fleeting, retrofitting options indicate potential for savings and progress toward this target when efficiencies are considered as fleet aggregates. The availability of such technology of course does not necessarily imply uptake, that is as much or more a factor of market economics.

Wind-hybrid propulsion is agreed by all reviewed literature as having high potential for Pacific domestic application. ADB concluded, "*approximately 25 per cent of a ship's fuel may be saved by the application of sail assistance without compromising required operational schedules*" [26]. With advances in technology and when deployed in combination with a basket of additional measures – improved propellers/rudders, hull-coatings, enhanced operational practices, etc. – savings of anywhere between 10% and 70% are achievable, depending on vessel type and purpose. Greatest efficiency is achieved when combined with new-build, advanced hull design and auxiliary power measures. Wind theoretically can provide 100% of all propulsion (and did for hundreds 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 when compared to RMI and Fiji which are considered close to ideal [19]. As a general rule of thumb, higher savings are available at smaller vessel scale.

Under a business-as usual scenario and in absence of any catalytic financial driver of scale, such as the PBSP, retrofitting will be more pivotal, given the likely slow pace of new vessel introduction. It needs to be clearly noted however, that while savings can be achieved, they will never achieve anything like those available from purpose designed new-build solutions. Any type of new vessel, even a diesel one, will offer massive reduction in emissions compared with a 30-year old vessel.

The immediate step in a successful Pacific transition of speed and scale will likely favour efficient new-build hulls with the most efficient diesel motors plus hybrids plus wind/solar auxiliary power. Ultimately a full transition must include alternatives to fossil fuel ICE propulsion. Planning for a Pacific island facing fuel transition must be approached with extreme caution. In many locations, bunkering for fossil fuel is still primitive comprising hand pumping from 200 l steel drums. Methanol and biofuels are currently the only alternatives that could be considered for retrofit of current storage and bunkering infrastructure. The infrastructural cost of any other alternative is likely highly prohibitive as a regional solution. As previously referenced, LNG has already been eliminated as a potential candidate fuel within any Pacific domestic scenario.

Finally, a transition to next generation Pacific facing shipping technologies offers an opportunity to introduce shipping services that are less reliant on conventional shoreside infrastructure through use of more appropriate vessel types and sizes. This is particularly true for outer island and smaller communities currently often serviced by aging large Ro-Ro and landing craft type vessels.

## 8. Conclusion

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 efficiency improvements and emissions savings, but more significant emissions reductions will come from fleet replacement with new build vessels.

The applicable measures identified above strongly suggest emissions reductions of 40% by 2030 are likely available to the PBSP using available technologies, with the critical caveat that this will only happen if appropriate financing modalities are made available. Full decarbonisation 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 advance 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 national, regional, and global policies and/or 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. Some of the internationally applicable solutions may not be suitable for Pacific domestic shipping, others may have application, meaning that a unique mix of solutions will be required. While this paper only looks at the applicability and availability of low- and zero-carbon technologies for PICs, it may provide useful information to other countries or regions with similar characteristics and operating in similar domestic shipping scenarios. As countries and regions increasingly assess and implement options to decarbonise their shipping fleets, transfer of knowledge, best practices, and lessons learned are likely to proliferate.

This paper, based on best available information available at time of preparation, provides a starting point for determining future abatement measures and options at Pacific-scale to inform the further development and implementation of the PBSP.

It is expected that new science and knowledge transfer will require periodic updating and revision to best provide the PBSP and other related initiatives with a reference to refine development of Pacific domestic shipping decarbonisation pathways.

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## Appendix

Category 1: Technologies that can increase energy efficiency.

| Abatement Measure | | Retrofit | New Build | Savings potential[a] | Applicability to Pacific domestic scenarios and potential savings | Availability to Pacific domestic scenarios |
|---|---|---|---|---|---|---|
| **Propulsion devices** including modifications to the propeller, propeller boss and adjacent area, (ducts, fins, cowlings), bulbous rudders, etc. | | Yes, depending suitability of device based on scale of vessel. | Yes | 1–25% [47]. Up to 12% propulsive fuel efficiency claimed but 2–8% is more realistic.<br>Ducts, fins etc. are considered relatively cheap and low technology measures, with costs increasing sharply for high efficiency measures such as contra-rotating propellers.<br>Savings vary considerably dependant on ship type, size and operating speed.<br>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. | High potential in selected applications.<br>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.<br>Innovation needs to be very specific to the individual vessel and its operating parameters.<br>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% [48]. However, most PBCF's effectiveness is reduced at slower steaming speeds and may be a constraint at operating speeds common to Pacific domestic vessels. | Available.<br>The technologies are generally well known and readily commercially available, primarily at large ship scale.<br>Most new builds internationally now incorporate latest known designs and innovations and could be made mandatory via national policy for appropriate Pacific future builds.<br>Retrofitting during routine dry-docking is also readily available. Locally situated research to determine the 'best-fit' of known innovation and technology for local operating scenarios and vessel types is needed. Specialist knowledge required. Some potential for localised componentry manufacture. |
| **Ship design** including changes in the hull shape, lightweight construction materials, addition of bulbous bows, etc. | Hull design | No, hull forms are largely fixed. | Yes | Individual vessel dependant but up to 25% efficiency[b] possible (when combined with other initiatives e.g. new propellers, etc.).<br>The design efficiency of ships has varied significantly over time. All large ship types analysed by Hoen et al. [49] witnessed a sharp improvement in the design efficiency of new ships in 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 [49]. 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 a and freight charges. | High potential if investment is available to re-fleet with new vessels.<br>Most work has been at large ship scale with less research into ships appropriate to Pacific domestic scale.<br>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 high if vessel design is tailored to identified transport need. | Available.<br>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.<br>Essential and high priority if financing available for Pacific re-fleeting with new builds. Opportunity for revitalisation of Fiji shipbuilding capacity and expansion of existing maintenance capacity. |
| | Air lubrication | Yes, for some types of vessels only. | Yes | 10–15% reduction in propulsive fuel possible [50], 4–5% savings [51] demonstrated in latest large-scale commercial deployment. | Low future potential.<br>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 | Not currently available at Pacific domestic scale. Limited future potential.<br>Recommend watching brief and research into Pacific application of low cost/low |

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| Abatement Measure | | Retrofit | New Build | Savings potential[a] | Applicability to Pacific domestic scenarios and potential savings | Availability to Pacific domestic scenarios |
|---|---|---|---|---|---|---|
| | | | | Some additional energy requirements for pumping Most effective on flat bottom ships. Efficiency gains decline rapidly as sea state increases. | high tech installation and maintenance costs suggest 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. | tech approach for landing craft/flat bottom cargo vessels. |
| | Bulbous bow | Yes, for large enough vessels | Yes | 3–7% in fuel savings on large cargo carriers [52]. Other devices or retrofit to reduce resistance can reduce $CO_2$ emissions of about 2–5% [53]. | Not applicable except in specific vessels.<br>Bulbous bows are common for large-scale shipping but can have negative efficiency effect on small-scale shipping. | Available.<br>Uptake not likely as probably very marginal or negative effect on most Pacific scale ships. May be seen on imported vessels. Retrofits are uncommon and unlikely cost effective. |
| | Aerodynamics | Yes, limited use largely restricted to bow shields. | Yes | No reviewed literature figures available.<br>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.<br>For new builds, this design parameter should be included in all new ship design. | Low potential. Should be incorporated in new ship design. | Limited availability. |
| **Main machinery and engine modification** (design improvements to the diesel engine, energy from waste heat recovery (WHR), etc. | | Yes, all engine types may be optimized in some manner. | Yes | 0.1–3% [54].<br>Marine diesel motors have nearly reached their maximum deign efficiency, although minor gains can still be expected. The most thermally efficient low-speed marine diesel engine is rated at 50% between fuel energy content and crankshaft power. Regularly maintained serviced motors will always be more efficient. Electronically controlled engines offer increased precision in fuel injection and exhaust emission control. Turbochargers for engines and transmissions also offer potential for future efficiencies. Diesel/electric hybrid drive systems can provide additional efficiency.<br>WHR has been identified as having a fuel reduction potential of 0–12% dependant on ship type [41,52–54].<br>Derating, especially when combined with permanent slow steaming and wind hybrids, can provide 1–3% additional savings [55]. | Low, but future potential if increasing new builds are introduced to Pacific fleets.<br>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 in the Pacific.<br>WHR is high cost for large ships and probably prohibitive for Pacific scale retrofits but could be considered for new builds. Given high age average of Pacific domestic fleet, new engines will almost certainly automatically increase efficiency considerably. However, this is probably not cost effective for many vessels given ship age. Much greater overall savings accrue from investment in new generation vessels rather than retrofitting with new improved main engines. | Available.<br>In general terms for existing vessels, the first priority should be maximising available efficiencies through enhanced regular maintenance and servicing regimes.<br>Smart technologies likely higher relative cost when employed at Pacific scales and remoteness.<br>WHR needs immediate Pacific focussed research.<br>All require, to varying degrees, capacity development across the Pacific domestic logistics chain to effect.<br>Cost effectiveness of the more sophisticated measures means it is probably not applicable to older, smaller Pacific vessels. |
| **Auxiliary** (energy management and recovery)<br>See also RE sections under Category 4 below | Autopilot upgrades<br>Hotel and secondary machinery systems/ equipment upgrades/ efficiencies<br>Smart controllers and battery buffers | Yes, for all sizes of vessels. | Yes | Main engine measures are also viable for auxiliaries. WHR could be diverted to either main or auxiliary assistance.<br>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. | Medium.<br>For many Pacific scenarios, auxiliaries are much larger percentage energy users given often long port times of Pacific domestic shipping.<br>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. | Available.<br>The first priority should be maximising available efficiencies through regular maintenance and servicing.<br>Smart technologies likely higher relative cost when employed at Pacific scales and remoteness and require significant investment in short and long term capacity development.<br>WHR needs immediate Pacific focussed research. |

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| Abatement Measure | | Retrofit | New Build | Savings potential[a] | Applicability to Pacific domestic scenarios and potential savings | Availability to Pacific domestic scenarios |
|---|---|---|---|---|---|---|
| | | | | g. pumps, fans, LEDS, etc. Autopilot upgrades. 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. | All require, to varying degrees, capacity development across the Pacific domestic logistics chain to effect. | Cost effectiveness of the more sophisticated measures means probably not applicable to older and smaller Pacific vessels. |

[a] Assuming a new build will always be higher efficiency and more cost effective over a whole of lifecycle analysis than retrofit of existing vessels.

[b] Merk et al. [40] summarise 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.

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

| Abatement Measure | | Retrofit | New Build | Savings potential[a] | Applicability to Pacific domestic scenarios and potential savings | Availability to Pacific domestic scenarios |
|---|---|---|---|---|---|---|
| **Speed/voyage optimisation related** | Slow steaming | Yes, may require engine derating. | Yes | 0–60% of propulsive fuel use. 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 saving [56]. | Low to medium applicability. Many domestic ships already employ voluntary slow steaming in periods of high fuel cost. Faster passage time usually demanded by passengers and majority of Pacific vessels are mixed cargo/ pax. | Available. Lower speeds are more effective if design speeds of ships are brought down as well. |
| | Increase ship size/ capacity | No, vessel configurations are fixed upon completion in the same manner as hull design. | Yes | Up to 30% emissions reduction [57]. Savings need to be considered over full logistics chain as smaller vessels/other modes needed to disperse from main ports. Savings assume vessels operate at capacity. | Low applicability. Would only benefit high volume routes. Many Pacific ports, especially for remote communities, can only cater for smaller vessels due to passage 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 resilience. | Available. |
| | Just-in-time Weather routing | Yes, this is a scheduling shift. | Yes | Highly variable dependant on ship, route, trade and communication with shoreside ports and operators. | High applicability. Weather routing will increase in importance with deployment of wind energy technologies. | Available. Just-in-time efficiencies assume synergies available with port/shoreside logistics chain componentry. |
| **Condition related** (e.g. trim, – hull coating selection, maintenance, etc.) | Ballast water trim | Yes, this entails system and maintenance optimization. | 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, this entails system optimization. | 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 [58]. | 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, maintenance is even more crucial for retrofits than newbuilds. | Yes | 2–8% emissions reduction potential. | High. Given high average age of Pacific domestic and low profit margins, on-going maintenance upkeep is a longstanding issue for many domestic scenarios. Historic Fiji trials in 1980s | Available. Strong potential for training on all vessels for masters, mates, supercargoes in load management best practices. |

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| Abatement Measure | | Retrofit | New Build | Savings potential[a] | Applicability to Pacific domestic scenarios and potential savings | Availability to Pacific domestic scenarios |
|---|---|---|---|---|---|---|
| | | | | | showed that basic maintenance of ship bilges, ballast, engines and machinery could achieve 4% savings [26]. | |
| | 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. Dry-dock/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 dry-dock 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 | N/A | N/A | ~1–5%[b] of total shipping emissions globally [59,60]. Achieved through auxiliary engines reduced energy consumption. Needs to be integrated with other route optimization tools, weather routing and shore side logistics, 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. | 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 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. | Low Availability and high financial/ institutional investment required. Except in major centres, domestic maritime infrastructure and substandard vessels remain a severe challenge to successive Pacific governments. Improved ship/port interface requires upgrades across the 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 on-going, in progress or planned for many countries, e.g. Nauru, Solomon Is, Vanuatu Kiribati, RMI and Tuvalu, which provide opportunities for energy efficiency as a priority. Long term planning capacity needs to be built into education/training regimes. |
| | Port side energy efficiencies[c] | N/A | N/A | 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 has undertaken initial studies and pilots in ports in Solomon Islands, Fiji and Vanuatu. The Solomon' s project provisionally reports energy savings of 8% (15t$CO_2$) with strong potential for increased savings over time [61]. |

[a] Assuming a new build will always be higher efficiency and more cost effective over a whole of lifecycle analysis than retrofit of existing vessels.
[b] If all ship waiting time reduce to zero. Data on this is scarce and fragmented.
[c] 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.

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

| Abatement Measure | | Retrofit | New Build | Savings potential [60][a] | Applicability to Pacific domestic scenarios and potential savings | Availability to Pacific domestic scenarios |
|---|---|---|---|---|---|---|
| | Soft sail | | Yes | | | |

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| Abatement Measure | | Retrofit | New Build | Savings potential [60][a] | Applicability to Pacific domestic scenarios and potential savings | Availability to Pacific domestic scenarios |
|---|---|---|---|---|---|---|
| **Wind propulsion**[b] | | Yes, dependent on deck space and equipment layout. | | 10–90% propulsion efficiency depending on scale[c]. Fiji 1980's trials on 274 and 300GT cargo/pax ferries confirmed average fuel savings of 23–30% [20,27][d] 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 [66]. Neoline has 2x soft-sail diesel/electric hybrids (5000 dwt freighters) under construction with projected operational efficiency savings up to 80–90%[e]. 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. | High for retrofit/new build subject to vessel type[f]. 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, new build and retrofit. Sail hybrids are currently deployed at various scales in the tourism and recreational maritime sectors in countries e.g. Fiji and there already exists mature secondary industry to support commercial scale manufacture and maintenance. All new build and retrofit options under the Cerulean and TLCSeaT RMI project for inter-island and intra-atoll work include variations of either soft-sail or rotors. | Available. The historic trials of Fiji ferries of 50 (new build), 274 and 300 (retrofit) tonne ferries all used Fijian manufactured and fitted technologies. The 50 t *Tai Kabara* was outer-island built. Soft sail rigs are available at technology levels from high cost/high tech (as in super yacht applications) to low cost/low tech (e.g. *Na Mataisau*). It is assumed Pacific domestic application will maintain innovation at the lower tech end. Fijian yards report capacity to build low/medium tech retrofits and new vessels to 30 m/200 t. Numerous ex-region options exist to any technology level. Specialist crew and master training is required. Technology is either locally procurable or importable. |
| | Fixed sail | Yes, dependant on deck space and equipment layout. | Yes | 8–30% propulsion efficiency depending on scale. 1980's trials on a variety of Japanese commercial vessels (including tankers, bulkers and general purpose) confirmed average fuel savings of 10–32% [71]. Walker Wingsails trials in 1986 were giving an average of 8% and up to 25% fuel savings [72,73]. Several international projects, including Tokyo University trials for 180k Capesize with trials showing 30% annual energy savings [71,73,74]. | Unknown but potentially low for retrofit/new build subject to vessel type. Fixed wing sails have not previously been used or studied for Pacific domestic use. International reviews find fixed sails have potential but identify safety concerns, design limitations (including classification society requirements), economic and business considerations and operational issues [73]. | Not currently available. Fixed wing sails have not previously been used or studied for Pacific domestic deployment. Pacific specific research needed before considering further. |
| | Rotor (e.g. Flettner rotors) | Yes, dependant on deck space and equipment layout. | Yes | 6–50% propulsion efficiency depending on scale, number of rotors and retrofit/new build. Since 2011, commercial trials have been completed on new build (10,500 dwt RoRo – 25% overall efficiency[g]), retrofits on 62000 GT tanker (2x rotors, 8.2% savings [74]), 4000 GT coaster (1 x rotor, 10–20%), 67k DWT Bulker (4 x rotor, 10%+) [75], 9700 DWT Ro-Lo carrier (1 x rotor, 5%), 58k GT Cruise liner (1x 24 m rotor, 3.6%) [78]. Advanced designs and modelling for numerous vessel types exist with savings projected up to 50% for new builds combining advanced hull and other componentry design[h]. | Medium to High. Savings potential increases with decrease in vessel size. Increasing knowledge of application and rotor designs and preliminary modelling on selected Pacific routes [81] and Fiji and RMI domestic applications. No cost/benefit or ROI available yet for Pacific application. C/B varies with installation prices ranging $300–800k per rotor. Maersk 2018 trials show savings equivalent to $200k p.a [76] and Vahs et al. have modelled $150,000 savings from a 2 rotor system costing $880,000 [82]. High potential for cost reductions as market matures. Some componentry could be built in Fiji. | Available. A small number of international commercial designs available and design shops capable of bespoke designs [82–84]. Advanced modelling available for retrofit application on current RMI government ships. Technology would need to be imported, Fijian yards report capacity for some component fabrication. Limited specialist training needed. |
| | Kite (e.g. Beluga Sails; Sky Sails) | Yes, dependant on deck space and equipment layout. | Yes | 10–15% propulsion efficiency on selected passages. However, annual savings in consumption on most routes | Very low applicability to Pacific scenarios and would only be practical on a very limited number of domestic routes. | Not available. No commercial models available or known current pilots. K Line announced a 20-year deal in 2019 to commence new trials with |

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| Abatement Measure | | Retrofit | New Build | Savings potential [60][a] | Applicability to Pacific domestic scenarios and potential savings | Availability to Pacific domestic scenarios |
|---|---|---|---|---|---|---|
| | | | | is on the order of 5.5%, as determined by the EU-funded Life project WINTECC48.<br>A limited number of trials and modelling have been undertaken with mixed reviews as to actual saving achieved.<br>Greatest application is likely in larger vessels on long predicable routes. | Internationally, kite development to date has not been able to overcome safety concerns.<br>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.<br>Kites were considered during the Tokelau ferry *Mataliki* design process and found to be unsuitable on cost, safety and technology level grounds despite good wind availability.<br>Specialist training required. | **France-based Airseas** [85].<br>Pacific specific research/verification would be required if international trials demonstrate future viability. |
| | Suction Wings (e.g. Ventifoil, Turbosail) | Yes, dependant deck space and equipment layout. | Yes | 10–30% propulsion efficiency.<br>Championed by Cousteau's *RV Alcyone* in the 1980's, the verification of savings has been questioned. | Low.<br>Lack of profile and data means that there is likely greater interest and uptake of other wind propulsion options. | Low availability.<br>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. |
| **Wind Turbines** | Auxiliary power supply | Yes, dependant on deck space and equipment layout. | Yes | Unknown.<br>Dependant on size, type, manufacturer and operating scenario. Requires battery storage, controllers, etc.<br>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. | Medium – High.<br>Effectiveness dependent on location and routes.<br>Combined with solar provides a hybrid RE auxiliary package.<br>Limited specialist training required.<br>Unlikely to provide full axillary power needs in any transport demand scenario so needs to be combined with additional generation source(s). | Available.<br>A wide range of maritime models commercially available and deployed worldwide in recreational vessels. These include both rotating blade and helix configurations.<br>Initial modelling available for RMI ship government retrofits. |
| **Solar** | Auxiliary power supply | Yes, dependant on deck space and equip layout. | Yes | Minimal to 32% of total fuel use[i]<br>Requires battery storage, controllers, etc.<br>Given that many Pacific domestic vessels have high port times, fuel use from auxiliary generation likely higher than global averages.<br>Medium potential for future cost reductions and likely medium potential of cost reduction in related componentry (e.g. batteries).<br>Actual emissions savings need to consider whole of life cycle of all componentry (to ascertain overall savings and costs. | High potential.<br>Unlikely to provide full axillary power needs in any transport demand scenario so needs to be combined with additional generation source(s).<br>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.<br>Some specialist training required. | Available.<br>Wide range of imported commercially available componentry.<br>Increasing deployment of terrestrial solar applications means increasing local capacity to install and service.<br>Current low cost effective Pacific capacity/access to 2nd generation/tertiary battery technology supply and servicing. |
| **Electric /Battery** | Main engines with diesel gensets | | Yes | Up to 100% emission reduction potential. | Low except for targeted application. | Low except for targeted application where potential is |

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| Abatement Measure | | Retrofit | New Build | Savings potential [60][a] | Applicability to Pacific domestic scenarios and potential savings | Availability to Pacific domestic scenarios |
|---|---|---|---|---|---|---|
| | Main engines with RE Shaft generator | Yes, but limited by integration into the existing systems. | | 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 [41]. | The key limiting factors are range, high CAPEX, high technology transfer needs and access to low-carbon electricity sources. Current Scandinavian trials suggest 95 km storage limits between charges for larger ferries and Ro-Ros [87]. 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 [43]. This implies, its use will be specialised and restricted to smaller vessel or high return use. | 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-gird 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, due to entire fuel system overhauls required. May be possible in specific situations | Yes | 0–60% emission reduction potential. Directly converts electrochemical energy by transforming into electric power without combustion. Releases both electrical 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 and ammonia. High-temperature fuel cells could become suitable for on-board energy for larger vessels such as cruise ships and container ships. Existing fuel cell solutions favour short range smaller vessels 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. Not currently available, current research at small scale ongoing. |
| **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 in ports cost USD 5–10 million per installation, mainly related to extending grid into port [41] The total share of a ship's energy demand that can be met through shore power is small[j] [43,60]. | Applicable in highly limited scenarios. No detailed current research is available on Pacific scenarios. Needs surplus shore power generation capacity from renewably sources or generated and transmitted at higher efficiency than onboard systems. This situation does not exist in PICs currently and other electricity users are more likely be higher priority for the foreseeable future. | 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. Larger scale application will require greatly increased RE energy generation capacity in all PICs. |
| **LNG/CNG** | | No, due to entire fuel system overhauls required. | Yes | Not considered. A previous regional study determined that LNG is not viable or appropriate for Pacific domestic deployment | Not applicable. There are competing expert opinion on the use of LNG as an alternative propulsion fuel internationally with | Not available. A previous regional study determined that LNG is not viable or appropriate for Pacific domestic deployment [88] given |

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| Abatement Measure | | Retrofit | New Build | Savings potential [60][a] | Applicability to Pacific domestic scenarios and potential savings | Availability to Pacific domestic scenarios |
|---|---|---|---|---|---|---|
| | | | | given lack of bunkering and high transition and transaction costs [86]. | some considering it a viable transition fuel and others considering it a 'red herring' and neither appropriate or cost effective for a decarbonisation transition pathway fuel. | 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, depending on drop-in compatibility of fuel type. | Yes | 25–100% overall emissions reduction available [41]. 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 [35]. Cost effectiveness is projected to improve as carbon taxes or similar MBM are introduced and fossil fuel subsides reduced. | Not applicable until potential feedstock can be economically sourced. Requires high-grade fuel to avoid storage issues. Full decarbonisation will require the Pacific ultimately adopting alternative fuel(s). A key advantage for biofuels is lower investment needs to modify existing bunkering facilities compared to 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 research of application to Pacific maritime domestic use. Applicability will be more favourable in high, wet islands. Atolls will require 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. |
| **Electro-fuels** | (including hydrogen, ammonia, and methanol) | Yes, depending on fuel type and existing fuel system, methanol is a possible retrofit option. | Yes | High. Significant and increasing research investment at international scale (UMAS consider an investment of more than $1trillion is required). | Low, major issues related to bunkering and supply infrastructure. Current research assumes localised green electricity surplus is required for local production. | Not available. Significant site specific R&D required. |

[a] Assuming a new build will always be higher efficiency and more cost effective over a whole of lifecycle analysis than retrofit of existing vessels.

[b] 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-hybridoptions (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 [19]. 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 2030 [40]. Overall $CO_2$ emissions reductions available by wind have been calculated to be up to 32% of fuel use [26,42]. Wind hybrid propulsion is agreed by all reviewed literature as having high potential for Pacific domestic application. ADB concluded, "*approximately 25 per cent of a ship's fuel may be saved by the application of sail assistance without compromising required operational schedules*" [26]. Greatest efficiency is achieved when combined with new-build, advanced hull design and auxiliary power measures.

[c] Merk et al. [41] quotes the abatement potential of wind technologies estimated to be around 10–60% [62] and 1–50% of reduction in $CO_2$ according to a meta-study of existing estimates [64]. The Neoline projection postdates those studies [65].

[d] Savings resulted from a retrofitted soft sail rig; engine tuning and retrimming ballast, with sail providing the majority of savings.

[e] Neoline claim their "transport solution will reduce GHG emissions by up to 90% on an ocean crossing and eliminate SOx and NOx emissions". Information on how this is calculated is not publicly available [67].

[f] 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 [10,13,31,33,35,54,55,66,69], and presentations in particular by Gilpin, D., Smith, T.,Traut, M., Vahs, M. etc. at SSTT 2014 [30].

[g] The new build vesselE-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 [75].

[h] Traut et al. modeled a 5500 DWT cargo ship with 3 x 27 m rotors could save up to 50% of main engine power under typical slow steaming conditions [79]. Vahs et al. are more conservative with modelling for their new Eco-Flettners at 17–25% depending on size [80].

[i] The potential $CO_2$ reduction reported in different international studies range from 0.2% to 12% according to Bouman et al. meta study [64]. 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 [86]. 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 tonnes of which 50 tonnes is saved through PVs.

[j] Smith et al. and ITF calculated that approximately 5% of all shipping's $CO_2$ emissions are currently generated in ports [43,60].

## References


[1] Republic of the Marshall Islands, Update Communication on the Marshall Islands Paris Agreement NDC in Accordance with UNFCCC Decision 1/CP.21, 24–25 and Articles 3 and 4 of the Paris Agreement, 2020. ⟨https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Marshall%20Islands%20Second/RMI%20NDC-UpdateUPDATED_01.20.2021.pdf⟩.

[2] ⟨http://www.imo.org/en/OurWork/TechnicalCooperation/GeographicalCoverage/AandP/Pages/Default.aspx⟩.

[3] Asian Development Bank, Responding to Climate Change in the Pacific: Moving from Strategy to Action, ADB, Mandaluyong City, 2010.

[4] Secretariat of the Pacific Community, Framework for Action on Transport Services 2011–2020': Improving the Efficiency, Effectiveness and Sustainability of Pacific Transport Services, SPC, Suva, 2011.

[5] P. Nuttall, A. Newell, B. Prasad, J. Veitayaki, E. Holland, A review of sustainable sea transport for Oceania: providing context for renewable energy shipping in the Pacific, Mar. Policy 43 (2014) 283–287, https://doi.org/10.1016/j.marpol.2013.06.009.

[6] P. Nuttall, M. Vahs, J. Morshead, et al., The case for field trialing and technology/knowledge transfer of emerging low carbon maritime technologies to Pacific Island Countries. Renewable Energy: Sources, Applications and Emerging Technologies, Nova Science Publishers, New York, 2016, pp. 159–185. ISBN 9781634856515.

[7] A. Irvin, A. Newell, L. Zay, et al., The Last Mile: the Costs of Shipping to Pacific SIDS (in preparation).

[8] United Nations Economic and Social Commission for Asia and the Pacific, Sustainable developing in the Pacific: progress and challenges. In Pacific Regional Report for the 5 year Review of the Mauritius Strategy for Further Implementation of the Barbados Programme of Action for Sustainable Development of SIDS, UNESCAP Sub-Regional Office for the Pacific, Suva, 2010.

[9] United Nations Conference on Trade and Development, Closing the Distance – Partnerships for Sustainable and Resilient Transport Systems in SIDS, UNCTAD, Geneva, 2014.

[10] A. Newell, P. Nuttall, B. Prasad, J. Veitayaki, Turning the Tide: the need for sustainable sea transport in the Pacific, Mar. Policy 75 (2016) 249–259, https://doi.org/10.1016/j.marpol.2016.01.009i.

[11] The Guardian, 2019. ⟨https://www.theguardian.com/environment/2019/sep/24/pacific-islands-seek-500m-ocean-shipping-zero-carbon?CMP=Share_iOSApp_Other⟩. (Accessed 24 Feburary 2020).

[12] ⟨https://mcst-rmiusp.org/index.php/projects/current-projects/pacific-blue-shipping-partnership⟩.

[13] P. Nuttall, A. Newell, B. Prasad, J. Veitayaki, E. Holland, A review of sustainable sea-transport for Oceania: providing context for renewable energy shipping for the Pacific, Mar. Policy 43 (2013) 283–287, https://doi.org/10.1016/j.marpol.2013.06.009i.

[14] B. Prasad, J. Veitayaki, E. Holland, et al., Sustainable Sea Transport Research Programme: toward a research-based programme of investigation for Oceania, J. Pac. Stud. 33 (2013) 78–95.

[15] A. Goundar, A. Newell, P. Nuttall, I. Rojon, J. Samuwai, King Canute muses in the South Seas: why aren't Pacific islands transitioning to low carbon sea transport futures? Mar. Policy 81 (2017) 80–90.

[16] Pacific Blue Shipping Partnership, Technical Working Paper 1, 2020. ⟨https://www.mcst-rmiusp.org/images/Projects/PBSP2019/PBSP_Technical_Working_Paper_1_v6.pdf⟩.

[17] Pacific Blue Shipping Partnership, Technical Working Paper 2, 2020. ⟨https://www.mcst-rmiusp.org/images/Projects/PBSP2019/Technical_Working_Paper_2_final.pdf⟩.

[18] Asian Development Bank, Oceanic Voyagers: Shipping in the Pacific. Pacific Studies Series, ADB, Manila, Philippines, 2007.

[19] J.R. Moon, Strengthening Inter-island Shipping in the Pacific Island Countries and Territories, Background Paper, ESCAP, 2013. ⟨http://www.unescap.org/sites/default/files/Background-Paper.pdf⟩.

[20] C.J. Satchwell, Preliminary Analysis of Log Data From the Fiji windship 'Cagidonu'. Ship Science Reports, University of Southampton, Southampton, 1986.

[21] O. Buhaug, J. Corbett, O. Endresen, et al., Second IMO GHG Study 2009, IMO, London, 2009. ⟨http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/SecondIMOGHGStudy2009.pdf⟩.

[22] Smith, Third IMO GHG Study 2014, IMO, London, 2014. ⟨http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/Third%20Greenhouse%20Gas%20Study/GHG3%20Executive%20Summary%20and%20Report.pdf⟩.

[23] B. Romera, T. Smith, B. Milligan, et al., Workshop Report: Nordic Action for a Transformation to Low-carbon Shipping, Nordic Council of Ministers, 2017. ISBN 978-92-893-5072-3. ⟨http://publications.lib.chalmers.se/records/fulltext/254665/local_254665.pdf⟩.

[24] Department for Transport, Clean Maritime Plan, Department for Transport, London, UK, 2019. ⟨https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/815664/clean-maritime-plan.pdf⟩.

[25] International Transport Forum, Decarbonizing Maritime Transport: The Case of Sweden, International Transport Forum Policy Papers, No. 46, OECD Publishing, Paris, 2018. ⟨https://doi.org/10.1787/99514381-en⟩.

[26] Asian Development Bank, Proceedings of Regional Conference on Sail-motor Propulsion, 18–21 November. ADB, Manila, Philippines, 1985.

[27] C.J. Satchwell, Windship technology, in: Proceedings of the International Symposium on Windship Technology (Windtech '85), Southampton, UK, 1985.

[28] B.R. Clayton, Wind assisted ship propulsion, Phys. Technol. 18 (1987) 53–60.

[29] Sustainable Sea Transport Talanoa, Programme and Presentations, 2012. ⟨https://www.usp.ac.fj/index.php?id=12461⟩.

[30] 2nd Sustainable Sea Transport Talanoa, Programme and Presentations, 2014. ⟨https://www.usp.ac.fj/index.php?id=16753⟩.

[31] P.R. Nuttall, Steering a course for the future with sticks, stones, grass and little sharkskin: the case for revitalisation of sail technology and sailing culture as a practical sea transport response to climate change and fossil fuel dependence/supply issues in Fiji, J. Pac. Stud. 32 (2012) 163–175.

[32] E. Holland, P. Nuttall, A. Newell, B. Prasad, J. Veitayaki, A. Bola, J. Kaitu'u, Connecting the dots: policy connections between Pacific Island shipping and global carbon dioxide and pollutant emissions reduction, Carbon Manag. 5 (1) (2014) 99–105.

[33] P. Nuttall, J. Kaitu'u, The Magnus effect and the Flettner rotor: potential application for oceanic shipping, J. Pac. Stud. 36 (2) (2016) 161–182.

[34] UNCTAD, Transitioning to Low Carbon Shipping Module – Sustainable Sea Transport Solutions for SIDS: Pacific Islands Countries Case Studies, Online SFTF-toolkit, UNCTAD, 2015. ⟨https://unctadsftportal.org/sftftoolkit/transitioningtolowcarbonshippingmodule/⟩.

[35] M. Vahs, S. Wagner, T. Peetz, et al., 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, University of Applied Sciences Emden/Leer, 2019. ⟨https://mcst-rmiusp.org/images/Projects/TLCSeaT_HEL_TechnicalAndOperationalOptionsCatalog.pdf⟩.

[36] ⟨https://mcst-rmiusp.org/index.php/projects/current-projects/cerulean-project⟩.

[37] ⟨http://mtccpacific.spc.int⟩.

[38] ⟨https://gmn.imo.org⟩.

[39] The Pacific Community, 2019. ⟨https://www.spc.int/updates/news/2019/10/reducing-greenhouse-gas-emissions-in-maritime-sector-saving-thousands-for-boat⟩.

[40] T. Smith, The Shipping Industry May Finally Be Turning To Wind Power – Interview at 2.46 min on, 2017. ⟨https://www.youtube.com/watch?v=EZoE_BKizxI⟩.

[41] O. Merk, L. Kirstein, R. Halim, Decarbonising Maritime Transport: Pathways to Zero-carbon Shipping by 2035, Case-specific Policy Analysis, International Transport Forum/OCED, Paris, 2018. ⟨https://www.itf-oecd.org/sites/default/files/docs/decarbonising-maritime-transport.pdf⟩.

[42] E. Bouman, E. Linstad, A. Rialland, A. Stromman, State of the art technologies, measures, and potential for reducing GHG emissions from shipping – a review, Transp. Res. Part D: Transp. Environ. 52 (2017) 408–421. ⟨https://www.researchgate.net/publication/315837106_State-of-the-art_technologies_measures_and_potential_for_reducing_GHG_emissions_from_shipping_-_A_review⟩.

[43] T. Smith, E. O'Keeffe, E. Hauerhof, et al., 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, Department of Transport, London, 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⟩.

[44] International Maritime Organisation Global Maritime Energy Efficiency Partnerships: Fleet and CO2 calculator. ⟨https://glomeep.imo.org/resources/fleet-and-co2-calculator/⟩. (Accessed 24 Feburary 2020).

[46] Pacific Community, National Technology Needs Assessment Report, 2019. ⟨https://gmn.imo.org/wp-content/uploads/2020/11/MTCC-Pacific-National-Technology-Needs-and-Barriers-Report-for-publication.pdf⟩.

[47] Schneekluth Hydrodynamik Schneekluth Wake Equalizing Duct. ⟨https://www.schneekluth.com/en/⟩ (Accessed 24 Feburary 2020).

[48] Fathom Shipping, Propeller Technology to Make Your Ship More Efficient, gCaptain 17 July 2012. ⟨https://gcaptain.com/propeller-technology-ship-efficient/⟩.

[49] M. Hoen, J. Faber, R. Vergeer, et al., Historical Trends in Ship Design Efficiency: The Impact of Hull Form on Efficiency, CE Delft, Delft, 2016. ⟨https://www.cedelft.eu/publicatie/historical_trends_in_ship_design_efficiency/1761⟩.

[50] SSPA Sweden AB, Hull Air Lubrication: Future and Challenges, 2018. ⟨https://www.sspa.se/ship-design-and-hydrodynamics/hull-air-lubrication-future-and-challenges⟩.

[51] J. Snyder, First Air Lubricated LNG Carriers Joins Maran Gas Fleet, 2019. ⟨https://www.rivieramm.com/news-content-hub/first-air-lubricated-lng-carrier-joins-maran-gas-fleet-56931⟩.

[52] T. Smith, C. Raucci, S. Hosseinloo, et al., CO2 Emissions from International Shipping: Possible Reduction Targets and Their Associated Pathways, UMAS, London, 2016. ⟨https://u-mas.co.uk/LinkClick.aspx?fileticket=na3ZeJ8Vp1Y%3D&portalid=0⟩.

[53] F. Tillig, W. Mao, J. Ringsberg, Systems Modelling for Energy-efficient Shipping. Report No 15:153, Department of Shipping and Marine Technology, Chalmers University of Technology, Göteborg, Sweden, 2015. ⟨https://research.chalmers.se/en/publication/211480⟩.

[54] P. Gilbert, A. Bows-Larkin, S. Mander, C. Walsh, Technologies for the high seas: meeting the climate challenge, Carbon Manag. 5 (4) (2014) 447–461, https://doi.org/10.1080/17583004.2015.10136766.

[55] R. Winkel, A. Van den Bos, U. Weddige, Study on Energy Efficiency Technologies for Ships – CLIMA.B3/ETU/2014/0023r, European Union, Luxembourg, 2015. ISBN: 978–92-79–48424-7.⟨http://publications.europa.eu/resource/cellar/302ae48e-f984–45c3-a1c0–7c82efb92661.0001.01/DOC_1⟩.

[56] J. Faber, D. Nelissen, Regulated slow steaming in maritime transport: and assessment of options, costs and benefits, Transport and Environment and Seas at Risk, CE Delft, 2012. ⟨https://www.cedelft.eu/publicatie/regulated_slow_steaming_in_maritime_transport/1224⟩.

[57] H. Lindstad, B. Asbjornslett, A. Stromman, The importance of economies of scale for reductions in greenhouse gas emissions from shipping, Energy Policy 46 (2012) 386–398, https://doi.org/10.1016/j.enpol.2012.03.077.

[58] Hapag-Lloyd, How Vessel Trim Optimisation Creates Efficiencies, 2017. ⟨https://www.hapag-lloyd.com/en/news-insights/insights/2017/03/how-vessel-trim-optimisation-creates-efficiencies.html⟩. (Accessed 24 Feburary 2020).

[59] Port of Rotterdam, 'Just-in-time' Sailing Saves Hundreds of Thousands of Tonnes of CO2, 2018. ⟨https://www.portofrotterdam.com/en/news-and-press-releases/just-in-time-sailing-saves-hundreds-of-thousands-of-tonnes-of-co2⟩. (Accessed 24 Feburary 2020).

[60] O. Merk, Shipping Emissions in Ports, International Transport Forum Discussion Papers. No. 2014/20 OECD Publishing, Paris, 2014. ISSN: 2223439X. ⟨https://www.oecd-ilibrary.org/transport/shipping-emissions-in-ports_5jrw1ktc83r1-en⟩.

[61] The Pacific Community, 'Green Pacific Port initiative' Looks to Improve Port Operations Across The Pacific, 2018. ⟨https://www.spc.int/updates/news/2018/09/green-pacific-port-initiative-looks-to-improve-port-operations-across-the⟩. (Accessed 24 Feburary 2020).

[62] The Maritime Executive, Flettner Rotor Exceeds Expectations, 2018. ⟨https://www.maritime-executive.com/article/flettner-rotor-exceeds-expectations⟩. (Accessed 24 Feburary 2020).

[64] E.A. Bouman, E. Lindstad, A.I. Rialland, A.H. Strømman, State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping – a review, Transp. Res. Part D: Transp. Environ. 52 (Part A) (2017) 408–421. ⟨https://www.sciencedirect.com/science/article/pii/S1361920916307015⟩.

[65] Neoline, Neoline Selects Neopolia's Offer for the Construction of its First Two 136 m Sailing Cargo Ships in Saint-Nazaire, 2019. ⟨https://www.neoline.eu/en/neoline-selects-neopolias-offer-for-the-construction-of-its-first-two-136m-sailing-cargo-ships-in-saint-nazaire/⟩. (Accessed 24 Feburary 2020).

[66] R. Held, Typical fuel analysis of a KWAI voyage, Sailing Vessel Kwai, 2017. ⟨http://svkwai.com/typical-fuel-analysis-kwai-voyage/⟩.

[67] ⟨https://www.neoline.eu/en/the-neoline-solution/⟩. (Accessed 24 Feburary 2020).

[69] P. Blinkhorne, Wind-assisted Propulsion for Sustainable Shipping in the South Pacific (Master's Thesis), University of Manchester, Manchester, UK, 2016.

[71] L. Mofor, P.R. Nuttall, A.P. Newell, 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⟩.

[72] D. Li, A New Type of Collapsible Wing Sail and its Aerodynamic Performance, in: Proceedings of the 36th International Conference on Ocean, Offshore and Arctic Engineering, Trondheim, Norway, 2017. DOI: 10.1115/OMAE2017-61084. ⟨https://www.researchgate.net/publication/318361455_A_New_Type_of_Collapsible_Wing_Sail_and_its_Aerodynamic_Performance⟩.

[73] G. Atkinson, H. Nguyen, J. Binns, Considerations regarding the use of rigid sails on modern powered ships, Cogent Eng. 5 (2018), 1543564, https://doi.org/10.1080/23311916.2018.1543564. ⟨https://www.cogentoa.com/article/10.1080/23311916.2018.1543564⟩.

[74] T. Waseda, The Wind Challenger Project: Developing Hybrid Sail Assisted Cargo Ship, Department of Ocean Technology, Policy, and Environment, The University of Tokyo Graduate School of Frontier Sciences. ⟨http://www.otpe.k.u-tokyo.ac.jp/en/project_details.html?key=1351657954⟩. (Accessed 24 Feburary 2020).

[75] Enercon. ⟨https://www.enercon.de/en/home/⟩.

[76] The Motorship, Maersk Tanker Rotor Sails Trials A Success, 2019. ⟨https://www.motorship.com/news101/engines-and-propulsion/maersk-tanker-rotor-sails-trial-a-success⟩.

[78] J. Hanses, LNG Cruise Ferry M/S Viking Grace, Norsepower, 2018. ⟨https://www.norsepower.com/cruise-ferry⟩.

[79] M. Traut, P. Gilbert, C. Walsh, A. Bows, A. Filippone, P. Stansby, R. Wood, Propulsive power contribution of a kite and a Flettner rotor on selected shipping routes, Appl. Energy 112 (2014) 362–372. ⟨https://www.sciencedirect.com/science/article/pii/S0306261913005928?via%3Dihub⟩.

[80] M. Vahs, Project MV Fehn Pollux, Eco Flettner GmbH, 2018. ⟨http://www.eco-flettner-rotor.com⟩.

[81] M. Traut, The Shipping Forecast – wind power, weather models, and fuel savings, in: Proceedings of the Presentation to 2nd Sustainable Sea Transport Talanoa, Tyndall Centre for Climate Change Research, University of Manchester, 2014. ⟨https://www.usp.ac.fj/fileadmin/files/conferences/2013/2014_Sustainable_Sea_Transport/Presentations/Day_2/1._Michael-traut-SCC.pdf⟩.

[82] M. Vahs, R. Oltmanns, An Innovative Wind Propulsion System for Greener Shipping, 2017. ⟨http://marigreen.eu/wordpress_marigreen/wp-content/uploads/2017/01/Eco-Flettner_description-short_2017.pdf⟩.

[83] H. Hoffmeister, Eco Flettner Rotor Sail Stands the Test, 2019. ⟨https://www.dnvgl.com/expert-story/maritime-impact/ECO-FLETTNER-rotor-sail-stands-the-test.html⟩. DNV-GL.

[84] Anemoi Marine Technologies Ltd, ⟨https://www.anemoimarine.com/flettner-rotors/⟩. (Accessed 24 Feburary 2020).

[85] World Maritime News, K Line to Cut Ship Emissions with Automated Power Kites, 2019.⟨https://worldmaritimenews.com/archives/278046/k-line-to-cut-ship-emissions-with-automated-power-kites/⟩.

[86] ⟨https://www.spc.int/updates/news/2019/10/reducing-greenhouse-gas-emissions-in-maritime-sector-saving-thousands-for-boat⟩. (Accessed 24 Feburary 2020).

[87] IRENA, Navigating the Way to A Renewable Future: Solutions to Decarbonize Shipping, Preliminary Findings, International Renewable Energy Agency, Abu Dhabi, 2019. ISBN: 978-92-9260-150-8, ⟨https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Renewable_Shipping_Sep_2019.pdf⟩.

[88] C. Morgan, D. Atkinson, LPG and Natural Gas as Alternative Energy Sources for the Pacific, PRIF, Sydney, 2016. ⟨http://prdrse4all.spc.int/sites/default/files/lpg_and_lng_report.pdf⟩.


## Further reading


[1] International Maritime Organisation, Global Maritime Energy Efficiency Partnerships Ship Emissions Toolkit, 2019. ⟨https://glomeep.imo.org/wp-content/uploads/2019/03/ship_emissions_toolkit-g1-online_New.pdf⟩.

[2] N. Rehmatulla, T. Smith, Barriers to energy efficiency in shipping: a triangulated approach to investigate the principal agent problem in shipping, Energy Policy 84 (2015) 44–47, https://doi.org/10.1016/j.oceaneng.2015.09.030.

[3] A.D. Couper, Sailors and Traders: A Maritime History of the Pacific, Peoples University of Hawai'i Press, Honolulu, HI, 2009.

[4] T. Searcy, Harnessing the wind: a case study of applying Flettner rotor technology to achieve fuel and cost savings for Fiji's domestic shipping industry, Mar. Policy 86 (2017) 164–172.

[5] Cruise News, Greek Dry Bulk Operator Reports Success with Flettner Rotor Sails Onboard mv AFROS, CSP Cruise Ship Portal, 2019. ⟨https://www.cruiseshipportal.com/news/cruise-news-maritime-news/rotor-sails-greek-dry-bulk-operator-reports-success-with-flettner-rotor-sails-onbord-mv-afros/⟩.