# A Global Fleet Under Wind:

## Scaling Wind Propulsion for Emission Reduction, Energy Demand and Equity

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SEAS AT RISK

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# Contents

# Executive Summary

## Global shipping currently emits over 1,000 million tonnes of CO2 each year, making it a significant contributor to climate change.

In 2023, the **International Maritime Organization (IMO)'s Revised GHG Strategy set targets of up to 30% reduction in greenhouse gas emissions by 2030 relative to 2008, up to 80% by 2040, and fully decarbonised by 2050**. Combined with the cumulative build-up of CO2 in the atmosphere, which accumulates over hundreds of years to drive irreversible climate impacts, early action is critical. **As renewable e-fuels may not be competitive at scale until the 2040s** if only weak policy interventions are applied (Aymer and Smith, 2025), the shipping sector **must turn to technologies available and scalable today** to cut emissions.

**Wind propulsion represents one such opportunity**. A proven, **commercially available** technology already deployed on around **100 large cargo ships worldwide in 2025**, it uses wind power from high-tech sails such as Flettner rotors to reduce the fuel consumption of a ship's main engine. It directly **supports the IMO's commitment to achieve at least 5%, striving for 10%, uptake of zero or near-zero emission technologies, fuels and energy sources by 2030** and it is one of the very few mature solutions capable of delivering a share of this near-term requirement.

**Until now, no study has assessed the decarbonisation potential of wind propulsion across the entire maritime fleet. This study addresses this gap.**

We split the fleet into 25 wind-suitable ship types, covering around 60% of global shipping emissions. Using state-of-the-art wind propulsion **modelling** across 1.74 billion kilometres of real voyage data from 2024, equivalent to **the distance from the Earth to Saturn, annual fuel and emission savings are calculated for 34,505 vessels, being conservative, we find that wind propulsion can cut fuel consumption by 1.0 to 12.5% depending on the ship type, and by 6.3%-9.4% across all wind-suitable vessels, depending on the number of sails installed.** This approach provides the most robust and comprehensive assessment to date of the technology's performance using real-world operational data.

Crucially, **emission savings are concentrated around top performers, where the top 16% of vessels account for 50% of total savings**. Predominantly bulk carriers and tankers, these vessels have high utilisation and lots of available deck space for wind installations, presenting a clear opportunity for targeted deployment. Alongside financial benefits, this **offers shipowners an increasingly valuable compliance tool for the Carbon Intensity Indicator (CII) as thresholds tighten over time.**

While these findings show meaningful fuel savings from wind propulsion, the results remain conservative. They reflect a 'plug and go' scenario: retrofitting today's suitable fleet with wind propulsion systems under current operational practices, with no design optimisation for newbuilds, weather routing, slow steaming, or primary wind design configurations. This is a limitation of this study rather than a limit of the performance of wind technologies, and the maximum potential of wind propulsion when paired with these complementary measures is even greater. Containerships are also not included, despite being suitable candidates for kite retrofits and emerging newbuild designs.

**Looking to 2050, wind propulsion could reduce the annual fuel consumption and CO2e of the wind-suitable fleet by 7.8%** under a strong uptake scenario compared to baseline ships fuelled by heavy fuel oil

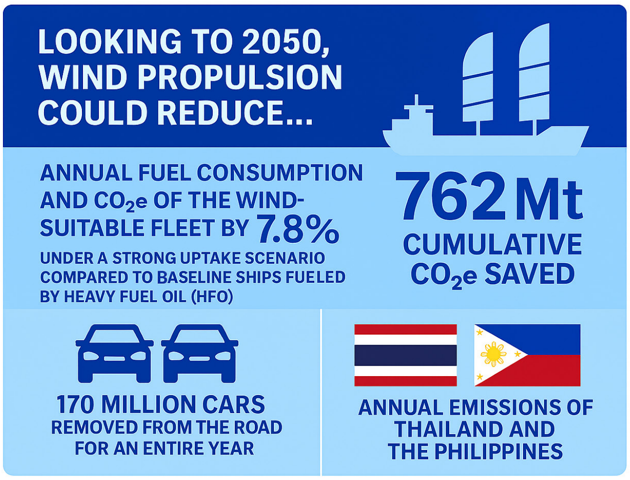
(HFO), with up to 762 million tonnes of cumulative CO2e saved. This is **roughly the equivalent of removing 170 million cars from the road for an entire year, or the annual CO2e emissions of Thailand and the Philippines combined**. But this is only possible with the right policy framework. Under a business-as-usual scenario, lacking sufficient policy frameworks, wind propulsion would deliver a mere 0.2% reduction. This is not a gap in technology; it's a failure of policy.

Uptake modelling also shows that wind propulsion can do something that future fuels cannot: it can reduce the total fuel demand now and across the next critical decade. In contrast, zero-emission fuel production, storage and distribution are still developing, making large-scale availability unlikely for at least a decade. **Every tonne of fuel avoided through wind propulsion eases the pressure on these constrained e-fuel supply chains, buys time for infrastructure to be developed, and allows renewable energy to be directed first toward essential uses such as clean heating**. Once developed, access to these expensive new e-fuels also risks being deeply unequal, especially for climate-vulnerable countries, small island developing states (SIDS), and least developed countries (LDCs). Wind propulsion can improve the accessibility of this transition.

The path forward for industry and policy is clear: **targeted deployment on high-utilisation vessels such as bulk carriers and tankers can deliver a disproportionate share of near-term emission reductions**. Such an approach can support a more balanced transition than solely focusing on new fuels, prioritising segments where early action is most feasible. While additional measures will be required to deliver decarbonisation in line with IMO and Paris Agreement targets, the results from this study show that wind propulsion can provide a meaningful contribution.

Overall, findings show that **wind propulsion offers an immediate pathway to reduce emissions over the crucial next decade. Given that the technology is commercially available today and eases the pressures on tomorrow's future fuels, it represents a low-risk solution that harnesses an abundant renewable energy source.** If backed by policy to ease financial barriers and accelerate deployment, wind propulsion could play a vital role in providing crucial near-term emissions reductions while new fuels come online. The alternative future, which relies solely on new fuels as a silver bullet, misses a critical window for action and leaves large cumulative emissions savings on the table that could help **limit global shipping's long-term impact on climate change.**

> **We find that wind propulsion can cut fuel consumption by 6.3%-9.4% across all wind-suitable vessels... Crucially, emission savings are concentrated around top performers, where the top 16% of vessels account for 50% of total savings.**



LOOKING TO 2050, WIND PROPULSION COULD REDUCE...

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762 Mt CUMULATIVE $CO_2e$ SAVED

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ANNUAL EMISSIONS OF THAILAND AND THE PHILIPPINES

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# Introduction

The maritime sector is the backbone of global trade, with around 60,000 merchant vessels over 1,000 GT operating worldwide. Together, these ships emit close to 1,000 Mt CO2 each year, accounting for 2-3% of global greenhouse gas emissions. To align with the Paris Agreement's 1.5°C limit, international shipping must cut carbon emissions by at least 34% by 2030 relative to 2008 levels and reach full decarbonisation by 2050 (Bullock et al., 2022).

In 2023, the International Maritime Organization (IMO) responded by adopting revised targets: up to a 30% reduction in GHG emissions by 2030, 80% by 2040 and net-zero by 2050 (IMO, 2023). At their most ambitious, these targets come close to a trajectory consistent with the Paris Agreement (Bullock et al., 2024).

However, ambitious declarations alone are not enough. Because CO2 accumulates in the atmosphere over time – a process known as cumulative emissions – the speed of decarbonisation matters as much as the overall end goal. Every tonne of CO2 emitted today adds to the warming that future reductions cannot undo. With current emission rates remaining high, the shipping sector must urgently deploy measures that are available today (Bullock et al., 2020). This makes reliance on the next generation of low-emission fuels, which are currently a significant focus of the IMO, inadequate as a sole response, given their high development costs and potential lack of competitiveness at scale until the 2040s with only weak policy intervention (Aymer and Smith, 2025).

Wind propulsion systems are emerging as a promising near-term decarbonisation solution for shipping. Modern wind technologies, including Flettner rotors, suction sails and wing sails, harness wind energy to provide propulsion, replacing engine power and saving fuel. As of the end of 2025, almost 100 commercial vessels are operating with these systems, with over 100 additional installations planned (IWSA, 2026).

Alongside near-term climate benefits, wind propulsion systems also offer wider opportunities. At the vessel level, reducing fuel demand directly lowers emissions while decreasing reliance on fuels both today and in the future. As future fuels are expected to be expensive, wind propulsion can help shield shipowners from price volatility and associated financial risks. At the system level, the implications extend beyond individual vessels: lowering aggregate fuel demand can ease pressure on fuel supply, infrastructure development, and overall transition costs. In a context where access to new fuels is expected to vary across regions, such demand-side reductions could play an important role in shaping the accessibility and affordability of the transition.

In practice, wind propulsion systems have already demonstrated fuel savings of 4.5-9% based on evidence from shipowners and vessel operators (DNV, 2024). Higher savings are expected on routes with favourable wind conditions, with fuel savings of up to 24% estimated on transoceanic routes across the North Atlantic and Pacific (Mason et al., 2023).

## Research contribution

Despite this growing body of evidence from individual vessels and specific routes, the potential impact of wind propulsion when applied to all suitable ships in the global fleet remains poorly understood. Emissions abatement across different ship types and global operating profiles remains largely unknown, as does the realistic contribution these systems could make toward shipping's decarbonisation by 2030, 2040 and 2050 if scaled up across the sector.

This report provides the first comprehensive assessment of wind propulsion fuel savings and uptake across the entire wind-suitable fleet. Using Automatic Identification System (AIS) ship tracking data and advanced wind propulsion modelling across 25 ship types, we quantify the emissions abatement potential of wind propulsion at a fleet scale and evaluate what a targeted, ambitious deployment could achieve over the coming decades.

These system-level effects are particularly relevant in the context of ongoing IMO discussions on designing the framework for implementing the IMO's revised GHG strategy.

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# Wind Propulsion Performance Across the Wind-Suitable Fleet

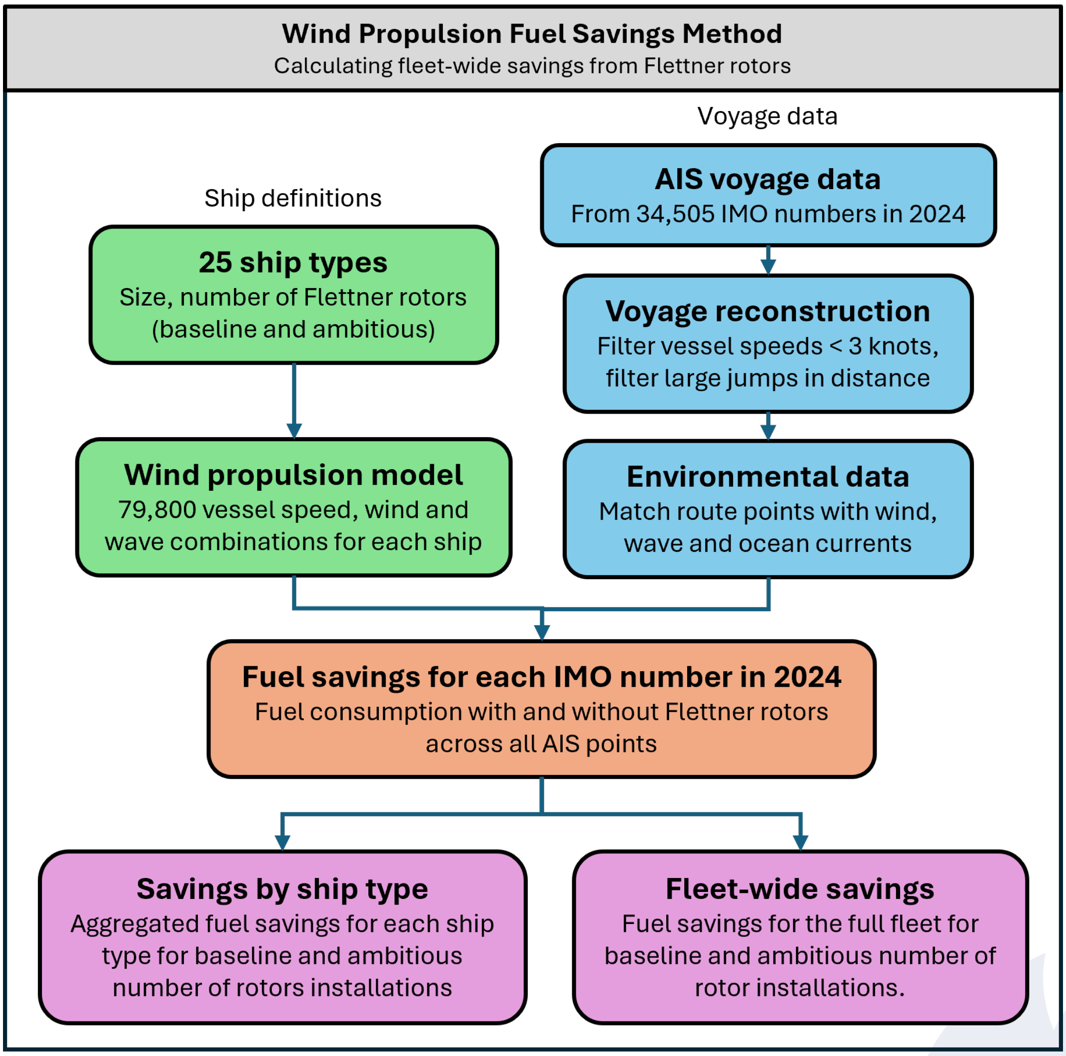


Figure 1: An overview of the method used to calculate wind propulsion fuel savings.

## Modelling and Data

We divide the maritime fleet into 25 total ship types that are suitable for wind propulsion (Table 1), which covers almost 60% of global shipping emissions (Figure 2) (Faber et al., 2020), the vast majority being from international shipping. Fleet data obtained from Kpler shows 48,154 ships operating across the 25 defined ship types in 2024. Out of these, 34,505 have available AIS data. Small general cargo ships, small passenger ships and small Ro-Pax ships account for over 90% of the vessels missing AIS data. For each ship type, we use the fleet data alongside utilisation (in dwt-km) to define the most typical vessel out of all ships in that range to model with wind propulsion.

Emissions from the ship types not included in this study, covering the remaining 40% of global shipping emissions, mainly stem from containerships and other smaller ship types such as tugs and fishing vessels. While modelling containerships fell outside of the scope of this study, this is a modelling limitation only, as these vessels are strong candidates for kite-based retrofits and emerging newbuild designs. Including these ships in future studies would further increase the potential contribution of wind propulsion than shown here.

Flettner rotors are selected as the wind propulsion device modelled in this study, as they represent one of the most technologically mature options currently available. However, other technologies, such as wing sails or suction wings, could have equally been considered. In practice, each vessel should undergo a bespoke assessment to determine the device best suited to its specific operational profile. This study does not account for such variations, and Flettner rotors are applied to all ships.

We model two configurations of Flettner rotor for each ship:

**Baseline**: a low number of sails installed. Values are based on numbers installed on vessels today.

**Ambitious**: a high number of sails installed. These levels may require newbuild vessel designs or policy support, particularly to improve the financial case for larger ships with many devices.

The number of sails installed for the baseline and ambitious configurations is tailored for each vessel and is based on vessel size. The exact numbers are outlined in Table 2. Rotor dimensions are scaled to vessel size, with the smallest ships installing 24-meter high, 4-meter diameter units, and the largest vessels installing 35-meter high, 5-meter diameter units. More details on Flettner sizing can be found in Appendix A.

Wind propulsion performance for each vessel is modelled using the AlbatrosDigital Shipyard platform, a cloud-based power prediction programme used commercially across the maritime industry. For any given operating condition for the vessel at sea – including ship speed, wind speed, wind angle, wave height and wave direction – the model balances the forces acting on the ship in four degrees of freedom to determine the most fuel-efficient way to run the vessel. Contributions from seven components are modelled, including calm water resistance, added resistance in waves, hull hydrodynamic side forces at non-zero leeway and heel, superstructure aerodynamic drag, rudder forces, propeller thrust and wind propulsion forces.

Flettner rotor aerodynamics are modelled using the Stormbird aerodynamic library, developed at the Norwegian University of Science and Technology (NTNU) as part of the Norwegian Research Council's KSP WIND project. Stormbird captures the important effects of wake shielding, aerodynamic interference from multiple rotors and diminishing returns as more rotors are added – effects that are neglected by simpler models. The model also optimises the RPM of each rotor individually, alongside leeway angle, heel angle, rudder angle and propeller RPM, to ensure that performance estimates reflect realistic operating behaviour. The power required to spin the rotors is included. More details on wind propulsion modelling can be found in Appendix B.

To capture real-world operating behaviour, we use real 2024 AIS voyage data from Kpler in hourly intervals and covering the 34,505 vessels within the defined wind-suitable fleet (Figure 3). Vessel speeds under 3 knots are removed to filter out port stays and low-speed manoeuvring. The vast majority of AIS data

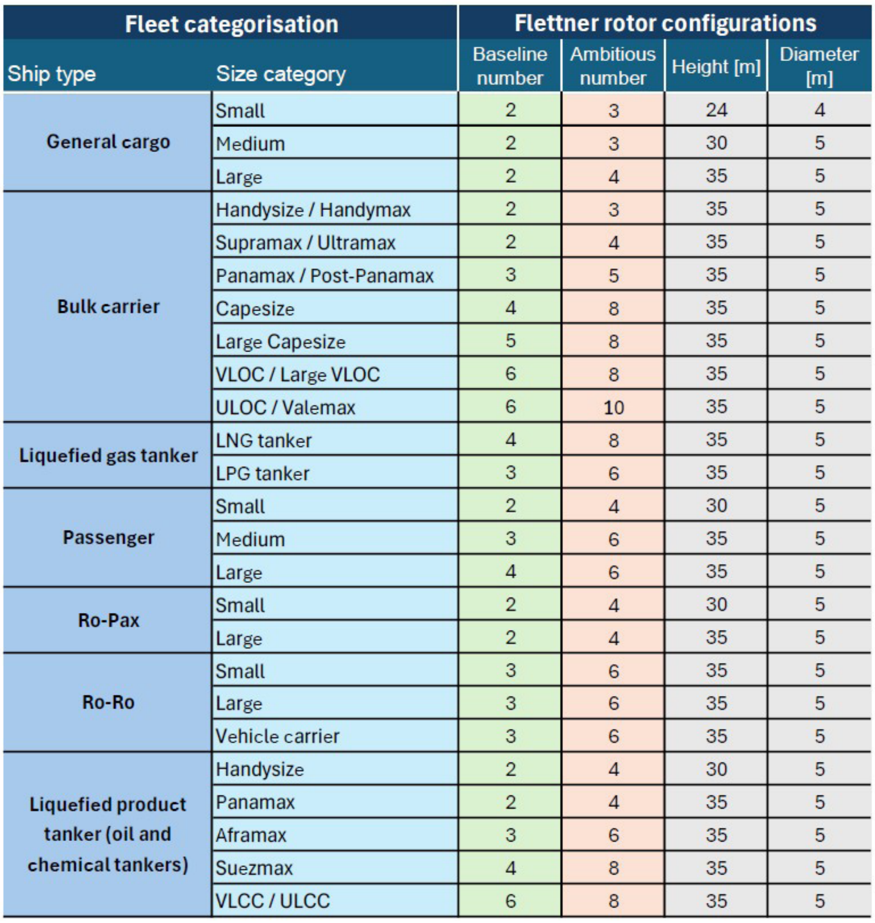
points are spaced in 1-hour time intervals, but some gaps extend beyond this. To address this, the AIS tracks of each ship are reconstructed into individual voyages, where a new voyage is created if an adjacent AIS point exceeds 48 hours in time or 1,000 km in distance. This leads to some missing AIS data, which will result in an underestimation of annual fuel consumption for the modelled fleet.

Once individual voyages are reconstructed, each AIS point is matched with real historical wind, wave and ocean current conditions along the route (Table 3), providing an accurate representation of the weather each vessel encountered. A global map of environmental conditions can be found in Appendix C, while an example of a shipping track reconstructed from AIS data can be found in Appendix D.

Fuel consumption is then calculated voyage by voyage using the reconstructed routes and corresponding weather conditions. At each point along a voyage, the historical wind, wave and ocean current conditions are combined with the appropriate vessel model, and the difference in fuel consumption with and without Flettner rotors installed provides an accurate estimate of fuel savings. When applied to the fleet of modelled wind-suitable ships, this approach produces the most robust, comprehensive and operationally grounded fleet-wide assessment to date of wind propulsion's potential contribution to maritime decarbonisation.

| Fleet categorisation | | | | |
|---|---|---|---|---|
| **Ship type** | **Size category** | **Unit** | **Modelled size** | **Category size range** |
| **General cargo** | Small | DWT | 14,000 | 0–20,000 |
| | Medium | DWT | 30,000 | 20,000–40,000 |
| | Large | DWT | 57,000 | 40,000+ |
| **Bulk carrier** | Handysize / Handymax | DWT | 37,000 | 10,000–40,000 |
| | Supramax / Ultramax | DWT | 63,000 | 40,000–70,000 |
| | Panamax / Post-Panamax | DWT | 80,000 | 70,000–120,000 |
| | Capesize | DWT | 180,000 | 120,000–190,000 |
| | Large Capesize | DWT | 210,000 | 190,000–220,000 |
| | VLOC / Large VLOC | DWT | 300,000 | 220,000–350,000 |
| | ULOC / Valemax | DWT | 400,000 | 350,000+ |
| **Liquefied gas tanker** | LNG tanker | CBM | 175,000 | 100,000–270,000 |
| | LPG tanker | CBM | 84,000 | 65,000–110,000 |
| **Passenger** | Small | GT | 15,000 | 0–25,000 |
| | Medium | GT | 40,000 | 25,000–60,000 |
| | Large | GT | 120,000 | 60,000+ |
| **Ro-Pax** | Small | GT | 10,000 | 0–20,000 |
| | Large | GT | 34,000 | 20,000+ |
| **Ro-Ro** | Small | DWT | 11,000 | 5,000–20,000 |
| | Large | DWT | 30,000 | 20,000+ |
| | Vehicle carrier | GT | 60,000 | 35,000–80,000 |
| **Liquefied product tanker (oil and chemical tankers)** | Handysize | DWT | 50,000 | 5,000–60,000 |
| | Panamax | DWT | 75,000 | 60,000–80,000 |
| | Aframax | DWT | 110,000 | 80,000–120,000 |
| | Suezmax | DWT | 160,000 | 120,000–200,000 |
| | VLCC / ULCC | DWT | 310,000 | 200,000+ |

Table 1: Sizes of the 25 ship types modelled in this study.



| Fleet categorisation | | Flettner rotor configurations | | | |
|---|---|---|---|---|---|
| Ship type | Size category | Baseline number | Ambitious number | Height [m] | Diameter [m] |
| General cargo | Small | 2 | 3 | 24 | 4 |
| | Medium | 2 | 3 | 30 | 5 |
| | Large | 2 | 4 | 35 | 5 |
| Bulk carrier | Handysize / Handymax | 2 | 3 | 35 | 5 |
| | Supramax / Ultramax | 2 | 4 | 35 | 5 |
| | Panamax / Post-Panamax | 3 | 5 | 35 | 5 |
| | Capesize | 4 | 8 | 35 | 5 |
| | Large Capesize | 5 | 8 | 35 | 5 |
| | VLOC / Large VLOC | 6 | 8 | 35 | 5 |
| | ULOC / Valemax | 6 | 10 | 35 | 5 |
| Liquefied gas tanker | LNG tanker | 4 | 8 | 35 | 5 |
| | LPG tanker | 3 | 6 | 35 | 5 |
| Passenger | Small | 2 | 4 | 30 | 5 |
| | Medium | 3 | 6 | 35 | 5 |
| | Large | 4 | 6 | 35 | 5 |
| Ro-Pax | Small | 2 | 4 | 30 | 5 |
| | Large | 2 | 4 | 35 | 5 |
| Ro-Ro | Small | 3 | 6 | 35 | 5 |
| | Large | 3 | 6 | 35 | 5 |
| | Vehicle carrier | 3 | 6 | 35 | 5 |
| Liquefied product tanker (oil and chemical tankers) | Handysize | 2 | 4 | 30 | 5 |
| | Panamax | 2 | 4 | 35 | 5 |
| | Aframax | 3 | 6 | 35 | 5 |
| | Suezmax | 4 | 8 | 35 | 5 |
| | VLCC / ULCC | 6 | 8 | 35 | 5 |

Table 2: Flettner rotor assumptions for the baseline and ambitious configurations, applied across the 25 ship types modelled in this study.

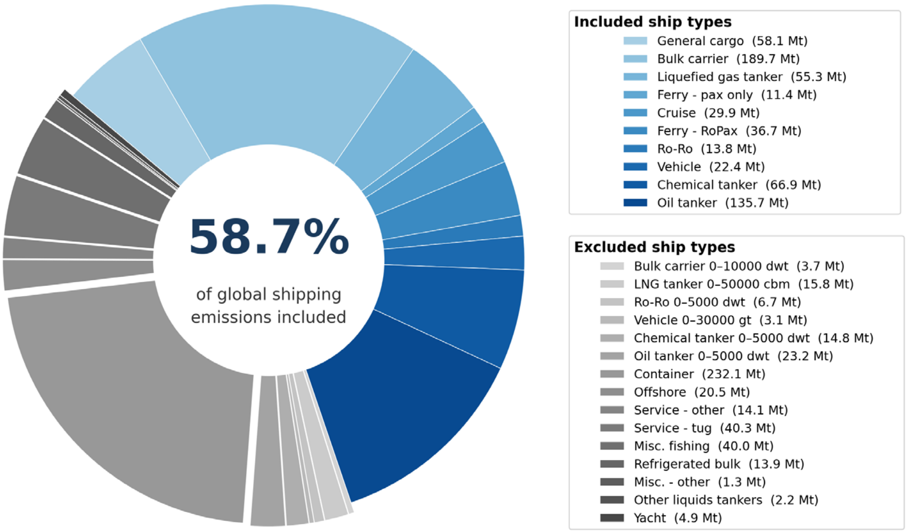
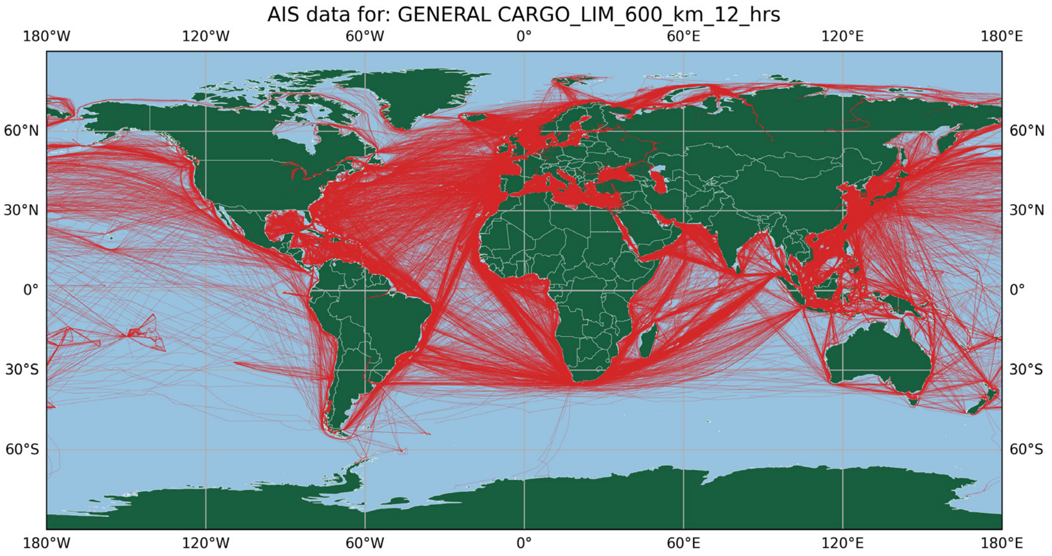


Figure 2: Total emissions covered by the 25 ship types modelled in this study relative to global shipping emissions. Data is obtained from Faber et al. (2020).



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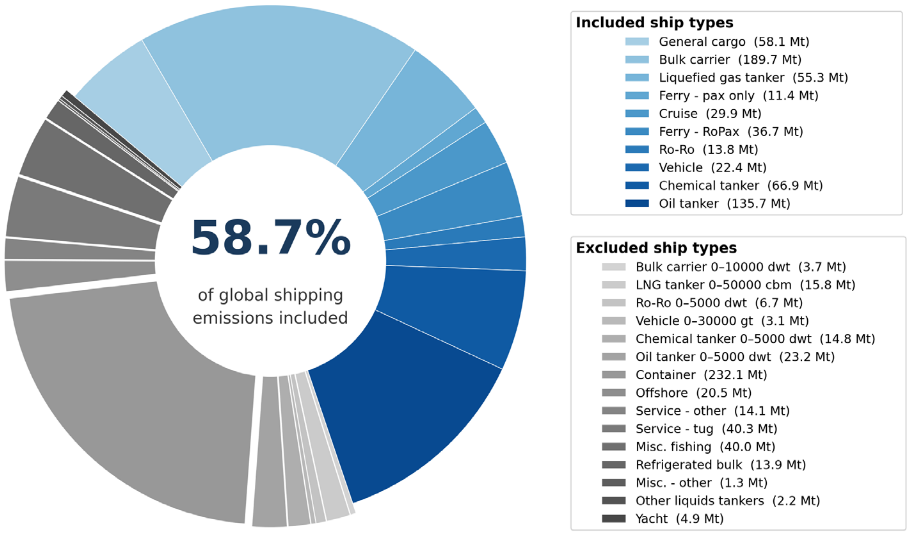


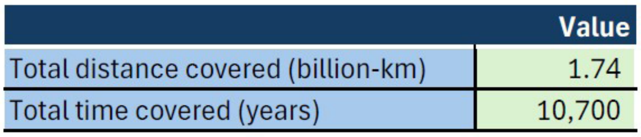
Figure 2: Total emissions covered by the 25 ship types modelled in this study relative to global shipping emissions. Data is obtained from Faber et al. (2020).

| Data | Provider | Dataset | Spatial resolution | Time resolution |
|---|---|---|---|---|
| Wind | European Centre for Medium-range Weather Forecasts (ECMWF) | ERA5 | 0.5 degrees | 1 hour |
| Ocean currents | Earth & Space Research (ESR) | OSCAR | 0.25 degrees | 24 hours |
| Waves | European Centre for Medium-range Weather Forecasts (ECMWF) | ERA5 | 0.5 degrees | 6 hours |

Table 3: Sources and resolution of the historical environmental data used in this study for 2024.

## Fuel and Emissions Savings

Aggregated across the 34,505 modelled vessels, we calculate wind propulsion performance over a total of 1.74 billion kilometres, equivalent to more than the distance between Earth and Saturn, and spanning 10,700 years of cumulative operational time (Table 4).



| | Value |
|---|---|
| Total distance covered (billion-km) | 1.74 |
| Total time covered (years) | 10,700 |

Table 4: The total cumulative distance and time covered.

For the wind-suitable ships and AIS tracks modelled in this study, we find that fuel savings reach 7.0 million tonnes for the baseline rotor configuration and 10.5 million tonnes for the ambitious rotor configuration (Table 5). This corresponds to well-to-wake CO2e savings of 29.5 million tonnes for the baseline configuration and 44.0 million tonnes for the ambitious configuration relative to baseline HFO fuelled ships (Table 6). Tank-to-wake and well-to-wake CO2 values are also shown in Table 6. Savings are for the main engine only, but include the fuel required to spin the rotors.

Findings show fuel and CO2 savings for the modelled ships reach 6.3% for the baseline configuration and 9.4% for the ambitious configuration, indicating that wind propulsion can deliver meaningful emissions reductions. Alongside providing financial benefits, these fuel savings also translate into improvements in a vessel’s Carbon Intensity Indicator (CII). With CII thresholds tightening over time, this presents wind propulsion as an increasingly valuable compliance tool – one that delivers rating improvements today without waiting for e-fuels to become available at scale.

Due to gaps in the AIS data (which is discussed further in Appendix D), the total absolute fuel and CO2 savings presented (in million tonnes) are underestimated. However, because wind propulsion is modelled over distances of more than a billion kilometres that cover the full range of operational conditions at sea, and given the significant computational effort involved, the presented percentage savings are robust.

These results represent savings achievable under a ‘plug and go’ scenario, where Flettner rotors are retrofitted on today’s fleet under current operational practices. They can therefore be considered as conservative estimates. In practice, deploying wind devices on all suitable ships in the global fleet should be enhanced by combining them with a range of complementary measures such as weather routing, slow steaming, hull optimisation for newbuild vessels, and primary wind designs. Continued work in these areas is needed to fully understand the optimised potential of wind propulsion across the global maritime fleet.

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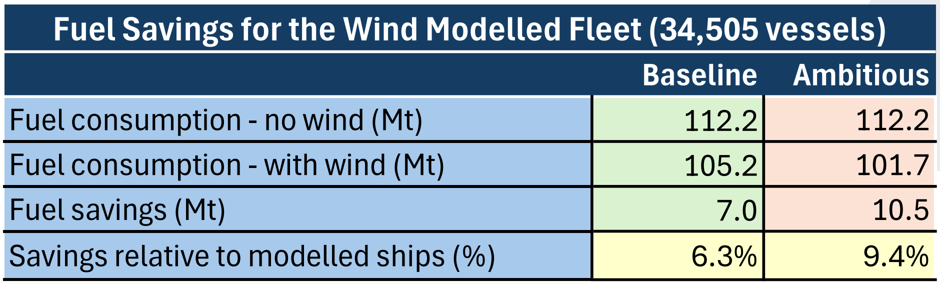
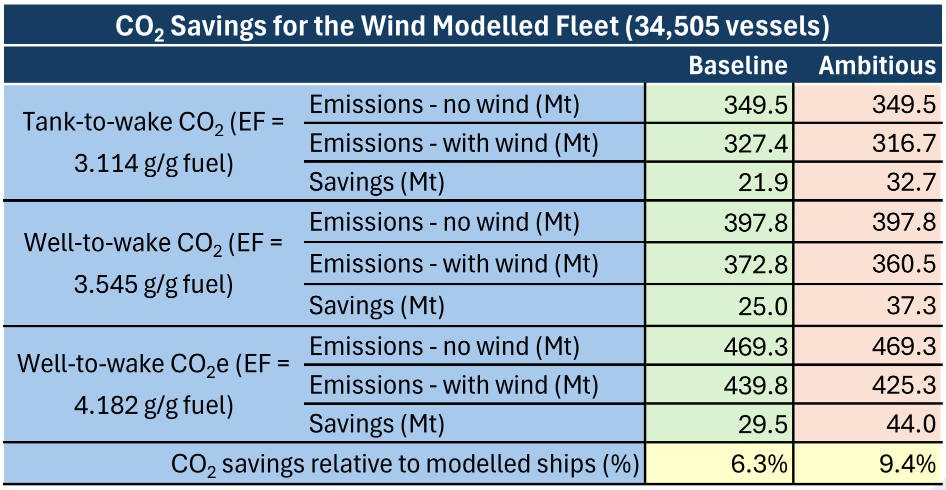


| Fuel Savings for the Wind Modelled Fleet (34,505 vessels) | Baseline | Ambitious |
|---|---|---|
| Fuel consumption - no wind (Mt) | 112.2 | 112.2 |
| Fuel consumption - with wind (Mt) | 105.2 | 101.7 |
| Fuel savings (Mt) | 7.0 | 10.5 |
| Savings relative to modelled ships (%) | 6.3% | 9.4% |

Table 5: Fuel savings aggregated across all 34,505 vessels modelled with wind propulsion, with baseline and ambitious configurations (Table 2). Savings are from the main engine only but include the energy required to spin the Flettner rotors.



| $CO_2$ Savings for the Wind Modelled Fleet (34,505 vessels) | | Baseline | Ambitious |
|---|---|---|---|
| Tank-to-wake $CO_2$ (EF = 3.114 g/g fuel) | Emissions - no wind (Mt) | 349.5 | 349.5 |
| | Emissions - with wind (Mt) | 327.4 | 316.7 |
| | Savings (Mt) | 21.9 | 32.7 |
| Well-to-wake $CO_2$ (EF = 3.545 g/g fuel) | Emissions - no wind (Mt) | 397.8 | 397.8 |
| | Emissions - with wind (Mt) | 372.8 | 360.5 |
| | Savings (Mt) | 25.0 | 37.3 |
| Well-to-wake $CO_2e$ (EF = 4.182 g/g fuel) | Emissions - no wind (Mt) | 469.3 | 469.3 |
| | Emissions - with wind (Mt) | 439.8 | 425.3 |
| | Savings (Mt) | 29.5 | 44.0 |
| | $CO_2$ savings relative to modelled ships (%) | 6.3% | 9.4% |

Table 6: Tank-to-wake and well-to-wake savings for the vessels modelled with wind propulsion, with baseline and ambitious configurations. Savings are for main engine emissions only, but include the energy required to spin the Flettner rotors. Emission factors (EF) are from Comer and Osipova (2021).

## Savings by Ship Type

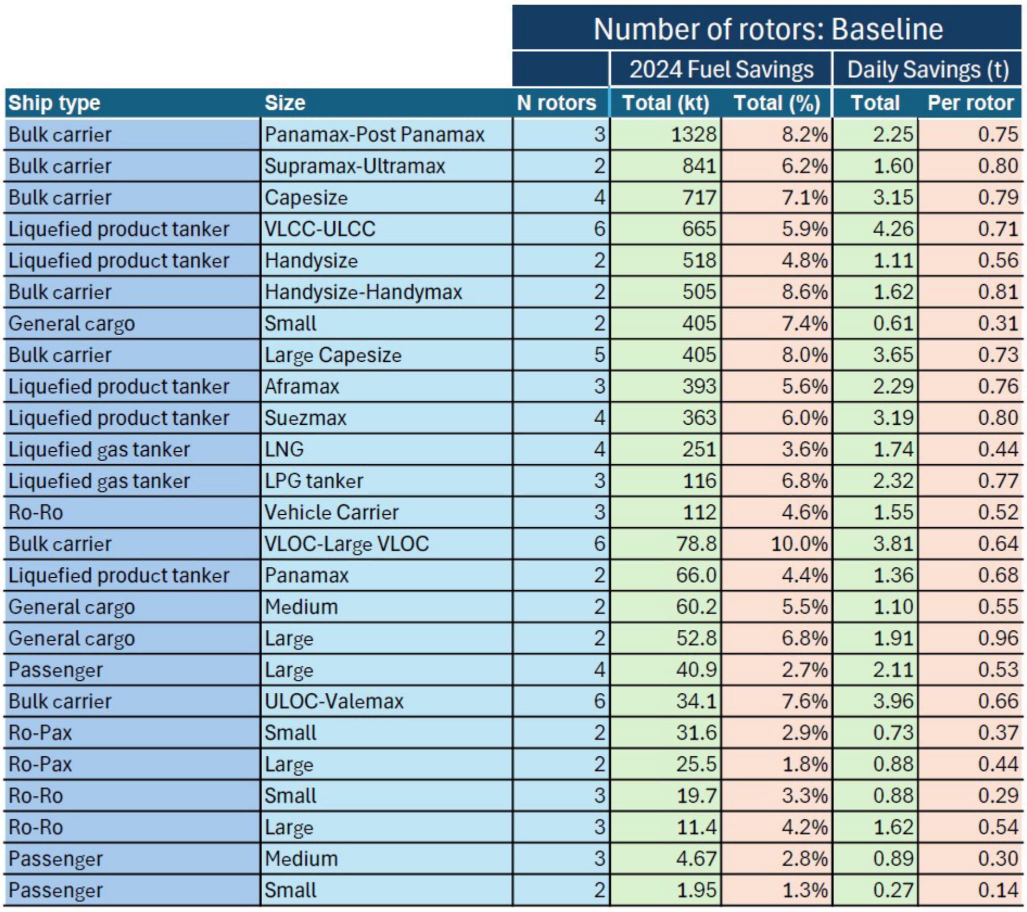
Performance varies significantly across vessel types (Tables 7 and 8). Bulk carriers and liquefied product tankers (made up of oil and chemical tankers) dominate the top-performing ships in terms of total fuel saved. This is driven not only by their high tonne-kilometre utilisation, but also by lower vessel speeds and ample deck space for installations.

Specific vessels achieving the highest daily fuel savings typically operate on long-distance global routes away from the equator. These routes present an additional advantage due to their strong compatibility with weather routing (Mason et al., 2023). Bulk carriers and tankers frequently operate along these routes, presenting further opportunities to enhance fuel savings.

In contrast, passenger, Ro-Ro, and Ro-Pax ships provide the lowest fuel savings to the fleet. These vessel types combine relatively low utilisation with higher average operating speeds (16-19 knots on average), which reduces the effectiveness of Flettner rotors due to increased apparent headwinds. However, these ship segments should not be considered completely unsuitable for wind propulsion. Alternative technologies, such as wing sails and suction sails, provide better propulsion in these operating conditions, and may provide larger fuel savings. It is also important to note that performance will vary within these vessel categories. Certain liner trade routes, particularly those operating in higher latitude regions such as the North Sea, may benefit from more favourable wind conditions. Identifying and targeting these routes presents a promising opportunity for future green shipping corridors focused on wind propulsion adoption.

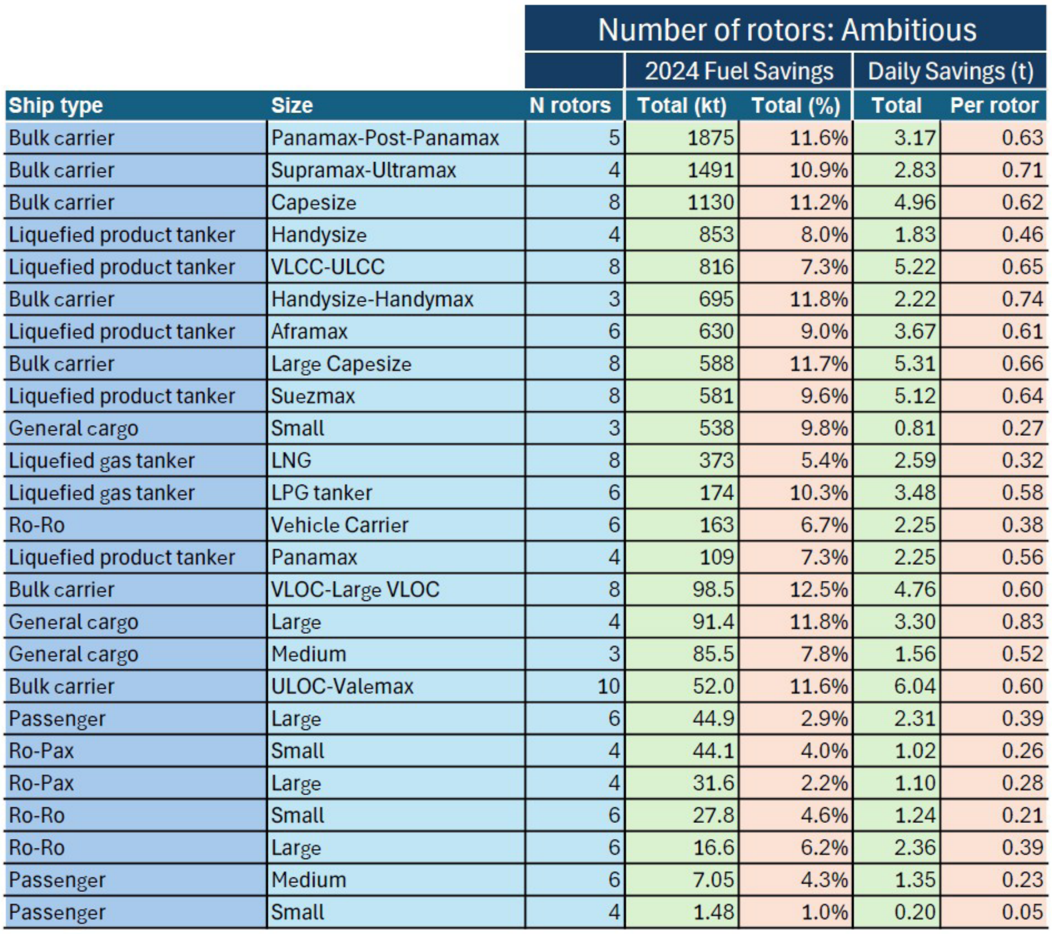
An exception should be noted for gas tankers that burn boil-off gas as fuel. For these vessels, wind propulsion is likely to increase speed rather than reduce fuel consumption, meaning reported savings may be overstated for this ship type.

Finally, while increasing the number of rotors per vessel leads to greater total fuel reductions, it also reduces the fuel savings per rotor. This is a finding that is consistent with the literature (Tillig and Ringsberg, 2020) and represents diminishing returns, which could affect a shipowner's decision to invest in an ambitious number of wind propulsion devices for each ship.



| | | Number of rotors: Baseline | | | | |
|---|---|---|---|---|---|---|
| | | | 2024 Fuel Savings | | Daily Savings (t) | |
| **Ship type** | **Size** | **N rotors** | **Total (kt)** | **Total (%)** | **Total** | **Per rotor** |
| Bulk carrier | Panamax-Post Panamax | 3 | 1328 | 8.2% | 2.25 | 0.75 |
| Bulk carrier | Supramax-Ultramax | 2 | 841 | 6.2% | 1.60 | 0.80 |
| Bulk carrier | Capesize | 4 | 717 | 7.1% | 3.15 | 0.79 |
| Liquefied product tanker | VLCC-ULCC | 6 | 665 | 5.9% | 4.26 | 0.71 |
| Liquefied product tanker | Handysize | 2 | 518 | 4.8% | 1.11 | 0.56 |
| Bulk carrier | Handysize-Handymax | 2 | 505 | 8.6% | 1.62 | 0.81 |
| General cargo | Small | 2 | 405 | 7.4% | 0.61 | 0.31 |
| Bulk carrier | Large Capesize | 5 | 405 | 8.0% | 3.65 | 0.73 |
| Liquefied product tanker | Aframax | 3 | 393 | 5.6% | 2.29 | 0.76 |
| Liquefied product tanker | Suezmax | 4 | 363 | 6.0% | 3.19 | 0.80 |
| Liquefied gas tanker | LNG | 4 | 251 | 3.6% | 1.74 | 0.44 |
| Liquefied gas tanker | LPG tanker | 3 | 116 | 6.8% | 2.32 | 0.77 |
| Ro-Ro | Vehicle Carrier | 3 | 112 | 4.6% | 1.55 | 0.52 |
| Bulk carrier | VLOC-Large VLOC | 6 | 78.8 | 10.0% | 3.81 | 0.64 |
| Liquefied product tanker | Panamax | 2 | 66.0 | 4.4% | 1.36 | 0.68 |
| General cargo | Medium | 2 | 60.2 | 5.5% | 1.10 | 0.55 |
| General cargo | Large | 2 | 52.8 | 6.8% | 1.91 | 0.96 |
| Passenger | Large | 4 | 40.9 | 2.7% | 2.11 | 0.53 |
| Bulk carrier | ULOC-Valemax | 6 | 34.1 | 7.6% | 3.96 | 0.66 |
| Ro-Pax | Small | 2 | 31.6 | 2.9% | 0.73 | 0.37 |
| Ro-Pax | Large | 2 | 25.5 | 1.8% | 0.88 | 0.44 |
| Ro-Ro | Small | 3 | 19.7 | 3.3% | 0.88 | 0.29 |
| Ro-Ro | Large | 3 | 11.4 | 4.2% | 1.62 | 0.54 |
| Passenger | Medium | 3 | 4.67 | 2.8% | 0.89 | 0.30 |
| Passenger | Small | 2 | 1.95 | 1.3% | 0.27 | 0.14 |

Table 7: Total fuel savings from wind propulsion for each ship type for the baseline rotor configuration.



| | | Number of rotors: Ambitious | | | | |
|---|---|---|---|---|---|---|
| | | | 2024 Fuel Savings | | Daily Savings (t) | |
| **Ship type** | **Size** | **N rotors** | **Total (kt)** | **Total (%)** | **Total** | **Per rotor** |
| Bulk carrier | Panamax-Post-Panamax | 5 | 1875 | 11.6% | 3.17 | 0.63 |
| Bulk carrier | Supramax-Ultramax | 4 | 1491 | 10.9% | 2.83 | 0.71 |
| Bulk carrier | Capesize | 8 | 1130 | 11.2% | 4.96 | 0.62 |
| Liquefied product tanker | Handysize | 4 | 853 | 8.0% | 1.83 | 0.46 |
| Liquefied product tanker | VLCC-ULCC | 8 | 816 | 7.3% | 5.22 | 0.65 |
| Bulk carrier | Handysize-Handymax | 3 | 695 | 11.8% | 2.22 | 0.74 |
| Liquefied product tanker | Aframax | 6 | 630 | 9.0% | 3.67 | 0.61 |
| Bulk carrier | Large Capesize | 8 | 588 | 11.7% | 5.31 | 0.66 |
| Liquefied product tanker | Suezmax | 8 | 581 | 9.6% | 5.12 | 0.64 |
| General cargo | Small | 3 | 538 | 9.8% | 0.81 | 0.27 |
| Liquefied gas tanker | LNG | 8 | 373 | 5.4% | 2.59 | 0.32 |
| Liquefied gas tanker | LPG tanker | 6 | 174 | 10.3% | 3.48 | 0.58 |
| Ro-Ro | Vehicle Carrier | 6 | 163 | 6.7% | 2.25 | 0.38 |
| Liquefied product tanker | Panamax | 4 | 109 | 7.3% | 2.25 | 0.56 |
| Bulk carrier | VLOC-Large VLOC | 8 | 98.5 | 12.5% | 4.76 | 0.60 |
| General cargo | Large | 4 | 91.4 | 11.8% | 3.30 | 0.83 |
| General cargo | Medium | 3 | 85.5 | 7.8% | 1.56 | 0.52 |
| Bulk carrier | ULOC-Valemax | 10 | 52.0 | 11.6% | 6.04 | 0.60 |
| Passenger | Large | 6 | 44.9 | 2.9% | 2.31 | 0.39 |
| Ro-Pax | Small | 4 | 44.1 | 4.0% | 1.02 | 0.26 |
| Ro-Pax | Large | 4 | 31.6 | 2.2% | 1.10 | 0.28 |
| Ro-Ro | Small | 6 | 27.8 | 4.6% | 1.24 | 0.21 |
| Ro-Ro | Large | 6 | 16.6 | 6.2% | 2.36 | 0.39 |
| Passenger | Medium | 6 | 7.05 | 4.3% | 1.35 | 0.23 |
| Passenger | Small | 4 | 1.48 | 1.0% | 0.20 | 0.05 |

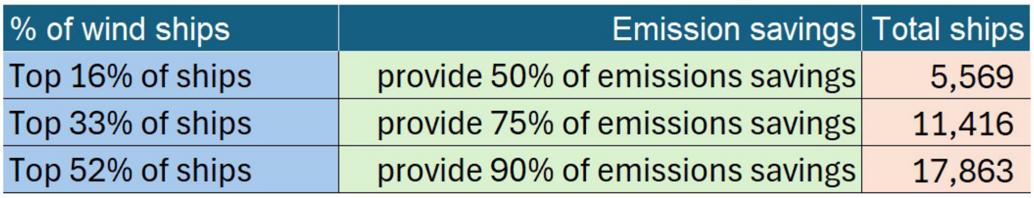
Table 8: Total fuel savings from wind propulsion for each ship type for the ambitious rotor configuration.

## A Targeted Adoption Strategy

This study identifies, for the first time, significant potential of targeting wind propulsion deployment on vessels that provide the largest annual fuel reductions. We find a strong concentration of savings across top vessels: the top 16% of vessels provide 50% of total emissions savings, the top 33% provide 75% of total emissions savings, and the top 52% provide 90% of total emissions savings (Table 9).

These high-impact vessels are primarily bulk carriers and tankers (Figure 4). This concentration of savings presents a clear adoption strategy for the shipping sector that centres around early scale-up on segments of the fleet where wind propulsion delivers the greatest benefit.

It is important to note that these results are based on 2024 data, and top-performing vessels may vary in different years, particularly for bulk carriers and tankers that operate on unpredictable routes. Nevertheless, whilst the ranking of individual vessels' fuel savings will shift from year to year, the dominance of bulk carriers and tankers as a category is driven by high-utilisation and available deck space, which remains constant over time. Future studies should capture these vessel categories across multiple years to further strengthen the evidence that these ships are a reliable focus for targeted deployment.



| % of wind ships | Emission savings | Total ships |
|---|---|---|
| Top 16% of ships | provide 50% of emissions savings | 5,569 |
| Top 33% of ships | provide 75% of emissions savings | 11,416 |
| Top 52% of ships | provide 90% of emissions savings | 17,863 |

Table 9: The number of top-performing ships that provide 50%, 75% and 90% of total emissions reductions modelled for 2024.

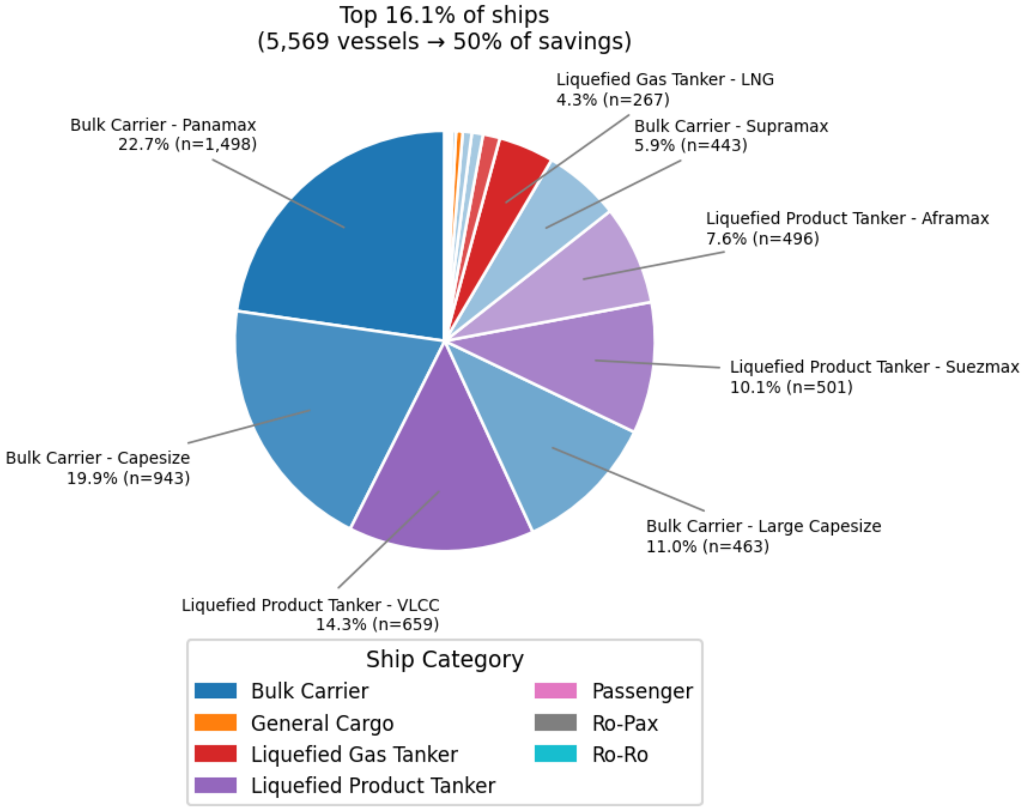


Figure 4: Ship types of the top 16% of vessels that provide 50% of total emissions saved for all wind-suitable ships in 2024.

# Scaling Up Wind Propulsion – Uptake Scenarios to 2050

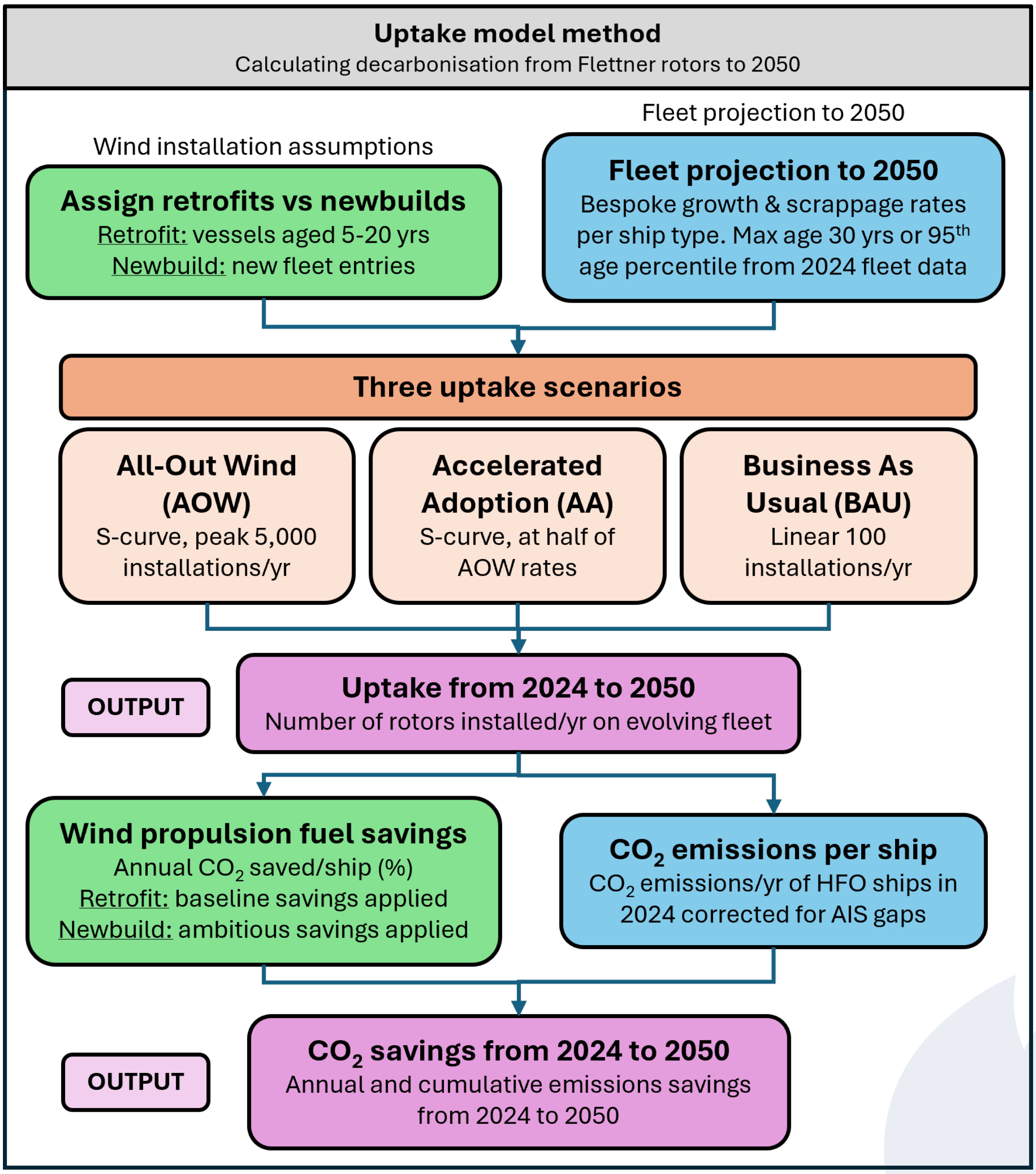


Figure 5: An overview of the method used to model wind propulsion uptake and calculate decarbonisation from 2024 to 2050.

## Uptake Modelling

To quantify wind propulsion's decarbonisation potential, we model the speed of uptake across the shipping fleet. Following on from modelling in the previous sections, only the 25 wind-suitable ship types are included in this analysis. Other ship types, such as containerships, remain excluded from the results shown.

As previously mentioned, fleet data from Kpler shows 48,154 ships operating under the defined 25 ship types in 2024. While only 34,505 ships had AIS data available (with 90% of the missing vessels comprising small general cargo, small passenger and small Ro-Pax ships), the full 48,154 ships are used to define starting fleet numbers in the uptake modelling. Average annual emissions per ship are used for each ship type from the previous section.

To model uptake, first we define installation assumptions, where retrofits are applied for vessels aged between 5 and 20 years, while newbuild installations are applied for newly constructed ships entering the fleet due to either scrappage or fleet growth.

Second, bespoke annual growth and renewal rates are defined for each of the 25 ship types. These assumptions can be found in Appendix E. A maximum vessel age for each ship is applied as the larger age between either 30 years or the 95th percentile ship age for each category, using fleet data from Kpler in 2024. Including the 95th percentile age allows ship types with older vessels, such as passengers and Ro-Pax, to operate until an older age. While the wind-suitable fleet is assumed to grow from 48,154 in 2024 to 75,200 in 2050, it is not a recommendation and demand reduction should be considered as a separate mitigation opportunity.

We then define three uptake scenarios for wind propulsion out to 2050, where each reflects a different potential policy and market environment:

**All-Out Wind (AOW)**: Strong, coordinated policy incentives trigger a step-change in deployment. Installations grow exponentially following an S-curve, peaking at 5,000 ship installations per year. This represents a global shift towards substantial levels of wind propulsion adoption.

**Accelerated Adoption (AA)**: Wind propulsion establishes itself as a mainstream decarbonisation solution, supported by policy and increased commercial confidence. Uptake accelerates, but with only half the number of annual installations than the All-Out Wind scenario and with half the total targeted installations by 2050.

**Business as Usual (BAU)**: No new policy support. Uptake continues at today's rate, increasing linearly by 100 ship installations per year. Wind propulsion installations grow slowly out to 2050.

This obtains the annual number of ships 1) with wind retrofitted, 2) with wind as a newbuild, and 3) with no wind installed for each scenario from 2024 to 2050. Every year, installations are assumed to spread evenly across each ship type. While our earlier results in this study showed clear benefits of a targeted adoption of wind on high-utilisation vessels, this is not included in this uptake modelling.

Finally, the projected fleet numbers from 2024 to 2050 are combined with the annual emissions per ship with and without wind propulsion for each ship type (corrected for AIS data gaps as outlined in Appendix F), to estimate fuel and CO2e savings each year. Baseline emissions savings are assumed for retrofit systems, while ambitious savings are assumed for newbuilds to reflect the greater potential of wind if integrated from the outset of the shipbuilding process. Improvements in ship CO2 intensity are included as an annual reduction of 0.75%. Although this is lower than recent historical rates, it reflects the observed trend of a slowing pace of efficiency improvements between 2008 and 2022 (ICCT, 2025).

> **"Wind propulsion uptake is assumed to grow through retrofits on vessels aged 5 to 20 years and on newbuilds entering the fleet due to either scrappage or fleet growth"**

## Uptake Scenario Results

The resulting uptake curves for all three scenarios are shown in Figure 6. The split between retrofit and newbuild installations can be found in Appendix G.

For the All-Out Wind scenario, we find that uptake is constrained from reaching its full potential. From around 2037 onwards, an installation ceiling is reached, where all vessels eligible for retrofit between 5-20 years old have already been installed with wind systems and no new retrofit installations can occur (Figure 7). This leaves a significant proportion of vessels older than 20 years without wind propulsion that must operate until their end-of-life until they can be replaced by newbuild wind ships. This creates an installation "excess", where uptake can no longer follow the intended s-curve. Instead, annual installations increase in a linear manner, governed by fleet growth and vessel scrappage rates.

This finding presents the first physical limitation to achieving an All-Out Wind scenario. Tackling this would require making retrofit installations suitable for older ships in the fleet. This may become feasible through a "plug-and-play" style of wind system, where shipowners could install wind propulsion on older ships with the option to easily transfer the system to a newer vessel when the older ship is scrapped.

While achieving the uptake rates defined in the All-Out Wind scenario would require a strong and coordinated effort across the maritime sector, the global shipping industry could be well-positioned to deliver wind propulsion at scale. Practically reaching peak deployment of 5,000 installations per year would require a minimum of around 200 shipyards operating at a capacity of one installation every two weeks. China alone has over 300 shipyards, and the EU has approximately 150 major yards. This could present wind propulsion as a commercial opportunity for shipyards that move early.

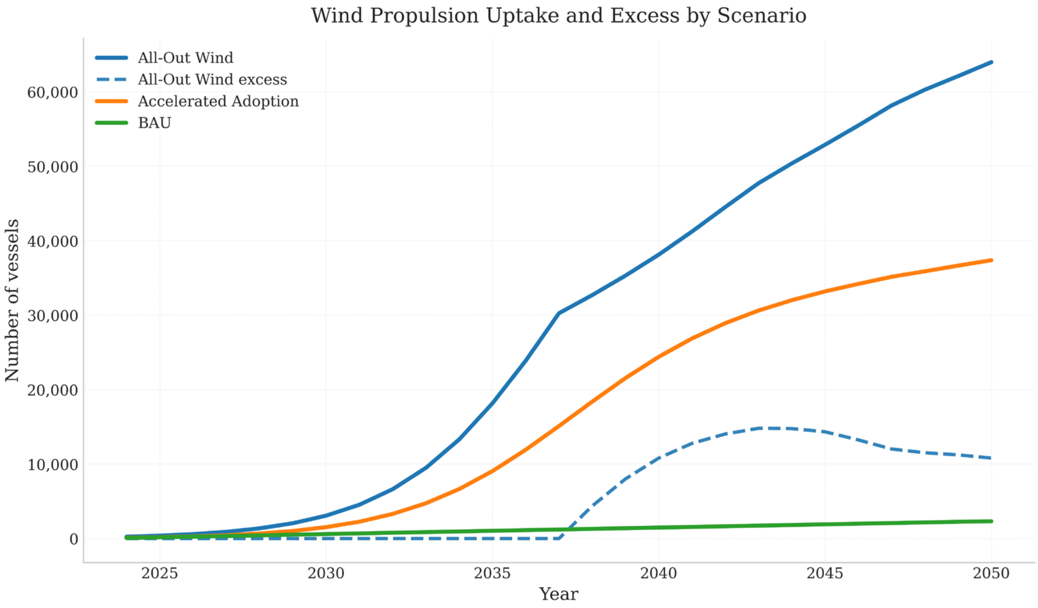


Figure 6: Annual adoption of wind propulsion across all wind-suitable ships from 2024 to 2050 for three uptake scenarios: Business as Usual (BAU), Accelerated Adoption (AA) and All-Out Wind (AOW).

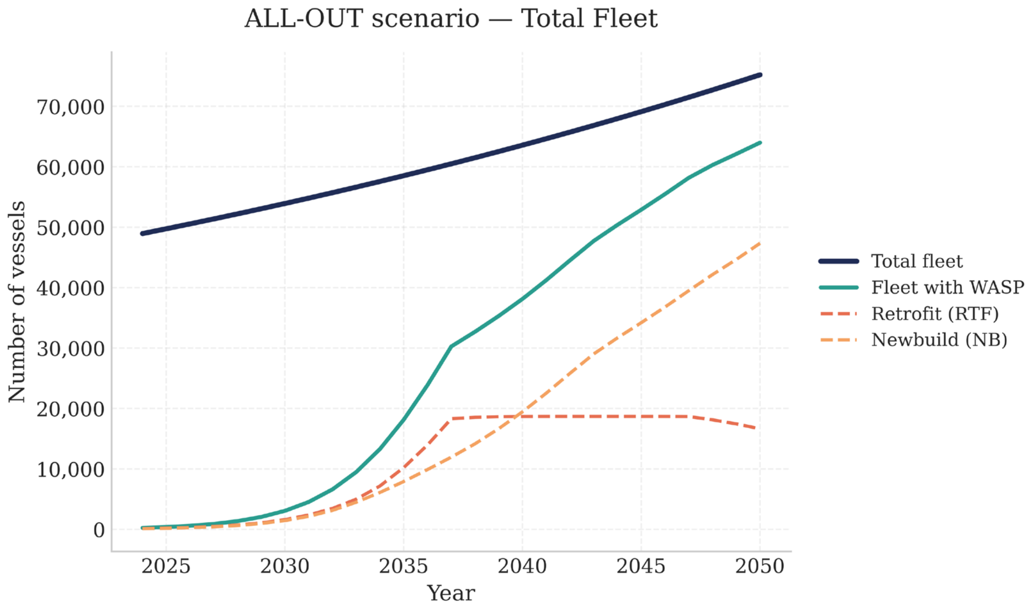


Figure 7: Annual adoption of wind propulsion across wind-suitable ships in the All-Out Wind scenario, showing the split between retrofit and newbuild installations. From 2037 onwards, all eligible ships aged 5-20 years have been retrofitted, resulting in an installation "ceiling".

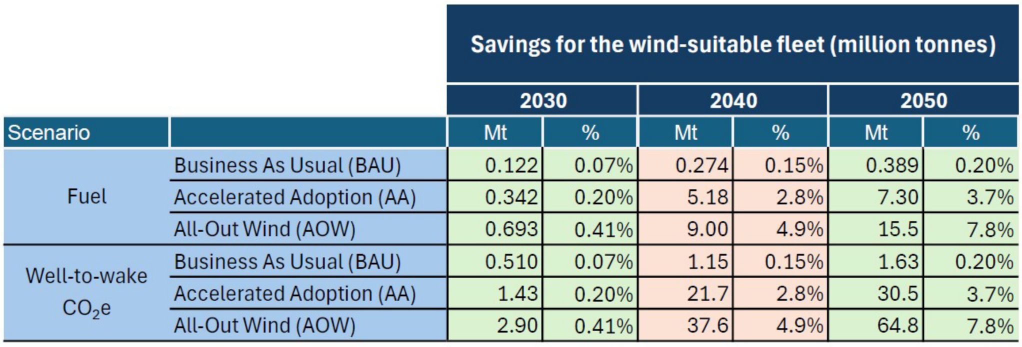
## Decarbonisation to 2050

Results show that wind propulsion delivers progressively larger emissions reductions over time as installations scale up within the fleet (Table 10, Figure 8). Under the All-Out Wind scenario, annual CO2e savings reach 2.90 Mt (0.4%) by 2030, 37.6 Mt (4.9%) by 2040 and 64.8 Mt (7.8%) by 2050. Savings are calculated relative to a baseline fleet fuelled by HFO and apply to only the subset of wind-suitable vessels modelled (over 70,000 ships by 2050). Savings are for main engine emissions but include emissions from spinning the rotors. The corresponding fuel savings are also shown in Table 10.

Conversely, under the business-as-usual scenario, CO2e savings reach only 0.2% by 2050. This highlights the need for sufficient policy frameworks to support adoption and realise wind propulsion's meaningful potential for decarbonisation.

Assuming these vessels operate internationally, and after accounting for previously excluded containership emissions as well as emissions from auxiliary engines and boilers, we estimate that a 7.8% reduction in emissions from wind-suitable vessels translates to a total CO2 reduction of approximately 4-5% from international shipping. As discussed previously, this should be considered a baseline 'plug-and-go' estimate that reflects no changes to current fleet operations and could be significantly improved through complementary measures such as weather routing. Containerships are also not included in this study, even though they are strong candidates for kite retrofits and are featured in emerging newbuild designs.

While other solutions will be needed alongside wind propulsion to achieve the IMO and Paris Agreement targets, these results show that the technology can reduce fuel demand now and over the next critical decade before new e-fuels come online at scale. For a shipowner, this lowers the financial risk of transitioning to new fuels, which are widely expected to come at a higher and more uncertain cost. This is particularly important for climate-vulnerable countries, small island developing states (SIDS) and least developed countries (LDCs), where access to expensive new fuels risks being deeply unequal. For the maritime fleet as a whole, these early cuts could ease the pressure on constrained e-fuel supply chains, lowering overall demand and buying time for the development of vital production, storage and distribution infrastructure.



|  |  | Savings for the wind-suitable fleet (million tonnes) |  |  |  |  |  |
|---|---|---|---|---|---|---|---|
|  |  | 2030 |  | 2040 |  | 2050 |  |
| Scenario |  | Mt | % | Mt | % | Mt | % |
| Fuel | Business As Usual (BAU) | 0.122 | 0.07% | 0.274 | 0.15% | 0.389 | 0.20% |
|  | Accelerated Adoption (AA) | 0.342 | 0.20% | 5.18 | 2.8% | 7.30 | 3.7% |
|  | All-Out Wind (AOW) | 0.693 | 0.41% | 9.00 | 4.9% | 15.5 | 7.8% |
| Well-to-wake $CO_2e$ | Business As Usual (BAU) | 0.510 | 0.07% | 1.15 | 0.15% | 1.63 | 0.20% |
|  | Accelerated Adoption (AA) | 1.43 | 0.20% | 21.7 | 2.8% | 30.5 | 3.7% |
|  | All-Out Wind (AOW) | 2.90 | 0.41% | 37.6 | 4.9% | 64.8 | 7.8% |

Table 10: Fuel and CO2e savings in 2030, 2040 and 2050 for the wind-suitable fleet across the three uptake scenarios. CO2e savings are relative to a baseline fleet fuelled by HFO and apply to only the subset of vessels modelled. Savings are for main engine emissions but include emissions from spinning the rotors.

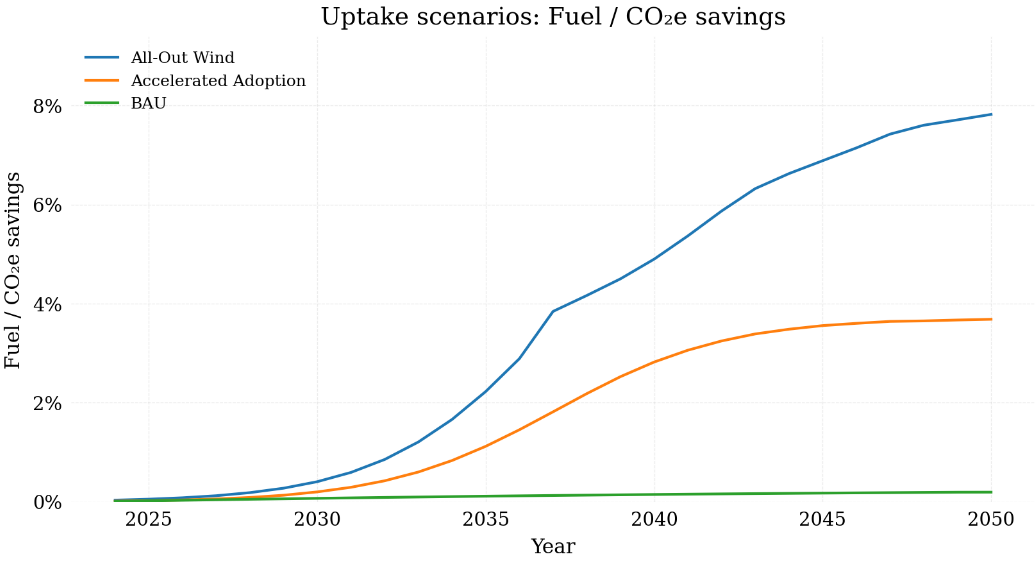


Figure 8: Fuel and CO2e savings under the All-Out Wind (AOW), Accelerated Adoption (AA) and Business as Usual (BAU) uptake scenarios. Savings are calculated relative to a baseline fleet fuelled by HFO and apply to only the subset of vessels modelled. Savings are for main engine emissions but include emissions from spinning the rotors.

## Cumulative emissions savings

Finally, results show that the early adoption and rapid scale-up of wind propulsion leads to large cumulative emissions savings (Table 11, Figure 9). Under the All-Out Wind scenario, cumulative CO2e savings reach 762 million tonnes by 2050, equivalent to removing around 170 million cars from the road for an entire year or the annual emissions of Thailand and Philippines combined.

This cumulative emissions impact is critical. As CO2 remains in the atmosphere for hundreds of years, it is the total build-up of CO2 over time that ultimately drives climate change. Early reductions are therefore vital, and the findings show that wind propulsion can provide significant cumulative savings to mitigate shipping's long-term climate impacts.

| | Cumulative emissions savings (million tonnes of $CO_2e$) | | |
|---|---|---|---|
| | 2030 | 2040 | 2050 |
| Business As Usual (BAU) | 2.06 | 10.8 | 25.1 |
| Accelerated Adoption (AA) | 3.96 | 110 | 391 |
| All-Out Wind (AOW) | 8.20 | 210 | 762 |

Table 11: Cumulative CO2e savings in 2030, 2040 and 2050 for the three wind propulsion uptake scenarios. Savings are relative to a baseline fleet fuelled by HFO.

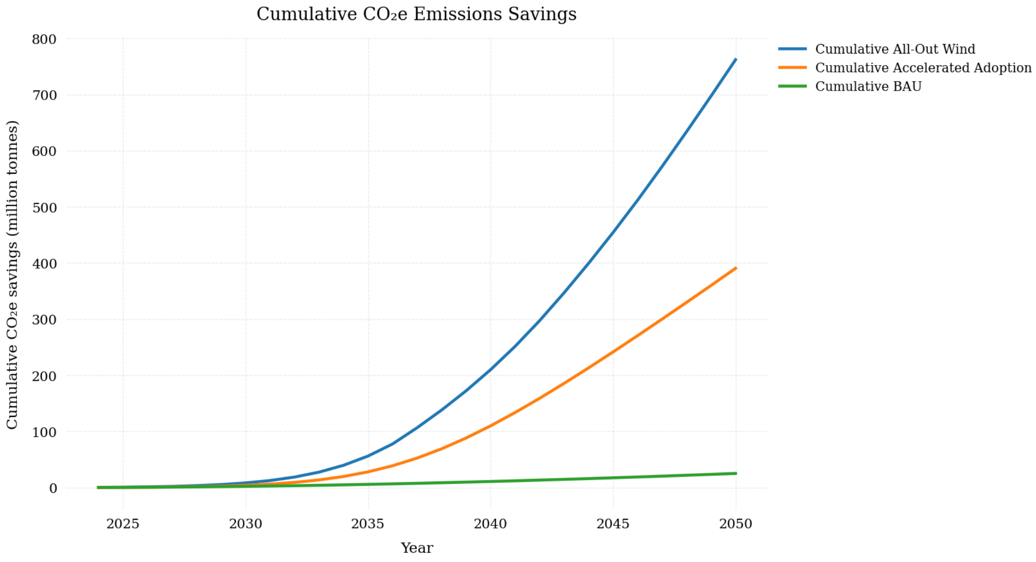


Figure 9: Cumulative CO2e savings for the three wind propulsion uptake scenarios from 2024 to 2050. Savings are relative to a baseline fleet fuelled by HFO.

# Conclusions

This study provides new insights into the CO2 savings achievable from scaling up wind propulsion across all suitable ships in the global fleet. By combining real-world ship tracking data from 2024 with state-of-the-art wind propulsion modelling, we show that Flettner rotors can reduce annual fuel consumption by up to 9.4% across the wind-suitable fleet.

Fuel savings vary significantly by vessel type, ranging from 1.0% to 12.5% depending on the number of sails installed. This corresponds to a daily fuel reduction of between 0.20 and 5.31 tonnes per vessel. Results reveal the largest savings for bulk carriers and tankers due to their high utilisation, relatively low speeds, and available deck space.

The results also highlight a strong concentration of savings, with the top performing 16% of vessels accounting for 50% of total emissions saved. This presents a clear adoption strategy to the sector, where incentives and regulations focused around high-utilisation vessels, predominantly in the bulk carrier and tanker segments, could deliver a disproportionate share of emission reductions in the near-term.

Looking forward to 2050, uptake modelling shows that wind propulsion could deliver CO2e reductions of 0.4% by 2030, 4.9% by 2040 and 7.8% by 2050 for the wind-suitable fleet given a strong future uptake scenario. This leads to 762 million tonnes of cumulative CO2e saved by 2050.

Importantly, these results demonstrate emissions reductions achievable with a technology that is already commercially available and without requiring changes to operational practices of the fleet. However, in practice, wind propulsion should be combined with the many available complementary strategies such as weather routing, slow steaming, hull optimisation for newbuild vessels and primary wind designs to provide even greater benefits to fleet-wide decarbonisation.

Overall, this study provides the most comprehensive assessment to date of wind propulsion decarbonisation and demonstrates that meaningful emissions reductions can be achieved using this existing technology. Wind propulsion should therefore be recognised as a critical bridging measure within shipping decarbonisation policy, enabling early emissions reductions and long-term cumulative emissions savings, while reducing reliance on the cost and availability of future fuels.

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# Appendix/Technical note

A. Sizing Flettner rotors for each ship

For the baseline and ambitious Flettner rotor configurations, rotor dimensions are scaled to vessel size: smaller vessels, such as small general cargo ships, are fitted with 24 m span, 4 m diameter units, mid-range vessels receive 30 m span, 5 m diameter units, and the largest vessel classes are fitted with 35 m span, 5 m diameter units.

For the majority of ship types, the number of rotors at each configuration level is determined by a target sail-area-to-displacement ratio that scales installed rotor area to hull displaced volume. For Ro-Ro and passenger vessel types, where hull proportions differ significantly from displacement-dominated ships, the number of units is instead governed by vessel length.

For horizontal placement, a programmatic layout algorithm defines a usable deck region spanning 60% of length overall, excluding the forward 10% for forecastle clearance and the aft 30% for stern equipment and exhaust gas paths. Units are placed from bow working aft within this region, and the algorithm evaluates both inline (centreline) and paired (port/starboard) arrangements where geometrically feasible, selecting the layout that maximises normalised centre-to-centre spacing.

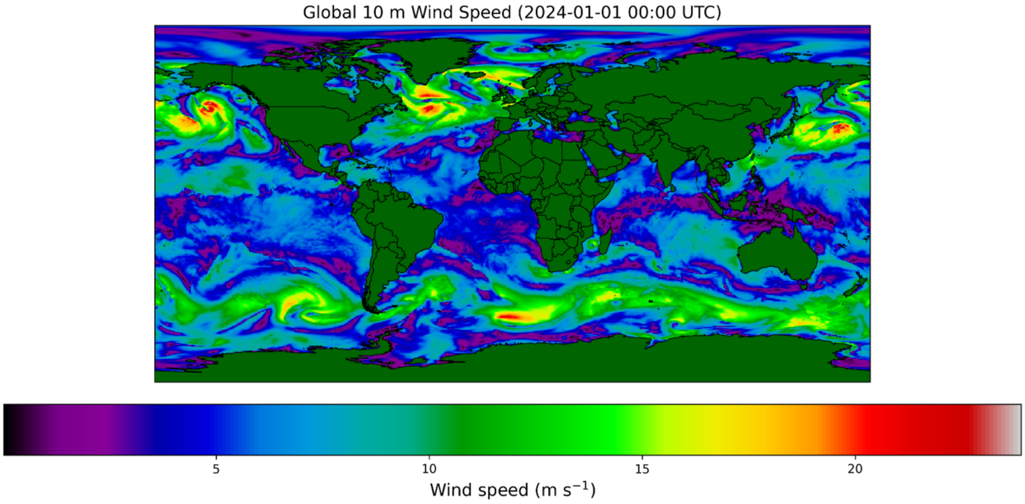
B. Wind propulsion modelling

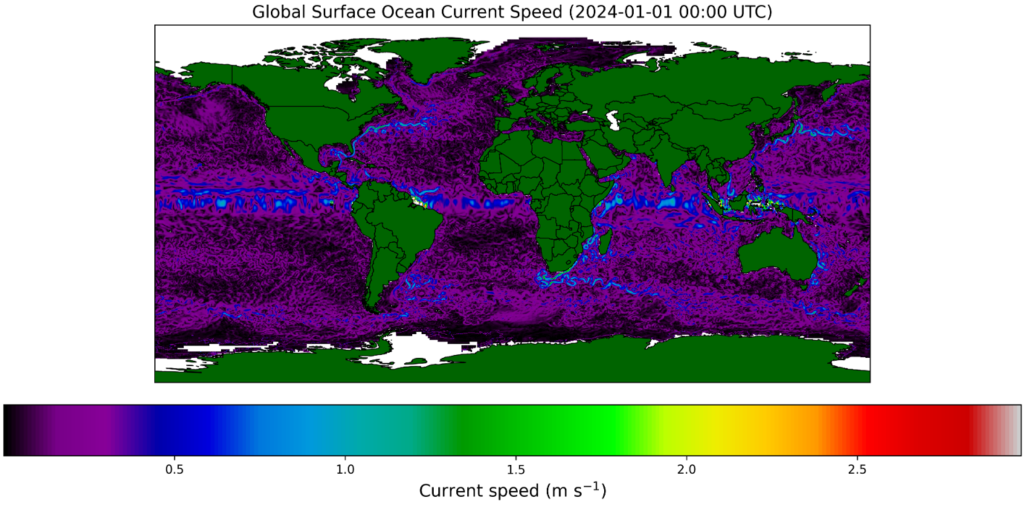
Wind propulsion performance for each vessel is modelled using the AlbatrosDigital Shipyard platform, a cloud-based power prediction programme used commercially across the maritime industry. At its core is a constrained-optimisation solver that determines, for each operating point, the minimum main engine fuel consumption subject to simultaneous equilibrium of forces and moments. The solver assembles contributions from seven component models — calm water resistance (with a 20% fouling margin for in-service hull degradation), spectral added resistance in waves, hull hydrodynamic side forces at non-zero leeway and heel, superstructure aerodynamic drag, rudder forces, propeller thrust (Wageningen B-series), and wind propulsion forces — and drives the residuals to zero across a full factorial grid of ship speeds, wind speeds, wind angles, wave heights and wave directions. For each vessel configuration, this yields 26,600 loadcase entries per configuration and 79,800 entries across the three configurations evaluated (no WPS, Baseline and Ambitious), providing a comprehensive fuel consumption matrix that captures performance across realistic operating conditions.

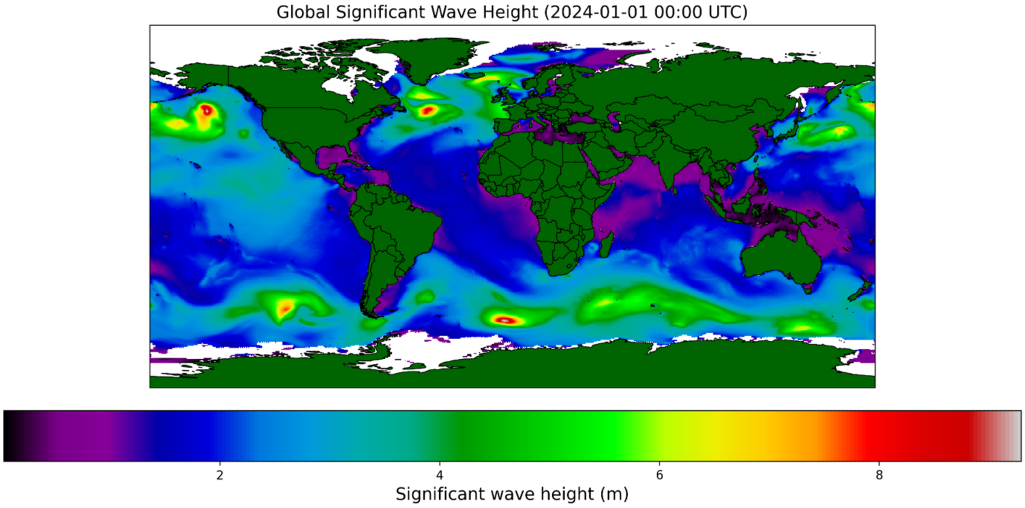
Flettner rotor aerodynamics are simulated using the Stormbird aerodynamic library, developed at NTNU as part of the Norwegian Research Council's KSP WIND project. Stormbird employs a quasi-steady discrete lifting line method in which each rotor is discretised into spanwise segments, and the solver iteratively determines the circulation distribution while accounting for the induced-velocity field from all neighbouring rotors. This captures the physically important effects of wake shielding, mutual aerodynamic interference and the diminishing incremental thrust gain as rotor count increases — interaction effects that are neglected by simpler models. Rotor RPM is treated as an explicit optimisation variable, and individual rotor spin rates are optimised simultaneously with leeway angle, heel angle, rudder angle and propeller RPM at every operating point, ensuring that fuel-saving estimates reflect a physically resolved equilibrium. The power required to spin the rotors is included in the net fuel balance, alongside added resistance in waves and operational rudder angle limits.

## C. Map of environmental conditions

The figures below show the wind, ocean currents and wave height conditions at a timestamp of 01-01-2024 00:00 UTC. Any missing data for ocean currents or waves near coastline areas are set to zero.


Global 10 m Wind Speed (2024-01-01 00:00 UTC)


Global Surface Ocean Current Speed (2024-01-01 00:00 UTC)

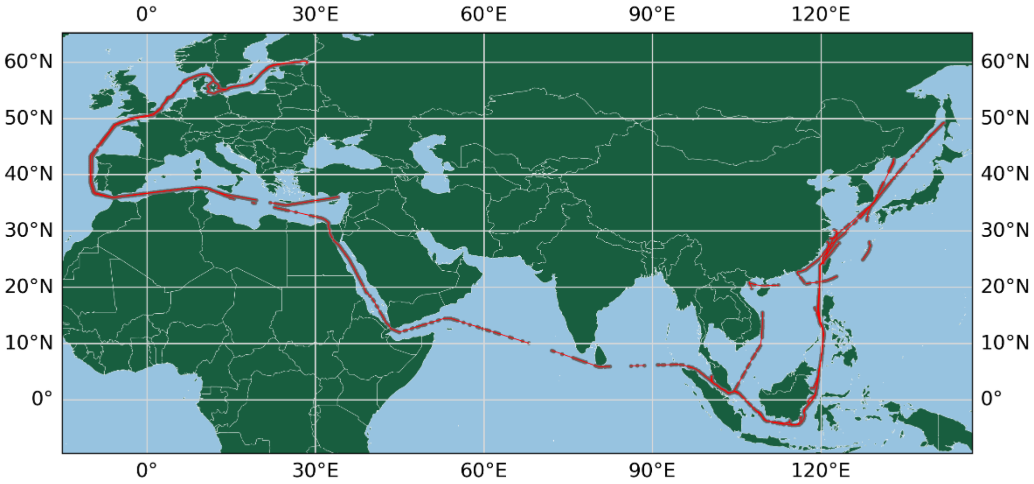

Global Significant Wave Height (2024-01-01 00:00 UTC)

## D Reconstructing shipping tracks from AIS data

The figure below shows an example of a reconstructed AIS track for IMO number 1047433 in 2024.

AIS data points were filtered to include only points with a navigational status of “Under way using its engine”. Alongside this, a minimum speed of 3 knots was applied to remove low-speed manoeuvring, while speeds above the 99.5% percentile were filtered to remove invalid points.

While the vast majority of AIS data points were spaced in 1-hour time intervals, some gaps extended beyond this. To address this, the AIS tracks were segmented into separate voyages when adjacent AIS data points were more than 48 hours or 1,000 km apart. This method leads to missing operational data, which is not interpolated or filled in like other studies (e.g. Faber et al. (2020)). As a result, this underestimates absolute annual emissions (in million tonnes) for each vessel. However, because wind propulsion is modelled over substantial distances that cover the full range of operational conditions, and given the significant computational effort involved, the presented percentage savings are robust.



## E. Uptake modelling: fleet growth and scrappage assumptions

Renewal rate for each ship type was set as high (1.6%), medium (1.0%), low (0.5%) or very low (0.2%) based on a literature review. Growth rates were set based on the average of all Gravity scenarios from the IMO's Fourth GHG Study.

A maximum ship age was initially set as 30 years old. However, as some ship types have many vessels that are significantly over 30 years old but are still operational, the maximum age for these ship types was adjusted and set as the 95th percentile.

| Ship type | Size | Renewal rate | Growth rate | Maxmium age |
|---|---|---|---|---|
| Bulk carrier | Handysize-Handymax | 0.5% | 2.3% | 30 |
| Bulk carrier | Supramax-Ultramax | 0.5% | 2.3% | 30 |
| Bulk carrier | Panamax-Post-Panamax | 0.5% | 2.3% | 30 |
| Bulk carrier | Capesize | 0.5% | 2.3% | 30 |
| Bulk carrier | Large Capesize | 0.5% | 2.3% | 30 |
| Bulk carrier | VLOC-Large VLOC | 0.5% | 2.3% | 30 |
| Bulk carrier | ULOC-Valemax | 0.5% | 2.3% | 30 |
| General cargo | Small | 0.2% | 1.6% | 58 |
| General cargo | Medium | 0.2% | 1.6% | 30 |
| General cargo | Large | 0.2% | 1.6% | 35 |
| Liquefied gas tanker | LPG tanker | 1.0% | 1.7% | 31 |
| Liquefied gas tanker | LNG | 1.0% | 1.7% | 30 |
| Oil tanker | Handysize | 0.5% | 0.0% | 42 |
| Oil tanker | Panamax | 0.5% | 0.0% | 30 |
| Oil tanker | Aframax | 0.5% | 0.0% | 30 |
| Oil tanker | Suezmax | 0.5% | 0.0% | 30 |
| Oil tanker | VLCC-ULCC | 0.5% | 0.0% | 30 |
| Passenger | Small | 1.6% | 1.6% | 65 |
| Passenger | Medium | 1.6% | 1.6% | 34 |
| Passenger | Large | 1.6% | 1.6% | 30 |
| Ro-Pax | Small | 0.2% | 1.6% | 62 |
| Ro-Pax | Large | 0.2% | 1.6% | 38 |
| Ro-Ro | Vehicle Carrier | 0.2% | 1.6% | 30 |
| Ro-Ro | Small | 0.2% | 1.6% | 41 |
| Ro-Ro | Large | 0.2% | 1.6% | 38 |
| Chemical tanker | Handysize | 0.5% | 1.8% | 30 |
| Chemical tanker | Panamax | 0.5% | 1.8% | 30 |
| Chemical tanker | Aframax | 0.5% | 1.8% | 30 |
| Chemical tanker | Suezmax | 0.5% | 1.8% | 30 |
| Chemical tanker | VLCC-ULCC | 0.5% | 1.8% | 30 |

### F. Uptake modelling: scaling CO2 emissions to cover AIS data gaps

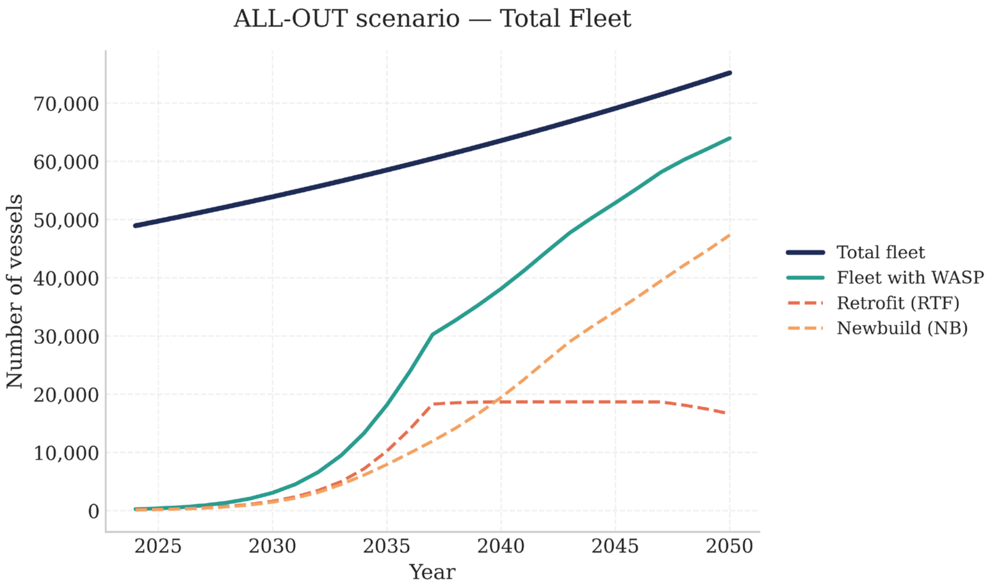
To estimate fleet-wide decarbonisation from wind propulsion out to 2050, the model first establishes baseline CO2 emissions for 2024 from the wind-suitable fleet modelled in this study. As the AIS data used here contains gaps that are not filled in (unlike in other studies, e.g. IMO's 4th GHG Study (Faber et al., 2020)), simply using fleet-wide fuel consumption would underestimate annual emissions. To address this, we introduce the following scaling.

Total CO2 emissions for 2018 are taken from Faber et al. (2020) for bulk carriers, oil tankers, chemical tankers, general cargo, liquefied gas tankers, ferry-pax/cruise, ferry Ro-Pax, Ro-Ro and vehicle carriers. These values are scaled to 2024 using a 9.4% growth assumption (OECD, 2025). Emissions for each ship type are then scaled to match these values, assuming that the difference accounts for the missing AIS data.

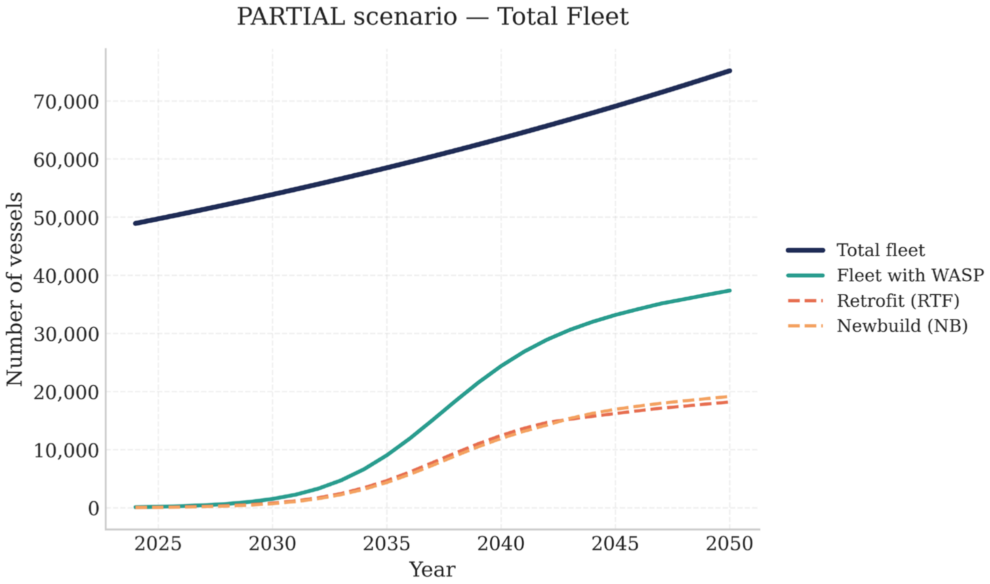
These resulting scaled values are used as the baseline 2024 emissions in the uptake model.

## G. Wind propulsion uptake model curves

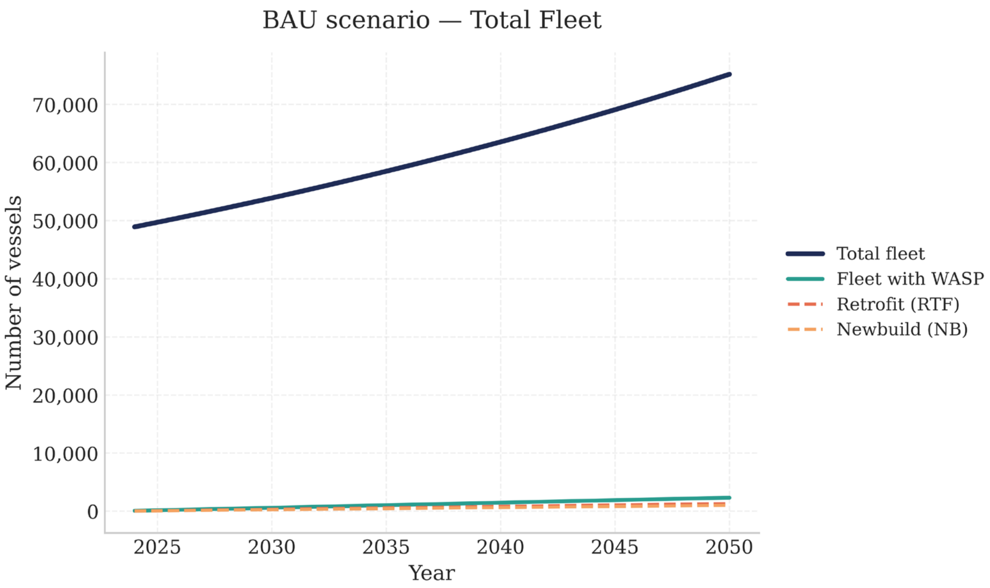
### Wind propulsion uptake for the All-Out Wind scenario



### Wind propulsion uptake for the Accelerated Adoption scenario



Wind propulsion uptake for the Business As Usual scenario



## Acknowledgements

This study was funded by Seas at Risk. Automatic Identification System (AIS) and wind propulsion performance data was partly funded by Seas at Risk and philanthropic funding from the shipping ‘breakthrough’ project at The University of Manchester.

Wind propulsion performance data was provided by AlbatrosDigital.

Historical AIS data in 2024 for the global fleet and fleet vessel particulars data was provided by Kpler.

Wind and waves data was provided by the European Centre for Medium-range Weather Forecast’s (ECMWF) ERA5 dataset (Hersbach et al., 2020), obtained from the Copernicus Climate Change Service (C3S) Climate Data Store.

Ocean currents data was provided by the Earth & Space Research’s (ESR) Ocean Surface Current Analyses Real-time (OSCAR) Surface Currents – Interim 0.25 Degree (Version 2.0) dataset (ESR, 2022). Dataset accessed 2026-01-16.

All views contained with this report are attributable solely to the named authors and do not necessarily reflect those of researchers within the wider Tyndall Centre for Climate Change Research.

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