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Research Article

Wind-assisted propulsion: Economic and ecological considerations

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Abstract
Wind propulsion is well known and has propelled ships for millennia. However, with the advent of fossil-fuel powered ships, wind energy lost its importance for cargo transport almost 100 years ago. Rising fuel prices, and a society more aware of the consequences of CO_2 emissions, fuels the revitalization of this energy source, and a variety of wind-assisted propulsion systems are on the market today. Key factors for the success of wind-assisted propulsion are discussed, and a case study for a multipurpose vessel is used as an illustration.

1. Introduction

The idea of wind-assisted propulsion systems (WAPS) as a powerful lever for saving energy and lowering emissions is not new. In 1988, Bertholdt and Riesch (1988) prophesized that: “Using the wind means using the most environmentally friendly energy source. Saving (fossil) fuel means emitting fewer pollutants. Time will come, in which this aspect will be considered more valuable than pure commercial interest.”

WAPS pioneer Peter Schenzle has argued that sea transportation particularly lends itself to the first steps away from carbon combustion for three reasons (Schenzle, 2010):

- Its uniquely low energy demand could be largely covered from solar sources.
- Wind is easily available at sea and can directly drive ships without transformation losses.
- Weather routing and energy management can largely compensate for the variable input.

The ambitious IMO targets are asking for just this. Cutting greenhouse gas emissions with mandatory targets has driven ship owners and operators to re-think their propulsion systems. One possible solution to cope with IMO’s requirements is to install a WAPS to supply part of the propulsive power.

The performance of modern WAPS is often underestimated in the marine industry. **Table 1** compares three high-performance marine vehicles that have set records in world circumnavigation:

- The “Earthrace”, https://en.wikipedia.org/wiki/MY_Ady_Gil, holds the circumnavigation record for power boats. The vessel was powered by twin diesel engines (2×400 kW), running on biofuel.

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- The “Tûranor PlanetSolar”, https://en.wikipedia.org/wiki/Tûranor_PlanetSolar, is the world’s largest solar-powered boat. 536 m^2 solar panels supply an average propulsion power of 20 kW.
- The “IDEC Sport”, https://en.wikipedia.org/wiki/IDEC_SPORT, is the world’s fastest going sailing vessel, with a sail area of 557 - 828 m^2. It circumnavigated the globe in 2/3 of the time of the powered racing trimaran “Earthrace”.

Table 1 Record-holding vessels for world circumnavigation.

Vessel	Earthrace	Tûranor PlanetSolar	IDEC Sport
Propulsion	Biofuel diesel	Solar cells	Sails
Circumnavigation time	61 days	160 days	40 days
Length	24.00 m	31.00 m	31.50 m
Breadth	7.00 m	15.00 m	22.50 m
Displacement	26 t	85 t	18 t

Of course, these boats are not directly comparable; however, they are all powered by 100 % regenerative energy with zero carbon dioxide emissions, and it becomes clear that the direct use of wind power provides efficient means for propulsion.

2. Technical aspects

The following discussion is largely taken from a more extensive paper of DNV colleagues (Hollenbach et al., 2020). We compare here three typical, but fundamentally different, WAPS, **Figure 1**: Rotor Sail (a.k.a. Flettner rotor), https://en.wikipedia.org/wiki/Flettner_rotor, Rigid Wingsail, https://en.wikipedia.org/wiki/Wingsail, and DynaRig, https://en.wikipedia.org/wiki/DynaRig.

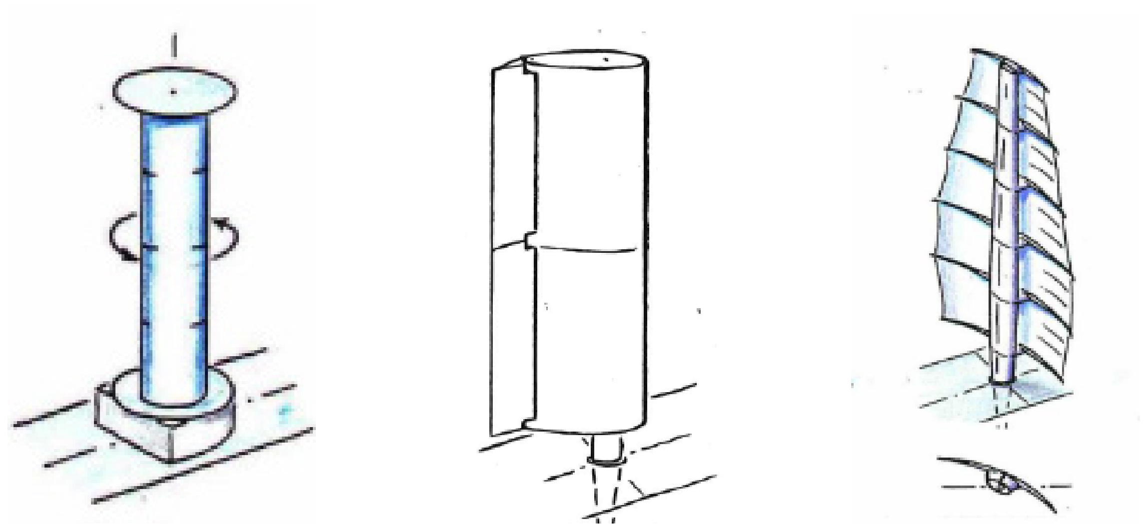

Figure 1 Rotor Sail (left), Rigid Wingsail (center), and DynaRig (right), (Schenzle, 1983).

These systems were chosen for three main reasons:

1. These devices are proven to be feasible; e.g., Rotor Sails are installed in presently operating commercial vessels; Rigid Wingsails are nothing else than vertical, fully-studied airplane wings; and DynaRigs are successfully used in several large sailing yachts.

2. These devices are the most likely ones to be adopted by the shipping industry, due to their market availability and reference installations. Also, most of the technical papers on WAPSs in recent years have focused on the development, implementation, analysis, and validation of these three devices.

3. Our limited time for this assessment. In the future, we may also assess other WAPS, including kites and turbosails.

The following subchapters will cover each of the selected WAPS devices, presenting the state-of-the-art and some history, available configurations, and further references.

2.1 Rotor Sails (Flettner rotors)

The Rotor Sail is an active rotating cylinder that generates aerodynamic loads due to the Magnus effect. It is commonly called a Flettner rotor, named after the German inventor Anton Flettner, who designed and built an experimental rotor vessel named “Buckau” in 1924, **Figure 2**. Two 15.6×2.8 m^2 Rotor Sails were installed, with a total rotor area of 87.4 m^2, as an additional source for propulsion to reduce fuel consumption. A few more ships were equipped with Rotor Sails in the decades to follow, but due to low oil prices, Rotor Sails had no convincing business case, and remained an exotic side note until the beginning of the new millennium, when interest in WAPS revived, with energy efficiency and reduced carbon footprints coming on the agenda.

In 2008, E-Ship 1 was launched, https://en.wikipedia.org/wiki/E-Ship_1, **Figure 3**. Four 27×4 m^2 Rotor Sails were installed. Enercon, the owner and operator of E-Ship 1, claimed operational fuel savings of up to 25 % compared to same-sized conventional freight vessels. In 2018, the “Maersk Pelican” was fitted with two 30×5 m^2 Norsepower Rotor Sails, **Figure 4**. Through measurements before and after installation, Norsepower determined fuel savings of 8.2 % during the trial period (Paakkari et al., 2020).

Advantages of Rotor Sail systems for cargo ships are:

- As for all WAPS, fuel savings and, thus, lower operational cost.
- Easy handling, not requiring extra crew, or even much training.
- Lower cost for installation and maintenance per thrust force than other WAPS (Borg, 1985).
- Very good maneuverability for ship.
- Passive load limitation: since all rotating cylinders have a maximum operating spinning velocity, if they encounter high wind speeds, their velocity ratio drops and, consequently, their aerodynamic loads follow the same trend. Thus, Rotor Sails depower themselves, which makes them a hurricane proof device, an advantage not inherent in other type of WAPS.

Disadvantages of Rotor Sails are:

- Rotor-induced vibrations may cause crew discomfort, or even structural damage.
- Rotor Sails are active rotating devices, requiring some electrical power to spin.
- Rotor Sails have a relatively small lift-to-drag ratio; thus, they are less effective for fast vessels, where the apparent wind angles are generally smaller.

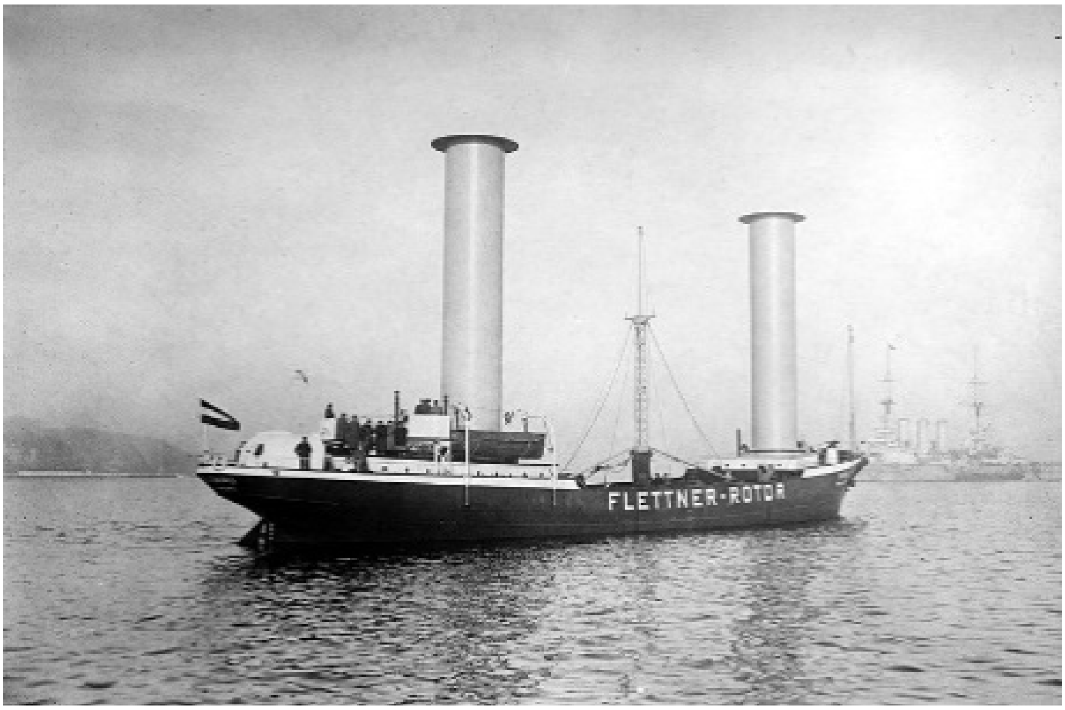

Figure 2 “Buckau” (1924).

Figure 3 “E-Ship 1” (2008).

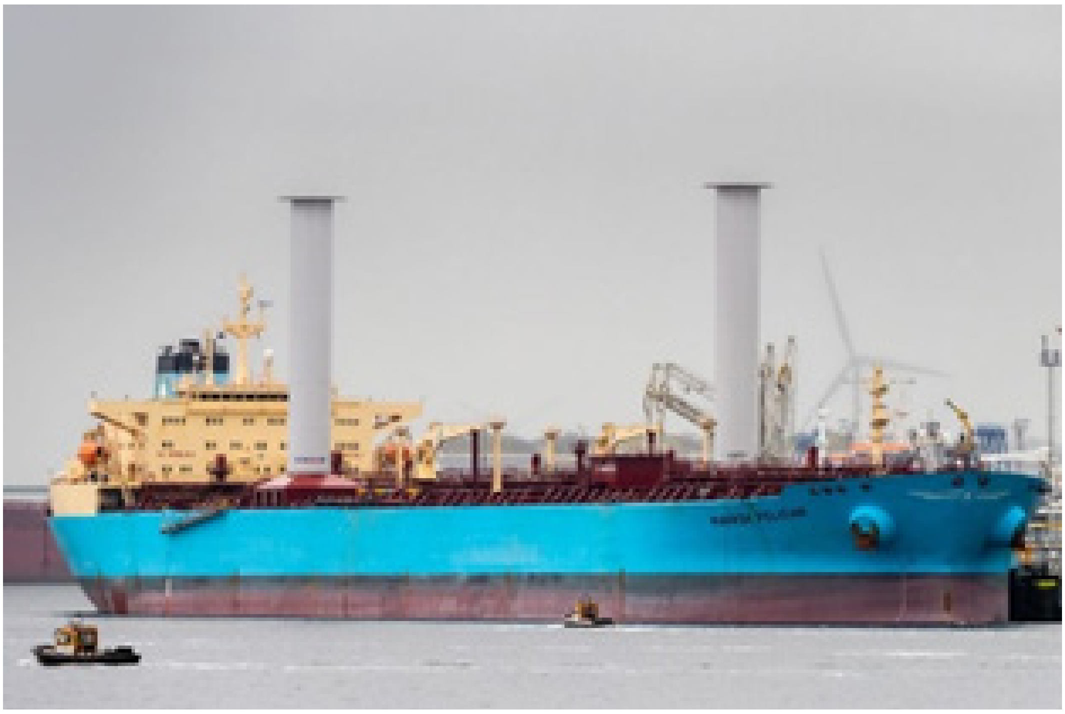

Figure 4 “Maersk Pelican” (2018).

2.2 Rigid Wingsails

Rigid Wingsails are airfoils, similar to airplane wings. Their main differences are their vertical orientation and their ability to generate lift on either side. This last characteristic is vital for a vessel since, unlike airplanes, they must tack while following the wind. For this reason, Rigid Wingsails have generally symmetrical NACA profile cross sections. Also, they may feature flaps:

- Leading-edge flaps increase the maximum lift of an airfoil by delaying its stall angle but are rarely implemented.
- Trailing-edge flaps generate additional lift through an increase in the effective camber of the airfoil, but also induce earlier stall. Plain flaps and slotted flaps are the most common in the maritime sector.

The idea of Rigid Wingsails dates back at least to the 1920s. In the 1960s, John G. Walker designed and built the ”Planesail”, a 10 m long Rigid Wingsail propelled cruiser, **Figure 5** (Walker, 1985). Popularly called Walker Wings, they were the first successful maritime implementation of Rigid Wingsails. In the 1980s, the U.S. government commissioned a study with Walker on the economic feasibility of wind-assisted propulsion in response to soaring fuel prices. While Rigid Wingsails fitted aboard commercial vessels demonstrated 15 - 25 % fuel savings, they failed to be widely implemented due to the low oil prices at the time. In the early 21st Century, Rigid Wingsails entered high-performance sailing, yielding unprecedented speeds, e.g., in America’s Cup regattas. Rigid Wingsails have featured in several high-profile design projects, such as the British Windship Technology project, https://windshiptechnology.com, **Figure 6**, and the Swedish Wind-Powered Car Carrier, “wPCC”, https://www.walleniusmarine.com/our-services/ship-design-newbuilding/ship-design/wind-powered-vessels, **Figure 7**. However, so far, these projects have remained at the design stage.

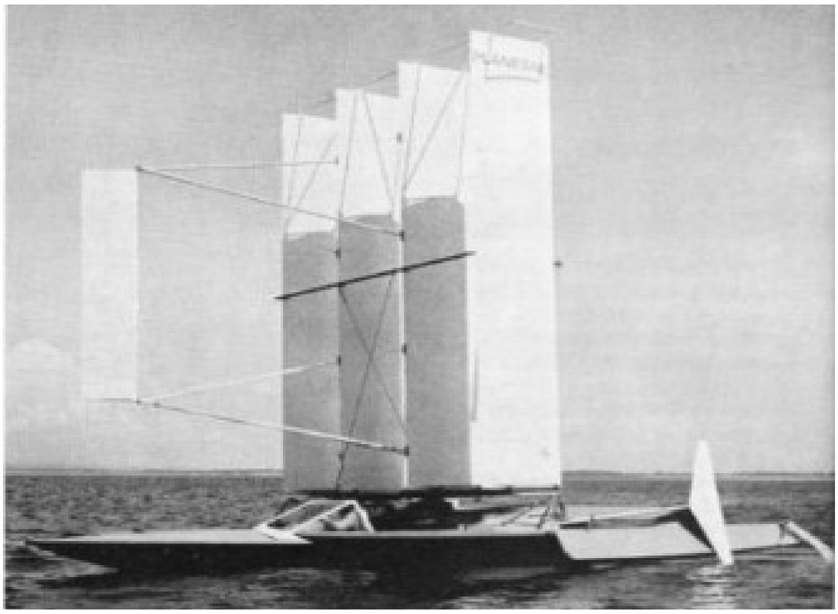

Figure 5 Planesail.

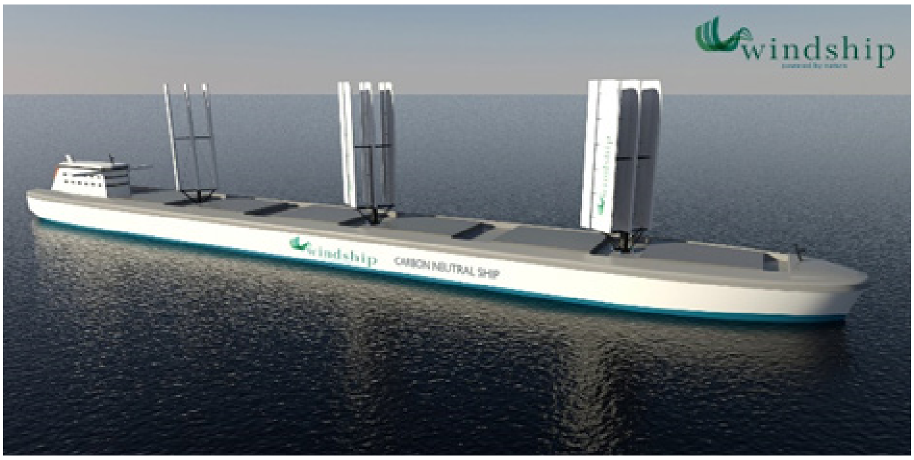

Figure 6 Windship Technology project.

Figure 7: “wPCC” project.

Advantages of Rigid Wingsails are:

- Easy handling, requiring no extra crew.
- Easy installation and maintenance.
- Most of them are retractable (less risk of overload in storms and easier cargo handling).

Disadvantages are:

- Relatively expensive (compared to traditional sails).
- Larger deck-space requirements (possible interference with cargo handling and other deck operations).

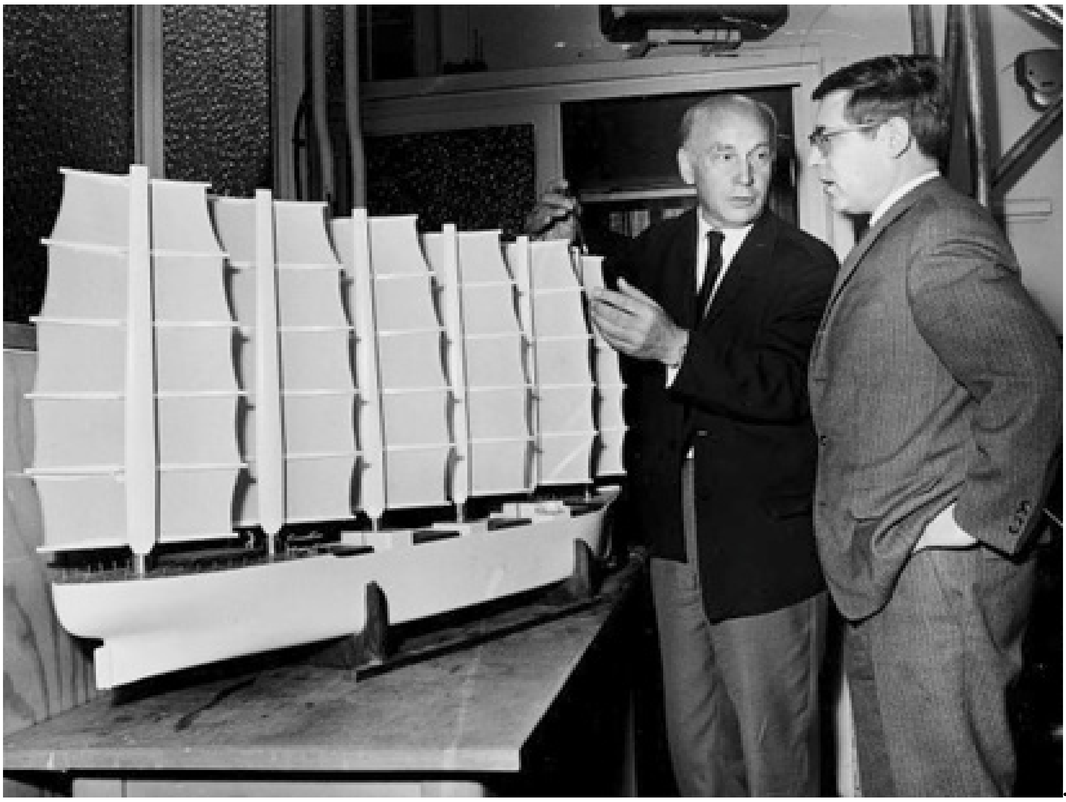

Figure 8 Wilhelm Prölss with DynaRig.

2.3 DynaRig

The DynaRig is a square rig developed in the late 1960s by Wilhelm Prölss. The main characteristic of this WAPS is its free-standing mast, with the yards connected rigidly to it. The sails are trimmed to the wind by rotating the mast. Prölss designed the DynaRig for cargo ships. He carried out wind tunnel tests for a 6-masted bulk carrier of 16,000 dwt at the Hamburg University in the 1960s and 1970s, **Figure 8**. The DynaRig proved to be about twice as efficient as traditional square rig sails. Prölss took patents of his design in all shipbuilding countries world-wide, but due to low fuel prices and the difficulty of building a full-scale mast with sufficient stiffness, the idea did not take off until the beginning of the new millennium.

Figure 9 WASP "EcoLiner" project.

The DynaRig was first installed on the megayacht "Maltese Falcon" in 2006 (Dijkstra et al., 2004). Ten years later, the DynaRig sailing yacht "Black Pearl" was released. Also, some design concepts for commercial vessels involve this technology, e.g., the WASP EcoLiner Project, **Figure 9**, https://www.dykstra-na.nl/designs/wasp-ecoliner.

Advantages of DynaRig are:

- Fully automated, requiring no extra crew.
- Similar to Rigid Wingsails, DynaRigs are highly controllable.
- Aesthetic design, appealing also to the yacht market.

The main disadvantage is:

- Higher lifecycle cost than for Rigid Wingsails.

2.4 Performance prediction program and route optimization model

DNV developed a 6 DoF (degrees of freedom) Performance Prediction Program (PPP) for wind-assisted cargo ships to contribute to the knowledge on WAPS performance, utilizing DNV's modular performance prediction workbench FS-Equilibrium. It is a fast and easy tool, able to predict reasonably accurately the performance of any commercial ship equipped with one of three different WAPS: Rotor Sails, Rigid Wingsails, and DynaRigs. The tool requires only ship main particulars and general dimensions as input data and is based on semi-empirical methods and a WAPS aerodynamic database created from published data on lift and drag coefficients. All WAPS data can be interpolated to scale to different sizes and configurations.

The PPP software has a modular set-up. Key modules are:

- Hull model (all forces acting on the hull, such as gravity, buoyancy, resistance, propeller thrust, wind forces, rudder forces, etc.)
- Rotor sails model (forces created by Flettner rotors)
- Rigid Wingsail model (forces created by Rigid Wingsails)
- DynaRig model (forces created by DynaRigs)

For all systems, it is assumed that they are carefully designed and fitted to the respective vessel to allow safe and efficient maneuvering. In case additional means for stability or leeway control are needed, these are included in the PPP setup. For additional details of the PPP, we refer to Hollenbach et al. (2020).

The Route Optimization Model (ROM) consists of an optimizer, a route evaluation algorithm, and the multi-objective optimization algorithm. The optimizer randomly selects a set of free variables. The route evaluation algorithm builds the route with these free variables. The optimizer checks if the route violates the constraints at any point of the route. If it does, the route becomes invalid, and is discarded right away. If the constraints are satisfied, the algorithm calculates the objectives according to the free variables selected. These objectives are feedback for the optimizer and the Non-dominated Sorting Genetic Algorithm II (NSGA-II) optimization algorithm. A new selection of free variables is based on this feedback. This process is repeated until the Pareto-optimal set is found. The route optimization differs from normal weather routing for cargo ships reflecting short-term course changes (tacking) required by WAPS ships but atypical for normal cargo ships. For details of the ROM, we refer to Hollenbach et al. (2020).

2.5 Fuel savings

Fuel savings strongly depend on the trading area and ship's speed. Higher typical wind speed v_w and the lower ship speed v increase the expected fuel savings. The correlations are nonlinear, making generic statements of X % savings to be expected by device Y dubious. Instead, case by case analyses are needed, employing performance prediction programs.

Norsepower, www.norsepower.com, gives for the "Maersk Pelican" (with 2 Flettner rotors) savings in sea trials of 8.2 % fuel consumption. **Table 2** gives the estimates of our PPP for various ship speeds and trading areas (with associated typical wind speeds). Savings range between 1.4 % and 41 %. For more details on the PPP prediction, please see Hollenbach et al. (2020).

Table 2 Estimated fuel savings for "Maersk Pelican", depending on ship speed and trading area.

v	**Tropical** v_w **= 6 m/s**	**North Sea** v_w **= 8 m/s**	**Nordic Ocean** v_w **= 10 m/s**
6 kn	25 %	39 %	41 %
8 kn	10 %	18 %	22 %
10 kn	4.7 %	9.1 %	13 %
12 kn	2.5 %	4.9 %	7.4 %
14 kn	1.4 %	2.8 %	4.4 %

Larger (rotor) sail area increases the fuel savings. Our PPP predictions for the "E-Ship 1" (4 Flettner rotors), validated against measurements for selected points, illustrate this impressively, **Table 3**. More than 100 % means here that wind power could be used to generate electrical energy for board systems if appropriate installations are in place.

Table 3 Estimated fuel savings for "E-Ship 1", depending on ship speed and trading area.

v	Tropical $v_w = 6$ m/s	North Sea $v_w = 8$ m/s	Nordic Ocean $v_w = 10$ m/s
6 kn	>100 %	>100 %	>100 %
8 kn	44 %	80 %	90 %
10 kn	21 %	40 %	52 %
12 kn	11 %	22 %	32 %
14 kn	6.2 %	13 %	20 %

Route optimization (tailored to WAPS) offers considerable additional savings. For transatlantic routes, we estimate for a ship like the "E-Ship 1" average savings (per year) of 8 - 20 % on westbound legs, and 12 - 38 % on eastbound legs, compared to using the Rhumb-line average (straight line on a navigation maps using Mercator projection).

3. Case study

The aim of this case study is to quantify the energy saving potential of wind-assisted propulsion for a typical cargo ship, and also look at the economical side. The virtual cargo ship used to perform these calculations is a multi-purpose vessel, similar in size to the "E-ship 1", **Table 4**. The ship is assumed to be outfitted with three Flettner rotors of 30×5 m^2.

Table 4 Case study ship.

L_{pp}	130 m	DWT	12550 tdw
B	21 m	speed	15 kn
T	8 m	trip	10,000 nm

The daily charter rate for such a vessel is currently 8,500 USD/d. The installation cost of the three Flettner rotors is assumed to be 2.250 million USD, and a yearly maintenance of 2.3 % of the initial investment is required. Depreciation is set at 10 years, and capital is subject to 4 % interest rate. The case study assumes a trip of 10,000 nm and considers 60 % sailing time (220 days/year) of the vessel. The consumption of the auxiliary power systems is estimated to be 2.2 t/d. The electric power needed to spin the three rotors is considered to be 100 kW and, thus, increases the auxiliaries fuel consumption by about 0.5 t/d. **Table 5** summarizes these assumptions. Although not yet implemented for shipping, discussions on trading schemes for emissions are ongoing and, at least for the EU, it seems likely that shipping will be included in the ETS. This would mean extra costs for using fossil fuel, and currently a ton of CO_2 is traded at 40 € (~50 USD/t), https://ember-climate.org/data/carbon-price-viewer.

Table 5 Economic assumptions.

Charter rate of conventional powered vessel	8,500 USD/d
Capital cost of WAPS installation	2.250 mUSD
Maintenance cost of WAPS system	2.3 % pa
Depreciation period	10 years
Interest rate	4 %
Auxiliary fuel consumption	2.2 t/d
Power to spin the rotors	100 kW ~0.5t/d
Fuel price	400 - 600 USD/t
CO_2 emission trading	50 USD/t
Costs for port call	50,000 USD/trip

Assuming a trading area in the Nordic Ocean, with an average wind speed of 10 m/s, our analyses predict savings in fuel consumption and CO_2 emission of 17 % (for 15 kn) to 60 % (for 6 - 8 kn), **Figure 10**. The speed reduction alone would already reduce the CO_2 emission by 60 %; thus, the total emission reduction (WAPS + speed reduction) can be more than 80 %. These savings are substantially lower if the ship is trading in low wind-speed areas, such as tropical areas. **Figure 11** shows possible CO_2 reductions for areas with mean wind speed of 6 m/s. Here, only for very low speeds, attractive savings can be achieved.

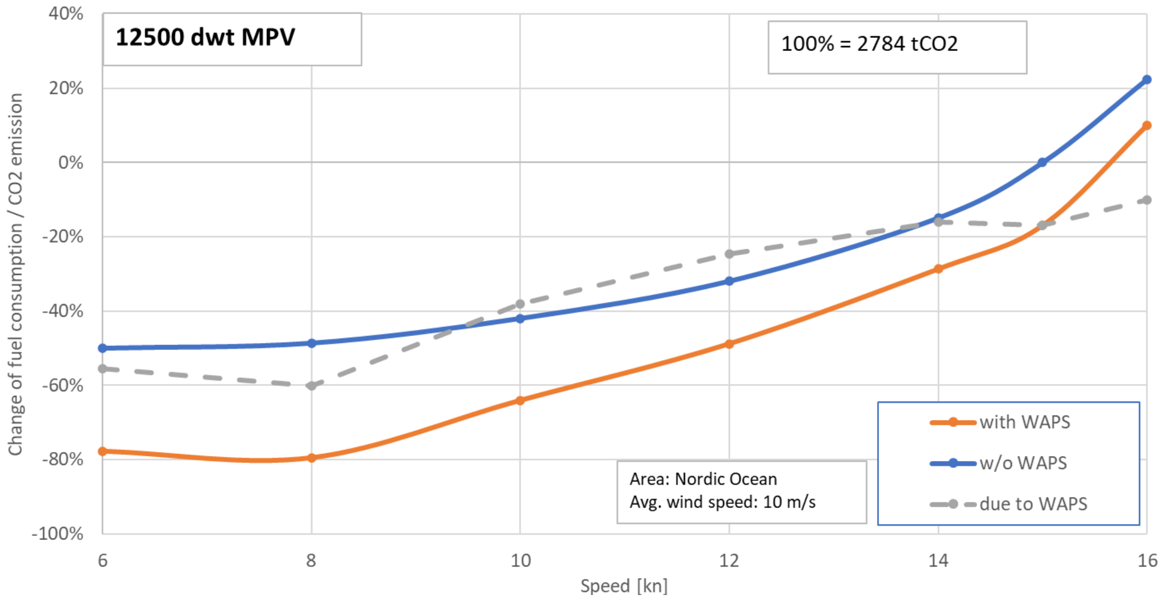

Figure 10 Fuel savings and CO_2 reduction due to WAPS at average wind speed 10 m/s.

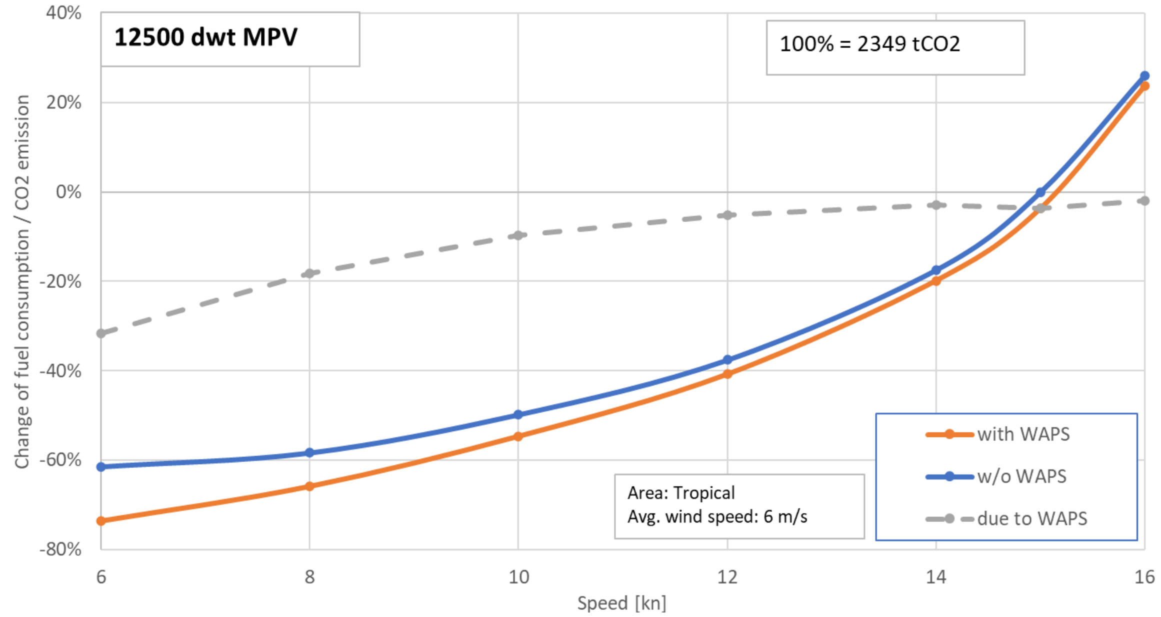

Figure 11 Fuel savings and CO_2 reduction due to WAPS at 6 m/s average wind speed.

Unfortunately, besides the attractive reduction in CO_2 emission, the economic side will always play an important role. Therefore, we have tried to assess the cost impact on a typical trip of 10,000 nm.

Fuel prices are changing frequently, and today, low sulfur fuel is traded at ~500 USD/t. Assuming the "Nordic Ocean" wind condition, with an average of about 10 m/s, the WAPS system provides attractive savings regardless of the speed, **Figure 12**. An optimum is at a ship speed of about 8 - 10 kn. The relative increase in costs for very low speeds is mainly a result of the charter costs, which are applicable on a daily basis, and anti-proportionally increase with the reduction of ship speed. The same applies to costs for powering the auxiliaries, and fixed costs such as port fees, pilots etc. **Figure 13** shows the split up of the total trip costs for different speeds for the WAPS supported vessel for an 8 m/s wind speed average. The different cost items considered are:

ME Fuel- cost for the fuel oil consumption of the main engine
Aux Fuel- cost for fuel oil consumption of the auxiliaries
CO_2- cost for CO_2 emission trading
Port, etc.- cost for ports, pilots, locks considered fixed per trip
WAPS cost- cost for depreciation and maintenance of the WAPS system
Fuel saving- amount of cost saved for fuel
CO_2 saving- reduced cost for CO_2 emission trading due to lower fuel consumption.

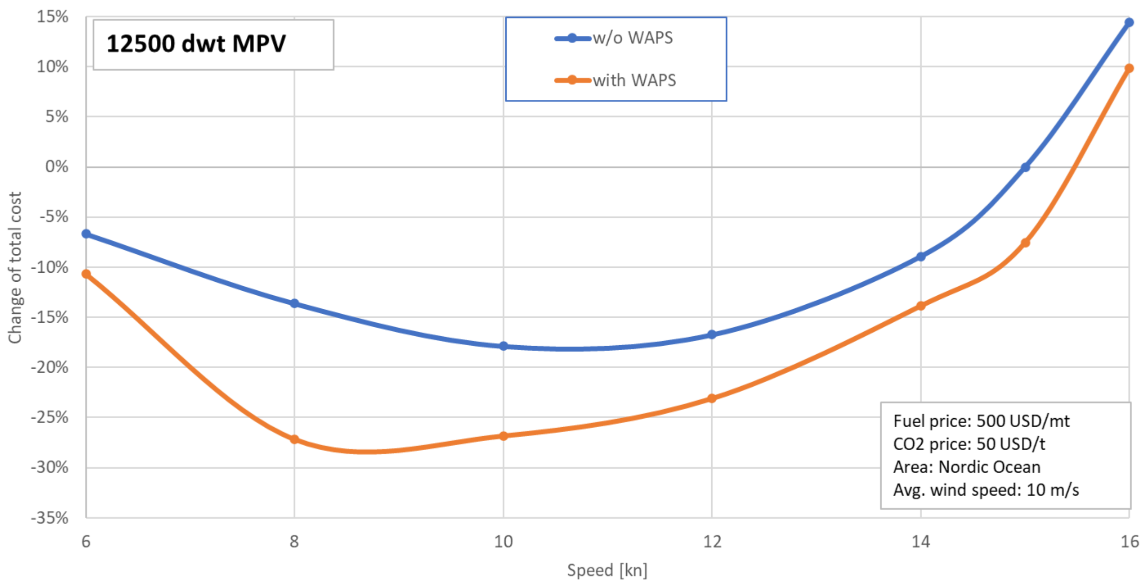

Figure 12 Cost reduction (North Atlantic trading, average wind speed = 10 m/s).

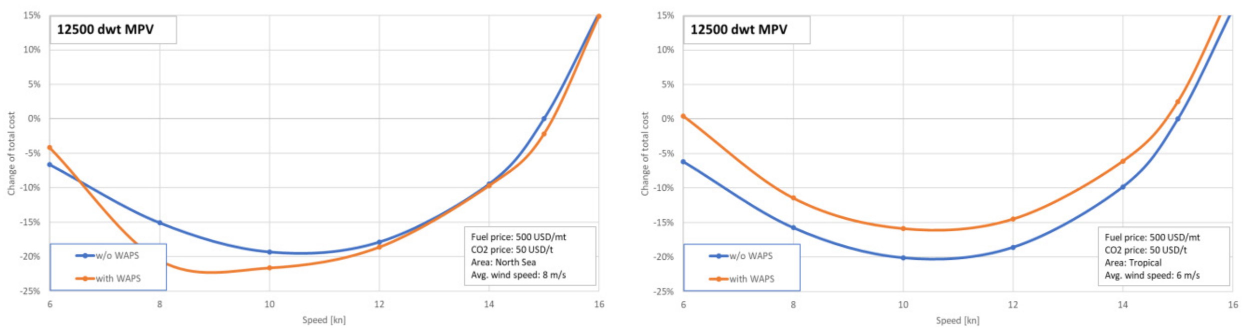

Figure 13 As **Figure 12**, but for 8 m/s (left) and 6 m/s (right) average wind speed.

Naturally, a wind-assisted propulsion system heavily depends on the wind speeds, and if the wind is not strong enough, the business case quickly becomes weak. **Figure 13** shows on the left side that, for an 8 m/s average wind area, the cost savings are marginal for speeds above 12 kn, and for even lower wind speeds 6 m/s (Bft. 4), the investment costs of the WAPS system cannot be recovered, regardless of speed.

4. Conclusions

Wind-assisted propulsion systems have gained in technical maturity, importance, and adoption in the maritime industry. In all cases, they save substantially on CO_2 emission and fuel consumption. The cost saving largely depends on future fuel prices and the possible cost of CO_2 emissions. However, global standard savings cannot be given; the business case depends in each application on many factors. Quick analyses are possible using semi-empirical performance prediction programs, as developed by DNV (Hollenbach et al., 2020). Such analyses can guide design and retrofit decisions, as well as operational optimization. From the presented data, the business case is weak if looking at monetary savings only. Additional measures to make CO_2 reductions attractive to the industry will help to make such systems even more relevant. It should also be taken into account that taking full advantage of such systems will require more flexibility in the schedules and, thus, additional demand on the logistic side.

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