Low C for the High Seas
Flettner rotor power contribution on a route Brazil to UK

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Abstract

Climate change presents shipping with the need to reduce its dependence on fossil fuels. Low carbon technology is considered a crucial element in rising to this challenge, demonstrated at the political level by regulation on the energy efficiency of new-builds. This paper analyses wind power as one category of technology in order to contribute to the body of knowledge that is needed to ascertain the potential for decarbonising shipping. Specifically, it combines a numerical model of a Flettner rotor with wind data from the UK Met Office's Unified Model to assess the potential wind power contribution along a route from Tubarao (Brazil) to Grimsby (UK). Applying the results to a typical bulk carrier equipped with three Flettner rotors making a round voyage on the route suggests possible fuel savings of 16%. More generally, the replicable results will allow for a deeper and, in turn, more realistic examination of the prospects for wind power. In doing so, the paper seeks to push the debate forward: by exploring wind power technology and by building accessible knowledge that may be key to a global sector meeting a global challenge.

Keywords: wind power, Flettner rotor, low carbon technology

1. Introduction

Facing climate change and its potentially devastating consequences, there is a need to reduce greenhouse gas emissions. In the shipping sector, the challenge is to reduce CO_2 emissions from fossil fuel combustion. As reflected by the International Maritime Organization's (IMO) regulation on the efficiency of new-builds, which was put in place in 2011, low carbon shipping technology is a key element in meeting that challenge. While it seems essential to substitute the fossil fuels currently in use, there is no ready alternative, and it is an open question when or whether one of the suggested options will make the break-through that would be needed. One energy source that is renewable and available on the high seas is wind: with a long and proud history in shipping, it deserves renewed focus, in the context of modern analysis tools and an international shipping system that has changed considerably since sailing ships last played a large role in it. While various technology options for harnessing wind power exist and have been demonstrated, their potential for powering ships on a global network of shipping routes remains unclear. Furthermore, knowledge about specific technologies often sits with individual companies. Developing a methodology for assessing the potential contribution from wind-power technologies on global shipping routes, this paper tries to shed some light onto these unresolved issues and to provide a basis for more detailed studies aimed at reaping the potential for wind-powered very low carbon shipping. More specifically, the methodology combines a shipping route and wind velocities along a route with a numerical performance model of a wind power technology, yielding the technology's power contribution towards propelling the ship. This paper presents the methodology by considering the route from Tubarao (Brazil) to Grimsby (UK), as described in section 2.1. The technology option chosen for this paper is a Flettner rotor, described in section 2.2. Wind velocities along the route are taken from the UK Met Office's Unified Model (cf. section 2.3). These three elements are combined to assess the potential power contribution along the route as outlined in section 2.4. Section 3 presents the results from the analysis, which are discussed in section 4. Conclusions are given in section 5.

2. Methods

The methodology for assessing the potential of wind power shipping technologies marries up three key elements: a shipping route, a numerical performance model of a wind power technology, and data representing wind velocities along the route. It is set up in a modular way so that different technologies may be studied along different routes, and there is a choice about the source of the wind data. On the one hand, the methodology is presented by choosing one sample case in each category; on the other, the samples chosen are of great significance in their own right.

2.1 The route: Tubarao to Grimsby

The route from Tubarao (Brazil) to Grimsby (UK) is analysed here. It is an important route for the iron ore trade to the UK. As Mander et al. (2012) argue, it may also become an important route for imports of biofuel in the future when biofuel becomes an integral element of the UK's energy future as is the case in some of the Department of Energy and Climate Change's (DECC) energy scenarios.

A typical ship serving the route was chosen based on a light analysis of a set of LMIU ship movement data from 2006: a bulk carrier of 50,000 dwt, 8 MW installed main engine power, and a service speed of 14.1 knots. The installed main engine power serves as a reference point when setting the simulated power contribution from the wind power technology in relation. The only vessel parameter that feeds into the wind power analysis along the route is travel speed. It is assumed that the sample vessel is travelling at 80% of its service speed, i.e. 11.3 knots (5.8 m/s), in line with quantitative analyses of slow-steaming, as in Lindstad et al. (2011). Contributions from three Flettner rotors are illustrated as a share of the propulsive power demand of the ship in section 3.3. Assuming 90% engine loading at service speed and power consumption to scale with the cube of the speed, the main engine power demand is 3.7 MW.

The route is defined by a set of waypoints, latitude and longitude coordinate pairs spaced at intervals that are small with respect to the grid resolution of the wind data (cf. section 2.3).

It is noted that while the route from Tubarao to Grimsby is analysed because of its significance to UK trade, the presented methodology may be readily applied to any other shipping route.

2.2 Numerical model of a Flettner rotor

Among technology options for wind-powered shipping, such as fixed wing sails, soft sails, kites, and others, the Flettner rotor has been selected for analysis in this paper, as one of the most promising technologies. A Flettner rotor is a rotating cylinder mounted upright on the ship. In sideways winds, the Magnus force generates a lift on the rotor, propelling the ship forward. The effect is well-known from many sports in which balls with a spin follow a curved trajectory. Invented by Anton Flettner, Flettner (1925), in the early 1920s, the concept was proved – one of his first rotor vessels is shown in figure 1 on the left - but could not compete with steam and diesel ships at the time. The concept has received renewed attention in recent years as the goal to reduce greenhouse gas (GHG) emissions and dependence on fossil fuels has come to the fore as evidenced by a number of CFD studies such as Craft et al. (2012). The largest contemporary vessel using Flettner rotors is wind turbine manufacturer Enercon's E-Ship 1 (figure 1, right), equipped with four rotors each of 27 m tall and 4 m in diameter.

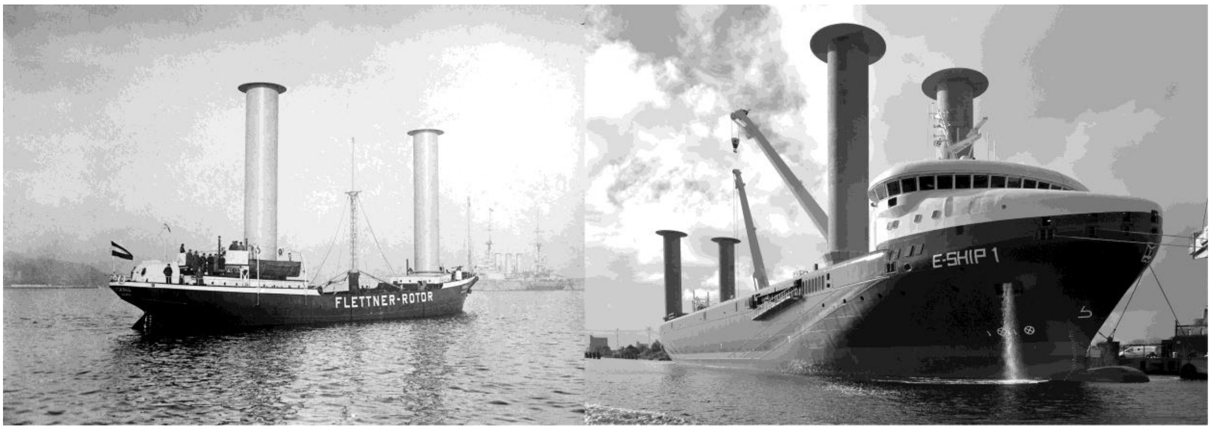

Figure 1: One of the first rotor ships, the *Buckau* (left), and the present-day rotor ship *E-Ship 1* (right)
Source: wikipedia.org (accessed on 10 August 2012, right photo by Carschten)

The Flettner rotor modeled here is 35 m tall and 5 m in diameter. Key to its aerodynamic performance are the lift, drag, and moment coefficients, respectively. They determine the lift force **l**, the drag force **d**, and the power p_{ME} that is needed to drive the rotor, according to the equations:

$$l = \tfrac{1}{2}\rho A v_a^2 c_L \tag{1}$$

$$d = \tfrac{1}{2}\rho A v_a^2 c_D \tag{2}$$

$$p_{L\&D.} = (\boldsymbol{l} + \boldsymbol{d}) \cdot \boldsymbol{s} \tag{3}$$

$$p_{motor} = \tfrac{1}{2}\rho A v_a^3 c_M \alpha \tag{4}$$

where **l** is the lift, **d** is the drag, $p_{L\&D.}$ is the power delivered by the rotor, p_{motor} is the power expended to drive the rotor. ρ = 1.2 kg/m^3 is the density of air, A is the area which is simply the rotor height times the diameter, v_a is the apparent wind speed, **s** is the ship velocity, and α is the ratio of the rotational speed of cylinder and the apparent wind speed. So the thrust is simply calculated as the projection of combined lift and drag onto the travel direction. The final power contribution from the Flettner rotor is given as the power delivered by the rotor minus the power expended to rotate it: $p_{L\&D}$ - p_{motor}. Note that Flettner lift acts in the direction vertical to the apparent wind while the drag acts in the direction parallel to the apparent wind, accounted for by vector notation. This neglects additional sideslip and rudder forces. Further simplifying assumptions are made when comparing the power delivered by Flettner rotors to the required main engine power. As main engine power is converted into propulsive power, transmission and propeller losses are incurred. While the errors entailed from these omissions cancel each other to some degree, they should be taken into account when interpreting the results. Also, note that the effect of the sea state on fuel consumption is neglected in the analysis. The rotational speed ratio is set to α=3.5. The aerodynamical coefficients are set to c_L=12.5, c_D=0.2, and c_M=0.2, respectively. The lift and drag coefficients are in line with the literature, Craft et al. (2012). The case is more difficult with the moment coefficient c_M. The value selected for this study is based on anecdotal evidence, not least from Flettner himself, Flettner (1925), and in line with unpublished results from CFD studies conducted at the University of Manchester (McNaughton, 2012, private communication). Finally, once the combined lift and drag reaches 220 kN, corresponding to an apparent wind speed of 13 m/s, the rotor motor is throttled to keep the lift and drag force, and the power fed into the motor at a constant level.

While this paper's focus lies on the Flettner rotor the methodology stands ready to be applied to any other wind-power technology simulated by a numerical model (essentially the thrust or transient propulsive power as a function of ship and wind velocity) allowing for comparisons between different options.

2.3 Wind data

Wind velocities along the route are taken from the Met Office's Unified Model analysis data. The Unified Model produces data sets four times a day, at 0, 6, 12, and 18 hours. In order to avoid diurnal or seasonal bias, one data set per week in 2011 has been downloaded, 53 datasets overall with near equal distribution among the daily time steps. Wind velocity is given by a Westerly component u, and a Southerly component v, on a grid of 1024 x 769 cells in the case of the u-component (1024 x 768 in case of the v-component), which are sampled at a level height of 37 m above the geoid.

2.4 Assessment of transient wind power contribution on the high seas

The three key elements of this study, the shipping route from Tubarao to Grimsby, a numerical performance model of a Flettner rotor, and a global wind velocity field from the Unified Model analysis data are combined to assess the transient power contribution along that route.

For every set of wind data used in this study, each corresponding to a specific point in time, the transient power contribution from the Flettner rotor is computed at every point along the route, assuming a ship speed of 11.3 knots. To this end, at every waypoint of the route, the wind velocity in the corresponding grid cell is read from the wind data, and the transient power contribution is calculated. Note that no other vessel parameter than its speed affects the calculation of the transient power. From the results, two averages are computed: first, power contribution is averaged over time, i.e. over all sets of Unified Model data sampling the wind data once a week over the course of 2011; second, the average of power input from the Flettner rotor is averaged along the route. Finally, assuming a setup with three non-interfering Flettner rotors - note this assumption is theoretically justified for inviscid flow, as used for lifting aerofoils for example - on the representative bulk carrier (cf. section 2.1), the wind power contribution is set in relation to the main engine power requirement.

3. Results

3.1 Average power contribution from the Flettner rotor

Figure 2 shows the average propulsive power contribution from the Flettner rotor along the route from Tubarao to Grimsby (left) and back (right). Values for all 53 wind data sets are shown as well as their average plotted as a flat line. The average power contribution is 200.6 kW on the out-going leg and 200.7 kW on the return leg.

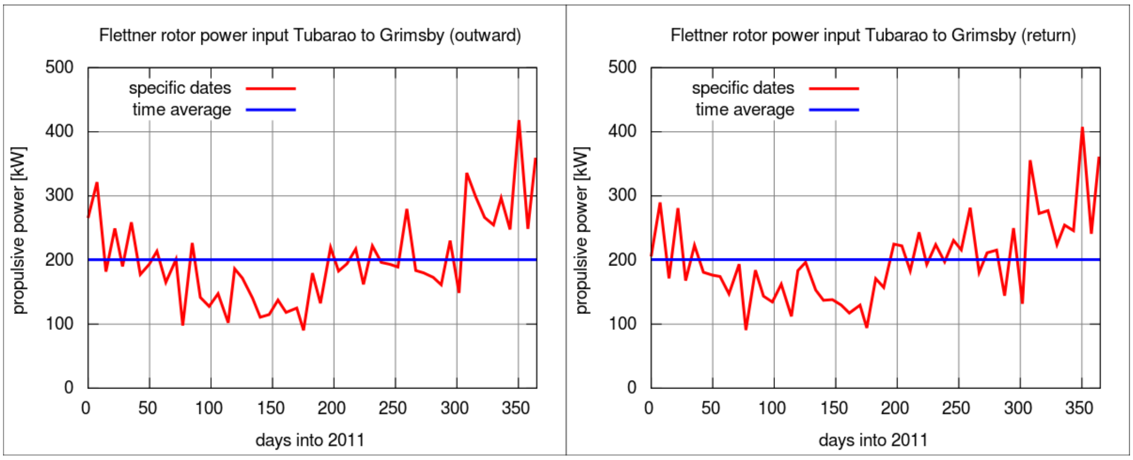

Figure 2: Average power contribution from the Flettner rotor along the route Tubarao to Grimsby, at 53 different times in 2011 (red), and average over all times (blue). Left: Journey from Tubarao to Grimsby. Right: Return journey from Grimsby to Tubarao.

Data: Authors

The highest Flettner rotor output is 418.2 kW on the outward route using the wind velocity field of 17 December 2011 at 18 hours, and the lowest is 90.4 kW in the same direction for data from 25 June 2011 at 6 hours.

3.2 Transient Flettner rotor power along the route

The previous section focused on the rotor's average power contribution over the route. This section looks at the rotor's transient power contribution along the route. To set this in relation to the actual power demand of ships serving the route, the following setup is considered: The typical bulk carrier serving the route - consuming 3.7 kW of main engine power (cf. section 2.1) – is fitted with three identical Flettner rotors that do not interfere with each other. In figure 3, the time-averaged transient power contribution from the three Flettner rotors is plotted as taking up a share of the power demand of 3.7 MW. The x-axis shows the distance travelled from Tubarao (at 0 km) to Grimsby (at 9319 km).

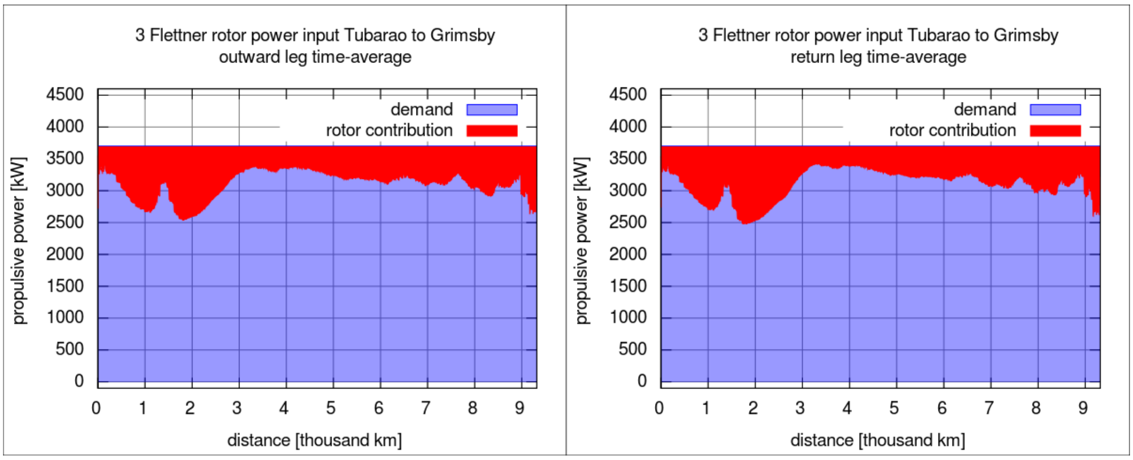

Figure 3: Time-averaged propulsive power generated by a set of three Flettner rotors, plotted as a share of the main engine power requirement of a slow-steaming, 50,000 dwt bulk carrier (cf. section 2.1 and 2.2). Left: On the way from Tubarao to Grimsby. Right: Returning from Grimsby to Tubarao.

Data: Authors

The average power contribution from the Flettner rotors is 16% in this setup, varying between 7.6% and 31.4% at locations along the route on the out-going leg, and between 7.3% and 33.0% on the return leg. In order to gain some understanding of the volatility of the wind power contribution, the latter is plotted for the times at which output is minimal and maximal, respectively. Figure 4 shows the wind power contribution at its lowest, on 25 June 2011, at 6 hours (top) and at its highest, on 17 December 2011, at 12 hours. At points the power delivered by the three Flettner rotors can be almost as high as the entire power required to propel the ship; at others, the power from the three Flettner rotors can even be slightly negative – due to incurred drag.

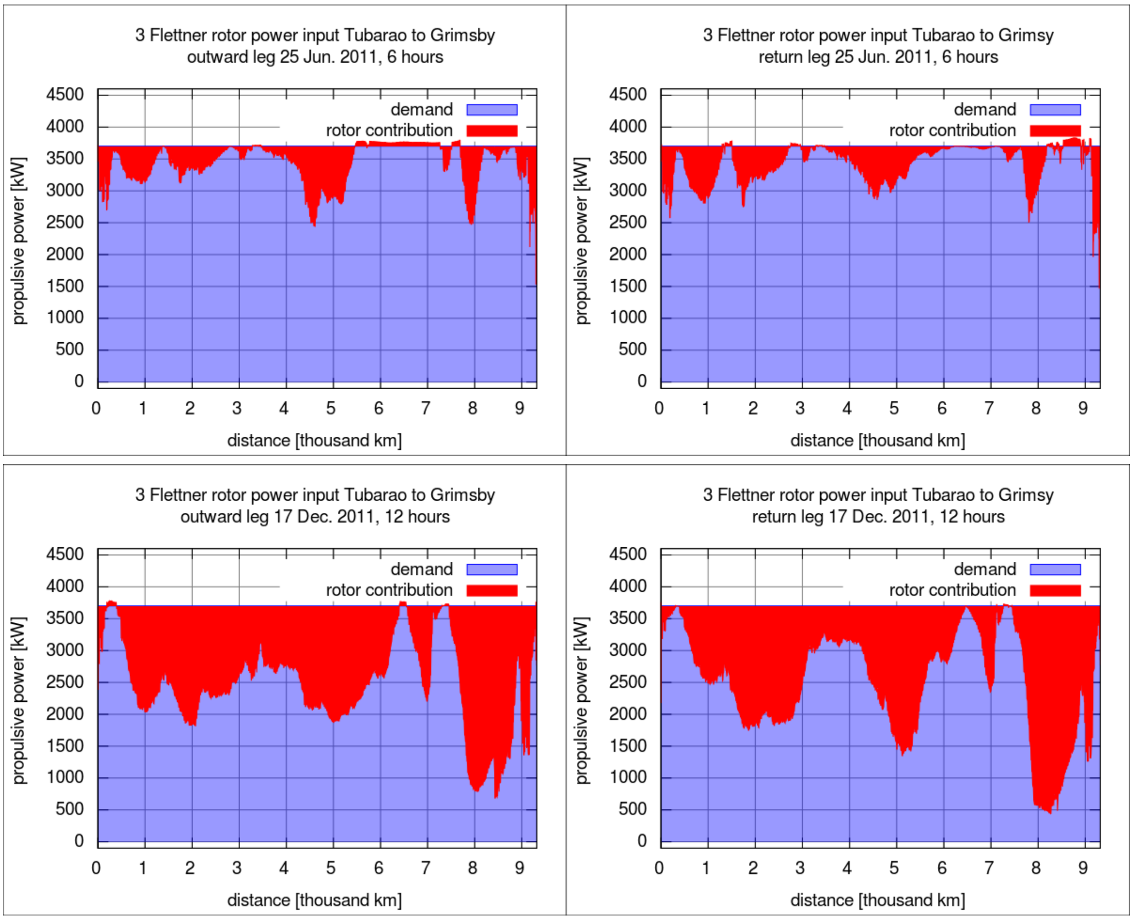

Figure 4: Propulsive power generated by a set of three Flettner rotors, as a share of the main engine power requirement of a slow-steaming, 50,000 dwt bulk carrier (cf. section 2.1 and 2.2). Top: on 25 June 2011, at 6 h, when the wind power contribution was lowest. Bottom: on 17 December 2011, at 12 h, when wind power contribution was highest (out of all 53 datasets). Left: On the way from Tubarao to Grimsby. Right: Returning from Grimsby to Tubarao.

Data: Authors

4. Discussion

4.1 Uncertainties and interpretation of results

The results presented in the previous section suggest possible savings of 16% under the considered setup, constituting a step change with respect to greenhouse gas reduction – urgently needed from a climate change perspective as argued by Gilbert et al. (2012). In considering the results, care is needed in accounting for uncertainties and simplifications in the model.

The parameters defining the aerodynamic performance of the Flettner rotor are subject to uncertainty. In particular, the lift, drag, and moment coefficients are not perfectly known. The moment coefficient is associated with the largest uncertainty, and any results produced in CFD studies or field trials should be monitored to increase confidence in the modelling of the technology.

As detailed in section 2.2, simplifying assumptions are made in comparing propulsive power delivered by the rotor(s) to the main engine power requirement. While transmission and propeller losses in converting main engine power into propulsion are fairly well-known, accounting for rudder and sideslip losses – due to the force on the rotor not always being aligned perfectly with the travel direction – or for variation of main engine efficiency according to the engine's operating point requires a more detailed investigation.

Clearly, the results apply to the route and the ship type considered and may look different on another route or when applied to a different ship. Beyond the size and power requirements of a ship, availability of desk space, height restrictions, and seakeeping and other naval architecture issues need to be addressed when looking at a more detailed case study.

While the results from the setup analysed in this study look promising, it is the key strength of the presented methodology that it may be readily applied to any other route, to any wind power technology, at any time, allowing for instructive analyses and comparisons. The next section deals with further developments and refinements of the methodology.

4.2 Outlook : next steps

First of all, it is intended to apply the methodology to a wider network of shipping routes, and to include a numerical performance model of a towing kite. The second intended development is to translate forces on the rotor into main engine power – and, in turn, fuel savings – more realistically. Third, there is some scope for optimisation. In the case detailed here, the ship travels at constant speed following a set route. Both transient speed and the exact route taken by the ship may be optimised with respect to fuel consumption. While wind data were sampled at specific times in the past, using real-time weather data is an option that merits further consideration. Finally, additional resistance due to sea state could be built into the analysis if the relevant wave data are read in from a weather model alongside the wind velocity data.

5. Conclusions

As shipping faces the challenge to reduce its CO_2 emissions and its dependence on fossil fuels, harnessing the wind as a renewable energy source available on the high seas is an attractive option. In order to make progress towards tapping into that potential, a methodology has been developed that combines a numerical performance model of a given wind power technology with wind data along global shipping routes. As a case study, the potential power contribution of a Flettner rotor on the route from Tubarao to Grimsby has been assessed. Under the further assumption of equipping a typical 50,000 dwt bulk carrier serving that route with three Flettner rotors, calculations suggest that 16% of the main engine power requirement could be replaced by wind power. Results may serve as a basis for more specific and more detailed studies, that ultimately will have to include economic considerations and address possible barriers to implementation of the technology. The presented methodology will allow for comparing different technologies, on different routes, with the goal of aiding progress towards lower carbon shipping.

6. Acknowledgements

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References

Craft, T. J., Iacovides, H., Johnson, N. and Launder, B. E. (2012), Back to the future: Flettner-Thom rotors for maritime propulsion?, Turbulence, Heat and Mass Transfer 7.

Flettner, A. (1925), The Flettner rotor ship, Engineering.

Gilbert, P., Bows, A., Walsh, C., Mander, S. and Traut, M. (2012), Mutiny on the high seas: exploring step-change technological mitigation in the shipping sector, Low Carbon Shipping 2012 conference, submitted.

Lindstad, H., Asbjørnslett, B. and Strømman, A. (2011), Reductions in greenhouse gas emissions and cost by shipping at lower speeds, Energy Policy, Elsevier.

Mander, S., Walsh, C., Bows, A., Gilbert, P. and Traut, M. (2012), Decarbonising the UK energy system and the implications for UK shipping, submitted to Carbon Management.

McNaughton, J. (2012), private communication.