graph-based convex optimisation method to solve future ship energy technology selection

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Abstract. This conference paper addresses modern challenges regarding sustainable ship design and operation by solving the optimal technology selection problem. Current shipbuilding methodologies fall short, particularly considering future alternative energy systems. The paper disseminates a novel to maritime graph-based modelling approach using Mixed Integer Linear Programming for constrained techno-economic optimisation.
This method is demonstrated through the exemplary cruise ships energy system optimisation over a continuous variation of carbon taxation levels, finding the optimal energy system pathways from a broad range of alternative fuels and machinery.
Results demonstrate the viability of fossil fuels and shore electricity at lower carbon taxation (less than 0.07 €/kg $CO_{2\,eq.}$), shifting towards fuel cell systems powered by LNG and bio-LNG at moderate taxation (from 0.07 to 0.3 €/kg $CO_{2\,eq.}$), and finally renewable hydrogen and ammonia (beyond 0.7 €/kg $CO_{2\,eq.}$), where further decarbonisation reaches a practical limit.
Using the new method engineers can perform early design of future ship prototypes, effectively mitigating design risks with a broader scope of possible technology pathways and reduced reliance on design iterations.

Keywords: graph flow optimisation, energy systems, alternative technology, decarbonisation, maritime industry

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1 Introduction

The traditional shipbuilding practice regarding new technology relies on case-studies based on iterative proxy-design methods (design spiral). The vast breadth of novel maritime energy system alternatives renders the iterative approach insufficient for exploring multiple decarbonisation technologies holistically and efficiently. Contemporary maritime energy systems require tools capable of navigating complex interactions and technology alternatives in a cohesive and systematic way.

Existing maritime energy optimisation methods primarily rely on transient simulations, genetic algorithms, or mixed-integer linear programming (MILP). While transient simulations and genetic algorithms excel in capturing detailed non-linear system behaviour, they become computationally intractable for large-scale exploration of diverse technology alternatives [4, 8, 20, 30]. MILP methods, meanwhile, are capable of efficiently identifying globally optimal solutions across diverse technologies [5,19,23,24,27,28,31], yet the equation-based MILP formulation becomes extensive and unintuitive when applied to a broad or even scalable, multi-domain problem. Graph-based energy hub (EH) modelling techniques are successfully employed in non-maritime applications [6, 7, 9, 15] and offer significant advantages by directly visualising subsystem interactions using directed graphs and automating the problem formulation.

This paper disseminates a novel method for maritime energy system optimisation using graph flow optimisation [22]. By formulating the energy system as a directed graph, the proposed approach can systematically identify and optimise the most suitable technology pathways for ship decarbonisation. The directed graph representation explicitly captures entire energy flow pathways, from primary energy sources (e.g., solar, biomass, wind, fossil sources), infrastructure and supply-chain considerations, commodities such as fuels, onboard ship storage and energy transfer technologies (e.g., bunkering, cold-ironing), to on-board conversion and final utilisation for propulsion, electricity, heating, cooling, and water provision.

The methodology employs a graph-oriented MILP approach, using the directed graph itself as the optimization problem. This enables direct modelling of complex relationships and interactions without manual Linear Program (LP) equation derivation. The methods algorithm automatically constructs the mathematical LP and renders a visual graph representation of the complete multi-domain resource flow system.

The subsequent Methodology section explains the multi-commodity graph flow optimisation framework, covering energy subsystem modelling and the integration of capital and operational expenditures (CAPEX, OPEX), and CO_2 taxation (CO2TAX). The Analysis Input Data section details the cruise ship operational demand scenarios, various fuels and conversion technologies. The Results showcase a sensitivity analysis of the full graph model, revealing how carbon taxation can trigger technology shifts, with implications for future ship design and regulatory strategies.

2 Methodology

Multi-Commodity Graph Flow Optimisation This paper employs Linear Programming (LP) to optimise maritime energy systems represented as directed multi-commodity flow graphs. By using graph-based problem formulations, alternative maritime energy and technology pathways, complex system interactions, and economic parameters can be efficiently integrated and optimally solved.

Table 1: Linear Program definition

minimise:	$f(\mathbf{x}) = \mathbf{c} \cdot \mathbf{x}$	*cost function*
such that:	$\mathbf{A}_{ub} \cdot \mathbf{x} \leq \mathbf{b}_{ub}$	*inequality constraints*
	$\mathbf{A}_{eq} \cdot \mathbf{x} = \mathbf{b}_{eq}$	*equality constraints*
	$\mathbf{l} \leq \mathbf{x} \leq \mathbf{u}$	*bounds*

The ship energy system model with various technologies in the same analysis is split into sub-systems, the major economic aspects in cruise ship energy are firstly bunkering, representing the fuel price of the supply chain, and secondly the conversion of stored energy using machinery sub-systems to sustain the operational demands of the itinerary. The resulting system represents the techno-economically best technology pathway and system size, after optimisation of the full graph model.

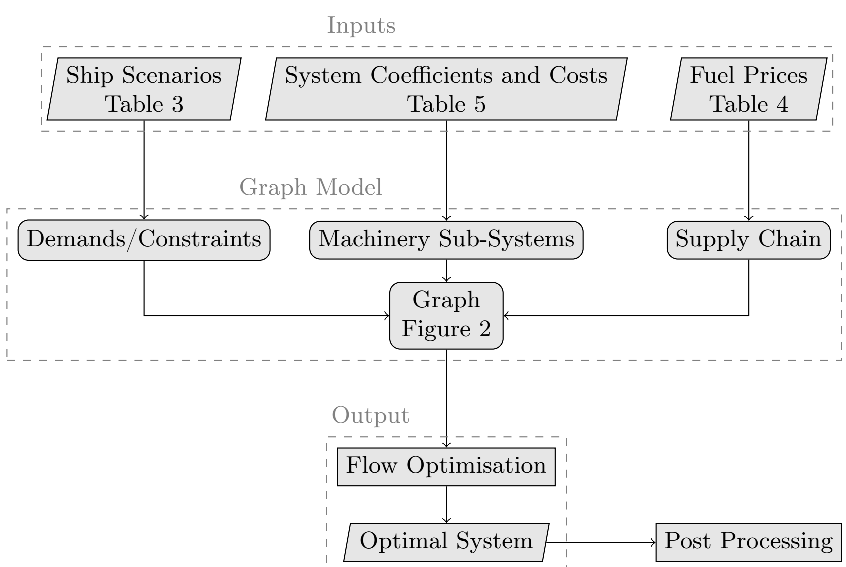


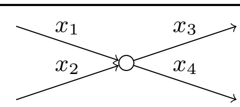
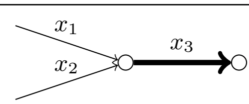
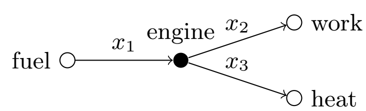
Fig. 1: Flowchart depicting the methodology.

Commodities Commodity nodes can represent the flow and quantity of a single type of commodity with their respective physical unit, such as kW, kWh, $\frac{\text{kg}}{\text{h}}$, or other numeric quantities like € or kg $\text{CO}_{2\,\text{eq.}}$. This type of node models conservation of flow, mass or energy, expressed mathematically as linear equality constraints.

Boundaries Flow source and sink nodes are used for open boundary modelling of undetermined flow quantities. Constrained boundaries are used to set known demands of a system, such as power demand or decarbonisation targets, enabling optimisation of minimal-cost energy flows of a system.

Machinery Modelling Machinery, such as engines, pumps, or heat exchangers, are modelled as nodes. Different to commodities, inputs and outputs of each machinery node are related through linear conversion ratios (such as efficiency coefficient, η) to a machinery flow variable $x_{m,i}$, for all scenarios i. Accordingly, input commodities (fuel) are converted linearly to output commodities (power, heat) within the optimisation. While linear relationships provide a simple formulation, piece-wise linearisation methods detailed in Section 2 allow more accurate non-linear machinery behaviours.

Table 2: All graph node types

Commodity		$\leftrightarrow$	$x_1 + x_2 = x_3 + x_4$
Boundary		$\leftrightarrow$	$x_1 + x_2 = x_3$ $x_3 = f(\text{scenario}_i)$
Machinery		$\leftrightarrow$	$x_1 = x_m/\eta$ $x_2 = x_m$ $x_3 = x_m(1-\eta)/\eta$

Economic Optimisation The graph based methodology optimises a single numeric quantity, in this work CAPEX of major components and OPEX regarding fuel costs are part of the objective function. Additionally, to analyse technology and energy system selection regarding potential future fuels, the well to wake emissions (WtW) are penalised with the carbon tax. The objective function for annual ship energy system operation is written out in Equation (1).

$$\texttt{minimize}(\text{CAPEX} + \text{OPEX} + \text{CO2TAX}) \tag{1}$$

By simultaneously considering both OPEX and CAPEX within the optimization framework, maritime system designs can be effectively evaluated for both short-term operational efficiency and long-term investment viability. The added CO2TAX cost term ensures that the economic-environmental optimal system is found for any given taxation value.

Multi-Scenario Optimisation with Capital Investment Real ship operations involve diverse scenarios (cruising, manoeuvring, port stays), each imposing distinct demands. Multi-scenario optimisation integrates operational profiles, sizing machinery for maximum flows observed across all scenarios. Machinery CAPEX is annualised using Equation (2) expressing the capital recovery factor (CRF), assuming an interest rate of 3% and a 20-year life.

$$CRF = \frac{r(1+r)^t}{(1+r)^t - 1} \tag{2}$$

Installed machinery capacity is determined by inequality constraints.

$$x_{m,max} = \texttt{max(}x_{m,1}\texttt{,}x_{m,2}\texttt{,}x_{m,3}\texttt{,}\cdots\texttt{)} \tag{3}$$

Machinery CAPEX is linearly related to maximum installed power in Equation (4) and included as cost terms in the objective function. This accounts for the one-time investment costs associated with installing or upgrading machinery and optimises multi-machinery investment while simultaneously meeting all operational demands.

$$CAPEX = \sum(m_{m,max} \cdot c_{machinery} \cdot CRF) \tag{4}$$

Operational expenditures (OPEX) are seamlessly integrated into the objective function as a linear cost term $c \cdot x$, where c represents the cost coefficient encompassing operational expenses such as fuel and maintenance.

$$OPEX = \sum(x_{fuel} \cdot c_{fuel}) \tag{5}$$

$$CO2TAX = \sum(WtW_{fuel} \cdot c_{CO_2}) \tag{6}$$

Non-linear Machinery Behaviour Mixed Integer Linear Programming (MILP) extends conventional Linear Programming (LP) by accommodating binary and integer variables alongside continuous ones and introducing special ordered sets (SOS) to solve non-linear problems using cut-and-branch method. This allows for modelling discrete design choices and approximating non-linear machinery behaviours with piece-wise linearisation, maintaining global optimality of the solution. Real machinery inputs and outputs typically depend on the load point. To accurately represent non-linear behaviours, a piece-wise linear approximation technique, special ordered sets of type 2 (SOS2) are employed. By discretising non-linear curves into linear segments, MILP maintains tractability and global optimality. Additionally, binary constraints enable machinery switching-off conditions.

3 Analysis Input Data

3.1 Reference Ship Operational Scenarios

The reference vessel is a mid-size cruise ship ($\approx$ 110,000 GT), selected due to its typical operational characteristics relevant for climate-neutral ship concept studies. Extensive operational data (January 2020, Caribbean Sea) covers propulsion, electricity, cooling, heating, and water demand.

The reference ship energy system includes four diesel generator engines fueled by HFO and MGO, an exhaust scrubber, exhaust heat recovery evaporators, oil-fired boilers, and a central AC distribution system supporting electric propulsion motors. Electricity consumption remains nearly constant, whereas propulsion varies significantly. Table 3 summarises key operational data.

A month's operational data is categorised into representative steady-state scenarios using K-means clustering [22], neglecting transient events. The optimal cluster number was selected based on silhouette and inertia metrics. The resulting operational scenarios detail demands according to ship modes, as shown in Table 3. These figures set the boundary conditions of the following optimisation analysis.

Table 3: Operational demand scenarios after k-means clustering

duration h	speed[1] kn	propulsion kW	electricity[2] kW	hotel kW	water m^3/h	heat[3] kW	Mode
3623	0.3	231	4995	2143	25	3859	Port
77	3.3	750	4913	2027	24	-4148	Port
486	3.8	1269	6110	1908	27	1484	Sea
650	11.3	6178	5182	1938	27	3786	Sea
747	14.9	10125	5260	2009	22	4570	Sea
1259	17.1	14102	5480	2050	27	5591	Sea
1391	18.1	17945	5660	2030	24	5849	Sea
218	18.3	21570	5510	1890	21	7287	Sea
308	19.1	25289	6020	2205	24	6560	Sea

[1] The vessel speed over ground is not zero in the port modes, this is due to clustering error, more clusters and therefore more scenarios reduce such errors.

[2] Auxiliary systems power consumption is included in electricity figure. Engine room ventilation fans are systems to sustain engine operation only, alternative technology might not need such high auxiliary power.

[3] Heat is hot water and steam energy consumption, negative value is excess steam dumping. Due to their similar temperature level and use onboard, HT water and steam are combined.

3.2 Considered Energy Sources

Relevant primary energy sources considered include fossil fuels (HFO, MGO, LNG), biofuels (bioLNG), renewable synthetic fuels (renewable liquid hydrogen reLH2 and renewable ammonia reNH3) and electricity (European grid mix and renewable electricity reEL). Fuel properties, costs, and lifecycle emissions (Well-To-Tank and Tank-To-Wake) follow official EU Fuel Maritime regulations [2] and reports [12] and are in Table 4.

Table 4: Fuel properties and prices

Fuel	LHV [a]	WtT [b]	TtW [b]	Fuel costs	
	$\frac{kWh}{kg}$	$\frac{kg\,CO_{2\,eq.}}{kWh}$	$\frac{kg\,CO_{2\,eq.}}{kWh}$	€/kWh	
VLSFO	11.25	0.048	0.282	0.0467	[1, 18, 25, 28]
MGO	11.86	0.052	0.275	0.0529	[1, 10, 25, 28, 29]
LNG	13.64	0.067	0.261	0.0480	[10, 13, 25, 29]
bioLNG	13.64	-0.216	0.261	0.0723	[21]
LH2	33.33	0.475	0.000	0.1182	[3, 10, 13, 16, 18]
reLH2	33.33	0.072	0.000	0.1649	[10, 16, 18, 21, 29]
NH3	5.17	0.436	0.000	0.0840	[13, 26]
reNH3	5.17	0.095	0.000	0.1746	[21, 26]
MOH	5.53	0.113	0.249	0.0711	[1, 13, 25, 28]
mixEL	-	0.504	0.000	0.0800	[14]
reEL	-	0.015	0.000	0.1000	[14]

[a] Lower heating value of combustion [2].
[b] Well to Tank and Tank to Wake values are defined in FuelEU Maritime regulation [2], and found in energy pathway WtT report [12].

3.3 Considered Energy Conversion Technologies

Primary marine energy conversion machinery includes internal combustion engines (ICE, dual-fuel DICE), solid oxide fuel cells (SOFC) and hydrogen polymer electrolyte membrane fuel cells (PEMFC), fuel to power conversion using machinery is expressed as power flow variables with unit kW. Internal power transfer between electric and mechanic systems are handled by motors and generators. Electric switchboards and other balance of power devices are neglected here. Also, pumps, compressors, the cooling system and minor energy converters are excluded from the analysis to focus on the major alternative technologies. PEMFC are low temperature machinery with no heat steam recovery potential, therefore fuel boilers are the additional steam production method next to exhaust gas boilers (EGB). The onboard fresh water demand is supplied only by reverse osmosis (RO),

Table 5: Ship machinery sub-systems

ICE CAPEX: 343 €/kW [10, 11, 13, 17, 18, 28], $\eta_{peak} = 47\,\%$	fuel $\xrightarrow{r_1}$ ICE; lub oil $\xrightarrow{r_2}$ ICE; ICE $\xrightarrow{r_3}$ mech. power; ICE $\xrightarrow{r_4}$ exhaust heat	$r_1 = 1/\eta\,\mathrm{kW}$ $r_2 = 0.00037\,\frac{\mathrm{kg}}{\mathrm{h}}$ $r_3 = 1\,\mathrm{kW}$ $r_4 = (1-\eta)/\eta\,\mathrm{kW}$
Single & Dual Fuel CAPEX: DICE 182 €/kW [3, 10, 17, 18, 28]	gas fuel $\xrightarrow{r_1}$ DICE; oil fuel $\xrightarrow{r_2}$ DICE; DICE $\xrightarrow{r_3}$ fuel; oil fuel $\rightarrow$ fuel	$r_1 = 0.1\,\mathrm{kW}$ $r_2 = 0.9\,\mathrm{kW}$ $r_3 = 1\,\mathrm{kW}$
Fuel oil Reheating	tank oil $\xrightarrow{r_1}$ Steam Coil; steam $\xrightarrow{r_2}$ Steam Coil; Steam Coil $\xrightarrow{r_3}$ oil fuel	$r_1 = 1\,\mathrm{kW}$ $r_2 = 0.01\,\mathrm{kW}$ $r_3 = 1\,\mathrm{kW}$
Fuel oil Boiler CAPEX: 22 €/kW [28]	fuel $\xrightarrow{r_1}$ Boiler $\xrightarrow{r_2}$ steam	$r_1 = 1.1\,\mathrm{kW}$ $r_2 = 1\,\mathrm{kW}$
Exhaust Gas Boiler CAPEX: 111 €/kW [28]	exhaust heat $\xrightarrow{r_1}$ EGB $\xrightarrow{r_2}$ steam	$r_1 = 1\,\mathrm{kW}$ $r_2 = 0.4\,\mathrm{kW}$
SOFC & PEMFC PEMFC CAPEX: 1450 €/kW, $\eta_{peak} = 60\,\%$ [3, 5, 10, 13, 18, 29] SOFC CAPEX: 2620 €/kW, $\eta_{peak} = 65\,\%$ [5, 13, 18, 29]	gas fuel $\xrightarrow{r_1}$ FC $\xrightarrow{r_2}$ electric power	$r_1 = 1/\eta\,\mathrm{kW}$ $r_2 = 1\,\mathrm{kW}$
Motor & Generator CAPEX: 138 €/kW [10, 11, 13, 17, 18, 28], $\eta = 95\,\%$	elec. power $\xrightarrow{r_1}$ motor $\xrightarrow{r_2}$ mech. power mech. power $\xrightarrow{r_1}$ generator $\xrightarrow{r_2}$ elec. power	$r_1 = 1/\eta\,\mathrm{kW}$ $r_2 = 1\,\mathrm{kW}$
Reverse Osmosis CAPEX: 22 000 €/m^3/d	electricity $\xrightarrow{r_2}$ RO $\xrightarrow{r_2}$ potable water	$r_1 = 0.005\,\mathrm{kW}$ $r_2 = 1\,\frac{\mathrm{kg}}{\mathrm{h}}$

4 Results

The assembled sub-systems comprise the analysis model and are shown in Figure 2, the four major ship commodity demands are set as boundary conditions for a fully coupled multi scenario optimisation. The presented energy system represents the major components and interactions in cruise ship machinery. Multiple alternative energy paths are modelled for various commodities. For example mechanical and electrical power can be sourced interchangeably from both mechanical engine shaft or fuel cells electrical power using generators or motors respectively. Steam can be made from excess exhaust gas heat or alternatively directly from fuel, steam dumping is necessary for edge cases when engine power is required but no heat consumed on board. The energy sources life cycle well to wake emissions (WtW) are additionally given a carbon tax cost per unit of greenhouse (GHG) gas emissions flow.

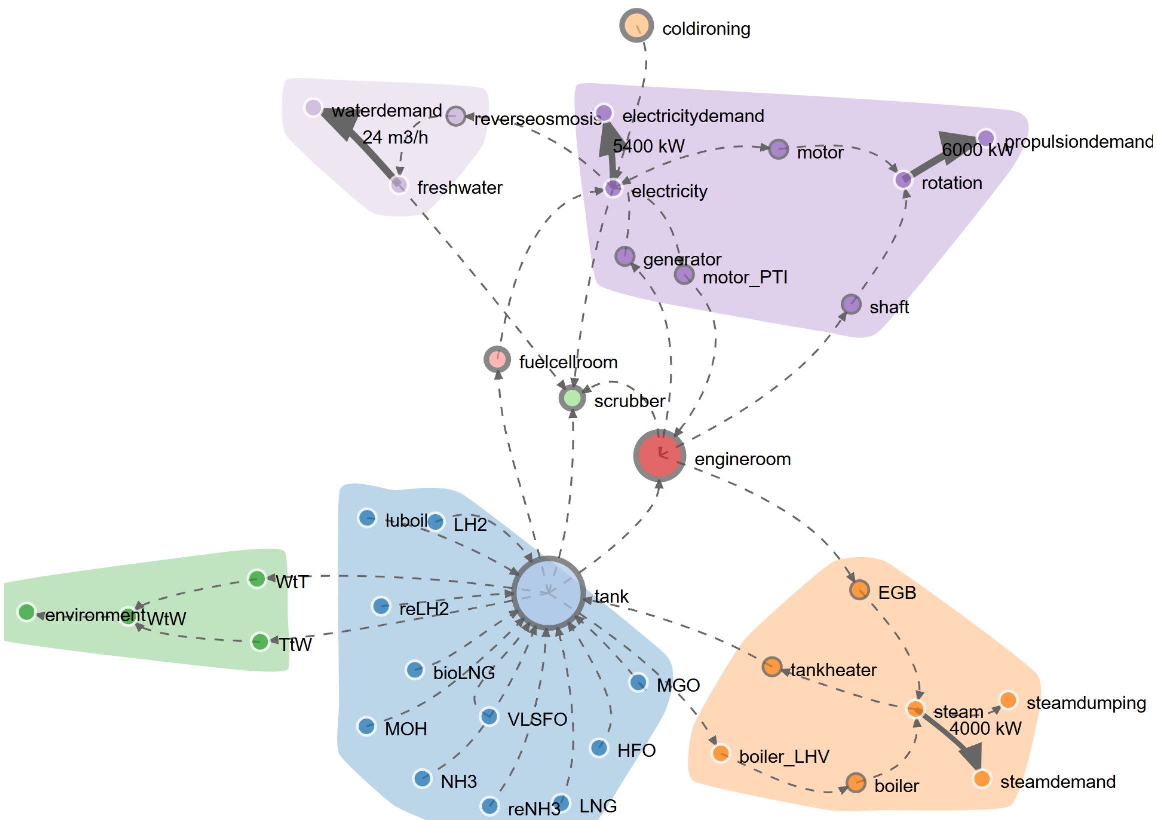


Fig. 2: Graph representation of the full energy system model

The result of the analysis is a single parameter sensitivity analysis of the carbon taxation value. The global cost objective function integrates energy supply chain well to tank as well as ship combustion tank to wake greenhouse gas emissions using CO2TAX term. Necessary technology changes are triggered as the global optima are be found for any carbon tax value. Figure 3 shows the results of holistic system optimisation for any carbon tax value in a range from $0.04\,€/\mathrm{kg\,CO_{2\,eq.}}$ to $2\,€/\mathrm{kg\,CO_{2\,eq.}}$. Both machinery size and annualised investment costs as well as bunkered energy quantities and fuel costs are showcased.

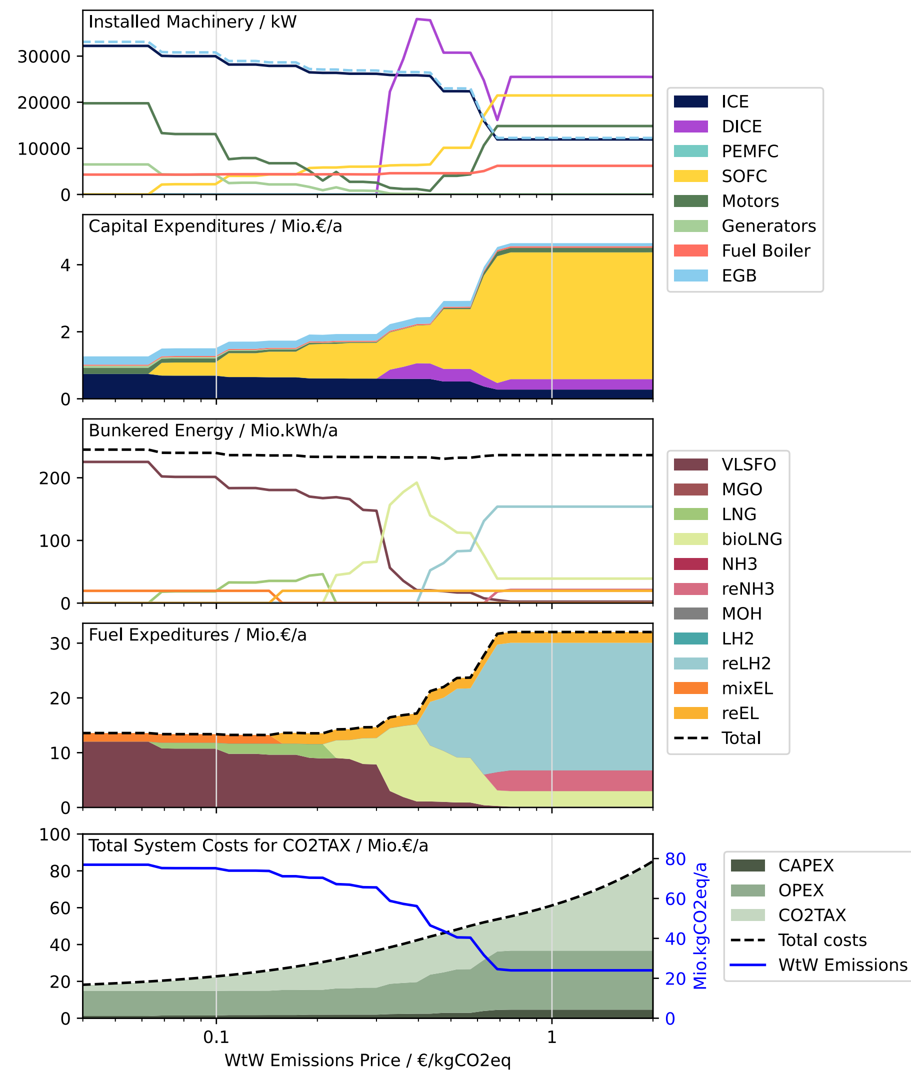


Fig. 3: Optimal fuel and machinery selection over carbon taxation.

5 Discussion

The following statements can be inferred from the optimisation results. The model results reflect the techno-economically optimal state-of-art cruise ship energy systems at low levels of carbon taxation (CO2TAX), namely combustion of very low sulphur fuel oil (VLSFO) in internal combustion engines (ICE) and electricity supply from shore during port stays.

Higher levels of carbon taxation trigger alternative fuel choices which emit less GHG but cost more per unit of energy. The first technology transition is the adoption of solid oxide fuel cell systems (SOFC) converting liquid natural gas (LNG) to electricity, happening at a taxation of 0.07 $€/\mathrm{kg}\,\mathrm{CO}_{2\,\mathrm{eq.}}$. A carbon tax of around 0.2 $€/\mathrm{kg}\,\mathrm{CO}_{2\,\mathrm{eq.}}$ is enough to render renewable electricity (reEL) more economical than EL during cold ironing, followed by bio based liquid natural gas (bioLNG) replacing LNG. Beyond 0.3 $€/\mathrm{kg}\,\mathrm{CO}_{2\,\mathrm{eq.}}$ is combusted in dual fuel engines (DICE) instead of VLSFO. At a taxation rate of 0.7 $€/\mathrm{kg}\,\mathrm{CO}_{2\,\mathrm{eq.}}$, renewable liquid hydrogen (reLH2) largely replaces methane fuels. Renewable ammonia (reNH3) is combusted instead of VLSFO in DICE. To cover the steam demand, large fuel boiler installations are required. It can be noted that the overall system reaches a decarbonisation plateau (WtW emissions in Figure 3), which is less energy efficient by that point, this can be seen in the slight increase of bunkered energy.

5.1 Limitations of the Study

The steam heat demand from ship operational data is not a by-product of the ICE technology which emits tremendous amounts of high temperature heat, the true first principles heat demand of various temperature levels is not included in the operational data set. Therefore, the large fuel boiler installations are likely unrealistic.

The effects of carbon tax on fuel prices and low carbon technology costs are assumed negligible. It was assumed that market dynamics do not alter the price of alternative technologies even with high carbon taxation. Although cold-ironing was modelled as available during port stays, fuels were assumed abundantly available at a fixed cost and during all scenarios, neglecting ship storage systems and port availability.

The graph-based approach can model model and optimise for multiple steady-state scenarios. Transient effects were not considered, important examples would be tank storage capacity and it's implications for ship displacement and volumetric shipbuilding costs, or engine start up effects.

The presented study does not adequately represent a ships lifetime, where various levels of fuel and taxation costs challenge optimal economic system selection. The questions of optimal system choices along a ships lifetime, alternative systems retrofit feasibility or costs of technology transition remain unanswered.

Energy storage costs, effects of weight and volumes as well as port availability and various price levels of novel fuels, are some significant vessel cost impacts yet to be considered in the methodology. Further, future fuel price uncertainty, technology learning curves and developments of renewable sources could render very different technology pathways as optimal, such considerations require further research.

6 Conclusion

This paper presented a novel graph-based optimisation method that is capable of selecting the technology choice with lowest life cycle costs by simultaneously finding the optimal system design. Through this novel method, maritime engineers can systematically internalise diverse technology choices, associated economic considerations (OPEX, CAPEX), regulatory constraints (emissions, safety), with full consideration for complex second- or higher-order-interdependencies within a cohesive modelling and optimisation framework. The developed approach thus closes critical methodological and modelling gaps identified in maritime energy system research, providing an intuitive, automated, and scalable solution to optimally navigate the complex landscape of maritime decarbonisation technologies.

The high level sub-system modelling approach was showcased, it requires only a reduced set of basic parameters, while automatic assembly and problem formulation completes the causal nexus of a ship system and significantly reduces modelling effort. Consequently, this graph-based approach simplifies the representation and communication of multi-domain relationships among shipbuilding experts, promoting collaboration and rapid system synthesis.

The graph model MILP formulation was optimised for various decarbonisation levels. By including well to wake greenhouse gas emission taxation in the economic objective function, a range of increasingly decarbonised ship energy systems were found. Such a sensitivity analysis of carbon taxation levels triggers various alternative technology pathways, the current optimum can be seen vertically along the x-axis in Figure 3.

Decarbonisation happens between 0.07 €/kg $CO_{2\,eq.}$ to 0.7 €/kg $CO_{2\,eq.}$. Taxation below this range does not incentivise techno-economic change, above this range no modelled technology or fuel choice can provide further reduction of WtW GHG emissions. Comparing these figures with current emission trading indices, the European ETS, which is fully applicable to maritime transport by 2027, is trading at around 0.08 €/kg $CO_{2\,eq.}$ since January 2022. According to this analysis, the ETS index is currently a tenfold too low to trigger major decarbonisation technologies, such as renewable ammonia or hydrogen and wide adoption of fuel cells systems. The price of carbon is expected to rise in the following decades and alternative systems and fuels can become economically feasible.

Techno-economic optimization using MILP is significant for future energy system technology assessment. The presented graph-based problem formulation method offers a more efficient modelling and effective technology comparisons for the multi-alternative ship energy systems and supply chains selection problem, which the maritime industry is facing now and in the coming decades.

This conference paper could successfully shows the granularity of the maritime decarbonisation journey for a single parameter sweep analysis. Effective MILP based optimisation methods in combination with flexible graph-based modelling techniques have yet to be implemented and compared against classic methods, such as transient simulations and extensive case studies, before the novel methods usefulness for early design stages can be assessed.

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