Sustainable shipping

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1 *Sustainable shipping*

How might ships become zero-carbon? How might they become less energy-intensive?

This note reviews some of the options.

From time to time I will use the container ship in figure 1.1 as an example. The energy intensity of freight transport by this container ship is 0.015 kWh per t-km. The *Ever Uberty* – length 285 m, breadth 40 m – has a capacity of 4948 TEUs, deadweight 63 000 t, and a service speed of 25 knots (13 m/s); its engine's normal delivered power is 44 MW. The thrust implied by a power to speed ratio of 44 MW to 25 knots is about 3.4 MN. It can transport a net cargo mass of about 64 000 tons.

Figure 1.1. The container ship *Ever Uberty* at Thamesport Container Terminal. Photo by Ian Boyle `www.simplonpc.co.uk`.

Make conventional ships more energy-efficient

Improve hulls and propellors

Example: the Nissan ship, which has an aerodynamic shape above the water.

A more extreme idea would be to switch from surface ships to submarines. The energy intensity of submarine freight-transport is discussed in SEWTHA, page 281.

Go slower

(Out of scope of this note.)

Replace small ships by bigger ships

(Out of scope of this note.) Because large ships are so much more energy-efficient, I focus attention on them in the rest of this note.

Generate low-carbon power on the ship

Solar power

Solar power is a ridiculous option, able to deliver less than 1% of the power of a conventional ship. It astonishes me that Toyota are investing in a 'solar-powered ship' as part of their green fluff, and that the media lap up this nonsense. It's a very simple calculation to confirm that solar power can never make an important contribution to a conventional ship. Imagine that we modify a ship the size of the *Ever Uberty* so that 90% of its top surface is solar panels. That's 10 000 m^2 of solar panels. The peak output of these panels, assuming a peak-power-per-area of 200 $\mathrm{W/m}^2$, would be

2 MW; the *average* output, night and day, assuming a power-per-area of 30 W/m^2, would be 0.3 MW. This is **0.7%** of the normal power delivered by the engine.

Wind power

Wind power has been demonstrated as a successful power source for shipping for hundreds of years.

We could clearly revert to the ship designs of the past. Are there credible ways of applying wind power to today's ships, with only minor modifications to ship anatomy, to ship routing, and to ship speeds?

Wind turbines, sails, and kites

Wind turbines could be mounted on ships. A typical on-shore turbine has a peak output of 2.3 MW, a hub height of 60 m, and a rotor diameter of 80 m. The *Ever Uberty* has a length of 285 m, and a breadth of 40 m, so two 2.3 MW turbines could be mounted within its length, three diameters apart. Their peak output, in ideal wind conditions, would be 4.6 MW, which would be about 10% of the normal power delivered by the *Ever Uberty*'s engine.

If the wind turbine idea were pursued, it is important to note that the turbine would, when operating, experience a substantial thrust in the direction of the apparent wind. If the ship is travelling upwind, with most of its power coming from non-wind-powered engines, this thrust could easily be large enough to eliminate any benefit from the turbine. A back-of-envelope calculation indicates that this undesired backwards thrust will kill the turbine's benefits if the boat's speed is (roughly) bigger than the true wind-speed. So turbines can be fine for boats that go substantially slower than the wind-speed.

But much of the time, the service speed of a conventional ship is bigger than the wind-speed. A force-4 wind is about 6.5 m/s; a force-7 wind is about 16 m/s. The service speed of the *Ever Uberty* is about 13 m/s.

A tentative conclusion is that wind-turbine-assisted-ships would work fine for cargo delivery at speeds slower than wind-speeds.

For ships that go faster than the wind, wind-turbine assistance will work for only some wind directions.

The *Ever Uberty* case study indicates a maximum assistance in the ballpark of 10% of normal power, assuming the perfect wind-speed and direction.

Flettner rotors

Flettner rotors are spinning cylinders that exploit the Magnus effect to deliver a thrust perpendicular to the apparent wind direction. The thrust is proportional to the wind speed.

The size of cylinders required to obtain a given thrust (in terms of area presented) is much smaller than the size of sails for a conventional sailing ship. Flettner rotors were reasonably-successfully demonstrated in the early 1900s, on ocean-going ships powered solely by their rotors. Reviews of those ships state that the power used to spin the rotors could have been better used to directly drive the ship by ordinary propellors, however. Nevertheless, back-of-envelope calculations (based on ideal flow theory) indicate that Flettner rotors are credible thrust generators. A detailed understanding of Flettner rotors remains a research challenge.

The *E-ship 1* is a modern cargo ship with four Flettner rotors that supplement a conventional engine. She is owned by Enercon. The rotors are 27 meters tall and 4 meters in diameter. Her typical service speed is 16 knots (8.2 m/s). Back-of-envelope calculations indicate that for a rotation rate of 2 Hz, and in a perfectly aligned force-4 wind, the four rotors would deliver a thrust equivalent to a 2.1 MW boost in power. (I'm assuming that the average wind speed corresponds to a force 4.) Given that the wind is not going to be perfectly aligned all the time, we can estimate that the average power boost is, say, one third of 2.1 MW, which is 0.7 MW. The power of the E-ship's conventional engine is 7 MW, so the saving from the Flettner rotors is estimated to be in the ballpark of 10%.

I emphasize this is a very rough calculation, and the answer given should not be trusted, except as a rough ballpark answer.

Nuclear power

(Out of scope of this note, for the time being.)

Alternative energy carriers

One way to make shipping zero-carbon is to make a zero-carbon energy-carrier elsewhere, then store it on the ship. The key things to consider about the energy carrier are whether its production has any sustainability concerns, and whether the energy carrier's volume or weight are unreasonable.

Biodiesel

Biodiesel has similar volume and weight per MJ to standard liquid fuels, and so a switch to biodiesel would require little change to ships and their operations. However, there are two concerns:

1. biodiesel may not be zero-carbon, as its production may involve emissions from fertilizer production or use, from land use change, or from other agricultural processes.

2. biodiesel production at scale would guzzle up immense land areas that we might like to hold for other purposes (eg, food, or nature).

Let's describe the land use that would be required for one ship, and the total land use to power all today's shipping by biodiesel. I'll assume that biodiesel is produced with a power per unit area of biofuel plantation of 0.5 W/m^2 (see SEWTHA for alternative figures and sources).

To power **one** 44-MW ship (such as the *Ever Uberty* at 0.5 W/m^2, assuming a 50%-efficient engine and an 80% load factor (i.e., that the ship is steaming 80% of the time), we require **140 km**^{2} of biofuel plantation.

To power all today's ships, which in the year 2000 used energy at a rate of 7.3 EJ per year (source IPCC), would require biofuel plantations with an area of 464 000 km^2, which is roughly two United Kingdoms, or twenty New Jerseys.

Now, biodiesel doesn't have to produced from dedicated biofuel plantations; it could be produced from agricultural and forest residues too; or from surplus forest production; and according to the IEA biofuels roadmap, these sources could provide significantly more than 7.3 EJ per year. This may be true, but the scale of the undertaking must be understood – if we use residues and by-products in place of dedicated biofuels, the land area from which residues and by-products would have to be collected, for a given output, will be much larger!

It *may* make sense for humanity to make sustainable biodiesel and dedicate it to shipping, but there will certainly be competing claims on biofuels: aviation, heavy road transport, and methane-production, for example.

Hydrogen

Hydrogen, at 700 bar, has an energy density of 123 MJ per kg and 5.6 MJ per litre. If we made a straight substitution of liquid fuels by hydrogen in ships, the volume of hydrogen would be roughly six times as big as the liquid fuel (about 43 MJ/kg and 33 MJ/l), for a given chemical energy content. The mass of hydrogen would be smaller than the mass of liquid fuel, but the high-pressure tank would probably more than cancel out that mass advantage.

Battery-powered ships

Real Lithium-ion battery packs have an energy to mass ratio of 120 Wh per kg (430 kJ per kg) (SEWTHA page 127). So a battery-powered ship would require battery packs with a mass 100 times greater than the mass of liquid fuel. I don't have a density for a Li-ion battery pack, but I imagine it is similar to that of liquid fuel, so the volume required would be 100 times greater too.

Heat-powered ships

A cold store and a hot store on the boat, both made perhaps of granite gravel, could be charged up using an on-board heat pump when the ship has access to low-carbon electricity. Then the heat pump could be used in reverse as a heat engine to drive the ship. For this idea to be viable a very efficient heat engine would be required; this is what Cambridge-based company Isentropic is developing.

If the cold store's operating temperature range were -150 to $-50\,^\circ$C, and the hot store's were 350 to $450\,^\circ$C (these numbers are picked just to give a quick rough estimate), then the heat and cold stored per unit mass of granite gravel would be about 79 kJ/kg and -79 kJ/kg respectively. The Carnot efficiency for $-150\,^\circ$C and $+350\,^\circ$C would be $(1-123/623) \simeq 0.8$; assuming a heat-engine efficiency of 0.6 (75% of Carnot), the useful energy delivered per unit mass of gravel would be $79\,\text{kJ/kg} \times 0.5 \times 0.6 \simeq 24\,\text{kJ/kg}$, or 6.6 Wh/kg.

That's twenty times worse than the lithium-ion battery pack. Have I made a slip in the numbers? Maybe I should assume a larger temperature range.

Compressed air

More here.

Notes and further reading

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1 *The energy intensity of freight transport by this container ship is 0.015 kWh per ton-km*. One TEU is the size of a small 20-foot container – about 40 m^3. Most containers you see today are 40-foot containers with a size of 2 TEU. A 40-foot container weighs 4 tons and can carry 26 tons of stuff. Assuming its engine is 50%-efficient, this ship's energy consumption works out to 0.015 kWh of chemical energy per ton-km. `www.mhi.co.jp/en/products/detail/container_ship_ever_uberty.html`