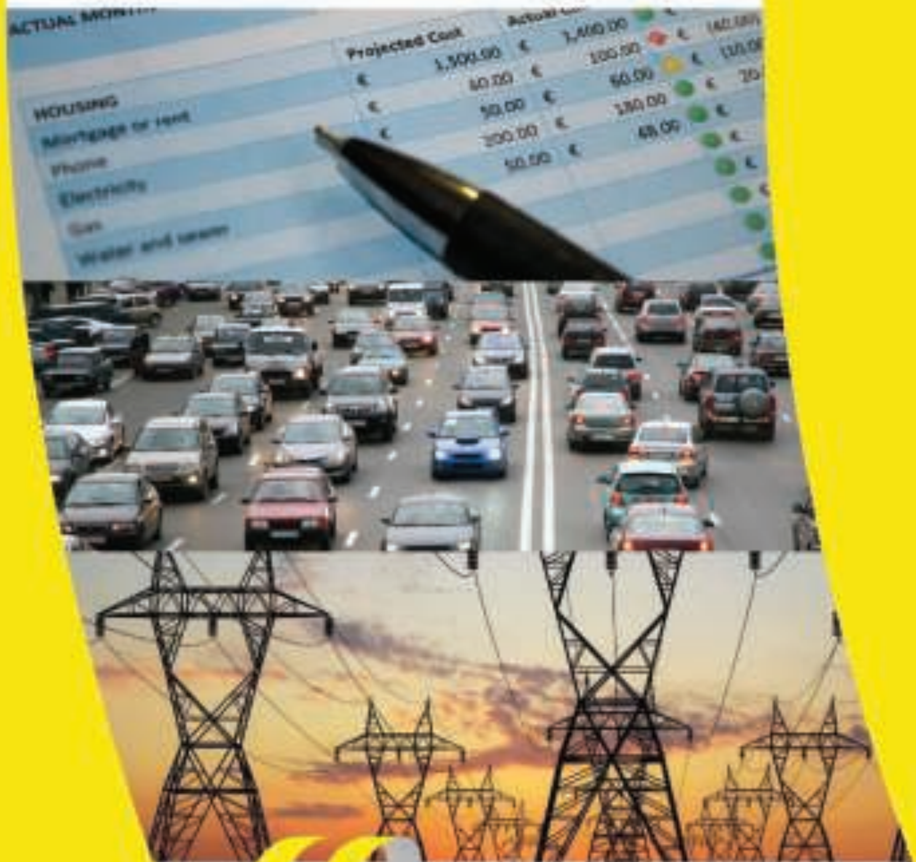
Study on the analysis of market potentials and market barriers for wind propulsion technologies for ships



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Study on the analysis of market potentials and market barriers for wind propulsion technologies for ships

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Content

Abstract

The study analyses wind as a renewable energy source for maritime transport and has the following objectives: the identification of barriers to the development and uptake of wind propulsion and possible actions to overcome these barriers, the estimation of the technologies' market and emissions savings potential and the associated economic and social effects.

Three key barriers have been identified:
1. (Trusted) information on the technologies.
2. Access to capital for building and testing of full scale demonstrators.
3. Incentives to reduce the ships' CO_2 emissions.

Possible actions to overcome these barriers are proposed, with the development of a standardized assessment method combined with test cases as an important starting point.

Power savings have been calculated for four generic propulsion technologies, six sample vessels, two speed regimes, considering AIS voyage profiles and sample routes.

Rotor and wingsail show similar, substantial relative savings, the kite higher (lower) savings for smaller (larger) vessels; savings are lowest for wind turbines. With increased speed absolute savings of rotor and wingsail rise.

In 2030, the market potential could amount to around 3,700–10,700 installed systems on bulkers and tankers, associated with approximately 3.5–7.5 Mt CO_2 savings and 6,500–8,000 direct and 8,500–10,000 indirect jobs.

Résumé

L'étude analyse le vent comme une source d'énergie renouvelable pour le transport maritime et ses objectifs sont les suivants : l'identification d'obstacles au développement et l'utilisation de la propulsion éolienne et les mesures possibles pour surmonter ces obstacles, l'évaluation du marché et des économies potentielles en émissions des technologies avec les effets économiques et sociaux associés.

Trois obstacles principaux ont été identifiés :
1. L'information (fiable) sur les technologies.
2. L'accès au capital pour la fabrication et les tests de dispositifs de démonstration grandeur nature.
3. Les incitations pour réduire les émissions de CO_2 des navires.

Des mesures possibles pour surmonter ces obstacles sont proposées, avec le développement d'une méthode d'évaluation standardisée combinée aux cas d'essai comme point de départ important.

Les économies d'énergie ont été calculées pour quatre technologies génériques de propulsion, six vaisseaux échantillons, deux régimes de vitesse, en tenant compte de profils de voyage à système d'identification automatique et de parcours échantillons.

Le rotor et l'aile rigide présentent des économies relatives semblables et considérables, le cerf-volant des économies supérieures (inférieures) pour les navires plus petits (gros) ; les économies sont les plus faibles pour les turbines éoliennes. À vitesse accélérée, les économies absolues du rotor et de l'aile rigide augmentent.

En 2030, le potentiel du marché pourrait atteindre quelque 3.700–10.700 systèmes installés sur des vraquiers et pétroliers, associés approximativement à 3,5–7,5 mt d'économies de CO_2 avec 6.500–8.000 emplois directs et 8.500 – 10.000 emplois indirects créés.

Executive Summary

Background

According to the most recent estimates, global shipping emitted on average about 1 billion tonnes of carbon dioxide annually in the period 2007–2012, equivalent to just over 3% of global anthropogenic emissions (UCL, CE Delft et al., 2015). This share is, despite market-driven and regulatory efficiency improvements, expected to increase significantly in the future, due to the growth of the sector and due to the emissions reductions that can expected to be achieved by the other sectors. Measures that can significantly reduce the CO_2 emissions of the shipping sector will therefore play an important role if the sector should become responsible for a 'fair share' of the global emissions reductions.

Measures that can achieve large emission reductions, like slow steaming, and renewable energy sources will be needed to de-carbonise maritime transport. Slow steaming has already been analysed to a greater extent and regarding biofuels, there are concerns about environmental impacts and availability. This is why this study focuses on wind propulsion technologies for ships.

Many innovative wind propulsion technology concepts have been and are being developed for commercial shipping. However, none of the technologies has reached market maturity yet.

Objectives of the study

The first aim of the study is to identify both the barriers to the development and uptake of wind propulsion technologies and the possible actions that can contribute to overcome these barriers.

The second aim is to estimate the market and emission savings potential of the wind propulsion technologies for 2020 and 2030.

And the third aim is to determine the economic and social effects associated with this market potential.

Approach

In a first step an inventory of the supply and the demand side of wind propulsion technology for ships has been carried out by means of a literature review, internet research, and information from the International Windship Association (IWSA).

Eleven (potential) suppliers of wind propulsion have provided information on existing or proposed technologies and their state of development and deployment. Supplemented by the expertise of the project team and from the literature this information has been summarized in technology factsheets.

Based on this information, five technologies have been selected for further analysis, and four models have been developed to calculate emission savings on ship level. A generic type of technology has thereby been considered respectively.

Power savings on ship level have been calculated for six sample ships: three ship types (tanker, bulker, container) and two different ship sizes respectively; two alternative vessel speed regimes have been accounted for.

The number and size of wind propulsion technology devices to be fitted have been chosen by means of a set of plausible rules, and sailing routes have been selected by means of two different methods. First, twelve sample routes have been chosen based on an analysis of EU trade data and second, AIS-data has been used to establish global routes taken by ships that correspond to the six sample ships.

The wind data used are read from ERA-Interim, 6-hourly, dataset on a 0.125°x 0.125° grid, at 10 m height.

A dynamic model, including learning effects, has been developed to model the diffusion of the wind propulsion technologies into the shipping fleet over time, the resulting fuel savings and the resulting CO_2 emissions savings.
The estimated emissions savings on ship level have been used as input into this model.

Both the barriers to the development and uptake of the wind propulsion technologies for ships and the possible actions to overcome these barriers have been inventorised by means of the project team's expertise, a literature review, and eleven in-depth interviews with (potential) wind propulsion technology providers. The relevance of these barriers and actions has subsequently been assessed by means of an online survey and a stakeholder workshop held in June 2016 in Brussels.

Case studies have been conducted to illustrate the relevance of some of the barriers.

Results

Inventory
Six main categories of wind propulsion technologies for ships can be differentiated: soft sails, rigid sails/wingsails, hull sails, towing kites, rotors, and wind turbines.

The inventory of the demand side of wind propulsion technologies for ships has shown that only two commercial vessels are currently equipped with a wind propulsion technology that is actively used.

On the supply side there are currently two providers of wind propulsion technologies for ships whose products are close to marketability and there are up to 24 additional wind propulsion technologies/concepts relevant for the aim of this study that could become available until 2030. The majority of the propulsion technologies have been developed for bulkers, tankers and general cargo vessels.

Five technology types have been selected to be further analysed, based on the available information and the state of development: soft sails, rigid/wingsails, towing kites, rotors and wind turbines.

Savings on ship level
For the six sample ships and the selected dimensions of wind propulsion technologies, relative power savings across the AIS-recorded voyage profiles (see Table 1) are found to be comparable for Flettner rotor and wingsails; for towing kites relative savings are, by comparison, higher for smaller vessels and lower for larger vessels; relative savings are lowest for wind turbines.

Table 1 **Average relative savings across the AIS-recorded voyage profiles - higher speed**

	Rotor	Wingsail	Towing kite	Wind turbine
Large bulk carrier (90,000 dwt)	17%	18%	5%	2%
Small bulk carrier (7,200 dwt)	5%	5%	9%	1%
Large tanker (90,000 dwt)	9%	9%	3%	1%
Small tanker (5,400 dwt)	5%	5%	9%	1%
Large container vessel (5,000 TEU)			1%	
Small container vessel (1,000 TEU)			2%	

For all technologies it holds that relative savings are higher for the lower speed which can be expected due to the much lower power demand at the lower speed.

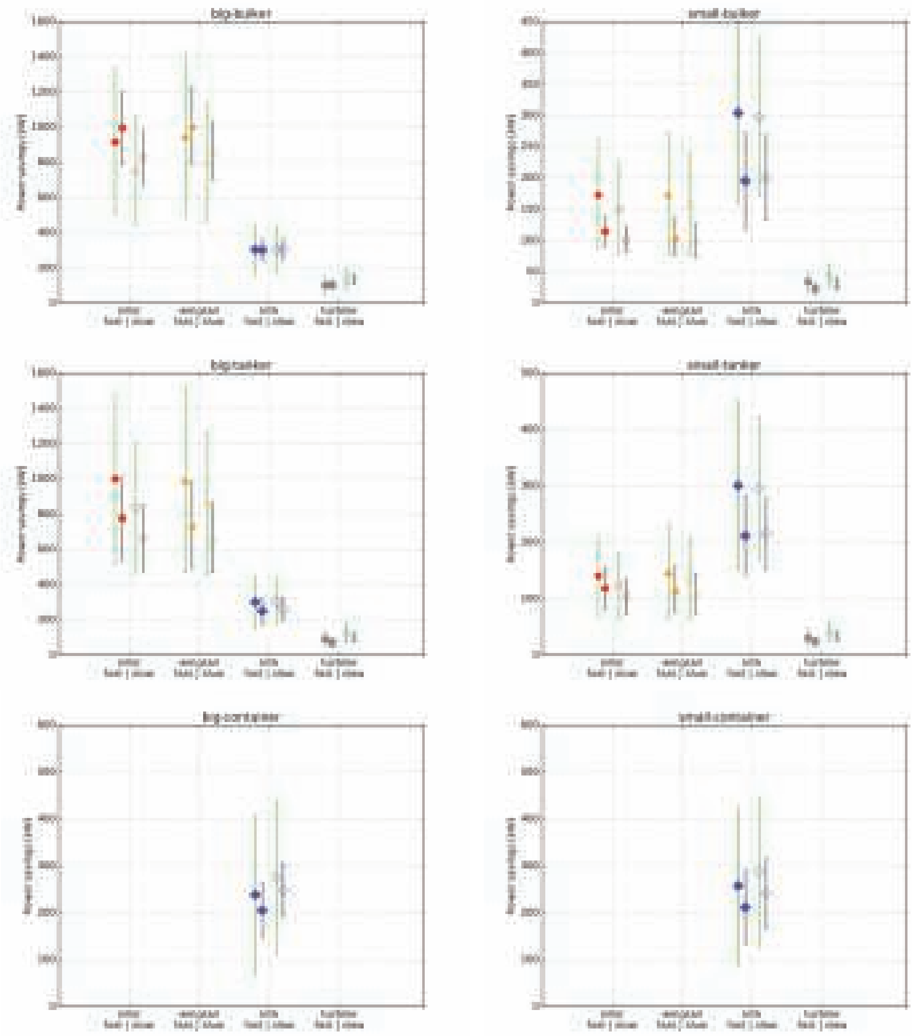
For the absolute savings (see Figure 1), however, this does not hold. Whereas for the towing kite and the wind turbine absolute savings tend to be equal or even lower at the higher speed, absolute savings are larger at the higher voyage speed for the wingsail and the rotor for all ship types considered.

This is a very important finding of the study and implies that that there is a barrier that has been overestimated so far: ships do not necessarily need to slow down for, at least some, wind propulsion systems to become cost efficient.

Relative savings of rotors and wingsails on the larger ships exceed relative savings on the smaller ships, especially on the bulker carrier. In part this is due to the fact that large vessels make more open ocean voyages on routes where they experience higher wind speeds than smaller vessels. In addition, larger vessels can be equipped with more and taller wind propulsion devices, with an additional effect from the higher wind speeds experienced by the taller devices on the larger ship.

The numerical results depend on the assumptions and parameters defining the models, each of which represents a category of technologies. Therefore, in isolation, they do not constitute a rating of the respective technologies. Instead, a specific technology may be assessed against the established baseline, together with factors like cost, ease of operation, and others. However, the results do clearly indicate the significant savings potential from the considered technologies, even in a business as usual mode of ship operations.

Figure 1 Average absolute power savings (solid symbols show savings averaged over sample routes, empty symbols averaged over sample fleet voyage profiles from AIS tracks)



Market potential and economic effects

Should some wind propulsion technologies for ships reach marketability in 2020, the maximum market potential for bulk carriers, tankers and container vessels is estimated to add up to around 3,700–10,700 installed systems until 2030, including both retrofits and installations on newbuilds, depending on the bunker fuel price, the speed of the vessels, and the discount rate applied. The use of these wind propulsion systems would then lead to CO_2 savings of around 3.5–7.5 Mt CO_2 in 2030 and the wind propulsion sector would then be good for around 6,500–8,000 direct and around 8,500–10,000 indirect jobs.

The diffusion process will however not have reached maturity in 2030 yet; this is expected to occur around 2040, when more newbuilds have entered the fleet (retrofits are more expensive than installation on newbuilds) and capital costs have further declined due to learning effects and economies of scales.

Barriers to the development and uptake of wind propulsion

A multitude of barriers has been identified that currently prevent the further development and uptake of the wind propulsion technologies.

Barriers that prevent the uptake of wind propulsion technologies are
1. Technical characteristics of the different wind propulsion technologies (WPTs) that can limit the applicability of the technologies, with retrofits naturally being more restricted than newbuilds.
2. Factors that have a negative impact on the cost efficiency of WPTs by negatively affecting the benefits, the performance or the costs of the WPTs (e.g. economic downturn).
3. Factors that contribute to the uncertainty of the cost efficiency of the WPTs; some of these uncertainty factors cannot be alleviated (e.g. fuel price volatility or economic cycles), whereas other factors are uncertain since not sufficient information on the performance, operability, safety, durability, and economic implications of wind propulsion is available yet and since the available information may only have a limited information value and may not be trusted or understood.
4. Access to capital for the uptake of WPTs.

In addition, there are barriers to the uptake of cost efficient abatement measures in general, like for example the split incentives between the ship owner and the operator or the scepticism of the sector.

And finally, there are barriers specific to the (further) development of WPTs, like the access to capital for the development of WPT, especially for building and testing of full scale demonstrators and the current legal/institutional framework.

The following three barriers have been identified as key barriers:
1. (Trusted) information on the performance, operability, safety, durability, and economic implications of the WPTs.
2. Access to capital for the development of WPTs, especially for building and testing of full scale demonstrators.
3. Incentives to improve energy efficiency/reduce CO_2 emissions of ships.

These key barriers are interrelated in different ways, with the most crucial interaction being a chicken-and-egg problem between the first and second key barrier.

Actions

In order to breach this chicken-and-egg problem, we see the development of a standardized method to assess WPTs combined with test cases to develop the assessment method as the most important starting point. Only if testing of demonstrators yields assessable information generated by an independent party, can the trust of ship owners and investors be gained and can public funds, which might be used to support the generation of the information, create a real value added.

When developing a standardized method to assess WPTs, the consistency of with the (to be developed) Energy Efficiency Design Index (EEDI) technical guidance for the conduction of performance tests of wind propulsion systems should be considered, but the evaluation method should not be restricted to the determination of the available effective power of the systems, but should also include the determination of the actual fuel savings.

Only after a standardized assessment method has been developed, it does make sense to take measures that improve the generation of more information on the WPTs, that improve the access to and value of this information, and that (also) improve the access to capital for the development and testing of full scale demonstrators.

Would there be sufficient incentives to improve the energy efficiency/reduce the CO_2 emissions of ships, some of these latter measures, especially the measures improving the access to capital may be superfluous. But since the incentive to improve the energy efficiency/reduce the CO_2 emissions of ships will probably not be improved in the short run, these measures should be taken if the development and uptake of WPTs is to be advanced.

The different stakeholders can thereby contribute with different actions to a different degree, which also holds for the European Commission.

Here some examples of actions that could be taken by the European Commission. The European Commission could:
- commission a study into the development of a standardized evaluation method of the performance of wind propulsion technologies, maybe combined with test cases;
- if performance tests were supported with public funds, set requirements regarding the use of a standardized assessment method (once developed), verification, and publication of test results;
- within the framework of the MRV regulation, give ships the opportunity to publish the use of innovative energy efficiency measures.

There are public funds available that fund, amongst other things, demonstration projects in the maritime shipping sector (e.g. Horizon 2020's 'Towards the energy efficient and emission free vessel' programme or Horizon 2020's SME Instrument Phase 2), but in order to improve the access to capital for companies that want to demonstrate the performance and operability of energy efficiency measures for maritime transport, the following actions could be taken:
- offer a payment scheme that is viable for SMEs;
- keep the administrative effort as low as possible without compromising accountability;
- offer programmes aimed specifically at demonstration projects for maritime shipping;
- offer programmes aimed at demonstration projects for maritime shipping without narrowing down the eligible technologies beforehand.

A comprehensive list of possible actions that the different stakeholders could take to alleviate the barriers to the development and uptake of wind propulsion technologies can be found in Chapter 5.

Résumé analytique

Contexte
Selon les estimations les plus récentes, le transport maritime mondial a émis un milliard environ de tonnes de dioxyde de carbone en moyenne annuellement au cours de la période de 2007 à 2012, l'équivalent d'un peu plus de 3% des émissions anthropogéniques mondiales (UCL, CE Delft, et al., 2015). Malgré les améliorations en termes d'efficacité axées sur le marché et réglementaires, cette part devrait augmenter considérablement à l'avenir, en raison de la croissance du secteur et de réductions d'émissions à prévoir dans d'autres secteurs. Les mesures capables de réduire de façon significative les émissions de CO_2 du secteur du transport maritime joueront donc un rôle important si le secteur est responsabilisé afin de contribuer sa 'part équitable' aux réductions mondiales d'émissions.

Les mesures capables d'engendrer de vastes réductions d'émissions, comme la navigation à vitesse réduite et les sources d'énergie renouvelables seront nécessaires pour décarboniser le transport maritime. La navigation à vitesse réduite a déjà été analysée de manière plus détaillée et concernant les biocarburants, leur impact environnemental et leur disponibilité sont une source d'inquiétude. Voilà pourquoi cette étude se focalise sur les technologies de propulsion éolienne pour les navires.

De nombreux concepts de propulsion éolienne innovateurs ont été et sont développés pour le transport maritime commercial. Toutefois, aucune de ces technologies n'a atteint une maturité commerciale à ce jour.

Objectifs de l'étude
Le premier objectif de l'étude est d'identifier aussi bien les obstacles au développement et à l'utilisation de technologies de propulsion éolienne que les éventuelles mesures capables d'aider à surmonter ces obstacles.

Le second objectif est d'évaluer le marché et les économies potentielles d'émissions des technologies de propulsion éolienne pour 2020 et 2030.

Et le troisième objectif est de déterminer les effets économiques et sociaux associés à ce potentiel du marché.

Approche
Comme première étape, un inventaire a été établi de l'offre et de la demande en matière de technologies de propulsion éolienne pour les navires, au moyen d'une analyse bibliographique, de recherches sur Internet et d'informations issues de l'International Windship Association (IWSA).

Onze fournisseurs (potentiels) de propulsion éolienne ont fourni de l'information concernant les technologies existantes ou proposées et leur état de développement. Complétée par l'expertise de l'équipe du projet et les ouvrages disponibles, cette information a été résumée dans les fiches d'information technologique.

Sur la base de cette information, cinq technologies ont été sélectionnées en vue d'une analyse plus détaillée et quatre modèles ont été développés pour calculer les économies d'émissions au niveau des navires. Un type générique de technologie a été envisagé respectivement.

Les économies d'énergie au niveau des navires ont été calculées pour six navires échantillons : trois types de navire (pétrolier, vraquier, conteneur), avec deux tailles différentes de navire respectivement, et deux régimes alternatifs de vitesse ont été pris en compte.
Le nombre et la taille des dispositifs technologiques de propulsion éolienne à installer ont été choisis au moyen d'un jeu de règles plausibles, et les routes maritimes ont été sélectionnées grâce à deux méthodes différentes. D'abord, douze itinéraires échantillons ont été choisis en s'appuyant sur une analyse de données commerciales de l'UE et deuxièmement, les données des systèmes d'identification automatique ont servi à établir les itinéraires mondiaux empruntés par des navires correspondant aux six navires échantillons.

Les données éoliennes utilisées sont lues grâce à un jeu de données ERA-Interim disponible toutes les six heures sur une grille 0,125°x 0,125°, à 10 m de hauteur.

Un modèle dynamique, y compris des effets d'apprentissage, a été développé pour modéliser dans le temps la diffusion des technologies de propulsion éolienne au sein de la flotte maritime, les économies de carburant résultantes et les économies résultantes en émissions de CO_2. Les économies en émissions évaluées au niveau des navires ont servi à alimenter ce modèle.

Les obstacles au développement et à l'utilisation des technologies de propulsion éolienne pour les navires et les mesures possibles afin de surmonter ces obstacles ont été inventoriés grâce à l'expertise de l'équipe du projet, à une analyse bibliographique, et à onze interviews détaillées avec des fournisseurs (potentiels) de technologies de propulsion éolienne. La pertinence de ces obstacles et mesures a ensuite été évaluée au moyen d'une enquête en ligne et d'un atelier organisé à Bruxelles pour les parties prenantes en juin 2016.

Des études de cas ont été menées pour illustrer la pertinence de certains obstacles.

Résultats

Inventaire
Six catégories principales de technologies de propulsion éolienne pour navires se distinguent : voiles souples, voiles rigides, voiles à coque, cerfs-volants de traction, rotors et turbines éoliennes.

L'inventaire de la demande en technologies de propulsion éolienne pour les navires a montré que seuls deux navires commerciaux sont actuellement équipés d'une technologie de propulsion éolienne activement utilisée.

Au niveau de l'offre, il y a actuellement deux fournisseurs de technologies de propulsion éolienne pour navires dont les produits sont pratiquement commercialisables et il existe jusqu'à 24 technologies/concepts supplémentaires de propulsion éolienne utiles dans le cadre de cette étude qui pourraient devenir disponibles d'ici 2030. La majorité des technologies de propulsion éolienne a été développée pour les vraquiers, les pétroliers et les navires généraux de marchandises.

Cinq types de technologies ont été sélectionnées en vue d'une analyse plus détaillée, basée sur l'information disponible et l'état du développement : voiles souples, voiles rigides/ailes rigides, cerfs-volants de traction, rotors et turbines éoliennes.

Économies au niveau des navires

Pour les six navires échantillons et les dimensions sélectionnées de technologies de propulsion éolienne, les économies relatives d'énergie à travers les profils de voyage enregistrés par les systèmes d'identification automatique (voir Tableaux 2) s'avèrent comparables pour le rotor Flettner et les ailes rigide0s ; pour les cerfs-volants de traction, les économies relatives sont, comparativement, plus élevées pour les navires moins volumineux et moins importants pour les navires plus volumineux ; les économies relatives sont les plus faibles pour les turbines éoliennes.

Tableau 2 Moyenne des économies relatives à travers les profils de voyage enregistrés par le système automatique d'identification – vitesse supérieure

	Rotor	Aile rigide	Cerf-volant de traction	Turbine éolienne
Gros vraquier (90.000 TPL)	17%	18%	5%	2%
Petit vraquier (7.200 TPL)	5%	5%	9%	1%
Gros pétrolier (90.000 TPL)	9%	9%	3%	1%
Petit pétrolier (5.400 TPL)	5%	5%	9%	1%
Gros porte-conteneurs (5.000 EVP)			1%	
Petit porte-conteneurs (1.000 EVP)			2%	

Pour toutes ces technologies, il en ressort que les économies relatives sont supérieures pour la vitesse inférieure, ce qui est à prévoir en raison de la demande d'énergie nettement inférieure à la vitesse inférieure.

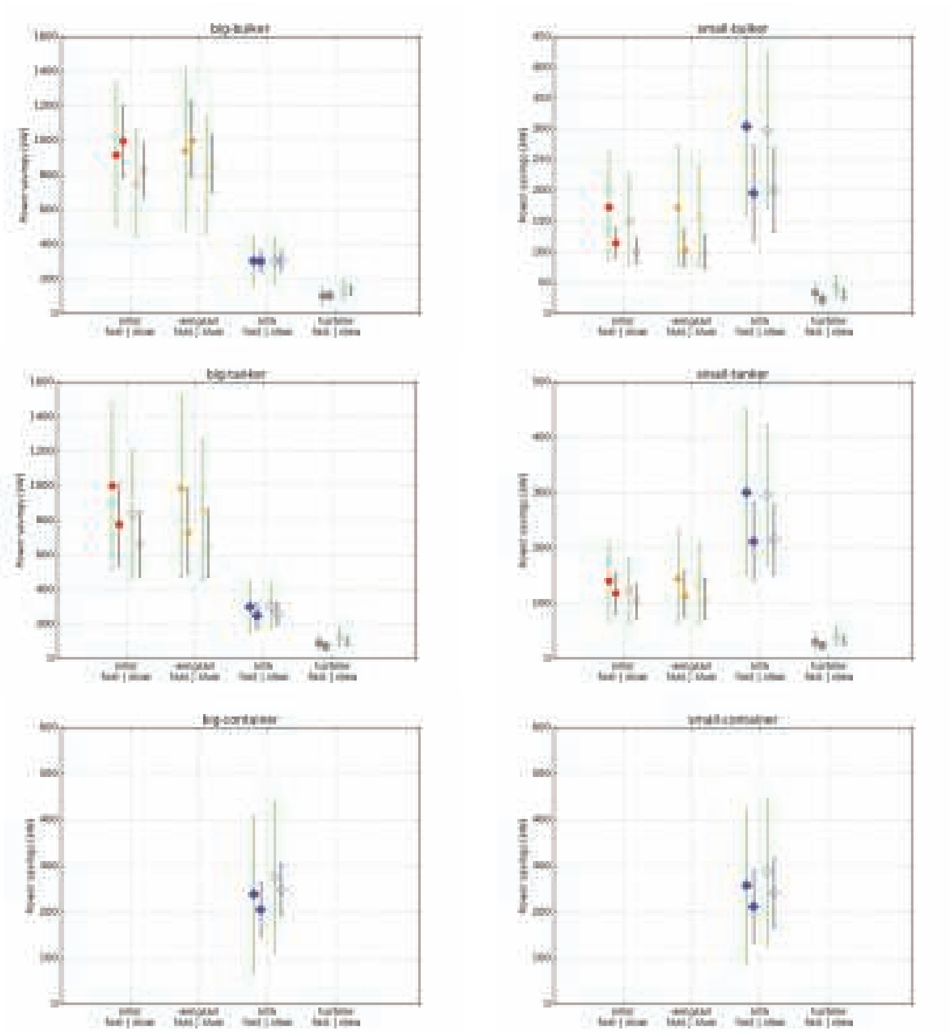
Pour les économies absolues (voir Figure 2), toutefois, ceci n'est pas valable. Alors que pour le cerf-volant de traction et la turbine éolienne, les économies absolues ont tendance à être égales voire même inférieures à la vitesse supérieure, les économies absolues sont plus importantes à la vitesse supérieure pour l'aile rigide et le rotor pour tous les types de navires considérés.

Ce résultat de l'étude est essentiel et il implique qu'il existe un obstacle qui a été surestimé jusqu'à présent : les navires ne doivent pas nécessairement ralentir pour qu'au moins certains systèmes de propulsion éolienne deviennent plus rentables.

Les économies relatives des rotors et voiles rigides sur les plus gros navires dépassent les économies relatives sur les plus petits navires, surtout sur le vraquier. Ceci est dû partiellement au fait que les plus gros navires effectuent plus de déplacements en pleine mer sur des itinéraires où ils subissent l'effet de vitesses du vent supérieures par rapport aux navires plus petits. De plus, les navires plus gros peuvent être équipés de plus de dispositifs de propulsion éolienne, de plus grande taille, avec un effet supplémentaire de vitesses du vent supérieures subies par les dispositifs de plus grande taille sur les navires plus gros.

Les résultats numériques dépendent des hypothèses et paramètres définissant les modèles, chacun représentant une catégorie de technologies.
Par conséquent, isolés, ils ne constituent pas un classement des technologies respectives. Au lieu de cela, une technologie spécifique peut être évaluée contre la référence établie, avec des facteurs tels que les coûts, la convivialité, etc. Cependant, les résultats indiquent clairement le potentiel considérable en économies des technologies envisagées, même en mode de fonctionnement au statu quo.

Figure 2 Économies moyennes absolues d'énergie (les symboles solides présentent des économies calculées en moyenne sur les itinéraires échantillons, les symboles vides ont été calculés en moyenne sur les profils d'itinéraire de flotte échantillons issues des données de systèmes automatique d'identification)



Potentiel commercial et effets économiques
Si quelques technologies de propulsion éolienne pour navires deviennent commercialisables depuis 2020, le potentiel commercial maximal pour les vraquiers, pétroliers et porte-conteneurs est estimé à quelque 3.700–10.700 systèmes installés jusqu'en 2030, y compris les rénovations et les installations sur de nouveaux navires, en fonction du prix des combustibles de soute, de la vitesse des navires et du taux de réduction appliqué. L'usage de ces systèmes

de propulsion éolienne entraînerait une économie de CO_2 d'environ 3,5–7,5 mt de CO_2 en 2030 et le secteur de la propulsion éolienne créerait alors quelque 6.500–8.000 emplois directs et 8.500–10.000 emplois indirects.

Toutefois, le processus de diffusion n'aura pas encore atteint sa maturité en 2030; il est prévu que ce niveau sera atteint aux alentours de 2040, lorsque de nouveaux navires auront intégrés la flotte (les rénovations sont plus coûteuses que l'installation sur les nouvelles constructions) et les coûts en capital auront baissé davantage en raison des effets d'apprentissage et des économies d'échelle.

Obstacles au développement et à l'utilisation de la propulsion éolienne
De multiples obstacles ont été identifiés empêchant actuellement le développement et l'utilisation ultérieurs des technologies de propulsion éolienne.

Les obstacles empêchant l'utilisation des technologies de propulsion éolienne sont
1. Les caractéristiques techniques des différentes technologies de propulsion éolienne (TPE) qui peuvent limiter l'applicabilité des technologies, les rénovations étant naturellement plus limitées que les nouvelles constructions.
2. Les facteurs ayant un impact négatif sur la rentabilité des TPE en nuisant aux avantages, aux performances ou aux coûts des TPE (le ralentissement économique, par exemple).
3. Les facteurs contribuant à l'incertitude de la rentabilité des TPE ; certains de ces facteurs d'incertitude ne peuvent pas être atténués (la volatilité des prix de carburant, par exemple, ou les cycles économiques), alors que d'autres facteurs sont incertains, car il n'y a pas encore suffisamment d'informations disponibles sur les performances, le caractère opérationnel, la sécurité, la durabilité et les implications économiques de la propulsion éolienne et il se peut que les informations disponibles n'aient qu'une valeur limitée et qu'elles ne soient pas fiables ou comprises.
4. L'accès au capital pour l'utilisation des TPE.

En outre, il existe des obstacles à l'utilisation de mesures de réduction rentables en général, comme par exemple, la dispersion des incitations entre le propriétaire du navire et l'opérateur ou le scepticisme du secteur.

Et enfin, il existe des obstacles spécifiques au développement (ultérieur) des TPE, comme l'accès au capital pour le développement de TPE, surtout pour la construction et les essais de dispositifs de démonstration grandeur nature et le cadre juridique/institutionnel actuel.

Les trois obstacles suivants ont été identifiés comme obstacles principaux :
1. Les informations (fiables) sur les performances, le caractère opérationnel, la sécurité, la durabilité et les implications économiques des TPE.
2. L'accès au capital pour développer les TPE, surtout en vue de la fabrication et des tests de dispositifs de démonstration grandeur nature.
3. Les incitations à améliorer l'efficacité énergétique/réduire les émissions de CO_2 des navires.

Ces obstacles principaux sont liés entre eux de plusieurs façons, l'action réciproque essentielle étant un problème de la poule et de l'œuf entre le premier et le second obstacle principal.

Interventions

Afin de résoudre ce problème de la poule et de l'œuf, nous envisageons le développement d'une méthode standardisée pour évaluer les TPE combinée à des cas d'essai pour développer une méthode d'évaluation comme point de départ essentiel. Ce n'est que si les essais donnent lieu à des informations évaluables générées par une partie indépendante que la confiance des propriétaires de navires et des investisseurs pourra être gagnée et que des fonds publics, qui pourraient servir à générer ces informations, pourront créer une réelle valeur ajoutée.

Lors du développement d'une méthode standardisée pour évaluer les TPE, la cohérence par rapport aux indications techniques de l'Indice de conception d'efficacité énergétique (à développer) pour l'exécution d'essais de performance sur les systèmes de propulsion éolienne devrait être prise en compte. Cependant, la méthode d'évaluation ne devrait pas se limiter à la détermination de la puissance effective disponible des systèmes, mais devrait également inclure la détermination des économies réelles en carburant.

Ce n'est qu'après le développement d'une méthode d'évaluation standardisée qu'il serait logique de prendre des mesures afin d'améliorer la génération de plus d'informations sur les TPE, améliorant l'accès à ces informations et leur valeur, et améliorant (également) l'accès au capital pour le développement et les essais sur les dispositifs de démonstration grandeur nature.

S'il y avait suffisamment d'incitations pour améliorer l'efficacité énergétique/ réduire les émissions de CO_2 des navires, certaines de ces dernières mesures, notamment celles améliorant l'accès au capital, pourraient être superflues. Cependant, comme l'incitation à améliorer l'efficacité énergétique/réduire les émissions de CO_2 des navires ne sera probablement pas améliorée à court terme, ces mesures devraient être prises pour faire progresser le développement et l'utilisation de TPE.

Les différentes parties prenantes peuvent donc contribuer aux différentes mesures à plusieurs niveaux, ce qui vaut également pour la Commission européenne.

Citons quelques exemples de mesures que la Commission européenne pourrait prendre. La Commission européenne pourrait

- commander une étude sur le développement d'une méthode d'évaluation standardisée des performances des technologies de propulsion éolienne, peut-être combinée à des cas d'essai;
- si les tests de performance sont soutenus par des fonds publics, définir des exigences concernant l'utilisation d'une méthode d'évaluation standardisée (une fois développée), la vérification et la publication de résultats d'essai;
- au sein du cadre de la réglementation MRV, offrir aux navires l'occasion de publier l'usage de mesures innovatrices d'efficacité énergétique.

Il existe des fonds publics disponibles qui financent, notamment, des projets de démonstration dans le secteur du transport maritime (le programme Horizon 2020 ‘Vers le navire éconénergétique et sans émission’ ou l'Instrument PME phase 2 du programme Horizon 2020), mais afin d’améliorer l’accès au capital des entreprises souhaitant présenter les performances et le caractère opérationnel des mesures d’efficacité énergétique pour le transport maritime, les mesures suivantes pourraient être prises:

- offrir un régime de paiement viable pour les PME;
- réduire autant que possible l’effort administratif sans compromettre la responsabilité;
- offrir des programmes ciblant spécifiquement les projets de démonstration pour la navigation maritime;
- offrir des programmes ciblant les projets de démonstration pour la navigation maritime sans limiter d’avance les technologies éligibles.

Consultez la liste complète des éventuelles mesures que les différentes parties prenantes pourraient prendre afin d’atténuer les obstacles au développement et à l’utilisation de technologies de propulsion éoliennes au Chapitre 5.

1 Introduction

1.1 Climate change and shipping

According to the most recent estimates, global shipping emitted on average about 1 billion tonnes of carbon dioxide annually in the period 2007–2012, equivalent to just over 3% of global anthropogenic emissions (UCL, CE Delft, et al., 2015). Despite market-driven and regulatory efficiency improvements, such as the IMO Energy Efficiency Design Index (EEDI), the emissions of international maritime shipping are expected to increase by 50-250% by 2050 emissions (UCL, CE Delft, et al., 2015). If global emissions would be reduced to levels compatible with a 2°C target and shipping emissions would continue to increase as projected, shipping would be responsible for 4-15% of total allowable emissions by 2050, thus increasing the burden on other sectors significantly.[1] This holds all the more true for a target well below 2°C.

The EU has long advocated action to address maritime GHG emissions (2002 Decision on the 6th Environment Action Programme; Directive 2009/29/EC). It has consistently preferred policies to be agreed at a global level because of the international nature of the sector. However, it has also indicated that when IMO Member States cannot agree on policies, the EU is willing to take early action (COM(2013) 479 final). It has adopted a regulation on the monitoring, reporting and verification (MRV) of carbon dioxide emissions from maritime transport (EU 2015/757) which, according to the impact assessment, can yield emission reductions of up to 2%. A next step in the EU policy to include international maritime emissions in the Community reduction commitment could be setting an emissions target, so that all sectors of the economy contribute to achieving the EU's emissions reductions, followed by implementation of an MBM (COM(2013) 479 final).

It is clear that policies currently implemented at a global level, such as the EEDI and the global data collection system, or at the EU level, such as MRV, will not result in an absolute reduction of emissions. In contrast to many other sectors, technological pathways to achieve deep cuts in emissions are not clear in maritime transport.

Most emission reduction measures have a potential of a few percent although all available measures combined may significantly reduce the CO_2 emissions of a ship.[2]. Technologies which can achieve large emission reductions are slow steaming, biofuels and wind propulsion.

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1 When global emissions are reduced in line with a 2°C target, but shipping emissions are allowed to follow a business as usual path, shipping emissions may increase to 10% of global emissions in 2050 (Öko-Institut; CE Delft, 2015). If all sectors reduced their emissions to the same extent, international shipping would keep its 2.2% share in global total CO_2 emissions. This would correspond to absolute CO_2 emissions of about 420 Mt of CO_2 in 2050, if a 2°C target was met (Traut, et al., 2015). The highest and lowest 2050 CO_2 emissions of shipping as projected in the 3rd IMO GHG Study (UCL, CE Delft et al., 2015) therefore correspond with a share of 4% and 15% of the total allowed 2050 CO_2 emissions.

2 The Second IMO GHG Study 2009 for example identifies a reduction potential of 25-75% per tonmile.

Slow steaming is already implemented to a large degree and its potential to reduce emissions, other advantages and disadvantages are well known (CE Delft; The ICCT; Mikis Tsimplis, 2012).

The use of biofuels in shipping has received some attention and pilot projects are being conducted, but their use in other transport sectors has revealed that there are concerns about the environmental impacts and the availability of fuels. Moreover, the price of biofuels is currently much higher than prices for other maritime fuels.

Many innovative wind propulsion technology concepts have been and are being developed for commercial shipping. However, none of the technologies has reached market maturity yet. Wind propulsion for ships has been the subject of a number of studies (Traut, et al., 2014); (EE Consultant, 2013); (Loyd's Register, 2015) and has also been included in most technology overviews and marginal abatement cost curves of shipping (Eide, et al., 2011); (CE Delft; Marena Ltd, 2011). However, realistic estimates of the emissions saving potential as well as a comprehensive overview of all barriers hindering uptake of all the different wind propulsion technologies is lacking, as is a detailed analysis of policy interventions to promote the uptake of wind propulsion.

1.2 Objective of the study

Against the background described in the previous Section, the general objective of this study contract is to provide support to the Commission services to explore how further support can be provided to ensure that wind propulsion technologies are deployed in the shipping sector.

In order to meet the general objective, the following specific objectives have been formulated:
- to identify relevant wind propulsion technologies and their deployment status;
- to identify the market potential of the identified technologies including CO_2 reduction potentials, fuel savings and costs;
- to analyse market barriers preventing the uptake of wind propulsion technologies including the current and near horizon drivers (market, regulatory, etc.) that will influence these barriers;
- to provide recommendations on possible actions at EU and global level (and if appropriate other levels) to promote the uptake of wind propulsion technologies.

1.3 Scope of the study

Since the study is carried out for the European Commission and the results will comprise an overview of possible actions at the EU level to promote the uptake of wind propulsion technologies, the study focusses on main ship types used on shipping routes from or to EU ports. Because of the importance of shipping for Europe, this covers all important ship types.

The emission reduction potential of wind propulsion technologies is assessed for the global operations of the relevant ship types, because ships sailing to EU ports are at times deployed in other parts of the world.
Also, greenhouse gas emission reductions naturally have a global relevance.

The market potential of technologies is assessed for 2020 and 2030. Over this timeframe, technology developments are more predictable than over longer periods.

The study identifies all wind propulsion technologies, whatever their level of maturity, and analyses the fuel and emission reductions and costs of those technologies for which technology providers exist, because otherwise cost estimates and performance data will be unreliable. We also include technologies of which the suppliers have suspended operations, as long as data are still available.

1.4 Outline of report

In Chapter 2 an inventory of the supply and demand side of wind propulsion technologies for ships are presented and technology types are selected for further analysis. In Chapter 3 the fuel savings of the selected wind propulsion technologies are first determined on ship level (Section 3.2) and, based on these results, the emissions savings and the market potential is determined on fleet level (Section 3.3). The social and economic effects associated with the expected market potential of wind propulsion technologies are presented in Section 3.3. The barriers to the uptake and development of wind propulsion technologies for ships are analysed in Chapter 4. Finally, possible actions to overcome the established key barriers are proposed in Chapter 5.

2 Wind propulsion technologies and their deployment status

2.1 Introduction

As a starting point for the analysis of the emissions savings and the market potential of wind propulsion technologies (WPTs) for ships, an inventory of the supply and demand side of WPTs has been carried out. For the identified technologies factsheets have been prepared and analysed. Based on the available information and the state of development, technology types are selected for further analysis.

2.2 Inventory of wind propulsion technologies

Based on a literature review, internet research and input from IWSA, an overview of wind propulsion technologies for ships, divided into supply and demand side, has been developed.

The supply side overview (see Table 3) comprises current wind propulsion technology providers, potential future wind propulsion technology providers (labelled as 'R&D company' in Table 3), as well as R&D projects.

Table 3 Wind propulsion technologies for ships: supply side overview

Category of technology	Company/Project		Name of product	Country
Soft sail	Modern Merchant Sailing Vessel	R&D company	Pinta-Rig	Germany
	Neoline project	R&D project		Canada and France
	sail	R&D project	Dynarig (Ecoliner)	Netherlands, Germany, Sweden, Denmark, Belgium, UK, France
	Seagate Sail	R&D company	Delta wing sail	Italy
	Smart green shipping alliance	R&D cooperation	Fastrigs	UK
Rigid sail/ wingsail	Eco marinepower	R&D company	Aquarius MRE System, EnergySail	Japan
	Oceanfoil	R&D company	Oceanfoil wing sail	UK
	Ocius Technology Ltd.	R&D company	Rigid Opening Sail	Australia
	Propelwind	R&D company		France
	Sail Freight International	R&D company	COMSAIL Wing	USA
	Wind + wing technologies	R&D company	Wingsail	USA
	Wind challenger project	R&D project		Japan
	WindShip Technology Ltd	R&D company	Auxiliary Sail Propulsion System	UK
	Wing systems	R&D company		USA
Hull sail	LadeAs	R&D company	Vindskip™	Norway
Towing kite	SkySails	Technology provider	SkySails Propulsion System	Germany
Rotor	Bridgeport Magnetics Group/ Poulsen Hybrid	R&D company	Monorotor	USA

Category of technology	Company/Project		Name of product	Country
	CRAIN	R&D company	Suction wing propeller*	France
	Magnuss	R&D company	Magnuss VOSS™	USA
	Norsepower	Technology provider	Norsepower Rotor Sail Solution	Finland
	sail	R&D project	Flettner Freighter	Netherlands, Germany, Sweden, Denmark, Belgium, UK, France
	Thiink	R&D company	THiiiNKSail rotor	Switzerland
	Turbosail	R&D company	Turbosail™ *	Singapore
	'Wind Hybrid Coaster' project	R&D project	Eco Flettner	Germany and Netherlands
Wind turbine	Inerjy	R&D company	EcoVert	USA (Florida)
	PROPit	R&D company		Sweden

* Note that both the *Turbosail* and the *Suction wing propeller* are systems that, just like the other systems subsumed under 'Rotor', make use of the Magnus effect. For both types of systems it holds that cylinders are vertically mounted on deck of the ships. However, the *Turbosail* and the *Suction wing propeller* have got, in contrary to the other systems, no external rotating parts and could therefore also be classified as a sail. They work with fans at the top of the cylinder to create boundary layer suction.

Six main categories of wind propulsion technologies for ships are thereby differentiated: soft sails, rigid sails/wingsails, hull sails, towing kites, rotors, and wind turbines.

Soft sails are flexible sails just as the traditional sails. Modern soft sails are characterised by very different innovative features, like for example freestanding square rigs, duplex rigs, rotating masts/spars, etc. Most of them are automated to a great extent.

Unlike traditional sails, which are flexible, **rigid sails/wingsails** are wing-shaped foils with varied geometry and configurations. They are often used in combination with flaps. The operating principle is the same as for any aerofoil: when moved through a fluid it produces an aerodynamic force consisting of lift and drag. By rotating to the optimum angle of attack, the lift can be maximised (Loyd's Register Marine, 2015).

The hull of a vessel can be shaped like a symmetrical aerofoil going in the relative wind, generating an aerodynamic lift, giving a pull in the ships direction, within an angular sector of the course. In this study this concept is referred to as **hull sail** (LadeAs, 2016).

Kites can tow ships if installed at the bow, making use of high altitude winds. Without any movement of the kite relative to the ship, forces developed by a kite would be in the order of magnitude of a traditional sail of the same area and would need to be rather large in order to propel a ship. Kites offered for ship propulsion are therefore dynamic kites that keep moving relative to the ship (CRAIN, 2014).

Rotors (rotating cylinders) can be vertically installed on a ship's deck so that the rotation together with the wind creates a pressure difference on the cylinder orthogonal to the wind direction, the so called Magnus effect that in turn gives a propulsive force (ScandiNAOS AB, 2013).

Wind turbines can, comparable to onshore wind turbines, be installed on ships to generate electricity. Some systems allow the power generated to be used for electric propulsion. Furthermore, forces generated by the blades of wind turbines could also be used to propel ships.

Regarding the scope of the inventory, several delimitation criteria have been applied:
- Frist, only the (potential) technology suppliers that (intend to) sell the actual wind propulsion technology are presented. All the companies higher upstream in the value chain are not incorporated.
- Second, concepts that are being developed for non-commercial shipping and/or very small vessels or are developed to enable the use of transport by ships for new markets have been omitted.
- Third, traditional soft sail designs have not been considered.
- Fourth, only those R&D projects have been considered that aim/have aimed at developing a prototype for a wind propulsion technology or that aimed at/resulted in a design that is ready to apply. R&D projects presenting visionary ship/propulsion designs, not/no longer aimed at the actual development and R&D projects aimed at comparing concepts for research purposes have been omitted.[3]
- Fifth, potential technology providers whose current status is very uncertain have been discarded.
- And sixth, only those wind turbine technologies that can contribute the propulsion of the ship have been considered.

The supply side overview shows that there are currently two providers of wind propulsion technologies for ships whose products close to marketability and that there are up to 24 additional wind propulsion technologies/concepts relevant for the aim of this study that may become available until 2030.

To get an idea of the geographic locations of the (potential) wind propulsion technology providers for ships, the headquarters of the companies and the locations of the institutes leading R&D projects have been mapped (Figure 3).

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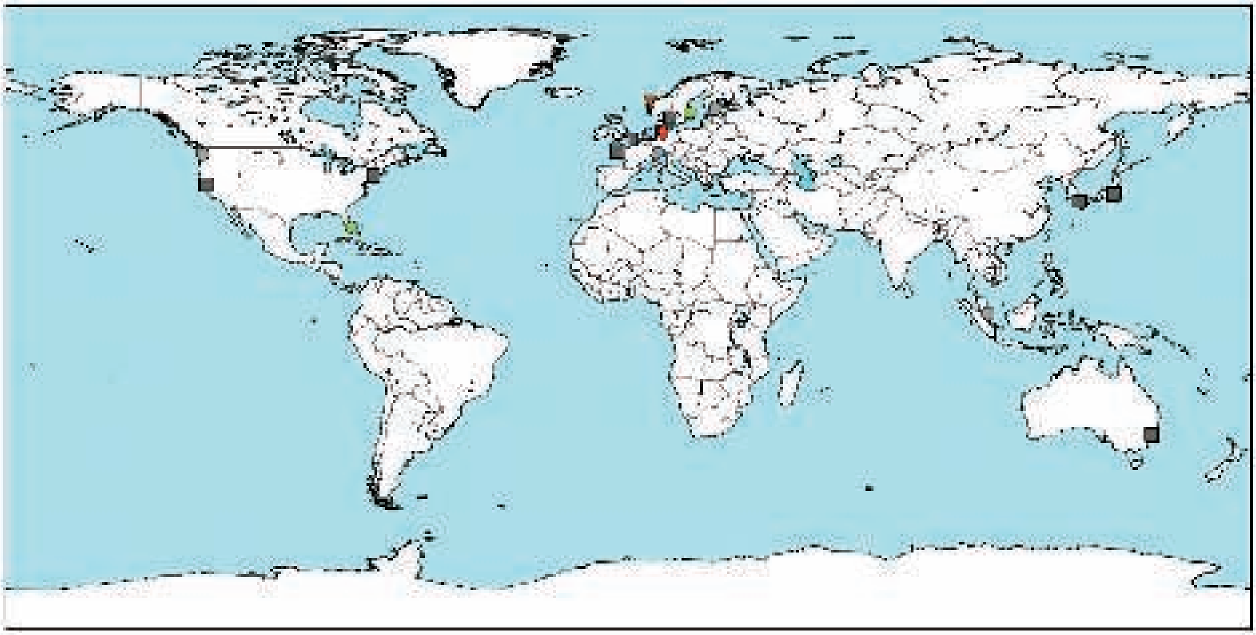
[3] The R&D projects, like for example the EffShip project that have compared different concepts are of course relevant when it comes to the determination of the performance of the different wind propulsion technologies.

Figure 3 Locations of (potential) wind propulsion technology providers



Soft sail=blue triangle, rigid sail/wingsail=squares, hull sail=brown triangle, kite=red rhomb, rotor=grey dots, turbine=green hexagon.

The map shows that (potential) wind propulsion technology providers are mainly located in Northern and Western European countries. Other locations are the coastal areas of the US, Japan, Italy, Singapore, and Australia. However, companies further up- or downstream in the value chain of the wind propulsion technologies might be located in other parts of the world.

Regarding the deployment of wind propulsion technologies for ships, the inventory shows (see Table 4) that currently two multi-purpose ships and one bulk carrier are equipped with a towing kite. However, to our knowledge, the installed systems are currently not in use. In addition, three ships (a research vessel, a RoRo vessel, and a RoLo vessel) are currently equipped with wind rotors; one rotor is planned to be installed on a general cargo ship.

Table 4 Wind propulsion technologies for ships: demand side overview

Technology	Specific technology	Ship name	Ship type	Status	Owner/operator
Towing kite	SkySails Propulsion System	MV 'BBC Skysails'	Multi-purpose ship	Installed	Briese Schiffahrts GmbH & Co. KG
		MV Theseus	Multi-purpose ship	Installed	Reederei Wessels
		Aghia Marina	Bulk carrier	Installed	Cargill
Rotor/ turbo sail	Turbosail	Alcyone	Research vessel	Installed	Cousteau Society
	Rotor Sail	M/S Estraden	RoRo	Installed	Bore
	Flettner rotor	E-ship 1	RoLo	Installed	Enercon
	Eco Flettner	MV Fehn Pollux	General cargo ship	Installation planned.	Fehn Ship Management GmbH & Co. KG

A consortium led by the Irish Defence Forces has also developed a kite based on the SkySails Propulsion System. This kite can be used not only for propulsive purposes, but also for surveillance purposes since the kite is equipped with sensors. The system has been tested on a Naval vessel (LÉ Niamh), but at present it is unclear whether the Irish Naval Service will actually use the kites on its patrol vessels (seai, 2015).

Note that in the 1980s several ships build in Japan had been equipped with rigid sails. To our knowledge none of these vessels is still in operation/using the sails (see Section 4.5.1 for more details)

2.3 Technology factsheets

For the different wind propulsion technologies that have been identified in the inventory (see Table 3), a technology factsheet has been prepared which can be found in Annex A of this report.

The technology factsheets cover the aspects relevant for the emission savings and market potential analysis and have been completed (as far as possible) based on information/data collated in a stakeholder survey, internet research, and a literature review.

In order to gather data and information that is relevant for the different tasks of this study, a survey has been carried out amongst the (potential) wind propulsion technology providers. Eleven of the (potential) propulsion technology providers have participated in this survey. Three participants are (potential) technology providers of soft sails, three of rigid sails, one of towing kites, three of rotors, and one of wind turbines. In Annex B a list of the participants is given. The questionnaire that has been used in the survey can be found in Annex C of the report. The questionnaire covers all the different topics of the study. Since the factsheets presented in Annex A are related to emission savings and market potential analysis, they do not cover all the topics addressed in the questionnaire.

The analysis of the technology factsheets shows that there are very different concepts of wind propulsion technologies under development which, despite of the differences, share some common principles.

Aim of the technology designs is of course to optimize the aerodynamic and energetic features of the wind propulsion technologies, but in contrast to the traditional sail concepts, a certain degree of automation is introduced to be able to adjust to different wind conditions without increasing the work load of the crew.

In conditions that do not allow the system to be operated, the systems' air resistance is tried to be minimized and the technologies are designed to minimize interference with loading and unloading of the vessels.
Here different approaches with different degrees of complexity can be observed, like for example foldable or retractable systems.

Regarding new build design concepts these often work with an overall optimized ship design, allowing for an optimal position of the wind propulsion technology on board, optimal hydrodynamic characteristics of the hull, adjusted engine power, etc. These overall concepts can be expected to be associated with a higher energy/CO_2 saving than retrofit solutions.

The majority of the propulsion technologies have been developed for bulkers, tankers and general cargo vessels and for the majority of the propulsion technologies the state of development in 2020 is not stated and can therefore expected to be uncertain. For many propulsion technologies performance data - which is relevant for determining for the emissions savings and market potential of the technologies - is given by the companies, but this is often only in terms of average/maximum fuel savings and it is often not clear what the underlying assumptions are and how the savings have been determined.

2.3.1 Technologies to be further analysed

Based on the available information and the state of development, five technology types have been selected for further analysis: a generic type of rotor, towing kite, rigid sail/wingsail, soft sail and wind turbine.

The hull sailing concepts will not be further analysed. Based on a review of available materials, there is no plausible prospect for this technology to play a significant (economically and with respect to emissions from the shipping sector) role within the timeframe of this study.

Note that the availability of the technologies until 2020 is also uncertain for soft and rigid sails/wingsails; the probability that these technologies become available until 2030 is much higher. In the market potential analysis we therefore assume that the technologies become gradually available in the period 2020 to 2030.

3 CO_2 reduction and market potential of wind propulsion technologies

3.1 Introduction

In this section, the fuel and CO_2 emissions saving potential of wind propulsion technology are first assessed on the level where the technology is applied, the individual ship level (Section 3.2). Results from this analysis underpin the following analyses, exploring the potential for uptake and penetration on the fleet level (Section 3.3). The social and economic effects associated with this market potential for wind propulsion technologies are presented in Section 3.4.

3.2 Fuel and CO_2 emission savings on ship level

3.2.1 General Approach

On the ship level, a number of elements are required in order to estimate savings from or, more generally, the performance of wind propulsion technology: an understanding of the technological concept; the vessel on which the technology is applied; the operational profile of that vessel; environmental conditions (including wind velocities) encountered by the vessel; and a counterfactual mode of operation against which performance is compared. In the following, these elements are presented in turn.

Four wind propulsion technology concepts have been selected: a Flettner rotor, a wingsail, a towing kite, and a wind power turbine. Some of these technologies come in many shapes and forms and, clearly, it is impossible to account for all designs. Instead, generic technology models are introduced for each of the four concepts in Sections 3.2.2-3.2.5. For each, the underlying concept and, where necessary, design choices, are presented first.

This ‘generic model’ is followed by a ‘model specification’ - which defines the parameters governing the aerodynamic performance of the technology, and defines the mode of operation of the technology. The approach follows the aim of modelling, as accurately as possible, the potential performance, and resultant fuel savings, of the respective technologies while establishing a clear and transparent methodology against which any specific design, or any specific performance data, may be compared.

Section 3.2.6 presents a set of sample vessels to apply wind propulsion technologies, followed by Section 3.2.7, which matches wind power technologies to the sample vessels, defining the applicability, size, and number of technology devices for deployment on each of the sample vessels.

In each case, the technology models yield a thrust force, a side force, and power consumption or production, as a function of ship speed, ship course, and wind velocity.

The propulsive efficiency, η_P is used to calculate power and, in turn, fuel savings from the generated thrust. That is:

$$p_{saved} = t \cdot v_{ship} / \eta_p$$

where t is the thrust and v_{ship} is the ship speed. A constant value of η_P=0.7 is assumed, a conservative assumption in the sense that, as part of the required thrust is provided by the wind power technology, the standard propulsion system is more lightly loaded, increasing efficiency. Effects not accounted for by this approach are discussed in Section 3.2.12. Fuel savings are estimated from power savings assuming a constant engine specific fuel consumption; CO_2 emissions saved are calculated by applying a CO_2 factor to saved fuel.

Section 3.2.8 defines the sample routes and operational profiles for the sample vessels. Section 3.2.9 provides the final element of the applied methodology: wind velocity data.

For each case -that is for each mapping of a technology to one of the sample vessels and, in turn, of the sample vessel to a route or operational profile-resultant power savings are calculated. Results are given in Section 3.2.10-Section 3.2.12, including an overview and discussion of the results and the data passed on to subsequent analysis steps building on the ship level results. Please refer to Annex D for a discussion of issues related to the modelling of the fuel savings potentials of wind propulsion technologies that are beyond the scope of this report.

3.2.2 Flettner Rotor

Generic Model

The rotor simulated in the performance analysis is a simple cylinder (with unspecified end disks), described by its height and width, that can be collapsed or retracted in unfavourable wind conditions. The performance is defined by its coefficients of lift C_L, drag C_D, and moment C_M. The rotational speed α, the ratio between the speed of the cylinder's surface and the apparent wind speed is assumed constant. If there are no savings to be made from operating the rotor it is switched off, and the rotor is collapsed or retracted unless there are savings to be made from the pure drag on the rotor. In addition, there is an apparent wind speed limit $v_{a,lim}$ beyond which it is assumed that rotor power and thrust remain constant.
As a function of ship speed and course, and wind velocity, the model returns the lift **l** and drag force **d** and the power p_{motor} consumed by the motor:

$$l = 0.5 \rho A C_L v_A^2$$

$$d = 0.5 \rho A C_D v_A^2$$

$$p_{motor} = 0.5 \rho A C_M \alpha v_A^3$$

Model Specifications

The performance parameters of the rotor models are:

$$C_L = 10.0$$

The drag coefficient differentiates between the rotating rotor including induced drag with coefficient C_D and the still rotor with drag coefficient C_{D2}

$$C_D = 3.0$$
$$C_{D2} = 0.3$$
$$C_M = 0.2$$
$$v_{A,\lim} = 18\ m/s$$

3.2.3 Sail

Generic Model

The sail model is that of a rectangular wingsail that is retracted if the combined lift and drag force opposes the forward motion of the vessel.
In standard condition, the sails are orientated to deliver maximum forward thrust, at a constant value of both the lift and drag coefficients, C_L and C_D, respectively. In tail winds, a drag-maximising orientation may be preferable. In these cases, there is a transition lift-maximising to drag-maximising mode, with a higher drag coefficient, $C_{D,max}$.

Model Specifications

The aerodynamic parameters of the sail are:

$$C_L = 2.0$$
$$C_D = 1.0$$
$$C_{D,\max} = 2.0$$

3.2.4 Towing kite

Generic Model

The towing kite is attached to the bow of the ship by a (very strong) rope.
At the other end of the rope, there is a gearbox which controls the kite.
In particular, it steers the kite on its flight trajectory, on which the force on the kite is in equilibrium: the sum of the lift and drag forces is equal and opposite to the rope force. Here, the kite is assumed to fly a circular pattern (specified by its radius, and the position of its centre point, defined by the azimuthal and zenith angles, as seen from the bow of the ship, and the length of the rope). The parameters that mainly determine the kite's performance are its lift coefficient C_L, its lift-to-drag ratio $l/d = C_L/C_D$, its size in terms of area A, and an upper limit for the force on the rope $F_{rope,max}$. The equations for lift l and drag d take the same form as for the rotor:

$$l = 0.5 \rho A C_L v_A^2$$
$$d = 0.5 \rho A C_D v_A^2$$

The force of the vessel is estimated as the average force on the rope, over a full circular pattern, neglecting any time-dependency of that force and also neglecting the effect of gravity on the motion of the kite.

Model Specifications

The performance parameters of the rotor models are:

$$C_L = 1.25$$
$$C_L / C_D = 4.5$$

The zenith angle $\gamma = 25°$, while the azimuthal angle $\beta = 0.35\delta$, where δ is the angle between the velocity of the ship and the velocity of the apparent wind. It is assumed that the kite is retracted if $\delta > 135°$.
The rope length is 350 m. The diameter of the circular flight pattern is 122 m.

3.2.5 Wind Turbine

Generic Model

The turbine model is based on an idealised 1-dimensional model.
The airflow through the turbine is confined to a stream tube, and the effect of the turbine is to extract kinetic energy from the airflow, thereby slowing it down, and experiencing a force in the direction of the wind velocity.
In this idealised model, the reduction in kinetic energy reaches a maximum at $a = v_2 / v_1 = 1/3$, with v_1 the apparent wind velocity, and v_2 the apparent wind velocity behind the turbine. This maximum corresponds to a power coefficient of $C_P = 59\%$ of the inflow of kinetic energy of $0.5 \cdot \rho A v_A^3$, with ρ the density of air, A the area swept by the turbine, and v_A the apparent wind velocity (Betz's law).
More generally, the power coefficient in this idealised case is:

$$C_P = 0.5(1 - a^2)(1 + a)$$

By the same consideration of momentum, the thrust coefficient $C_{T,ideal}$ is:

$$C_{T,ideal} = 1 - a^2,$$

which determines the force d on the turbine:

$$d = 0.5 \rho A C_T v_A^2$$

The model applied here deviates from the idealised model in assuming additional losses, with the force on the turbine larger than in the idealised case, summed up by a loss coefficient k_l, so that:

$$C_{T,ideal} = C_T (1 + k_l)$$

Furthermore, a conversion efficiency relates the kinetic energy (per unit of time) fed into the turbine to its electrical power output:

$$P_{el.} = \eta_{gen.} \cdot C_P \cdot 0.5 \rho A v_A^3$$

Thus far, the model yields both electrical power generation and the drag force on the rotor as a function of the parameter a. Between the cut-in speed and reaching the turbine's rated power, a is held constant at $a = a_a$; between reaching its rated power and its cut-out speed, a reduces in line with a constant power output equal to the turbine's rated power output.
It is assumed that the electrical power generated by the turbine is replaces main engine power for propulsion. The turbine is retracted if the apparent is outside the range defined by the turbine's cut-in and cut-out speed, or if the combined effect of the drag force on and the power generated by the turbine is a power loss.

Model Specifications

The parameters governing the performance of the turbine model are:
The cut-in speed of the turbine is 3.0 m/s, the cut-out speed 15.2 m/s.
The other parameter values are:

$$a_0 = 2/3$$
$$k_l = 0.002$$
$$\eta_{gen.} = 0.95$$

3.2.6 Sample vessels

Six sample vessels have been selected for detailed voyage simulation: two tankers, two dry bulkers, and two container carriers, with a large and a small sample vessel in each category. The main ship particulars are presented in Table 5. The most important parameters, in relation to this study, are the main dimensions, and the installed main engine power together with the design speed.

Table 5 Overview of sample vessels' main particulars and voyage speeds

Category	Bulker	Bulker	Tanker	Tanker	Container	Container
Size	7,200 dwt	90,000 dwt	5,400 dwt	90,000 dwt	1,000 TEU	5,000 TEU
Service speed	13.25 kts.	14 kts.	13.8 kts.	15 kts.	17.55 kts.	24.9 kts.
Main engine power	2,802 kW	8,445 kW	2,827 kW	12,850kW	10,166 kW	47,744 kW
Length	107 m	244 m	97 m	231 m	138 m	286 m
Beam	18 m	40 m	17 m	42 m	23 m	32 m
Depth	9 m	21 m	8 m	21 m	12 m	21 m
Fast voyage	12.3 kts.	12.3 kts.	13.0 kts.	13.0 kts.	17.5 kts.	19.0 kts.
Slow voyage	10.5 kts.	10.5 kts.	11.0 kts.	11.0 kts.	14.9 kts.	16.1 kts.

For each ship category, two voyage speeds are simulated. The higher voyage speed is taken as the average between average observed voyage speeds in 2007 and 2016, according to MEPC 70-INF.9 (IMO, 2016). A speed reduction of 15% - broadly corresponding to the maximum difference observed for a ship category between (slow) speeds in 2012 and (higher) speeds in 2007/2016 - is assumed for the lower voyage speed, as presented in Table 5.

3.2.7 Matching technologies to sample vessels

In order to assess the savings potential, choices have to be made about the number and size of wind power technology devices to be fitted to the vessels. On the one hand, results depend critically on these choices. On the other hand, there is no single correct answer. In making that choice for a specific ship, a number of criteria would merit consideration that could not be accounted which cannot meaningfully be applied to a whole category of vessels and technologies. Nonetheless, it is possible to lay out a set of plausible rules for the selection process, tailored to each of the four technologies, as follows.

For the rotors, the total projected area (i.e. number of rotors x height x diameter) divided by the deadweight to the power of 2/3 does not exceed a limit of 0.45. The number of rotors minus 1 times the diameter divided by the length of the ship does not exceed a limit of 0.06. The aspect ratio, i.e. the height divided by the diameter is in the range [6,8].

As rotors need available deck space they are not fitted to container vessels. The maximum rotor height is 50 m.

A single kite of a fixed size of 400 m^2 is fitted to each of the sample vessels. Due to deck space constraints, the kite is the only technology fitted to container carriers.

For the sails, the total projected area (i.e. number of sails x height x width) divided by the deadweight to the power of 2/3 does not exceed a limit of 2.25. The number of sails minus 1 times the width divided by the length of the ship does not exceed a limit of 0.3. The aspect ratio, i.e. the height divided by the diameter, is in the range [2.5,3]. As sails need available deck space they are not fitted to container vessels. The maximum sail height is 50 m.

The vertical axis wind turbine has a diameter of 38m and a height of 20 m, with a rated power output of 280 kW. The minimum distance, along the length of the ship, between wind turbines is 100m, and the combined area (height x diameter) divided by the deadweight to the power of 2/3 does not exceed a limit of 2.5.

The matching between the size and number of wind power technology devices is presented in Table 6. The criteria and the matching incorporate information on the dimensions of technologies that suppliers aim to provide.

Table 6 Mapping of number and size of technology devices to sample vessels

Technology/Ship	Parameter	Container, 1,000 TEU	Container, 5,000 TEU	Tanker, 5,400 dwt	Tanker, 90,000 dwt	Bulker, 7,200 dwt	Bulker, 90,000 dwt
Rotor	Number	x	x	2	3	2	3
	Height			22 m	48 m	24 m	48 m
	Diameter			3 m	6 m	3.5 m	6 m
Kite	Number	1	1	1	1	1	1
	Area	400 m^2	400 m^2	400 m^2	400 m^2	400 m^2	400 m^2
Sail	Number	x	x	3	5	3	5
	Height			25 m	50 m	27 m	50 m
	Width			9 m	17 m	10 m	18 m
Turbine	Number	x	x	1	3	1	3
	Height			20 m	20 m	20 m	20 m
	Diameter			38 m	38 m	38 m	38 m

3.2.8 Routes and operational profiles

There are two separate methods by which routes have been chosen for calculating savings from wind power technology. The first is based on an analysis of EU trade data; twelve shipping routes are chosen to best represent, geographically, the main trade flows considered, as presented in Table 7 and in Figure 4.

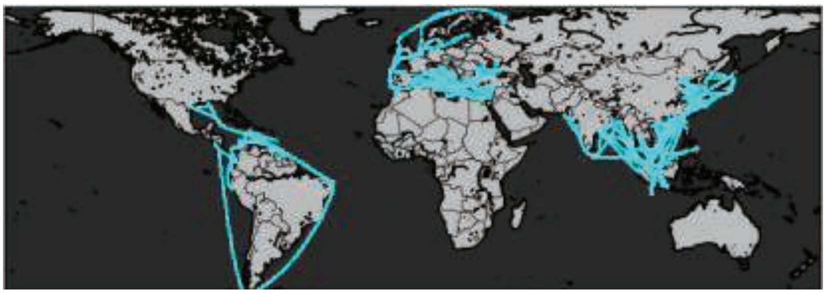
Table 7 Twelve sample trade routes

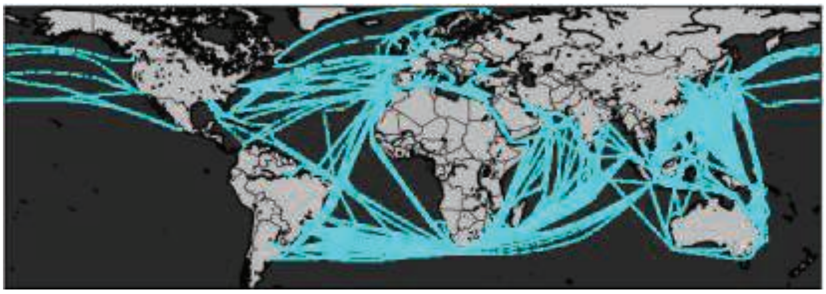
Number	Origin	Destination
1	Al Jubayl	Rotterdam
2	Bergen	Rotterdam
3	Hamburg	Riga
4	Hamburg	Rotterdam
5	Immingham	Rotterdam
6	Lagos	Rotterdam
7	Long Beach	Shanghai
8	Norfolk	Rotterdam
9	Novorossiysk	Taranto
10	Rotterdam	Shanghai
11	Rotterdam	Taranto
12	Rotterdam	Tubarao

Figure 4 Map with the sample routes

The second method uses AIS-data to track ships. For each sample ship type, both terrestrial and satellite AIS messages are collected for a set of vessels of the same type and similar size. The AIS-data cover a full year. For each vessel, AIS messages are time-ordered, subjected to a quality filter discarding faulty messages, and complemented by a pathfinding algorithm where there are gaps in coverage, assuming the shortest routes between two geographical locations. Ships are considered active if ship speed is greater than three knots. Very few vessels were ignored because they were active for less than 90 days in a year. Ship tracks for the sample of small and large bulkers, respectively, are shown in Figure 5.

Figure 5 AIS tracks of sample fleet of small bulkers (above) and large bulkers (below)





Every location report with the ship active is considered part of the operational profile, and weighted by the time difference to the preceding AIS report (so as not to give undue weight to periods with frequent messages/high coverage vis-a-vis periods of infrequent messages/low coverage).

The latter method has some advantages: it accounts for actual ship movements; and this includes not just ship types (which may be inferred from trade data) but also ship size (for example, smaller vessels can be seen to trade more locally), as well as actual sailing dates and routes. Savings are estimated for both the sample trade routes and the AIS-derived operational profiles. Results for the sample routes indicate geographical differences in wind conditions and which trade routes may promise higher savings.
The AIS-derived operational profiles give a realistic picture of actual trading profiles of ships in the type and size category under consideration. As ships typically do not just ply a single route, the variation in average savings across vessels can be expected to be smaller than the variation across different routes. In addition, the operational profiles indicate the number of days spent at sea, allowing to estimate annual savings from average savings on voyage.

3.2.9 Wind data

Wind data are read from ERA-Interim, 6-hourly, dataset, on a 0.125°x 0.125° grid, at 10 m height. Since wind speed varies with height above sea level, an adjustment is made, following the assumption that the wind speed profile follow the power law:

$$v / v_{10\,m} = (h / 10\,m)^{P}$$

with an exponent P = 0.11. The effective wind speed applied in the rotor and the rigid sail model is calculated as the average of the adjusted wind speed over the height of the installation, from a base height of 10 m. The effective wind speed for the kite model is calculated according to the above power law, at the height of the centre of the kite’s circular flight pattern.

3.2.10 On the presentation of results on the ship level

In order to gauge the performance of and, in turn, the savings from the technologies under consideration, Section 3.2.10 presents the propulsive power provided by each of the technologies. More precisely, propulsive power yielded by a generic model representing the respective technology is shown as a function of the true wind angle, for a given ship speed and a range of true wind speeds. These polar plots show varying shapes, revealing some of the characteristics of the technology.

Section 3.2.11 then moves on to present simulated savings for each of the six sample ships, and for each of the technologies deemed applicable to the respective ship.

Savings are calculated for each of the set of twelve trade routes and for a set of voyage profiles, recorded over the course of one year, from vessels representing the sample ship type and size category.

Rotor

Figure 6 shows propulsion power savings due to a single rotor of 30 m in height and 5 m in diameter. The ship speed is 14 kts., wind speeds are 4, 8, 12 and 16 m/s. Sailing straight into a headwind (labelled 0° in the polar plots), no savings can be achieved. Similarly, the only savings from a tail (180°; opposite to 0°) are comparatively small (due to the drag on the rotor). Ideally, the rotor experiences a beam wind (90°; 270°) to effectively exploit its high lift factor. Stronger wind corresponds to higher savings. In the given range, the rotor's contribution to propulsive power is highest for a wind speed of 16 m/s. The kink in the curve is due to the throttling of the rotor as the apparent wind speed exceeds 18 m/s.

Figure 6 **Thrust force from a rotor of 30 m in height, and 5 m in diameter, for ship speed of 14 knots, for various values of true wind speed, as a function of true wind angle**

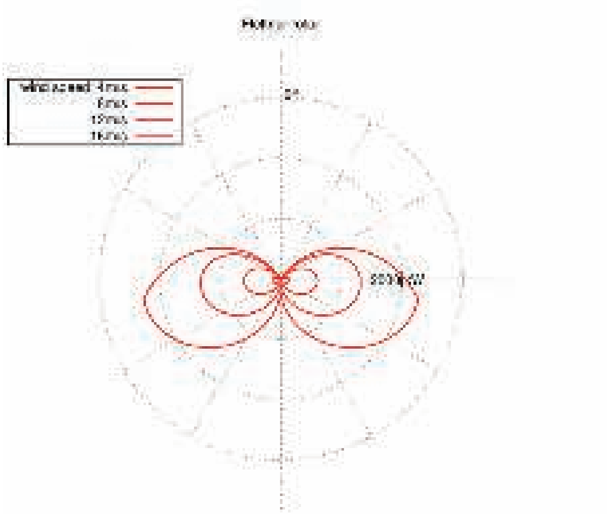
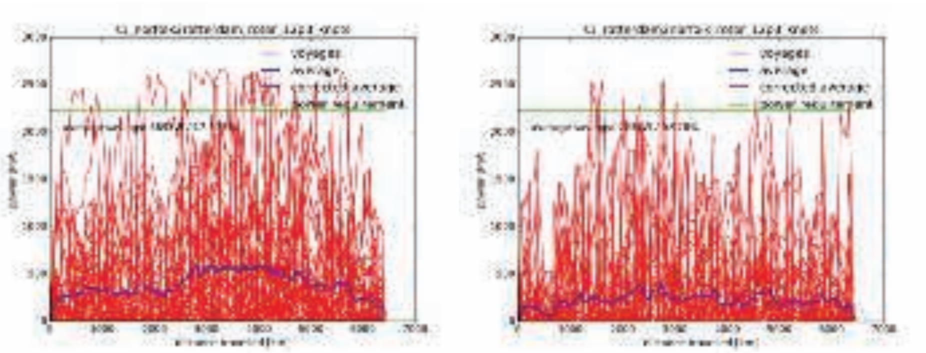


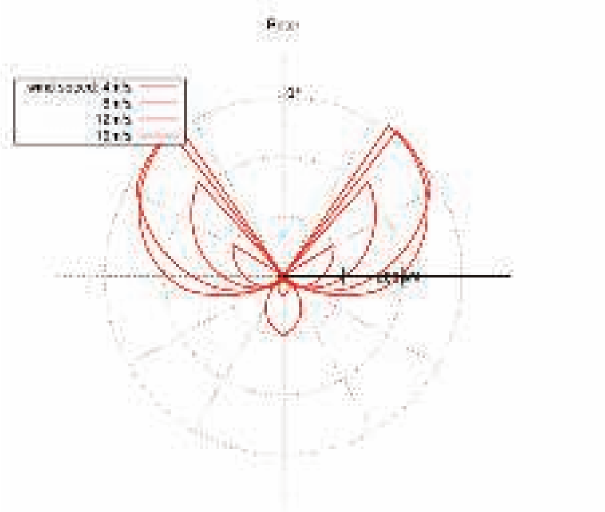
Figure 7 shows the same model, with adjustments made for the size and number of rotors on the 90,000 dwt bulker, travelling at 12.3 knots on the route Norfolk to Rotterdam, for weekly sailing dates throughout the year 2014.

Figure 7 **Rotor on 7,200 bulker on route Norfolk to Rotterdam, at 12.3 knots, weekly sailing dates 2014**



Since a constant voyage speed is assumed, savings cannot exceed power requirements. This accounts for the difference between the average and the corrected average - the latter discarding excess propulsive power - in the figure. Analogous results have been produced for all routes, ship types, technologies, and the base case and slow steaming voyage speeds.
Figure 8 shows the sideways force, i.e. the aerodynamic force from the wind propulsion technology installation that is vertical to the ship's direction of travel, on a rotor. For a headwind, the rotor does not deliver any savings and is retracted, hence there is no side force on the rotor. At some point, as the true wind angle moves towards a beam wind, the rotor is activated.
The apparent wind speed is highest at this angle, and so is the sideways force acting on the rotor. As the true wind angle moves beyond a beam wind, the side force decreases, all the way to zero at the apparent wind angle for which the sideways components of the lift and drag force cancel each other out. Beyond this angle, the side force increases again to reach a local maximum for a tail wind (as long as the true wind speed is greater than the ship speed).

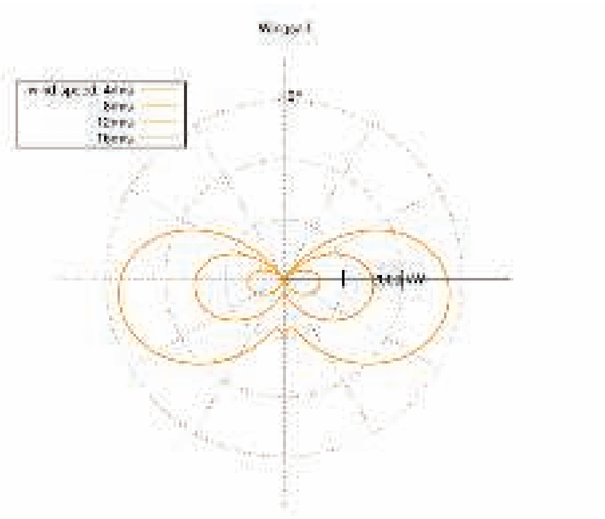
Figure 8 Side force from a rotor of 30 m in height, and 5 m in diameter, on a ship travelling at 14 knots, for various value of true wind speed, as a function of true wind angle



Wingsail

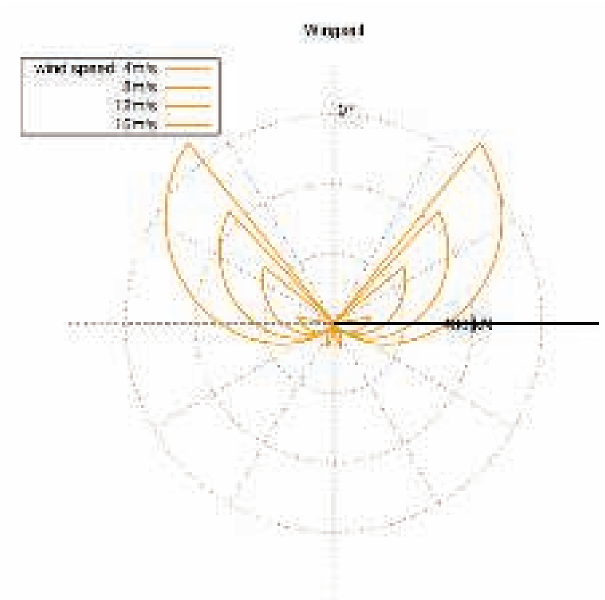
Figure 9 shows the propulsive power contribution of a wingsail of 50 m in height and a chord length of 20 m. The ship speed is 14 kts. Wind speeds are 4, 8, 12 and 16 m/s. The angular functions look similar to those for the rotor. The main differences arise from the different lift-to-drag ratio and because no power is required to operate the wingsail. As the sail model transitions between lift mode, and drag mode for a tail wind, there is a kink in the curve.

Figure 9 Thrust force from a wingsail of 50 m in height, and 20 m in diameter, for ship speed of 14 knots, for various values of true wind speed



Qualitatively the side force acting on the wind sail, shown in Figure 10, is similar to the side force acting on a Flettner rotor (cf. Figure 8). The shape of the curves differs for tail winds, as the sail transitions into a pure drag mode, so that there is no side force in this case.

Figure 10 Side force from a wingsail of 50 m in height, and 20 m in diameter, on a ship travelling at 14 knots, for various true wind speeds



Towing kite

The polar curves of the towing kite differ qualitatively from those of the rotor and the wingsail. Strong tailwinds present ideal operating conditions for a towing kite.

Figure 11 Thrust force from a kite of 50 m^2 in area, for ship speed of 14 knots, for various values of true wind speed

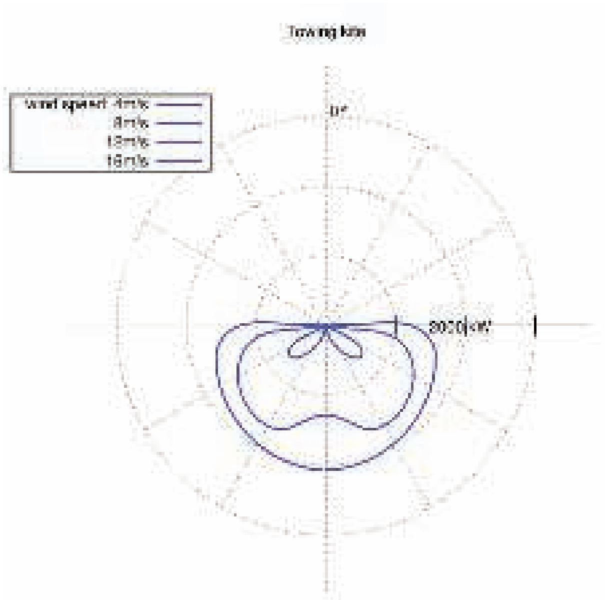


Figure 12 Kite on 7,200 bulker on route Norfolk to Rotterdam, at 12.3 knots, weekly sailing dates 2014

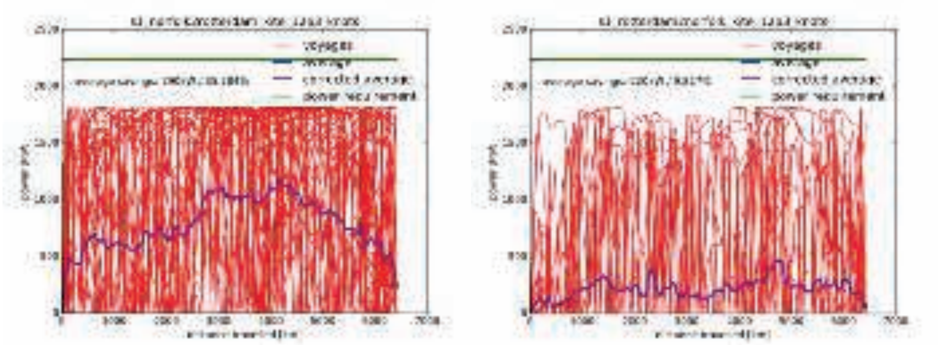
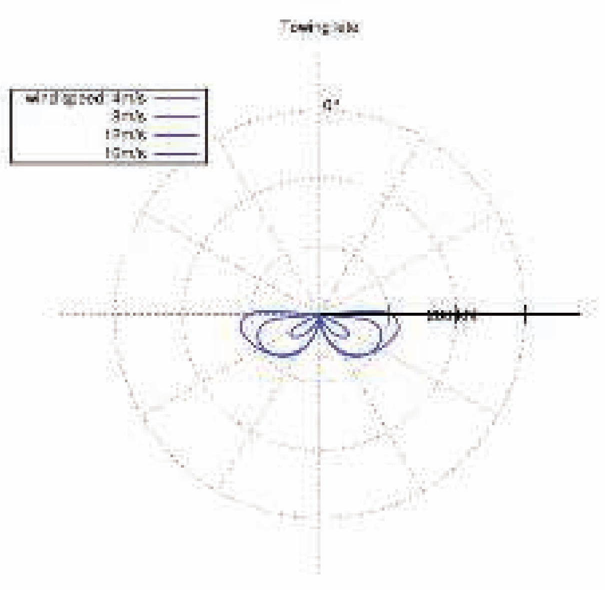


Figure 12 shows propulsive power savings from a kite on the small bulker, on the transatlantic route between Norfolk and Rotterdam. A strong prevalence of westerlies means favourable conditions going East, compared to much smaller savings on the return journey. Because of the polar characteristics, the difference between outgoing and returning journey is much smaller for the rotor (cf. Figure 7) and the wingsails.

The average side force exerted by the kite is, by comparison, much smaller than that exerted by the rotor or the wingsail, as evidenced by Figure 13.

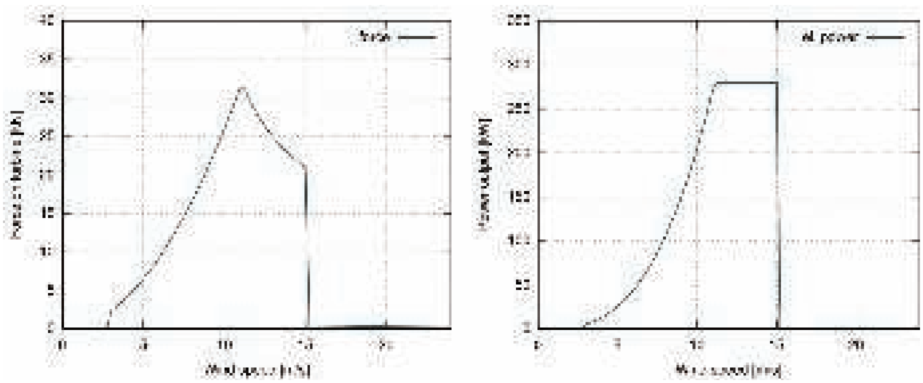
Figure 13 Side force from a towing kite of 400 m^2 in area, on a ship travelling at 14 knots, for various true wind speeds



Wind turbine

The performance of the wind turbine, considered in isolation, depends on the apparent wind speed only. Figure 14 shows the force on the turbine, and the electrical power generated by the turbine, as a function of wind speed.
No power is generated below the cut-in speed. Above the cut-in speed, the generated power increases with wind speed until the rated power maximum is reached. From this point, power output is constant until the turbine is switched off at the cut-out speed.

Figure 14 Force on and power generated by the wind turbine, as a function of apparent wind speed



The more complicated shapes of the turbine's polar curves, as shown in Figure 15, follow from the dependency between ship speed and apparent wind speed and angle. Note the difference in magnitude when comparing Figure 15 and Figure 16 with the corresponding plots for the other technologies.

Figure 15 Thrust force from a vertical axis turbine of 20 m in height in 38 m in diameter, for ship speed of 14 knots, for various values of true wind speed

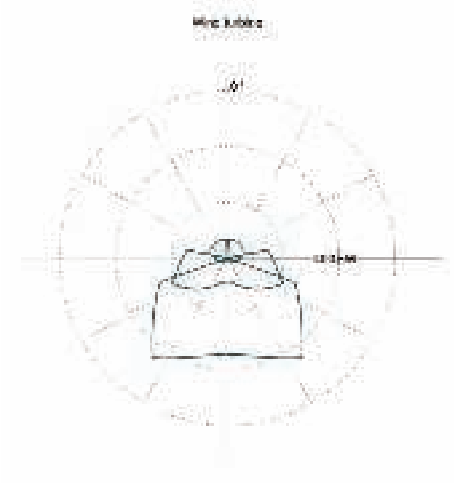
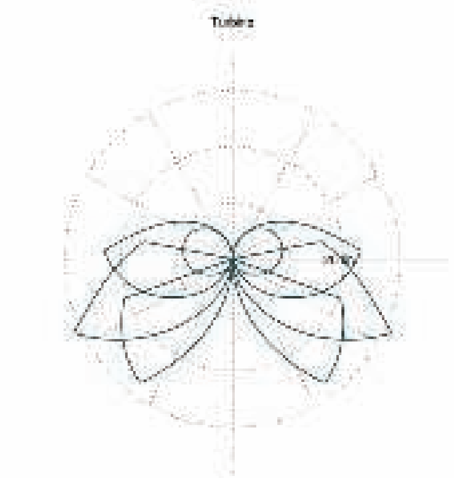


Figure 16 Side force from a vertical axis turbine of 20 m in height in 38 m in diameter, for ship speed of 14 knots, for various values of true wind speed



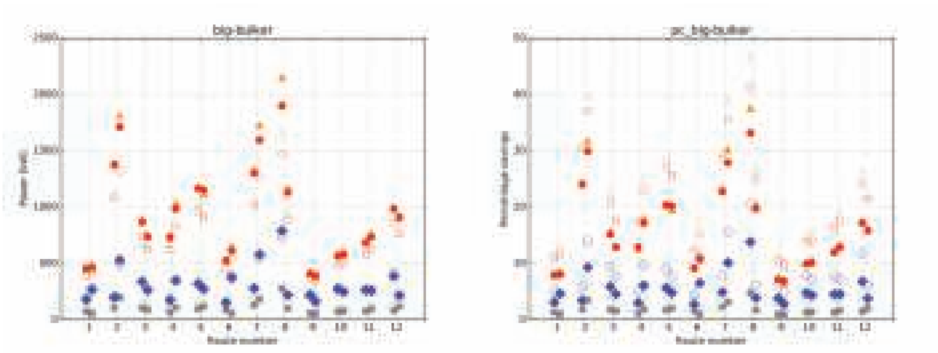
3.2.11 Savings by ship type

This section shows results from the simulation of each of the technologies matched to each of the applicable sample ships (cf. Section 3.2.6). The results are presented by sample ship, and there are two sets of main results for each of the ship types. The first set gives average savings along each of the twelve selected trade routes (Section 3.2.8). The second set shows results based on the voyage tracks of a number of vessels representing the sample ship's type and size category, as reconstructed from their AIS records (cf. Section 3.2.8). In each case, two ship speeds are assumed. The AIS tracks provide only the location and the point in time (over the course of a year) but a ship speed as detailed in Table 5 is assumed.

Large bulk carrier

Figure 17 shows the propulsive power savings by each of the four technologies, for the large bulk carrier, on each of the twelve sample trade routes, with absolute savings shown on the left, and percentage savings on the right. Empty symbols correspond to the slow steaming speed, at 85% of the standard voyage speed assumed in this report (cf. Section 3.2.6).

Figure 17 **Large bulk carrier savings - sample routes**



In the case of the wingsail and the rotor, absolute savings are larger at the higher voyage speed, mainly since, for a given forward thrust, power goes with the speed. However, since the power requirements increase faster with the speed than do absolute power savings, percentage savings are higher for the lower voyage speed. Because the kite and the turbine operate best under a tailwind, and a tailwind is both more likely and, other things equal, stronger for a slower voyage speed, absolute savings tend to be equal or even lower at full voyage speed; and the difference in terms of percentage savings is even more marked.
Qualitatively, the performance characteristics of the sail and the rotor are very similar. That is, auspicious routes for employing a rotor are also auspicious routes for employing a wingsail. This extends to the towing kite and the turbine, but the correlation is not quite as clear.

Figure 18 **Large bulk carrier savings - AIS**

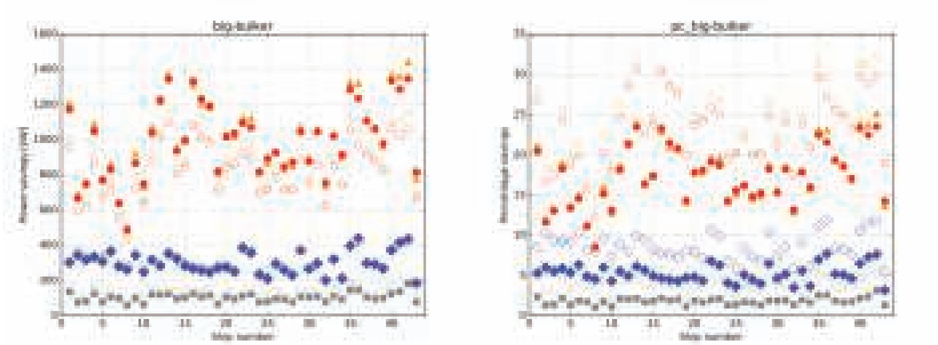
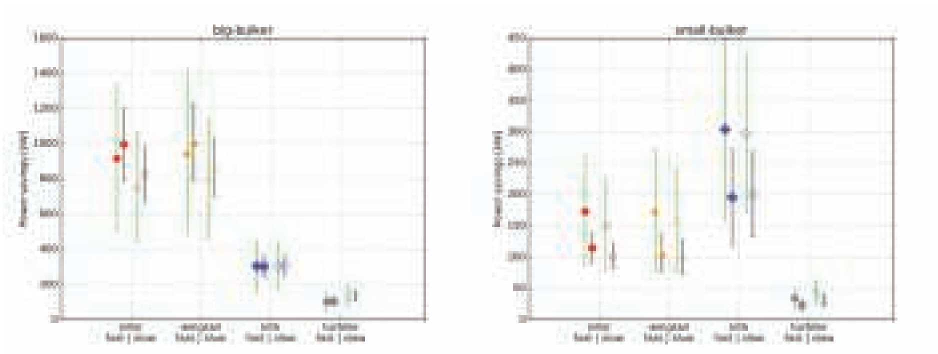


Figure 18 shows savings for the same sample ship, equipped with the same technologies, along the AIS-recorded voyage profiles of vessels of the same type and size category. Results are qualitatively similar to the sample route case. Percentage savings are 17.4% for the rotor (23.2% in the slow speed case); 17.6% for the wingsail (24.3% in the slow speed case); 5.3% for the kite (8.6% in the slow speed case); and 1.8% for the turbine (3.8% in the slow speed case). Figure 19 shows average savings across the sample routes, alongside average savings across voyage tracks from different ships. As expected, the standard deviation across sample routes is larger than across the representative ship tracks – as ships are expected to ply many routes and therefore be subjected to more average wind conditions than exist on a single route.

Figure 19 Bulker average savings, with standard deviation



Small bulk carrier

Figure 20 presents savings from wind power technologies applied on a small bulk carrier, on the set of sample trade routes. The same routes are most favourable as in the case of the big bulker. The biggest difference lies in the respective size and number of the technology devices (cf. Section 3.2.7). Since only a single kite is fitted to a vessel, with a maximum size of 400 m^2 for both the small and the large bulk carrier, similar power savings are expected, in absolute terms. In percentage terms, savings from the kite are therefore much larger on the small bulk carrier. They are also larger in comparison to the savings from the rotor and the wingsail, due to the different scaling assumptions for the latter two technologies.

Results from simulating the four technologies for AIS-recorded voyage profiles are shown in Figure 21. In comparison, model-calculated savings for the real-world voyage tracks turn out slightly lower than on the sample routes, perhaps because more small bulk carriers' trade on coastal routes, and fewer on open sea routes. Percentage savings are 5.1% for the rotor (7.3% in the slow speed case); 4.7% for the wingsail (7.2% in the slow speed case); 8.7% for the kite (14.4% in the slow speed case); and 1.0% for the turbine (2.2% in the slow speed case). As in the case of the larger bulk carrier, the standard deviation of average savings is smaller for the AIS-tracked voyage profiles than the average across sample routes (see Figure 20).

Figure 20 Small bulk carrier savings – sample routes

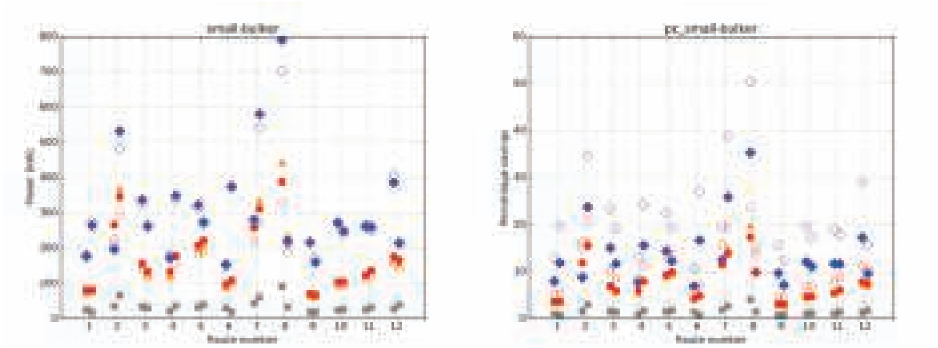
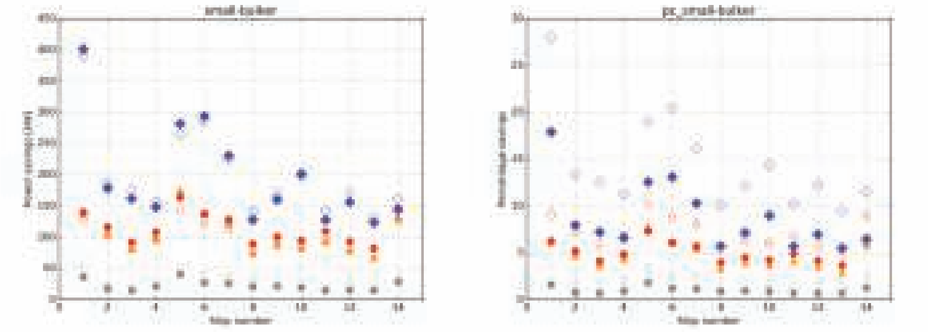


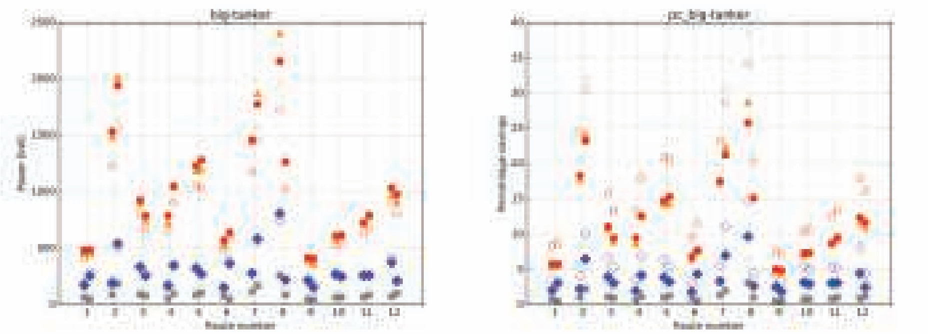
Figure 21 Small bulker savings - AIS



Large tanker

Figure 22 shows wind power savings on the twelve sample routes, for the large tanker. Qualitatively, the results are very similar to those for the large bulker carrier. The results of the Flettner rotor model and the wingsail model are similar. Due to their scaling with the size of the vessel, savings are much larger than those from the kite, and those from the turbine, which are smaller still.

Figure 22 Large tanker savings - sample routes



The results for the AIS-recorded voyage tracks, shown in Figure 23 confirms those results. Savings assessed along the AIS tracks are slightly lower on average than the average across the sample trade routes. Percentage savings are 9.3% for the rotor (13.1% in the slow speed case); 8.9% for the wingsail (13.2% in the slow speed case); 3.0% for the kite (5.1% in the slow speed case); and 0.9% for the turbine (2.0% in the slow speed case). As expected, the standard deviation of savings from different vessels' voyage profiles is smaller than the standard deviation across the different sample routes (see Figure 24).

Figure 23 Large tanker savings - AIS

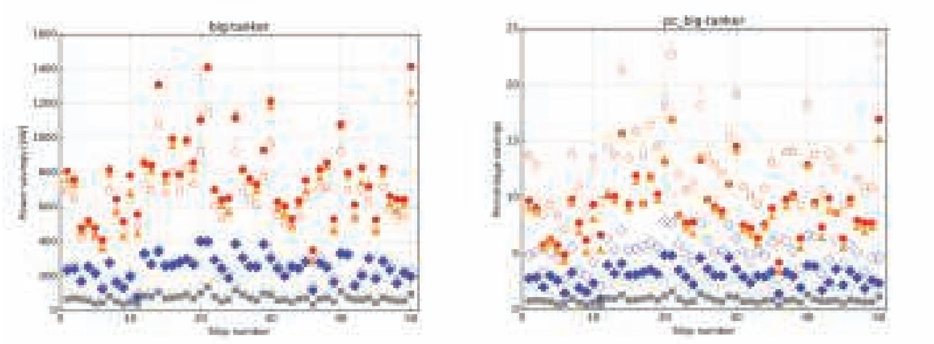
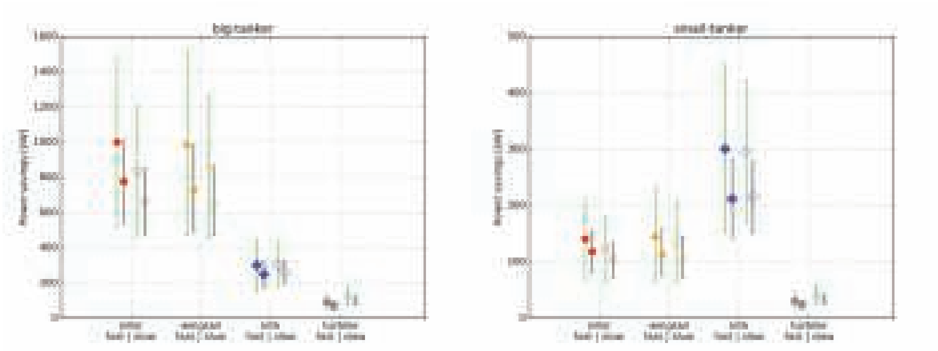


Figure 24 Tanker average savings, with standard deviation



Small tanker

Figure 25 shows average savings from applying the four different wind power technology on the small tanker, along the twelve sample trade routes. As in the case of the bulk carrier, the kite achieves relatively higher savings on the smaller vessel, because it does not scale with the size of the ship like the rotor and the wingsail do.

Figure 26 shows average savings for the set of voyage tracks of representative vessels, recorded from AIS. Percentage savings are 5.0% for the rotor (7.2% in the slow speed case); 5.0% for the wingsail (7.6% in the slow speed case); 9.0% for the kite (15.1% in the slow speed case); and 1.0% for the turbine (2.3% in the slow speed case).

These savings are smaller than average savings across the sample trade routes - but average savings across sample routes and voyage profiles agree to within a range of one standard deviation (see Figure 24).

Figure 25 Small tanker savings - sample routes

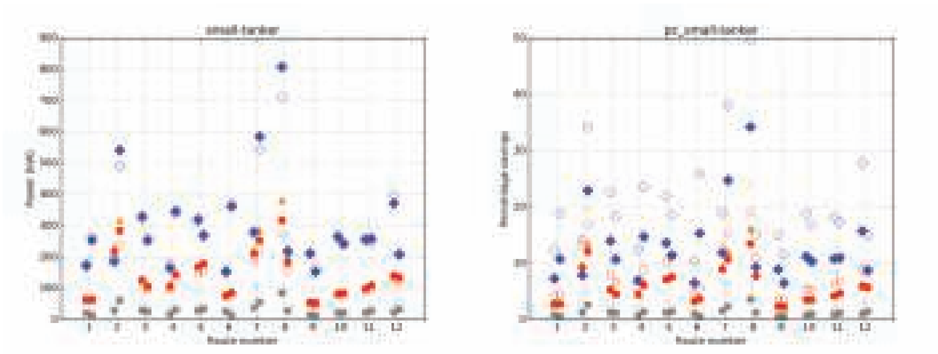
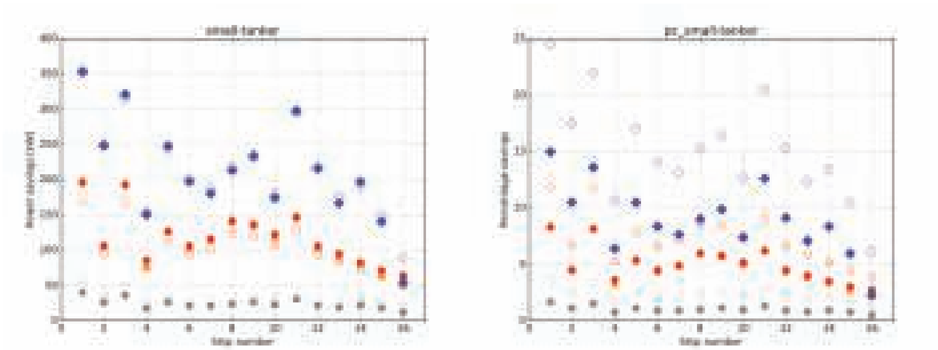


Figure 26 Small tanker savings - AIS



Large container carrier

Potential savings from wind power technology are smallest for container carriers. Due to constrained deck space availability, towing kites are the only wind power technology applicable to container carriers, within the time horizon of this study. Container carriers typically travel at higher speeds than bulk carriers or tankers. However, towing kites are best-suited for lower ship speeds. As a consequence, absolute power savings for the big container carrier are larger for the smaller voyage speed on all of the sample trade routes, as shown in Figure 27, and for each of the representative AIS-recorded voyage profiles, as shown in Figure 28. In comparison with the other vessel types, and in comparison with results for the smaller container carrier, percentage savings are smallest on the large container carrier. However, beside the points raised above, the principal reason is the larger propulsive power requirement of the large container vessel - i.e. percentage savings shown on the right hand side of Figure 27 and Figure 28 represent a smaller slice of a bigger pie. Average savings across the AIS-recorded voyage profiles are 1.0% (and 1.9% for the slower voyage speed), slightly lower than the average across the sample trade routes. As for all other ship types, the variation is smaller across AIS-recorded voyage tracks than across the different sample trade routes (see Figure 29).

Figure 27 Large container carrier savings – sample routes

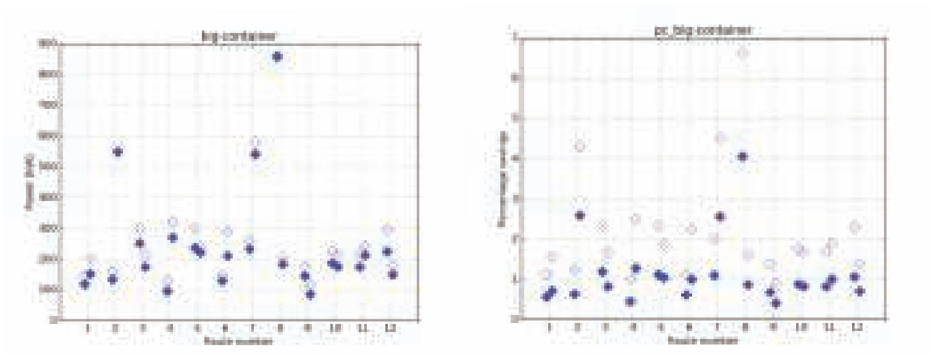


Figure 28 Large container carrier savings - AIS

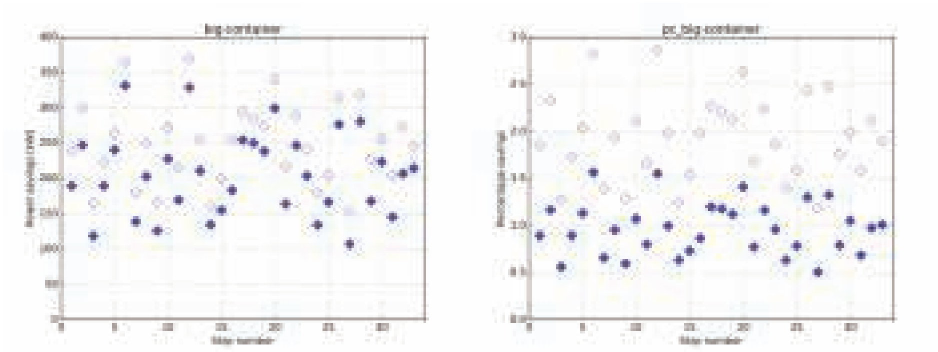
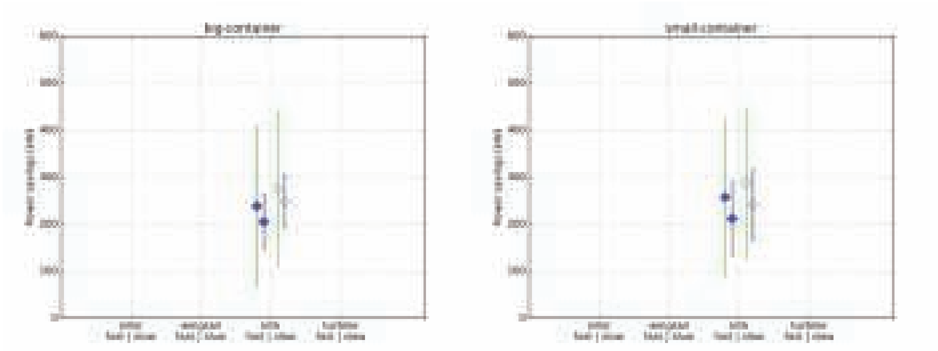


Figure 29 Container carrier average savings, with standard deviation



Small container carrier

The results for the small container carrier are very similar to those on the large container carrier. Due to its slightly lower voyage speed, average savings along the sample routes, shown in Figure 30, are slightly higher - while percentage savings are significantly larger, due to the smaller power requirements. The same holds for results on the AIS-recorded voyage tracks, shown in Figure 31, with average percentage savings of 2.1% under the assumption of a voyage speed of 17.5 knots, and of 3.9% under the slower voyage speed of 14.9 knots.

Figure 30 Small container carrier savings - sample routes

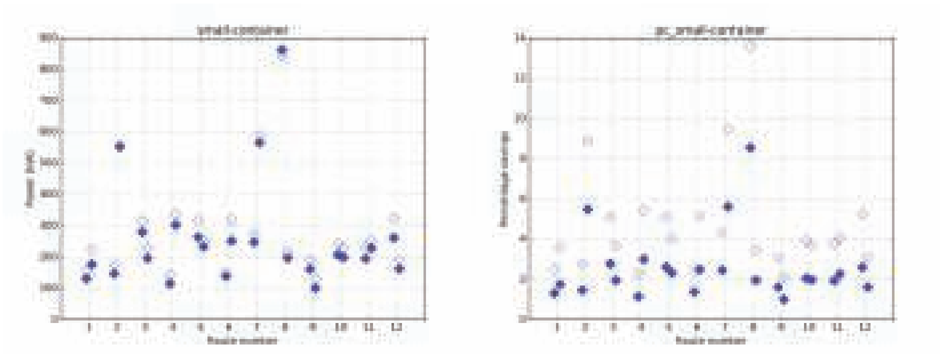
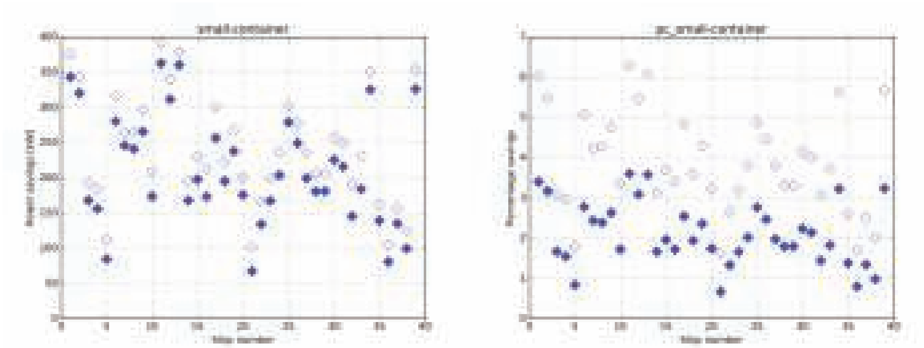


Figure 31 Small container carrier savings - AIS



3.2.12 Overview and discussion of main results

The following two tables give an overview of the relative average power savings across the AIS-recorded voyage profiles of the different wind propulsion technologies and sample ships considered. In Table 8 the relative savings for the higher speed and in Table 9 for the lower speed is given.

Table 8 Relative average savings across the AIS-recorded voyage profiles - higher speed

	Rotor	Wingsail	Towing kite	Wind turbine
Large bulk carrier (90,000 dwt)	17%	18%	5%	2%
Small bulk carrier (7,200 dwt)	5%	5%	9%	1%
Large tanker (90,000 dwt)	9%	9%	3%	1%
Small tanker (5,400 dwt)	5%	5%	9%	1%
Large container vessel (5,000 TEU)			1%	
Small container vessel (1,000 TEU)			2%	

Table 9 Relative average savings across the AIS-recorded voyage profiles - lower speed

	Rotor	Wingsail	Towing kite	Wind turbine
Large bulk carrier (90,000 dwt)	23%	24%	9%	4%
Small bulk carrier (7,200 dwt)	7%	7%	14%	2%
Large tanker (90,000 dwt)	13%	13%	4%	2%
Small tanker (5,400 dwt)	7%	8%	15%	2%
Large container vessel (5,000 TEU)			2%	
Small container vessel (1,000 TEU)			4%	

Relative savings are comparable for Flettner rotor and wingsails; for towing kites relative savings are, by comparison, higher for smaller vessels but lower for larger vessels; relative savings are lowest for wind turbines.

Both the Flettner rotor and the wingsail show very similar characteristics. They can be scaled with ship size, so that they have the potential to yield significant savings for all vessels with enough available deck space to accommodate them. In fact, the results indicate that relative savings for the larger bulker exceed those for the smaller bulker. In part this is due to the fact that large bulkers make more open ocean voyages, on routes where they experience higher wind speeds, than smaller bulkers, as indicated by Figure 5. The other reason is due to the size and number of wind propulsion technology devices, with an additional effect from the higher wind speeds experienced by the taller devices (on the larger ship). In practice, for a given vessel corresponding to the specs of the small bulker to be fitted with sail or rotor technology, it may turn out that a choice of somewhat larger devices than assumed here is optimal. However, it is noteworthy that some wind propulsion technologies can be scaled with vessel size and may, in relative terms yield similar or even larger savings.

Because a single kite, of the same size, is matched with each of the vessels, its power contribution, in absolute terms, does not vary much between the various sample vessels. That stands in contrast with the rotor and the wingsail which are scaled with the size of the vessel and of which more than one may be installed on a vessel, if deck space allows. On containers, the towing kite is the only option considered. This is due to one of the towing kite's big advantages – it requires very little deck space. The operational concept of the kite is by far the most complex of the four technologies considered. Consequently, the underlying assumption of performance according to model design is stressed here.

For all of the sample vessels, the turbine yields the smallest savings, by comparison. Out of the four technologies, the turbine is the concept least represented by suppliers. Two points are to be noted: results depend strongly on the cut-in speed, and, more importantly, the rating and the cut-out speed. Mounted a turbine on a moving ship means that the apparent wind can be significantly stronger than the true wind speed; also, because a vessel moves around, wind conditions can be expected to be more variable than in a fixed location. A wider window of wind speeds could increase a wind turbine's contribution. In addition, a major advantage - neglected in this report - is the wind turbine's ability, setting it apart from the other technologies, to produce electricity even when the ship does not move.

For all technologies it holds that relative savings are higher for the lower speed which can be expected due to the much lower power demand at the lower speed.

For the absolute savings this, however, does not hold. Whereas for towing kites and the wind turbine absolute savings tend to be equal or even lower at the higher speed, in the case of the wingsail and the rotor absolute savings are, for all applicable ship types considered, larger at the higher voyage speed. This is a very important dynamic between the aims of profit maximisation and overall minimisation of CO_2 intensity.

Note that while the methodology used is comprehensive in scope (to the best of the authors' knowledge, no similarly comprehensive effort has compared such a wind array of technologies in a single setup) there are some aspects and effects that are not considered. In most cases, these depend on the specific design of the technology; of the vessel; or on the operation of a vessel equipped with the technology.

Among the most important factors in determining the accuracy of the presented results are the following: whether the technology performs as intended at all, e.g. whether a towing kite can be launched, kept on its design flight pattern, and be retracted according to wind conditions, as assumed by the model; the sizing of the technology (in relation to the vessel); and how the vessel is operated - in terms of speed and routing.

If the purpose is to select between two technologies on offer, it is important to keep in mind that the results presented are still technology-agnostic. The numbers will look different if the (relative) sizes of the devices are changed. However, the presented methodology gives a clear, transparent, and comprehensive framework against which any specific technology can be compared.

In the following, the purpose is not to select between competing technologies. Rather, the purpose is to give insight into the potential of wind power technology on the fleet level. With the focus on this aim, the methodology laid out above, and the wind power technologies in particular, are defined in line with both the literature and information received from suppliers.

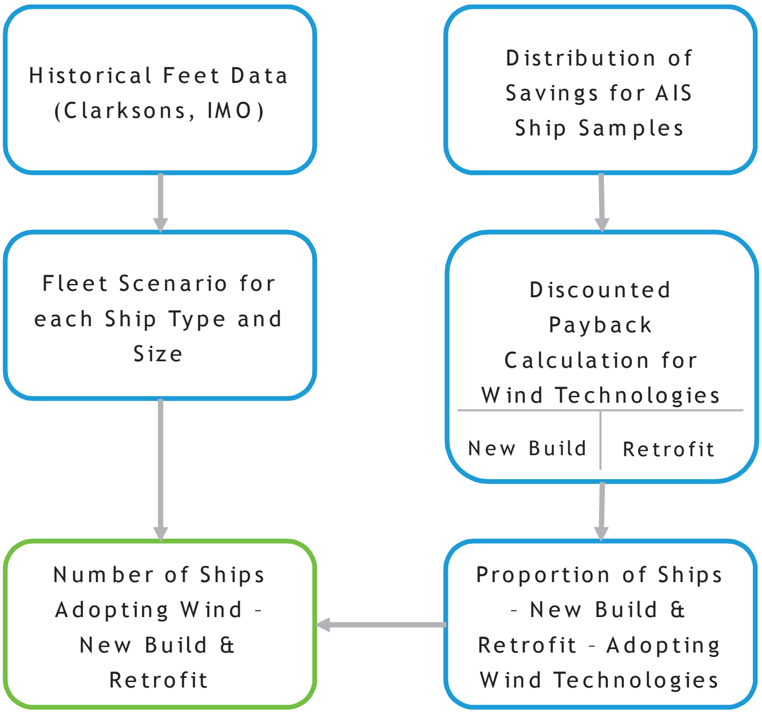
For each sample vessel type, annual power savings for the AIS-tracked representatives are passed on to the next stage of economic modelling, with the distribution giving an indication of the variability in savings and, therefore, an indication of potential early vs. late adopters with in a ship type and size category.

3.3 Fuel, emissions savings, and market potential on fleet level

The fuel reductions on a ship level reported in Section 3.2 above have been used as input into a model for the estimation of the diffusion of wind technologies into the shipping fleet. A dynamic model, including learning effects, has been developed to model the adoption of wind technologies over time, the resulting fuel savings and the resulting CO_2 emission savings.

The structure of the model is shown in Figure 32.

Figure 32 **Wind technology diffusion model structure**



The model has two main components: a payback calculation which determines the decision to adopt wind technologies or not and a scenario of the overall fleet size for the different types and sizes of ships considered.

Fleet scenarios

The assessment has been undertaken for the ship types described above: large and small tankers, large and small bulk carriers, and large and small container ships. The parameters of these ships and the assumptions made to calculate the reduction in power due to the fitting of the wind technologies are reported above (Section 3.2.6-Section 3.2.10).

The fleet scenarios have been developed using two sources: Clarksons data in ship orders (TNA, 2016) and IMO (2014). The Clarksons data gives orders for ships for the period 2007 to 2017. IMO (2014) has historical data on fleets from 2007 to 2012 and then makes projections for the fleets from 2015 to 2050. The most important part of the diffusion calculation is the period to 2030. The historical newbuildings deliveries and orders data have been combined with approximate average fleet age from UNCTAD (2015) to infer scrapping rates. These scrapping rates are then combined with the IMO (2014) fleet projections to project new orders and fleet sizes forward to 2030 and to 2050.

Modelling decisions to adopt wind technology

The diffusion of the technology is determined by a discounted payback period calculation. This calculation uses the data on the costs of installation i.e. CAPEX, operation and maintenance of the different wind technologies reported in the questionnaires to the wind technology providers.
The costs were scaled to the size of the technologies assumed to be fitted in the calculations for power savings described above.

As reported above, AIS ship track data was analysed for samples of each of the ship types considered to provide average% power savings over a year's operation. For each of the example ships in the AIS-data, a payback period calculation was made for both the higher and lower speeds and their different distributions of savings over the sample ships (bulk carriers, tankers and container vessels of two different sizes respectively). The fleet adoption was calculated for all ship sizes from the lower size to the higher size.
This therefore covered small and medium sized ships, apart from the smallest category of oil tankers (0-5,000 dwt).

This made the following assumptions:
- required payback time to decide to install the WPTs: 5 years;
- discount rate for future cash flow: 5% p.a.;
- HFO price: $ 450 per tonne in 2020, increasing to $ 550 per tonne in 2030.

The assumed discount rate is high for a social discount rate, but it should be noted that it is low for a company discount rate, where 8.5%, as used in the sensitivity analysis (based on discussions with industry), is a low value for a large company considering a large strategic investment. Internal rates of return of 20% are common.

The bunker price assumes a recovery of bunkers between current bunker prices of around $ 200-220 per tonne in 2016 by 2020 and a further slow increase, reflecting possible restrictions in future HFO supply and the current assessment that that oil prices in 2016 are at a historical low (EIA, 2016).

The current very low oil price will probably increase and if the global sulphur cap is enforced, low sulphur fuel or sulphur removal apparatus will be required. These will either increase the bunker price or generate extra costs for investment in the cleaning equipment. Therefore, a significant increase over current bunker prices by 2020 is possible.

A sensitivity analysis was performed to assess the possible range of outcomes. This assumed a lower bunker price, starting at $ 300 per tonne in 2020 and a higher discount rate of 8.5% in accordance with reported industry values.

The savings from using wind, used the power savings estimations for each sample ship, with the observed numbers of days at sea per year from the AIS-data. IMO 2014 reports average fuel use for each ship type and size, together with the average operating speed and the average days at sea. As (IMO, 2014) shows, AIS-data may show significant variations from ship reports. The analysis reported in Section 3.2 above uses more recent AIS-data, which generates different estimates of days at sea and average operating speed. Therefore, the average annual fuel use from (IMO, 2014) was scaled to the estimated average days at sea and average operating speed for the current sample. The average annual fuel use and power savings were then applied to the current sample, to provide an estimate of the fuel use for each ship. The percent saving calculated in the current analysis for each ship in the sample was applied to the relevant estimate of annual fuel use to calculate an estimate of fuel savings for each individual ship.

The payback calculation was started from 2020, assuming that the wind technologies would be developed enough by 2020 to be fitted and deployed over a full year of operation. The payback calculation identified the most cost effective technology from the questionnaire data obtained. It should be noted here that the questionnaire data did not generate costs for Flettner rotors. Therefore, the most cost effective WPT was assessed. For bulk carriers and tankers, this was found to be the wingsail. For container carriers, the limitations on deck space mean that the only practicable WPT is the kite and therefore the calculations for the large and small container ships used the kite data. Each ship, representing a different AIS track, was calculated separately. Different costs for installation in newbuildings and retrofits were based on the questionnaire data. This produced a distribution of payback times for each ship type and size of payback times. The AIS-data also plot the different annual voyage pattern for each individual ship, such that the distributions vary due to both different ship characteristics and the different routes for the ships in the sample. The proportion of the sample that met the payback criteria was calculated. This proportion was then applied to the fleet numbers for each ship type and size to estimate the number of newbuildings and retrofits adopting wind technology. This calculation was made dynamic through the incorporation of learning effects. The literature on learning in energy technologies assumes a learning rate of 20% production cost reduction for each doubling of installed capacity. Because the installations in this case take place over a range of ship types and sizes, the learning effect is assumed to be less and a learning rate of 10% per capacity doubling was assumed. An initial level of five demonstration installations running in operational ships by 2020 was assumed to initiate the simulation.

This diffusion calculation is more realistic than global projections of technology uptake. It incorporates two important new sources of data: the calculation from physical and principles of the performance of the wind technologies and actual estimates of costs from the industry.
Furthermore, because the AIS-data shows individual ships and their individual routes, a realistic distribution of the potential savings for a fleet, allowing for the variation in routes can be estimated. This is a critical advance in the literature, because the ships operating over the most favourable combination of routes can be found. If the decision is made solely on a business case basis, this will lead to a typical innovation diffusion curve in which these ships will be the first to adopt wind technologies. However, once a few ships do adopt the technology, the installation cost will come down as experience with the technology is developed. This will then lead to more ships adopting the technology. The critical insight is that, for the technology to be adopted, it is only necessary for the most favourable ships to meet the decision criterion for the adoption process to start.

Results
Results for the different ship types for technology uptake are shown below. The power savings estimates and hence fuel savings estimates for the sample ships are assumed to apply to the fleet of ships in the (IMO, 2014) data which covers the sample ship size for each type of ship i.e. for the large and small sizes of each ship type.

The results are limited because detailed AIS-data and estimates of power savings have been made for two sizes of ship for each ship type. Around 8% of the tanker fleet, 26% of the bulk carrier fleet and 62% of the container fleet in 2012 IMO (2014) are covered directly by the fuel savings estimations. However, interpolating between the large and small sizes of ship enables 37% of oil tankers (which does not include the large numbers of tankers below 5,000 dwt) and 87% of bulkers to be included.

The calculations do not consider all the barriers considered in the next section.

However, the model does impose a limitation on the acceleration of installations, to reflect the time take to spread the engineering expertise in designing WPTs and the time for shipyards to learn how to install the new technology.

The tables and figures shown in this section are for the baseline run at the higher speed. The results for the other three scenarios, with 85% of this high operating speed and with the lower bunker price and higher discount rate are shown in Annex E.

Thus the results represent a theoretical maximum speed of uptake of technologies, given the data and assumptions reported.

While the full range of technologies for which data are available were examined for tankers and bulkers, container ships were only assessed for kites, because of their restricted availability of deck space to fit other WPTs. As the savings estimates for kites were relatively small, there was no uptake of wind technologies on container ships under all the scenarios examined.

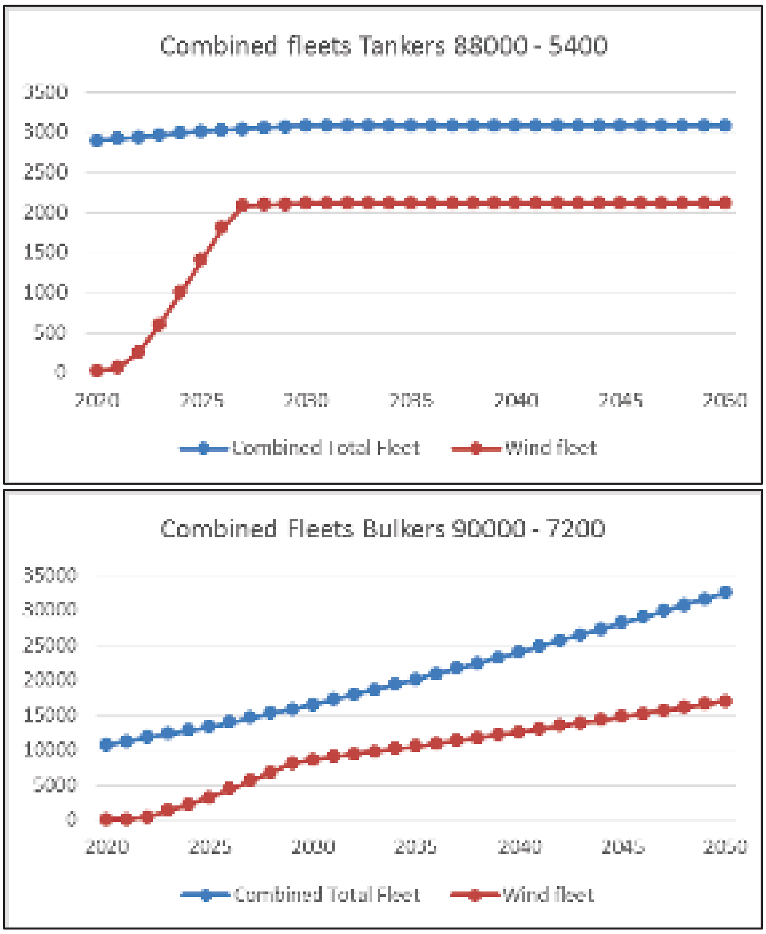
Table 10 Numbers of ships fitted with sail, new build and retrofit; summary to 2030

Ship type	Build Type	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Tanker (5,000-120,000 dwt)	Fleet	2,892	2,915	2,938	2,961	2,984	3,008	3,022	3,036	3,050	3,064	3,078
	New build with sail	0	20	64	149	199	206	201	205	206	207	208
	Retrofit with sail	15	22	126	197	199	201	201	202	203	204	205
Bulker (0-100,000 dwt)	Fleet	10,718	11,231	11,743	12,256	12,768	13,281	13,914	14,547	15,180	15,813	16,446
	New build with sail	0	30	172	497	459	608	712	723	723	734	662
	Retrofit with sail	0	22	126	409	426	443	464	485	506	527	548

Table 11 Numbers of ships fitted with sail, new build and retrofit; summary to 2050

Ship type	Build Type	2015	2020	2025	2030	2050
Tanker (5,000-120,000 dwt)	Fleet	2,921	2,892	3,008	3,078	3,078
	New build with sail	0	0	206	208	196
	Retrofit with sail	0	15	201	205	205
Bulker (0-100,000 dwt)	Fleet	8,653	10,719	13,281	16,446	32,435
	New build with sail	0	0	608	662	1,257
	Retrofit with sail	0	0	443	548	1,081

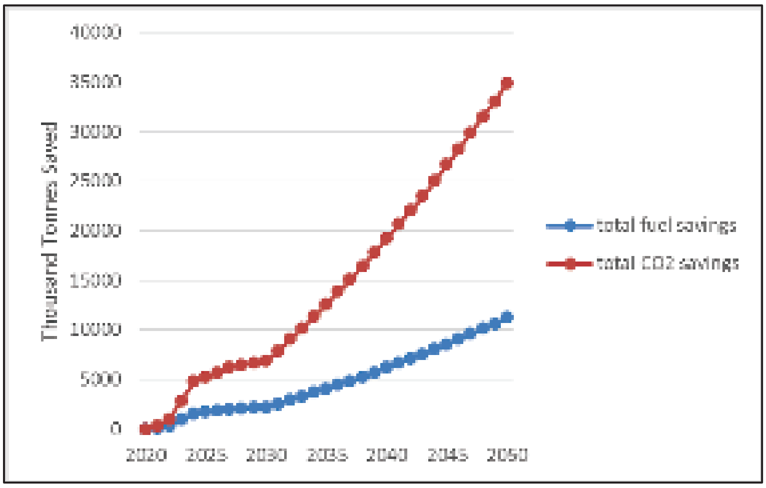
Figure 33 Adoption pathways by ship type



The dry bulker ships have the highest savings and the earliest adoption.
This is a very positive outcome, because the bulker fleet is in 2016 much larger than the oil tanker fleet and this difference is projected to increase as bulk transport increases with global economic activity while the projected reduction in fossil fuel demand leads to a stagnation in the oil tanker fleet.
By 2030, there are large numbers of ship (around 2100 tankers and 8600 bulkers) with wind technologies installed, but the process of diffusion reaches maturity only around 2040.

The resulting fuel and CO_2 emission savings from the adoption of wind technologies in the tanker and bulker fleets are shown in Figure 34.
These increase to a saving of around 6.8 million tonnes of CO_2 per year by 2030 and 35 million tonnes CO_2 per year by 2050, a major GHG reduction This would be around 0.75% of the projected total emissions of all ships in 2030 and 3.7% of the projected total emissions of all ships in 2050.

Figure 34 Fuel and CO_2 savings from adoption of wind technologies in the tanker and bulker fleets



Overall, these results represent an important insight: given a bunker price increases from the current (2016) historically low levels to $ 450 per tonne, wind technologies will be financially attractive if a few ships have demonstration wind technologies installed. Furthermore, the results are actually similar in 2030 for the different scenarios, in terms of the new installations per year. This is because after only 2-3 years, the take-up is so high that all ships in the samples with significant savings are being fitted with wind, both newbuild and retrofit. To put it another way, by the time 100+ installations have been completed, the learning effect is large enough to have brought the costs down such that all newbuilds and retrofits make financial sense, given our cost data and the oil prices and discount rates that have been assumed. If there is a significant knowledge spillover (for which we have made a fairly conservative assumption of 10% installation CAPEX reduction per doubling of cumulated installations) then the costs would decline quickly enough to make all ships for which significant savings could be expected viable. Given the global nature of the industry and the high similarity in hull forms of bulkers and tankers from different shipyards, this is argued to be a reasonable assumption. The conclusion to be drawn from these results is that the expansion of industry capacity, both in terms of design knowledge of wind technologies and the engineering expertise for installation will be a critical factor in the diffusion of the technology as well as the projected financial returns.

The three further sets of results are shown in Annex E. The results are similar in the longer run. For a reduction in operating speed by 15% (slow steaming) 1,980 tankers and 5,730 bulkers have WPTs, with a similar total CO_2 saving in 2030 of 7.4 Mt. The uptake of WPTs is slightly slower, because the reduced operating speed reduces the base fuel use, with a lower potential for savings, assuming the ship design does not change and a reduction in capacity per ship, because of longer voyages, leads to a reduction in net revenue compared to the full speed case. However, the distribution of savings over the sample of ships is also less peaked, such that as learning effects come to dominate, a higher overall proportion of the fleet is financially attractive than in the full speed case. Slow steaming may reduce fleet capacity, but a lower design power would enable further savings to be made, which are not reflected in these calculations.

If a lower initial bunker price of $ 300 per tonne and a higher industry discount rate of 8.5% is assumed, 2,050 tankers and 7,500 bulkers have WPTs installed by 2030 in the full speed case, so the uptake is rather slower. CO_2 savings in 2030 are reduced to 6.2 Mt.

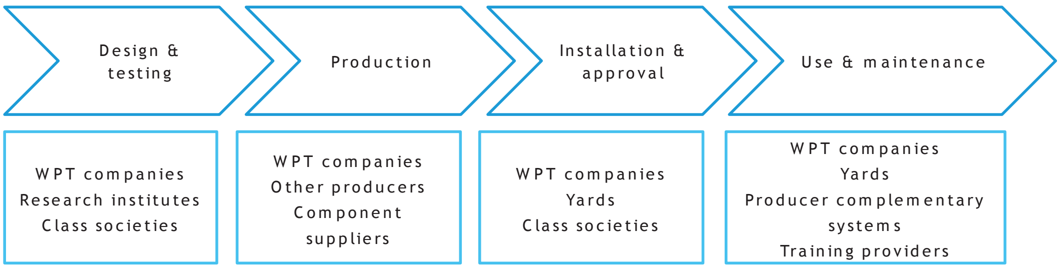
If this lower oil price and higher discount rate are combined with the slow operational speed, 1,050 tankers and 2,660 bulkers have WPTs installed by 2030, so the uptake is rather slower. CO_2 savings in 2030 are reduced to 3.4 Mt.

3.4 Economic and social effects

3.4.1 Economic effects of wind propulsion technologies

With increasing marketability of the WPTs, employment will rise not only in the companies that develop the technologies, but also in the entire value chain of the technologies.

Figure 35 Value chain of wind propulsion technologies



As depicted in Figure 35, the WPT companies may, depending on how much they are vertically integrated, be active in the entire value chain, i.e. in the R&D phase, the production, installation, and maintenance of the technologies. If the level of vertical integration is low, other companies will be involved in the production, installation and maintenance of the wind propulsion systems. Yards can play a role here too. Classification societies are called on in the testing and installation phase. As secondary effects, suppliers of components for the production of WPTs and producers of systems that are complementary to the WPTs, like voyage optimisation systems, are part of the value chain too. Once the technologies are installed and used on board ships, crew members will be responsible for handling and maintaining the systems. This may not require extra crew members, but both crew members responsible for handling and maintenance and crew members responsible for operating the ship will need extra training so that providers of the according trainings are also part of the value chain.

Current employment

The current level of employment in the companies developing wind propulsion technologies is difficult to estimate. From our survey amongst (potential) wind propulsion technology providers, it can be concluded that the number of employees differs highly (3 to 45 FTE) between the companies, mainly depending on the stage of development of the technology. Applying the average level of employment of the companies that participated in the survey to the roughly 20 companies that have been identified to develop wind propulsion technologies for commercial ships (see Table 3) it can be estimated that currently around 150 people work full time in these companies.

Expected employments effects in 2030

In order to estimate the direct and indirect employment effects associated with the development and use of wind propulsion technologies in 2030, the expected 2030 market potential as determined in Section 3.3 and the associated expected turnover are taken as a starting point. A ratio job/turnover ratio for the direct and indirect employment is subsequently applied to the expected 2030 turnover. Ideally these ratios should be determined specifically for the wind propulsion technology sector, however, given the fact that none of the wind propulsion systems has reached marketability yet and that most of the companies are still engaged in the design phase only, the currently available employment data is not sufficient to allow for a projection. As an alternative approach, the job/turnover ratio of a comparable sector, the marine equipment sector, is drawn on. SEA Europe (2016) has estimated the turnover, direct and indirect employment level for the European marine equipment sector (see Table 12) and based on this estimations it can be established that there are on average almost 6 direct jobs and more than 7 indirect jobs associated with each million euro of turnover.

Table 12 Turnover and employment of European marine equipment

Marine equipment sector	Direct	Indirect
Turnover in billion €	60	-
Employment	350,000	436,000
Jobs per million € turnover	5.8	7.3

Source (turnover, employment): SEA Europe, 2016.

Transferring this ratio to the wind propulsion technology sector and the 2030 market potential (see Section 3.3), the wind propulsion sector could be good for around 6,500-8,000 direct and around 8,500-10,000 indirect jobs, depending on the bunker fuel price and ships' speed. Whether these jobs will constitute additional jobs will highly depend on the economic climate in 2030 and on the geographic location of the jobs.

3.4.2 Social effects of wind propulsion technologies

If the uptake of wind propulsion technologies leads to additional employment, then there will be demand for employees with different skills and educational background.

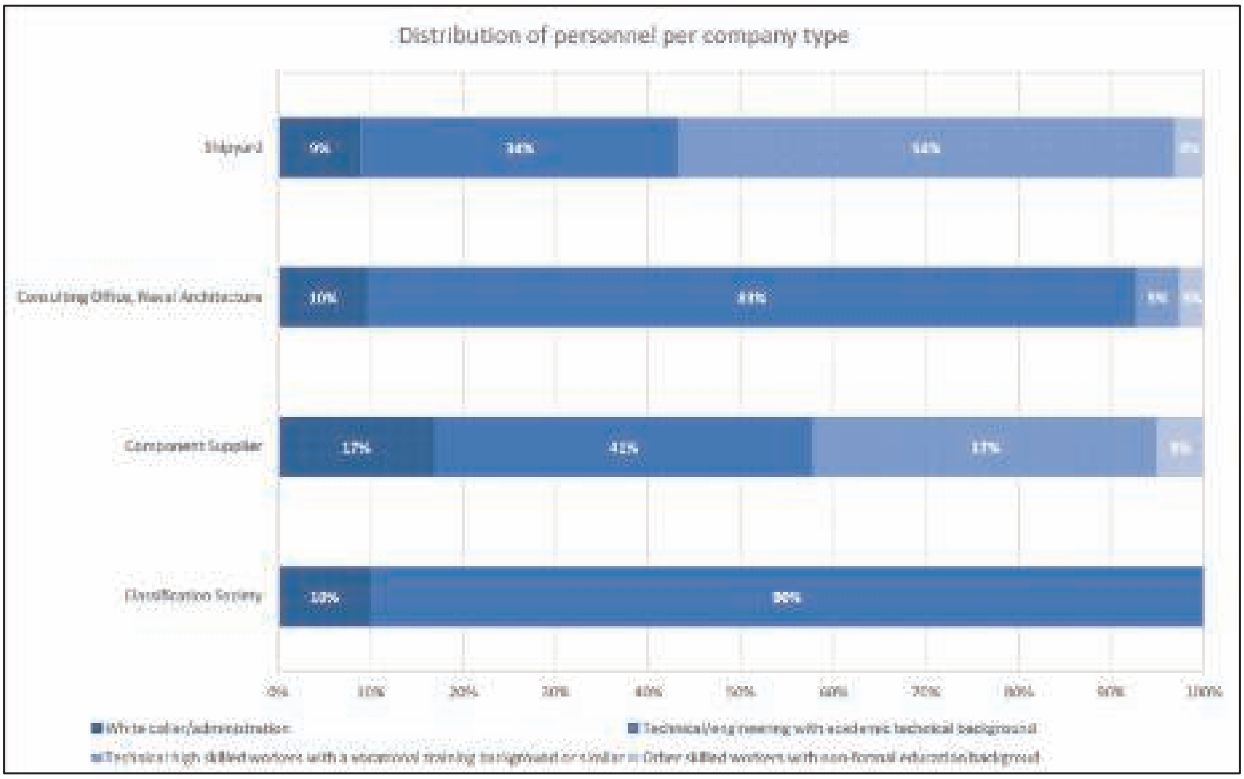
The distribution of personnel differs between the company types in the value chain of wind propulsion technologies for ships.

According to SEA Europe (see Figure 36), personnel working for classification societies has predominantly (90%) got an academic technical/engineering background; for component suppliers and shipyards this is only 40% and 35% respectively. In these companies a large share of the personnel are high skilled workers with a vocational training background (40 and 50%). For all four company types it holds that there is a relatively low share of the personnel that is skilled but has got no educational background. The remaining personnel are white collar/administrative personnel representing around 20% of the personnel of component suppliers and 10% of the personnel of all the other company types.

The companies developing wind propulsion technologies can, once the systems have achieved market maturity, be expected to have a similar personnel structure as component suppliers.

Next to the demand for employees with different skills, the uptake of wind propulsion technologies will also lead to the extension of the skills of certain employees in the value chain. Crew members responsible for the handling and maintenance of the wind propulsion technologies and crew members responsible for operating the ships will for example need to be trained.

Figure 36 Distribution of personnel per company type



Source: SEA Europe, 2016.

4 Barriers to uptake and development of wind propulsion technologies

4.1 Introduction

Many innovative wind propulsion technology concepts have been and are being developed for commercial shipping. However, none of the technologies has reached market maturity yet. In order to find out how the uptake and development of the wind propulsion technologies could be advanced, we have determined and assessed the barriers to the uptake and development of the technologies. The results of this analysis are presented in this chapter. In the following chapter (Chapter 5) possible actions to overcome the main barriers identified will be presented.

In order to get a long list of potentially relevant barriers, we have carried out a literature review and conducted eleven in-depth interviews with (potential) wind propulsion technology providers. The relevance of these barriers has subsequently been assessed by means of an online survey and a stakeholder workshop held in June 2016.

Three key barriers to the uptake and development of wind propulsion technologies have thereby been established:
1. Access to capital for the development of wind propulsion technologies (WPTs).
2. Incentive to improve energy efficiency/reduce CO_2 emissions of ships.
3. (Trusted) information on the performance, operability, safety, durability and economic implications of the WPTs.

In the following we will discuss important barriers to the uptake and development of wind propulsion technologies with the three key barriers (indicated in bold in the text) being discussed in more detail. To illustrate the relevance of some of the barriers, three case studies will be presented (see Section 4.5).

The barriers are discussed differentiating:
1. Barriers to the uptake of WPTs (see Section 4.2).
2. Barriers to the uptake of cost efficient abatement measures in general (see Section 4.3). and
3. Barriers to the (further) development of WPTs (see Section 4.4).

Note that since there is a large overlap between the literature on the uptake and development of abatement technologies in general and to the uptake and development of wind propulsion technologies. We have chosen to only give a list of the literature that has been used for the analysis (see the following text box and not to reference to all the relevant studies in the text.

Literature reviewed:
– Carbon War Room and UCL (2014)
– CE Delft et al. (2012)
– CE Delft and Marena Ltd (2011)
– E&E (2015)
– Ecorys et al (2012)
– IMarEST (2010)
– IMO (2011)
– IRENA (2015)
– Lewis-Jones (2015)
– Lloyd's Register Marine (2015)
– Maddox Consulting (2012)
– RAENG (2013)
– Rehmatulla et al. (2013)
– Rehmatulla et al. (2015)
– Rojon 2013
– Rojon and Dieperink (2014)
– Sail (2015)
– UCL (2015)

4.2 Barriers to the uptake of WPTs

We see four necessary conditions for the adoption of WPTs. A wind propulsion system (WPS) is only adopted by a ship owner/long-term charterer[4] if, first, the system can be applied to the ship under consideration, second, the system is cost efficient, third, the ship owner can, to a certain degree, ex ante be sure about the system's cost efficiency, and, fourth, the ship owner is able to finance the acquisition and installation of the system. We therefore differentiate the following four main categories of the barriers that can prevent the uptake of WPTs:
1. Applicability of the WPS.
2. Cost efficiency of WPS.
3. Certainty of cost efficiency.
4. Access to capital.

The different barriers to the uptake of WPTs will be discussed for each of the four categories in the following.

Experience has shown that abatement technologies, although cost efficient, are often not adopted by the shipping sector. This makes the four above mentioned conditions necessary but not sufficient conditions for the uptake of WPTs. In Section 4.3 we therefore discuss barriers to the uptake of cost efficient abatement technologies too. Most of these barriers are not specific for WPTs but are barriers to the adoption of abatement technologies by the shipping sector in general.

[4] Next to ship owners, long-term charterers may, after coordination with the ship owner, also decide to adopt a WPT. For the reader's convenience we hereinafter refer to 'ship owner/long-term charterer' as 'ship owner'.

4.2.1 Applicability of the WPS

The technical characteristics of the different WPTs can limit the applicability of the technologies with retrofits naturally being more restricted than newbuilds.

Due to their deck space requirement, most of the WPTs (soft/rigid sails, rotors, wind turbines) cannot be applied to all existing ship types/sizes. In general tankers and bulkers provide more deck space than container ships, ferries, and cruise ships. Towing kites, installed at the bow of a ship, require far fewer deck space, allowing kites to be used on most ship types, at least if the accommodations of the ships are not positioned at the bow.

The heeling of the ship caused by WPTs, especially by soft/rigid sails, may not be acceptable for certain ship type, like for example passenger ships and would require alleviation either by ballast or stabilisers, if possible.

Ships equipped with a WPT may, due to their dimensions and the dimensions of the on land infrastructure (e.g. cranes, bridges), not be able to load/unload in all ports/at all quays or sail on each route. These infrastructural barriers may restrict the applicability of (certain sizes) of WPTs, at least if the logistical chain cannot be adjusted accordingly. Again this barrier is the least relevant for towing kites which have a relative small superstructure. There are concept designs for rigid sails and rotors that are retractable. For these designs this barrier would also not be relevant.

The (potentially) available dimensions of WPTs may be too large for smaller ships – the wind forces acting on a small ship equipped with a relative large system can be too strong for the structure of the ship and/or could pose a risk to the ship's stability.

4.2.2 Cost efficiency of WPS

There are factors that have a negative impact on the cost efficiency of WPSs by negatively affecting the benefits, the performance or the costs the WPTs. Due to these factors the deployment of a WPS is/can become unprofitable either in general or if applied to certain ships.

Incentive to improve energy efficiency/reduce CO_2 emissions of ships

The incentive to improve the energy efficiency/reduce the CO_2 emissions of ships has been identified as a **key barrier** to the development and uptake of WPTs.

For existing ships there is no regulation in place that internalizes the external costs of their CO_2 emissions (an overview of the current regulatory framework for the energy efficiency of ships is given in the text box below). Owner of existing ships have therefore got a suboptimal incentive to take up energy efficiency measures - ships that were retrofitted with a WPS would currently not benefit from a compliance cost reduction.

Low bunker fuel prices and overcapacity in the market can also be expected to lead to a lower uptake of WPTs: lower bunker fuel prices reduce the fuel expenditure savings that can be achieved by using WPTs and overcapacity increases the probability of under utilization/laying up of the ship and thus of less benefits from the WPT. For some WPTs (towing kites) however overcapacity can also have a positive effect on the benefit from WPTs: if in times of overcapacity the average speed of ship declines, the performance of some WPTs improves.

According to stakeholders, this currently does not seem to be the case: given the severe overcapacity, ship owners invest into energy efficiency measures in order to stand out from the competitors and to secure cargoes. The fact that some ship owners, on a voluntary basis, certify the design efficiency of their ships, seems to affirm this assessment.

Current regulatory framework for the energy efficiency/the GHG emissions of ships

The IMO Energy Efficiency Design Index (EEDI) requires new build ships[5] to attain a specific design efficiency and the required EEDI, which depends on the ship type and size, will become more stringent over time. The installation of wind propulsion technologies is rewarded by the EEDI. The EEDI regulation considers wind propulsion technologies as innovative mechanical energy efficiency technologies that contribute to the reduction of the main engine power (MEPC.1/Circ. 815), but until now no ship equipped with a WPT has been EEDI-certified.

Existing ships are currently not obliged to improve their energy efficiency or to reduce their GHG emissions.

The IMO requires all ships to have a Ship Energy Efficiency Management Plan (SEEMP) on board but does not obligate an improvement of the energy efficiency.

And MEPC 70 has adopted mandatory requirements for new and existing ships of 5,000 GT or above to collect their fuel consumption as well as other, additional, specified data including proxies for transport work. This data collection system is intended to be the basis for a further policy debate.

MEPC 70 has also approved a 2017 to 2023 roadmap for developing a ‘Comprehensive IMO strategy on reduction of GHG emissions from ships’, but whether and which measures to enhance the energy efficiency or to address GHG emission from international shipping will be taken is not clear yet.

Measures that would require an improvement of the operational energy efficiency of existing ships have been discussed in the IMO in the past, but there is still a controversy regarding a meaningful efficiency metric. And also market based measures to internalise the external costs of greenhouse gas emissions have been discussed at IMO level, but no consensus could be reached.

The EU MRV regulation (2015/757) obliges new and existing ships of 5,000 GT or above to, from 2018 on, monitor, report and verify their fuel consumption and other relevant information on voyages to and from EU ports. The reported data will, in contrast to data collected under the IMO regulation, be made public. The MRV regulation is the first step of the three-tiered strategy of the EU Commission (COM(2013) 479 final) with the aim to gradually include maritime GHG emissions in the EU’s commitments.

5 EEDI applicable as per 1 July 2013 (keel laying date) or 1 January 2013 (building contract) to bulkers, gas carriers, tankers, container ships, general cargo, refrigerated cargo and combination carriers and as per 1 March2016 (keel laying date) or 1 September 2015 (building contract) also to LNG carriers, RoRo cargo and passenger ships, and cruise ships.

Other factors affecting the cost efficiency

Just as for other innovative technologies, the (non-)recurring costs of the systems can be expected to be relatively high given that the systems are produced on a small scale and given that the according service infrastructure is not established on a worldwide scale yet.
Wind conditions fluctuate on a specific route over time. If a ship is chartered for a short period of time only, the charterer/shipper may therefore not benefit from a WPS, even if wind conditions are on average favorable on this route. Charterers may therefore not be prepared to pay more hire for a ship that is equipped with a WPS and shipper not may not be prepared to pay higher freight rates if goods are carried by a ship equipped with a WPS.

The dimensions of the available WPTs - be it because the supplier cannot offer these dimensions yet or because the technology is not fully scalable - may be too small for certain ship sizes to have a significant impact.

The design of existing ships may not be optimized for the use of WPTs, reducing the efficiency of retrofitted WPTs.

4.2.3 Certainty of cost efficiency

If the cost efficiency of WPTs is associated with a high uncertainty, the uptake of WPTs will naturally be relatively low. Different factors add to the current uncertainty of the cost efficiency of the WPTs.

Inherent uncertainty of WPTs

Not only differ average annual wind conditions between routes, but wind conditions also fluctuate on a specific route over time; if ships do not sail on a regular basis on certain routes, the annual savings and thus the cost efficiency of a WPS is difficult to assess.

Economic fluctuations

Economic fluctuations contribute to the uncertainty of the cost efficiency of all CO_2 abatement measures. The volatility of the bunker fuel price and fluctuations of the capacity utilisation of the ships lead to an uncertainty regarding the expected monetary benefit that can be achieved by using CO_2 abatement measures.

For WPTs, the fluctuation of the capacity utilisation adds another uncertainty factor. The average speed of vessels tends to increase/decrease in times shortage/overcapacity reducing/increasing the performance of WPTs.

(Trusted) information on the performance, operability, safety, durability, and economic implications of WPSs

(Trusted) information on the performance, operability, safety, and reliability of WPSs has been identified as one of the **key barrier**s to the development and uptake of WPTs and will be discussed in the following two subsections.

Availability of information

Next to the above mentioned uncertainty factors, there are other uncertainty factors that impede the assessment of the cost efficiency of the WPTs for a potential buyer. These uncertainties are related to the actual performance, operability, safety, and durability of the WPSs as well as economic implications of the use of WPTs. These uncertainty factors can, in contrast to the uncertainty factors mentioned above, potentially be resolved by testing of and long-term experience with the WPSs.

The following aspects are, next to the actual performance of the systems, considered uncertain by stakeholders:

Some stakeholders have doubts concerning the operability of wind propulsion systems. Do the systems actually function as they should? Moving parts of WPSs on board a ship are considered a safety risk and WPTs are, at least if not fully retractable, feared to add to the instability of ships under adverse weather conditions.

The strong forces that act on the WPSs also raise concerns regarding maintenance costs and the life time of the systems.

The use of WPTs may also lead to unwanted interaction between ship and WPS (e.g. vibration, noise of rotors) and the WPS might therefore not be usable/not be useable to its full potential.

If the complete lifecycle of a ship is considered, the second hand price of a ship equipped with WPT is feared to be lower than for a conventional ship, at least if the WPS cannot be easily removed: A ship equipped with a WPT may have less potential buyers if the ship is less flexible due to infrastructural restrictions and since potential buyer/long-term charterers may be sceptical.

And finally, due to infrastructural restrictions, a ship may get less orders/be hired less.

Potential buyers do not dispose of sufficient information that is crucial for the assessment of the cost efficiency of the WPTs, because the information is not available yet. Only for a little number of WPTs full scale validations and demonstrations have been carried out and long-term experience is missing.
In the 1980s a number of wind-assisted cargo ships equipped with rigid sails were actually built in Japan (see Section 4.5), but a detailed documentation of the experience with these ships is, at least publicly, not available.

The reason why the information that is relevant for the assessment of the cost efficiency of WPTs is not available yet are actually barriers to the development of WPTs (see Section 4.4). Demonstration projects/full scale validation is costly and access to capital is difficult if there is no proof of sufficient future demand/market potential (chicken and egg problem) and, in addition, since not many ship owners are willing to participate in/share the risk of pilots.

Value of available information

The value of the available information on the performance of WPTs can be perceived as limited for two reasons: the available information may have only limited relevance for a specific potential buyer and potential buyers may not trust or understand the available information.

The performance of WPTs depends on many variables: the route the ship sails, the direction in which the route is sailed, the dimension of the wind propulsion system under consideration, the ship type on which it is installed, whether the ship is a new build with a design adjusted to wind propulsion system or not, etc. For a potential client it is therefore important to get performance data specific for his case. A (potential) technology provider however will not be able to cover a wide range of cases in advance.

In addition, data stemming from tests of demonstrators are often underestimation of the performance of wind propulsion systems in the sense that the dimension of demonstrators is often suboptimal for the ship the system is tested on.

Regarding the information on WPTs, there is also an asymmetric information situation between potential users and (potential) technology providers. Potential buyer may therefore be sceptical about the information provided by (potential) technology providers, especially if the information is not provided in a transparent way (e.g. specifying the circumstances under which the performance data has been collected), if it has not been verified by a third party, and if the information has not been gathered and assessed according to a standardized approach.

No standardized approach for the assessment of the performance of wind propulsion technologies has been developed yet. The installation of wind propulsion technologies is rewarded by the EEDI and a method for the assessment of the available effective power of wind propulsion systems has been developed to this end (see the following text box), but the aim of this assessment is to provide an estimation of the average performance of a wind propulsion system rather than an assessment for routes relevant for a ship owner. And a technical guidance to the conduction of the performance test has also not been established yet.

Assessment of the available effective power of wind propulsion systems for the calculation of the attained EDDI

The '2013 Guidance on the treatment of innovative energy efficiency technologies for calculation and verification of the attained EEDI' (MEPC.1/Circ. 815) specifies the calculation of the available effective power of wind propulsion systems. The formula includes a global wind propulsion matrix and a technology specific force matrix. The global wind propulsion matrix gives the wind probability on the main global shipping routes; the force matrix should give the force characteristic of the specific WPT for any combination of wind speed and wind angle relative to heading given the reference speed and should be determined by means of a performance test carried out by the ship owner. A technical guidance to the conduction of the performance test has not been established yet.

4.2.4 Access to capital

Whether there are barriers to the access of capital when it comes to the funding of the uptake of the technologies is difficult to assess, since the supply of the systems is still very limited.

The funding of the uptake of WPTs can however, at least at present, expected to be difficult, given that a major investment is involved and given the current overcapacity in the shipping market. The liquidity of the shipping sector itself is low and banks can expected to be reluctant to provide funding for abatement measures if ship owners have difficulties to fulfil their current payment obligations. The above mentioned uncertainty of the cost efficiency of WPTs could certainly play a role here too.

There are different public programmes that support the uptake of energy efficient technologies or energy efficient ships. The KfW bank for example offers soft loans for 'Green Shipping' investments for owners of German flagged ships (KFW IPEX-Bank, 2016) and ship financier KfW IPEX-Bank takes the energy efficiency of the vessels into account. The EIB also provides loans for shipping. As laid out in the EIB's Transport Lending Policy (EIB, 2011), the projects have to fulfil certain criteria. Ships have to be EU flagged, the projects should have high European value added, etc.

4.3 Barriers to the uptake of cost efficient technologies

Experience has shown that in many cases abatement technologies, although cost efficient, are not adopted by the shipping sector. In this section we therefore discuss barriers to the uptake of cost efficient abatement technologies. Some of these barriers are not specific for WPTs but are barriers to the adoption of abatement technologies by the shipping sector in general.

4.3.1 Commercial agreements/legal aspects

Some commercial agreements/legal aspects are, at least in the short-run, a barrier to the uptake of WPTs.

In most time charter agreements it is determined that the charterer pays for the fuel consumed by the ship. This also means that only the charterer can profit from fuel expenditure savings. This gives ship owners no incentive to invest into energy saving devices. This is referred to as the 'split incentives' problem between ship owners and operators.

And also the terms and conditions of specific charter parties can impede the uptake of WPTs. Speeding up to avoid a delay of a ship equipped with a wind propulsion system may not be perceived as a feasible option under certain charter parties, since this higher speed may not be covered by the consumption clause of the charter party.

Commercial agreements between consignors and consignees may not allow for the adjustments in the logistical chain necessary for the use of WPTs.

4.3.2 Scepticism

The shipping sector is, with the exception of some early movers, known to be a conservative sector. Innovative technologies will, even if cost efficient, not easily find its way into the sector and may even not be considered for adoption at all. For WPTs this may hold even more, since the operation of a ship equipped with a WPT differs from the operation of a conventional ship.

Negative publicity related to a specific abatement measure under development may thereby wrongly contribute to scepticism regarding comparable products.

4.3.3 Access to capital

The very same abatement measure can be considered cost efficient or not cost efficient, depending on the assessment criteria. A measure may, for instance, be labelled as cost efficient if a payback time of five years is expected whereas it is labelled as being not cost efficient if a payback time of three years is expected. Measures that, from a social point of view or from the ship owner's point of view, are assessed to be cost efficient may therefore not be considered cost efficient by investors. This could lead to a limited access to capital and therefore to a suboptimal uptake from the point of view of social welfare.

4.3.4 Cost efficiency

Cost efficient CO_2 abatement measures will obviously not be adopted if there are alternative measures with superior cost efficiency.

Cost efficient CO_2 abatement measures might also not be adopted, since they only appear to be cost efficient while they are actually not. In order to determine the actual cost efficiency of a measure the total cost of ownership has to be considered as well as indirect costs, like e.g. costs for crew training, voyage optimization systems, loss of cargo space, etc.

4.4 Barriers to the (further) development of WPTs

For many WPTs it holds that a performance indication is only given based on computational simulations and/or small scale wind tunnel tests - results from demonstration projects/full scale tests cannot be provided since R&D companies find it difficult to raise sufficient funds to this end. And even if demonstrators/full scale models have been build, it is often difficult for developers to find ship owners (banks) that are willing to participate in trials.

4.4.1 Access to capital

The access to capital for the development of WPTs, especially for building and testing of full scale models and demonstration projects has been identified as the **most important key barrier** to the development and uptake of wind propulsion technologies. This barrier has therefore been analysed in more detail (see text box hereafter). The capital sources used by (potential) WPT providers and the access possibilities to different capital sources has, as far as possible, been analysed to this end.

Access to capital for (potential) WPT providers

Wind propulsion technologies have been/are being developed by different constellations of private and public parties.

First, there are projects in which new concept designs of vessels equipped with WPSs have been developed (e.g. Ecoliner and Flettner Freighter in the Sail project). These projects have been carried out by public-private consortia where the actual building of the design is not part of the project but could well be a spin-off project.

Second, there are private-public consortia with partners from industry and science that, in the first instance, aim at developing and building a full scale prototype of a WPT and at testing it on land and, in a second stage, aim at demonstrating the performance/operability in a pilot project on a ship (e.g. Wind Challenger Project, Wind Hybrid Coaster project as part of the MariTIM project).

Third, there are companies that have developed a WPS themselves and exclusively for their own use (Enercon).

And fourth, there are companies that develop WPTs for commercial purposes and do not structurally collaborate with public institutions; some of which seek collaboration with existing other industry players.

Funding naturally differs between these types of constellations.

For the two projects carried out in EU countries that fall into the first two types of constellations, half of the budget stems from EU Interreg programmes that support cross border (Interreg A), transnational (Interreg B) or interregional (Interreg C) projects with the funds stemming from the European Regional Development Fund. The other half of the budget that has to be provided through match-funding, stems from the project partners. Part of these partners however are also national/regional public parties.

There is no information publicly available as to how Enercon financed the development of the rotor equipped E-Ship 1.
Companies that develop WPTs for commercial purposes feature different financial models, with capital stemming from private funds of the company founders, from selling company shares, from capital increases, from venture capital loans, from public funds or from grants.

In many cases the companies start off with the private funds of the company founders.

Some WPT companies have issued company shares. Zeppelin Power Systems GmbH & Co. KG for example held a small share in the SkySails Holding GmbH & Co. KG.

Some companies were able to raise venture capital provided either by different single parties (SkySails e.g. raised € 15 million in 2010) or by syndicates/ funds. A few venture capital funds are supported by public funds. The EIB for example has a venture capital facility that contributes to venture capital funds. The facility has for example supported the Power III Fund of the clean tech focused venture capital intermediary from which Norsepower was able to receive funding.

Public funds have further been used both in terms of subsidies and soft loans, with subsidies stemming from EU funds (e.g. Horizon 2020 programme[6], LIFE programme) or national funds (e.g. national public innovation funds like for example Inviatlia in Italy or Tekes in Finland and soft loans from national financial intermediaries like KfW in Germany or Finnvera in Finland).

There are private initiatives which award grants to innovative green technologies, such as wind propulsion technologies (e.g. Orcelle Grant). The scope of these grants is however rather small compared to the total capital requirements.

For those companies that develop WPTs for commercial purposes, it is noticeable that, first, the companies have to draw on different sources of capital to be able to fund the development of their products, second, that, although the share differs highly, none of the companies has been able to develop its product without public funds and, third, that in many cases the companies are unable to access capital for building and testing of full scale demonstrators. The companies are generally small companies that are not able to cover the high costs with their own funds and they are often not able to attract sufficient private and public external capital to this end.

Many companies find it difficult to meet the expectations regarding the return on investment and the payback time of venture capital investors, especially given the current adverse economic conditions and banks are reluctant to provide funding for the development of WPTs. Not only have banks had negative experiences with ship financing, the above mentioned uncertainties regarding the technologies play an important role here too. But independent of these uncertainties find banks it difficult to assess wind propulsion technologies, given that no standardized assessment approach has been established so far. Some banks stated that they are only willing to provide a loan if the national government acted as a guarantor.

Some stakeholders also state that there are, in principle, sufficient EU funds available, but that the administrative effort for applying to EU funds is very high and often prohibitively high for small R&D companies. And also the time span between application and the actual granting

[6] E.g. 'Smart, Green and Integrated Transport' programme.

of the funds is stated to be too long for small companies. In contrary, the administrative effort for applying to regional/national funds seems to be much lower, but the funds granted seem in many cases not to be sufficient to cover the required expenses for the development of a wind propulsion system.

In contrary, other stakeholders emphasize that especially for the national funding schemes it holds that grants are disbursed only after the project has been completed.
Some WPTs developers state that they have tendered for public support, but without success. A company was for example able to receive Horizon 2020 SME phase 1 support, but not phase 2 support which especially is aimed at the demonstration of the technology. The company does not know why the application has not been successful.

Finally, there are potential investors (e.g. pension funds) and public funds, which would be willing to invest into environmental projects but that are only interested in large scale projects - small R&D companies therefore do not qualify for these sources of capital.

4.4.2 Legal/institutional framework

Innovative technologies like WPTs are naturally not covered by the existing legal/institutional framework. To avoid risks, developers may therefore be hesitant and those who move ahead may be confronted with additional costs.

Class rules for WPTs are for example not fully developed yet and ship owners then face the challenge to prove that potential risks can be managed to an acceptable level. According to Lloyd's Register's 'Guidance Notes for Flettner Rotor Approval' (Loyd's Register, 2015) the party seeking approval has to carry out a risk assessment in which reasonably foreseeable hazards to the safe operation of the ship and to the ship's occupants are identified and it is demonstrated that these hazards can adequately be controlled.

4.5 Case studies

4.5.1 Case Study 1: Wind-assisted ships in the Japanese fleet in the 1980s

Almost 20 wind-assisted cargo ships equipped with rigid sails were built in Japan in the 1980s. These ships probably account for the majority of wind-assisted ships built after the emergence of the motor ship.

Japan initiated a large research programme in the 1960s aimed at lowering the costs of maritime transport. The reason for this programme was likely the dependence of the Japanese economy on maritime imports and exports. Initially, the programme aimed to lower the costs of transport by lowering the number of crew on board and increase the automation (Vinkoert, 1986).
After the oil crises of the 1970s, the aim of reducing fuel consumption became more prominent (Watanabe, et al., 1983). One of the ways to do so was wind-assisted sailing.[7]

The research and development programmes into wind-assisted ships were funded by government grants and lottery receipts (Vinkoert, 1986).
Several research institutes and shipyards were involved. The most prominent designers of sails were Nippon Kokan K.K. and the Japan Marine Machinery Development Association (JAMDA) (Nippon Kaiji Kyokai, 1985).

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[7] The programme also developed other fuel-efficiency improvements, such as new bulbous bow forms (Miyata, et al., 2014).

In 1980, the coastal tanker Shin Aitoku Maru set sail. It was a 1,400 dwt tanker designed to sail at 12 knots and equipped with two rigid sails with a total sail area of just below 200 m^2. The sails were built by Nippon Kokan K.K. during the first two years, the ship consumed 8-10% less fuel than a comparable ship without sails (Watanabe, et al., 1983).

The Shin Aitoku Maru was followed by at least 16 ships with rigid sails built by at least six different yards for at least six different owners (Nance, 1985); (Murayama & Kitamura, 1986). Most of these ships were coastal bulkers and tankers with a deadweight between 600 and 5,000 tonnes. These ship types were popular in the 1980s and several thousands of similar ships were built in Japan in the 1980s.[8] Several wind-assisted ships were part of a series of ships of which one was equipped with sails. Two oceangoing vessels were also equipped with sails: the bulk carriers Usuki Pioneer (1983, 26,000 dwt) and Aqua City
1984, 31,000 dwt). The first experiences with the Usuki Pioneer showed a considerable reduction in fuel, albeit at relatively low speeds and in favourable wind conditions (Vinkoert, 1986).

Some of the ships are still sailing, but according to photos on the internet apparently the sails have been removed. In some cases this was due to new owners that operated the ships on routes with height restrictions due to bridges (Hanayama, 2016). Also, cargo capacity could be expanded by removing the sails and the power trains used to rotate them. No new wind-assisted ships were built after 1990. Three reasons are cited in the literature for the demise: high maintenance costs (O'Rourke, 2006); an accident with a wind-assisted ship that broke free of its moorings in a port and damaged other ships (Atkins, 1996) and persistent low fuel prices (Ouchi, et al., 2013).

The case of Japanese Wind-Assisted Ships built in the 1980s highlights several barriers and actions to overcome them.

The barriers related to the development of rigid-sail technology were overcome through government funding. This was available partly because it was part of a wider effort to lower the costs of shipping, towards which goal much research funding was directed.

It is not clear whether the adoption of the technology was also aided by subsidies. What is clear, however, is that the risk for ship owners and yards was reduced by the fact that sails were fitted so one of a series of ships: if the technology would not be useful, the sails could be taken off and the ship could still be used in the same trade as the sister-ships.

The performance of the wind-sails on the Shin Aitoku Maru and the Usuki Pioneer were shared widely in reports, thus lowering the informational barrier and generating trust in the technology.

The demise of the wind-assisted ships was probably due to the fall in fuel prices, as well as lower financial results of the shipping companies in the 1980s due to low freight rates (Vinkoert, 1986).

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[8] As of May 2016, over 1,700 of Japanese built tankers, bulkers and general cargo ships with a dwt between 600 and 5,000 tonnes are still active in the fleet. Clarksons World Fleet Register.

4.5.2 Case study 2: Towing kites

This case study is about a wind propulsion technology that, although very advanced in its development, has not been able to reach market maturity yet.

The towing kite technology is one of the few wind propulsion technologies that have been developed almost up to the stage of marketability. Two different sizes of towing kites have been developed by a German producer and have been tested on different ships over a longer period of time. The technology has been installed on newbuilds and has also been retrofitted. The company did also enter into a joint venture that would have been responsible for selling and servicing the system. The development and deployment however have come to a halt. The system is still installed on three vessels but currently not actively used and the part of the company that was focused on wind propulsion has been liquidated April this year as a result of insolvency (Handelsregister.de, 2016). The remaining parts of the company focus on vessel performance management as well as the use of kites for power production.

Based on a literature review and information from ship operators, we see a combination of different factors that seem to have frustrated the further advancement of the development and the deployment of the technology.

First, technical challenges in the development of the technology and economic adverse conditions have played a role.

According to the company that has developed the towing kite (Wessels, 2009), the following two challenges arose in the first phase of testing: the operating time of the kites was suboptimal due to limited launch opportunities during heavy sea and some of the component's resilience and stamina when exposed to harsh conditions at sea were suboptimal too. As a consequence, the company developed an integrated launch and recovery module with, according to the company, an improved endurance of the components and improved launching features, which also made operating easier for the crew.

Economic conditions have been adverse (economic crisis, low oil price) after the improved system had been developed. As a consequence, orders were cancelled and no additional orders have been placed.

This is in line with the statement of ship operators that installed a system but does not use it and also decided to not order further systems at the moment. He states that under the current economic conditions deployment of wind propulsion technologies is not economic which is why they decided to pause their engagement in wind propulsion technologies.

Other barriers to the uptake of the system have been specified by a chartering company that purchased a vessel with a towing kite system, but uninstalled the system and a long-term charterer that decided not to use an installed system anymore.

It was stated that the system would need specific wind conditions and could only be operated at daylight, that the system would not be cost efficient on short haul voyages and thus not attractive for certain trade patterns, and that an adjustment of routes to heavy wind routes would have been necessary.

Regarding the crew, the system was assessed to be too labour intensive and crew training was stated to be a challenge, given that the charterer's crews change on a regular basis.

The financial challenges of the supplier were finally mentioned too.

Access to capital however seems not to have been a barrier for the towing kite company. The company was able to procure public funds for testing its technology (e.g. LIFE funding for WINTECC project and European Fisheries Fund & Mecklenburg-Western Pomerania funding for testing kites on a fishing vessel) and to raise venture capital (€ 15 million in 2010 (SkySails GmbH, 2011)). Ship owners' willingness to cooperate and contribute to tests seems also not to have played a role here.

4.5.3 Cast study 3: Environmental first movers

The third case study is about environmental first movers in the shipping sector that actively investigate wind propulsion for ships and consider wind propulsion only as a long-term option for their fleet.

The ship owner under consideration operates his own ships - the split incentives problem does therefore not apply - and is known to be an environmental first mover in the shipping sector, investigating, testing and applying different types of innovative environmental measures. The ship owner has also investigated wind propulsion technologies.

Findings of in-house studies of the ship owner are not known to us, but two master theses (Silvanius, 2009) and (Delin, 2010) have been supervised by the ship owner which analyse wind propulsion technologies for the specific context of the ship owner. More in specific, the master theses theoretically investigate the

- saving potential and profitability of different wind propulsion technologies for a specific ship of the ship owner, using wind statistics from routes relevant for this ship;
- design of a ship optimized to use wind as main propulsion.

The master theses specify general barriers to the uptake of wind propulsion for ships as well as disadvantages of the specific wind propulsion technologies if compared with each other.

Regarding wind as *main* propulsion, it is concluded that it is technically feasible (at least for sails and rotors - kites do not produce sufficient power), but that the sector would have to accept a significant reduction of the ship speed. Fixed time schedules could then be challenging too. A hybrid solution together with a weather independent propulsive system is expected to be a more realistic option.

When comparing different types of WPTs for wind-assisted shipping, the following criteria are used: performance, payback time, capital expenditures, complexity of installation, maintenance costs, and safety.

The comparison is carried out for a specific ship of the ship owner and for relevant routes of this ship. It is concluded that:

- kites have the least power performance at 20 knots, need specific wind speeds, have long payback time, high maintenance costs, require crew training, and it would have severe consequences if the controlling system would fail;
- rotors have, according to the model calculations, the best performance and lowest payback time (almost the same as for wing), but in practice it is expected that they cannot perform at peak since they would not have got all the working fluid volume they need, have a global drag reducing

effect due to delayed separation expected, are easier to install and require less maintenance than kites, might need to be retractable with the cavity to recover being larger than for a wing;
- wings have the least performance at 15 knots, though the payback time is comparable to rotors, are expected to have, just as rotors, a global drag reducing effect due to delayed separation, are cheap to build and maintain, easiest to install, might need to be retractable with the cavity to recover being smaller than for a rotor;
- wind turbines are not profitable.

Overall it is concluded that the wing would be the best option for the ship owner.

Wind propulsion is also incorporated in the roadmap for ships as published by the ship owner (Fagergren, n.d.); according to this roadmap, hybrid electric propulsion, including fuel cells and wind propulsion, will, in the long run, play an increasingly important role alongside with a reduction of the design speed of the vessels and alternative fuels. A concept design of a visionary zero emission ship that was developed by the ship owner is also equipped with wind propulsion and the ship owner has contributed to a study on wind turbines for ships (Chalmers; PROPit AB, 2014) with actual wind measurements during two years on eight different ships.

However, to our knowledge, the ship owner has so far not tested any wind propulsion systems on-board yet. Why this is the case, we don't know, but apparently other energy efficiency measures, at least in the short- and medium run, seem to be more attractive for the ship owner's ship type and trading pattern - the eight ships ordered by the ship owner since 2013, which are called highly efficient RoRos, are/will at least not be wind-assisted.

5 Possible actions to overcome the market barriers

5.1 Introduction

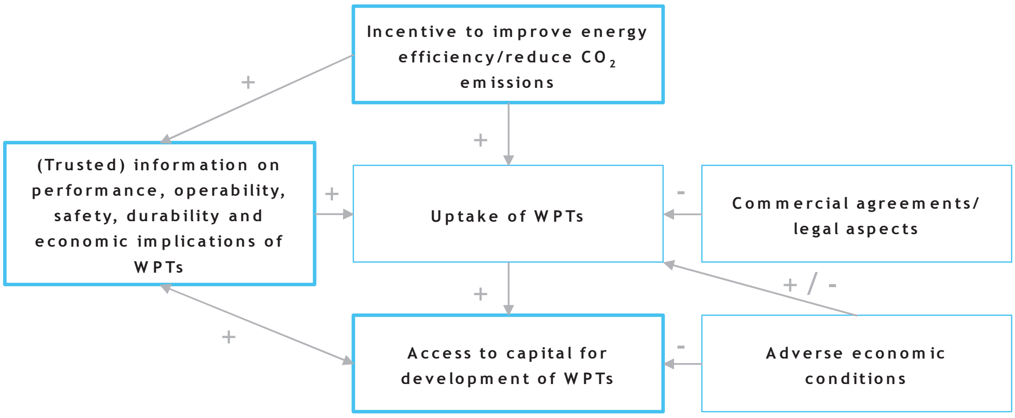
A range of barriers to the development and uptake of wind propulsion technologies has been identified (see Chapter 4). In a next step, possible actions which can contribute to overcome these barriers are identified and discussed. Focal points are thereby possible actions to overcome the three established key barriers; possible actions to overcome other barriers are briefly discussed. For all barriers, relevant actors are allocated to the possible actions.

5.2 Possible actions to overcome the key barriers

Three key barriers to the development and uptake of wind propulsion technologies have been identified. First, companies developing wind propulsion technologies find it difficult to raise funds, especially for building and testing of full scale demonstrators, second, ship owners/long-term charterers have too little incentive to improve the energy efficiency/to reduce the CO_2 emissions of their ships, and, third, there is a lack of sufficient information on the performance, operability, safety, durability and economic impacts of the WPTs as well as a lack of trust regarding the information that is available.

Figure 37 illustrates the interaction of the three key barriers (thick-framed boxes).

Figure 37 Interaction of barriers to the development and uptake of wind propulsion technologies



Incentives to improve the energy efficiency/to reduce the CO_2 emissions of ships can be expected to raise the ship owners' willingness to participate in demonstration projects with WPTs which might have a positive impact on the availability of information on WPTs. Moreover, incentives to improve the energy efficiency/to reduce the CO_2 emissions of ships and the availability of trusted information on the WPTs can both be expected to directly stimulate the uptake of WPTs and, by raising the market potential, can also be expected to indirectly improve the access to capital for the development of WPTs.
But the availability of trusted information can also have a direct impact on the access to capital for the development of WPTs – the more reliable information on WPTs becomes available, the higher the confidence of potential investors in their risk assessment. However, in order to generate reliable information on WPTs, full scale demonstrators need to be build and tested and WPT developers cannot do so without access to capital, making this a chicken-and-egg problem.

5.2.1 (Trusted) information on the performance, operability, safety, durability, and economic implications of WPTs

This barrier has, as described in more detail under Section 4.2.3, several layers. On the one hand, there is not sufficient information available regarding the performance, operability, safety, durability, and economic implications of WPTs yet, because there is no long-term experience with WPTs and full scale demonstrators have hardly been build and tested, the latter because wind propulsion technology developers find it difficult to find ship owners that are willing to participate in pilot projects and find it difficult to raise capital to build and test full scale demonstrators, with the lack of (trusted) information impeding the access to capital, leading to the above mentioned chicken-and-egg problem. On the other hand, the value of the available information might be restricted since it might be not specific enough for potential user and because potential user might not trust the information.

This complex barrier can naturally not be solved by means of one measure. However, we see one important starting point for the barrier to be solved which is the creation of the prerequisites that allow for the assessment of the information that becomes available on WPTs.

Actions to facilitate assessment of information

Only if testing of demonstrators yields assessable information generated by an independent party, can the trust of ship owners and investors be gained and can public funds, which might be used to support the generation of the information, create a real value added.

The development of a standardized method to assess full scale WPTs installed on a ship is crucial in this context.

This standardized evaluation method should, in the first instance, focus on the assessment of the performance and should stipulate how and under which circumstances the performance should be assessed and how the testing conditions and testing results should be reported.

The assessment of the available effective power of a wind propulsion system is already required if ships want to use a wind propulsion system in order to comply with the Energy Efficiency Design Index (EEDI). Consistency of the standardized evaluation method with the EEDI technical guidance for the conduction of performance tests of wind propulsion systems should therefore be considered, but the valuation method should not be restricted to the determination of the available effective power of the systems, but should also include the determination of the actual fuel savings.

Whether the performance data obtained by applying the standardized assessment are verified by a third party is, though crucial, of course up to the developer of the WPT, but if building and testing of WPTs is supported with public funds, third party verification could be one of the support requirements. This also applies for the support of lab tests and simulations.

A test case could be very useful for the development of a standardized evaluation method and could thus be supported with public funds.

Concrete actions:

- Companies developing WPTs could take the initiative and set up a draft assessment method, could get tests verified by a third party and report test results transparently.
- The IMO/EU Commission could commission a study into the development of a standardized evaluation method of the performance of wind propulsion technologies, maybe combined with a test case.
- Companies developing WPTs, the EU Commission, and national authorities could advocate the further development of the EEDI technical guidance for the conduction of performance tests for wind propulsion technologies.
- The EU Commission/national authorities:
  - Could, if performance tests were supported with public funds, set requirements regarding the use of a standardized assessment method (once developed), verification, and publication of test results; national authorities could design measures that support testing of technologies in such a way that third party verification and publication of test results are rewarded. E.g. if test results are verified and published, a share of a paid-off soft loan could be refunded.
  - Could support the use of advanced fuel consumption monitoring systems for ship owners participating in trials.

Actions to advance the generation of information

The generation of information on WPTs can be supported by facilitating access to capital for the development of WPTs, especially for building and testing of full scale demonstrators (see Section 5.2.2 for a detailed discussion).

Other concrete actions:

- EU Commission/national authorities could support ship owners if they participated in a demonstration project.
- EU Commission/IMO could set up a system that facilitates matching between ship owners willing to participate in demonstration projects and developers of energy efficiency measures/CO_2 reduction measures.
- National authorities could, in its role as ship owner, support the generation of information, by participating in demonstration projects on state-owned ships, like patrol boats or navy vessels. In the Netherlands for example, trials with biofuel have been carried out on state-owned ships.

Actions to increase information value

The performance of WPTs depends on many variables, it is therefore important for ship owners to get performance data specific for their fleet. A (potential) technology provider however will not be able to cover a wide range of cases in advance. To alleviate this problem software could be developed by means of which ship owners can get an indication of the ship/fleet specific performance of a WPT. The GloMEEP energy efficiency appraisal tool (GLoMEEP, ongoing) is an example for such a tool and actually also includes WPTs, but does not allow for considering route specific wind conditions.

Concrete action:
- Companies developing WPTs/IMO/EU Commission/national authorities can fund the development of software with which ship owners can get an indication of the ship/fleet specific performance of WPTs.

Actions to improve access to information
Finally, there are different actions that can contribute to the dissemination of information on WPTs.
- companies developing WPTs/IMO/EU Commission could set up a platform containing information on measures of which performance has been verified by third parties;
- the IMO/EU Commission could facilitate an ongoing discussion among ship owners/operators and research institutes in order to exchange information and experience regarding energy efficiency measures and to get a better understanding of possible concerns.

5.2.2 Access to capital for the development of WPTs

For companies that develop WPTs for commercial purposes, the access to capital for the development of WPTs, especially for building and testing of full scale models and demonstration projects seems to be very difficult (see Section 4.4.1 for a detailed discussion of this barrier). The mainly small companies (SMEs) are not able to cover the high costs with their own funds and are not able to attract sufficient private and public external capital to this end. The available information on the WPTs does not allow a sound risk assessment for potential investors and companies find it difficult to meet the expected return on investment of venture capital investors. Regarding public funds, funds of some programmes seem not to be sufficient for demonstration projects while programmes with sufficient funding seem to be associated with an administrative effort that is too high and a payment scheme that is not viable for small companies. For some potential investors/public funds the projects are too small.

The development of a method to assess WPTs in a standardized way plays a crucial role in overcoming the chicken-and-egg problem between the access to capital for development of WPTs and the availability of trusted information on WPTs (see Section 5.2.1 for a detailed discussion).

Due to an insufficient regulation of CO_2 emissions from maritime shipping and current low bunker prices, the demand for energy efficiency measures will be suboptimal low from a welfare perspective; the thus limited market potential then contributes to a limited access to capital. Supporting the development of energy efficiency measures with public funds could therefore be warrantable.

Concrete actions:
- EU Commission/national authorities:
  - There are public funds available that fund, amongst other things, demonstration projects in the maritime shipping sector (e.g. Horizon 2020's 'Towards the energy efficient and emission free vessel' programme or Horizon 2020's SME Instrument Phase 2), but in order to improve the access to capital for companies that want to demonstrate the performance and operability of energy efficiency measures for maritime transport the following actions could be taken:
    - offer a payment scheme that is viable for SMEs;

    - keep the administrative effort as low as possible without compromising accountability;
    - offer programmes aimed specifically at demonstration projects for maritime shipping;
    - offer programmes aimed at demonstration projects for maritime shipping without narrowing down the eligible technologies beforehand.
  - Since ship owners need to be convinced about the performance and the operability of energy efficiency measures and could, if convinced, be an important multiplier, a public support programme could take the alternative approach by offering funds for a demonstration project whereas ship owners willing to participate receive funding for buying a demonstrator of a technology of their choice.
  - Next to support in terms of subsidies, public support for venture capital funds (as done by EIB) aimed at investments in energy efficiency measures could be intensified.
- National authorities could in addition alleviate the access to capital for the development of energy efficiency measures in different ways, for example by granting tax benefits to the investors or offering to lend a large share in a consortium loan to get other lenders on board.
- Companies developing WPTs :
  - can improve their access to capital by seeking more cooperation with different actors in the value chain of WPTs:
    - pooling of projects might enable them to gain access to funds aimed at larger projects;
    - WPT companies could try to enter into a long-term agreement with a shipper (shippers of high-value goods may be willing to accept higher transport costs if the ship/CO_2 efficient transport can be used for promotional purposes);
    - cooperation with companies in other EU countries/EU regions may qualify projects for specific EU public funds.
  - could license the technology to a financially stronger company.

5.2.3 Incentive to improve energy efficiency/reduce CO_2 emissions of ships

The incentive to improve the energy efficiency/reduce CO_2 emissions of ships is currently suboptimal from a social welfare perspective. This leads to a suboptimal uptake and market potential of energy efficiency measures, limiting also the access to capital for the development of the measures and to a lower willingness of ship owners to participate in demonstration projects.

A stronger incentive to improve the energy efficiency of ships can be achieved by either adjusting existing environmental regulatory measures and incentive schemes or by implementing additional environmental regulatory measures or incentive schemes.

Stricter Energy Efficiency Design Index (EEDI) requirements could incentivize the uptake of different technical efficiency measures and the formula for the attained EEDI could be a adjusted to give innovative energy efficiency technologies more weight. For both adjustments of the EEDI, the according timing would need to be carefully chosen. To adjust the formula for the attained EEDI makes probably more sense once some experience with the EEDI verification of ships equipped with wind propulsion systems have been made.

The reduction of the installed propulsion power is an option for compliance with the EEDI. However, the EEDI regulation (Regulation 21.5) also requires that the installed propulsion power should not be less than the propulsion power needed to maintain the manoeuvrability of the ship under adverse conditions. The uptake of WPTs could be incentivised by allowing ships equipped with wind propulsion systems to reduce their main engine power to a higher extent than ships not equipped with an additional propulsion system. This should however only be allowed if the safety of the ship is not impaired. MARIN is currently investigating this issue in a study commissioned by the Dutch Ministry of Infrastructure and Environment.

Different additional measures to incentivize the uptake of energy efficiency measures could considered for implementation at IMO level.

Market based measures for all ships and measures to improve the operational energy efficiency of existing ships have been discussed at the IMO, but there is still a controversy regarding a meaningful operational efficiency metric and no consensus could be reached regarding market based measures.

Alternative measures, like an energy efficiency design index for existing ships or a renewable energy target could also be considered by the IMO.

An energy efficiency design index for existing ships would however have the drawback that costs for existing ships to improve their design efficiency is higher than for newbuilds and that the reduction potential of the instrument is restricted to the potential of technical measures.

And for a renewable energy target for the shipping sector it holds that the basis for the target would have to be chosen carefully. Should the target for example be related to the energy consumption of ships of the same flag or to the fleet of a ship operator?

The incentive to improve energy efficiency/reduce CO_2 emissions of ships could also be increased If other sectors were allowed to use carbon credits from the shipping sector to comply with their sectoral environmental obligations, then the return on investment of CO_2 saving devices like WPTs could be improved. This would however require that the CO_2 reduction that can be achieved specifically by the use of a wind propulsion system would need to be determined. The thrust of the WPT can relatively easily be determined, but the assessment of the thereby obtained reduction of the main engines' fuel consumption is less straightforward.

The data ships report for the compliance with the EU MRV regulation will be made public. If ships that use innovative energy efficiency measures could report and publish the use of these measures this could be an incentive to install such measures. However, the performance of the WPTs may not be reflected in the published data, at least if the ships equipped with WPTs faced relatively unfavourable conditions (e.g. in terms of the cargo carried) in the reporting period compared to other ships.

Several ports have implemented schemes that reward environmental ships by, for example, granting rebates on port dues. If these schemes rewarded the fact that a WPT is installed on a ship, this could contribute to the uptake of these systems. Comparable to these environmental port incentives programmes, flag states could also reward environmentally friendly ships by granting rebates on their fees/taxes.

Liberia for example has recently decided to reward environmental friendly ships by granting a tonnage tax discount (Liberian Registry, 2016).

Concrete actions:
- IMO member states/NGOs with consultative status to IMO could on the short term advocate stricter EEDI requirements, the implementation of measures aimed at improving the energy efficiency of ships in operation/ to reduce the GHG emissions of all ships, and, if the safety of ships is not impaired, the use of WPT to comply with the EEDI minimum power requirement. In the long run, they could advocate a higher reward of energy efficiency technologies by the EEDI.
- The EU Commission could, within the framework of the MRV regulation, give ships the opportunity to publish the use of innovative energy efficiency measures.
- WPT developers could draw the attention of the organisations responsible for port/flag state environmental incentive schemes to incorporate WPTs.
- Flag states could reward environmentally friendly ships by granting rebates on their fees/taxes.

5.3 Possible actions to overcome other barriers

Commercial agreements/legal aspects

Some commercial agreements/legal aspects are a barrier to the uptake and thus indirectly to the development of WPTs.

Commercial agreements between consignors and consignees that may not allow for the adjustments in the logistical chain necessary for the use of WPTs can be adjusted/renegotiated in the long run. Whether consignees are willing to do so, will depend on different factors like the costs of the change of the supply chain, the consignees' market positions, the environmental awareness of their costumers, etc. A requirement to label a product with its life cycle emissions could for example give a product that is transported with an efficient ship a competitive advantage.

In order to alleviate the split incentives problem between ship owners and ship operators, two main approaches for solving this problem have been proposed: one approach is to find a way that ship owners can share in the fuel expenditure savings, by for example adjusting charter parties accordingly, and the second approach is, based on experience from the build environment, an approach in which a third party carries the investment costs and the ship operator pays off the investment from his fuel expenditure savings achieved by the use of the financed measures (Carbon War Room and UCL, 2014).
This would however require that the reduction that can be achieved by the use of the measure would need to be determined very precisely.

6 Conclusions

Many innovative wind propulsion technology concepts have been and are being developed for commercial shipping. However, none of the technologies has reached market maturity yet.

A multitude of barriers has been identified that currently prevent further development and uptake of the wind propulsion technologies (WPTs).

The following barriers have been established as key barriers:
1. (Trusted) information on the performance, operability, safety, durability and economic implications of the WPTs.
2. Access to capital for the development of WPTs, especially for building and testing of full scale demonstrators.
3. Incentive to improve energy efficiency/reduce CO_2 emissions of ships.

These key barriers are interrelated in different ways, with the most crucial interaction being a chicken-and-egg problem between the first and second key barrier. In order to generate reliable information on WPTs, full scale demonstrators need to be build and tested. WPT developers need access to capital in order to build and test full scale demonstrator, but without reliable information on WPTs, the risk assessment of potential investors is very uncertain and thus impedes the WPT developers' access to capital.

In order to breach this chicken-and-egg problem, we see the development of a standardized method to assess WPTs, combined with test cases to develop the assessment method, as the most important starting point. Only if testing of demonstrators yields assessable information generated by an independent party, can the trust of ship owners and investors be gained and can public funds, which might be used to support the generation of the information, create a real value added.

When developing a standardized method to assess WPTs, the consistency of the standardized evaluation method with the (to be developed) EEDI technical guidance for the conduction of performance tests of wind propulsion systems should be considered, but the evaluation method should not be restricted to the determination of the available effective power of the systems, but should also include the determination of the actual fuel savings. A test case could help to develop a standardized assessment method.

Only once a standardized assessment method has been developed, does it make sense to take measures that improve the generation of more information on the WPTs, that improve the access to and value of this information, and that (also) improve the access to capital for the development and testing of full scale demonstrators.

If there were sufficient incentives to improve the energy efficiency/reduce the CO_2 emissions of ships, some of these latter measures, especially the measures improving the access to capital may be superfluous. But since the incentive to improve the energy efficiency/reduce the CO_2 emissions of ships will probably not be improved in the short run, these measures should be taken if the development and uptake of WPTs is to be advanced.

The different stakeholders can thereby contribute with different actions.

A very important finding of the study is that there is a barrier that has been overestimated so far. The absolute savings that can be achieved by the wind propulsion technologies are found to depend differently on the speed of the vessel. Whereas for the towing kite and the wind turbine absolute savings tend to be equal or even lower at the higher speed, absolute savings are larger at the higher voyage speed for the wingsail and the rotor for all ship types considered. This implies that ships do not necessarily need to slow down for, at least some, wind propulsion systems to become cost efficient.

This insight has been generated with a new methodology for assessing potential fuel savings for individual ships and their actual routes sailed from AIS-data.

Should some wind propulsion technologies for ships reach marketability in 2020, the maximum market potential for bulk carriers, tankers and container vessels is estimated to add up to around 3,700–10,700 installed systems until 2030, including both retrofits and installations on newbuilds, depending on the bunker fuel price, the speed of the vessels, and the discount rate applied. The use of these wind propulsion systems would then lead to CO_2 savings of around 3.5–7.5 Mt CO_2 in 2030 and the wind propulsion sector would then be good for around 6,500–8,000 direct and around 8,500–10,000 indirect jobs.

The process of diffusion will however not have reached maturity in 2030 yet; this is expected to occur around 2040, when more newbuilds have entered the fleet (retrofits are more expensive than installation on newbuilds) and capital costs have further declined due to learning effects and economies of scales.

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Annex A Technology factsheets

Two different types of templates have been used for the technology factsheets, one for technology providers and R&D companies and one for R&D projects.

For technology providers and R&D companies the factsheet template as presented in Table 13 has been used.

Table 13 **Technology factsheet template regarding (potential) wind propulsion technology providers**

Type of wind propulsion technology	
Specific technology	
R&D company	
Location of technology provider	
Main characteristics of technology	
Ship types/sizes	
Retrofit/new builds	
Start of R&D activity	
Current state of development of technology	
Current state of deployment of technology	
2020/2030 state of development	
2020/2030 state of deployment	
Publicly available performance data	
References	www.monorotor.com/

For R&D projects the factsheet template as presented in Table 14 has been used.

Table 14 **Technology factsheet template regarding R&D projects**

Type of wind propulsion technology	
R&D project	
Aim of the project	
Organisations	
Project duration	
Technology analysed	
Technology developed	
Current state of development of technology	
Current state of deployment of technology	
2020/2030 state of development	
2020/2030 state of deployment	
Performance data	
References	

The templates focus on the current and future applicability of the technologies and their expected performance.

Regarding the performance data, only the non-confidential, publicly available data has been incorporated.

Note that the information provided in the factsheets is the information as stated by the (potential) technology providers and R&D companies in the survey or on their websites and has not been subject to a plausibility check.

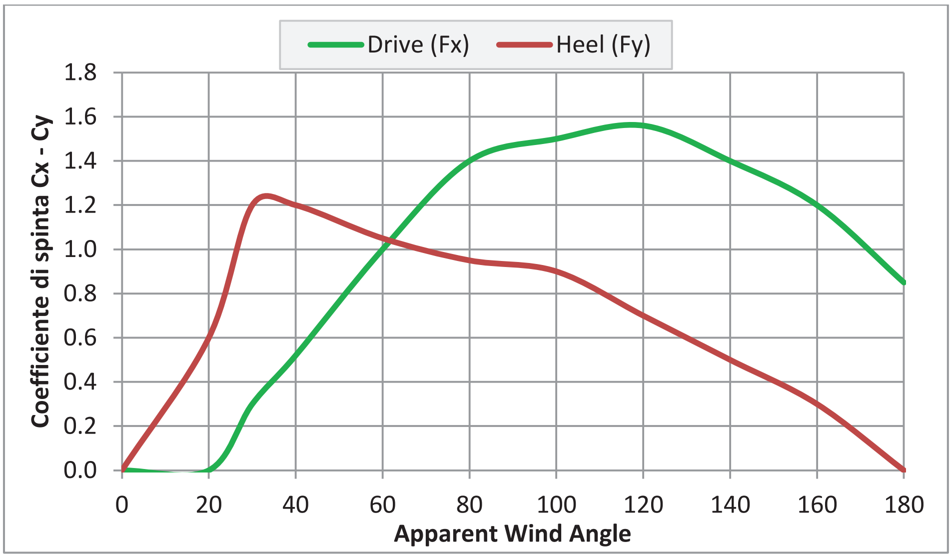
A.1 Soft sails

Type of wind propulsion technology	Soft sail
Specific technology	Pinta-Rig
R&D company	Modern Merchant Sailing Vessel
Location of R&D company	Germany
Main characteristics of technology	Aim of the company is to build a modern merchant sailing vessel equipped with automated square rigs, more in specific a bulk carrier for iron ore of about 70,000 dwt with five masts and a sail area of 10,465 square meters. The ship will not have a main engine, but 4 smaller diesel-generators of 600 KW being able to drive the ship with 10 to 12 knots in a case of an emergency.
Ship types/sizes	Cargo/bulk carriers
Retrofit/new builds	
Start of R&D activity	1978
Current state of development of technology	Prototype developed, wind tunnel tests and ship model water tank tests have been carried out.
Current state of deployment of technology	
2020/2030 state of development	Uncertain
2020/2030 state of deployment	Uncertain
Publicly available performance data	
References	Personal communication with Modern Merchant Sailing Vessel and websites: www.modern-merchant-sailing-vessel.com www.host-be.de/sss/images/stories/aktuell_mit_Segel.pdf

Type of wind propulsion technology	Soft sail
Specific technology	Delta Wing Sail
R&D company	Seagate Sail
Location of R&D company	Italy
Main characteristics of technology	Seagate Sail is developing a collapsible, automatic delta wing sail (2 booms are controlled through the control of the position of three lead cars within three guides). It aims at making a standard sail module of 500 m^2 to replicate every 40 m of free deck. The company develops a complementary technology ('Cruise control') to automatically regulate the motor thrust as a function of the driving force that is extracted from the wind.
Ship types/sizes	Ships from 60 m up to any size with sufficient deck space.
Retrofit/new builds	Both at least for tankers, bulk carriers and RoRo ships.
Start of R&D activity	2010

Type of wind propulsion technology	Soft sail
Current state of development of technology	Patents for the delta wing sail and the cruise control are registered, the system has been aerodynamically been validated in wind tunnel test and a kinematic validation on a 7 m demonstrator has been carried out.
Current state of deployment of technology	Promotion of the technology to stakeholders.
2020/2030 state of development	Ready for sale in 2020.
2020/2030 state of deployment	With sales volume rising f cost efficiency increases. Possibly the price can be halved by 2030.
Publicly available performance data	Expected relative fuel saving on an annual basis: 9% for RoRo, 13% for bulk carrier, 16% for tankers. See Figure 38 for the aerodynamic performance as established by wind tunnel tests.
References	Survey and website: http://seagatesail.com/

Figure 38 Aerodynamic performance of the Delta Wing Sail System



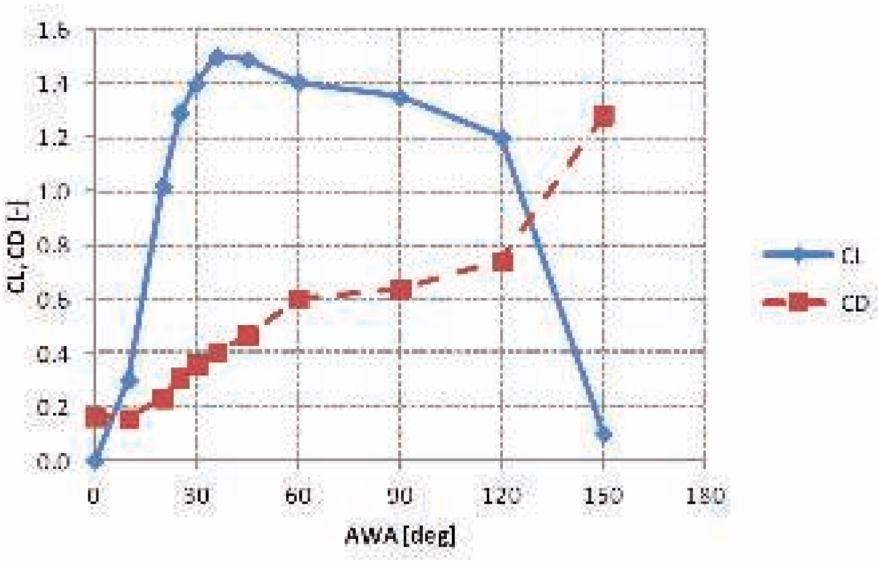
Type of wind propulsion technology	Soft sail
Specific technology	Fastrigs
R&D company	Smart green shipping alliance (SME with an alliance of shipping businesses from across industry).
Location of R&D company	UK
Main characteristics of technology	Hybrid sailing merchant ship using fastrigs (Future Automated Sail Technology). These automated square rigs are freestanding and capture wind for both smaller sailing-hybrid ships and provide wind assistance for larger vessels. The soft sail technology, based on the rig used on the Maltese Falcon is adapted to an industrialised automated square rig sail system, with an off-the-shelf Rolls-Royce LNG Bergen engine powered by waste derived liquid biomethane (LBM). Up to 50% of the propulsion comes from wind.

Type of wind propulsion technology	Soft sail
Ship types/sizes	Focus lies on small to medium size ships (up to 25,000 dwt) as a sailing hybrid (more than 50% contribution to propulsion) new build solution. Dry-bulk vessels, tankers, general cargo ships are target.
Retrofit/new builds	Both. Retrofits can be made on any size vessel to provide wind-assist (that is where wind makes a less than 50% contribution to the propulsion).
Start of R&D activity	SGSA was born out of B9 Shipping which has been active in the field for more than 20 years.
Current state of development of technology	Model testing of a 3,000 dwt concept vessel has been carried out.
Current state of deployment of technology	-
2020/2030 state of development	
2020/2030 state of deployment	
Publicly available performance data	Concept design testing indicates that new builds – where aero/hydro is optimised – can save 50% fuel on several routes of interest to shippers.
References	Survey and website: www.smartgreenshippingalliance.com/fastrigs/

Type of wind propulsion technology	Soft sail
R&D project	Neoline project
Organisations	Néoline France/Canada
Technology analysed	The Neoliner is a 5,300 tons RoRo ship fitted with innovative duplex rigging and equipped with an electric diesel auxiliary propulsion system. The polyvalent vessel is able to adapt to different type of merchandises (container, bulk, linear). Duplex rigging where masts are not aligned on a transverse axis, but as a perpendicular couple. Specifications: Length overall: 120 m Breadth overall: 21.50 m Displacement: 9,480 t Total sail surface: 4,300 m^2 Average commercial speed under sail: 11 kts Cargo capacity: 230 TEU or 5,300 t or 745 linear meters
Technology developed	Concept design phase finished.
Current state of development of technology	
Current state of deployment of technology	
2020/2030 state of development	
2020/2030 state of deployment	
Performance data	The daily fuel consumption of the Neoliner is 0.5 ton/day and 20-30 tons/day for a classic cargo ship.
References	www.neolinetransport.com/en/neo_acc.php

Type of wind propulsion technology	Soft sail
R&D project	Sail (Ecoliner)
Aim of project.	The activities of SAIL were to develop and test hybrid sailing concepts that lead to new business opportunities and a more sustainable future.
Organisations	17 partners from seven North Sea Region member states have been cooperating in the project: the province of Fryslân (NL), knowledge institutes, universities and ship operators from The Netherlands, Germany, Sweden, Denmark, Belgium, United Kingdom and France.
Project duration	2012-2015
Technology analysed	Dynarig
Technology developed	-
Current state of development of technology	Dykstra Naval Architects have created a design concept of the so-called Ecoliner, a 8,000 dwt multi-purpose cargo vessel equipped with three masts equipped with a Dynarig. The concept design phase is finished; extensive voyage simulations have been performed and wind tunnel tests have been carried out.
Current state of deployment of technology	-
2020/2030 state of development	Uncertain
2020/2030 state of deployment	Uncertain
Performance data	Lift and drag coefficient for the maximum driving force have been determined in wind tunnel tests for a 3 masts and 1,200 m^2 of sail area per mast configuration (see Figure 39).
References	sail (2015a), Dykstra Naval Architects (2013)

Figure 39 Sail force coefficients for maximum driving force



Source: sail (2015a).

A.2 Rigid sails

Type of wind propulsion technology	Rigid sail
Specific technology	Aquarius MRE™ (Marine Renewable Energy)/EnergySail
R&D company	Eco marine power
Location of R&D company	Japan
Main characteristics of technology	Aquarius MRE System is an advanced integrated wind & solar power system for shipping, using rigid sails, solar panels & energy storage modules to tap into renewable energy by harnessing the power provided by the wind and sun. The array of rigid sails will be automatically positioned by a computer system to best suit the prevailing weather conditions and can be lowered and stored when not in use or in bad weather. The rigid sails are based on EMP's EnergySail® technology and can even be used when a ship is at anchor or in harbour.
Ship types/sizes	Designed for large ships that operate at sea. Much of the technology will also be suitable for smaller vessels such as coastal freighters, passenger ferries, tourist boats and Unmanned Surface Vessels (USV's).
Retrofit/new builds	
Start of R&D activity	
Current state of development of technology	Patent pending for EnergySail, patent registered for Aquarius MRE™. One prototype built and passed feasibility testing in a test lab. A 2nd prototype is being built at a factory now and will be used for testing onshore and on a ship. Testing is due to start this year
Current state of deployment of technology	The first sub-system, the Aquarius Management & Automation System (MAS) is now available and the EnergySail has passed lab tests. Sea trials for the system are due to start during 2015-2016.
2020/2030 state of development	
2020/2030 state of deployment	
Publicly available performance data	Estimation that on an annual basis the system will reduce fuel consumption on an ocean going ships of between 5-20% (taking into account unfavourable weather conditions and days when the ship is not at sea). On smaller and/or specialised vessels the fuel savings and emission reductions could be significantly higher. On a large ship, 1,000 tonnes or more of bunker fuel could be saved annually by using the Aquarius MRE System.
References	Survey and website: www.ecomarinepower.com

Type of wind propulsion technology	Rigid sail
Specific Technology	Oceanfoil wingsail
R&D company	Ocean foil
Location of R&D company	UK
Main characteristics of technology	Oceanfoil®'s fuel-assist aerofoil technology uses wingsails to capture effective directional thrust from wind power. Each Oceanfoil® wingsail consists of three aerofoils attached to a tail fin or rudder, with each sail resembling the wing of an aeroplane

Type of wind propulsion technology	Rigid sail
	positioned vertically. Each wingsail is free to move on a central bearing, and when not in use remains in a feathered mode. There are two main wingsail position settings; ahead thrust or astern thrust. The astern thrust can also be used to slow the vessel. A vessel can be equipped with up to six Oceanfoil® wingsails, depending on the size of the vessel. Oceanfoil®'s wingsails are automatically controlled via a computer from the bridge so do not require crew resource. Once turned on, the computer will automatically optimise the position of the wingsails relevant to the wind for maximum efficacy.
Ship types/sizes	Tankers
Retrofit/new builds	Both
Start of R&D activity	
Current state of development of technology	Sea and model trials
Current state of deployment of technology	
2020/2030 state of development	
2020/2030 state of deployment	
Publicly available performance data	During the most recent trials in model testing, as well as in Computational Fluid Dynamic analysis, the new improved Oceanfoil® wingsail technology has been shown to deliver potential reduction in fuel consumption of up to 20%.
References	http://oceanfoil.com/

Type of wind propulsion technology	Rigid sail
Specific technology	Rigid opening Sail (R.O.S.)
R&D company	Ocius Technology Ltd.
Location of R&D company	Australia
Main characteristics of technology	A solar sail from flat, hinged and collapsible steel affixed to the deck between the main hatches, powered by simple, hydraulic motors. Sails are up to 35 m x 10 m when folded - 35 x 20 m when unfolded. System is activated, controlled, and deactivated by a computer with manual over-ride.
Ship types/sizes	Bulkers, tankers, general cargo.
Retrofit/new builds	Both for tankers and bulkers; General cargo: new builds only.
Start of R&D activity	2000
Current state of development of technology	Design, patent, prototype development.
Current state of deployment of technology	Used in scale models and unmanned surface vessel prototypes.
2020/2030 state of development	-
2020/2030 state of deployment	-
Publicly available performance data	Expected relative savings from this optimisation are approx. 20% if voyage is crossing the equator and 40% if staying in same hemisphere. Expected relative fuel saving: 20-40% from wind at 13.6 knots by 'motor sailing'.
References	Survey and website: http://ocius.com.au

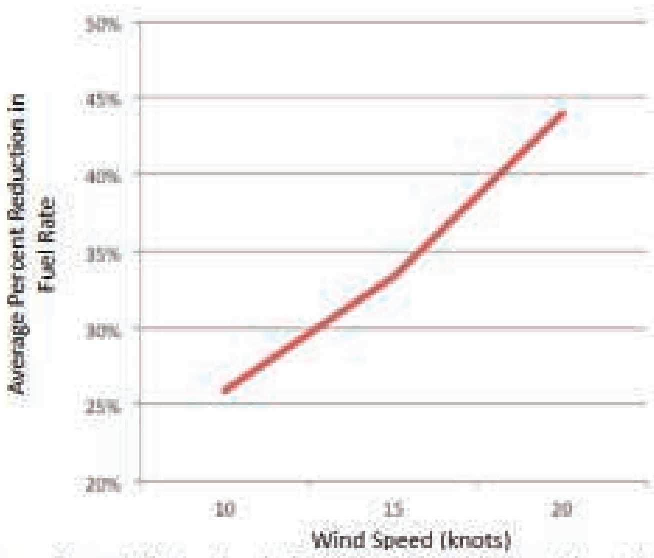
Type of wind propulsion technology	Rigid sail
Specific technology	PROPELWIND
R&D company	Propel Wind
Location of R&D company	France
Main characteristics of technology	Applying sailboat technology to the propulsion of merchant ships. Both for main propulsion and assistance to propulsion. The rigid articulated wing-sail that is used in high-tech sailing competition was selected as the basic device. Characteristics: 360 degrees free rotation, foldable, hydraulic, heavy duty materials, few moving parts, automatic control.
Ship types/sizes	Small vessels: cruise, light cargo. Max. 10,000 dwt
Retrofit/new builds	Both
Start of R&D activity	2008
Current state of development of technology	Startup R&D: studies and investigation on a midsize LPG tanker.
Current state of deployment of technology	9 wingsail configurations tested by CFD(aero/hydro).
2020/2030 state of development	
2020/2030 state of deployment	
Publicly available performance data	A suitable wingsail set can propel a 10,000 dwt ship during 90% of the time, drastically reducing fuel costs and emissions by a factor between 10 and 15, while maintaining a commercially acceptable average speed on reasonably favourable routes. The average fuel saving is 30%, with 23% on the mainly upwind leg and 37% on the other one.
References	PROPELWIND (2013) and website: www.propelwind.com/pw/home.html

Type of wind propulsion technology	Rigid sail
Specific technology	Auxiliary Sail Propulsion System (ASPS)
R&D company	Windship Technology Ltd.
Location of R&D company	London, UK
Main characteristics of technology	ASPS uses fixed wingsail technology, whereby two 35-metre high masts installed on the deck of a vessel with each mast being fitted with three aerodynamic wings, 40 feet (12 metres) above the deck. The masts (or rigs) rotate automatically to exploit the power of the prevailing wind and, as the speeds and angles of the wind change, the system develops more power, allowing reductions in engine power to be made in order to achieve the same speed and so maximise on fuel saving.
Ship types/sizes	ASPS can best be applied to large vessels (40,000 dwt and above). The focus market are bulk carriers.
Retrofit/new builds	Both possible for bulk carriers.
Start of R&D activity	The company has started working on wind propulsion in 2011.
Current state of development of technology	Patent applications are pending in 18 countries that are crucial for shipping. A full scale CFD test has been carried out, but a prototype has not been build yet.

Type of wind propulsion technology	Rigid sail
Current state of deployment of technology	-
2020/2030 state of development	In principal, the system can be ready for sale in 2019.
2020/2030 state of deployment	
Publicly available performance data	Handy/Panamax type bulkers are expected to save on average 30% fuel per annum. The power curve for 2 triple Windship rigs shows that at 30 knots apparent wind speed and an apparent wind angle of 70 to 120 degree, about 90% of the main engine power can be substituted by the system. The lift coefficient of the ASPS can be up to 2.5.
References	Survey and website: www.windshiptechnology.com/

Type of wind propulsion technology	Rigid sail
Specific technology	Wingsail
R&D company	Wind + wing technologies
Location of R&D company	USA
Main characteristics of technology	Wind + Wing developed a computer controlled hard wing sails to provide a wind-assist hybrid ferry propulsion system. The Wingsail functions as an independent system on-board the vessel, using the small solar panel to provide electrical power for a GPS unit, an ultrasonic wind-speed monitor, and the wing trim tab that is used to settle wing to the optimal angle relative to the incident wind direction. Photon Composites constructed the wing out of carbon fibre, and it is completely powered by a small photo-voltaic cell on the side of the wing. System is fully automatic with on/off button. When the wing is on, it will automatically set itself to the optimal wind angle and will start saving fuel, When it is off, it gets out of the way and acts like a giant weather vane. Specifications: Wing height: 15 m, 25 m, 30 m
Ship types/sizes	Passenger ferries
Retrofit/new builds	Both
Start of R&D activity	
Current state of development of technology	Patent application, technology is developed. Technology has been demonstrated on a test vessel. The aim is to launch a fully operational, public passenger ferry in 2017.
Current state of deployment of technology	Ready for sale in 1-2 years
2020/2030 state of development	Adoption of the technology on local level and steady growth on regional/national/world level.
2020/2030 state of deployment	
Publicly available performance data	At wind speeds of 10 to 20 knots and with a boat speed of seven knots through open water, average fuel rate reductions from wind-assist for the study period ranges from 26 to 44%. If the test vessel is traveling in an optimal angle to the wind, these efficiency gains ranged from 34 to 56% (depending on wind speed). See figures below.
References	Survey, UC Berkeley TSRC and Wind+Wing Technologies (2014), and website: www.windwingtech.com/

Figure 40 Average percent reduction in fuel rate by wind speed from use of wingsail



7: Average Percent Reduction in Fuel Rate by Wind Speed from Use of Wingsail

Table 1: Percent Improvement in Fuel Rate by Wind Speed and for "Average" and "Optimal" Wing Angles

Wind Speed (knot)	Avg. Fuel Rate Percent Improvement	Under Optimal Wind Angles
10	26.0%	34.4%
15	33.3%	36.9%
20	44.4%	56.1%

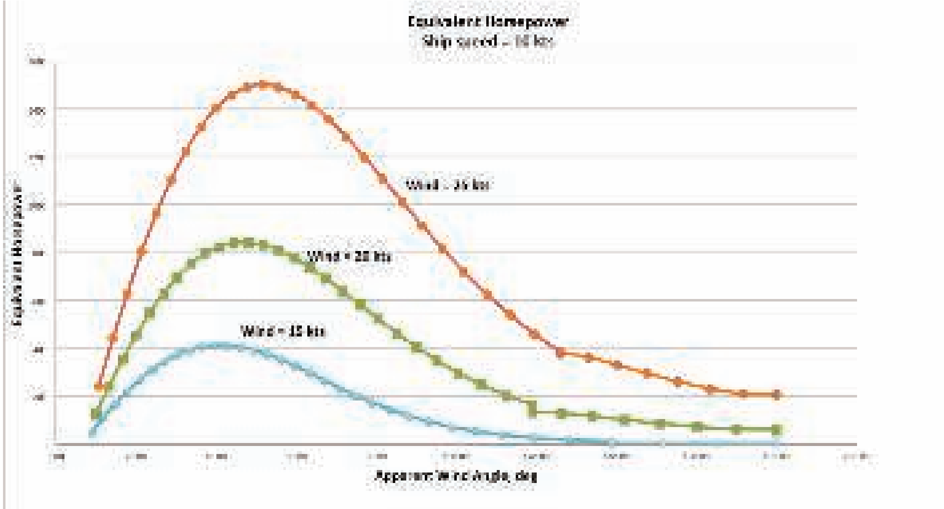
Figure 41 Pilot of median fuel burn rate reduction by wind angle to boat (with trend line)

Figure 10: Plot of Median Fuel Burn Rate Reduction by Wind Angle to Boat (with trend line)

Type of wind propulsion technology	Rigid sail
Specific technology	No specific name
R&D company	Wing systems
Location of R&D company	USA
Main characteristics of technology	The wing system consists of an A-frame rig to a large single or multi hull vessel. Potential benefits of the A-frame rig configuration are a geometrically rigid structure that ties into the ship's hull form while keeping decks clear for cargo handling and a sailing geometry that provides some measure of dynamic stability and damping of motion in a seaway.
Ship types/sizes	
Retrofit/new builds	
Start of R&D activity	
Current state of development of technology	
Current state of deployment of technology	
2020/2030 state of development	
2020/2030 state of deployment	
Publicly available performance data	A completed large scale model tests indicates the possibility of significant fuel savings in motor sailing mode. Further testing awaits refinement of rig details and development of a standardized procedure for expansion of performance data.
References	www.wingsystems.com/Wind-Assisted-Shipping.aspx

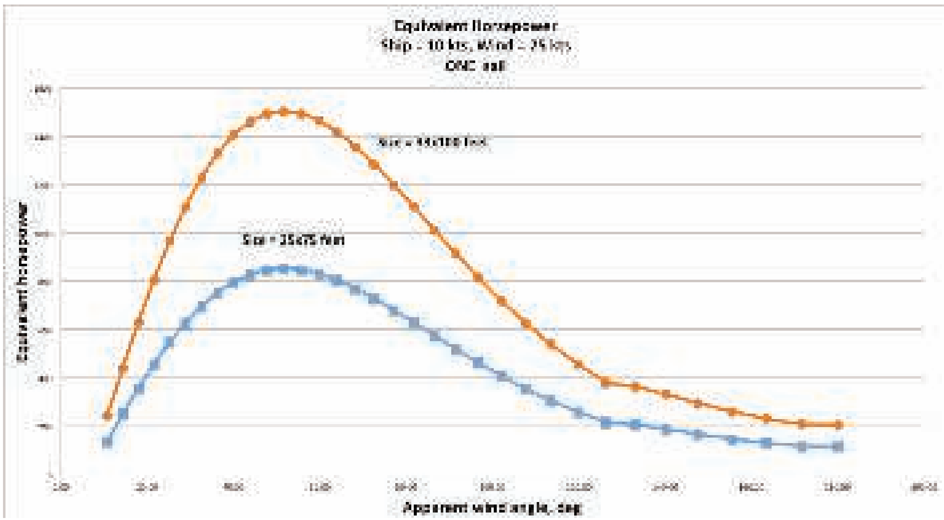
Type of wind propulsion technology	Rigid sail
Specific technology	COMSAIL Wing
R&D company	Sail Freight International
Location of R&D company	USA (New York State)
Main characteristics of technology	Wings that are supported on the top and on the bottom by means of a bi-pod rigging system.
Ship types/sizes	Tankers and bulk carriers.
Retrofit/new builds	
Start of R&D activity	1985
Current state of development of technology	Patent is pending.
Current state of deployment of technology	
2020/2030 state of development	
2020/2030 state of deployment	
Publicly available performance data	Figure 42 and Figure 43 give the equivalent horsepower, depending on the apparent wind angle for alternative wind speeds and alternative sail sizes respectively.
References	Sail Freight International and ViGYAN Inc.(2013) and website: http://sailfreight.weebly.com/

Figure 42   Equivalent horsepower depending on apparent wind angles for alternative wind speeds



Source: Sail Freight International and ViGYAN, Inc.(2013).

Figure 43   Equivalent horsepower depending on apparent wind angles for alternative sail sizes



Type of wind propulsion technology	Rigid sail
R&D project	Wind Challenger Project
Aim of project	Development of a large rigid sail system
Organisations	The project is an industry-university joint research project lead by The University of Tokyo.
Project duration	The project started in 2009 and is still going on.
Technology analysed	
Technology developed	The WCP has developed a large rigid sail of light material that has a self-rotating mechanism and is retractable (vertically telescope reefing).
Current state of development of technology	On-land test with a large scale sail model (1/2.5 size, Height: 20 m, breadth:10 m) has been carried out in 2014. The detailed design of a real sail equipped ship is expected to be finished in 2016. The service of the 1st ship is aimed at in 2017.
Current state of deployment of	-

Type of wind propulsion technology	Rigid sail
technology	
2020/2030 state of development	
2020/2030 state of deployment	
Performance data	Nine rigid sails (total sail area 9,000 m^2) are expected to generate forward thrust enough to drive a 180,000 dwt bulk carrier at the speed of 14 knots, in case of wind velocity of 12 m/s from a beam. When 4 of the sails (height: 50 m and width: 20 m) are installed on a 84,000 dwt bulk carrier, it is estimated that more than 30% yearly average energy saving is possible for the round voyage between Yokohama, Japan and Seattle, USA. This result is based on the optimum routing simulation.
References	Ouchi et al (2013) and website: http://wind.k.u-tokyo.ac.jp/project_en.html

A.3 Hull sails

Type of wind propulsion technology	Hull sail
Specific technology	Vindskip (Vindskip's Wind Power System)
R&D company	LadeAs
Location of R&D company	Norway
Main characteristics of technology	Vindskip™ is a hybrid merchant vessel for sustainable sea transport, driven by the wind and LNG. Unique is the shape of the hull, both above and below the water line. The vessel has a hull shaped like a symmetrical air foil going in the relative wind*. This will generate an aerodynamic lift giving a pull in the ships direction, within an angular sector of the course. With an LNG propulsion system in addition, starting the ship from zero up to the desired speed, the aerodynamic lift now generated can be exploited to generate pull and thus saving fuel ** True wind is the wind measured on board of a stationary ship. When the ship starts moving, the so-called relative (or apparent) wind is being generated. The Wind Power System of Vindskip utilizes this Apparent Wind and generates a positive force in the longitudinal direction of the ship as a function of the angle of attack*
Ship types/sizes	Dry cargo ships type such as RoRo, RoPax, PCTC, passenger and container ships.
Retrofit/new builds	New builds
Current state of development of technology	Patent registered
Current state of deployment of technology	
2020/2030 state of development	
2020/2030 state of deployment	
Publicly available performance data	Fuel savings estimated at 60%, reduction in emission estimated at 80%
References	www.ladeas.no/

A.4 Towing kites

Type of wind propulsion technology	Towing kite
Specific technology	SkySails Propulsion System
Technology provider	SkySails GmbH
Location of technology provider	Germany
Main characteristics of technology	The SkySails-System consists of three main components: a towing kite with rope (the flying system), a launch and recovery system and a steering (control) system for fully automatic operation. The SkySails System tows the ship using large, dynamically flying towing kites. The towing kite is made of high-strength and weatherproof textiles. It is double-walled and fitted with chambers along its entire length as well as ports at the front end. Kite surfaces: 160-600 sqm, 2 MW propulsion power; system weight abt. 30 tons
Ship types/sizes	All types and sizes of vessel (minimum length of 100 m and max. speed of 18 knots)
Retrofit/new builds	Both
Start of R&D activity	SkySails was established in 2001.
Current state of development of technology	Developed
Current state of deployment of technology	Ready for sale. The system is installed on 3 multi-purpose vessels and ordered for another 3 vessels (two general cargo vessels and a bulk carrier). 300 patents in 16 patent families issued/applied for.
2020/2030 state of development	-
2020/2030 state of deployment	SkySails plans to equip 3,000 cargo ships and fish trawlers, as well as numerous superyachts, with SkySails-System by the year 2020. SkySails estimates to save an accumulated 78 million barrels of fuel and 34 million tons of CO_2 emissions by 2020.
Publicly available performance data	The SkySails System generates up to 25 times more energy per square meter than conventional sails propulsion systems. This equals up to 2,000 kW of propulsion power in good wind conditions. Fuel consumption can be cut in half on good days and save an average of 10-15% in fuel every year. Expected average fuel saving: 2-3 tons/day; up to 10 tons/day in good wind conditions. SkySails-System SKS C 160 is capable of saving 198 tons of fuel and 632 tons of CO_2 per year when installed on a cargo vessel crossing waters with a high wind energy potential like the North Atlantic or the North Pacific Ocean and using route optimization. The SKS C 320 with doubled sail area is twice as powerful and effective regarding savings.
References	Survey, Beluga et al. (2010) and website: www.skysails.info/english/skysails-marine/skysails-propulsion-for-cargo-ships/advantages/

A.5 Rotors

Type of wind propulsion technology	Rotor
Specific technology	Norsepower Rotor Sail Solution
Technology provider	Norsepower
Location of technology provider	Finland
Main characteristics of technology	The Norsepower Rotor Sail Solution is a modernized version of the Flettner rotor, a spinning cylinder that uses the Magnus effect, which harnesses wind power to propel a ship. Rotor Sail height of 18, 24 or 30 metres. The weight of a single unit varies from 21 t (18 m x 3 m) up to 45 t (30 m x 5 m). The system is fully-automated.
Ship types/sizes	Mainly designed for tankers, bulk carriers, RoRo vessels, ferries and cruise vessels, which are bigger than 5,000 dwt.
Retrofit/new builds	Retrofit and new vessels
Start of R&D activity	Company was established in November 2012
Current state of development of technology	Patented, proven and ready for sale.
Current state of deployment of technology	The first of the Rotor Sail Solution was installed on M/V Estraden (9,700 dwt RoRo carrier) in 2014 (prototype) and the second (commercial order) was installed on-board the vessel in November 2015.
2020/2030 state of development	
2020/2030 state of deployment	By 2022: delivery of the solution to 200 vessels, reaching the targeted long-term cost and price levels.
Publicly available performance data	Fuel savings of 5 up to 30% for vessels with multiple, large rotors traveling on favourable wind routes.
References	Survey, NAPA (2015), Suominen (2015) and website: www.norsepower.com/

Type of wind propulsion technology	Rotor
Specific Technology	Turbosail™
Technology provider	Turbosail
Location of technology provider	Singapore
Main characteristics of technology	In contrast to the traditional Flettner rotor, the Turbosail is a non-rotating fan-driven design and is therefore sometimes not classified as a rotor but as a sail (e.g. suction sail).
Ship types/sizes	
Retrofit/new builds	
Current state of development of technology	The technology is patented and is fully developed.
Current state of deployment of technology	The research vessel *Alcyone* build 1985 is equipped with two turbosails.
2020/2030 state of development	
2020/2030 state of deployment	
Publicly available performance data	When compared to the thrust coefficient of the best sails ever built (Marconi or square types, i.e. ships of the American Cup or the Japanese wind propulsion system) that of the Turbosail is 3.5 to 4 times superior.

Type of wind propulsion technology	Rotor
	Average fuel savings of 35% have been demonstrated by the research vessel *Alcyone*. When installed on large bulk carriers or oil tankers, the Turbosail™ system is expected to provide on average 10% fuel savings.
References	Bureau Mauric (2013), CML (2014), and websites www.turbo-sail.com www.cousteau.org/fr/technologie/turbovoile

Type of wind propulsion technology	Rotor
Specific technology	Monorotor
R&D company	Bridgeport Magnetics Group Poulsen Hybrid
Location of technology provider	USA (Conneticut)
Main characteristics of technology	Monorotor is a single rotor concept where the rotor is located at the forepeak above the forecastle, or at the aft of the superstructure, straddling the stern. Monorotors will be made available in several models with diameters ranging from 8 to 24 meters, featuring one of three standard driveshaft assemblies, and a height of 20-25 meters.
Ship types/sizes	Cargo
Retrofit/new builds	Both. Easy retrofit on bulk carriers and tankers.
Current state of development of technology	Patents pending, no full size prototype or sea trial yet.
Current state of deployment of technology	-
2020/2030 state of development	
2020/2030 state of deployment	
Publicly available performance data	Saves 20-35% on fuel consumption dependent on wind conditions.
References	Poulsen Hybrid (2012) and website: www.bluebird-electric.net/ship_boat_design_building/monorotor_wind_assisted_ship_propulsion.htm

Type of wind propulsion technology	Rotor
Specific technology	Magnuss VOSS
R&D company	Magnuss
Location of technology provider	USA (New York)
Main characteristics of technology	Magnuss Vertically-Variable Ocean Sail System (VOSS) is a mechanical sail. The sail is a 100-foot tall spinning, hollow, metal cylinder that propels a ship. The rotating, retractable cylinder harnesses the wind to propel a ship by means of the Magnus Effect, wherein a rotating cylinder in an air stream generates a force roughly perpendicular to the air stream.
Ship types/sizes	Cargo ships (dry bulk and tankers)
Retrofit/new builds	Both
Start of R&D activity	Magnuss was founded in 2011

Type of wind propulsion technology	Rotor
Current state of development of technology	
Current state of deployment of technology	-
2020/2030 state of development	
2020/2030 state of deployment	
Publicly available performance data	Magnuss VOSS™ technology can save vessels up to 50% in fuel costs under optimal wind conditions.
References	http://magnuss.com/index.html

Type of wind propulsion technology	Rotor
Specific technology	ThiiiNK Sail rotor
R&D company	Thiiink
Location of technology provider	Switzerland
Main characteristics of technology	THiiiNKSail© uses large scale rotors, fitted with a sail flap which gives superior performance particularly for more narrow upwind tacks. The THiiiNK folding flettner rotors can be hydraulically folded onto a vessel's deck.
Ship types/sizes	Initial target market are tankers
Retrofit/new builds	Both
Start of R&D activity	
Current state of development of technology	
Current state of deployment of technology	-
2020/2030 state of development	
2020/2030 state of deployment	
Publicly available performance data	The new 'THiiiNKSail©' technology improves the performance of a standard Flettner rotor by up to 50% mainly due to an increase in lift.
References	www.thiiink.com/

Type of wind propulsion technology	Rotor
R&D project	sail (Flettner Freighter)
Aim of project	The activities of *sail* were to develop and test hybrid sailing concepts that lead to new business opportunities and a more sustainable future.
Organisations	17 partners from seven North Sea Region member states have been cooperating in the project: the province of Fryslân (NL), knowledge institutes, universities and ship operators from The Netherlands, Germany, Sweden, Denmark, Belgium, United Kingdom and France.
Project duration	2012-2015
Technology analysed	Flettner Rotor
Technology developed	-
Current state of development of technology	C-Job Naval Architects have created a concept design for a cargo ship equipped with 4 Flettner rotors and a main engine running on LNG, the so-called Flettner Freighter.
Current state of deployment of technology	-
2020/2030 state of development	Uncertain.

Type of wind propulsion technology	Rotor
2020/2030 state of deployment	Uncertain.
Performance data	With a rotating cylinder 8–10 times more power can be absorbed from the wind compared to sails or wing-shaped structures of similar size. **Fuel Saving** – While sailing at 13 knots of speed, fuel can be saved on headings between 30–170 degrees relative to the true wind. The greatest contribution can be obtained at headings between 80–100 degrees. – The rotor applied on a vessel is effective from wind speeds starting from 2 Bft and its effectiveness increases significantly with the wind speed. – In fully loaded condition while sailing in 4 Bft wind, the average power contribution over all headings of four Flettner rotors can be approximately 18% of the normal upright resistance, with a maximum of 38% when sailing at half wind headings (power delivered to rotors subtracted in calculations). In 6 Bft wind, the average contribution can be approximately 50% with a maximum of 95%. – The aft set of rotors can be moved longitudinally over the hold. This feature ensures the sail balance can be obtained in all headings and wind speeds resulting in the optimum forward thrust and minimum resistance. – Another side effect which can also contribute to fuel savings is the gyroscopic force that is generated by the rotors while rotating, which may contribute to the damping of undesirable rolling motions.
References	sail (2015a), sail (2015b)

Type of wind propulsion technology	Rotor
R&D project	'Wind Hybrid Coaster' project as part of the MariTIM project.
Aim of project	The aim of the project was to develop a new generation of Flettner rotors particularly suitable for coastal shipping.
Organisations	The project was carried out by a German-Dutch private-public consortium of 15 partners. The MariTIM project was managed by MARIKO GmbH.
Project duration	Project started September 2011
Technology analysed	Flettner rotor
Technology developed	Eco Flettner
Current state of development of technology	The concept of the rotor has been finished and a prototype (height: 18 m, diameter: 3 m) has been build. The rotor is almost ready to go into production. Expected to be ready for sale in one year (end 2017).
Current state of deployment of technology	The project is in preparation for a one-year test phase on a general cargo ship – the 'MV Fehn Polllux'.
2020/2030 state of development	

Type of wind propulsion technology	Rotor
2020/2030 state of deployment	Uncertain
Performance data	Under optimal conditions 100% the rotor can take over 100% of the propulsion. The expected relative fuel saving depends on size and number of the rotors. For a 3,800 dwt ship with main engine power of 1,200 kW and 2 rotors (3 x 18m) at European coastal trade and with a service speed of 12 kn, the average fuel savings are estimated to be between 11% and 25%.
References	MariTIM (2015a,b,c), survey, and website: www.maritim-de-nl.eu/projekte/wind-hybrid-coaster/

Type of wind propulsion technology	Rotor
Specific technology	Suction wing propeller
R&D company	CRAIN (Centre de Recherche pour l'Architecture et l'Industrie Nautiques)
Location of technology provider	France (La Rochelle)
Main characteristics of technology	The suction wing concept is based on the boundary layer suction, preventing flow separation associated with a thick profile. Compared to rotors, there is no external rotating part. Incidence needs to be adjusted but the system is mostly fixed.
Ship types/sizes	Small vessels up to VLCCs. Preferred market: retrofitting of existing vessels of 50,000 dwt and more with service speed of 12 knots or less.
Retrofit/new builds	Both
Start of R&D activity	2009
Current state of development of technology	Reduced scale prototype is under construction.
Current state of deployment of technology	
2020/2030 state of development	Full scale testing
2020/2030 state of deployment	
Publicly available performance data	The suction wing concept is able to generate lift coefficients (about 8) in the same order of magnitude than rotors and much higher than standard profile (soft or rigid sail). As a consequence, the size of the system can be reduced (at least by a factor 4 compared to conventional sails/wings) The system requires energy to run (in order to suck the air inside), as well as the rotor to rotate, but energy consumption is relatively low. The system shows a better lift to drag ratio compared to rotors. Relative fuel savings are expected to lie in the 10% to 35% range, depending on the size of the system.
References	Survey

A.6 Wind turbines

Type of wind propulsion technology	Wind turbine
Specific technology	Eco Vert ™
R&D company	Inerjy
Location of R&D company	USA (Florida)
Main characteristics of technology	Vertical-axis electrical generation wind turbine for either supplementing hotel load or providing electrical propulsion energy.
Ship types/sizes	Can be integrated on a multihull down to 50 T and a monohull down to 100 T. For load supplementation the turbine may be used on any larger sized vessel of any type.
Retrofit/new builds	Both
Start of R&D activity	R&D activity on wind power started in 2009 and R&D regarding vessel use in 2015.
Current state of development of technology	Seeking multiple demonstration applications/ currently working on demonstration vessel.
Current state of deployment of technology	Land-only with a few pending changes required for marine version.
2020/2030 state of development	This plan will be market driven. Currently investigating interest level and establishing partnerships for the yacht concept demonstration (Gemma One).
2020/2030 state of deployment	
Publicly available performance data	Main engine equivalent power: 70 kW, 300 kW or custom size. Expected relative fuel savings: Approximately 8 l/hr diesel (70,000 l annually full time) for 70 kW machine, 34 l/hr (300,000 l annually full time) for 300 kW machine in annual average conditions, route and location dependent. Almost 50% of the kinetic energy in the wind within the boundary of space that the blades pass through is converted into usable electricity. EV75 is designed to produce <25kN force at its hub in a 69.5m/s wind.
References	Survey and website: http://inerjy.com

Type of wind propulsion technology	Wind turbine
Specific technology	Foldable wind turbines
R&D company	ProPit
Location of R&D company	Sweden
Main characteristics of technology	PROPit has developed foldable wind turbines on board for commercial ships, providing fuel savings by letting on-board wind turbines create thrust and electricity. The rotation of the wind turbine produces electrical power through a conventional generator to replace electricity otherwise generated by the auxiliary diesel engines, thus reducing the need for fuel oil combustion. To the extent where there is surplus power this can be transmitted to an electrical engine connected to a shaft generator. The turbine is designed to produce not only electricity but also thrust, which assists in driving the ship forward.

Type of wind propulsion technology	Wind turbine
	The wind turbines are ship-mounted and the masts are foldable in an automated bridge controlled operation.
Ship types/sizes	Commercial ships (ocean going tankers or bulk carriers).
Retrofit/new builds	
Start of R&D activity	
Current state of development of technology	
Current state of deployment of technology	
2020/2030 state of development	
2020/2030 state of deployment	
Publicly available performance data	Two different cases were analysed, one for a VLCC with 260,000 dwt and one for a product tanker with 11,000 dwt. Fuel savings ranging from 15 to 28% for the larger and between 6 and 16% for the smaller ship have been established with high certainty in both studies. This has been verified by research at Chalmers University of Technology and through a broad industry collaboration.
References	http://propit.se/

Annex B List of survey participants

The following eleven (potential) wind propulsion technology providers have participated in the survey:

Soft sails:
- Modern Merchant Sailing Vessel
- smart green shipping alliance
- Seagate Sail

Rigid sails:
- Eco Marine Power
- Ocius Technology Ltd.
- Windship Technology Ltd.

Towing kite:
- SkySails GmbH

Rotor:
- CRAIN
- Norsepower
- ‘Wind hybrid challenger project’(Eco Flettner)

Wind turbines:
- Inerjy

Annex C Quenstionnaire

Questionnaire on wind propulsion systems for ships

1. Please let us know about your **company:**
   a Where are you located?
   b What is the size of your company?
   c Is it a subsidiary of a larger company?
   d Is wind energy technology the principal concern of your company?
   e When did your company start working on wind propulsion technologies?

2. **Which** wind propulsion **system** are you currently developing/offering?

3. What is the **basic working principle** of this wind propulsion system?

4. What is the main **difference** between your system and other systems of the same propulsion type (like e.g. other rotors or other rigid sails, etc.)?

5. To which **types** and **sizes** of **vessels** can (do you expect) your system (to) be applicable?

6. What is (has been) the initial market for the system pilot test and demonstration?

7. Please describe the **physical characteristics** of the propulsion system you offer and are planning to offer until 2020 and 2030:
   a What are the physical dimensions (such as e.g. height, square metres, weight, etc.) of the different systems you offer?
   b How can the system be adjusted/optimised for individual ships?

8. Please describe the **installation** of the propulsion system:
   a Is your system for new build vessels, retrofit, or both?
   b Where on the ship should the system be installed?
   c Which changes do you need to make to the original ship structure in order to install your system?
   d Do you need to strengthen significantly the original ship structures in order to install and operate your propulsion system in a safe way?
   e What choices of new build ship design criteria could be affected (e.g. deck configuration)?
   f Where (in terms of location) can the system be installed (e.g. dry dock, port, etc.)?
   g Can installation take place in any shipyard around the world or are there specific requirements/conditions?
   h What stakeholders are involved in the process of installation?
   i How long does it typically take to install the system? Can the system be installed during the standard dry docking period?

9. Please describe the **operation** of the propulsion system:
   a. Please describe how the system is activated, controlled, and deactivated.
   b. Is it a manual/semi-automated/fully-automated system?
   c. Does your system require additional crew members to operate the system and are specific skills and trainings required?
   d. Which are the optimal operating conditions (preferred wind speed, speed regime, etc.)?
   e. Since a ship's maneuverability will be affected by the extra forces induced by the wind devices, do you require extra training for the crew members/captain to adjust their navigation behaviour to best use the wind power?
   f. Is there a need to/a benefit from changing or re-optimising sailing routes and/or sailing speed and how should these be optimised?
   g. What are the expected relative savings from this optimisation?
   h. Under which conditions can the technology not be operated?
   i. Are there areas/regions/routes where ships are not allowed to operate the propulsion system and why?
   j. Are you aware of routes/trades that lend themselves very well for the operation of your system?
   k. Are there complementary systems that ship operators have to use to ensure optimal operation of your propulsion system (such as a weather routing system)?

10. Please specify what can be said about the **performance** of the technology:
   a. Can you specify the expected main engine equivalent power of your system?
   b. What is the expected relative fuel saving on a daily and annual basis?
   c. Under which conditions (route, weather, speed, etc.) is this annual relative saving attainable and which determining factors play a key role here?
   d. What numbers describe the aerodynamic performance of the system (e.g. lift and drag in various wind conditions, fuel consumption of the system, etc.)?
   e. For your technology, what are the best estimates of these parameters (including uncertainty ranges)?
   f. What forces act on your wind technology devices and on the ship?
   g. Does the wind power technology require or produce energy (and if so, how much) or does it just generate thrust or lift?
   h. Is there any other specific information relevant to the performance of your system?
   i. How have these effects been determined (e.g. pilots, test bed, model calculations, etc.)?
   j. Have the reported effects been verified by a third party?

11. Please describe the **maintenance** of the system:
   a. What scheduled maintenance is required?
   b. Which parts might be most likely to suffer from wear?
   c. What is the expected technological lifetime of the system?

12. Please indicate the **costs** of the wind propulsion systems you currently offer/plan to offer in the next 10 years (differentiated for retrofit/newbuilds and for the different propulsion system models you offer):
    a What are the (expected) capital and installation costs per propulsion system?
    b What are the (expected) annual operational costs per propulsion system?
    c What are the (expected) annual maintenance costs per propulsion system?
    d How do you expect these costs to have changed in 2020 and 2030?

13. Can you give an indication of the expected **payback time** of your system?

14. Please describe your current and expected **market position**:
    a What is the current state of development of your wind propulsion system (e.g. blue print only, patent application, prototype state, demo, class approval, ready for sale)?
    b If applicable: when do you expect your system to be ready for sale?
    c If applicable: what is the current state of deployment of your system?
    d Which are the immediate next milestones and is there a roadmap towards achieving them?
    e Have you entered/will you enter into any partnership with other companies to develop/supply your product and how do your companies complement each other (specific skills, etc.)?
    f What developments do you aim for by 2020 and 2030 in terms of technological development and deployment?
    g Do you perceive any regulatory developments which (will) positively impact upon your market/business strategy?

15. **Employment effects** in the value chain of the wind propulsion systems:
    a How many employees in terms of FTEs (full-time equivalents) work in the field of wind propulsion systems in your company?
    b If you are not positioned at the very beginning of the value chain: which are your main ancillary companies regarding the wind propulsion systems?
    c If you are not positioned at the end of the value chain: which are your costumers?
    d Can you give a rough estimation of the FTEs in these up- and downstream companies that are related to your demand and supply regarding the wind propulsion system?

16. Please consider the main **barriers** to meeting your business objectives:
    a What are the main barriers you have encountered/you foresee regarding the *development* of your propulsion system? (How well can the technology be protected? What lessons have been learned from demonstrations? Etc.)
    b What are the main barriers you have encountered/you foresee regarding the *deployment* of your propulsion system? (Ship operators consider moving parts to be a risk, etc.)
    c What is needed from your point of view to overcome these barriers?

Annex D Notes on wind technology modelling

D.1 Further considerations and caveats

This section addresses important issues relating to the modelling of the fuel savings potential of wind propulsion technology that are beyond the scope of this report. In most cases, this is because any application of wind propulsion technology must factor in the specific details of the wind propulsion technology; the vessel on which it is to be applied; and the expected operational profile of the vessel – in order to ensure key criteria are met and to seek to achieve an optimal outcome.

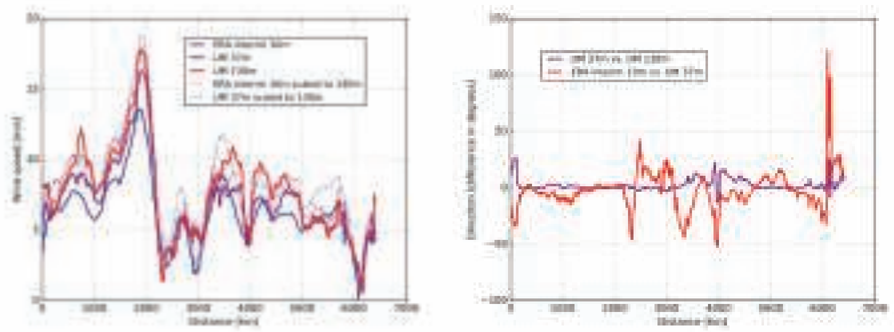
D.2 Routing

In deriving the savings potential of wind propulsion technologies, performance modelling assumes that ships operate as usual, and at constant speed irrespective of employed wind propulsion technology. This is a conservative approach as it may be possible to increase savings, and reduce fuel consumption by adapting the route or varying voyage speed, depending on wind conditions encountered on the route. Thus it is worth noting that even without any changes to a ship's operational profile, significant savings can be achieved.

D.3 Wind and weather conditions

The analysis of the potential savings from wind propulsion technologies is based on prevailing wind velocities encountered on route. The wind velocities are taken from the ERA-Interim model and scaled to the relevant height above sea level. In order to develop a better understanding of the model data and the scaling assumption, data are compared against analysis data from the Met Office's Unified Model. Figure 44 shows wind speeds along the sample route from Norfolk to Rotterdam, on 1 January 2011. Lines show the wind speed at a height of 10m according to analysis data from the ERA-Interim model; and at height levels of 37m and 130m, respectively, according to analysis data from the Unified Model; dotted lines show the data at height levels of 10 m and 37m, respectively, scaled to a height level of 130 m. Both models agree well, and the scaling rule given in Section 3.2.9 appears appropriate. On the right hand side of Figure 44, differences in wind direction are shown to be small. The difference is larger between the ERA-interim model at 10 m height and the Unified Model at 37 m, than between the Unified Model at 37 m and 130 m height.

Figure 44 Wind speed data on 1 January 2011, on the route from Norfolk to Rotterdam

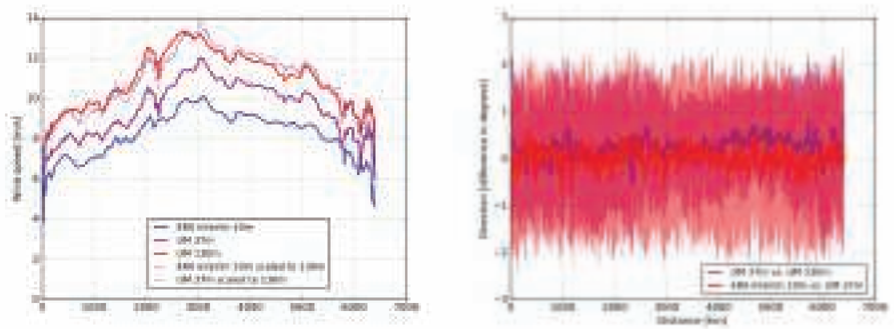


Left hand side: Wind speeds from the ECMWF ERA-Interim data set at a height level of 10 m above sea level; the same data scaled to a height level of 130 m; wind speeds from the Met Office Unified Model analysis data at height levels of 37 m and 130m, respectively; and the 37m data scaled to a height level of 130 m.

Right hand side: The difference in wind direction between the two Unified Model datasets, and between the ERA-Interim dataset and the Unified Model dataset at 37 m height.

The agreement is even better when considering averages (weekly dates over the course of 2011), as shown in Figure 45. The right hand side of Figure 45 shows the mean difference in wind direction, and its standard deviation. Taken together, this evidence indicates that the scaling rule is accurate.

Figure 45 Wind speed data averaged over weekly dates throughout 2011, on the route from Norfolk to Rotterdam.



Left hand side: Wind speed.

Right hand side: Mean and standard deviation of difference in wind direction between Unified Model data at height levels of 130 m and 37 m; and between Unified Model data at 37 m and ERA-Interim data a 10 m.

Beside wind conditions, other environmental conditions like waves, currents, or water temperature also affect ship resistance and fuel consumption. They have not been considered in this report. However, in an attempt optimise a route to exploit wind, with the objective of minimising fuel consumption, it may be useful to include other parameters lest the search for good wind conditions lead to higher added resistance from waves.

D.4 Side forces

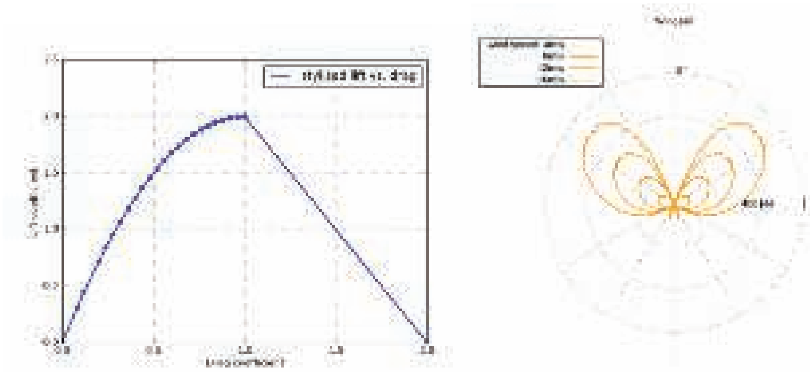
Depending on wind conditions, large side forces can act on wind propulsion devices. The side force, and the moments that it creates need to be balanced by the ship. In particular: the heeling moment leads to a heel angle – so that the righting moment of the ship hull balances the overturning moment of the superstructure. The side force also induces a leeway angle which creates a lifting force on the hull. That hull force, together with the sideways force on the ship's rudder, balance the side force on the superstructure.

The distribution of forces between the hull and the rudder is determined by the requirement that any yawing moments be balanced. The pivot point of a vessel, i.e. the effective point of attack of the lifting force on the hull, is near to its bow. Unless the wind propulsion devices are also located near the bow, the rudder is needed to keep the ship on course. The lifting forces on the hull and the rudder, and the heel angle all induce additional resistance.

A quantitative analysis of the additional resistance is beyond the scope of this report. Two points are worth stressing, however. First, presented estimates are over-optimistic in ignoring side force effects. Second, some of the side forces given in Section 3.2 are overestimates in comparison to realistic implementation of a given technology which would account for more detailed effects that have been impossible to consider for the whole range of technologies and vessels considered in this report. For simplicity, the wingsail and the rotor technology are both described by constant lift and drag coefficients. However, lift and drag coefficients of a wingsail are functions of the angle of attack of the wind. While the rotor is symmetric and therefore experiences no variation in angle of attack, the rotational speed can be varied, leading to a variation in lift and drag coefficient.

For example, consider the stylised lift and drag coefficients of a sail given in Figure 46. The dots along the curve show points, corresponding to integer angles of attack, that maximise forward thrust for some angle for apparent wind. If the ship travels into a near head wind, it is preferable to have lower drag, even at the cost of lower lift, i.e. a point on the left is selected. At some point, e.g. for beam winds, the point of maximum lift is preferable. Finally, for a tail wind, maximising drag is the best option – the point on the right hand side of the curve. The right hand side of Figure 46 shows the side force in this case, which is slightly smaller than the side force calculated from constant lift and drag coefficients in Figure 10. The polar curve showing propulsive power from this configuration, in Figure 47, indicates marginally higher savings than calculated in Section 3.2, as shown in Figure 9. In order to keep things as widely applicable as possible, the modelling framework is kept as simple as possible. For the implementation of a specific technology, a more detailed strategy for orientating sails relative to apparent wind, or for setting the rotational speed of rotors, will be required.

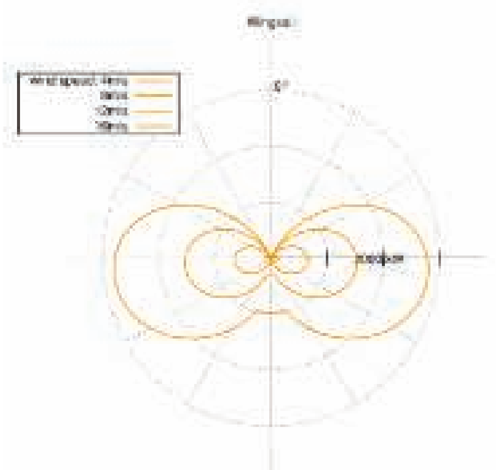
Figure 46 **Varying lift and drag with angle of attack**



Left hand side: Stylised relationship of lift and drag coefficient, varying with angle of attack of apparent wind, for a sail. Dots correspond to integer angles of attack selected to optimise forward thrust.

Right hand side: Polar curve of side force on the sail, with integer angle of attack selected to maximise forward thrust.

Figure 47 **Propulsive power for the wingsail, as in Section 3.2.10, but with variable angle of attack, as in Figure 45. Thrust is slightly increased (cf.Figure 8)**



In summary, side forces induce heel and leeway angles which, in turn, induce additional resistance. This effect has not been accounted for in this report but may be expected to be significant. Beyond these static considerations, wind propulsion technologies may also affect the dynamic behaviour, e.g. the rolling motion, of a vessel. There is some evidence that wind propulsion technology can have a beneficial impact on ship dynamics (Satchwell, 1986), but an assessment of this is beyond the scope of this report.

D.5 Multi-device interference

In some cases, more than one wind propulsion technology device may be installed on deck of a vessel, raising the question about interference of the airflow around them. Lower levels of interference may be expected for winds from the side than for head or tail winds. In some cases, interference may have a positive effect, though in most conditions it is expected to be negative (Ouchi, et al., 2013). Various considerations will determine the fitting of a set of wind propulsion technology devices to a vessel. Besides the potential aerodynamic interference of multiple devices, they include availability of deck space, structural mechanics, and expected impact on yawing and manoeuvrability (cf. Section D.4). The answer to this question will have to account for the specifics of those factors and is beyond the scope of this report.

D.6 Engine and propulsion efficiency

For a ship travelling at constant speed, its engine has to deliver the power required to overcome the ship's resistance. As wind conditions vary, the required power varies, in some instances up to pure sailing mode when no engine power is required at all to maintain speed. In building or retrofitting a vessel with wind propulsion technology, the main engine and how it is operated deserve special attention. The widespread uptake of slow steaming following the financial crisis of 2008 has shown that it is possible to run diesel engines at a small fraction of their rated power output. However, some precautions may need to be taken to avoid damage to the engine. Also, an engine's specific fuel oil consumption may be somewhat reduced at low power output, in turn lowering fuel savings. Engine specific fuel oil consumption has been assumed constant in this report. In practice, in a newbuild or retrofit of wind-assisted propulsion technology, the engine and how it will be operated deserve special consideration.

D.7 Structural integrity

The structural integrity of any wind propulsion technology devices is assumed a given in this report. As vessels operate outside and often in remote locations, this is crucial. Any integration of wind propulsion technology needs to ensure this criterion is met while seeking to optimise performance and satisfying other constraints, e.g. regarding deck space and cargo handling. Commenting on issues around structural integrity goes beyond the scope of this report. Furthermore, because long-term wear, and extreme weather conditions seldom encountered may affect structural integrity, empiric data gathered on the sea may play an important role in demonstrating that this criterion is, in fact, sufficiently met.

Annex E Diffusion modelling results

E.1 Sensitivity analysis: Slow speed, oil price 2020 450 $ per tonne, discount rate 5%

Table 15 Numbers of ships fitted with sail, new build and retrofit; summary to 2030

Ship type	Build Type	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Tanker (5,000-120,000 dwt)	Fleet	2,892	2,915	2,938	2,961	2,984	3,008	3,022	3,036	3,050	3,064	3,078
	New build with sail	0	3	14	64	70	107	120	154	160	169	175
	Retrofit with sail	0	0	23	122	199	201	201	202	203	204	205
Bulker (0–100,000 dwt)	Fleet	10,718	11,231	11,743	12,256	12,768	13,281	13,914	14,547	15,180	15,813	16,446
	New build with sail	0	8	31	166	339	528	620	632	631	641	575
	Retrofit with sail	0	6	23	122	426	443	464	485	506	527	548

Table 16 Numbers of ships fitted with sail, new build and retrofit; summary to 2050

Ship type	Build Type	2015	2020	2025	2030	2035
Tanker (5,000-120,000 dwt)	Fleet	2,921	2,892	3,008	3,078	3,078
	New build with sail	0	0	107	175	173
	Retrofit with sail	0	0	201	205	205
Bulker (0–100,000 dwt)	Fleet	8,653	10,719	13,281	16,446	32,435
	New build with sail	0	0	528	575	1,095
	Retrofit with sail	0	0	443	548	1,081

Figure 48 Adoption pathways by ship type

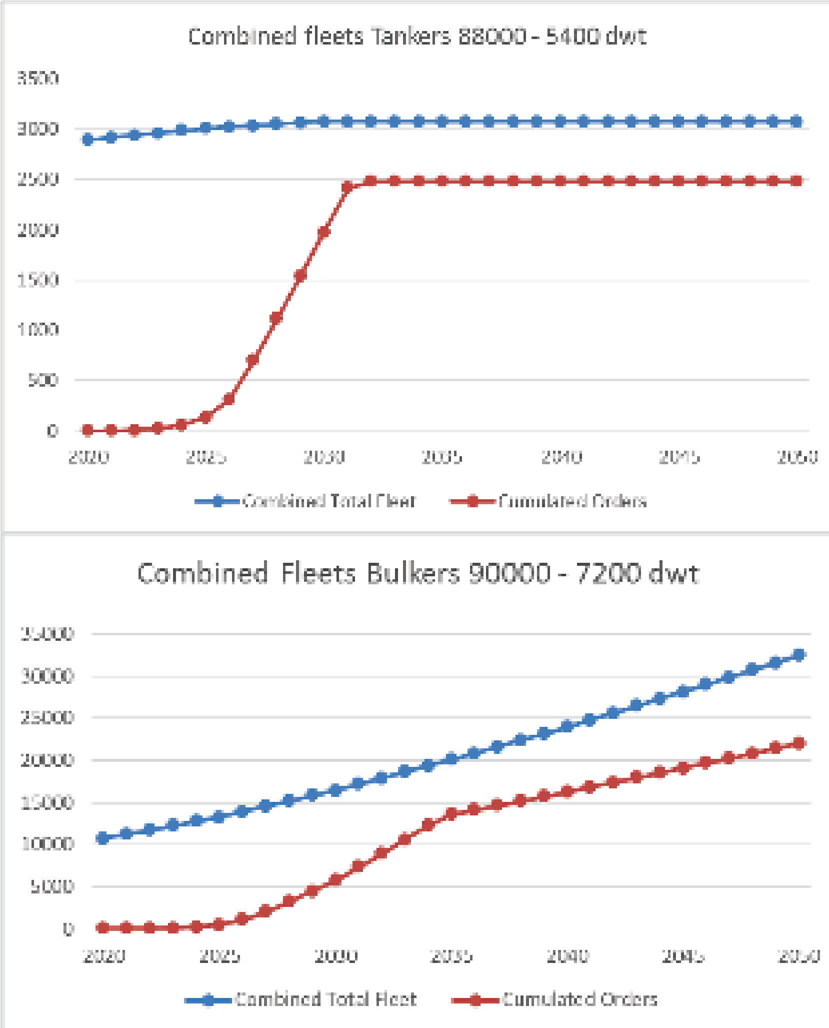
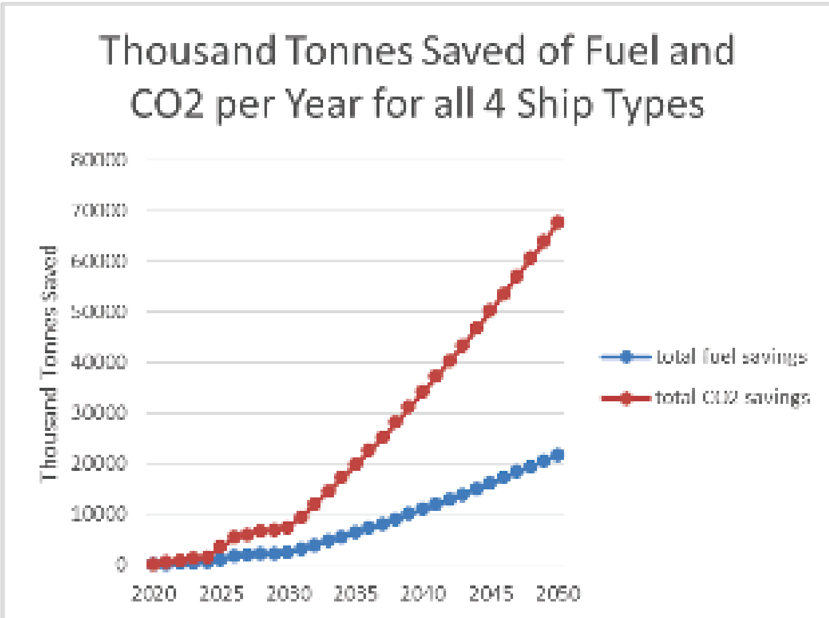


Figure 49 Fuel and CO_2 savings from adoption of wind technologies in the tanker and bulker fleets



E.2 Sensitivity analysis: Full speed, oil price 2020 300 $ per tonne, discount rate 8.5%

Table 17 Numbers of ships fitted with sail, new build and retrofit; summary to 2030

Ship type	Build Type	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Tanker (5,000-120,000 dwt)	Fleet	2,892	2,915	2,938	2,961	2,984	3,008	3,022	3,036	3,050	3,064	3,078
	New build with sail	0	3	9	24	79	130	156	187	188	192	199
	Retrofit with sail	0	0	17	90	199	201	201	202	203	204	205
Bulker (0 – 100,000 dwt)	Fleet	10,718	11,231	11,743	12,256	12,768	13,281	13,914	14,547	15,180	15,813	16,446
	New build with sail	0	8	23	123	298	528	605	632	631	641	575
	Retrofit with sail	0	0	17	90	426	443	464	485	506	527	548

Table 18 Numbers of ships fitted with sail, new build and retrofit; summary to 2050

Ship type	Build Type	2015	2020	2025	2030	2035
Tanker (5,000-120,000 dwt)	Fleet	2,921	2,892	3,008	3,078	3,078
	New build with sail	0	0	130	199	193
	Retrofit with sail	0	0	201	205	205
Bulker (0-100,000 dwt)	Fleet	8,653	10,719	13,281	16,446	32,435
	New build with sail	0	0	528	575	1,095
	Retrofit with sail	0	0	443	548	1,081

Figure 50 Adoption pathways by ship type

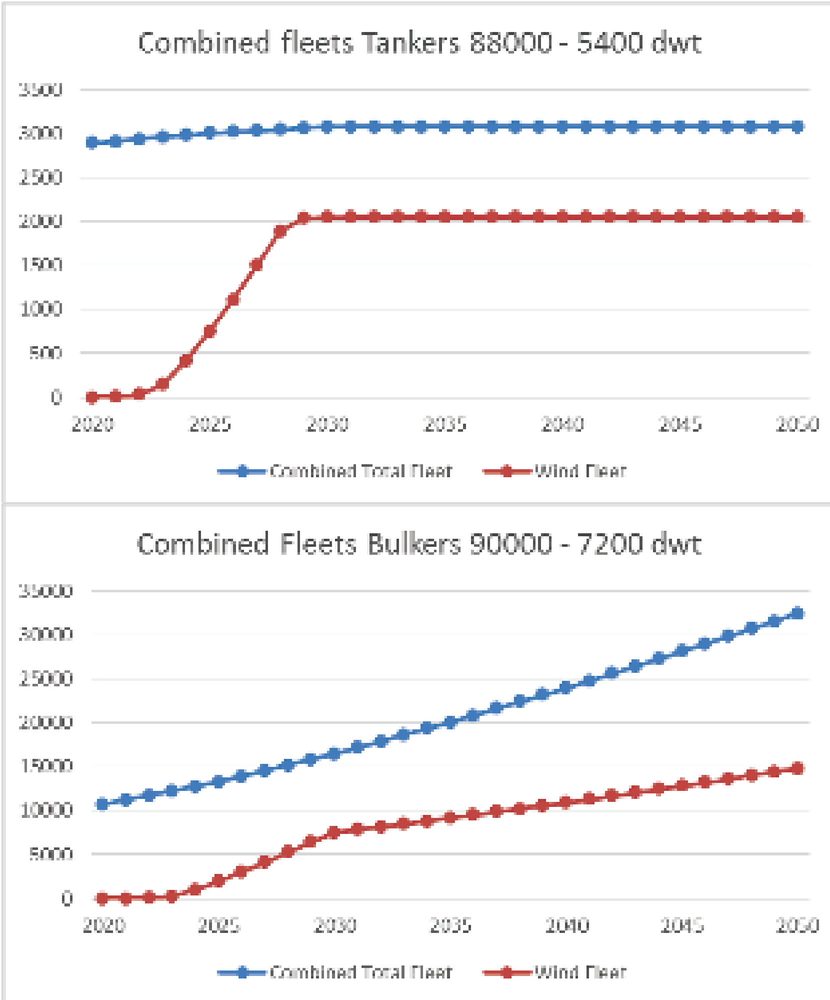
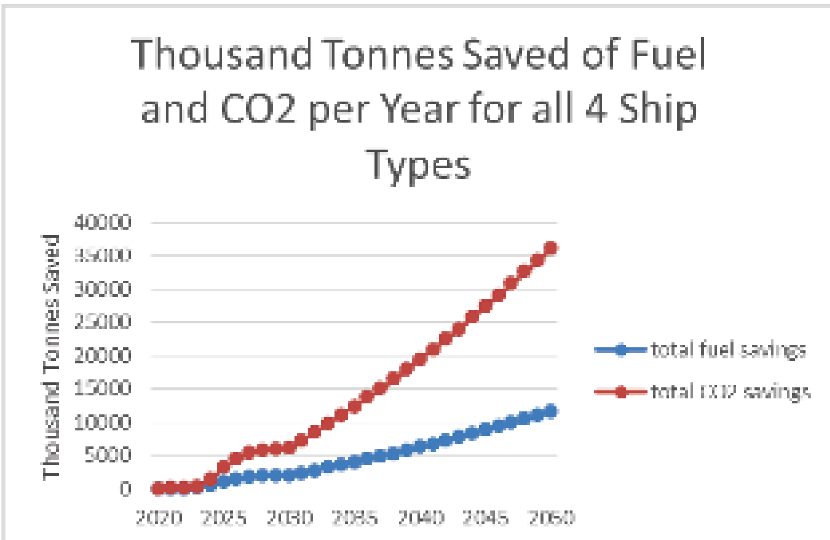


Figure 51 Fuel and CO_2 savings from adoption of wind technologies in the tanker and bulker fleets



E.3 Sensitivity analysis: Slow speed, oil price 2020 300 $ per tonne, discount rate 8.5%

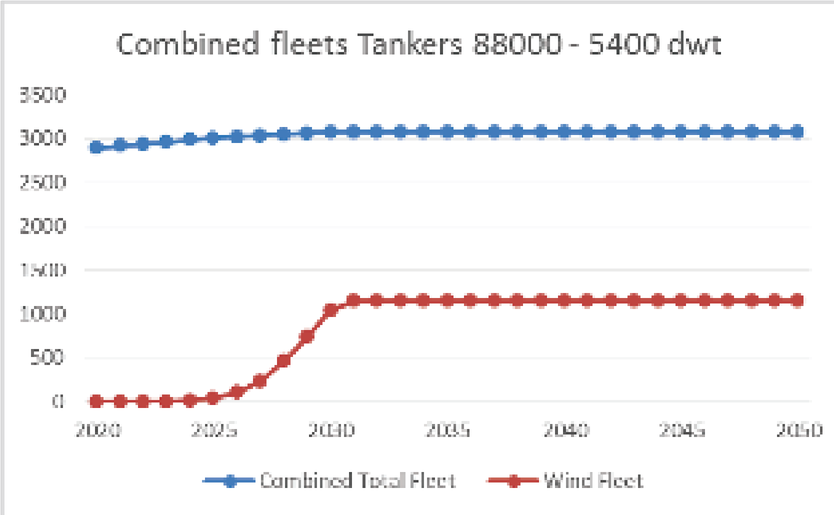
Table 19 Numbers of ships fitted with sail, new build and retrofit; summary to 2030

Ship type	Build Type	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Tanker (5,000-120,000 dwt)	Fleet	2,892	2,915	2,938	2,961	2,984	3,008	3,022	3,036	3,050	3,064	3,078
	New build with sail	0	3	14	64	70	107	120	154	160	169	175
	Retrofit with sail	0	0	23	122	199	201	201	202	203	204	205
Bulker (0-100,000 dwt)	Fleet	10,718	11,231	11,743	12,256	12,768	13,281	13,914	14,547	15,180	15,813	16,446
	New build with sail	0	8	31	166	339	528	620	632	631	641	575
	Retrofit with sail	0	6	23	122	426	443	464	485	506	527	548

Table 20 Numbers of ships fitted with sail, new build and retrofit; summary to 2050

Ship type	Build Type	2015	2020	2025	2030	2035
Tanker (5,000-120,000 dwt)	Fleet	2,921	2,892	3,008	3,078	3,078
	New build with sail	0	0	107	175	173
	Retrofit with sail	0	0	201	205	205
Bulker (0-100,000 dwt)	Fleet	8,653	10,719	13,281	16,446	32,435
	New build with sail	0	0	528	575	1,095
	Retrofit with sail	0	0	443	548	1,081

Figure 52 Adoption pathways by ship type



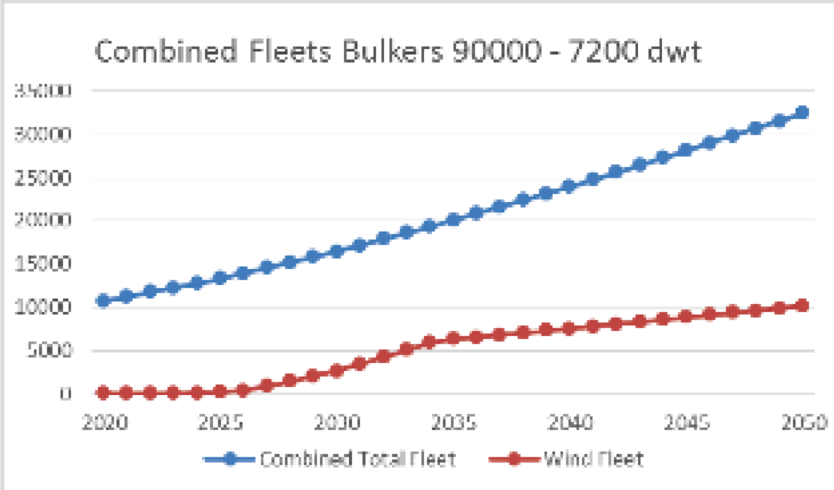


Figure 53 Fuel and CO_2 savings from adoption of wind technologies in the tanker and bulker fleets