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Research Article

ORC assisted ballast water treatment under the EU ETS: Comparative assessment of UV, electrochlorination, and thermal options

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ABSTRACT

Ballast water treatment (BWT) is mandatory, and its lifecycle cost increasingly depends on carbon pricing. This study quantifies the energy and cost trade-offs of three options for a BDELTA-type handymax bulk carrier (ballast pump 1,600 m^3 h^{-1}; 34 operations yr^{-1}): filtration + UV with double pass, filtration + electrochlorination (EC) at 10 mg L^{-1} TRO, and an exploratory thermal pasteurization case (55 °C) using waste-heat plus a fired boiler. A 100 kW Organic Rankine Cycle (ORC) recovers main-engine waste heat and supplies BWT electricity; surplus generation is credited to hotel loads. Costs include fuel and EU ETS allowances (80 USD tCO_2, 70% coverage in 2025) and are annualized with a 7% discount rate over 20 years. A deterministic model is complemented with a ±10% Monte Carlo analysis of key parameters. ORC output exceeds the electrical demand of UV and EC, leaving substantial surplus. The resulting net annualized costs are 20 kUSD yr^{-1} for UV+ORC and about -2.9 kUSD yr^{-1} (a small net saving) for EC+ORC, while thermal treatment remains prohibitive at 1.96 MUSD yr^{-1} because the boiler must supply most of the heat. The ranking is robust in the Monte Carlo results; variations in fuel and ETS price move totals but do not change the preference for UV/EC over thermal. The thermal pathway is presented as a feasibility case rather than a type-approved solution. Overall, coupling UV or EC with a modest ORC module yields low net operating cost for treatment electricity while reducing ETS exposure through avoided auxiliary-generator use. Thermal pasteurization is only economically plausible if near-free, high-grade heat and effective heat recovery are available, and the approach can be validated under current IMO/USCG protocols. Thermal treatment may be economically plausible only when continuous waste-heat recirculation (multi-pass) is used with well-insulated tanks. In practice, it is unlikely to be viable for short trials.

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INTRODUCTION

Maritime transport accounts for 90% of the total commercial volume, mainly due to rapid economic and technological advancements. Ships do not only transport cargo and passengers; they also carry ballast water. Ballast water refers to fresh or salt water stored in a ship's ballast tanks and cargo holds. It is primarily used to enhance the vessel's stability and maneuverability, especially when the ship is not carrying cargo or when operating in conditions that require high stability. Ballast is typically stored in the lower tanks of unloaded ships, helping to adjust the vessel's center of gravity and achieve balance. By doing so, ballast water ensures stability and improves the ship's handling. Approximately 10 billion tons of ballast water are transferred annually across the global waters [1]. However, large volumes of ballast water taken from the sea also unintentionally draw in living marine organisms. Ballast-water transport is recognized as a major pathway for invasive aquatic species.

The BWM Convention has established specific discharge standards for treated and compliant ballast water. According to

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these standards, the discharged ballast water must contain fewer than 10 viable organisms per cubic meter (m^{-3})) that are greater than or equal to 50μm in minimum dimension (>50μm), and fewer than 10 viable organisms per milliliter (mL^{-1})) that are between 10 and 50μ m in minimum dimension (10-50μm) [2].

To meet the discharge standards, nearly all ships are expected to be equipped with one or more ballast water management systems (BWMS), which function essentially as onboard water treatment units. These systems employ various treatment methods, such as filtration, chlorination, ozonation, pasteurization, and ultraviolet (UV) radiation, either individually or in combination, to process the water. BWMS prototypes have undergone extensive testing to obtain "type approval" in accordance with the IMO Code and Guidelines, ensuring their suitability for use and their safety for the crew, the vessel, and the environment. Once type approved, these systems can be installed onboard ships [3]. However, selecting a BWTS involves economic tradeoffs. Capital expenditure (CAPEX) for retrofitting can be substantial, and operational costs (OPEX) – including energy and consumables – add ongoing burdens. Therefore, one should investigate each technology carefully.

Bui et al. [4] reviewed IMO compliant BWMS and showed that, by September 2020, 84 systems had been accepted, most employing filtration/mechanical separation followed by physical or chemical treatment (or both); among them, UV (40) and electrochlorination (22) dominated. They also documented the phase out of D 1 in favor of D 2 by September 2024 (MEPC.287(71)), the CAPEX/OPEX concerns raised in MEPC 69/4/4, and the MEPC.290(71) experience building phase. Technologies were grouped as non-active (UV, filtration, deoxygenation, heat) and active (electrolysis, AOP, ozone), with 47 active substance BWMS having Final Approval by November 2021. Finally, they noted the rarity of heat–deoxygenation+-filtration packages (4 in Australia, none in the US) and flagged waste heat driven thermal desalination of ballast water as promising.

Dong et al. [1] shipboard tested the NiBallast NB 600 BWMS (600 m^3 h^{-1}) that combines filtration, 10 μm membrane separation and nitrogen based deoxygenation. Five trials on JIN HAI HUA between August 2020 and March 2021 at 537–607 m^3 h^{-1} verified performance under real operating conditions. All discharges satisfied the IMO BWMS Code D 2 standard, with the shortest holding time being <3 days. The authors note that the system uses no chemicals and produces no by products, making it attractive for certain ship types. Deoxygenation created a low oxygen environment, lowering DO in tanks by about 4.7 mg L^{-1} on average during holding, complementing the physical removal achieved by filtration and membranes.

Duan et al. [5] set up a mesoscale BWMS-representative rig to examine how filtration pore size modulates electrolysis performance in ballast water treatment. The 50 μm filter removed ≥50 μm organisms by 80.95 ± 0.23%, whereas 200–2000 μm filters stayed <10%. Pore size governed TRO decay when filtration was coupled with electrolysis: the 50 μm case became significant after 45 min, 200–500 μm after ≥3 h, while 2000 μm showed no effect over 24 h compared to that without filtration.

Lee et al. [6] evaluated four electrolysis based BWTS at a type approved land based facility using 500 t challenge water across seawater, brackish, and freshwater, holding TRO at 10 mg L^{-1} and tracking DBP formation for 120 h per IMO G9. They compared side stream (high HOCl) and in stream (full flow, low HOCl) configurations, finding THMs and HAAs increased over five days while HANs decreased, with THMs dominating. Brominated DBPs prevailed in marine/brackish matrices due to high Br, whereas chlorinated species dominated freshwater. SUVA rose above 4 after electrolysis, indicating aromatization of DOC. Although all samples met the <0.2 mg L^{-1} TRO discharge limit after neutralization, no specific DBP discharge standard exists.

Li et al. [7] evaluated an amperometric total residual oxidant (TRO) sensor integrated into an electrochlorination based BWMS through land based biological efficacy (BE), operation & maintenance (>47 h) and shipboard trials, benchmarked against the standard DPD colorimetric probe. In 10 of 11 valid land-based cycles the average inter sensor deviation stayed within ±10%, with accuracy deteriorating at higher salinity. O&M tests over >47 h showed comparable TRO values (4.8–6.6% deviation) and resistance to electrode passivation. A smoothing control logic cut the amperometric signal's SD from 0.94→0.56 mg L^{-1} (O&M 2) and 2.15→1.33 mg L^{-1} (SB), i.e., ~40% fluctuation reduction, delivering stability comparable to or better than DPD.

Seridou et al. [8] investigated ozone nanobubbles (OzNBs) for ballast water disinfection across 1.5–15 PSU and 10^7–10^5 CFU mL^{-1} E. coli, benchmarking against dissolved ozone (DO_3). At 1.5 PSU, OzNBs yielded higher TRO and complete kill at all loads, while DO_3 achieved only ~4 log reduction at 10^7 CFU mL^{-1}. Salinity shortened TRO half-life from 3.4 to 0.40 min as it rose from 1.5 to 15 PSU (2.6 ppm), evidencing salinity driven ozone depletion. At low salinity and high (10^7 CFU mL^{-1}) / medium (10^6 CFU mL^{-1}) bacterial loads, OzNBs increased TRO by 6 fold and 7 fold in the first minute, respectively. The authors conclude OzNBs raise ozone utilization efficiency for BWTS, but continuous mode trials at ≈30 PSU are still required.

Ning et al. [9] critically reviewed micro/nanobubble (MNB) assisted AOPs and concluded that MNBs enhance pollutant removal mainly by boosting ROS utilization at the gas liquid interface, while often lowering EE/O. They reported $k_{w\text{-}MNBs}/k_{w/o\text{-}MNBs}$≥1.33 and consistently lower EE/O for MNB assisted cases versus the base AOPs. For ozone systems, MNBs increased k_La by 1.54-5.16x and dissolved O_3 by 1.14-8.89x over macrobubbles, but bromate formation remains a regulated risk.

Wang et al.[10] evaluated a filtration + medium-pressure UV-C BWTS (Cyeco; 40 μm filter; 200 m^3 h^{-1}; 550 W m^{-2} average UV intensity) at 0, 2, 24, and 120 h holding times using natural seawater. Zooplankton (≥50 μm) fell below the D-2 limit (<10 ind m^3) in all cases, with a strong correlation between holding time and reduction ($R^2 = 0.918$, $p < 0.001$). At 0 h, phytoplankton (10–50 µm) still exceeded the standard after the first UV pass and required a second UV-C treatment, while the strongest impact was observed at 24 h. The authors stress that when holding time is very short, higher UV doses or multiple UV-C passes may be required, and they explicitly frame the work against the problem of DNA repair/regeneration after UV treatment.

Iswantoro et al. [11] simulated a mechanical / thermal BWTS that repurposes main-engine exhaust heat via a shell-and-tube exchanger to raise ballast-water temperature to 68–75 °C, a range they state is sufficient to kill microorganisms. Building directly on Balaji & Yaakob's line of studies, they cite (i) large shipboard waste-heat availability (43,844 kW unloading; 7,453 kW loading)[12], (ii) 15–33% exhaust-gas heat recovery delivering 55–75 °C and >95% mortality, [13] (iii) exchanger cost/temperature/lifetime optimization via a Lagrangian method [14], and (iv) lab tests showing 80–95% mortality at 60–65 °C for 60 s [15]. They also reference prior syntheses that report >98% effectiveness for pure heat treatment [11], positioning thermal BWTS as a potential alternative within the IMO BWM framework.

Against this background, we frame ballast water treatment as a joint energy and carbon decision and evaluate three routes on a handymax case ship: filtration + UV (double pass), filtration + electrochlorination (EC), and an exploratory thermal treatment boundary case. A 100 kW organic Rankine cycle (ORC) sized to main engine waste heat supplies the BWT electrical load; when generation exceeds demand, the surplus is credited to hotel loads. We compute annualised costs by coupling ship specific duty and capital recovery with fuel use and EU ETS allowance purchases under 2025 coverage, and we report both gross totals (before crediting) and net totals (after surplus ORC credits). The system is examined with a ±10% Monte Carlo on unit energies, prices, maintenance and CAPEX, and with a simple ETS price/coverage sensitivity. The purpose is to place the UV/EC on a consistent techno economic footing with a thermal boundary case once carbon costs are internalised, and to show how waste heat recovery alters both operating cost and ETS exposure for owners.

SYSTEM DESCRIPTION

Ballast-water management involves much more than selecting a single treatment device; it requires understanding the vessel's machinery, trading pattern and regulatory environment. The case considered here is a BDELTA-type handymax bulk carrier of 43 500 DWT fitted with two 800 $m^3\ h^{-1}$ ballast pumps and a MAN 5S50ME-B9.3 main engine. The ballast water capacity is 16 170 m^3 [16] and the vessel makes 34 ballast operations per year, yielding an annual pumped volume of $V_{total} = 34 \times 16{,}170 = 549{,}780\ m^3$ of water. At normal continuous rating (NCR) the engine delivers 4 690 kW [16], with roughly half of the fuel energy rejected as waste heat, creating an opportunity to integrate a waste-heat recovery system [17]. Table 1 lists baseline parameters such as fuel price (555 USD t^1), specific fuel consumption (0.00023 t kWh^{-1}) and discount rate (7%), which will be used consistently throughout the calculations. It should be noted that the specific fuel consumption (SFC) value used in this study refers to net electrical output, including generator losses. Throughout this paper, monetary values are expressed in thousand US dollars (kUSD) and million US dollars (MUSD); kUSD = 10^3 USD and MUSD = 10^6 USD.

Filtration + UV irradiation

The ultraviolet (UV) option combines a filter to remove sediment and organisms with a bank of medium-pressure UV-C lamps that inactivate remaining microorganisms. UV systems are attractive because they avoid chemical residuals, but they are sensitive to water clarity and flow rate. Under IMO rules, certain UV systems can discharge immediately, whereas the US Coast Guard requires a hold period to ensure organisms cannot reproduce [18]. To reflect stricter operational practice across regimes we adopt a double-pass configuration: water is irradiated once during ballasting and again during deballasting. The Wärtsilä Aquarius UV datasheet gives a lamp load of 0.126 kWh m^3 at 500 $m^3\ h^{-1}$ [19]; however, the ballast pump also needs power to overcome pressure losses. Both the UV and electrochlorination (EC) systems rely on automatic self-cleaning filters upstream of the reactor. In this study pressure drops due to filtration is assumed 0.3 bar and corresponding pump workload on ballast pumps are included in OPEX for both cases. This adjustment has a minor effect on the total OPEX but provides a more realistic comparison of the systems operating requirements.

Table 1. Key design parameters

Parameter	Value
Ballast flow rate Q_{ship} ($m^3\ h^{-1}$)	1600
Ballast volume per trip (m^3)	16 170
Trips per year	34
Annual ballast volume V_{total} (m^3)	549 780
Specific fuel consumption of the auxiliary machine (t fuel/kWh)	0.00023
Fuel cost (USD/t)	555
UV specific energy (kWh m^{-3})	0.126
EC chlorine energy (kWh m^{-3})	0.045
Pump efficiency (%)	80
Pressure drop at EC and UV unit (bar)	0.3
Thermal temperature rise at BWS heater (°C)	40
Sea water temperature (°C)	15
ORC net output (kW)	100
UV system – unit energy consumption (incl. pumps) (kWh m^{-3})	0.1364
EC dosing (mg L^{-1})	10 mg L^{-1} active chlorine
Discount rate i (%)	7 %

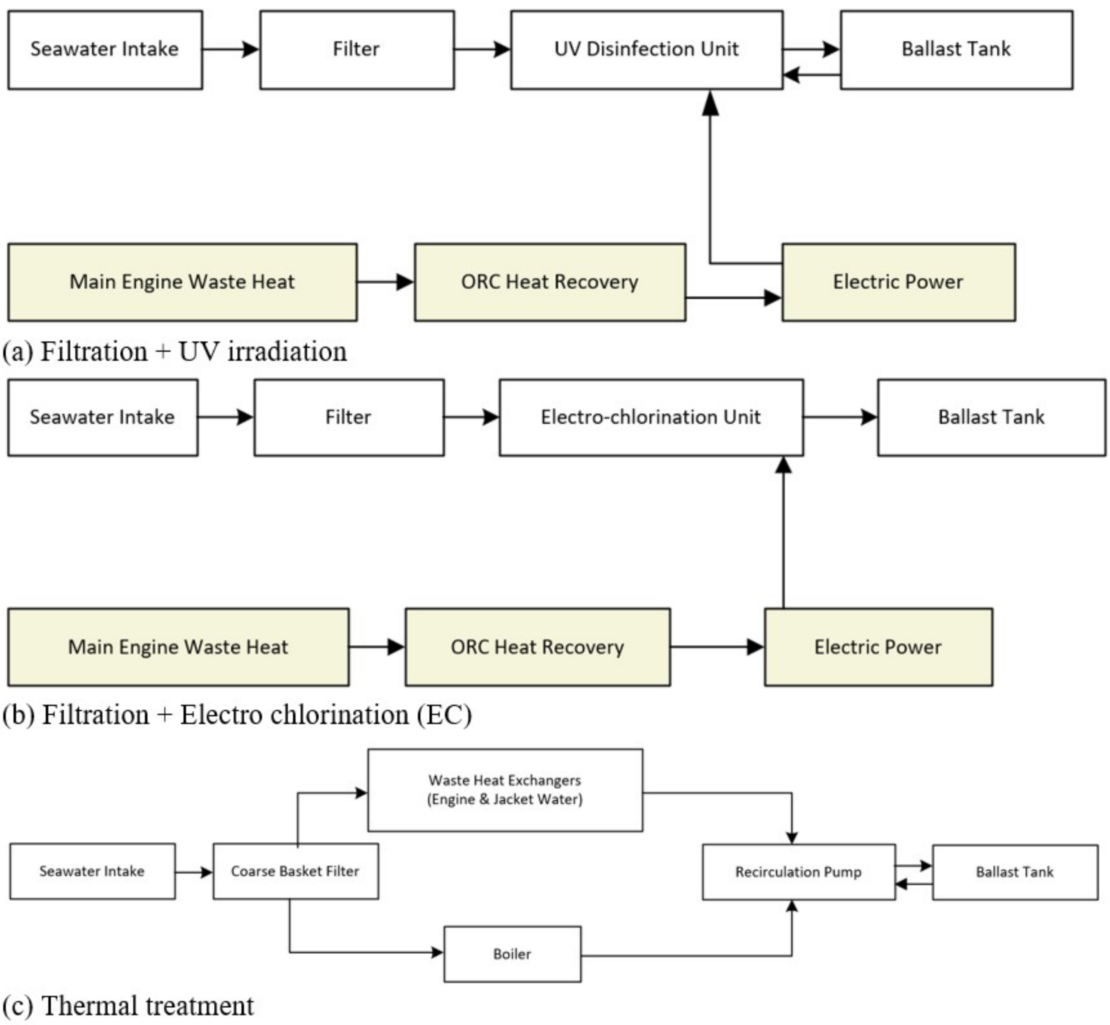

Figure 1. Ballast water treatment system scenarios

Cost scaling follows Jee & Lee's retrofit study [20], which lists 500 k USD for the UV at 2 x 1 000 $m^3 h^{-1}$ (2016 prices). After CPI uplift to mid-2025 (× 1.31), the item becomes 655k USD. Applying the linear scaled down for shop fabricated equipment (R = 0.80) and adding a 20% yard allowance gives 524 kUSD for equipment and 104.8 kUSD for installation. Thus, the UV package requires around 628.8 k USD CAPEX.

Jee & Lee's [20] annual OPEX (6 934 USD y^{-1}) bundles energy and maintenance; removing the fuel slice for the 30-kW lamp load, inflating the remainder with CPI, and scaling linearly with flow yields 7047 USD y^{-1} for lamps, consumables and service excluding electricity charges. The pump-work-per-volume is calculated by dividing the pressure drop by pump efficiency and converting to kilowatt-hours:

$$e_{pump} = \Delta p \,/\, (\eta_p \times 3.6 \times 10^6) \;\; \text{kWh m}^{-3}$$

where Δp = 0.3 bar = 3×10^4 Pa and the pump efficiency ηp = 0.8. Substituting these values gives epump ≈ 0.0104 kWh m^{-3}. Adding this to the lamp energy yields a total specific energy per pass of e_{total} = 0.126 + 0.0104 = 0.1364 kWh m^{-3}.

Because the UV system treats the water twice, the annual electrical energy consumption is

$$E_{UV} = 2 \times e_{total} \times V_{total} \approx 2 \times 0.1364 \times 5.50 \times 10^5 \approx 1.50 \times 10^5 \text{ kWh.}$$

To convert energy demand to fuel, we multiply by the specific fuel consumption (SFC = 0.00023 t fuel kWh^{-1}), obtaining mfuel ≈ $1.50\times10^5 \times 0.00023 \approx 34.5$ t y^{-1}. The fuel cost at 555 USD t^{-1} is approximately 19 200 USD y^{-1}. Burning 34.5 t of fuel emits 108.7 t of CO_2; if 70 % of these emissions fall under the EU-ETS at 80 USD t^{-1}, then the carbon cost is 6 100 USD y^{-1}.

When combined with energy and carbon costs, the OPEX of the UV system without any ORC support is about 32 300 USD y^{-1}. It should be noted that these calculations for the case where EC based system providing the required electricity from marine auxiliary generators. ORC assistance would be eliminating partial/total external electricity need for both EC and UV scenarios.

Filtration + Electrochlorination (EC)

Electrochlorination systems disinfect ballast water by generating hypochlorite solution on board. First, a self-cleaning filter removes larger organisms and sediments; then a portion of the ballast flow is diverted to an electrolysis cell where saltwater is converted into hypochlorite. The resulting oxidant, dosed to about 10 mg L^{-1} total residual oxidant (TRO), is injected back into the main stream and mixed via a static mixer. Sufficient hold time is required so that oxidants can kill or inactivate plankton and pathogens; depending on organism load and water chemistry, reported holding times range from a few hours to several days [18]. After treatment, neutralizing agents such as sodium thiosulphate may be required to comply with discharge limits, and care must be taken to minimize brominated by-products in marine water [6].

The dominant electrical load in an EC system is the production of hypochlorite. In this study it is assumed that producing hypochlorite at a 10 mg L^{-1} dose consumes approximately 0.045 kWh per cubic meter equivalent to about 4.5 kWh per kilogram of active chlorine. Additional energy is consumed by the ballast pump to overcome head losses through the filter and electrolyzer. Using the same conservative pressure drop (Δp = 0.3 bar) and pump efficiency (ηp = 0.8) as in the UV case, the hydraulic work per cubic meter is 0.0104 kWh m^{-3}. Because the EC unit only runs while ballasting (one pass), the annual electrical energy consumption is

$$E_{EC} = (0.045 + 0.0104) \times V_{total} \approx 3.05 \times 10^4 \text{ kWh} \quad (1)$$

This corresponds to a fuel use of about 7 t y^{-1} at an auxiliary generator SFC of SFC_{aux}= 0.00023 t fuel kWh^{-1}. At fuel cost, c_f=555 USD t^{-1}, the fuel cost would be

$$C_{fuel_{ec}} = E_{EC}\, SFC_{aux}\, c_f \quad (2)$$

while burning 7 t of fuel the system would be emitting extra CO_2. With 70 % of emissions covered under the EU ETS (ϕ_{ETS}) at 80 USD t^{-1} (ETS_{CO2}), the carbon cost contribution can be calculated as

$$C_{CO_2,EC} = m_{fuel} \times f_{CO_2} \times ETS_{CO_2} \times \phi_{ETS} \quad (3)$$

Where f_{CO2} represents carbon factor of auxiliary generator fuel which is 3.15 kg CO_2/kg fuel.

In their 2016 analysis, Jee and Lee [20] report an annual OPEX of 9 601 USD for a side stream EC system treating 2×1 000 $m^3 h^{-1}$, which is assumed in this study includes both electricity and maintenance. To derive a pure maintenance cost and normalize it to today level, this study subtracts the nominal electricity cost of running a 35 kW electrolysis cell for about 126.5 h y^{-1} on the reference vessel [20]. The remainder is assumed represents lamps, electrodes and routine service. After escalating by the consumer price index (× 1.31) to mid-2025 and scaling down to the 1 600 $m^3 h^{-1}$ ballast pump (ratio = 0.8), the maintenance cost can be calculated. Total OPEX of the EC system is defined as follows:

$$OPEX_{EC} = C_{maint} + C_{fuel_{ec}} + C_{CO_2,EC} \quad (4)$$

It should be noted that these expenditures do not cover ORC benefits. In this study ORC is combined with UV and EC scenarios to meet the electric load of the systems.

On the capital side, Jee and Lee [20] list a 2016 equipment cost of 450 k USD for a side stream EC unit. After applying the CPI escalation (× 1.31), scaling with flow rate (1 600/2 000) and adding a 20 % shipyard allowance, the total installed cost is estimated as 565920 USD in this study.

Thermal Treatment

A shipboard field trial applied short-time high-temperature heat treatment during ballasting. Ballast water was heated for a few seconds to 55 °C–80 °C using a steam heat exchanger and a pre-heater; this treatment caused high mortality in bacteria, phytoplankton and zooplankton[21]. Therefore a 55 °C heat treatment scenario is also evaluated in this study. Although the short time 55 °C treatment proved highly effective against bacteria in this trial, the experiment pre dates [21] the current IMO D 2 protocol and would require independent validation under current test protocols; this study does not assess biological compliance.

In the partial recovery scenario, the exhaust stream is allowed to cool from 300°C to the sulphur-dew-point limit of 120°C (120°C is assumed for the fuel and water content used in this study) Since the exhaust gas cannot be cooled below Sulphur dew point, we cannot harness all the waste heat. The exhaust gas recovery ratio is defined as:

$$\eta_{EG} = \frac{T_{ex}-T_{rec}}{T_{ex}-T_0} \quad (5)$$

where T_{ex} represents the temperature of the exhaust gas stream, T_{rec} is the exhaust gas temperature at the exit of the waste heat recovery heat exchanger, T_0 is the ambient temperature. Total heat recoverable heat rate can be calculated as:

$$\dot{Q}_{EG} = \eta_{EG}\left(Ex_f\,\dot{Q}_{fuel}\right) \quad (6)$$

Here, Exf is the fraction of the heat rate discharged through the exhaust stream. Q_{fuel} is the heat rate attained via the combustion of the fuel. 25% of the heat is discharged through the exhaust steam and 5% of it through the jacket water cooling Q_{JW}.

$$\dot{Q}_{JW} = 0.05\dot{Q}_{fucl} \quad (7)$$

These constraints capture 65% of the theoretical exhaust enthalpy and 100% of the available jacket water enthalpy, providing 2.0MW of heat. The design flow (1600 m^3h^{-1}) still needs 74.5 MW to reach the sterilization set point of 55°C, so an auxiliary boiler must supply the deficit. So, in this study three separate parallel lines are considered for thermal treatment. First is the exhaust gas heater, second is the jacket water heater and the third one is a boiler. All three-heating system is designed to increase ballast water temperature from 15°C to 55°C.

Total heat rate demand to increase the temperature of the ballast water Q_{balast}, can be calculated as:

$$\dot{Q}_{balast} = \rho_{sw} c_p \Delta T \frac{\dot{V}}{3600} \quad (8)$$

Where V is the volume flow rate of the ballast water (m^3/h), ρ_{sw} is the density of the sea water (kg/m^3), c_p is the specific heat of the sea water (J/kg K) and ΔT is the temperature difference of ballast water which is targeted as 40 K in this study.

Preliminary design results show that the amount of waste heat is not attainable only with exhaust stream. The heat deficit is completed via a boiler system. The heat rate for boiler is calculated via:

$$\dot{Q}_{boiler} = \dot{Q}_{balast} - \dot{Q}_{waste} \quad (9)$$

Where Q_{waste} is the sum of recovered exhaust waste heat rate (Q_{EG}) and jacket water heat rate (Q_{JW}).

Based on the heat balance, sizing of the heat exchangers are conducted via logarithmic mean temperature method. Shell and tube heat exchanger design is considered for the exhaust gas recovery system while plate heat exchanger is used for the jacket water system. Exhaust gas heat exchanger sizing is calculated as follows:

$$\Delta T_{1,EG} = T_{h,in,EG} - T_{c,out,EG} \quad (10)$$

$$\Delta T_{2,EG} = T_{h,out,EG} - T_{c,in,EG} \quad (11)$$

$$LMTD_{EG} = \frac{\Delta T_{1,EG}-\Delta T_{2,EG}}{\ln\left(\frac{\Delta T_{1,EG}}{\Delta T_{2,EG}}\right)} \quad (12)$$

$$\dot{Q}_{EG} = U_{EG} A_{EG} LMTD_{EG} \quad (13)$$

For the counter flow exhaust gas economizer, the two terminal temperature differences ($\Delta T_{1,EG}$,$\Delta T_{2,EG}$) are combined via the logarithmic mean temperature difference (LMTD) expression; multiplying this LMTD by the overall heat transfer coefficient U_{EG} and the required surface area A_{EG} yields the heat duty Q_{EG}.

Design considerations of the heat exchangers are tabulated on Table 2.

Heat exchanger areas were determined with the logarithmic mean temperature difference (LMTD) method (Eq. 12). For the exhaust unit, U=100$Wm^{-2}K^{-1}$ (shell and tube) and LMTD=165.2 K yield A_{EG}=92.9m^2. For the jacket water (plate heat exchanger), U=1500$Wm^{-2}K^{-1}$ and LMTD=48.5 K_{give} A_{JW}= 6.5m^2.

Multiplying the boiler heat (74.5 MW) by the annual ballast throughput (344 h) and dividing by an 85% boiler efficiency results in 30$GWhy^{-1}$ fuel energy. Even with aggressive waste heat recovery, thermal treatment is an order of magnitude more carbon and cost intensive than UV or electro-chlorination.

The system must circulate 1 600 m^3h^{-1} of ballast water through a thermal treatment system with a pump head of 10 m. Assuming a pump efficiency of 80 %, the hydraulic power is calculated using

$$P_{pump,ideal} = \frac{\rho_{water}\, g\, Q_{pump}\, H}{1000} \quad (14)$$

Table 2. Heat exchanger sizing

HX	Hot / cold stream path (°C)	Type	U($Wm^{-2} K^{-1}$)	LMTD (K)	Area (m^2)
JW-HX	90→80/15→ 55	Plate HX	1500	48.5	6.5
EG-HX	300→120/15→55	Shell and Tube HX	100	165.2	92.9

By considering the pump efficiency, pump work is estimated as

$$P_{pump} = \frac{P_{pump,ideal}}{\eta_{pump}} \approx 55.9\, kW. \quad (15)$$

Operating for 344 hours per year, the annual pump energy consumption is

$$E_{pump} = P_{pump} \times t_{year} \quad (16)$$

Fuel consumption of the auxiliary generator supplying the BWT is computed using simple multiplications. If E_{year} (E_{year} is E_{pump} if only pump is used electric) is the annual energy demand and SFC is the specific fuel consumption, then the fuel consumed per year is

$$m_{fuel} = E_{year}\ S_{FC} \quad (17)$$

The associated fuel cost is

$$C_{annual\,fuel} = m_{fuel}\ \ c_{fuel} \quad (18)$$

where c_{fuel} is the unit fuel price (555 USD t^{-1}). The carbon dioxide emissions are given by

$$m_{CO_2} = m_{fuel}\ \ \beta_{CO_2} \quad (19)$$

where β_{CO_2} = 3.15 t CO_2 t^{-1} fuel. The cost of carbon allowances is then

$$C_{annual\,CO_2} = m_{CO_2}\ \phi\ \ c_{CO_2} \quad (20)$$

with c_{CO_2} = 80 USD t^{-1} and coverage factor ϕ = 0.70 for 2025 [22].

Two waste-heat exchangers are required a plate exchanger (6.5 m^2) and a shell-and-tube exchanger (92.9 m^2) whose combined area is 99.4 m^2. Heat-exchanger capex is approximately assumed 200 USD m^{-2}, giving a base cost

$$C_{HX,base} = 200\, USD\, m^{-2} \times 99.4\, m^2 \approx 19{,}900\, USD. \quad (21)$$

The fired boiler must deliver Q_{boiler}≈74.5 MW of heat (after subtracting the 2 MW recovered from waste heat. Equipment cost of a boiler with the desired capacity is assumed 570 K USD in this study. A 20 % shipyard allowance is added all the units covered in this analysis.

Pump pricing for 30 kW power is assumed 20000 USD each. Two pumps are installed for redundancy, so pump cost is around 40 000 USD.

Summing the waste-heat exchangers, the scaled boiler heat-exchanger and the pumps yields a total equipment cost.

The operating cost has three components: fuel, carbon emissions and electricity.

The boiler delivers 74.5 MW of heat for 344 hours y^{-1}(34x16170/1600), so the annual heat requirement is

$$E_{heat} = 74.5\, MW \times 344\, h = 25{,}609\, MWh\, yr^{-1} \quad (22)$$

Assuming 85 % boiler efficiency (η_{boiler} = 0.85), the fuel energy required is

$$E_{fuel} = \frac{E_{heat}}{\eta_{boiler}} \approx \frac{25{,}609}{0.85} = 30{,}129\ MWh\, yr^{-1} \quad (23)$$

The annual fuel mass is

$$m_{fuel} = \frac{E_{fuel}}{42000000\ J/kg} \approx\ yr^{-1} \quad (24)$$

In the thermal treatment scenario, we model a simplified arrangement in which the incoming ballast water passes through a coarse basket filter. This filter serves only to protect the heat exchanger and pump from large debris; it is not intended to remove organisms, and therefore its capital cost and the associated head loss are excluded from the CAPEX and OPEX calculations. The model further assumes a well insulated ballast tank and neglects detailed heat loss calculations; the intent is to explore the feasibility of increasing the temperature of ballast water to 55 °C for using recovered waste heat. The required insulation cost should be further investigated in the following studies. Since no thermal ballast water management system operating at this temperature has yet received IMO or USCG type approval, the thermal scenario should be regarded as an exploratory case study based on values reported in the literature. Practical implementation would require the treated water to be cooled before discharge to avoid thermal pollution; commercial heat-based systems incorporate a regeneration section that preheats incoming ballast water and cools the treated water prior to discharge.

Waste Heat Recovery with Organic Rankine Cycle

To reduce the electrical burden of the ballast water treatment (BWT) system and improve overall energy efficiency, the first two scenarios envisage installing a compact Organic Rankine Cycle (ORC) unit that converts low grade waste heat from the main engine into electricity. Commercial modules can produce up to 100 kW net electrical output with the existing waste heat stream with an ORC efficiency of around 8%. At this output the ORC more than meets the requirements of the UV and EC systems: ballast operations on this handymax bulk carrier (34 voyages per year, each lasting about ten days). In other words, ballast treatment demands only a small fraction of the ORC's total annual generation, leaving the remaining to cover so called hotel loads (lighting, HVAC, control systems and other auxiliaries). Hence a single ORC module installed in the engine room can fully power the ballast water treatment plant and simultaneously reduce auxiliary generator operation.

The investment and operating cost assumptions for the waste heat recovery unit draw on the U.S. Environmental Protection Agency's Waste Heat to Power fact sheet [23]. That document reports installed costs for ORC systems in the range of $1 900–$4 500 per kW and estimates total power costs by splitting amortized capital and operating and maintenance (O&M) costs; for ORCs the O&M component is $0.009–0.018 per kWh, or roughly 0.9–1.8 cents per kilowatt hour. Using the detailed project cost in Pinto et al.[24] study as a starting point—USD 450 000 for a 200 kW ORC (2 set of 125 kW) Scaling this linearly to 100 kW gives ≈ USD 225 000 in 2021 dollars with a BLS inflation factor of 1.21, yielding about USD 272 000, and added a 20 % shipyard integration allowance for piping, mounting and commissioning, bringing the installed cost to roughly USD 326000. For operating expenses, we adopted an O&M rate about 1.2 cents per kilowatt hour so supplying the energy for ballast treatment would cost accordingly per year in maintenance.

In the base case the ORC is supplied exclusively by the main-engine exhaust-gas stream; jacket-water heat is not considered to not add extra heat exchanger to the system. The recoverable exhaust duty is computed as 1.5 MW. In summary, a 100 kW waste-heat-recovery unit sized to the available 1.5 MW heat stream can fully power the ballast-water-treatment system while leaving a large share of its output for hotel loads with a capacity factor of 0.8. Its installed cost is estimated at ≈ 0.33 MUSD (2025 dollars), with only a small fraction allocated to the BWT plant; annual O&M costs are minimal.

Using waste heat for electricity also reduces fuel consumption and carbon emissions. Under the EU Emissions Trading System, shipping companies must surrender allowances for 70 % of their emissions from 2025 and 100 % from 2026. Allowances (EUAs) currently trade is considered 80 USD/t CO_2, while failing to surrender sufficient allowances incurs also penalty. By cutting CO_2 emissions from both ballast treatment and hotel loads, the ORC reduces the number of allowances that must be purchased and lowers the risk of penalties. For a bulk carrier the avoided emissions could translate into avoided ETS costs on handymax the order of tens of thousands of euros per year.

In summary, integrating an ORC unit in the UV and EC based scenarios allows the ballast water treatment system to run entirely on recovered waste heat. The ORC's constant output means that it does not need to be scaled differently for UV or EC; whichever technology is selected, the excess electricity can be redirected to hotel loads. This dual benefit of free electricity and reduced CO_2 emissions strengthens the economic case for waste heat recovery on board ships subject to tightening carbon regulations.

Capital and Operating Costs

Capital costs are annualised using the capital recovery factor

$$\mathrm{CRF} = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{25}$$

Multiplying CAPEX by CRF yields the equivalent annual cost (EAC), reflecting both depreciation and the cost of capital. Using i=0.07 and n=20 y results in "CRF" is found as 0.0944 , so each million dollars of investment corresponds to about 94,400 USD y^{-1}. We assume a 20-year life for all BWT packages; although UV lamps require periodic replacement, this cost is captured in OPEX, while the main reactor housing and control electronics can operate over the ship's lifetime. If a shorter life is desired, the model can easily adjust the CRF for that subsystem.

For each treatment system, the operating expenses (OPEX) are assembled from three components: (i) maintenance, estimated by taking the vendor-reported OPEX from Jee & Lee [20], subtracting the energy cost on the reference vessel, then inflating to 2025 and scaling with the ship's flow-rate ratio; (ii) fuel costs for remaining purchased energy, computed as the residual electricity or heat load after the ORC offset multiplied by the specific fuel consumption (0.00023 t fuel kWh^{-1}) and the 2025 fuel price; and (iii) carbon charges, obtained by multiplying the fuel consumed by the CO_2 emission factor (3.15 t CO_2 t^{-1} fuel), the ETS price (80 USD t^{-1} CO_2) and the coverage fraction (70 %). The ORC's own operating and maintenance cost is calculated separately as 0.012 USD per kWh of electricity produced and added to the UV and EC scenarios. When the ORC produces more electricity than the ballast-water system consumes, the surplus is converted to fuel and CO_2 savings and subtracted from the OPEX of the UV and EC cases.

We adopt the official phase-in schedule for shipping under the EU Emissions Trading System: shipping companies must surrender allowances covering 40% of their verified 2024 emissions by 30 September 2025, 70% of their verified 2025 emissions in 2026, and 100% of their emissions from 2026 onward (first full surrender in 2027) [25]. Failure to surrender sufficient allowances triggers an excess-emissions penalty of EUR 100 per tCO_2e in addition to the obligation to surrender the missing allowances; names of non-compliant operators are disclosed. In this study, penalties are not modelled in the cost base; only the allowance cost is included [26].

To explore how uncertainties in energy intensity, fuel price, CO_2 price, maintenance, capital costs and penalties affect annual costs, we perform a Monte Carlo simulation with 500 iterations. Each uncertain parameter is perturbed uniformly by ±10 % around its nominal value. For each iteration we recompute the energy demand, OPEX, carbon cost, depreciation (using CRF) and total annual cost for the three scenarios. Histograms of the resulting cost distributions reveal the relative sensitivity of each option to parameter variability.

RESULTS AND DISCUSSION

This section reports the techno economic performance of three ballast water treatment (BWT) options: filtration + UV, filtration + electrochlorination (EC), and an exploratory thermal treatment system evaluated on a BDELTA type handymax bulk carrier (1,600 $m^3 h^{-1}$; 34 ballast operations per year). Model inputs, ship particulars and the cost formulation (including the capital recovery factor approach) are those defined in Section 2 of the manuscript (Table 1 and Eqs. (25) for annualisation), while the thermal energy balance and heat exchanger sizing follow the recovery and LMTD relations presented in Eqs. (5)–(13). The thermal configuration is treated as a case study rather than a type approved solution, consistent with the qualification given in Section 2.3.

Figure 2(a) contrasts the net annual OPEX of the three options. "Net" here means that, for the UV and EC based solutions, the electricity generated by the 100 kW ORC first offsets the BWT electrical load and any surplus ORC power is credited back as avoided auxiliary generator fuel and avoided EU ETS payments. With the assumed trading pattern and EU ETS coverage ($\varphi = 0.70$ in the 2025 base case), both UV+ORC and EC+ORC achieve negative net OPEX: −69,701 USD y^{-1} and −87,051 USD y^{-1}, respectively. The thermal alternative sits at the other extreme with 1,891,250 USD y^{-1} net OPEX, driven by boiler fuel and the associated carbon cost. These values already foreshadow two robust messages: (i) an ORC sized to ship waste heat can over supply the electrical needs of UV and EC treatment, turning the ballast plant into a net saver of fuel and EUAs; and (ii) even with aggressive waste heat recovery from exhaust and jacket water, thermal treatment remains dominated by fired boiler duty. The dominance of the latter is consistent with the energy balance developed in Section 2.3 and the LMTD based exchanger sizing (Table 2).

Figure 2(b) then adds annualised CAPEX to form total annual cost. As seen in Figure 2(b), after adding depreciation (CRF = 0.0944; 20 year life), UV+ORC yields about 20,425 USD y^{-1} and EC+ORC about −2,860 USD y^{-1}, while the thermal option reaches roughly 1.96 MUSD y^{-1}. The small positive figure for UV and the slightly negative figure for EC reflect two effects. First, ORC O&M (0.012 USD kWh^{-1}) and UV/EC maintenance survive the surplus credit and must be covered by depreciation. Second, the installed cost of the EC package is lower than the UV package in the adopted scaling (≈ 0.566 MUSD vs. 0.629 MUSD equipment + 20 % install), so after annualisation EC+ORC turns the corner into a slightly net beneficial annualised balance. The underlying CAPEX/OPEX structure follows the cost scaling and annualisation principles introduced in Section 2.1–2.4 and Eq. (25).

To understand the drivers behind those totals, Figures 3 (a) and (b) decompose the annualised costs. Figure 3a (gross, before surplus credits) shows that UV+ORC and EC+ORC carry only maintenance and ORC O&M (≈ 7.0 k and 7.8 k USD y^{-1} for UV; ≈ 9.8 k and 7.8 k USD y^{-1} for EC), because the ORC already covers their BWT electricity and thus they have no "remaining" fuel or carbon payments in the base case. In stark contrast, the thermal bar is dominated by fuel for the boiler (≈ 1.43 MUSD y^{-1}) and EU ETS cost (≈ 0.456 MUSD y^{-1}), with only a minor pump electricity slice (≈ 2.5 k USD y^{-1}). Those proportions mirror the heat rate arithmetic in Section 2.3: even after using exhaust and jacket water heat, the boiler must still supply about 74.5 MW during ballasting to reach 55 °C, implying ~30 GWh y^{-1} of fuel energy (85 % boiler efficiency) and, in turn, large fuel and CO_2 liabilities. For the thermal system, a separate maintenance line item is not included as boiler fuel and ETS charges dominate OPEX; a sensitivity adding 5% of installed CAPEX as annual maintenance increases the annualised total less than 2% and does not change any ranking. Based on the findings, it can be said that instead of an instant temperature rise in the ballast water, a system with multiple passes and recirculation should be considered with a well-insulated tank for a more extended period for the thermal ballast water treatment system. Otherwise, the heat rate of the waste heat-heat exchanger does not meet the demand for the required BTWS load, and excessive boiler fuel is used for the treatment.

Once the surplus credit is applied (Figure 3b), the UV and EC stacks gain a negative "credit" segment that overwhelms their small gross O&M. Numerically, the annual credit equals the value of surplus ORC electricity monetized as avoided fuel purchases plus avoided EUAs: about 84.6 k USD y^{-1} in the UV case and 104.7 k USD y^{-1} in the EC case (the EC credit is larger because the EC unit consumes less electricity than UV, leaving more ORC output for hotel loads). After adding depreciation, those credits lead to the net totals reported in Figure 2b.

Figures 4 (a) and (b) bring the mechanism into focus. The ORC produces 652,800 kWh per year (100 kW, 80 % capacity factor, 34 voyages × 10 days), whereas annual BWT electrical demand is about 150,000 kWh for UV (double pass irradiation plus filtration head) and 30,467 kWh for EC (chlorine generation plus head). In other words, the ORC's annual generation exceeds the UV load by roughly 503 MWh and the EC load by about 622 MWh. That headroom is central: it turns the BWT module into a net exporter of electricity to hotel loads and, with EU ETS in force, a net reducer of allowance obligations. The system description in Section 2.4 anticipates exactly this pattern an ORC sized to the available low-grade waste heat more than meets the BWT load on a handymax cycle and the results of this study here quantify it for the case ship. Furthermore, these results show the potential of EU ETS charge that can shipowners could avoid easily.

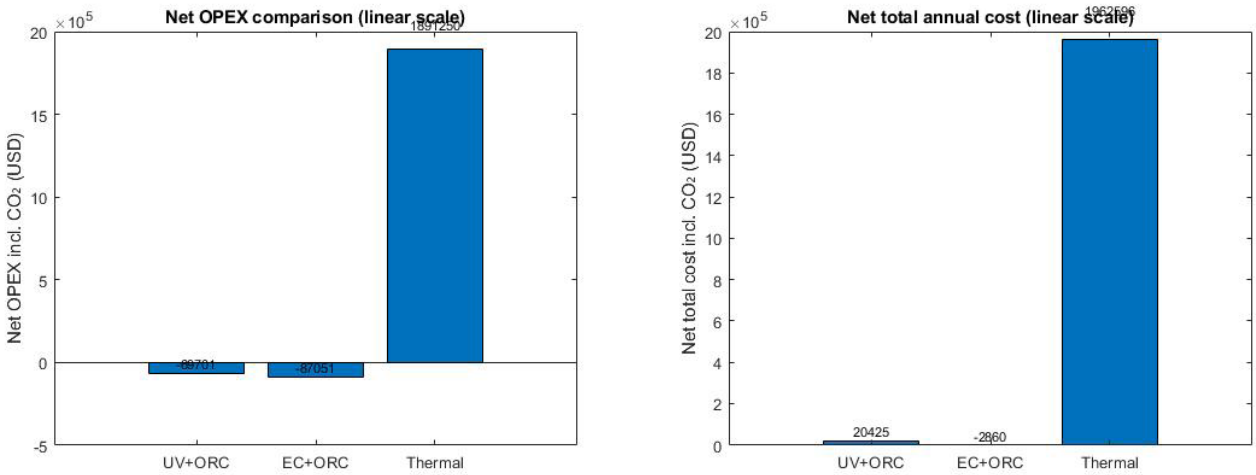

Figure 2. (a) Net OPEX (USD y^{-1}) including EU ETS effects and surplus ORC credits: UV+ORC, EC+ORC, and Thermal. (b) Net OPEX + annualized CAPEX

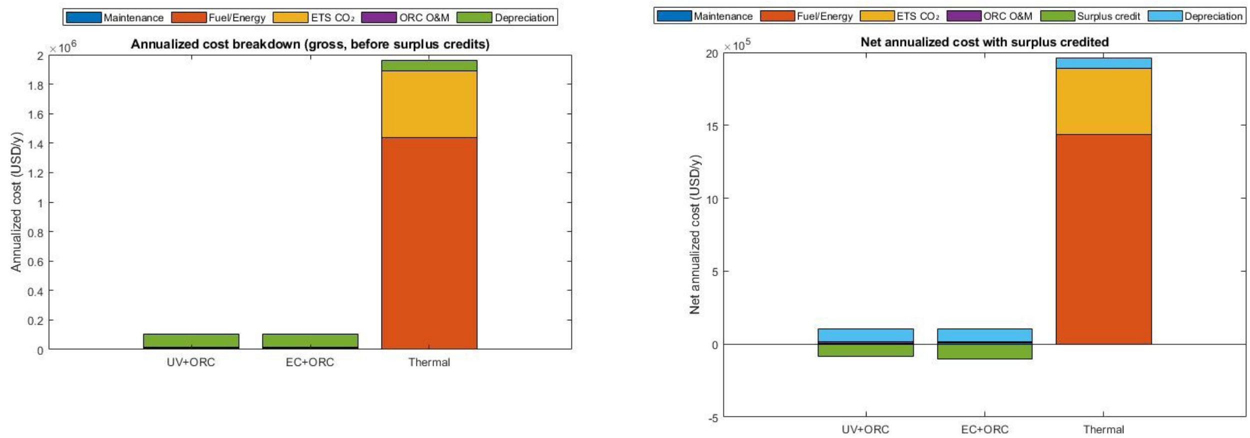

Figure 3. (a) Annualized cost breakdown (USD y^{-1}), gross (before surplus credits): stacked bars showing Maintenance, Fuel/Energy, EU ETS CO_2, ORC O&M, and Depreciation. (b) Net annualized cost breakdown with surplus credited

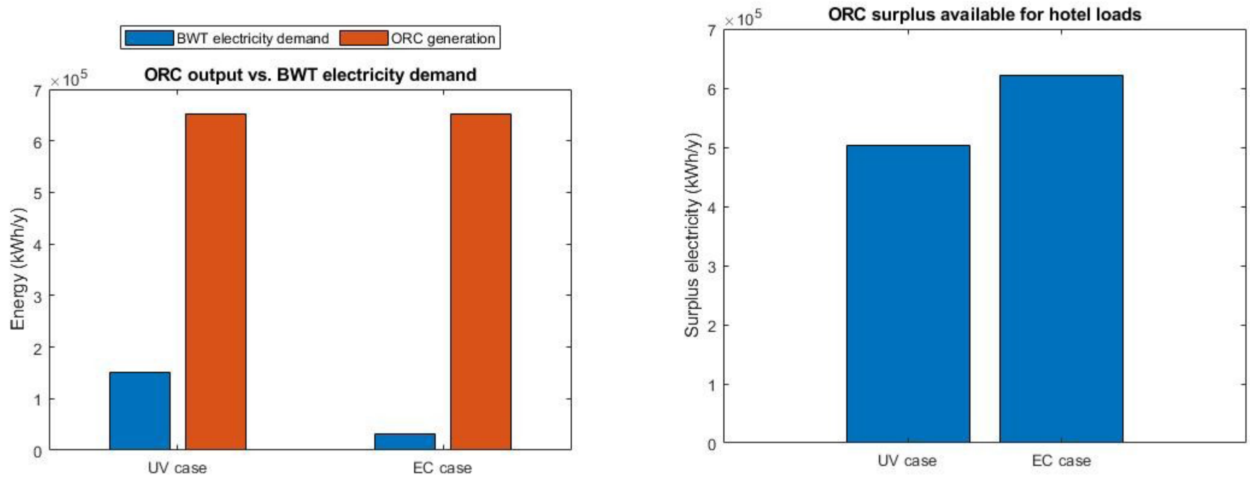

Figure 4. (a) ORC annual generation vs. BWT electricity demand for UV and EC (kWh y^{-1}), (b) Surplus ORC electricity available for hotel loads after meeting BWT demand (kWh y^{-1})

Figure 5 compares annual CO_2 associated with each scenario's energy purchases for BWT. UV+ORC and EC+ORC are effectively zero because the ORC covers their entire BWT load in the base case. The thermal system emits about 8,135 t CO_2 y^{-1}, directly reflecting the boiler's fuel use (fuel carbon factor of 3.15 t CO_2 per tonne fuel as used throughout Section 2). Independently of the BWT load, the ORC saves about 150 t y^{-1} of auxiliary generator fuel, equivalent to about 473 t CO_2 y^{-1} in avoided emissions a benefit that appears in the surplus credit portion of Figures 3–4.

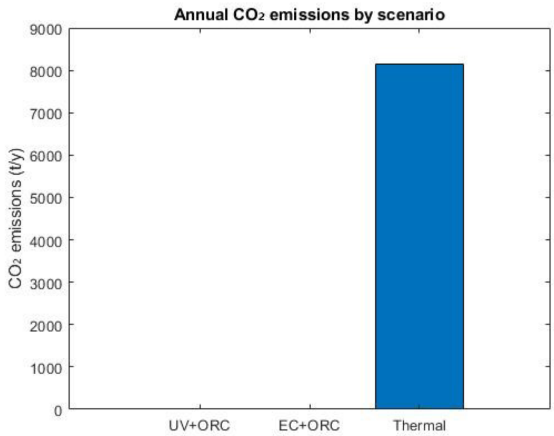

Figure 5. Annual CO_2 associated with energy purchases for BWT under each scenario (t y^{-1})

The economic implications per unit of treated ballast are summarized in Figure 6. Using the annualized totals and the annual throughput (Vtotal = 549,780 m^3), UV+ORC comes out near 0.037 USD m^{-3}, EC+ORC dips slightly negative at −0.005 USD m^{-3} because the surplus credit exceeds depreciation and O&M, while the thermal case is approximately 3.57 USD m^{-3}. A negative "LCO" should be read carefully: it does not imply that the BWT process is intrinsically free; it means that, for this ship and trading profile, the ORC's hotel load benefits more than pay for the EC module's annualized cost. If the ORC were credited to hotel loads outside the BWT accounting boundary, the EC bar would shift upward by exactly that credit.

Figures 7 and 8 present two views of the 500 run Monte Carlo, where key inputs (unit energies, fuel/CO_2 prices, φ, maintenance and CAPEX) vary uniformly by ±10 %. These Monte Carlo results are gross (no surplus credit). Even on this conservative basis, UV+ORC and EC+ORC cluster tightly around 105 k and 102 k USD y^{-1}, respectively (medians 105.2 k and 101.7 k; 5–95 % ranges about 98.7–111.9 k and 95.8–108.1 k). Thermal, by contrast, spans a wide band (median near 1.98 MUSD; 5–95 % roughly 1.82–2.12 MUSD), underlining its sensitivity to fuel and carbon price swings.

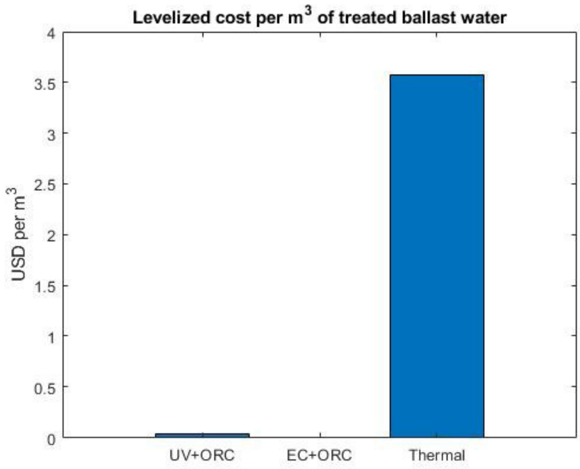

Figure 6. Levelized cost per cubic meter of treated ballast water (USD m^{-3}) based on net total annualized cost and annual throughput

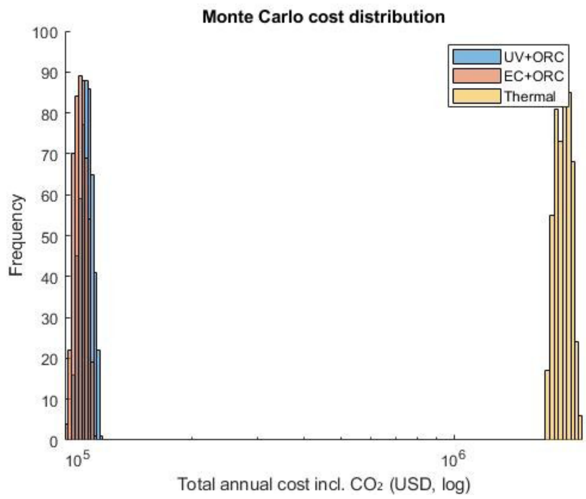

Figure 7. Monte Carlo distributions (500 runs; ±10 % uniform perturbations; gross costs, no surplus credit): log scale histograms of total annual cost for UV+ORC, EC+ORC, and Thermal

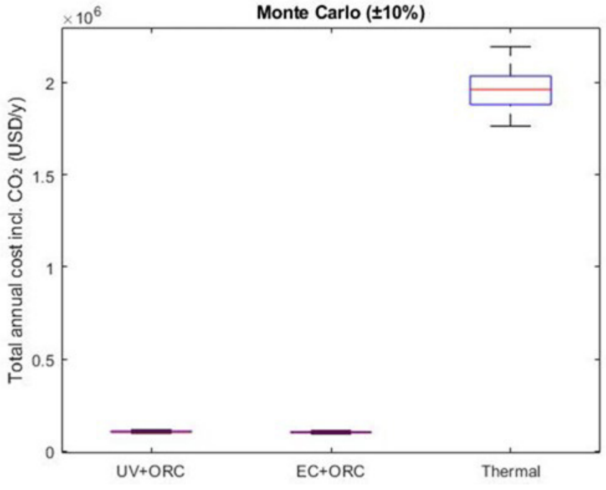

Figure 8. Monte Carlo box and whisker plots (25th, 50th, 75th percentiles) of total annual cost (gross)

The log scale histogram (Figure 7) makes clear that thermal sits an order of magnitude to the right of the UV/EC clusters; the box and whisker view (Figure 8) quantifies the spread and shows little overlap among options. Put simply, modest input uncertainty does not change the ranking: thermal remains far costlier; UV and EC remain close, with EC slightly lower in the adopted scaling and O&M assumptions.

UV/EC OPEX and CAPEX values used here are derived from the totals reported by Jee & Lee [20], after removing the reference ship's energy component, adjusting the remaining maintenance and service costs to 2025 using CPI inflation, and scaling by the flow-rate ratio. Since certain system elements are not explicitly detailed in the reference, such as whether pump energy due to filter headloss is included in OPEX, we model the 0.3 bar filter loss as separate pump work. Similar normalization methods are applied throughout the model. This normalization aligns legacy cost data with current operating conditions. Sensitivity analyses and Monte Carlo simulations show that reasonable variation in this assumption does not affect the technology ranking.

Because ETS design is evolving, we also tested how total annualized cost responds to changes in allowance price and coverage φ while holding all baseline inputs fixed. Figure 9 plots three panels ($\varphi = 0.40, 0.70, 1.00$) against ETS prices of 0, 50, 80, 100, and 120 USD t^{-1} CO_2. Two asymmetric effects emerge. First, the thermal case becomes rapidly more expensive with higher ETS prices and coverage: for $\varphi = 0.40$ and 0 USD t^{-1} it sits near 1.51 MUSD y^{-1}; at $\varphi = 1.00$ and 120 USD t^{-1} it rises to about 2.48 MUSD y^{-1}. Second, UV+ORC and EC+ORC become cheaper as ETS strengthens, because their carbon credits on surplus ORC electricity rise while their own BWT related carbon outlay remains zero (the ORC still fully covers the BWT load across the tested range). At $\varphi = 0.70$ and 80 USD t^{-1}, the totals match the base case (≈ 20.4 k and −2.9 k USD y^{-1} for UV and EC, respectively); at $\varphi = 1.00$ and 80 USD t^{-1} they drop further (≈ 11.7 k and −13.7 k USD y^{-1}). Policymakers typically frame rising carbon prices as a cost risk; for configurations that export ORC power, it is a hedge that improves the annual balance.

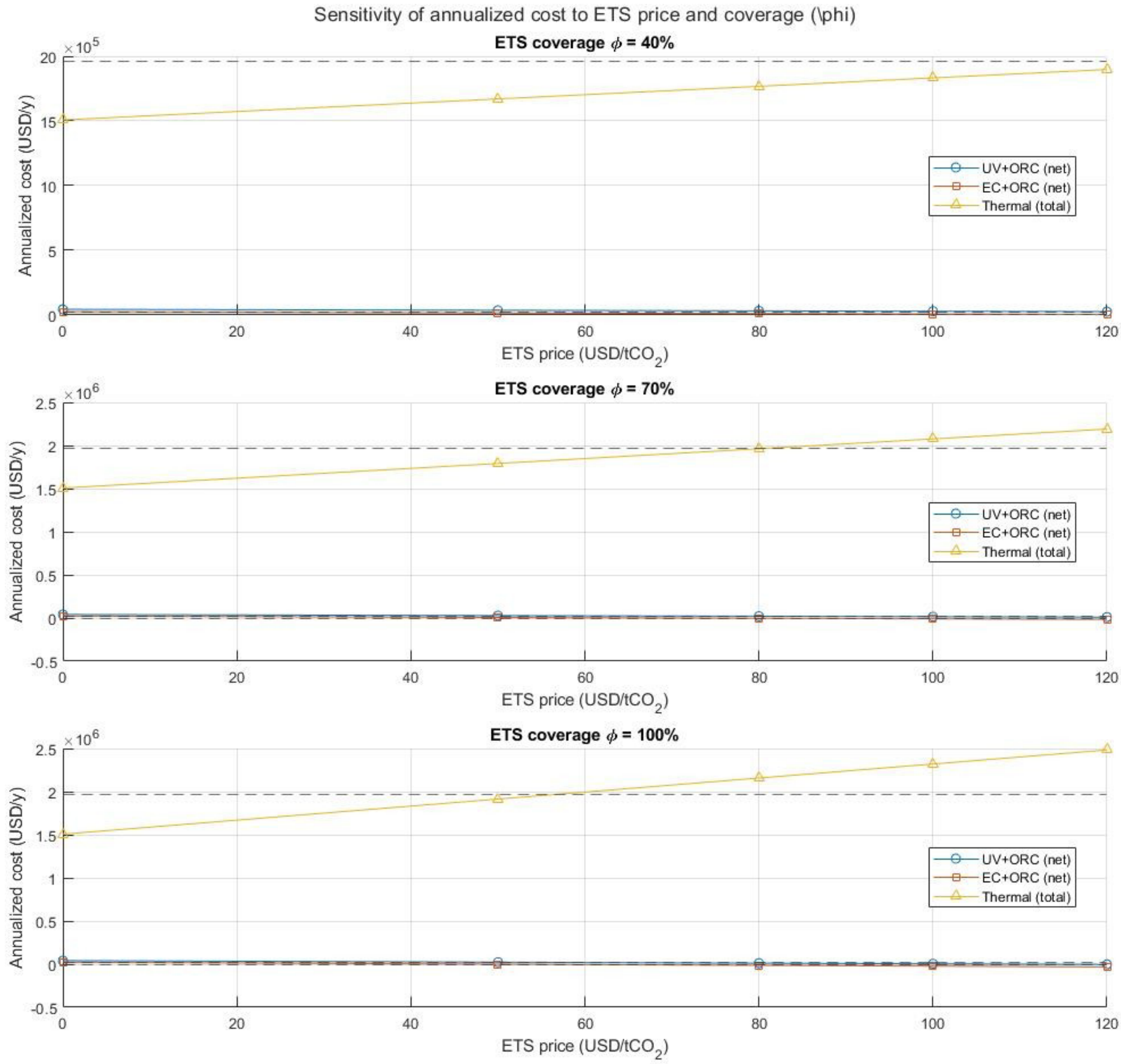

Figure 9. Sensitivity of net total annualized cost to ETS price (0–120 USD t^{-1} CO_2) and coverage (φ = 0.40, 0.70, 1.00)

The thermal treatment system is valuable as a boundary case for the energy and carbon accounting, but it should remain flagged as exploratory. As noted in Section 2.3, the 55 °C concept used here draws on literature evidence and an earlier field trial predating the current D 2 protocol, and such a system would need to be revalidated under today's type approval framework. It may also imposes practical requirements heat exchanger footprint, boiler integration, and cooling of treated water prior to discharge that make it more complex than UV/EC packages already in commercial service. The cost and emissions outcomes above reflect those realities: even with idealized waste heat recovery and well insulated tanks, the remaining boiler duty dominates OPEX and ETS exposure.

These scenarios are constructed from performance data reported in the literature and do not claim that the configurations necessarily meet the IMO D 2 biological standard: laboratory tests have shown that 50 μm filters remove ≥80 % of organisms ≥50 μm, whereas larger pores achieve <10 % removal [5]; electrochlorination systems can produce trihalomethanes and haloacetic acids, with brominated by products dominating in marine and brackish waters[6]; and UV-based systems may leave viable organisms [27] that necessitate holding periods. Confirming whether the specific UV and EC configurations studied here achieve D 2 compliance under real operating conditions is beyond the scope of this energy–cost analysis and should be addressed in future biological testing. These results apply to a 43 500 DWT handymax carrier operating 34 ballast cycles per year. Vessels with different sizes, pump capacities or trading patterns may experience different maintenance burdens, filter clogging behavior and by product management costs.

What the results mean for selection on this ship. Taken together, the results support three operational conclusions for the case ship and assumptions used:

1.UV+ORC and EC+ORC are financially resilient choices in an ETS world. ORC output comfortably exceeds BWT electricity needs on this trade, turning UV and EC into net contributors to ship wide energy efficiency. The ranking between UV and EC depends on detailed CAPEX/O&M scaling; under the Jee & Lee[20] based values adopted in the manuscript, EC+ORC has a slight edge in annualized cost.

2.Thermal treatment is quantifiably uneconomic in this configuration, primarily because the necessary boiler energy dwarfs waste heat recovery. Its annualized cost is about two orders of magnitude higher than UV/EC once the ORC benefits are accounted for, and it remains highly sensitive to carbon price exposure. These outcomes are aligned with the energy balance derivation and exchanger sizing in Section 2.3. Thermal options would be viable only if the marine engine's waste heat were continuously used to heat the ballast water with multiple passes using a circulation pump. Such a system would require longer periods to reach the sterilization temperature. Therefore, a well-insulated ballast tank would be required. Such a system could not be used for short trials. Another drawback of a fully waste-heat-driven system, as described above, would be cooling. Since ballast water cannot be discharged at higher temperatures, it would also need to be cooled. A holistic investigation is still required for a case like this.

3.Policy tightening tends to improve the UV/EC cases but worsen the thermal case. Stronger ETS parameters increase the value of ORC surplus and, therefore, the net economics of UV/EC; the thermal case moves in the opposite direction. This asymmetry is visible across all panels in Figure 9.

Finally, the thermal case remains an exploratory engineering estimate; regulatory acceptance and biological efficacy of the all proposed systems are outside the scope of this study. It is modelled to illustrate the physics and the cost consequences if one attempted a heat based disinfection system on this hull.

CONCLUSIONS

This study quantified the techno economic performance of three ballast water treatment (BWT) pathways on a BDELTA type handymax bulk carrier—filtration + UV, filtration + electrochlorination (EC), and a literature based thermal treatment case—when an Organic Rankine Cycle (ORC, 100 kW) supplies BWT electricity and the EU ETS cost is accounted for in 2025 conditions (coverage factor 0.70). Using a single, ship specific operational profile and consistent capital recovery, we compared annualized costs with and without crediting surplus ORC power to hotel loads. The main contribution is an end to end, code reproducible framework that links process energy, fuel, and allowance purchases to total cost, and that separates gross costs from net costs after ORC credits. The analysis shows that ORC assisted UV and EC are economically competitive under current carbon prices, whereas thermal treatment is dominated by boiler fuel and ETS charges. The thermal pathway was modelled as an exploratory, reference to bound the economics of heat only solutions. Limitations include vendor to ship scaling for CAPEX/OPEX, a single vessel and duty cycle, simplified hydraulics and heat loss assumptions for the thermal system, omission of by product management and neutralization chemistry (and cost) in EC, and the treatment of compliance strictly via allowance costs (no penalties). Within these bounds, the ranking of options is robust to uncertainty and to plausible changes in ETS price and coverage.

Key findings can be summarized as follows:

- With carbon priced and surplus ORC credited to hotel loads, EC + ORC yields the lowest net annualized cost; UV + ORC is a close second, while the thermal case is an order of magnitude higher due to boiler fuel and associated ETS costs.
- Thermal BWT could only be feasible with continuous waste heat recirculation (multi pass), well insulated tanks, and active cooling; it is impractical for short trials and warrants holistic evaluation.
- Using the study's base year (fuel 555 USD t^{-1}; ETS 80 USD tCO_2; coverage 70%), net totals are near zero for EC + ORC and about two × 10^4 USD y^{-1} for UV + ORC, versus roughly two × 10^6 USD y^{-1} for thermal.
- The 100 kW ORC more than covers UV/EC BWT electricity; surplus power reduces auxiliary generator fuel and ETS outlay for hotel loads, which is the decisive lever that drives EC and UV net costs down.
- Monte Carlo perturbations (±10% on major inputs) preserve the ordering EC ≤ UV << Thermal and show that fuel and ETS prices dominate cost spread; maintenance and CAPEX variability are second order for UV/EC under ORC support.
- Levelized cost per treated cubic meter is lowest for EC + ORC, slightly higher for UV + ORC, and vastly higher for thermal; the gap widens as ETS prices rise or coverage increases.
- ETS sensitivity (0–120 USD tCO_2; coverage 0.4–1.0) shifts absolute costs almost linearly but does not change the technology ranking; UV/EC remain competitive across foreseeable ETS phases, thermal does not.

Future studies should include (i) validate EC and UV duty assumptions with ship specific water quality data and holding time requirements, (ii) expand the framework to include DBP control, neutralization chemistry, and compliance risk modelling, and (iii) test different ship sizes, trading patterns, and ORC sizes/heat sources under evolving ETS coverage and prices to generalize the results. (iv) Quantify biological removal efficacy and verify IMO/USCG D-2 compliance for the studied configurations under ship-specific operating conditions, and explicitly link the energy/cost assumptions to the measured kill rates and required hold times.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

USE OF AI FOR WRITING ASSISTANCE

During the preparation of this work the author used OpenAI ChatGPT in order to improve readability and language. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

ETHICS

There are no ethical issues with the publication of this manuscript.

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NOMENCLATURE

Symbols

Symbol	Definition	Units
A	Area (e.g., heat-exchanger surface)	m^2
c	Specific heat capacity at constant pressure	$J\ kg^{-1}\ K^{-1}$
c_f	Fuel price per unit mass	$USD\ t^{-1}$
E	Energy or energy rate; context specifies whether total energy (kWh) or power (kW)	kWh, kW
e	Specific energy per unit volume (e.g., UV lamp energy per m^3)	$kWh\ m^{-3}$
fCO_2	CO_2 emission factor of fuel	$t\ CO_2\ t^{-1}$ fuel
i	Discount rate used for capital recovery	—
LMTD	Logarithmic mean temperature difference	K
m	Mass or mass flow rate	kg, $t\ yr^{-1}$
n	Economic lifetime for investment calculations	yr
P	Power (mechanical or electrical)	kW
Q	Heat rate or heat load	kW, W
R	Ratio (e.g., flow-rate ratio)	—
SFC	Specific fuel consumption	t fuel kWh^{-1}
T	Temperature	K, °C
U	Overall heat-transfer coefficient	$W\ m^{-2}\ K^{-1}$
V	Volume or volumetric flow	m^3, $m^3\ h^{-1}$
Δp	Pressure difference	Pa
ΔT	Temperature difference	K
ρ	Density	$kg\ m^{-3}$
φ	Fraction (e.g., ETS coverage)	—

Greek Letters

Symbol	Definition
η	Efficiency (subscripts indicate component: p for pump, EG for exhaust-gas recovery, etc.)
φ	Coverage fraction for emissions subject to ETS
ρ	Density of a fluid

Subscripts and superscripts

Subscript / superscript	Meaning
balast	Pertaining to ballast-water heating load
boiler	Relating to boiler heat requirement
c, h	Cold and hot sides of a heat exchanger
EG	Exhaust-gas stream or component
fuel	Associated with fuel (e.g., Q_{fuel})
in, out	Inlet and outlet conditions (temperature or flow)
JW	Jacket-water stream or component
ORC	Organic Rankine Cycle quantities
p, pump	Pump or pumping quantities
ref	Reference value used for scaling
ship	Values specific to the case ship
total	Denotes an annual or total quantity
UV, EC	UV-radiation system or electrochlorination system

Acronyms

Acronym	Meaning
AOP	Advanced Oxidation Process
BWMS	Ballast Water Management System
BWTS	Ballast Water Treatment System
CAPEX	Capital Expenditure
CPI	Consumer Price Index
CRF	Capital Recovery Factor
DBP	Disinfection by-product
EC	Electrochlorination
ETS	Emissions Trading System
HAA	Haloacetic acid
HAN	Haloacetonitrile
LMTD	Logarithmic Mean Temperature Difference
MNB	Micro-/nanobubble
NCR	Normal Continuous Rating
O&M	Operations and maintenance
OPEX	Operating Expenditure
ORC	Organic Rankine Cycle
SFC	Specific fuel consumption
THM	Trihalomethane
TRO	Total Residual Oxidant
UV	Ultraviolet