Figure 1: *Fehn Pollux* on sea trials Source: MariGREEN

Flettner rotors reduce fuel consumption and emissions

RETROFIT PROJECT In order to reduce greenhouse gas emissions from shipping, a renaissance of wind energy for ship propulsion seems to be obvious. Retrofitting the multi-purpose freighter *Fehn Pollux* with a Flettner rotor showed significant CO_2 reductions. The following report by scientists from the Hochschule Emden/Leer, University of Applied Sciences, Germany, Professor Capt Michael Vahs, Professor Dr Jann Strybny, Thomas Peetz, Moritz Götting, Sascha Strasser and Marcel Müller, reveals information on important aspects of planning retrofits or newbuildings with Flettner rotors and is based on the results of the sea trials and the first phase of testing under normal operating conditions.

In June 2018, a German-Dutch project consortium under the scientific direction of the Emden/Leer University of Applied Sciences retrofitted and commissioned the latest rotor development of the Eco-Flettner type on the test ship *Fehn Pollux* of the Leer-based shipping company Fehn Ship Management. The retrofitting concept is groundbreaking in terms of easy transferability to other ships. Upscaling to a significant share of the world merchant fleet could make a substantial contribution to climate protection.

The most frequently asked question in connection with modern sail drives, is about the performance potential and the associated fuel savings. Transparent performance data is required to enable an economic prognosis for the use of Flettner rotors on ships. The Faculty of Maritime Sciences at Emden/Leer University of Applied Sciences has developed an automatic control and monitoring system for Flettner rotors that also records extensive operating and environmental data.

The data shows that all previous assumptions and model calculations are basically correct. With regard to the performance potential, the first series of measurements show even higher rotor forces compared with model calculations. This is a further benefit for Flettner rotor efficiency and could help the technology achieve a breakthrough as a building block for low-emission shipping.

Retrofit concept

An important development objective for the Eco-Flettner within the framework of the "MariGreen" [1] project is the transferability of the retrofitting concept to a larger share of the existing world merchant fleet in order to achieve significant reductions in fuel consumption and emissions. The structural features of the multi-purpose freighter *Fehn Pollux* provide an ideal basis for this, as there are a large number of ships worldwide with a similar arrangement of holds and superstructures.

The installation of a wind propulsion system supporting the main engine demonstrated average fuel savings of about 10% to 15% on the test ship. In previous analyses, the Flettner rotor was technologically favoured because it combines high sailing performance with minimum space requirements and the advantages of a fully automated system. Furthermore, the construction is robust and insensitive to wear, offering further advantages compared with other sailing systems, e.g., based on textile sails adapted from the field of yachting.

The central question of the choice of the installation location on the ship was preceded by a detailed analysis of all relevant factors. To avoid any impairment to existing operating procedures, a rotor position outside the cargo area had to be found. The only installation site available was the foreship in front of the cargo holds.

The aerodynamic and hydrodynamic conditions were investigated using computational fluid dynamics (CFD) flow simulations and model tests. The installation on a raised foundation and the use of a lower end-plate not provided for in previous Flettner rotors ensure very favourable flow conditions around the rotor. The introduction of the sail forces on the forecastle deck leads to a reduction of yaw moments caused by side forces of the sail, yielding good steering characteristics during rotor operation. It is therefore advantageous over a midship or aft installation.

The rotor was reinforced in accordance with existing classification regulations to counteract the effects of wave impact, which led to a slight increase in its weight. DNV GL checked and approved the compliance with the regulations regarding the visibility from the bridge and the radar visibility in advance. Further investigations by the Department of Maritime Sciences of the University of Applied Sciences Emden/Leer included simulations on the full mission ship-handling simulator, the results of which were validated during sea trials.

View from the bridge and radar detection

During early stages of the project, plans had to be submitted to demonstrate that both the view from the bridge and the operating conditions of the radar met the requirements of relevant regulations [2]. The rotor causes a visually blind sector of 2° in the area of the midship line, well below the limit value of 5°. To check the blind spot, the officer of the watch must change position on the bridge at regular intervals. During the installation works, a special training programme was conducted for the staff including exercises on a full mission ship-handling simulator.

The effect of the rotor on bridge visibility was not perceived as significant by the nautical experts involved in the test and is similar to that on ships with cranes on the midship line (Figure 3). Changing position on the bridge by just a few metres allowed an unrestricted field of vision.

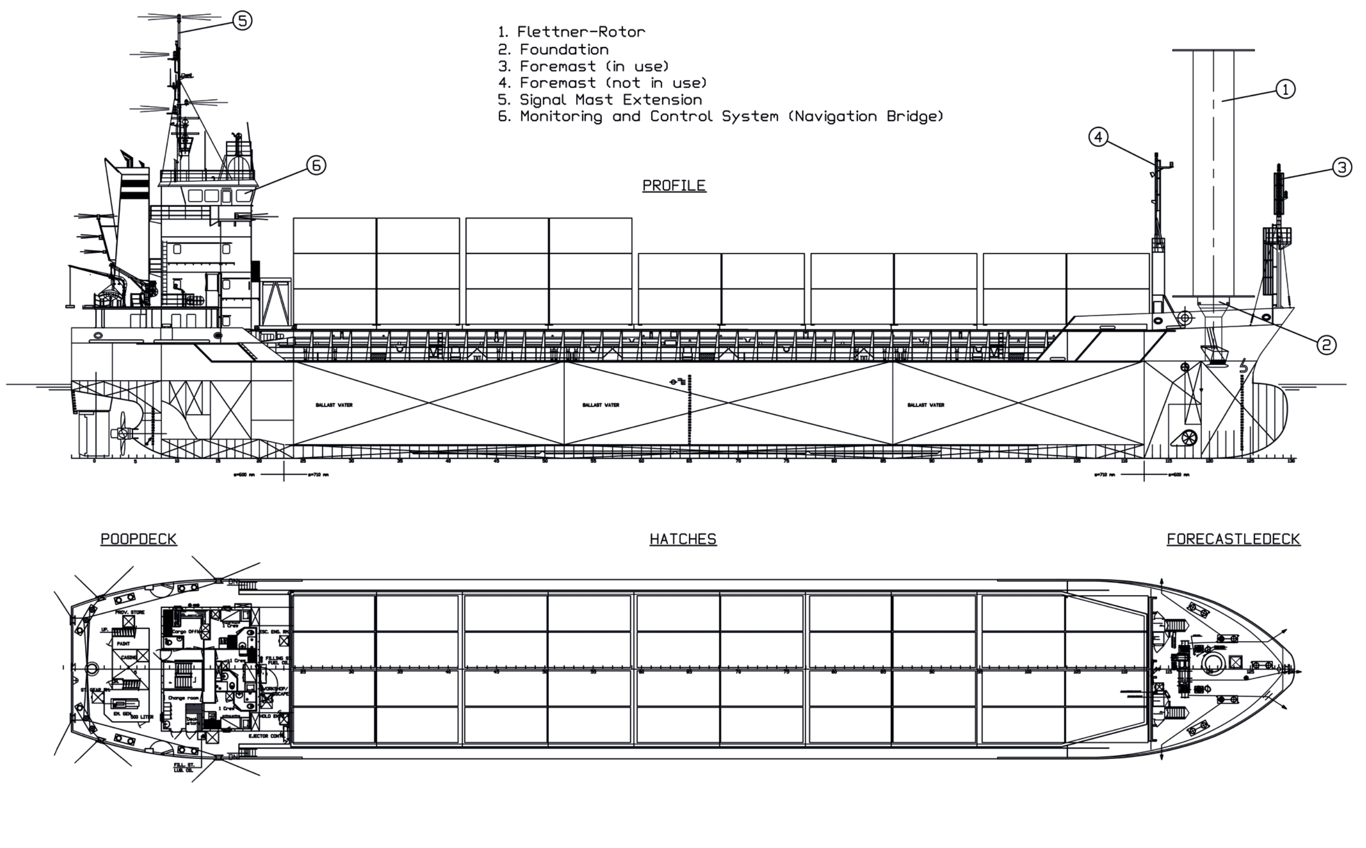


Figure 2: Arrangement drawing for retrofitting the *Fehn Pollux*

Source: ABH Ingenieurtechnik GmbH, Emden

Figure 3: View from the bridge of the test ship *Fehn Pollux*
Source: Hochschule Emden/Leer, University of Applied Sciences

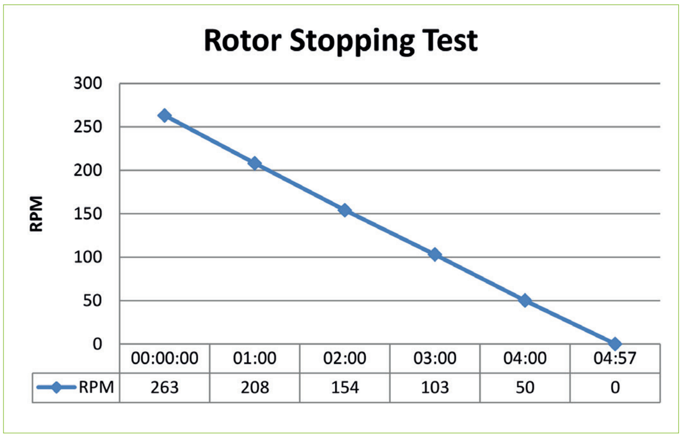


Figure 7: Rotor speed (rpm) after the stop function has been activated. After four minutes and 57 seconds the rotor is stopped.

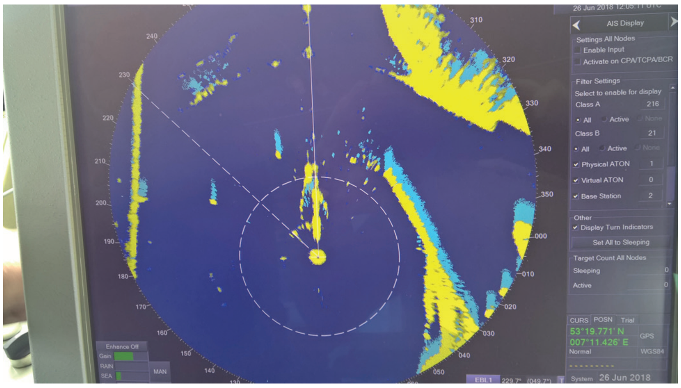


Figure 4: Radar image during a detection test with a small vehicle (circled in red) in the area of the rotor shadow
Source: Hochschule Emden/Leer, University of Applied Sciences

During planning of the rotor installation, a 1° radar blind spot behind the rotor had been assumed. Due to the different locations of the two radar antennas, however, there is an unrestricted radar view when both antennas are used simultaneously. However, the blind spot could not be observed during sea trials.

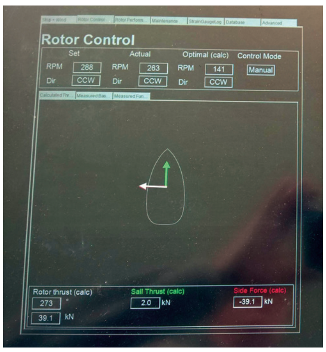
A radar detection test was carried out with a small vessel. Figure 4 shows that the vessel could be observed on the radar at close distance in front of the ship, although it was completely covered by the rotor. Possible causes for the detection of the target in the blind sector of the rotor are its material properties (GRP) with respect to the transmission of radar waves and diffraction effects in the shadow area.

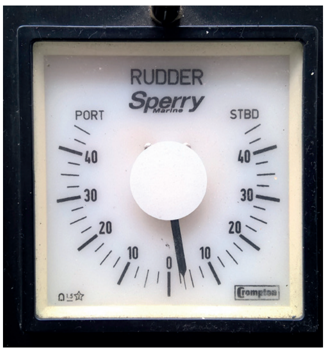
Steering performance

The influence on the steering characteristics was tested with maximum transverse forces of the rotor on courses in the wind. During the test runs, a side force of approximately 40 kN was achieved with moderate winds equivalent to Beaufort force 4, which corresponds to approximately 50% of the maximum possible side force. The ship could easily be kept on course with autopilot control, therefore. The required rudder angles were below 5° at a ship speed of about ten knots, and below 10° at a slower speed of about five knots. The small effect on the steering capability of the test ship can be attributed to good rudder performance values and, in particular, to the foreship installation close to the hydrodynamic centre of the hull.

Testing the stop function of the rotor

In order to stop the effect of the rotor forces on the ship as quickly as possible, an electric brake was installed. After pressing the stop button on the bridge console, the rotor stopped within approximately five minutes (Figure 7). The stop curve has a linear characteristic. The rotor should be stopped prior to port manoeuvres to prevent any adverse interference.





Figures 5/6:The "Rotor Control" display (left) shows a rotor side force of 39.1 kN (circled in red) acting on the ship. The rudder angle indicator (right) shows that a rudder position of only about 3° to starboard is required to keep the ship on course with autopilot control.
Source: Hochschule Emden/Leer, University of Applied Sciences

Validation of rotor performance

For the prediction of the rotor's propulsion power and associated fuel savings, numerous model tests and simulations were performed using the wind tunnel of TU Hamburg-Harburg and numerical CFD methods at the Center for Modelling and Simulation at the Emden/Leer University of Applied Sciences. The rotor's control and monitoring system displays the rotor forces and propulsion power in real time and comprises additional functions for performance optimisation. In addition to values from model calculation, force measurements are displayed in real time. The rotor force is measured in two axes (longitudinal and side force) by sensors specially adapted for onboard application.

The force measurement sensors were calibrated by means of a tensile test with load cells. Since certain inaccuracies cannot be excluded during the calibration, an additional measuring method for validating the rotor forces under real operating conditions was tested. For this purpose, a high-resolution measurement of the ship's heeling angle resulting from rotor side forces was carried out during the sea trials.

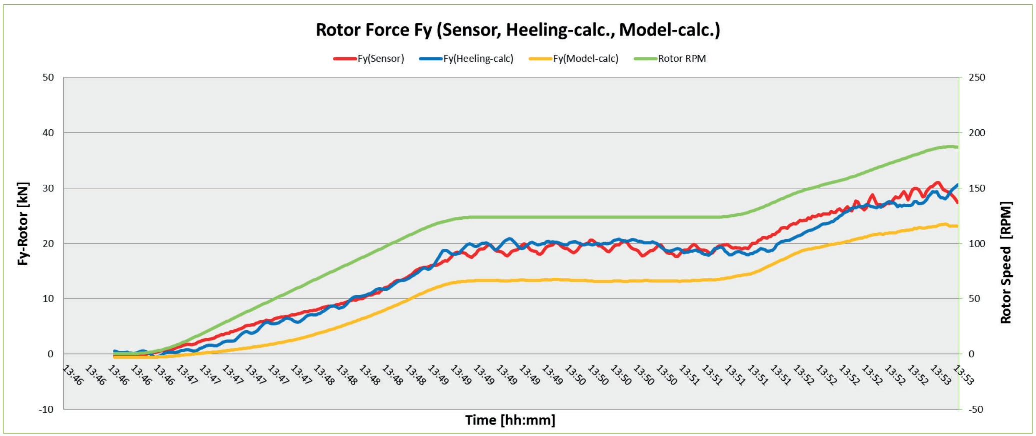


Figure 8: High correlation of rotor force values from force measurement (red), heel angle measurement (blue) and model calculation in real time (yellow). The rotor speed (green) can be used to control the rotor force. The measurements show significantly higher values than the model calculation.

As shown in Figure 8, the rotor forces recalculated from the heeling angle show a high correlation with the measured values of the force sensors and the values of the model calculation. The values of the rotor force both from the sensors (red) and from the heeling measurement (blue), however, are on average about 10% to 40% above the values of the model calculation (yellow). From this it can be concluded that a full scale Flettner rotor generates higher aerodynamic forces under real conditions than predicted by model calculations based on small-scale wind tunnel testing. This may be caused by the influence of the ship structures on the air flow, surface effects on the rotor as well as errors from upscaling the model test results. Since this project was the first to perform precise force measurements on Flettner rotors in real ship operation, no comparative results from other projects were available.

Performance measurement in real ship operation

The additional thrust generated by the Flettner rotor can be used either to increase the ship's speed for saving voyage time or to reduce power and fuel consumption at constant speed. Therefore, in addition to the force measurement on the rotor, the ship's speed was measured with GPS and the fuel quantity was measured by a signal transmitter to record the fuel rack setting on the main engine.

Since the electric drive of the Flettner rotor is fed from the shaft generator and thus directly from the main engine, the fuel measurement provides the correct total consumption including rotor operation. To evaluate the rotor performance, the ship's speed and engine power as well as fuel consumption with and without rotor was compared. However, as the ship's speed at a given propulsion power ›

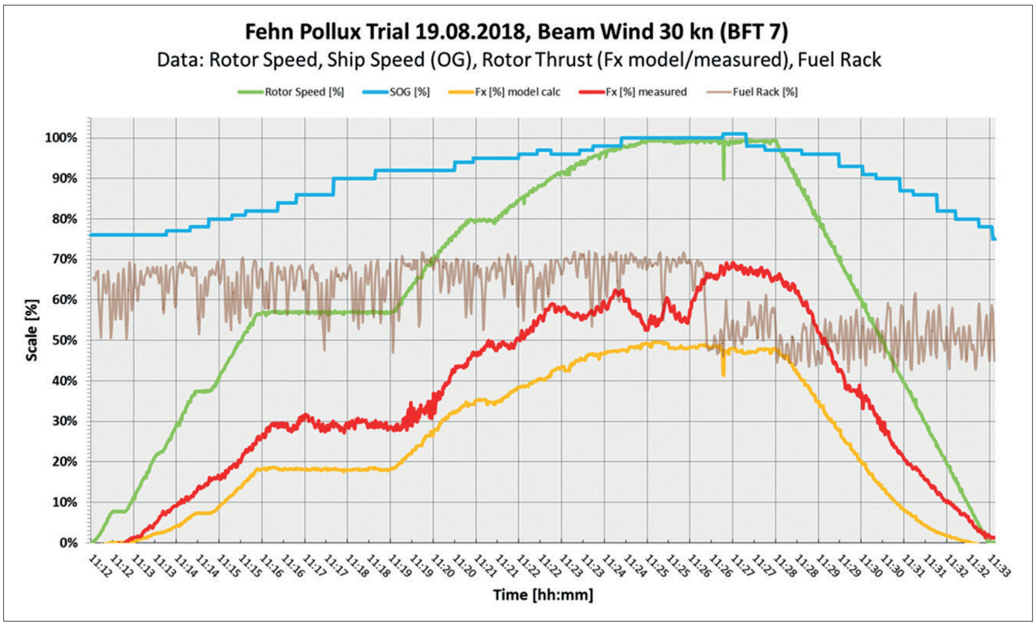


Figure 9: Graph showing the measured values of a performance test during regular service of the Eco-Flettner rotor on the *Fehn Pollux*

depends on many other factors, it is difficult to evaluate the data. To solve the problem, measurements were carried out over short periods under constant environmental conditions, during which the Flettner rotor was first switched on and then switched off again. If the main engine setting remained constant, the increase in ship's speed could be measured and a backward calculation of the rotor power could be made. If the vessel achieved the same speed when the rotor was switched off, the influence of environmental factors on the ship's speed during the measurement could be excluded. Similarly, after switching on the Flettner rotor, the fuel rack setting of the main engine could be reduced and measured while maintaining a constant ship speed. The measurement results were used to validate the previous model calculations.

The following example shows the increase and decrease of the ship's speed by switching the rotor on and off with a constant main engine setting. Figure 9 shows the relationship between rotor speed (rpm), rotor thrust (Fx) and ship speed over ground (SOG). The fuel rack setting of the main engine is initially constant and then reduced at the end of the measurement. The fluctuating fuel rack filling values result from the engine controller keeping constant propeller pitch and rpm under changing load conditions in rough sea. The ship steers a south course (180°) with easterly winds of Force 7 on the Beaufort scale (about 30 knots), so the wind direction is from port abeam (approximately 90°).

The measured values in the diagram show a clear correlation of the rotor thrust curve (Fx, red and yellow) and the ship speed (SOG, blue) with the rotor speed (green). When the rotor accelerates to 260 rpm (100%), the measured rotor thrust values (Fx measured, red) go up to a maximum of approximately 70 kN (70%). The ship's speed increases by 2.5 knots – from 7.6 to 10.1 knots – with almost constant main engine filling (fuel rack, brown).

At full rotor speed the filling is then reduced by approximately 15% with only a minor influence on the ship's speed. When the rotor is switched off, the rotor speed and rotor thrust go back to zero within approximately five minutes, correlating with the reduction of the ship's speed. The measured rotor thrust (Fx measured, red) is significantly higher than the model calculation (Fx model calc, yellow), confirming the results of the sea trials.

To evaluate the rotor power, it can be compared with power from the main engine. In the test, the rotor was used to increase the ship's speed and compared with the equivalent power required for the main engine to achieve the same speed increase. This is based on model tests carried out in the towing tank of the DST research institute at the University of Duisburg-Essen in order to determine the required main engine power as a function of ship's speed. The resulting function curve must be

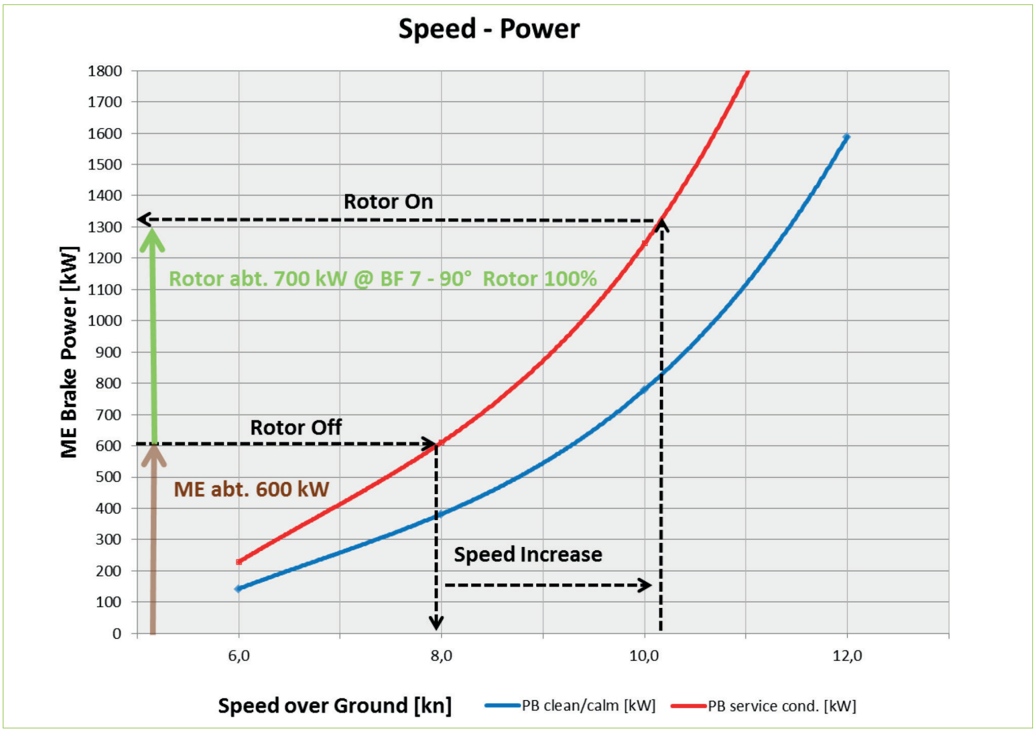


Figure 10: Rotor power and main engine power in relation to ship speed

corrected for added resistance and deviating draught/trim that occur under real conditions (service conditions). The measured ship's speed over ground must be corrected for the influence of the prevailing ocean current (here approximately +0.3 knots).

Figure 10 shows the red speed-power curve for sailing under service conditions. The function curve is laid through the measuring point of the initial situation "Ship without rotor" (Rotor Off). The equivalent power of the main engine for the same speed increase as produced by the rotor (Rotor On) can be estimated by the red curve. The resulting propulsive power of the rotor is in order of 700 kW of power provided by the main engine, taking efficiencies of gearbox, shaft and propeller into account. This is above the main engine power of approximately 600 kW. In normal charter service of *Fehn Pollux*, the main engine power is limited to about 650 kW (Eco-Speed).

In summary, the following performance figures were recorded from the test:

- Rotor thrust approximately 70 kN
- Rotor propulsion power approximately 700 kW equivalent to the main engine

For assessment purposes, it should be pointed out that these are high performance values that are close to the performance maximum. However, they are significantly higher than the previous assumptions based on model tests.

Outlook

The first test results of the *Fehn Pollux* showed that the retrofit concept of a Flettner rotor on the forecastle deck has advantages in terms of aerodynamic behaviour which have a positive effect on the manoeuvring characteristics and the propulsion performance. The disadvantages in terms of visibility from the bridge and radar limitations are within acceptable limits and fulfil all legal requirements. For the forthcoming transition of the world merchant fleet towards sustainable and low carbon marine propulsion, it is important that a rotor installation on the foreship is transferable to a significant number of other vessels.

According to validated performance models and route simulations, the annual average power potential of the Flettner rotor installed on the *Fehn Pollux* is in the range of approximately 100 kW to 150 kW in addition to the main engine power. These values naturally depend on the wind conditions along the route.

Depending on the required ship speed and the actual power of the main engine, fuel savings of approximately 10% to 20% can be expected on the *Fehn Pollux*. A reduction in speed leads to higher percentage savings, so a combination with slow steaming could lead to higher overall percentage savings. The previous data and results from the project already allow a relatively reliable prognosis of the achievable savings.

Clear data transparency was provided during the project by validated measurements. This is essential to reassure shipowners, shipbuilders and investors about the validity of this new technology and to enable them to carry out economic appraisals of their own. The project can also be used as proof that converting fleets in this way can reduce CO_2 emissions, but that the process must be supported by appropriate measures in order to achieve important climate policy goals in good time.

› PROJECT DETAILS

The development and testing of the "Eco-Flettner" wind drive is part of the MariGreen project, funded within the framework of the INTERREG V A programme Germany-Netherlands with funds from the European Regional Development Fund (ERDF) and through national co-financing from Germany and the Netherlands.

Lead partner of the project is MARIKO GmbH in Leer. The aim of the MariGreen project is to prepare the maritime industry, especially small and medium-sized enterprises, for the future requirements of environmental protection, climate protection and resource and energy efficiency in shipping through cooperation with universities and research institutions. An essential prerequisite for the realisation of the project is the cooperation in the German-Dutch border region in the field of green shipping that has developed in recent years.

Thirteen companies and research institutions from Germany and the Netherlands worked together to develop the Eco-Flettner [3].

References

[1] www.marigreen.eu
[2] e.g., SOLAS Chapter V, Regulation 22
[3] http://marigreen.eu/projects/wind-windship-engineering-and-design/

› TECHNICAL DATA

Vessel Data *Fehn Pollux*	
Type	Multi-purpose cargo ship suitable for containers and grains
Built	1996
LOA	89.77m
Beam	13.17m
Draught	5.68m
Deadweight capacity	4,211 tonnes
Tonnage	2,844gt
Main engine	MWM Deutz SBV 9M 628, 930 kW
Speed approximately	10 knots
Rudder	Becker type flap rudder

Rotor Data	
Type	Eco-Flettner
Height of the cylinder	18.00m
Diameter of the cylinder	3.00m
Diameter of end plates	6.00m
Projected area	$54m^2$
Speed	263 rpm max
Drive	Electric motor, 75 kW max, average power depending on wind conditions, e.g., 30 kW
Thrust	approximately 80 kN max, depending on wind conditions
Propulsive power	The savings potential depends on the wind conditions along the route and other factors. Under medium-to-good wind conditions, an annual average of approximately 2 kW main engine equivalent power can be saved per $1m^2$ of projected rotor area (for guidance). Precise predictions are made by route simulations for a specific ship.