Wind Powered Vessels with Hybrid and Autonomous Technologies

K. Goh, KNUD E. HANSEN, Australia

Royal Institute of Naval Architects – Power & Propulsion Alternatives for Ships
Europort Rotterdam 8th November 2017

SUMMARY

Reducing CO2 for shipping is a high priority but making small efficiency gains in current internal combustion technology and using wind assisted systems is unlikely to make the significant changes to greenhouse gases that are being sought.

In circa year 2000 KNUD E. HANSEN had developed an impressive concept design for a fully wind powered vessel – The WindShip. Comprehensive research into the economics and sail technology showed that a wind powered vessel for bulk and liquid cargo was feasible on certain trading routes, but in the year 2000 the additional capital expenditure was not able to be recovered due to very low fuel prices.

Today the economic and environmental situation make the WindShip much more attractive. The new WindShip 2025 concept combines hybrid diesel, solar and battery technologies to enable the WindShip to be even more economical. Autonomous and unmanned operation reduce operating costs and simplify the ship design and systems required. Cargo capacity is also increased.

A new calculation model combines the performance of the sail rig and hybrid power system as well as operational costs and was benchmarked against the previous studies to ensure accuracy. The findings demonstrate that very large savings in emissions and the cost of operation are now possible within technology that is available today.

PREVIOUS STUDIES

In 1996-1998, KNUD E. HANSEN participated in a comprehensive wind powered ship study sponsored by the Danish Environmental Agency. The study involved both technical and economic feasibility. The study was performed in two phases, and settled on a 50,000 DWT bulk carrier initially and a product tanker in the later phase.

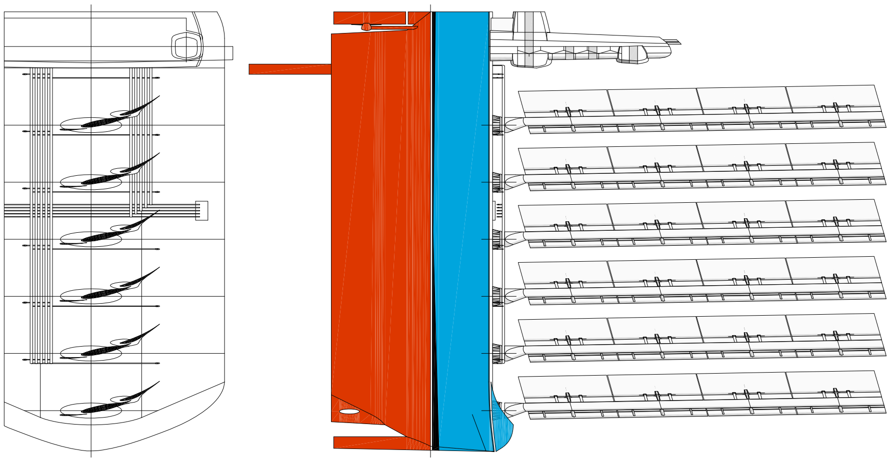


Figure 1 - KNUD E. HANSEN WindShip (circa 2000)

An exhaustive review of sail rig technology was undertaken and a novel and powerful high-lift wing sail was developed that offered impressive performance. The wing had a very high lift coefficient of about 3.0, compared to the DynaRig of about 1.5. This meant that the required sail area could be vastly reduced.

The sail rig consisted of a number of wing sections on each mast. In order to tack the wing sections would rotate about the mast. The wing could also be reefed in case of extreme wind conditions or during bulk loading operations.

The high-lift wing was able to sail much closer to the wind than other square type rigs. About 40 degrees was achievable. Another advantage was the robustness of the rigid wing sections. Compared to cloth type sails, that would need replacing every few years due to UV degradation, the wing could be built from composite panels and have the same life time as the vessel.

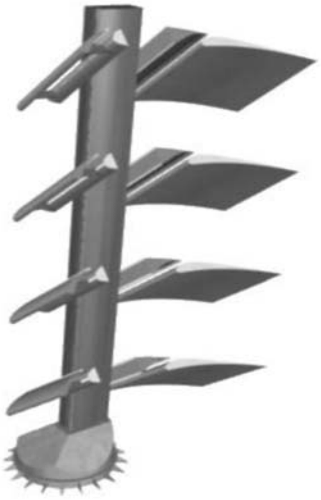


Figure 2 - High lift wing sail changing direction

Technical & Economic Analysis

The technical study was extensive and analysed:

- Sail rig performance
- Wing & mast design
- Hull form & resistances
- Hydrostatic stability
- Longitudinal stability under sail

In a favourable wind, the vessel could sail at speeds close to 20 knots. The vessel was also provided with twin azimuthing thrusters and a bow thruster for auxiliary propulsion and docking without tug assistance.

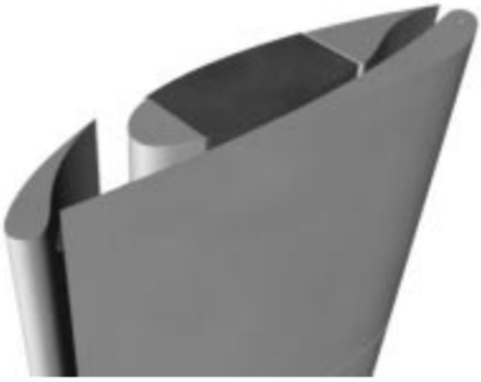


Figure 3 - Wing section reefed

An economic study was undertaken by Maersk Brokers which examined two product tanker trading routes and compared the WindShip to a conventional tanker with 2-stroke motor propulsion. The WindShip was only economically viable on some of the trading routes chosen, while using up to 10% more fuel on others equatorial routes where the average wind speed was only about 5m/s.

Table 1 - Convention vs WindShip on Atlantic trade

SPEED/CONSUMPTION	11 [knots]	12 [knots]	13 [knots]
Conventional Ship [tonnes / 24 hr]	17	23	30
WindShip [tonnes / 24 hr]	14.2	20.0	27.1
Difference	16.5 %	13%	9%

Although the fuel consumption was reduced, the poorer economic performance of the WindShip compared to conventional motor ships was attributed mainly to the speed being fixed at a relatively high speed of 13 knots to provide a direct comparison with existing vessels and poor wind conditions on particularly the trading routes chosen. Other factors included the lower propulsive efficiency of azimuth thruster system and the higher capital costs of the WindShip.

REVISITING THE WINDSHIP

With a renewed focus on reducing CO2 emissions and the coming global cap of 0.5% sulphur bunker fuel, the economic and political climate is now looking much more positive for the return of wind power ships.

In addition, maturing technologies in the fields of solar power, battery storage, fuel cells and autonomous control, provide further reasons to move on from the traditional motor ship.

The purpose of this study is to take the promising WindShip concept developed in the late 90's and see if the concept can be justified economically for the year 2025, the proposed in-service date for the new WindShip, the WindShip 2025.

New Calculation Model

The first step was to develop a new calculation model that would be able to quickly verify the basic economics of the WindShip and compare them to a conventional motorship. The model should be able to calculate sailing performance by wind and auxiliary propulsion systems for any chosen sailing route and thereby also inform the fuel consumption based on generally accepted efficiencies.

The 50,000 DWT Handymax bulk carrier studied previously would serve as the basis of the new WindShip calculations, since the performance was already known from extensive model testing. Although further performance optimisations to the sail rig were possible from the knowledge gained from the previous study, it was decided to utilise the data set as closely as possible to ensure accurate benchmarking of the new calculation model.

Table 2 - Conventional vs WindShip main particulars

50,000DWT Bulk Carrier	Conventional	WindShip (year 2000)
Length BPP	210 m	210 m
Beam	32 m	32 m
Draft	11.9 m	11.9 m
Block	0.77	0.75
Lightweight	11,500 t	12,000 t
Cargo Capacity	69,000 m^3	71,000 m^3
Propulsion efficiency	0.6	0.6
Installed prop'n power	8,000 kW	6,000 kW
Prop'n power SFC	0.18 kg/kWh	0.2 kg/kWh
Design speed	14.0 kn	13.0 kn
Typical elec. load	465 kWe	400-500 kWe
Aux. power SFC	0.2 kg/kWh	0.2 kg/kWh

The speed and resistance from model testing of the hull and sail rig was translated from the polar plots of wind speed and direction into a spreadsheet. From the resistance of the hull and sail rig, the effective power and theoretical shaft power was calculated from the estimated propulsion efficiency of 60%.

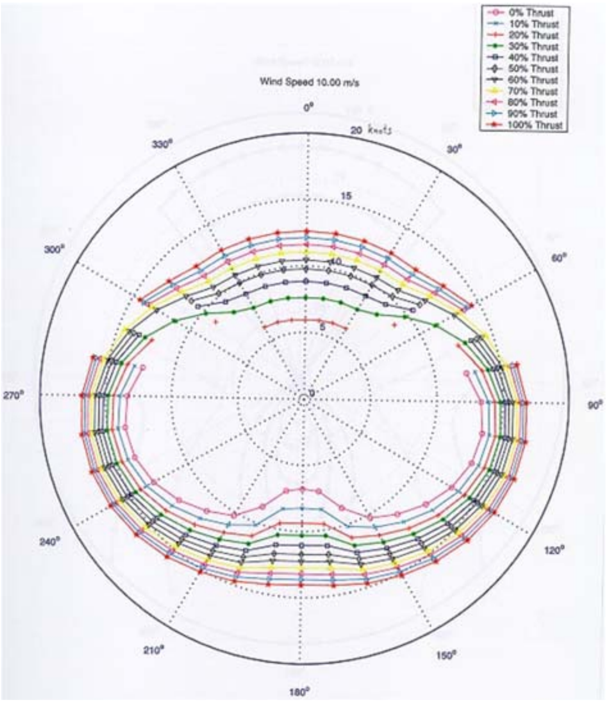


Figure 4 - WindShip performance at 10m/s wind

Two common dry bulk routes were chosen for analysis. The Trans-Atlantic route from Rotterdam to New York City and ballast return was selected since it was known that this route has good average wind conditions of 8m/s. The other route chosen was a long Trans-Pacific grain trade route from Vancouver to Shanghai with ballast return. It is known that the wind conditions on this route results in a lower wind average.

Global wind data was sourced from the European Centre for Medium-range Weather Forecast (ECMWF). The vessel course was plotted directly and divided into 16 legs. Three trials for each route were calculated and averaged for three different speeds, 8, 11 and 13 knots. Weather routing was not applied.

From the vessel course, the relative direction of the wind was calculated for each leg and from the wind speed, the vessel speed was known. If the vessel was pointing higher than 45 degrees into the wind, the vessel would tack and the additional distance from the tacked course was calculated for that leg. Additional electrical load was also allowed for turning the wing sections when changing tack.

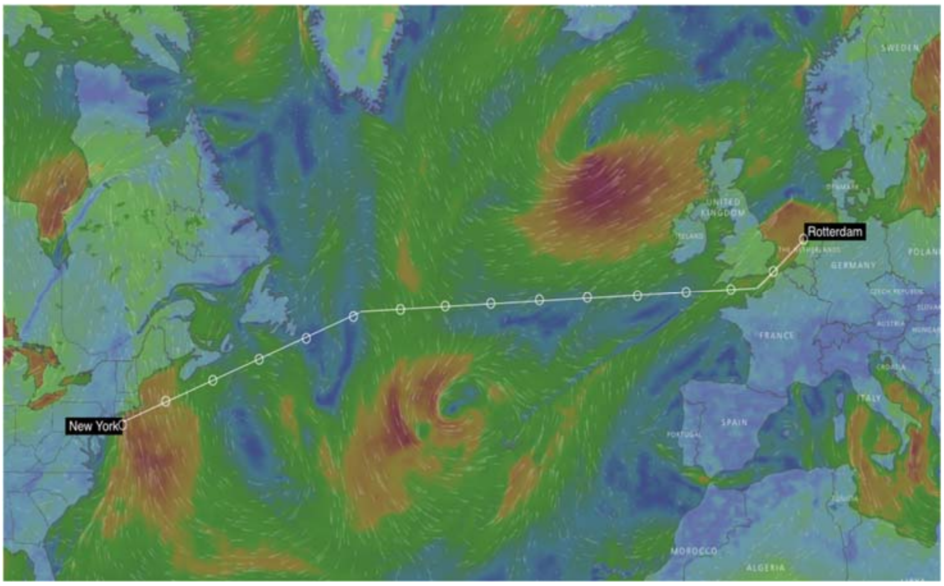


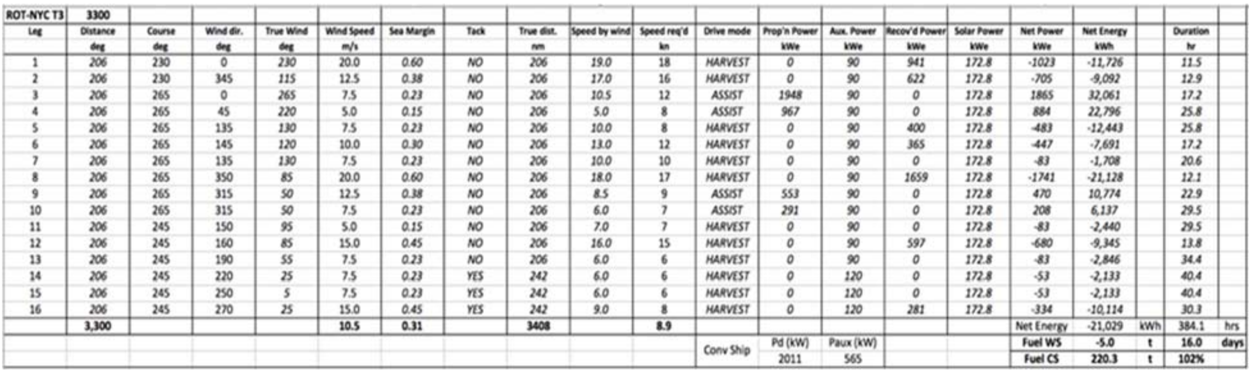
Figure 5 - Wind data on Atlantic trade route

Benchmarking Calculations

For the benchmarking calculations, the WindShip was generally allowed to run as fast as the wind would allow. Auxiliary propulsion was used if the sail power was insufficient to make the required average speed. Sea margin was also added based on the wind speed.

The WindShip fuel consumption was calculated based on the auxiliary propulsion requirement and the service electrical load. The return voyage at ballast condition was calculated at 85% of the deadweight fuel consumption. The price of fuel used for the benchmarking calculation was 200 USD/ton for HFO and 300 USD/ton for MDO.

Table 3 - Calculation model on Atlantic trade at 11 kns



ROT-NYC T3	3300																			
Leg	Distance	Course	Wind dir.	True Wind	Wind Speed	Sea Margin	Tack	True dist.	Speed by wind	Speed req'd	Drive mode	Prop'n Power	Aux. Power	Recov'd Power	Solar Power	Net Power	Net Energy		Duration	
	deg	deg	deg	deg	m/s			nm		kn		kWe	kWe	kWe	kWe	kWe	kWh		hr	
1	206	230	0	230	20.0	0.60	NO	206	19.0	18	HARVEST	0	90	941	172.8	-1023	-11,726		11.5	
2	206	230	345	115	12.5	0.38	NO	206	17.0	16	HARVEST	0	90	622	172.8	-705	-9,092		12.9	
3	206	265	0	265	7.5	0.23	NO	206	10.5	12	ASSIST	1948	90	0	172.8	1865	32,061		17.2	
4	206	265	45	220	5.0	0.15	NO	206	5.0	8	ASSIST	967	90	0	172.8	884	22,796		25.8	
5	206	265	135	130	7.5	0.23	NO	206	10.0	8	HARVEST	0	90	400	172.8	-483	-12,443		25.8	
6	206	265	145	120	10.0	0.30	NO	206	13.0	12	HARVEST	0	90	365	172.8	-447	-7,691		17.2	
7	206	265	135	130	7.5	0.23	NO	206	10.0	10	HARVEST	0	90	0	172.8	-83	-1,708		20.6	
8	206	265	350	85	20.0	0.60	NO	206	18.0	17	HARVEST	0	90	1659	172.8	-1741	-21,128		12.1	
9	206	265	315	50	12.5	0.38	NO	206	8.5	9	ASSIST	553	90	0	172.8	470	10,774		22.9	
10	206	265	315	50	7.5	0.23	NO	206	6.0	7	ASSIST	291	90	0	172.8	208	6,137		29.5	
11	206	245	150	95	5.0	0.15	NO	206	7.0	7	HARVEST	0	90	0	172.8	-83	-2,440		29.5	
12	206	245	160	85	15.0	0.45	NO	206	16.0	15	HARVEST	0	90	597	172.8	-680	-9,345		13.8	
13	206	245	190	55	7.5	0.23	NO	206	6.0	6	HARVEST	0	90	0	172.8	-83	-2,846		34.4	
14	206	245	220	25	7.5	0.23	YES	242	6.0	6	HARVEST	0	120	0	172.8	-53	-2,133		40.4	
15	206	245	250	5	7.5	0.23	YES	242	6.0	6	HARVEST	0	120	0	172.8	-53	-2,133		40.4	
16	206	245	270	25	15.0	0.45	YES	242	9.0	8	HARVEST	0	120	281	172.8	-334	-10,114		30.3	
	3,300				10.5	0.31		3408		8.9						Net Energy	-21,029	kWh	384.1	hrs
											Conv Ship	Pd (kW)	Paux (kW)			Fuel WS	-5.0	t	16.0	days
												2011	565			Fuel CS	220.3	t	102%	

A simple regression based cost model was used to calculate new building costs based on steel and equipment weights, block coefficient, installed power and machinery type. The building cost of the total sail rig was estimated at 5.0 MUSD for year 2000, which resulted in a 23% increase over the conventional motor ship cost. The capital financing period was 10 years. Operating costs were taken from the previous study, which was based on year 2000 costs for benchmarking. Manning, maintenance, stores and administration costs where the same as the motor ship. Insurance costs reflected the increased cost of the WindShip and port dues were reduced since tugs would not be needed for docking.

The results calculated with the new economic model were very close to the previous study. Like the 1998 study, the model showed that a WindShip was not economically viable in the year 2000, in principle because at 13 knots speed, the marginal saving on fuel consumption that the sail rig provided was out weighed by the less efficient auxiliary propulsion system, the higher consumption for medium-speed engines and the higher capital cost of the WindShip.

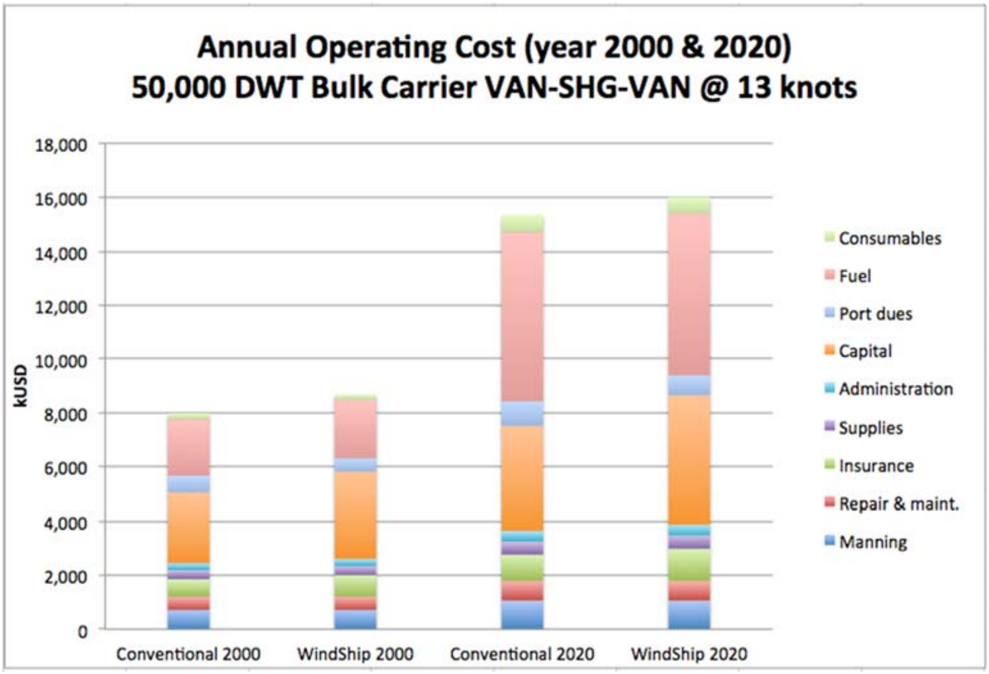


Figure 6 - Conventional & WindShip annual

The results showed similar or better operating costs for the conventional bulk caririer and the WindShip on the Rotterdam – New York City route where the average wind speed was 8.6 m/s and the fuel saving could offset the higher capital costs. However, the Vancouver-Shanghai route where the average wind was only 6.7 m/s had a 10% higher operating cost.

The cost model was then updated represent costs for year 2020 to check the economic viability of WindShip built today. Annual inflation of 2% was applied to both capital and operating costs. The fuel price increased to 600 USD/ton for 0.5% low sulphur HFO and 800 USD/ton for 0.1% sulphur MDO. The calculations showed that the WindShip was now only 4% more expensive to operate on the Vancouver-Shanghai route at 13 knots and would likely have the economic advantage at lower speeds.

THE WINDSHIP 2025 CONCEPT

With the tipping point for economic viability likely to be triggered by the IMO global 0.5% sulphur cap in 2020, it is now the time to see what the WindShip 2025 concept could achieve.

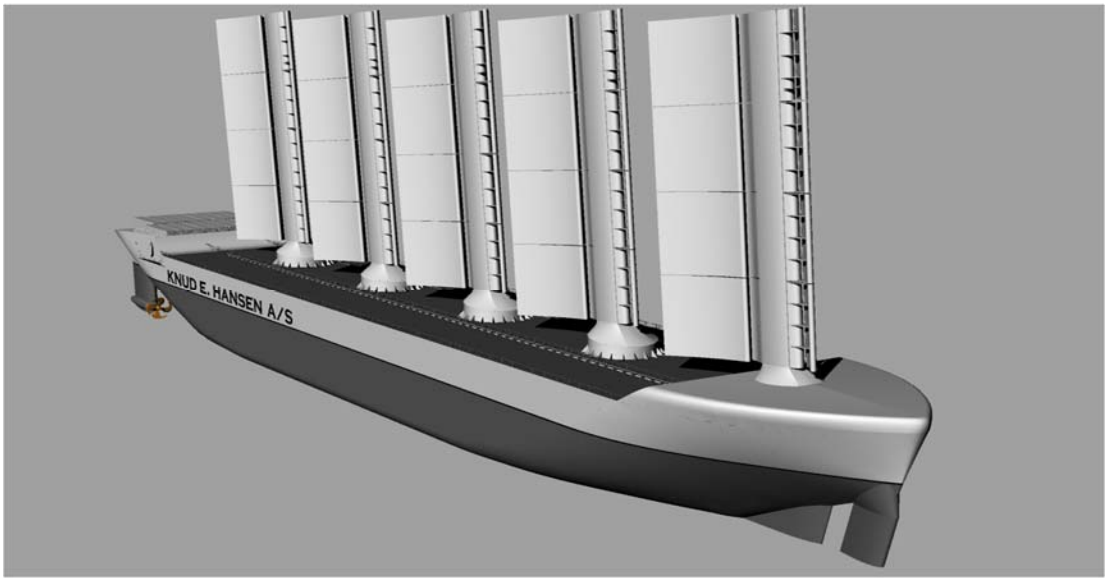


Figure 7 - WindShip 2025 Concept

Auxiliary Propulsion

Although sailing ship once plied the world's oceans powered only by the wind, this is not desirable for the WindShip. An effective auxiliary propulsion system for the Windship will allow the vessel to:

- Maneuver in and out of port unassisted
- Assist in course keeping and improving the efficiency of the sail rig
- Sail when no or little wind (<2.5m/s) is available
- Assist the sail power to keep to a schedule
- Take-home-power should the sail rig become compromised

Another benefit of the new auxiliary propulsion system is the possibility of using the system as a wake-turbine generator when there was excessive wind. A number of different energy storage systems were considered including flywheels and electrolysis of water into hydrogen, however the simplest and most mature technology with a high round-trip efficiency is lithium-ion batteries. This would necessitate using an electric propulsion drive system.

The new WindShip has an auxiliary propulsion system using two aft azimuthing electric pods with controllable pitch propellers. The calculation model was modified to allow for energy storage from a Power-Take-In and Power-Take-Out propulsion system utilising lithium-ion batteries. The turbine efficiency was estimated at 50% of the difference of effective powering requirements for the vessel speed by sail and the harvesting speed for the known wind speed. The stored power could then be used when wind conditions were not favourable or when a higher speed was needed to meet the sailing schedule. In favourable wind and a harvesting speed of 16 knots, about 2,000 kWe can be generated and stored. A power of 2 MWe is enough to power the WindShip at 11 knots and run all auxiliaries when there was no wind to sail.

Unmanned & Autonomous Operation

The WindShip 2025 will be an unmanned vessel, the sail rig being ideally suited for mechanisation and automated control. This also has the possibility to eliminate all life-saving equipment, hotel systems and large associated electrical loads such as HVAC and lighting. Removing the vessel superstructure also reduces the aerodynamic drag and improves the performance of the sail rig.

To reduce the complexity further and to reduce breakdown and fire risks for an unmanned vessel, the WindShip 2025 also has no engine room. sGenerator machinery and fuel storage is containerised and can be carried according to the requirements of the route. High-speed diesel generators are not as efficient and distillate MGO fuel is more expensive but this was necessary to work with the PTO-PTI propulsion system and the unmanned concept.

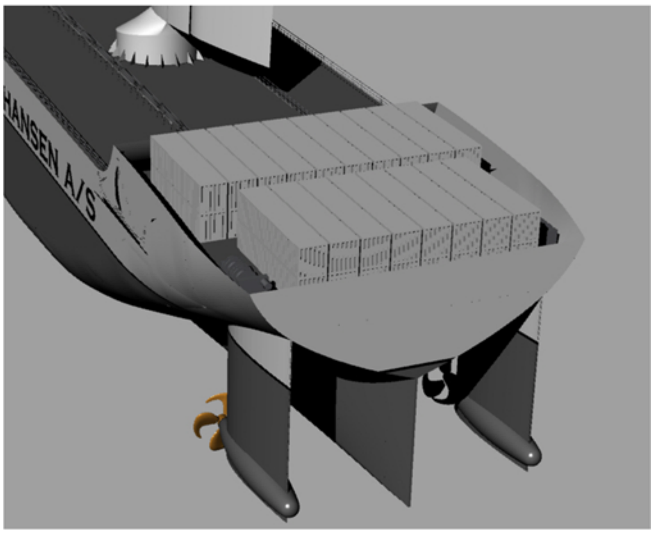


Figure 8 - Containerised Power System

A standard forty-foot container module is able to house a 3,000 kWe diesel generator, so only two would be needed for the 13 knot design speed. A forty-foot ISO tank is able to store about 40 tons of fuel. Ten to twelve tanks are enough for almost any voyage up to 5,000 nm at 13 knots.

Energy Storage System

The lithium-ion battery is one of the key technologies that is enabling a clean and energy efficient future. With excellent cycle capability and a high round-trip-efficiency of about 90% they are an obvious choice for the WindShip 2025 concept.

The previous high cost of lithium-ion batteries has been dropping quickly, driven by the increasing maturity and uptake of electric vehicles and on-site energy storage. From a price of over 1,000 USD per kWh in 2010, *Bloomberg* report that the cost of Li-ion batteries is reducing at 21.6% per year. If this trend continues, a cost of under 100 USD per kWh is certainly possible by 2025. To allow for the containerised housing system, a conservative cost estimate of 150 USD/kWh is used.

The batteries system would also be containerised. Each forty-foot ISO container can conservatively store 2,500 kWh of lithium-ion batteries with adequate room for cooling and power management systems. The storage limit would likely be determined by the container weight limit of 30 tons.

How much storage should be provided is the other battery factor. A 2.5 MWh battery container can only power the WindShip at 6 knots for 3 hours, 8 knots for 1.5 hours and 10 knots for one hour. Powering is only half of the storage calculation with harvesting being just as important. In a good wind of over 15m/s the sail rig could propel the WindShip at 19 knots, which is an effective power of 11 MW. If the harvesting speed is 17 knots (effective power of 7.5 MW), then the harvested power is 1.7 MWe and able to fully recharge a 2.5 MWh battery container in about 1.5 hours.

It was decided to trial two different battery configurations. A base battery configuration of 10 containers with a 25 MWh storage capacity and a maximum battery configuration of 40 containers with 100 MWh.

Table 4 - Battery Configuration

Battery Config'n	Number of 40ft ISO units	Storage Capacity	Cost	Range at 8 kn	Range at 11 kn	Range at 13 kn
Base	10	25 MWh	3.75 MUSD	133 nm	78 nm	54 nm
Maximum	40	100 MWh	10.0 MUSD	532 nm	322 nm	216 nm

Solar Power System

Solar power through photovoltaic cells is another key technologies that is enabling a clean and energy efficient future. Lightweight and modular, they are also an obvious choice for the WindShip 2025 concept. Although the energy density is still very low at about 200 Watts per square meter, it is envisaged that solar panels can be fitted to the upper surface of the wing sections and virtually all flat deck areas. It is estimated that the vessel can be installed with 7,200 square meters of solar panels producing a peak power of 1,440 kWe, enough power to sail at 7 knots and run all service loads at the same time.

When there are periods of very little wind, or when the WindShip 2025 is at anchor or in port, the sails can track the sun to maximize energy harvesting and recharging of batteries. Even if the vessel is sailing by the wind, solar radiation from reflection off the sea surface can still provide a significant amount of energy. The calculation model uses a tracking factor of 0.7 and an untracked factor of 0.3 and also allows for a 40% daylight factor to allow for cloud and nighttime.

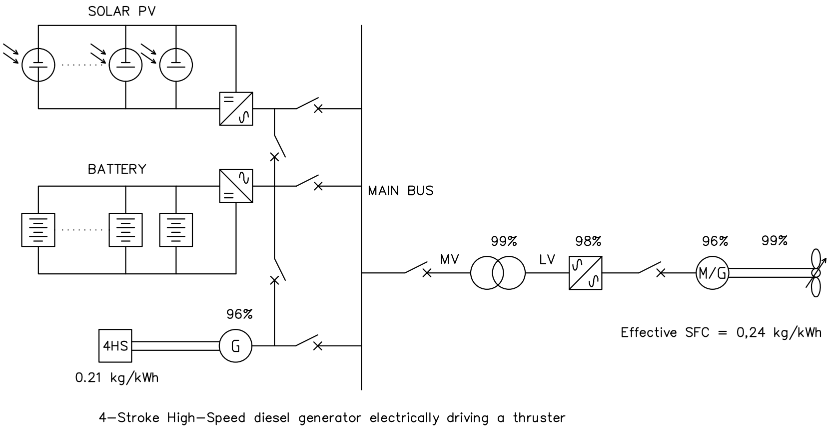


Figure 9 - WindShip 2025 power system

The previous high cost of photovoltaic cells has been dropping quickly, driven by the increasing maturity and global uptake of solar power both on-site and mass energy harvesting and distribution. From a price of about 1100 USD per kW in 2010, *Bloomberg* report that the cost of photovoltaic cells is reducing at 24.3% per year. If this trend continues, a cost of under 50 USD per kW is possible by 2025. Since a large part of the cost will be installation and support structures for the solar panels a much more conservative cost of 500 USD per kW has been used.

Fuel Cells

A fuel cell device combines hydrogen and oxygen to make electricity with water and heat being the waste products. The main benefits are the simplicity with no moving parts, higher energy efficiencies compared to internal combustion engines and less-polluting waste products. Although use of fuel cells for ship propulsion is in its infancy, the concept works well with the unmanned WindShip and large scale implementation for shipping may be ready by year 2025. DNV recently undertook a detailed fuel cell study looking into the technology, safety aspects and regulatory requirements in preparation for wide spread use fuel cells in the near future.

The efficiency of the fuel cell itself is currently between 45-60% depending on type, the rest of the energy being lost as waste heat. With high temperature fuel cells, the waste heat has the potential to be recovered through a steam turbine or a Stirling Engine, increasing the overall efficiency to 85%. An additional benefit of the high temperature fuel cells are the ability to directly use LNG and converting to hydrogen through a process called internal reforming.

For the WindShip 2025, the fuel cells would be containerised and replace the generator engine modules. Containerised LNG tanks would be carried instead of the diesel tanks. The fuel cell version of the WindShip 2025 is also included in the economic study. A factor of 1.5 was applied to the machinery costs to reflect the likely higher costs of the fuel cells, which will not have reached high levels of economy of scale.

WindShip 2025 Costs

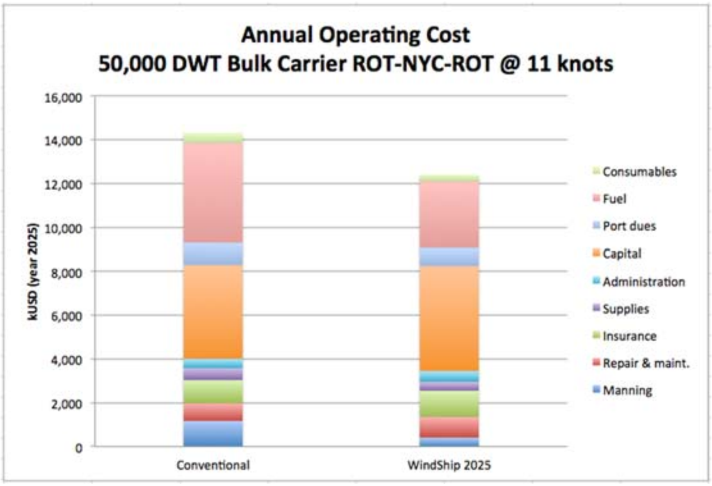


Figure 10 - Annual cost for Atlantic trade at 11 kns

The cost model allowed for the reduction of about 500 tons of steel by removing the superstructure and engine casing. Equipment costs was also reduced by 500 tons since there was no hotel services, no life saving equipment or engine room. A pump room for ballasting control is still required and switchboard rooms for distribution of power and housing of the propulsion drives. Machinery costs were calculated based on 4-stroke power, plus a 1.25 factor for a diesel-electric system, 1.5 factor for azimuthing pods and 0.6 factor for the containerised generators set. An unmanned automation cost of 1 MUSD was also added to the capital cost of the WindShip.

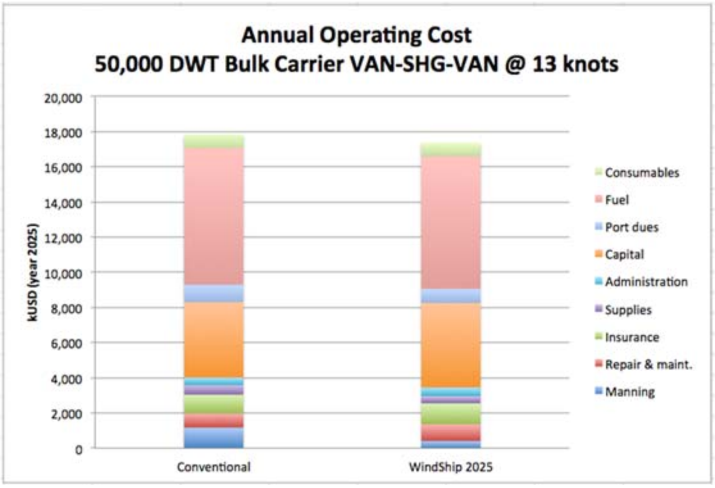


Figure 11 - Annual cost for Pacific trade at 13 kns

Regarding annual operating costs, manning was reduced to a third of the motorship, since the unmanned WindShip would still require crew to command and monitor the vessels from a shore based control station. It is foreseeable, that is the future there will be only a few people in charge of an entire fleet of ships operating autonomously 99% of the time, however traditional jobs will still remain, including inspection and maintenance of the WindShip when at anchor or docked.

Maintenance cost was increased to reflect the needs of the sail rig and the fact that there was no crew aboard to cater for daily maintenance tasks. Insurance costs of 2.5% also reflected the increased capital costs of the vessel. Administration costs where also increased slightly the increased to reflect the real-time video and control communication system needed for autonomous operations. Annual inflation of 2% was applied to both capital and operating costs.

The fuel price increased to 800 USD/ton for 0.5% low sulphur HFO and 1000 USD/ton for 0.1% sulphur MDO.

CALCULATION RESULTS

The calculations showed that the WindShip 2025 concept was economically viable on both the Rotterdam - New York City route and the Vancouver – Shanghai route at all speeds of 8, 11 and 13 knots. A total operational cost saving of about 15-20% can be expected with the WindShip 2025 compared to a conventional motor ship.

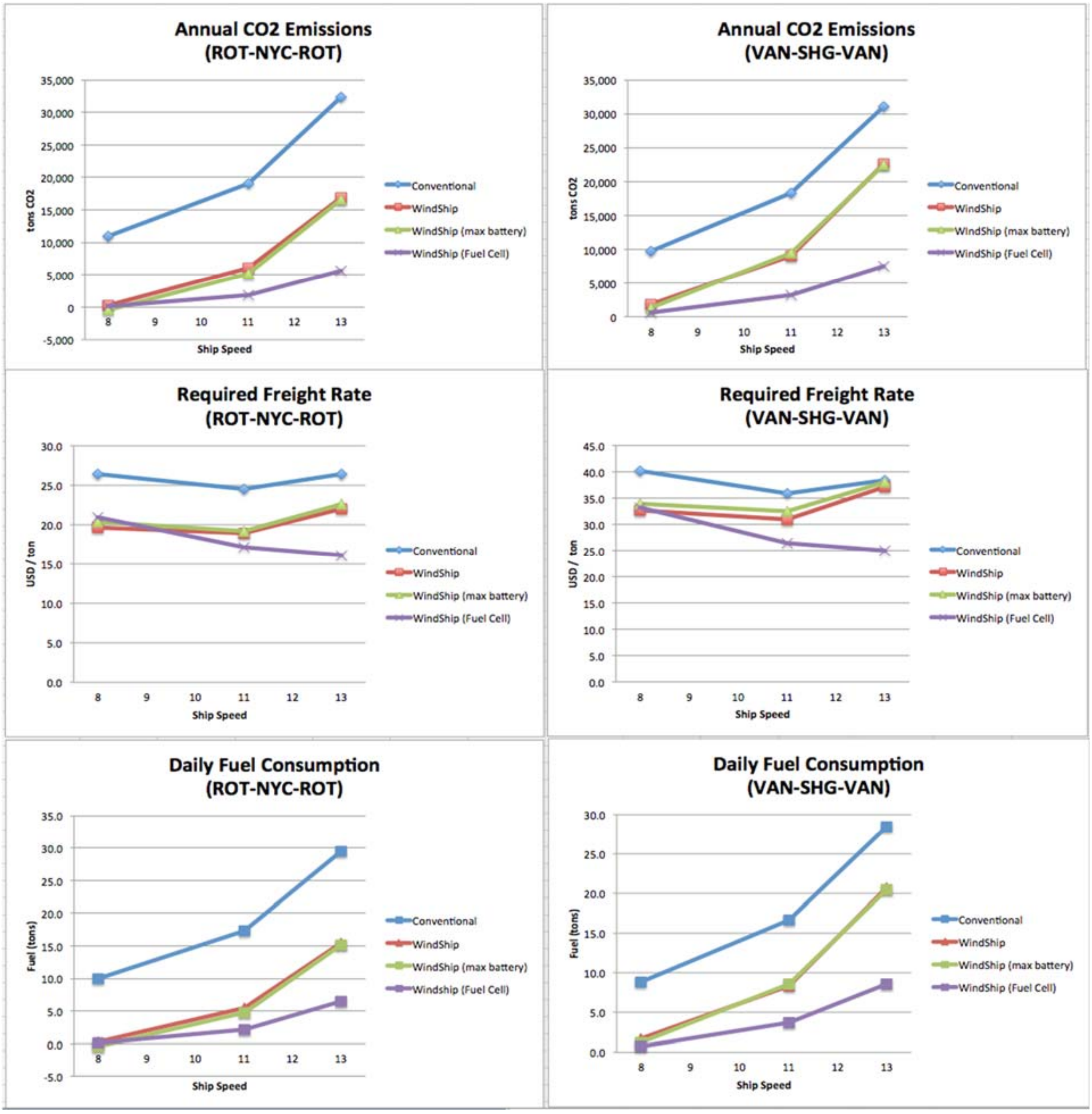


Figure 12 - Performance on Atlantic & Pacific trade routes

The Required-Freight-Rate was best for both the conventional motor ship and WindShip 2025 at about 11 knots. There was a saving of only a 2-3 percent at 13 knots on the Vancouver – Shanghai route, but the CO2 saving was still considerable.

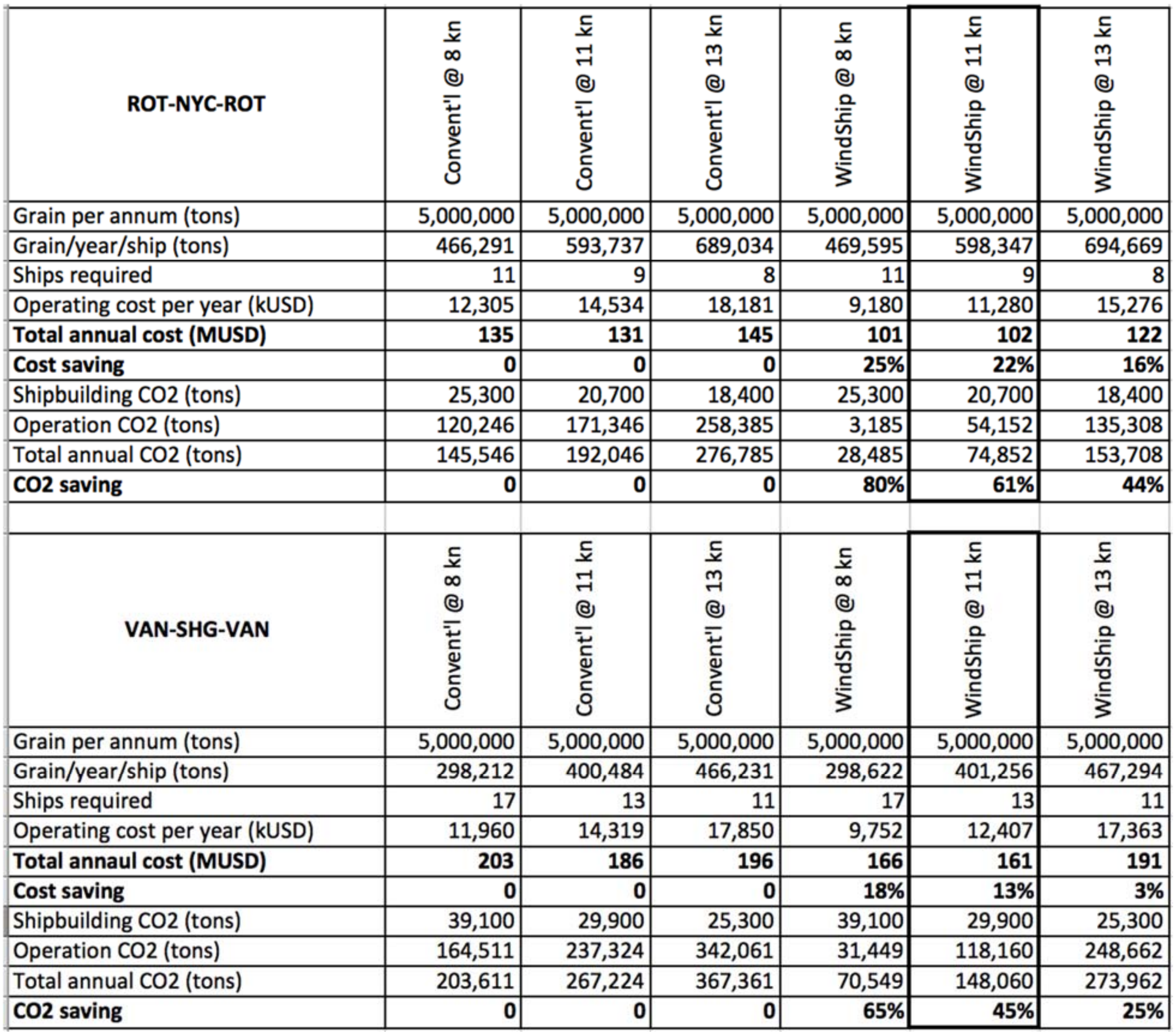
The shipbuilding CO2 was also added to the operational CO2 to a get the complete environmental impact and calculated at 5 tons of CO2 for every ton of the ship lightweight and the total pro-rated over a 25 year vessel life.

It can also be seen that the 'max-battery' WindShip was not able to recover the higher capital cost on either route at any speed.

The fuel cell Windship with its much higher efficiency compared to the diesel generators, was by a significant margin, showing the best economic and environmental performance. However, due to immaturity of the technology and as-yet largely unknown costs of large scale implementation, the results presented in this report should be interpreted with caution.

When the results are presented in a hypothetical trade scenario of shipping 5 million tons of grain per year for a conventional motor ship and the WindShip 2025, the implications for fleet size and operational costs become more apparent.

Table 5 - Fleet economics for Atlantic & Pacific bulk trade



ROT-NYC-ROT	Convent'l @ 8 kn	Convent'l @ 11 kn	Convent'l @ 13 kn	WindShip @ 8 kn	WindShip @ 11 kn	WindShip @ 13 kn
Grain per annum (tons)	5,000,000	5,000,000	5,000,000	5,000,000	5,000,000	5,000,000
Grain/year/ship (tons)	466,291	593,737	689,034	469,595	598,347	694,669
Ships required	11	9	8	11	9	8
Operating cost per year (kUSD)	12,305	14,534	18,181	9,180	11,280	15,276
Total annual cost (MUSD)	**135**	**131**	**145**	**101**	**102**	**122**
Cost saving	**0**	**0**	**0**	**25%**	**22%**	**16%**
Shipbuilding CO2 (tons)	25,300	20,700	18,400	25,300	20,700	18,400
Operation CO2 (tons)	120,246	171,346	258,385	3,185	54,152	135,308
Total annual CO2 (tons)	145,546	192,046	276,785	28,485	74,852	153,708
CO2 saving	**0**	**0**	**0**	**80%**	**61%**	**44%**

VAN-SHG-VAN	Convent'l @ 8 kn	Convent'l @ 11 kn	Convent'l @ 13 kn	WindShip @ 8 kn	WindShip @ 11 kn	WindShip @ 13 kn
Grain per annum (tons)	5,000,000	5,000,000	5,000,000	5,000,000	5,000,000	5,000,000
Grain/year/ship (tons)	298,212	400,484	466,231	298,622	401,256	467,294
Ships required	17	13	11	17	13	11
Operating cost per year (kUSD)	11,960	14,319	17,850	9,752	12,407	17,363
Total annaul cost (MUSD)	**203**	**186**	**196**	**166**	**161**	**191**
Cost saving	**0**	**0**	**0**	**18%**	**13%**	**3%**
Shipbuilding CO2 (tons)	39,100	29,900	25,300	39,100	29,900	25,300
Operation CO2 (tons)	164,511	237,324	342,061	31,449	118,160	248,662
Total annual CO2 (tons)	203,611	267,224	367,361	70,549	148,060	273,962
CO2 saving	**0**	**0**	**0**	**65%**	**45%**	**25%**

CONCLUSIONS

Lower speeds than 13 knots and larger fleets must be accepted to reduce operating costs and environmental impact.

An average wind speed of at least 6.5 m/s is required if a 13 knot service is to be economically viable. The WindShip will not be economically viable on equatorial routes.

Despite using less efficient high-speed diesel generators and more expensive distillate fuel, the WindShip is still more cost effective and less polluting than a conventional 2-stroke motor ship.

About 15% higher capital costs for shipbuilding must be accepted for the WindShip 2025. This does not include R&D and prototyping costs.

The cost of battery storage needs to drop below 50 USD/kWh for energy harvesting to be cost effective.

FUTURE STUDIES

The high-lift wing sail rig is to be optimised further for performance and cost. For example a three section wing instead of four will be investigated.

Future study to also include other sail systems such as Flettner rotors which have a very high lift coefficient and a simpler construction compared to the WindShip high-lift wing sail. The disadvantage of Flettner rotors is the reduced effectiveness in head and following winds.

A more detailed performance model will be developed to allow weather routing and better modeling of the PTO-PTI energy system.

Fuel cells provide direct conversion of fuel into electricity and high total efficiency has been demonstrated. As the technology matures more accurate modeling is required to ensure that the economic and environmental benefits can be realised.

The azimuthing propulsion pods required for WindShip 2025 do not currently exist. The pods require large controllable pitch propellers that can cover the full range of propulsion and harvesting efficiently at different vessel speeds. The propulsion motors will need multiple windings to ensure the most efficient supply and harvesting of energy at vastly different power levels.

Alternative arrangements for the azimuthing pods will be investigated. For example a Counter-Rotating-Propeller arrangement with just a single azimuthing pod could have advantages.

The economic arguments here do not consider full environmental and social impact of fossil fuels. *Siemens* has investigated such factors in a recent study to support the wind industry. Such impacts and associated cost should be included in any future economic study.

REFERENCES

Modern Wind Ships – Phase 1, *KNUD E. HANSEN 1997*
Modern Wind Ships – Phase 2, *KNUD E. HANSEN 1999*
EMSA Study On The Use Of Fuel Cells In Shipping – *DNV/GL 2017*