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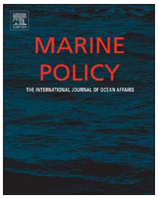

Harnessing the wind: A case study of applying Flettner rotor technology to achieve fuel and cost savings for Fiji's domestic shipping industry

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ARTICLE INFO

Acronyms:
CO$_2$Carbon dioxide
COP 21Conference of the Parties 21 in Paris
GHGGreenhouse gas
GSFSGovernment Shipping Franchise Scheme
GSSGovernment Shipping Service
IRRInternal rate of return
IMOInternational Maritime Organization
IRENAInternational Renewable Energy Agency
NPVNet present value
ROIReturn on investment
PICPacific island country
USDUnited States Dollars
TPUTransport Planning Unit
UNFCCCUnited Nations Framework Convention on Climate Change

ABSTRACT

For over 5000 years, humans have successfully harnessed the power of wind to transport people and goods across the world's oceans. This research expands on previous studies of the unique Flettner rotor propulsion system and the demonstrable success in reducing fuel consumption and carbon dioxide (CO$_2$) emissions. Recent examples such as Enercon's *E-ship 1* have proven seaworthy and economically viable along major shipping routes. The remote Pacific island countries (PICS), however, have the unique characteristics of retaining a remarkable seafaring heritage while remaining on the periphery of global commerce. With data obtained from a field study of Fiji's domestic shipping, this research analyzes the potential for implementing Flettner rotor systems to achieve more economically viable alternatives to the current situation. The findings show that with an incremental approach and the addition of a government fuel savings incentive, the Government Shipping Franchise Scheme (GSFS) subsidies could be significantly lowered for Fiji's ten uneconomical shipping routes. Four scenarios of 5%, 10%, 15%, and 25% fuel savings contrast the baseline data on one extreme with a zero-emissions scenario on the other. The most likely fuel savings scenario of between 10% and 15% results in a 20-year government savings of between 348,042 and 522,063 U.S. dollars and a 20-year cumulative reduction in CO$_2$ emissions of between 2931 and 4396 t. The paper concludes that Flettner rotors show promising results in reducing fuel consumption and CO$_2$ emissions and recommends future studies in collaboration with the Fiji government to develop practical strategies of implementation.

1. Introduction

A variety of renewable energy technology options exist that could theoretically improve cost performance and reduce carbon dioxide (CO$_2$) emissions from sea transportation in Pacific Island countries (PICs). Earlier studies have revealed linkages between sea transportation, fossil fuel dependence, and the negative impacts on local and regional economies [1–3]. As the irrefutable evidence and overwhelming consensus in the scientific community on climate change becomes ever more apparent, industry leaders must take urgent action to ensure the transition to a clean economy. While the shipping industry remains unbound to any global agreements or targets set by the United Nations Framework Convention on Climate Change (UNFCCC),[2] governments, industry, technological firms, and the finance sector should work in a coordinated, concerted effort to reverse the growing emissions of the shipping industry [1,3,4].

Having one of the most robust economies (GDP approximately US $8.3 billion) and institutional capacities among PICs, Fiji is best positioned to be the first island country to systematically implement sustainable shipping solutions [2,3,5]. Fiji contains over 330 islands (110 of which are inhabited), has a population of approximately 915,000, and relies on blue water sea transportation to connect the various islands' economies. While some shipping routes are economically viable, 10 routes are considered uneconomic and require assistance from Fiji's Government Shipping Franchise Scheme (GSFS), which was originally implemented to fund 42% of the cost of the fuel to attract private operators to service the routes monthly [6].

Despite the fact that 10,000 t and smaller vessels, which carry around 4% of global cargo load, account for approximately 26% of all global shipping emissions [7], the majority of research and development opportunities – as well as available funding – are allocated to larger vessels for inherent economic rationalization. It is in this backdrop that the older, more inefficient ships comprising the entirety of Fiji's domestic shipping fleet can benefit from much needed research and practical applications. Despite these challenges, the reward of demonstrating to the world a commitment to the development of a new

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[2] Under the Kyoto Protocol, the authority of setting emissions standards and targets for the shipping industry until 2020 are delegated to the International Maritime Organization (IMO).

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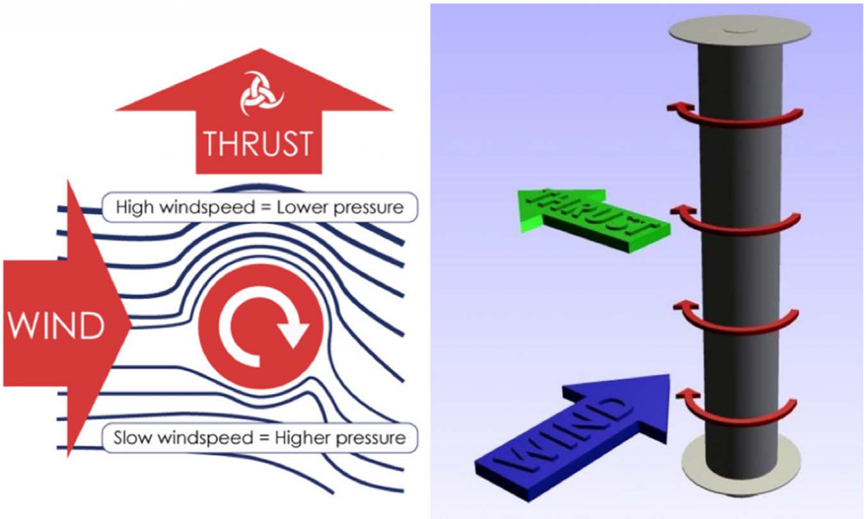

Fig. 1. Magnus effect on rotating cylinder.
(Source: http://www.norsepower.com/rotor-sail-solution/technology)

interisland shipping program based on renewable energy technologies could act as a catalyst to propel other developments in sustainable shipping. Furthermore, the incentives and possibilities in the wake of the twenty-first Conference of Parties (COP 21) in Paris reveal significant funding opportunities available for countries committed to clean energy and reducing CO_2 emissions [8].

This paper is a data-driven case study of Flettner rotors – one of the more promising applications – in comparison with the current baseline scenario and a theoretically zero emissions scenario to determine the overall economic feasibility and its effectiveness at reducing CO_2 emissions in Fiji's domestic shipping industry. The Flettner rotor is a viable renewable energy technology option, as recent research shows potential savings of 24.1% of normal engine power on the Suva, Fiji to Uvea, Wallis & Futuna route [9]. The theoretical fuel savings are significant for the oil-dependent PICs economies; however, a more realistic economic assessment is necessary to determine the underlying business case of implementing such technologies. In a market-based economic system, the priority of shipping owners, charterers, and operators is maximizing profits; if applications such as Flettner rotors prove financially interesting and profitable, businesses are likely to show much more interest in implementing them as quickly as possible. The four Flettner rotor scenarios represent fuel savings potentials of 5%, 10%, 15% and 25% when compared with the baseline scenario. Additionally, a zero emissions scenario represents 95% fuel savings to account for more realistic operational measures, where it would be unadvisable to have no diesel backup for safety considerations (such as navigating close to shoal water, anchoring, or in the absence of wind).

2. Flettner rotors: theoretical foundations and practical trials

In order to fully demonstrate the economic and emissions reduction potential of introducing Flettner rotor technology to the domestic shipping routes of Fiji, an examination of the relevant scientific principles and historical developments of the technology provides a background understanding of the research findings. This section begins with an exposition on the Magnus effect, as it is the underlying principle on which Flettner rotors function, followed by key historical experiments and designs over the past century as well as current trends in research and development. With this background information, an analysis of the more recent data from Fiji's uneconomical domestic shipping routes will have sufficient context to develop scenarios of realistic economic feasibility.

2.1. The Magnus effect

Centuries ago, artillerists and ballistics experts – along with ball players of certain sports – observed unexpected trajectories of spherical objects. The explanation for this appeared as early as 1742, when B. Robins opined that these deviations in trajectories were due to the ball's rotation itself. In the first half of the 19th century, Robins experimented with spheres containing offset centers of gravity that resulted in corresponding deflections in the actual path of the spheres [10]. Robins showed that a sphere rotating in different variations resulted in a transverse force acting upon the sphere itself. Heinrich Gustav Magnus scientifically verified the eponymous effect in 1853 by experimenting with a centrifugal blower producing an air stream over a brass cylinder [10].

The Magnus effect is closely related to the Bernoulli principle, which correlates velocity and pressure of a moving fluid. As pressure increases, velocity of the fluid must decrease, and vice versa. Bernoulli's equation expresses this statement:

$$P = C - \frac{1}{2}dv^2 \tag{1}$$

Eq. (1): Bernoulli's equation

where P is pressure, C is a constant, d is the constant density of fluid, and v is the fluid velocity. This equation, simplified for study in ideal conditions at constant elevation, is similar to the Magnus effect, the difference being that the rotation of a rotating or spinning object itself causes the change in velocity. The following equation shows this force:

$$Fm = S(w \bullet v) \tag{2}$$

Eq. (2): Force from rotating object

where Fm is the Magnus force vector, S is the air resistance coefficient, w is the object's angular velocity, and v is the velocity of the fluid [11]. Subsequently, Lord Rayleigh mathematically proved this, demonstrating that airflow around the cylinder, if superimposed with a circular motion, generates lift at a right angle to the airflow [12]. In other words, rotation of the cylinder induces a perpendicular Magnus force, or lift (Fig. 1). This effect is noticeable in sports such as tennis and golf. Professional tennis players use this effect to cut the ball over, under, left, or right in order to produce a lift force in the opposing direction. Similarly, golf professionals know how to benefit from the Magnus effect in certain swings, such as driving the ball greater distances with lift generated by applying an undercut. The lift force is similarly applied to a cylinder, which is the basis for the technological application of Flettner rotors for ships.

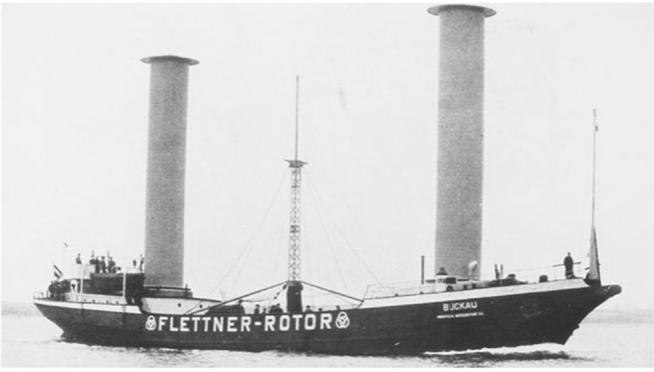

Fig. 2. First Flettner rotor ships *Buckau* (later renamed *Baden-Baden*), circa 1925. (Source: http://www.deutsches-museum.de/en/information/young-people/inventors-trail/drivetrains/flettner-rotor/)

2.2. From theory to sea: the first flettner rotor ship

In the early 1920s, a young German mathematics and physics teacher named Anton Flettner learned of the quantitative study of the Magnus effect on rotating cylinders at the Institute of Aerodynamics in Göttingen (Ergebnisse Aerodynamische Versuchsanstalt, Göttingen) under the guidance of Ludwig Prandtl. Together with his experimentation of improving sail ships, this caused Flettner to invent an eponymous “upright-mounted cylinder rotated by a motor” for ship propulsion [13,14]. In the first well-documented and successful trial, two rotating cylinders – each 18.3 m in height and 2.8 m in diameter – provided propulsion to a rebuilt German sailing ship called *Buckau* (later renamed *Baden-Baden*) in 1924 [14,15]. Projecting disks were added to prevent airflow entry into the area of negative pressure and to minimize induced drag, advantages that ensured greater efficiency of the Magnus effect [16].

The striking image of *Buckau* reveals the innovative design of this first Flettner rotor ship and the practical application of the Magnus effect on sea transportation (Fig. 2). This unique appearance and the remarkable functionality of the Flettner rotor ship drew contemporaneous attention and praise:

> *On May 9, 1926, there sailed into New York harbor a huge, decidedly unconventional ship whose strange appearance gave rise to widespread interest and publicity. Mounted on its deck were two enormous rotating cylinders, each of which was 45 feet high and 9 feet in diameter. The ship looked awkward and top-heavy, yet it had just crossed the Atlantic Ocean from Germany carrying a crew of 14 and using only the rotating cylinders for motive power for 70% of the distance [15].*

The 6,200-nautical mile voyage described in the aforementioned passage reportedly used approximately 12 t of fuel oil, whereas a similar ship without rotors would have used around 45 t [17].

Building on the momentum of *Buckau*, in 1926 the German shipyard A.G. Weser constructed a larger vessel named *Barbara*, this one powered by three rotors [18]. However, despite the proven seaworthiness and functionality of the Flettner rotor application, the invention could not compete with the steam and diesel engines and the rapidly expanding supply of inexpensive fossil fuels of its era [19]. Furthermore, a major setback to the Flettner rotors on *Buckau* was that the rotation of the cylinders required power from motors, rather than relying solely upon wind. In fact, this proved to be the most significant issue, since the propulsion system was less economical in comparison to other means available at the time [14].

However, when compared with traditional sailing vessels, the Flettner rotor vessel demonstrated significant advantages. Whereas soft sails require continual adjustments with changing wind directions and speed – and thus laborious efforts, the Flettner rotor only requires simple adjustments in the speed of the electric motor[3] [20]. In the case of a shift in wind direction of 180 degrees, one simply must reverse the rotation of the cylinders; additionally, a Flettner rotor ship with two cylinders can turn in place by rotating each cylinder in opposite directions [20]. Furthermore, the rotor proved to be extremely durable and seaworthy due to its peculiar load characteristic of leaning into the wind rather than being pushed to leeward as in a traditional sailing ship [21]. This technological innovation was ahead of its time and could have caught on as a common ship propulsion systems, but the rise of cheap MDO around 1928 made it untenable. In the current market-driven era of maximizing profits first and foremost, shipping companies and ship builders have little incentive to experiment and perfect renewable energy technologies. Thus, the Flettner rotor ship design lay dormant, waiting for the right time to reactivate the shipping industry's focus on systems of greater energy efficiency and lower fuel consumption.

2.3. Modern developments in rotor technology: 1980 – present

The oil shock of the late 1970s proved to be the spark that ignited a renewed interest in fuel savings and energy efficient technologies. Various feasibility studies, innovative designs, and supporting financial mechanisms coalesced under a new economic incentive to promote greater fuel savings [21,22]. A comprehensive collection of critical research from the early 1980s, *Windship Technologies: Proceedings of the International Symposium on Windship Technology* reveals a consortium of policy experts, naval architects, and economists advancing the study and implementation of wind-assist vessels [23]. In this, C. Satchwell documents soft sail retro-fit trials of a 274-ton coastal passenger and cargo ship in Fiji, saving an average of 23% fuel at more than 30% internal rate of return (IRR) [23]. A thorough review of these proceedings provides insight into key aspects related to windship technologies of the 1980s, especially the relevant research, implementation and sea trials of Flettner rotor vessels of that time.

Beginning in 1980, renowned explorer Jacques-Yves Cousteau began searching for a new exploration vessel of unique design characteristics and a more efficient propulsion system. Partnering with fellow Frenchman L. Malavard, Cousteau and his team embarked on a new system – different from a rotorship in that the cylindrical-like masts do not rotate – with the development of the trademarked Turbosails propulsion system [24]. In 1982, the prototype system was installed on *Moulin à vent*, an existing Solaris catamaran, to experiment and refine the Turbosails system (Fig. 3) [25]. The local trials were extremely successful, with the single 30-meter squared cylinder able to propel the 42-ton catamaran at a surprisingly quick speed of 8 knots; however, the trans-Atlantic trial revealed performance and structural integrity issues, ultimately leading to the collapse of the sail itself [25]. After fine-tuning the system and redesigning the hull to suit the propulsion system and meet the functional purpose of the Cousteau Society, the team developed and delivered a vessel purportedly capable of saving 20–60% fuel [26].

The launch of Costeau's *Alcyone* in 1985 revealed the ultimate design of the Turbosail propulsion system, featuring two identical sails, each 10 m high with 21 m^2 of surface area (Fig. 4) [25,27]. The unique hull design was essentially a monohull bow and catamaran stern that provided added stability and strength. Together with an automated servosystem that synchronizes the Turbosails with its twin diesel engines, the *Alcyone* reportedly saves one-third the fuel that a similar sized vessel consumes under conventional propulsion [27]. For over thirty years, *Alcyone* has been a flagship vessel of ocean conservation and exploration voyages around the world – a testament to the functionality and strength of its Turbosails system [28].

Also during this time of high oil prices, the Wind Ship Company –

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[3] However, the Flettner rotor may be powered by means other than an electric motor, such as diesel or other alternatives.

First exhilarating moments: the prototype takes an early trial run off Marseilles.

Fig. 3. *Moulin à vent* sea trials with prototype Turbosails system.
(Source: http://www.usmarinegroup.com/75/)

Fig. 4. Cousteau vessel *Alcyone* in harbor with its trademarked Turbosails propulsion system visibly dominant.
(Source: https://commons.wikimedia.org/wiki/File:Rotorship_Alcyone_in_harbour.jp)

headed by naval architect Lloyd Bergeson – determined that the Flettner rotor is the most economically feasible and technologically practical system for wind-assisted shipping in a comparative study of 75 wind-assist rigs [29]. Bergeson fitted a prototype aboard *Tracker*, a 13-meter, 18-ton launch. The single rotor was 7.3 m high and 60 cm in diameter, driven by a variable speed hydraulic motor. With an average wind speed of 12.9 knots, *Tracker* averaged 6.0 knots and saved approximate 27% of fuel [30]. Although research, experiments and practical sea trials confirmed the practicality and efficiency of this technology, the return of low oil prices once again induced another hiatus on wind-assist progress.

More recently however, the rising insecurity of oil prices together with forthcoming regulations on shipping emissions has led to another renewed interest in wind-assist research and technology [21]. This recent growth in research and development around the world – from engineering studies at Hochschule Emden-Leer and the University of Flensburg in Europe to German clean energy giant Enercon's noteworthy and large-scale vessel *E-Ship 1* (Fig. 5) – is encouraging. This latter example is a promising model for large vessels in its comprehensive design based on efficiency at multiple levels – from hull and propeller shape to advanced Flettner rotors for propulsion assistance. Its design is such that the exhaust from the diesel engines is recycled as a driving force for a steam turbine that assists in electricity generation used to rotate its four Flettner rotors. The contribution of *E-Ship 1* to clean transport is considerable, for not only is it used to primarily transport Enercon's wind turbines and converters, but it directly attributes for up to 15% fuel savings depending on weather conditions [31].

Fig. 5. Enercon's *E-Ship 1*.
(Source: Enercon E-Ship 1: A wind-hybrid commercial cargo ship. 4th Conference on Ship Efficiency. Hamburg, 23–24 September 2013.)

3. Application to Fiji's uneconomical domestic shipping routes

With the exposition of the Flettner rotor described above, a more holistic approach of developing realistic economic scenarios is possible. This section combines the data collected from field research in Fiji with a specific budgetary model to demonstrate feasible scenarios of Flettner rotor applications in Fiji.

3.1. Background route data

From the aggregate 2014 route data provided by the Government of Fiji's Transport Planning Unit (TPU), results from previous research of the lower southern Lau route are extrapolated to determine an approximate baseline scenario for all of Fiji's ten uneconomical domestic shipping routes given in Table 1 [3]. In total, the 10 uneconomical routes comprise a total of 3930 nautical miles per month, or 47,160 nautical miles per year (Table 1) [3]. Assuming the routes remain constant in both distance and number of voyages per month, this total

Table 1
Aggregate annual distance of uneconomical routes.

Route	NM/voyage	Voyage/month	NM/month
Northern Lau I	201	1	201
Northern Lau II	396	1	396
Upper Southern Lau	417	2	834
Lower Southern Lau	416	1	416
Yasayasa Moala	281	2	562
Rotuma	822	1	822
Kadavu	118	2	236
Lomaiviti I	140	1	140
Lomaiviti II	140	1	140
Yasawa-Malolo	183	1	183
Total NM/month			3930
Total NM/year			**47,160**

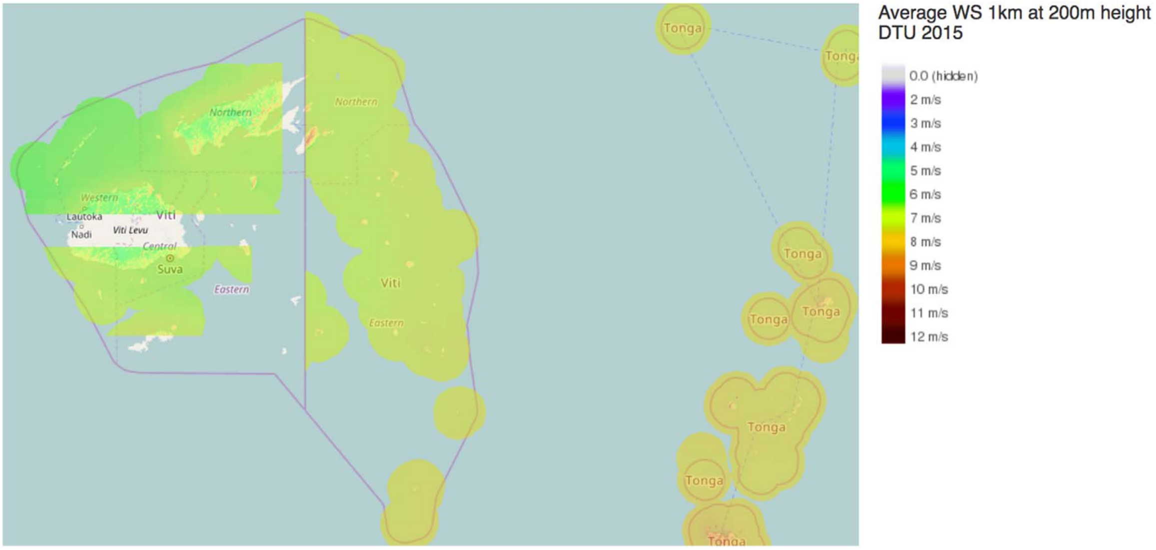

Fig. 6. Average wind speed in Fiji.
(Source: http://irena.masdar.ac.ae/?&map=103&utm_medium=email&utm_source=May 2016Update&utm_campaign=Version2-1&utm_content=GWA)

distance provides an initial baseline number from which to calculate all the necessary data for economic modeling, fuel consumption, and CO_2 emissions.

Before commencing any economic assessment of possible scenarios, a necessary task is to determine a general understanding and description of climatic wind conditions in Fiji. First, a supply of favorable wind speed and direction increases the potential for valuable efficiency gains. The International Renewable Energy Agency's (IRENA) Global Atlas provides a general overview of Fiji's average annual wind speed (Fig. 6). Another, more accurate source of both speed and direction, the Fiji Meteorological Service's 2015 data reveals the overall wind speed of between 4.2 and 6.3 knots, predominantly from the east to southeast [32]. And despite the less favorable conditions of the southeast trade winds during certain months of the year, for purposes of this assessment scenarios of between 5% and 25% fuel savings are indeed viable. Without primary data collection over the entire climatic cycle and key points along the routes, the most-likely assumption of fuel savings lies between 10% and 15%.

Table 2
Establishing baseline financial data.

Data	Unit	Lower Southern Lau	Aggregate total, uneconomical routes
Fuel cost after government concession	USD/l[a]	0.83	–
Approximate fuel cost-distance	USD/NM	11.13	–
Annual distance	NM	4992	47,160
Fuel consumption, annual	Metric tons	60	571
Total fuel cost, annual	USD	55,538	525,000[b]
O & M estimate, annual	USD	–	1400,000[c]
Cargo revenue, annual	USD	–	441,000[b]
Passenger revenue, annual	USD	–	769,000[b]
GSFS support, annual	USD	–	717,000[b]

[a] All currency reported in USD and based on exchange rate of 0.48 FJD/USD.
[b] Values given in Appendix 3 rounded to nearest thousand (1000).
[c] Estimate assuming minimum profit after GSFS support.

3.2. Baseline scenario and assumptions

With a general understanding of the favorable wind conditions in Fiji, the next step in determining the baseline scenario is to aggregate the total cargo and passenger flows as well as the estimates in cost and fuel consumption data from the field research (Table 2). The fuel price is based on the March 2015 government concession rate and, when combined with consumption quantity, is expressed as U.S. dollars (USD) per nautical mile. Additional variables include the total subsidies provided by the GSFS, and an estimate of operation & maintenance costs. This estimate assumes a small profit margin that is only possible with GSFS support. Extrapolating this data for all ten uneconomical routes rounded to the nearest thousand USD provides the baseline financial estimation for all fuel savings scenarios.

These initial estimates are necessary for the development of the baseline scenario and the five alternative models that examined in the subsequent section. The scenarios consider retrofitting a single Flettner rotor of the same size on each of the service vessels for direct comparison. The alternative scenarios are estimates of Flettner rotor fuel savings of 5%, 10%, 15%, and 25% as well as one zero-emission vessel design based on the Greenheart Project vessel as described in Section 3.3, all compared against a baseline scenario and set to a 20-year period. For all five alternative scenarios, the technological implementation is programmed for installation every two years, allowing for practical, incremental alterations of the five vessels required to service the ten routes. Furthermore, for theoretical comparisons, this financial modeling necessitates important assumptions and constraints in a more dynamic and variable real-world application. These include:

- Annual inflation rate of 1%
- All associated costs increase at the rate of inflation over the 20-year period
- Fuel costs for the Flettner rotor engine are excluded from the fuel savings percentages
- The GSFS subsidy decreases at the same rate of fuel savings, while increasing at the rate of inflation
- The revenue from cargo grows 2% annually on top of inflation to reflect the increasing freight rate or possible growth in transportation of goods, while the revenue from passengers grows only at the rate of inflation (reflecting the expressed concern of surveyed passengers)
- The fuel price reflects the government concession allocated to the shipping industry in Fiji
- The fuel consumption and CO_2 emissions are extrapolated from *MV*

Table 3
Baseline scenario key figures.

Figure	Unit	Year 0	20-year total
Expenditure	**USD**	**1,925,000**	**44,735,449**
- O & M	USD	1400,000	32,534,872
- Fuel	USD	525,000	12,200,577
Revenue	**USD**	**1,927,000**	**44,979,876**
- Cargo	USD	441,000	10,446,434
- Passenger	USD	769,000	17,870,940
- GSFS	USD	717,000	16,662,502
Fuel consumption	**Tons/year**	**571**	**11,999**
CO_2 emissions	**Tons/year**	**1,832**	**38,467**

Liahona, the vessel servicing the lower southern Lau islands and most likely the smallest of the ships on the subsidy scheme [3]

- A single Flettner rotor is assumed to be compatible with all ship designs for a standardized comparison

This final assumption listed above is most likely an underestimate of fuel consumption, since most vessels are larger and carry more passengers and cargo. Additionally, the growth in both passenger revenue and cargo revenue may grow at a faster rate than this model's estimate. Thus, the final financial benefits in this economic assessment are likely to be more conservative than the true values, erring on the side of caution considering a recent lack of proof-of-concept models at this scale.

Considering the assumptions listed above and a constant distance, route timing, and fuel consumption over the course of 20 years, the baseline scenario reveals an annual fuel consumption of 571 t, resulting in annual CO_2 emissions of 1832 t. The cumulative expenditure on fuel alone amounts to over $12 million and the cumulative injection of subsidies afforded by GSFS is $16,662,502 (Table 3).[4] In other words, for this 20-year period, Fiji's local economy loses more than $12 million in the form of fossil fuel imports, resulting in over 38 thousand tons of harmful CO_2 emissions into the atmosphere. At the same time, the national government is injecting over $16 million into this uneconomical system. Of course, domestic shipping is a necessary service to keep the island communities connected, supplied with goods and services, and to support the interconnectivity of the island nation. By examining alternative fuel savings scenarios with the application of the Flettner rotor system and a zero-emission vessel, improvements in finances, fuel savings, and emissions reductions become apparent.

3.3. *The Greenheart Project: a zero-emission alternative for comparison*

In contrast to the Flettner rotor scenarios for domestic shipping in Fiji, a scenario of a zero-emission vessel shows the extreme end of fuel savings and CO_2 reduction potential. While the Flettner rotor can provide a fractional amount of emissions reductions and fuel savings, a zero-emission vessel presents an alternative model of fuel savings. One design for consideration is the vessel planned by Greenheart Project, which is of an appropriate size and design for most of the domestic routes in Fiji (Fig. 7) [34]. Of course, modifications to the basic configuration should be considered, such as a passenger deck and an adequate cargo hold. The unique A-frame mast that acts as a crane, together with the stern gate and the twin bilge keel design, are critical to the small islands of Fiji that have inadequate or non-existent piers.

Central to this design is the renewable energy technology and battery storage. A combination of sail, solar PV, and lead-acid batteries could theoretically provide the propulsion, auxiliary, and ancillary power to meet most of the energy demand for the vessel [34]. For a more realistic estimate, the zero-emission scenario in this model uses a 95% reduction in fuel consumption. The remaining five percent represents a possible estimate of fuel needed for tight maneuvering, unfavorable weather conditions, or emergency situations. Table 4 below highlights the key characteristics of the Greenheart Project vessel.

Fig. 7. Greenheart Project's zero-emission vessel concept.
(Source: http://greenheartproject.org/en/)

4. Economic assessment of fuel savings options

The financial modeling of the four Flettner rotor scenarios and one zero-emission scenario stems from the baseline calculations of the initial operational year. Maintaining consistency with the above assumptions, these models require additional measures to promote and advance the idea of implementing such alternative technological options. First, to reduce the GSFS subsidies and promote greater fuel efficiency, the models require the use of a simple fuel savings incentive. In this case, the amount of fuel saved each year, per the point estimates of each scenario, are considered as an income to the shipping operators provided by the government. As the forecasting reveals, the gradual reduction of GSFS funds more than compensates the government's efforts to promote fuel efficiency while saving money over the 20-year period.

The capital required for Flettner rotor installation or a new-build zero-emission vessel is set to five separate investments, once every two years, within the first 10-year period. This allows for the continued operations of four vessels while the fifth vessel undergoes refurbishment or replacement. In the meantime, a Government Shipping Service (GSS) vessel or another alternative must be contracted to service the applicable route. While this research does not explore funding sources, the required capital can come in many forms, such as government loan, donor grant, or equity financing. For purposes of establishing a common cost of installation, delivery of a typical system with multiple Flettner rotors is estimated to cost $1 million [33], while the new build Greenheart Project vessel is estimated to cost $2 million [34].[5] For purposes of comparison, the scenarios assumes a 5% interest rate on each of the investments. The annual payments are held constant, but each of the five investments increases per the inflation rate.

4.1. *Flettner rotor scenarios*

The first economic assessment compares the investment potential of installing five Flettner rotor systems on the five separate vessels that

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[4] All monetary values are represented in USD.

[5] The lowest estimate is $1.5 million, however taking into consideration likely unforeseen costs, this research assumes an additional $0.5 million. Indeed, the results would be even more favorable for the zero-emission scenario [34].

Table 4
Greenheart Project vessel design specifications.

Design feature	Details	Design feature	Details
LOA	32 m	Primary propulsion	Sail
Beam	7.5 m	Sail area	400 m^2 (approx.)
Draft		Mast design	A-frame (to double as crane); folding to deck
Displacement	220 t	Auxiliary power	Solar panels
Hull speed	10–11 knots	Batteries	600 kWh (approx.); deep-cycle lead-acid; approx. 20 t to further act as ballast
Hull material	Steel	Motors	150 kW (x2); secondary power
Cargo hold/handling	3 TEU/70 t bulk; stern RORO ramp	Keel design	Twin bilge keels for operational stability

Table 5
Key financial figures of four Flettner rotor scenarios.

Financial figure	5%	10%	15%	25%
Interest on investment	806,132	806,132	806,132	806,132
Expenditure	44,260,414	43,785,379	43,310,344	42,360,275
O & M	32,534,872	32,534,872	32,534,872	32,534,872
Fuel	**11,725,542**	**11,250,507**	**10,775,473**	**9,825,403**
Revenue	44,805,855	44,631,834	44,457,813	44,109,771
Cargo	10,446,434	10,446,434	10,446,434	10,446,434
Passenger	17,870,940	17,870,940	17,870,940	17,870,940
GSFS	**16,013,740**	**15,364,979**	**14,716,217**	**13,418,694**
Fuel savings incentive	**474,741**	**949,481**	**1,424,222**	**2,373,703**
Net cash flow	−260,690	40,323	341,337	943,364
NPV	−213,647	33,047	279,741	773,129
ROI	−5.008%	0.775%	6.558%	18.124%

Table 6
Key financial figures of zero-emission scenario.

Financial figure	Amount
Interest on investment	1612,263
Expenditure	35,709,789
O & M	32,534,872
Fuel	**3,174,917**
Revenue	41,176,212
Cargo	10,446,434
Passenger	17,870,940
GSFS	**3,838,767**
Fuel savings incentive	**9,020,071**
Net cash flow	3854,160
NPV	3158,655
ROI	37.023%

operate the routes in this analysis. With all independent variables held constant, the four models represent incremental fuel gains resulting in ultimate fuel savings of 5%, 10%, 15% and 25% (Table 5). As previously explained, the dependent variables linked to these fuel savings percentages are the GSFS subsidies and a fuel savings incentive.

While a 5% reduction in fuel consumption shows a negative net present value (NPV) and return on investment (ROI), the remaining three scenarios result in overall positive investment values. Although the actual fuel savings is dependent on wind and sea conditions, a safe estimate shown from previous studies is between 10% and 15% fuel savings. This shows a probable NPV of between $33,047 and $279,741 over the 20-year period, thus making this an economically profitable investment. Under more favorable wind conditions, the possibility of saving 25% or more fuel from Flettner rotors indicate upwards of a $773,129 NPV over the same period. Indeed, the most important factor – one that is reliant on natural wind and sea conditions – is greater fuel savings that will ultimately yield improved cost performance as efficiency improves.

4.2. *Zero-emission scenario*

The final scenario is the best-case example of introducing zero-emission vessels. The model of choice for this assessment is the Greenheart Project vessel. Based on the most-likely estimate of $1.5 million, and adding a significant buffer for potential unforeseen costs, the assessment here assumes a $2 million investment per vessel [34]. As implemented with the Flettner rotor systems mentioned above, this scenario introduces one additional vessel every two years until all five are replaced.

Additionally, while the goal is for a truly zero-emissions vessel, this assessment assumes a more realistic requirement for a small amount of fuel when performing accurate mooring and anchoring manoeuvres and when operating in unfavorable weather conditions. Therefore, this model estimates fuel consumption to be 5% of the baseline scenario after the 9th year, indicating the highest percent of fuel savings to be 95%. Another important point in this calculation is that beginning in the 9th year, the GSFS subsidy is eliminated. The alternative government support comes in the form of the fuel savings incentive. This results in the greatest possible government savings while still supporting the domestic shipping industry in a more sustainable manner. The following section discusses these findings and other important economic comparisons between each scenario.

The key financial figures show that investment in zero-emission vessels to service the uneconomical domestic routes yield the greatest NPV of $3,158,655 and a 20-year return on investment of 37.023% (Table 6). Most noticeable of this scenario is the significant reduction in both expenditures on fuel and the aggregate revenue from GSFS subsidies while simultaneously realizing a sizable increase in revenue from the fuel savings incentive.

4.3. *Summary of economic assessment*

The Flettner rotor option is an economically viable alternative to the current services only if the vessels were to achieve at least 10% annual fuel savings. A safe estimate is a savings of between 10% and 15%. The additional financial benefit of this is a significant reduction in fuel costs as well as a reduction in government subsidization (Table 7). These additional savings can be placed in a separate fund for future investment in zero-emission vessels or reinvestment in Flettner rotor technology. Furthermore, the higher investment in a zero-emission option yields a substantially higher return on investment, further benefitting from an elimination of the GSFS subsidy as well as additional savings that can be reinvested in a succession of zero-emission vessels. Indeed, this is the closest option to a both economically- and environmentally-sustainable outcome.

5. Environmental impacts and CO_2 abatement potential

The environmental benefit of adopting Flettner rotor technology or a zero-emission vessel is a reduction in greenhouse gas (GHG) emissions. The incremental fuel savings is realized in a stair-step manner, as the technology is installed on one vessel every two years. The total fuel savings of each scenario is achieved after all five vessels adopt the Flettner rotor system or, in the case of the zero-emission scenario, are replaced with new-builds. Thus, starting from the ninth year, the final

Table 7
Summary of economic assessment.

	NPV (US$)	ROI (%)	20-year cumulative fuel savings (US$)	20-year cumulative, additional gov't savings (US$)
Baseline	200,319	–	–	–
5% fuel savings	−213,647	−5.008%	474,741	174,021
10% fuel savings	33,047	0.775%	949,481	348,042
15% fuel savings	279,741	6.558%	1424,222	522,063
25% fuel savings	773,129	18.124%	2373,703	870,105
Zero-emission	3158,655	37.023%	9020,071	3803,664

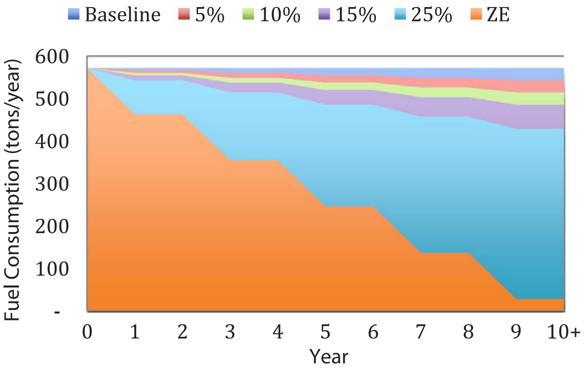

Fig. 8. Projected annual fuel consumption.

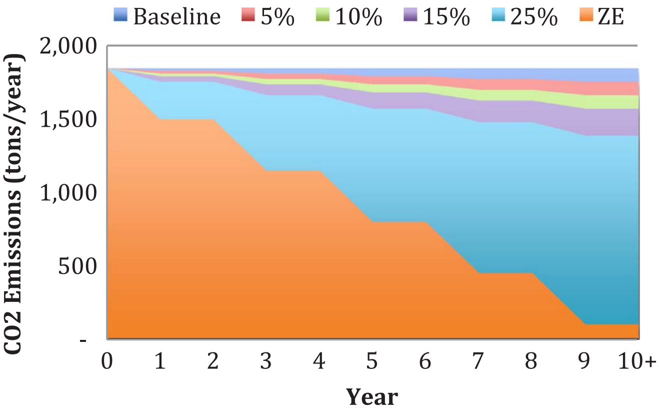

Fig. 9. Projected annual CO_2 emissions.

annual fuel consumption of each scenario remains steady (Fig. 8). The baseline scenario shows consistent annual fuel consumption levels of 571 metric tons; it neither grows nor diminishes over the 20-year period due to the consistency of route distance, scheduling, and fuel consumption. As for the zero-emission scenario, the final level of annual fuel consumption is 29 metric tons, or 95% less than the baseline scenario. While theoretically a zero-emission vessel should eponymously produce zero CO_2 emissions, for practical reasons this assessment leaves a five percent margin for close maneuvering and unfavorable operating conditions.

Directly corresponding to the fuel consumption curves, the CO_2 emission levels are likewise incrementally reduced in each scenario (Fig. 9). The baseline emissions amount to 1832 metric tons per year, while on the other extreme the zero-emission option is ninety-five percent lower at year nine – or 92 metric tons per year.

Clearly, the environmental benefits of implementing Flettner rotor technology are significant as efficiency increases. The final scenario of replacing the current five vessels with zero-emission types in the likes of the Greenheart Project design. According to Holland et al. (2014), sea transport represents approximately 22% of Fiji's domestic fossil fuel imports, or roughly 78 million liters per year [35]. Using the same density and conversion factors as the initial calculations for the lower southern Lau route fuel consumption, the total energy demand of Fiji's sea transport sector is 70,200 t. The greatest fuel savings from the zero-emission scenario is 543 t per year, or less than one percent of the total for this sector. Although a miniscule amount, much greater savings can be realized if these efficiency gains are applied to the entire domestic shipping industry rather than just the uneconomical routes. However, this is outside the scope of this analysis.

In sum, the zero-emission scenario presents the greatest environmental benefits, with a cumulative fuel savings of 8685 t and a cumulative CO_2 emissions reduction of 27,843 t (Table 8). The Flettner rotor technology, however, also offers a significant number of cost savings that would put these uneconomical shipping routes on a more economically viable track while simultaneously reducing CO_2 emissions.

6. Conclusions

This analysis stems from one example of how to improve Fiji's most uneconomical shipping route – that of the lower southern Lau island group – by offering a technological solution in the form of Flettner rotors. This shows potential in achieving fuel and cost savings, especially when applied to all of Fiji's uneconomical shipping routes. This analysis indicates that Flettner rotor technology is an economically viable solution that provides fuel savings and CO_2 emissions reductions; furthermore, investment in zero-emission vessels presents the greatest ROI and CO_2 emissions reductions over the 20-year period. While the values used in this analysis are basic estimates, the possibility of significantly higher fuel prices that would increase the cost for government to cover the GSFS subsidies provide greater reasons to adopt this renewable energy technology.

While a range of renewable energy technologies is available, this

Table 8
Projected fuel savings and CO_2 emissions reductions.

	Fuel savings		CO_2 emissions reduction	
	20-year cumulative (t)	Annual year 9 and above (t/yr)	20-year cumulative (t)	Annual year 9 and above (t/yr)
Baseline	–	–	–	–
5% fuel savings	457	29	1465	92
10% fuel savings	914	57	2931	183
15% fuel savings	1371	86	4396	275
25% fuel savings	2285	143	7327	458
Zero-emission	8685	543	27,843	1740

research considers Flettner rotors, as it presents a compelling case for low-carbon shipping in Fiji. Alternatives include soft sails, fixed wings, biofuels, and solar photovoltaic and storage systems. Indeed, a future study focusing on various combinations of technologies will greatly contribute to the field of research in low-carbon shipping.

The most beneficial and lasting solution, as evidenced by the findings of this analysis, is a zero-emission vessel such as that proposed by the Greenheart Project. Despite the higher investment, the rewards of having a new fleet of specially designed vessels servicing Fiji's numerous islands would be a showcase of low-carbon shipping to the rest of the world. Rather than continuing the cycle of replacing old, high-maintenance vessels with slightly less old, high-maintenance vessels, Fiji can realize economic, environmental, and social benefits from adopting Flettner rotor systems or even an entirely new fleet of zero-emission vessels.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.marpol.2017.09.020.

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