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QUANTITATIVE ASSESSMENT OF PROPELLER AND SILICONE HULL COATING RETROFITS IN LNG CARRIERS USING OPERATIONAL PERFORMANCE DATA

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Abstract

This thesis quantitatively assesses two energy efficiency retrofits fitted to two LNG carriers, LSA and PL: a silicone fouling-release coating and Propeller Boss Cap Fins (PBCF). Using ISO 19030 based comparison of pre- and post-retrofit data, each retrofit's effect on required power is measured across speed and loading condition, then converted into fuel-cost savings and investment metrics.

Both retrofits show a measurable, positive improvement. The silicone coating reduces required power by 0.54% to 8.01%, larger in Ballast than Laden and at low speed than high speed. PBCF reduces required power by 10.42% (Laden) and -2.43% (Ballast) at real average speed, a small Ballast loss offset by Laden's larger gain, on a thinner data sample.

Both retrofits recover their cost well within their economic life: the silicone coating returns an NPV of approximately EUR421,000, based on measured fuel consumption rather than power reduction (IRR 34.6%, payback 2.24 years), and PBCF returns an NPV of approximately EUR2.1 million (IRR over 490%, payback 74 days), reflecting its low capital cost.

Neither retrofit's benefit is fixed: both vary meaningfully with loading condition and speed, showing that evaluating retrofits against a vessel's real operating profile gives a more defensible economic case than a single-point estimate.

Keywords: LNG carrier retrofit performance; ISO 19030; silicone fouling-release coating; Propeller Boss Cap Fins; retrofit economic evaluation

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1. Introduction

1.1 Introduction to LNG Carrier

Liquefied natural gas (LNG) carriers are purpose-built vessels designed to transport natural gas in liquid form at approximately -162°C, at which temperature its volume is reduced to roughly 1/600th of its gaseous state. Because perfect insulation is not achievable, a small fraction of the cargo continuously vaporizes during the voyage due to heat ingress through the tank insulation, this boil-off gas (BOG) is either used as fuel for the vessel's propulsion plant, re-liquefied, or, in older designs flared. The handling of BOG is a defining characteristic of LNG carrier design and propulsion selection, and is directly relevant to this thesis since both case-study vessels use BOG-capable dual-fuel propulsion.
LNG carriers are broadly categorized by cargo containment system into two families: Moss (spherical, self-supporting independent tanks) and Membrane (thin primary and secondary barriers supported by the ship's hull structure). This thesis considers Membrane-type vessels exclusively for both vessels. Restricting the case study to Membrane-type vessels keeps the hull-form variable controlled between the two ships analyzed.
The two (2) LNG carriers that are used as case studies in this thesis, summarized in Table 1.1. Vessel LSA uses an X-DF dual-fuel two-stroke propulsion arrangement on a twin-skeg configuration with a Mark III Flex Membrane Containment System. Vessel PL uses a dual-fuel diesel-electric (DFDE) propulsion arrangement with an NO96 membrane containment system. They differ in construction (corrugated stainless steel for Mark III Flex versus Invar alloy for NO96), and the two vessels differ in propulsion philosophy (main engine dual-fuel versus diesel-electric).

Particulars	LSA	PL
Type	LNG Carrier, X-DF, Twin Skeg, Mark III Flex	LNG Carrier, Electric Propulsion, DFDE, NO96
Capacity	174,000 CBM	159,000 CBM
LOA	299.06 m	294.2 m
LBP	291.00 m	283.2 m
Breadth	46.40 m	44.0 m
Depth	26.5 m	26.0 m
Design draught	11.5 m	11.5 m
DWT	82,063 MT	89,874 MT
Service speed	19.5 knots	19.5 knots

Table 1.1 - Principal particulars of the two case-study vessels

1.2 Introduction to Energy Efficiency Devices

A wide range of energy efficiency technologies is commercially available to reduce the fuel consumption and emissions of existing ships, including waste heat recovery systems, air lubrication systems, wind-assisted propulsion (rotor sails, kites, wing sails), speed and voyage optimization, and a broad family of hydrodynamic retrofits covering both the hull and the propeller. The two retrofit technologies quantified in this thesis, silicone foul-release hull coating and a propeller boss cap fin (PBCF). Propeller boss cap fins consist of a propeller boss fitted with short blades inclined to convert hub vortex energy into additional torque and thrust transmitted back to the shaft. Silicone foul-release coatings are a class of hull coating that reduces frictional resistance and inhibits the settlement of marine organisms through low surface energy, non-toxic mechanism, as an alternative to biocide-based antifouling paints. Both technologies are retrofittable during a scheduled dry-docking without structural modification.

1.3 The Importance of Hull Coatings & Propeller Performance

The total resistance experienced by a ship moving through water is the sum of several components, among which frictional resistance, arising directly from the condition of the wetted hull surface, typically accounts for the largest share for a vessel operating at moderate speed. A smooth, clean hull minimizes this frictional component, while marine biofouling (algae, barnacles and other organisms) increases surface roughness and can raise frictional resistance substantially over the course of an operating interval between dry-dockings. Hull coating technology has evolved considerably over recent decades.
Tributyltin (TBT)-based antifouling paints were phased out internationally in the 2000s on environmental grounds, prompting a shift first to copper-biocide antifouling systems and subsequently to biocide-free foul-release coatings such as silicone and fluoropolymer systems, which resist fouling settlement through low surface energy rather than toxicity. The choice and condition of hull coating therefore have a direct influence on a vessel's fuel consumption.
Propeller performance is similarly central to a vessel's overall energy efficiency, since the propeller is the final stage converting delivered engine power into thrust. Propeller efficiency can be decomposed into an open-water efficiency component (the propeller's intrinsic hydrodynamic performance in isolation), a hull efficiency component (arising from the interaction between the hull's wake field and the propeller), and a relative rotative efficiency component (arising from the difference between open-water and behind-hull flow conditions). Degradation of any of these components, whether through propeller surface roughening, blade damage, or a deteriorating hub vortex, increases the delivered power required to maintain a given speed.

1.4 Problem Statement

Retrofit technologies such as silicone hull coatings and propeller boss cap fins (PBCF) are widely marketed as effective means of reducing fuel consumption and greenhouse gas emissions on existing vessels. However, the figures usually quoted for these technologies originate from model-scale testing or from the manufacturers themselves, under idealized conditions that rarely reflect the variability of real ship operation. For a shipping company evaluating whether to invest in such retrofits, two distinct but connected questions remain open: how much benefit is realized once the vessel returns to service, and under what operating conditions is that benefit maximized. This thesis addresses both questions using real operational data collected from the two LNG carriers before and after retrofit installation.

1.4.1 Quantify Retrofit Impact

Manufacturer-provided performance curves for propeller and hull coating retrofits are typically derived from controlled model-basin tests or CFD simulations, and do not account for the combined effect of weather, sea state, vessel loading, and gradual hull and propeller fouling that a vessel experiences over years of commercial service. As a result, the actual in-service fuel and power savings delivered by a retrofit are seldom known with confidence by the operator. This creates a first, empirical problem: using real operational data from before and after each retrofit, isolate and quantify the genuine performance improvement attributable to the retrofit itself, separated from the noise introduced by operating conditions and by the natural degradation of hull and propeller condition over time.

1.4.2 Define Optimum Operational Conditions

Even where a retrofit's average benefit is known, that benefit is not constant across all operating conditions: speed and loading condition each influence how much of the retrofit's theoretical advantage is actually captured in practice, and trim can matter too where continuous draft data allows it to be assessed. A retrofit that performs well at one speed or in one loading condition may deliver materially smaller, or larger, gains outside that range. This creates a second, decision-oriented problem: determine the operating conditions, speed, loading condition, and trim where available, under which each retrofit's measured benefit is maximized.

1.5 Methodology Overview

To address these two problems, this thesis combines naval-architecture and a techno-economic approach. On the engineering side, speed-power and speed-consumption data from two LNG carriers were filtered, assessed and compared before and after retrofit installation, using filtered operational data (limited to comparable weather, slip, draft, and speed conditions) to isolate the retrofit's true effect. The primary comparison follows the ISO 19030-1 'Dry-docking performance' indicator: the first year of operation following the vessel's previous drydock, or her delivery where no prior drydock exists, is compared against the first year of operation following the retrofit drydock, so that both periods represent a similarly fresh hull and propeller condition and the comparison isolates the effect of the retrofit itself rather than the general benefit of any drydock. On the techno-economic side, these quantified performance gains are translated into fuel cost savings and standard investment metrics (NPV, IRR, payback period) and are combined with the engineering results to identify the operating conditions that maximize the retrofit's economic benefit.

2. Propulsion Efficiency Drivers in LNG Carriers

This chapter reviews the literature underpinning the performance assessment method applied later in this thesis. It draws on ISO 19030, 'Ships and marine technology - Measurement of changes in hull and propeller performance', which provides the general principles, default measurement method, and expected accuracy benchmarks used throughout this thesis. Shaw and Lin (2021) demonstrate ISO 19030's application to fleet-scale hull and maintenance evaluation using ship big-data analysis, and Tsereklas-Zafeirakis et al. (2016) propose a related techno-economic evaluation methodology for energy efficiency retrofits on a bulk carrier, indicating that the combined engineering-and-economic approach taken in this thesis has precedent in the literature for other vessel types.

2.1 Hull Surface Condition and Coating Performance

Hull surface roughness increases between two dry-docking intervals through two distinct mechanisms: physical degradation of the coating itself (cracking, mechanical damage, corrosion) and biological fouling (the settlement and growth of slime, weed and hard fouling organisms such as barnacles). An analysis of a dataset of hull roughness surveys carried out on 283 ships in dry-dock between 2003 and 2014 found a mean increase in average hull roughness of approximately 10 micrometers per year since the previous dry-docking, averaged across the surveyed fleet (Stenson et al., 2014, as reported in Yeginbayeva and Atlar, 2018). A separate, widely used simplified assumption, also adopted in the uncertainty analysis underlying ISO 19030-1 (International Organization for Standardization, 2016), is a linear degradation in speed-power performance of approximately 2,6% per year averaged across a vessel's dry-docking interval, independent of speed and draught. This figure provides a useful literature benchmark against which the degradation trend measured for LSA and PL can be compared.
Silicone foul-release coatings differ from this general pattern in an important way: because they resist fouling settlement through low surface energy rather than biocide release, their performance degradation over the dry-docking interval is driven primarily by mechanical wear and any residual slime accumulation, rather than by hard fouling growth.
Hu et al. (2020) review the underlying mechanism in more detail: silicone-based fouling-release coatings rely on the low surface energy and low elastic modulus of polydimethylsiloxane (PDMS), which weakens the adhesion of fouling organisms rather than poisoning them, so that fouling that does settle is more easily removed by the shear forces of vessel movement. The same review notes that the long-term durability of these coatings under continuous immersion remains an active area of research, consistent with this thesis's use of a single first-year measurement as a simplifying assumption rather than a fully characterized multi-year performance curve.

2.2 Propeller Performance and Retrofit Effects

Propeller boss cap fins (PBCF) target the hub vortex specifically: a conventional propeller boss cap generates a strong rotational vortex immediately downstream of the hub, wasting a portion of the energy delivered to the propeller. PBCF fins break up this vortex, converting the recovered rotational energy into additional thrust. Manufacturer literature reports fuel savings in the range of 3% to 5% at constant speed compared with an equivalent vessel without PBCF, corresponding to roughly a 1% increase in thrust and a 3% reduction in torque at the propeller (Nojiri, Ishii and Kai, 2011). These figures originate from manufacturer sea trials and model tests under controlled conditions.
Independent academic assessment supports figures in a broadly similar range: Mizzi et al. (2017), citing the same manufacturer's claim of up to 5% fuel savings, developed an optimised PBCF geometry using computational fluid dynamics and found a net propeller efficiency gain of 1.3% for their specific design, illustrating that PBCF's realised benefit depends materially on the specific fin

geometry and the vessel it is fitted to, not solely on the general concept.
The two vessels studied in this thesis also represent different generations of LNG carrier propulsion technology, a genuine confound when comparing their absolute efficiency levels directly. LSA uses a two-stroke dual-fuel (X-DF) main engine arrangement, a more recent development offering higher thermal efficiency through direct mechanical drive. PL uses a four-stroke Dual Fuel Diesel Electric (DFDE) arrangement, in which several generating sets supply electrical power to the propulsion motors, DFDE and the closely related Tri-Fuel Diesel Electric (TFDE) configuration represented approximately 32% of the global LNG carrier fleet in 2018, valued for fuel flexibility across heavy fuel oil, distillate fuel, and boil-off gas, and for the operational redundancy of multiple generating sets (Bonello, Gonzalez Gutierrez and Suarez De La Fuente, 2021).

2.3 Operational Factors Affecting Efficiency

A ship's delivered power at a given speed is influenced by a range of operational and environmental factors beyond hull and propeller condition, which must be controlled for or filtered out to isolate the retrofit effect. Based on the data available for LSA and PL, the following operational parameters are used in this thesis: speed through water, draft, cargo carried, condition, shaft power, fuel and gas consumption and the resulting equivalent consumption, wind speed, propeller slip, and rudder angle. Wind speed and slip are used directly as filtering criteria, following ISO 19030-1 reference conditions, rudder angle is used to exclude periods of significant helm use that would add resistance unrelated to hull or propeller condition. The remaining parameters (speed, power and consumption) form the basis of the speed-power and speed-consumption performance values.

3. Operational Data and Performance Metrics Framework

This chapter introduces the operational data used, where they come from, which parameters are recorded, and the data-quality and filtering considerations that shape how it is used.

3.1 Data Sources and Structure

LSA's operational data are recorded by a high-frequency onboard integrated alarm and monitoring system, logging continuously at hourly resolution. PL's operational data are recorded through a noon-report telegram system, logging once daily. Both datasets were exported from their respective platforms.

3.2 Data Sources: Raw and Calculated Parameters

The parameters used from LSA's dataset include raw values recorded directly by the monitoring system (date and time (UTC), cargo volume, loading condition, rudder angle, and speed through water) and values calculated by the system itself (slip, Beaufort scale, corrected total shaft power, and main engine fuel oil equivalent). For PL, most parameters are manually entered by the crew as part of the noon report (telegram date, telegram type, loading condition, average speed, wind force, speed through water, and main engine shaft power), while only slip and total auxiliary engine LSMGO equivalent consumption are calculated by the reporting platform.

3.3 Data Quality Challenges

The two datasets differ in a further way beyond logging frequency. PL's reference period (2019) predates the installation of high-frequency monitoring on board entirely, only noon-report data exist for that period. High-frequency monitoring was installed on PL partway through the evaluation period (2024-2025). To keep the comparison fair, only noon-report data are used for PL in both periods, rather than mixing noon-report and high-frequency data across the two halves of the comparison.

3.4 Data Filtering and Preprocessing Strategy

Beyond the fixed reference condition filters, further preprocessing removes records that are not usable regardless of condition: non-numeric sensor-error codes ('I/O Timeout', 'Bad') are converted to missing values and excluded, records logged while the vessel is in port, departure or arrival conditions (speed through water at or near zero) are excluded, since the reference condition speed filter already requires speed through water above 10 knots, and for PL specifically, only noon-report telegrams are used, excluding arrival and departure telegrams as well, which cover partial, non-representative periods rather than a full day's operation.
Loading condition is determined as follows:

- LSA: cargo volume above 160,000 cubic meters is treated as Laden, cargo volume below 6,000 cubic meters is treated as Ballast. This is applied together with the vessel's own logged Condition tag.
- PL: the vessel's own logged Condition Type is used directly, no cargo volume threshold is available for PL.

4. Methodology for Performance Assessment

This chapter sets out the ISO 19030 criteria used: the data preparation process, the reference and evaluation curve approach, the performance indicator, and the filtering method used to isolate each retrofit's effect.

4.1 Data Preparation Pipeline

LSA's data are logged continuously at hourly resolution through the ship's Integrated Alarm and Monitoring System, transmitted to the server database every hour. LSA main engines are two WinGD 5X72DF two stroke direct reversible engines which use the Otto's cycle with gas injection in the mid stroke, with individually metered fuel and gas flow via Coriolis flow meters. PL's data are sourced from daily noon-report telegrams from the company's ERP system. PL's propulsion is Dual fuel diesel-electric, with four Wartsila 9L50DF generator engines. Both datasets required cleaning: non-numeric sensor-error codes ('I/O Timeout', 'Bad') were converted to missing values and excluded. LSA records with a negative wind-corrected shaft power were dropped.
Fuel consumption is used on an energy equivalent basis rather than raw mass, since VLSFO and LNG have different calorific values: LSA's figure is her main engine VLSFO equivalent consumption, PL's is her LSMGO equivalent consumption. The two vessels' propulsion architectures also differ: LSA's main engines are direct-drive with individually Coriolis type flow meters, so her consumption figure is propulsion specific. PL is diesel-electric (DFDE): four generators supply a common busbar for both propulsion and hotel/cargo load, so PL's only available consumption figure reflects total electrical demand, not propulsion alone. This is expected to make speed-consumption a noisier metric for PL than for LSA, and is a property of the vessel's architecture rather than a data-quality issue. The reference-condition filters applied to both vessels' data, following ISO 19030-1, are given in Table 4.1.

Condition	Ballast / Laden
Speed through water	> 10 knots
Rudder angle	-5 deg to +5 deg
Slip	-1% to +1%
Beaufort scale	< 4
Ballast	< 6,000 m3
Laden	> 160,000 m3

Table 4.1 - ISO 19030-1 Reference-Condition Filters

4.2 Hydrodynamic Performance Modelling (incl. Model Validation and Benchmarking)

The hydrodynamic performance model fits each vessel's speed-power relationship to a curve of the form:

$$Shaft\ Power = c * Vessel's\ Speed^{n}$$

fitted separately to the reference-period (pre-retrofit) and evaluation-period (post-retrofit) data. Table 5.1 gives the resulting predicted power at each round-number speed for LSA, comparing the reference-period curve (2020) against the evaluation-period curve (2025); Table 5.2 derives the difference between them as an absolute and percentage saving. At 10kn, for example, the reference curve predicts 3,657kW in Laden condition and the evaluation curve predicts 3,364kW, a saving of 293kW (8.01%) attributable to the silicone retrofit at that specific speed. The same fitting method is applied to both vessels and both loading conditions, giving four independently fitted curves per vessel (reference and evaluation, Ballast and Laden).

4.3 Key Performance Indicator: Percentage Power Reduction

The Key Performance Indicator used is the percentage reduction in shaft power at matched speed, calculated directly from each vessel's fitted reference-period (pre-retrofit) and evaluation period (post-retrofit) curves. At a given speed V, the reference period curve gives the pre-retrofit expected power, and the evaluation period curve gives the post-retrofit expected power.
The percentage power reduction at that speed is:

$$Power\ Reduction\ (\%) = 100 * \frac{(P\ ref(V) - P\ eval(V))}{P\ ref(V)}$$

This is calculated at every round number speed across each vessel's realistic operating range from 10 to 22 knots, giving a full speed dependent picture rather than a single average figure. The resulting speed-by-speed tables (Tables 5.1-5.4) are the basis for the results throughout the rest of this thesis. A positive value means less power is needed to achieve the same speed after the retrofit.

4.4 Retrofit Impact Assessment Method

Both vessels' data are filtered to calm, steady conditions before any comparison is made: wind below Beaufort 4, slip between -1% and 1%, and power greater than zero. Two of ISO 19030-1's standard filters, water depth and water temperature, could not be applied to either vessel, since neither dataset records usable values for them. A rudder angle limit of -5 to 5 degrees was applied to LSA; PL's data does not record rudder angle, so this filter could not be applied to her. Data are split by each vessel's own logged loading condition (Ballast or Laden), confirmed against a cargo volume threshold for LSA: cargo volume above 160,000 cubic meters is treated as Laden, below 6,000 cubic meters as Ballast, applied together with her logged Condition tag. PL's split relies on her logged Condition Type directly, since no cargo volume threshold is available for her.
Within each condition, outlier points are removed using Chauvenet's criterion (Taylor, 1997), consistent with the outlier-detection method described in ISO 19030-2, Annex I: for each point, the criterion checks how likely a difference that large would be by chance given the sample size; if fewer than half an occurrence would be expected, the point is dropped as a bad reading. This check runs twice before the Performance Indicator is calculated.

5. Case Study: LNG Carrier Analysis

The two retrofits are implemented and analyzed as independent, parallel case studies, not compared against one another: LSA received a silicone hull coating, PL received a propeller boss cap fin (PBCF).

5.1 Vessel Selection and Retrofit Description

5.1.1 LSA - Silicone Hull Coating Retrofit

The retrofit is Hempaguard X7 (Hempel A/S, product 89900), a high-solids fouling-defense coating combining a hydrogel-silicone with a low-biocide component (ActiGuard technology), rated for up to 90 months' service and 120 days' idle time (150-micron reference DFT, 70% volume solids) (Hempel A/S, n.d.). The silicone application targets 19.0 knots design speed and a 60-month service interval, matching LSA's 19.5-knot service speed and the 5-year economic life assumed for the retrofit's investment appraisal.
Coverage is not uniform: the vertical sides (7,950 m2) received the full silicone system (primer, tiecoat, two coats of X7 at 100-micron DFT each), the flat bottom (9,450 m2) retained conventional biocidal antifouling.

5.1.2 PL - Propeller Boss Cap Fin Retrofit

PBCF is a propeller boss cap fitted with short fins that convert the hub vortex's rotational energy into additional thrust, also reducing stern vibration, propeller noise, and rudder erosion. It was installed on PL at her second drydock. The manufacturer's own technical literature reports a fuel consumption reduction of up to 5% at constant speed, corresponding to roughly a 3% reduction in propeller shaft torque and a 1% increase in thrust (Nojiri, Ishii and Kai, 2011).

5.2 Pre- vs Post-Retrofit Performance Analysis

The percentage power reduction is calculated at every filtered point in each vessel's reference and evaluation periods, using an operational reference curve fitted to that vessel's own pre-retrofit data, split by loading condition and reported across three metrics.

5.2.1 LSA - Silicone Coating Performance Analysis

Reference period: 27 Feb 2020 - 28 Feb 2021 (post-delivery, no silicone). Evaluation period: 28 Feb 2025 - 27 Feb 2026 (post-silicone). LSA's February 2025 drydock was her first since delivery in February 2020, so the reference period is her as-delivered condition rather than a post-drydock one; no intermediate drydock or hull work falls between the two periods. Filtering, including the cargo-volume threshold confirming loading condition, retained a substantial sample in both periods.

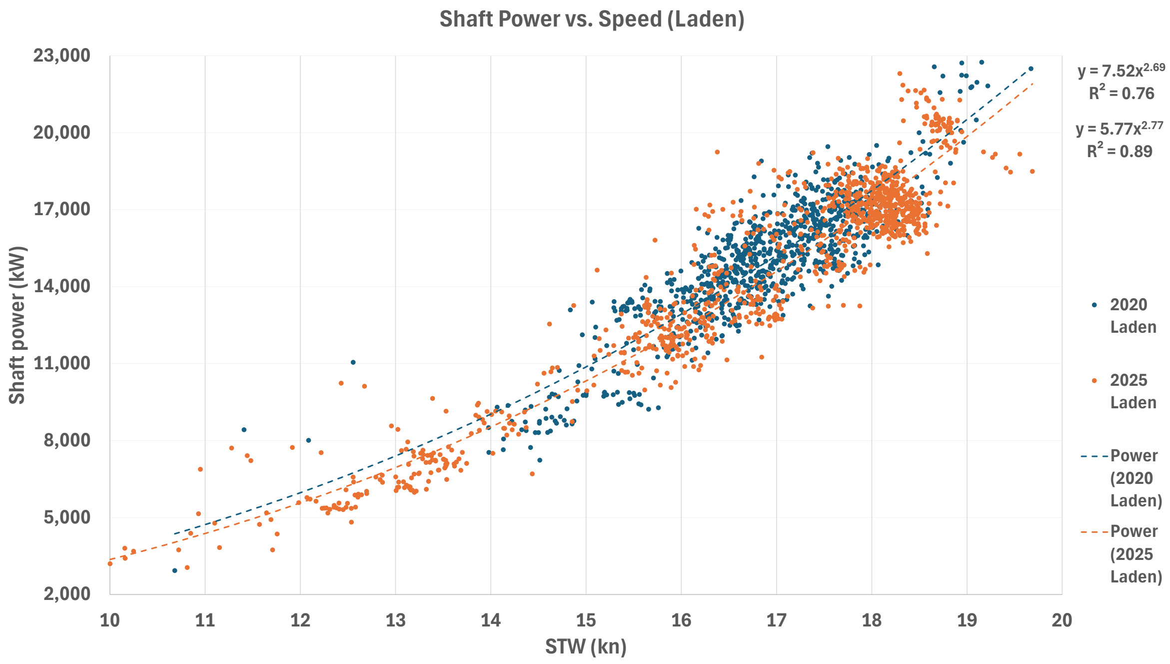

Figure 5.1 - LSA Speed-Power, Laden

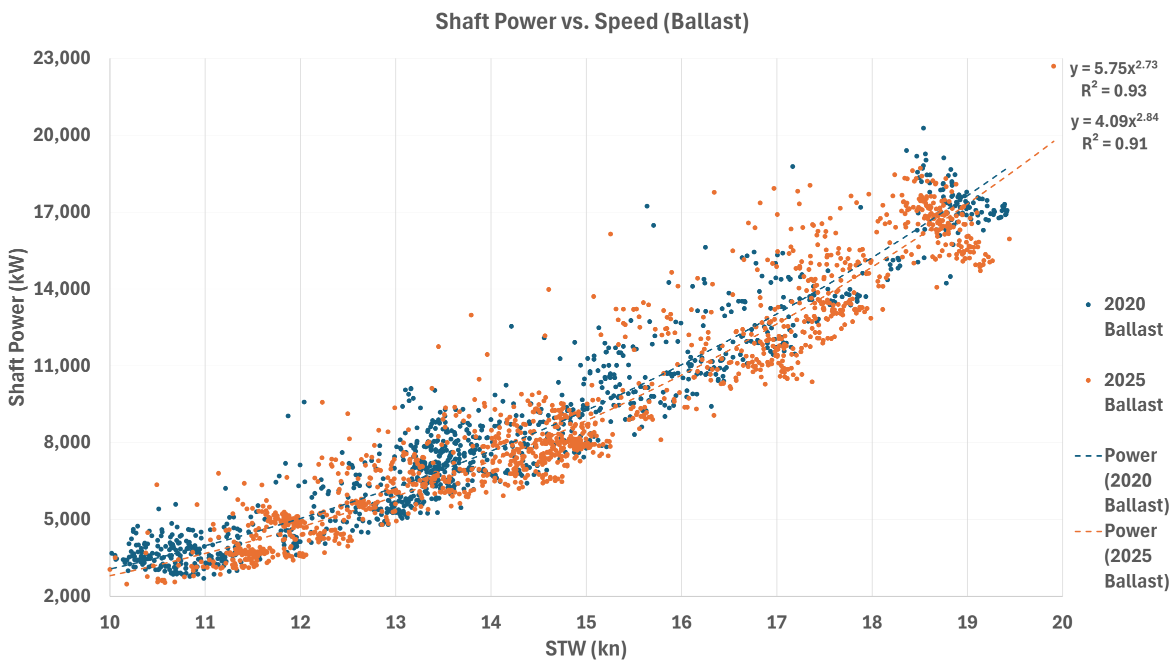

Figure 5.2 - LSA Speed-Power, Ballast

Speed (kn)	Laden 2020 (kW)	Laden 2025 (kW)	Ballast 2020 (kW)	Ballast 2025 (kW)
10	3,657	3,364	3,065	2,821
11	4,724	4,378	3,975	3,697
12	5,968	5,570	5,039	4,733
13	7,400	6,950	6,268	5,940
14	9,031	8,531	7,671	7,331
15	10,870	10,325	9,259	8,917
16	12,929	12,342	11,040	10,710
17	15,216	14,595	13,025	12,721
18	17,742	17,095	15,221	14,962
19	20,517	19,853	17,639	17,444
20	23,549	22,879	20,287	20,178

Table 5.1 - LSA Speed-Power Performance, Laden and Ballast condition

Speed (kn)	Laden Saving (kW)	Laden Saving (%)	Ballast Saving (kW)	Ballast Saving (%)
10	+293	+8.01%	+244	+7.97%
11	+346	+7.31%	+277	+6.98%
12	+398	+6.68%	+306	+6.07%
13	+450	+6.09%	+327	+5.22%
14	+500	+5.54%	+340	+4.43%
15	+546	+5.02%	+342	+3.69%
16	+587	+4.54%	+330	+2.99%
17	+621	+4.08%	+304	+2.33%
18	+647	+3.65%	+260	+1.71%
19	+664	+3.24%	+195	+1.11%
20	+670	+2.84%	+109	+0.54%

Table 5.2 - LSA Speed-Power Saving, Laden and Ballast condition (derived from Table 5.1)

Speed-power shows the largest relative benefit at low speed, decreasing steadily with speed in both conditions.
The same breakdowns are not attempted for PL: her reference period sample is already thin at the condition level (29 points each, against 611-970 for LSA) due to noon-report frequency, and splitting further leaves too few points to trust.

5.2.2 PL - Propeller Boss Cap Fin Performance Analysis

Reference period: 18 Mar 2019 - 18 Mar 2020 (pre-PBCF). Evaluation period: 27 Jun 2024 - 27 Jun 2025 (post-PBCF). Noon-report frequency gives substantially smaller filtered samples than LSA's (26-84 points per cell vs. several hundred to over a thousand), results are reported with this difference in statistical power kept in view.

PL’s speed-power comparison is given in two steps: the measured power before and after the retrofit (Table 5.3), then the resulting saving calculated from those two columns (Table 5.4).

The curve fits underlying these figures are only moderately strong (R2 = 0.67 for Laden 2025, R2 = 0.73 for Ballast 2025, Figures 5.3-5.4), meaning roughly a quarter to a third of the variance in measured power is not explained by speed alone. Since the reported saving is the difference between two such curves, this uncertainty compounds rather than cancels: a small percentage difference is being measured against a comparatively wide scatter in each underlying curve. The resulting saving should be read as a point estimate with a wide margin rather than a precise figure.

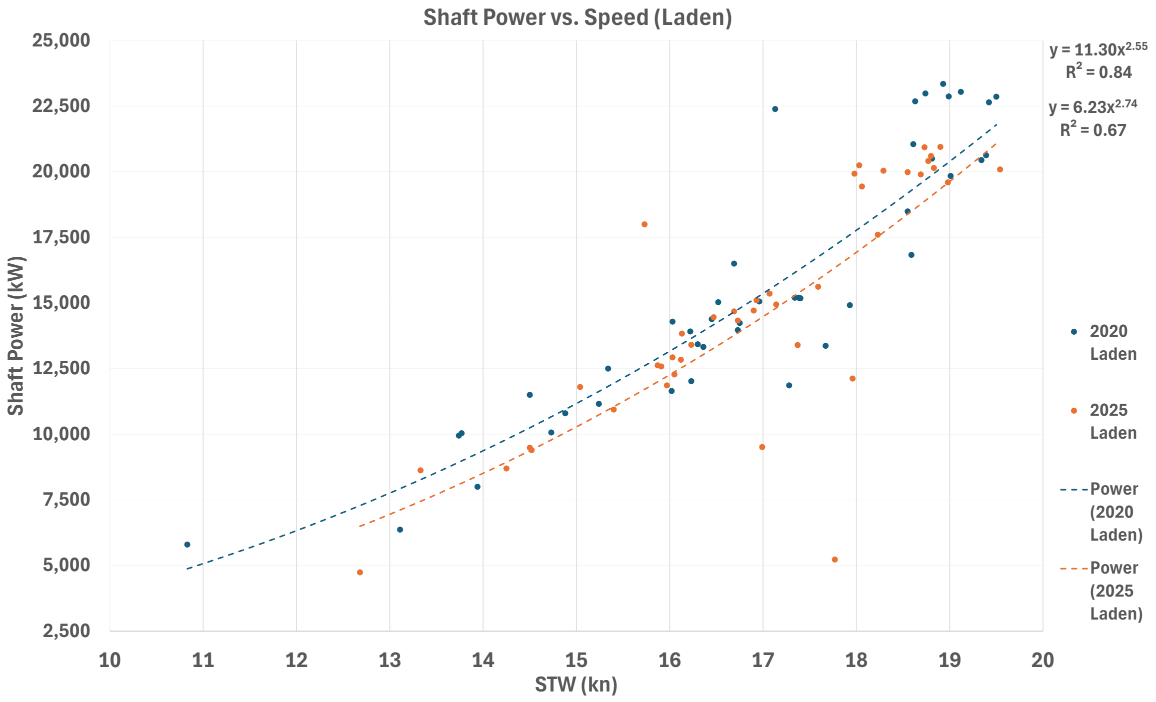

Figure 5.3 - PL Speed-Power, Laden

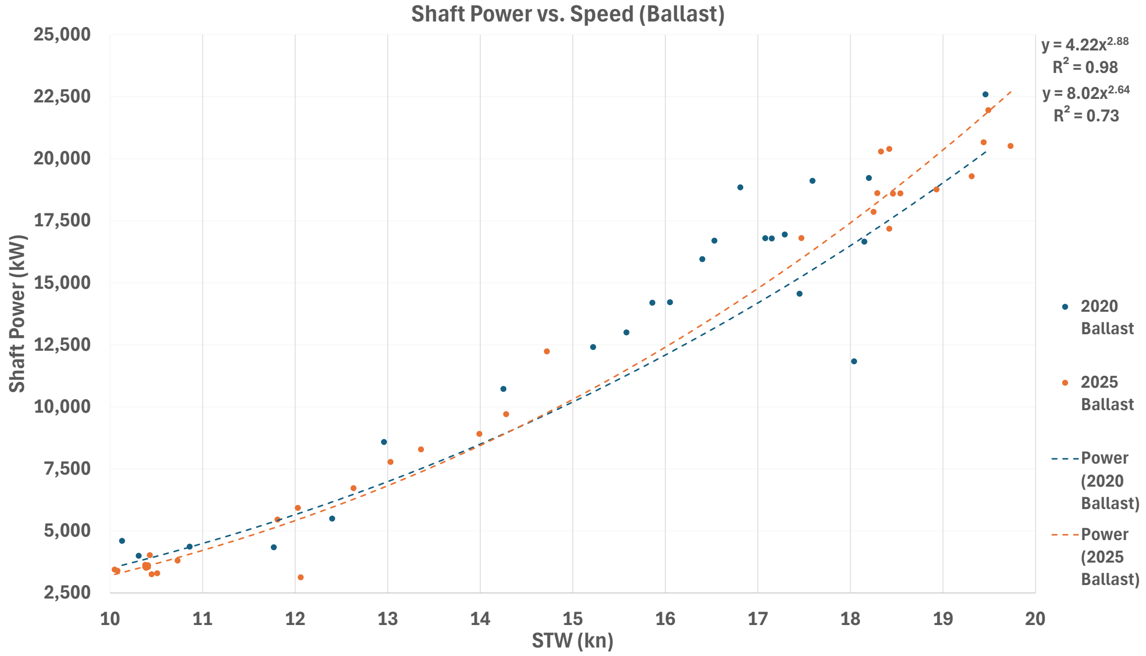

Figure 5.4 - PL Speed-Power, Ballast

Speed (kn)	Laden 2020 (kW)	Laden 2025 (kW)	Ballast 2020 (kW)	Ballast 2025 (kW)
10	3,977.56	3,390.76	3,205.13	3,497.18
11	5,070.18	4,400.79	4,217.68	4,497.53
12	6,327.79	5,583.48	5,419.01	5,658.70
13	7,758.43	6,950.25	6,824.15	6,989.90
14	9,369.83	8,512.26	8,447.99	8,500.07
15	11,169.49	10,280.46	10,305.27	10,197.90
16	13,164.62	12,265.57	12,410.62	12,091.84
17	15,362.26	14,478.15	14,778.53	14,190.17
18	17,769.22	16,928.58	17,423.41	16,500.97
19	20,392.15	19,627.07	20,359.55	19,032.15

Table 5.3 - PL Speed-Power Performance, Laden and Ballast condition

Speed (kn)	Laden Saving (kW)	Laden Saving (%)	Ballast Saving (kW)	Ballast Saving (%)
10	+586.80	+14.75%	-292.04	-9.11%
11	+669.39	+13.20%	-279.85	-6.64%
12	+744.30	+11.76%	-239.69	-4.42%
13	+808.17	+10.42%	-165.75	-2.43%
14	+857.57	+9.15%	-52.08	-0.62%
15	+889.03	+7.96%	+107.38	+1.04%
16	+899.05	+6.83%	+318.78	+2.57%
17	+884.10	+5.76%	+588.36	+3.98%
18	+840.64	+4.73%	+922.44	+5.29%
19	+765.08	+3.75%	+1,327.40	+6.52%

Table 5.4 - PL Speed-Power Saving, Laden and Ballast condition (derived from Table 5.3)

PL's speed-power pattern matches LSA's: both Laden and Ballast show a benefit that decreases with speed, largest at low speed. FOE consumption is not reported for PL: her noon-report data produce results too noisy to be usable, consistent with the reliability limitation already noted for her diesel-electric consumption figure.

5.3 Assessment and Application of Results

5.3.1 LSA - Assessment and Application of Results

Looking at the full speed-power curves rather than the single averaged figure, the improvement is not uniform across speed: at lower speeds (10-15 knots) the silicone retrofit needs roughly 3-8% less propulsive power for the same speed, in both Laden and Ballast, while at higher speeds (17-20 knots) the improvement narrows to around 2%. Fuel consumption follows the same general pattern, largest saving at low speed, though the exact magnitude differs from the power-based figure at any given speed.

5.3.2 PL - Assessment and Application of Results

On the speed-power curves specifically, the improvement is largest close to design draft and design speed, roughly 3-14%, against a smaller but still positive 1-6% in Ballast. The Laden improvement is more modest once averaged across the full range, around 4%.

6. Techno-Economic Optimization of Operational Conditions

This chapter identifies when each retrofit's benefit is largest: greater power reduction means greater fuel savings and greater financial return. Loading condition is the clearest driver for either retrofit, but a point estimate alone does not show how confident that conclusion is.

6.1 LSA - Optimal Trim by Speed Band

This is a purely operational question: given the ship as she is today, with the silicone retrofit installed, which trim setting uses the least power at a given speed? Only 2025 (post-retrofit) data is used - there is not before/after comparison here. Within each speed band, a separate curve is fitted to each trim category's real data, and the predicted power at the band's mid-speed is compared across the three trim categories. Bands or trim categories with fewer than roughly 20 real data points are excluded rather than reported, since a small sample can look artificially good or bad by chance.

Each 2025 reading is classified into one of three trim categories based on her actual trim at that point: By Bow (trim below -0.3m), Even (-0.3m to 0.5m), or By Stern (trim above 0.5m). These boundaries follow the natural clustering in LSA's own trim data: a dense central cluster sits between roughly -0.3m and 0.5m, with a clear thinning of readings beyond 0.5m marking the transition into by-stern trim, and a further, more gradual thinning below -0.3m marking the transition into by-bow trim.

Speed band	Ballast - best trim (power)	Laden - best trim (power)
10-12kn	Even (3,431 kW)	insufficient data
12-14kn	Even (6,279 kW), near-tie with by-bow	insufficient data
14-16kn	Even (8,274 kW)	Even (10,369 kW)
16-18kn	By-stern (12,132 kW)	Even (14,549 kW), near-tie with by-stern

Table 6.1 - LSA Optimal Trim by Speed Band (2025 data only)

Laden's 10-14kn range cannot be answered: every trim category there has too few points (4-18) to trust a result either way, so no recommendation is made rather than reporting an unreliable one. Even trim is the best or joint-best choice in five of the six bands where a result can be given. The one exception is Ballast at 16-18kn, where by-stern trim uses less power (12,132 kW against 12,600 kW for even), and all three trim categories are well supported there (79-140 points each), making this the most statistically solid finding in the table. A closer look within the 14-16kn Ballast band shows even trim ahead through most of the range but by-stern's fitted curve overtaking it above roughly 15.5kn. This crossover is not treated as confirmed, since by-stern's fit in that band rests on only 19 points and an unusually shallow curve shape compared with the other categories.

6.2 PL - Optimal Speed Band by Condition

Rather than a single speed, PL's speed-power saving (Table 5.4) is grouped into three bands to identify where the retrofit's impact is largest, per condition.

Speed band	Laden	Ballast
10-13kn	+12.53%	+5.30%
13-16kn	+8.59%	-0.18%
16-19kn	+5.27%	-4.84%

Table 6.2 - PL Average Speed-Power Saving by Speed Band

Laden's largest average impact is in the 10-13kn band, but this should not be read at face value: her reference period has only one real data point below 13kn, so most of that band's result comes from the curve extrapolating well beyond any real measurement, not a genuine finding. The comparison between 13-16kn and 16-19kn is properly supported in both periods (9-33 points each) and shows a clear, trustworthy trend: benefit decreases steadily as speed increases, from +8.59% to +5.27%. Within the range that can be trusted, lower speed in general is better for Laden. Ballast shows the same pattern as Laden: benefit decreases as speed increases, from +5.30% at 10-13kn through roughly breakeven at 13-16kn (-0.18%) to a loss at 16-19kn (-4.84%). This is consistent with the trend found for Laden, both conditions showing the retrofit's benefit concentrated at lower speeds. PBCF's benefit for PL is therefore decreasing with speed in both loading conditions, with Ballast reaching a loss at higher speed sooner than Laden does, possibly because Ballast's shallower draft leaves the propeller less deeply submerged, altering the wake field the hub-vortex-recovery fins operate in and reducing their effectiveness.

7. Economic Evaluation of Retrofit Solutions

This chapter converts the retrofits' measured performance benefit into fuel-cost savings and standard investment metrics, using the one-off and, where applicable, recurring costs actually incurred for each retrofit.

7.1 Cost Structure of Retrofits

7.1.1 LSA - Silicone Coating

Item	Cost (EUR)
Drydock hull coating cost with Conventional SPC antifouling application	90,838
Drydock hull coating cost with Silicone application	245,902
Cost difference between Silicone and Conventional paint application	155,064
Silicone material (invoiced separately)	380,934
Total one-off cost	535,998

Table 7.1 - LSA Silicone Retrofit Cost

LSA's silicone retrofit cost has two components: additional labor and yard cost for silicone surface preparation, due to full blasting, and the silicone material itself, invoiced separately (Table 7.1). The recurring cost is assumed to repeat this same incremental pattern (the price difference between silicone and conventional antifouling) at each future 5-year recoat, rather than the full recoat cost, since a standard recoat would be required regardless of coating type. This assumes future labour and material costs stay broadly in line with current levels.

7.1.2 PL - PBCF

Item	Cost (EUR)
PBCF device	49,349.87
Shipyard installation	16,000.00
Total one-off cost	65,349.87

Table 7.2 - PL PBCF Retrofit Cost

PL's PBCF retrofit cost has two components as well: the device itself and shipyard installation (Table 7.2). PBCF is treated as having no material recurring cost over its economic life, as a passive device with no consumables.

7.2 Fuel Savings Quantification

Annual fuel cost saving is calculated as the measured Performance Indicator (as a percentage) applied to each vessel's baseline annual fuel consumption, valued at a fuel price. Each vessel uses her own fuel basis: LSA's figure is VLSFO equivalent, PL's is LSMGO equivalent. For both, the base-case price is taken from the evaluation period with the reference period price given as context. Both prices are Ship & Bunker's published G20 index annual averages, converted to EUR. Applying a speed-power Performance Indicator to a fuel-mass baseline implicitly assumes that the percentage reduction in power translates directly into the same percentage reduction in fuel burned, i.e. that specific fuel consumption stays constant at that operating point. This assumption does not always hold: LSA's own measured fuel-consumption saving differs from her power saving at a given speed. Where a directly measured fuel-consumption Performance Indicator is available and treated as reliable, it is used instead of power, avoiding this assumption; this is the case for LSA's base case. PL's calculation relies on the power-based Performance Indicator throughout, since her only fuel-consumption figure is excluded as unreliable, and so carries this assumption without an independent check.

7.2.1 LSA - Silicone Coating

LSA's fuel consumption saving, the direct input to the calculation below, is given in Tables 7.3-7.4.

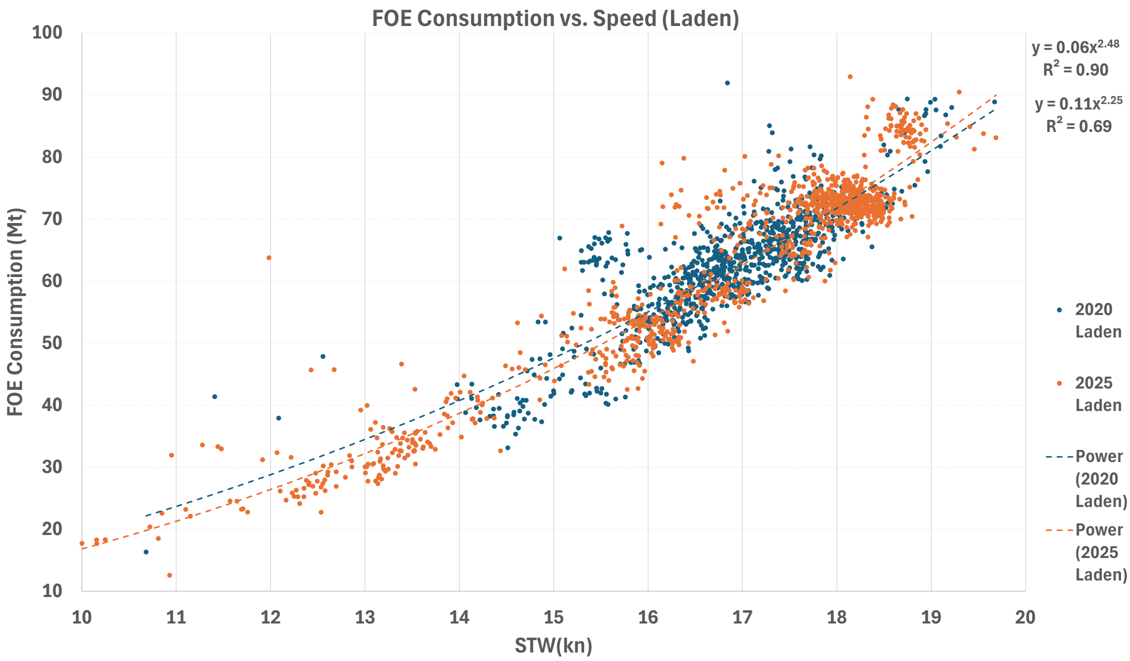

Figure 7.1 - LSA FOE Consumption vs Speed, Laden condition

Speed (kn)	2020 FOE (Mt/day)	2025 FOE (Mt/day)	Saving (Mt/day)	Saving (%)
10	19	17	2	+11.94%
11	24	21	2	+10.03%
12	29	26	2	+8.25%
13	34	32	2	+6.59%
14	41	39	2	+5.02%
15	48	46	2	+3.53%
16	55	54	1	+2.13%
17	63	63	0	+0.78%
18	72	72	0	-0.50%
19	81	82	-1	-1.73%
20	91	94	-3	-2.91%

Table 7.3 - LSA VLSFO-Equivalent (FOE) Consumption Saving, Laden condition

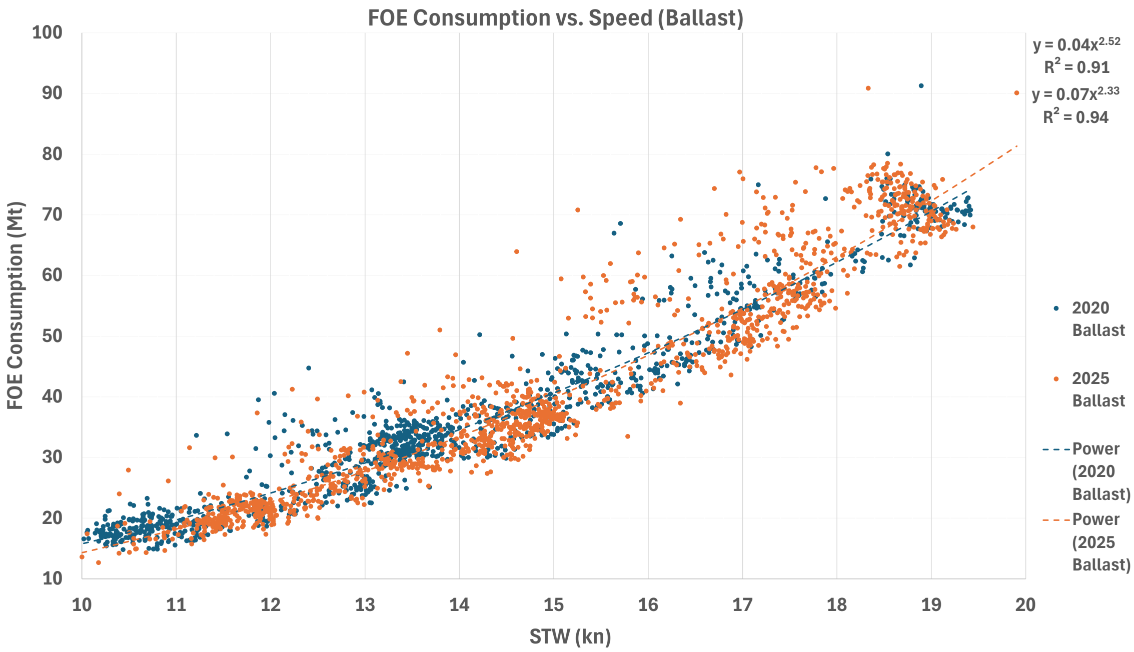

Figure 7.2 - LSA FOE Consumption vs Speed, Ballast condition

Speed (kn)	2020 FOE (Mt/day)	2025 FOE (Mt/day)	Saving (Mt/day)	Saving (%)
10	16	14	1	+9.38%
11	20	18	2	+7.72%
12	24	23	1	+6.18%
13	29	28	1	+4.74%
14	35	33	1	+3.39%
15	41	40	1	+2.11%
16	47	47	0	+0.90%
17	54	55	0	-0.25%
18	62	63	-1	-1.35%
19	71	72	-2	-2.40%
20	80	82	-3	-3.40%

Table 7.4 - LSA VLSFO-Equivalent (FOE) Consumption Saving, Ballast condition

FOE consumption broadly follows the speed-power trend at low-to-mid speed, with savings highest at low speed and declining as speed increases. Above ~17-18 knots, the evaluation-period consumption curve is fitted to a comparatively noisy sample (R2 = 0.69 for Laden 2025), and the resulting saving turns negative there while speed-power's saving remains clearly positive to 20kn; given this inconsistency with a metric that should track the same underlying physical cause, consumption values above ~17-18kn are treated as unreliable rather than a genuine finding. Since fuel consumption, not shaft power, is what directly determines fuel cost, the economic base case uses the measured FOE consumption saving rather than the speed-power saving, at 15kn, within the range where the two metrics agree well. Baseline annual consumption is 19,306 tons VLSFO-equivalent (LSA's continuous logging, reference year, all conditions combined), using her real average operating speed (~15kn, not the 19.5kn service speed). Table 7.5's Ballast and Laden baselines sum to a smaller 18,732 tons, since they exclude the roughly 3% of the year spent loading and unloading cargo alongside, which has no sailing condition to assign a saving to; the 574-tonne difference does not affect Table 7.5's result, which is built directly from the Ballast and Laden figures rather than from the all-conditions total. VLSFO price: EUR324/t (2020 reference) vs. EUR464/t (2025 evaluation, base case). Table 7.5 gives the resulting annual saving.

Condition	Baseline (t/year)	% Saving	Tons Saved	EUR
Ballast	10,143	2.11%	214.0	99,214
Laden	8,589	3.53%	303.2	140,554
Total	18,732	-	517.2	239,768

Table 7.5 - LSA Annual Fuel-Cost Saving (real average speed, 15kn)

Two named alternative comparisons illustrate the sensitivity of this figure to the assumptions made: speed-power in place of FOE consumption at 15kn, which gives a higher total of EUR373,388, since the power-based saving is larger than the consumption-based saving at this specific speed despite both metrics agreeing on the general trend; and her rated service speed (19kn) using speed-power, which gives a smaller annual saving of EUR181,205 since her benefit decreases with speed. FOE consumption at service speed is not used for this comparison, since consumption above ~17-18kn is not treated as reliable.

7.2.2 PL - PBCF

For PL the Baseline annual consumption is estimated at 22,884 tons LSMGO-equivalent, from PL's own noon-report data across the reference year, the same one-report-per-day basis used. Noon reports cover 256 of the 365 reference year days. The base case uses her real average operating speed (approximately 13kn, not her 19.5kn service speed). Fuel price: LSMGO averaged EUR563 per tonne in the reference year (2019) and EUR678 per tonne across the evaluation period (2024-2025), the base-case price. Table 7.6 gives the resulting annual saving.

Condition	Baseline (t/year)	% Saving	Tons Saved	EUR
Ballast	14,838	-2.43%	-360.6	-244,631
Laden	8,046	10.42%	838.4	568,825
Total	22,884	-	477.8	324,193

Table 7.6 - PL Annual Fuel-Cost Saving (real average speed, 13kn)

Her rated service speed (19kn) is a named alternative comparison, giving a net annual loss of approximately EUR497,000: her benefit decreases with speed in both conditions, and Ballast specifically turns from a gain at low speed into a substantial loss (-6.97%) at 19kn, outweighing Laden's continued positive contribution. This reinforces rather than undermines the case for using her real average operating speed as the base case: the service-speed scenario is not just smaller, it is actively unprofitable, underlining how much the choice of representative speed affects the economic conclusion.

7.3 Financial Metrics (NPV, IRR, Payback Period)

Following ISO 19030-1's own default of a 1-year reference and evaluation period, the measured annual benefit is treated as the representative annual saving and held flat across each retrofit's economic life in the base case: 5 years for silicone, approximately 10 years for PBCF. Net Present Value, Internal Rate of Return and payback period are calculated from the resulting annual cash flow against the one-off cost, at an 8% discount rate.
The 8% rate reflects a moderate, risk-adjusted cost of capital consistent with shipping investment appraisal practice: Cullinane and Panayides (2000) find that UK-based ship operators' capital budgeting decisions are typically evaluated against an expected cash flow discounted at a risk-adjusted rate rather than the risk-free rate, and Drobetz, Albertijn and Johns (2018) set out the standard cost-of-capital frameworks from which such a rate is typically derived. As a current market-based anchor, GuruFocus (2026) reports a Transportation industry median WACC of 7.93% and a ten-year median WACC of 7.32% for Seanergy Maritime Holdings, a comparable listed dry-bulk shipping company; 8% sits close to both figures. This thesis does not independently derive a company-specific weighted average cost of capital, since the capital structure and cost of debt of either vessel's operator are not available; 8% is used as a reasonable point estimate consistent with

these benchmarks; its effect on the results is tested directly later in this chapter.

7.3.1 LSA - Silicone Coating

Metric	Value
One-off cost	EUR535,998
Annual saving (real average speed base case)	EUR239,768
Economic life	5 years
Discount rate	8%
NPV	EUR421,326
IRR	34.6%
Simple payback	2.24 years

Table 7.7 - LSA Investment Metrics

The retrofit recovers its cost within its economic life and remains comfortably positive at the 8% hurdle rate.

7.3.2 PL - PBCF

Metric	Value
One-off cost	EUR65,349.87
Annual saving (real average speed base case)	EUR324,193
Economic life	10 years
Discount rate	8%
NPV	EUR2,110,012
IRR	496.1%
Simple payback	0.202 years (74 days)

Table 7.8 - PL Investment Metrics

Even at this materially more conservative base case than her rated service speed, the investment case remains extremely strong: PBCF is a genuinely low-cost device, and even a modest absolute tonnage saved translates into a saving many times the device's cost.

7.4 Sensitivity and Risk Analysis

Rather than testing each risk separately, this section asks a single, practical question: how much would conditions have to worsen, all at once, before the retrofit stops paying for itself? Three factors are stressed together, by the same percentage, simultaneously: the fuel saving achieved, the fuel price, and the number of days sailed in a year (fewer sailing days means less baseline fuel burned overall, so less to save from). Reducing all three by the same amount as X means the annual EUR saving shrink to (1-X) cubed of its base-case value, since the three factors multiply together. The combined stress test finds the value of X at which NPV falls to exactly zero: the worst simultaneous deterioration the investment can absorb before it becomes a loss.

7.4.1 LSA - Silicone Coating

	Base case	At breakeven (NPV = 0)
Combined reduction	0%	17.6%
Annual fuel saving (EUR)	239,768	134,244
NPV @ 8%	EUR421,326	EUR0

Table 7.9 - LSA Combined Stress Test

All three factors would need to fall by 17.6% simultaneously before LSA's silicone retrofit reaches breakeven (Table 7.9): fuel saving down from 2.11%/3.53% to roughly five-sixths of those values, VLSFO price down from EUR464 to around EUR382 per tonne, and sailing days cut by close to 18% - a much less severe combination than the power-based figure would suggest, reflecting fuel consumption's smaller measured saving relative to power reduction.
The flat-benefit assumption is more optimistic for silicone than for PBCF: an antifouling coating is subject to mechanical wear and biofilm accumulation over its service life, and long-term durability under continuous immersion remains an active area of research (Hu et al., 2020), whereas PBCF is a passive metal fitting with no comparable degradation mechanism. As a conservative check, applying the general hull-roughness degradation rate already cited earlier in this thesis (approximately 2.6% per year, as a proxy rather than a silicone-specific rate) to LSA's annual benefit over her 5-year economic life reduces NPV from EUR421,326 to approximately EUR376,500, a 10.6% reduction; the investment remains clearly positive under this more conservative assumption.

7.4.2 PL - PBCF

	Base case	At breakeven (NPV = 0)
Combined reduction	0%	68.9%
Annual fuel saving (EUR)	324,193	9,739
NPV @ 8%	EUR2,110,012	EUR0

Table 7.10 - PL Combined Stress Test

All three factors would need to fall by 68.9% simultaneously before PL's PBCF retrofit reaches breakeven (Table 7.10): fuel saving collapsing to less than a third of its base-case value, LSMGO price down from EUR678 to around EUR211 per tonne, and sailing days cut by more than two-thirds. This is an extreme, essentially implausible combination: PBCF's low-cost relative to PL's fuel bill makes the investment case exceptionally robust.

7.5 Discount Rate Sensitivity

Although the observed average is 8%, a sensitivity analysis was conducted to assess how the results change under more stressed assumptions. Accordingly, scenarios of 8%, 10%, and 12% were examined.

Discount Rate	LSA NPV (EUR)	PL NPV (EUR)
8%	421,326	2,110,012
10%	372,911	1,926,676
12%	328,312	1,766,413

Table 7.11 - NPV Sensitivity to Discount Rate

Both retrofits remain clearly NPV-positive across this range, so the choice of discount rates within a conventional shipping cost-of-capital band does not change the investment conclusion for either vessel.

8. Conclusions

This chapter interprets the results against existing literature, discusses their meaning, states the limitations of the data and methods used, sets out directions for future research, and concludes the thesis.

8.1 Discussion of Findings

Both retrofits measured benefits sit within published ranges. PL's PBCF result in Laden at her real average operating speed (10.42%) compares well against Hansen et al. (2011, 3.5-4% on an Aframax tanker), the manufacturer's own reported figure of up to 5% (Nojiri, Ishii and Kai, 2011; corroborated by Mizzi et al., 2017), and Zaragoza et al. (2026, up to 38% for LNG carriers under specific conditions); Ballast is already a small loss (-2.43%) at this speed, consistent with PBCF's benefit decreasing with speed and Ballast crossing into loss earlier than Laden does. LSA's silicone coating (0.54% to 8.01%) is broadly consistent with published fouling-release figures, on the modest end since the coating has not yet had a multi-year service life to demonstrate its full benefit. Beyond the headline numbers, both vessels show the retrofit's benefit concentrated at low speed and, for LSA, largest with even trim, speed-power and fuel-consumption metrics agree closely for LSA within the reliable range (10-17kn), with consumption above that treated as unreliable given a weak curve fit (R2 = 0.69) rather than a real finding.

Several limitations constrain how confidently these results generalize. PL's noon-report data, far sparser than LSA's continuous logging, produces confidence intervals spanning tens of percentage points; neither vessel's dataset included water depth or temperature, and PL additionally lacks rudder angle and continuous draft, preventing the trim-band analysis applied only to LSA. The economic analysis further rests on a single year of post-retrofit data held flat across each retrofit's life and a single representative speed rather than each vessel's full operating profile, though the combined stress test confirms both retrofits remain financially sound under considerable simultaneous deterioration in these assumptions, PBCF's case markedly more so given its far lower capital cost relative to the fuel bill it acts on.

8.2 Recommendations for Future Research

This section sets out directions for extending this research and practical improvements that would strengthen a repeat of this study.

8.2.1 Further Research Directions

A noon-to-noon versus high-frequency-to-high-frequency comparison for PL's evaluation period, using the high-frequency data that became available partway through it, would show how much of the difference between the two vessels' results reflects data resolution rather than the retrofits themselves.

Speed-power and fuel consumption results for LSA agree closely at low-to-mid speed, but diverge above ~17-18kn, where consumption's evaluation-period curve fit is comparatively weak (R2 = 0.69) and its saving turns negative while power's stays positive, confirming whether this is genuinely measurement noise, rather than a real physical effect, and establishing a firmer basis for the consumption metric at high speed, would need a larger post-retrofit sample. PL offers no equivalent cross-check, since her only consumption figure is already excluded as unreliable.

8.2.2 Potential Improvements

Neither vessel's dataset included water depth or water temperature, so two of ISO 19030-1's reference conditions could not be applied to either. Logging these steps forward would bring future studies fully in line with the standard's default method.
PL's dataset lacks rudder angle and a continuous draft reading, both available for LSA. Adding these would remove a stated asymmetry between the two case studies.
PL's noon-report data, at roughly one twenty-fourth the density of LSA's continuous logging, is the main limitation on the statistical strength of her results: confidence intervals on her speed-power savings span 30-70 percentage points at a given speed, several times wider than the point estimate itself. Continuous high-frequency monitoring, already fitted to LSA, would put both case studies on equal footing.
PL's diesel-electric architecture means her only available consumption figure covers all electrical demand rather than propulsion alone, making it an unreliable performance metric regardless of data frequency.

8.3 Conclusions

Both retrofits assessed in this thesis deliver a genuine, measurable performance improvement, consistent in direction with the wider literature and grounded in each retrofit's underlying physical mechanism rather than an isolated statistical artifact. The benefit is not constant: it is concentrated at low speed for both vessels and, where trim data allowed a finer breakdown, even keel trim outperforms the alternatives across most of LSA's realistic operating range. This speed, and condition of dependence, not a single averaged figure, is the most useful description of what each retrofit delivers.
Economically, both retrofits are comfortably justified within their respective economic lives, though the two cases differ sharply in character rather than merely in scale: PBCF's extremely rapid payback reflects its low capital cost against PL's large fuel bill, not a difference in the underlying quality of the two technologies, while silicone's longer payback reflects its materially higher upfront cost. Both retrofits withstand considerable simultaneous deterioration in the underlying assumptions before becoming unprofitable, PBCF markedly more so.
Beyond the individual retrofit results, this thesis contributes a transferable comparison of two different retrofit-assessment challenges: LSA's continuous, high-resolution data supports a granular, high-confidence analysis, while PL's lower-frequency noon-report data still supports a directionally useful, wider-uncertainty assessment. The practical takeaway for operators is that evaluating a retrofit against a vessel's real operating profile, not its rated service speed or a single averaged figure, produces a materially more defensible economic case, as this thesis's own PL findings, where the choice of representative speed changed the annual saving by a wide margin, demonstrate directly.

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