Maritime decarbonization pathways: a trade-off between operational and technical measures

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Setting the context

Context

- Maritime transport:
  - **80%** of merchandise by value[a]
  - **3%** of world carbon emissions[b]
- Containerships:
  - **15%** of total cargo mass shipped
  - **26%** of maritime carbon emissions

[a] OECD. (2022). Ocean shipping and shipbuilding.

[b] Faber, J., Hanayama, S., Zhang, S., & Pereda, P. (2021). *Fourth imo greenhouse gas study* (tech. rep. No. 4). International Maritime Organization. London.

Challenges :

- Specific sector: *"Hard-to-abate"*
- **IMO policies:** EEDI, SEEMP, EEXI[a]
- **EU policies:** FuelEU, ETS expansion[b]

What are the best strategies for a shipowner faced with a carbon price?

[a] IMO. (2024). Improving the energy efficiency of ships.

[b] EU Council. (2023). Fueleu maritime initiative: Council adopts new law to decarbonise the maritime sector - consilium.

Motivation

- **Idea:** Understand the effect of a market policy such as *carbon price* on shipowners' optimal strategies
- Focus on liner shipping :
  - Routes already established and change little over the year[a]
  - Few price fluctuations

[a] Corbett, J. J., Wang, H., & Winebrake, J. J. (2009).The effectiveness and costs of speed reductions on emissions from international shipping. *Transportation Research Part D: Transport and Environment*, *14*(8), 593–598. https://doi.org/10.1016/j.trd.2009.08.005

How to decarbonize maritime shipping?[a]:

- Operational measures
  - Optimal speed
  - Optimal fleet deployment
  - Optimal route
- Technical measures
  - Energy-saving measures
  - Fuel change
  - CCS

[a] Faber, J., Wang, H., Nelissen, D., Russell, B., & St Amand, D. (2011). Marginal abatement costs and cost effectiveness of energy-efficiency measures [MARINE ENVIRONMENT PROTECTION COMMITTEE, 62nd session, Agenda item 5, MEPC 62/INF.7, 8 April 2011, ENGLISH ONLY]. Faber, J., Hanayama, S., Zhang, S., & Pereda, P. (2021). *Fourth imo greenhouse gas study* (tech. rep. No. 4). International Maritime Organization. London.

Litterature review

Maritime shipping & carbon policies

- Market-based measures
  - K. Wang et al., 2015
  - Psaraftis et al., 2021
  - Cariou et al., 2023

LSFD

- General :
  - Perakis and Jaramillo, 1991
  - Jaramillo and Perakis, 1991
  - S. Wang and Meng, 2017
- Environmental applications :
  - Kontovas, 2014
  - Zhu et al., 2018
  - Gu et al., 2019

Fleet adaptation

- Slow Steaming
  - Corbett et al., 2009
  - Lindstad et al., 2011
  - Norlund and Gribkovskaia, 2013
  - Woo and Moon, 2014
  - Cepeda et al., 2017
  - Taskar and Andersen, 2020
- Technological measures
  - Faber et al., 2011
  - Ren and Lützen, 2015
  - Yuan et al., 2016
  - Zhen et al., 2020
  - Schwartz et al., 2020
  - Irena et al., 2021

Problem Description and Contribution

Problem Description

Operational Strategies

- Speed management, fleet deployment
- Port congestion
- Speed reduction $\longrightarrow$ fleet expansion

Technical Strategies

- Tech maturity.
- High upfront and operational costs.

Contribution

- Existing research: fleet operations, technical strategies
- Trade-offs between these strategies under carbon pricing need exploration
- This study examines operational and technical strategy trade-offs within carbon market contexts.

Why is This Important?

Understanding the efficiency and temporal trade-off between operational and technical measures to make optimal policies

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Hypotheses

- Liner shipping company
  - Multiple **established route**
  - Vessels of **different types** and **homogenous in type**
  - **Exogenous capital interest rate**
  - **Exogenous pair-port demand**
- **Weekly cost minimization** of firm
  - Optimal **speed**
  - Optimal **number of vessels**
  - Optimal **flow of container**
  - Optimal **energy saving measures mix**
  - Optimal **fuel mix**

- $r \in \mathcal{R}$: routes set
- $i \in \mathcal{I}_r$: route-specific leg set with $\mathcal{I}_r = \{0, 1, 2, ..., N_r\}$ and $N_r \in \mathbb{N}^*$ the number of port-calls by route
- $p, o, d \in \mathcal{P}$: ports set
- $v \in \mathcal{V}$: vessel types set with $\mathcal{V}_r \subset \mathcal{V}$
- $m \in \mathcal{M}$: energy-efficiency measures set with $\mathcal{M}_v \subset \mathcal{M}$
- $f \in \mathcal{F}$: fuel set with $\mathcal{F}_v \subset \mathcal{F}$

Flowchart

Inputs

Vessel costs: Weekly operating costs, Port-entrance fee
Fleet: Energy efficiency, Capacity, Vessels price, Min/max speed
Routes: Distances, Time in ports
Demand
Innovation: Measures list, Abatement potential, Non-recurring & recurring cost

⟹

Cost minimization

- Voyage cost
  (fuel, carbon)
- Operating cost
  (crew, maintenance)
- Measure recurring cost
- Capital cost
  (vessel, measures)

⇑

Simulation parameters

- Carbon price

⟹

Outputs

- **Optimal speed**
  (by route in knot)
- **Optimal fleet mix**
  (by route and vessel type)
- **Optimal measures mix**
  (by route, measure and vessel type)
- **Carbon emissions**
  (for the entire firm)

Objective function

$$\min_{\mathcal{X}^*} \quad C^V + C^O + C^{CH} + C^M + C^K \tag{1}$$

Objective: Find optimal decision vectors :

- ${\mathcal{X}_1}^*$ (2): speed, number of vessels, fuel mix and measures
- ${\mathcal{X}_2}^*$ (3): cargo flow

$${\mathcal{X}_1}^* = \left\{ {s_r}^*, {m_{r,v}}^*, {m^M_{r,v,f,m}}^*, {m^F_{r,v,f}}^* | r \in \mathcal{R}; v \in \mathcal{V}_r; m \in \mathcal{M}_v; f \in \mathcal{F}_v \right\} \tag{2}$$

$${\mathcal{X}_2}^* = \{ {lo_{o,r,v,i}}^*, {di_{o,r,v,i}}^*, {fl_{o,r,v,i}}^* | o \in \mathcal{P}; r \in \mathcal{R}; v \in \mathcal{V}_r; i \in \mathcal{I}_r \} \tag{3}$$

Cargo flow and demand

We employ an "origin-link-based fleet deployment model"[1,2]

- The demand is set between **2 ports**: $o, d \in \mathcal{P}$
- Through cost minimisation, the model gives optimal path

Equation (4) gives the equilibrium between fulfilled demand $D_{o,d}$ and cargo flow.

$$\sum_{r \in \mathcal{R}} \sum_{\substack{i \in \mathcal{I}_r \\ p_{r,i} = d}} (lo_{o,r,i} - di_{o,r,i}) = D_{o,d} \qquad d \neq o, \forall (o,d) \in \mathcal{W} \tag{4}$$

[1] Wang, S., & Meng, Q. (2017). Container liner fleet deployment: A systematic overview. *Transportation Research Part C: Emerging Technologies*, 77, 389–404. https://doi.org/10.1016/j.trc.2017.02.010

[2] Herrera Rodriguez, M., Agrell, P. J., Manrique-de-Lara-Peñate, C., & Trujillo, L. (2022). A multi-criteria fleet deployment model for cost, time and environmental impact. *International Journal of Production Economics*, 243, 108325. https://doi.org/10.1016/j.ijpe.2021.108325

$t_{r,i}^{tot}$: total time for a leg i on the route r (5)

$$t_{r,i}^{tot} = t_{r,i}^{sea} + t_{r,i}^{man} + t_{r,i}^{ber} + t_{r,i}^{canal} \quad (5)$$

$t_{r,i}^{sea}$: time at sea, depends on distance and speed (6)

$$t_{r,i}^{sea} = \frac{d_{r,i}}{s_r} \quad (6)$$

Manoeuvring time $t_{r,i}^{man}$ and Canal time $t_{r,i}^{canal}$ depends on data.

Berthing time $t_{r,i}^{ber}$ use cargo moved and berthing time parameter tp_v^{ber} (7)

$$t_{r,i}^{ber} = \max_v \left(\sum_{o \in \mathcal{P}} [lo_{o,r,v,i} + di_{o,r,v,i}] \, tp_v^{ber} \right) \quad (7)$$

Maintenance of a weekly service (8).

$$168 * m_r^R = \sum_{i \in \mathcal{I}_r} t_{r,i}^{tot} \quad (8)$$

Fuel consumption: Main engine

We consider a cubic law[a][b] using:

- Sea margin (Sea conditions effect) - *%*
- Specific fuel consumption - *g/kWh*
- Main engine power - *kW*
- Speed - *knots*
- Design speed - *knots*

We consider SFC as a function of load (9) and load as a function of speed and design speed (10):

$$SFC_{r,v,f} = SFC(Load_{r,v}) \tag{9}$$

$$Load_{r,v} = \left(\frac{s_r}{s_v^{Design}}\right)^3 \tag{10}$$

Cubic law is defined as (11):

$$fc_{r,v,f} = sm * SFC_{r,i,v,f} * P_v^{me} * \left(\frac{s_r}{s_v^D}\right)^3 * t_{r,i}^{sea} \tag{11}$$

[a] Notteboom, T., & Cariou, P. (2009). Fuel surcharge practices of container shipping lines: Is it about cost recovery or revenue-making. 24–26.

[b] Corbett, J. J., Wang, H., & Winebrake, J. J. (2009). The effectiveness and costs of speed reductions on emissions from international shipping. *Transportation Research Part D: Transport and Environment*, 14(8), 593–598. https://doi.org/10.1016/j.trd.2009.08.005

Fuel consumption: Other engines and total

Auxiliary engines and boiler engines fuel consumption are time linear[3] (12):

$$fc^{oe}_{r,i,v,f} = t^{sea}_{r,i} cp^{sea}_{v,f} + t^{man}_{r,i} cp^{man}_{v,f} + t^{ber}_{r,i} cp^{ber}_{v,f} \tag{12}$$

Total fuel cost for a vessel using fuel f (13):

$$C^{fc}_{r,v,f} = \sum_{i \in \mathcal{I}_r} \left[fc^{me}_{r,i,v,f} \left(p^{Fme}_f + \varepsilon^{me}_f p^C \right) + fc^{oe}_{r,i,v,f} \left(p^{Foe}_f + \varepsilon^{oe}_f p^C \right) \right] \tag{13}$$

[3] Cariou, P., Parola, F., & Notteboom, T. (2019).Towards low carbon global supply chains: A multi-trade analysis of co2 emission reductions in container shipping. *International Journal of Production Economics*, *208*, 17–28. https://doi.org/10.1016/j.ijpe.2018.11.016

Carbon abatement measures

Energy-saving measures[a,b]:

- $m^M_{r,v,f,m}$: number of vessels applying m
- $\tau^M_{v,m}$: carbon abatement potential for measure m on vessel v
- Some measures are not simultaneously applicable[b] (14, 15)

To estimate carbon emissions reduction : **geometric average** (16) weighted by the **share of vessels applying this measure** (17)

$$\sum_{m \in \Theta_n} m^M_{r,v,f,m} \leq m^F_{r,v,f} \tag{14}$$

$$\forall n \neq m, \Theta_n, \Theta_m \subseteq \mathcal{M}, \Theta_n \cap \Theta_m = \emptyset \tag{15}$$

$$\prod_{m \in \mathcal{M}_v} \left(1 - \tau^M_{v,m}\right)^{x^M_{r,v,f,m}} \tag{16}$$

$$x^M_{r,v,f,m} = \frac{m^M_{r,v,f,m}}{m^F_{r,v,f}} \tag{17}$$

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[a] Faber, J., Wang, H., Nelissen, D., Russell, B., & St Amand, D. (2011). Marginal abatement costs and cost effectiveness of energy-efficiency measures [MARINE ENVIRONMENT PROTECTION COMMITTEE, 62nd session, Agenda item 5, MEPC 62/INF.7, 8 April 2011, ENGLISH ONLY].

[b] Irena, K., Ernst, W., & Alexandros, C. G. (2021).The cost-effectiveness of co2 mitigation measures for the decarbonisation of shipping. the case study of a globally operating ship-management company. *Journal of Cleaner Production*, *316*, 128094. https://doi.org/10.1016/j.jclepro.2021.128094

Alternative fuels

We consider $m^F_{r,v,f}$ the number of vessels v using fuel f with (18)

$$\sum_{f \in \mathcal{F}} m^F_{r,v,f} = m_{r,v} \tag{18}$$

We have fuel-specific parameters for **Main Engine** (ME) and **Other Engines** (OE) with:

- $cp^a_{v,f}$: OE consumption parameter for activity a using fuel f
- p^{Fme}_f, p^{Foe}_f: ME and OE fuel price (different if dual-fuel)
- ε^{me}_f, ε^{oe}_f: ME and OE emission factor

Total annual voyage cost includes emission reduction from measures, vessel-specific parameters, fuel and carbon cost, canal fee $c_{r,v}^{canal}$ and port entrance fee c_v^{entr} (19)

$$C^V = \sum_{r\in\mathcal{R}} \sum_{v\in\mathcal{V}_r} x_{r,v}^V \left(\sum_{f\in\mathcal{F}_v} x_{r,v,f}^F \left[\left(\prod_{m\in\mathcal{M}_v} \left(1 - \tau_{v,m}^M\right)^{x_{r,v,f,m}^M} \right) C_{r,v,f}^{fc} \right] + c_{r,v}^{canal} + N_r c_v^{entr} \right) \tag{19}$$

Weekly operational cost (20), measure recurring cost (21)[4].

$$C^{O} = \sum_{r \in \mathcal{R}} \sum_{v \in \mathcal{V}_r} m_{r,v} c_v^{opr} \tag{20}$$

$$C^{M} = \sum_{r \in \mathcal{R}} \sum_{v \in \mathcal{V}_r} \sum_{f \in \mathcal{F}_v} \sum_{m \in \mathcal{M}_v} m^{M}_{r,v,f,m} c^{M}_{v,m} \tag{21}$$

[4] Faber, J., Hanayama, S., Zhang, S., & Pereda, P. (2021). *Fourth imo greenhouse gas study* (tech. rep. No. 4). International Maritime Organization. London.

Capital cost

We consider annualized capital cost[5][6] using capital interest rate r^K and life expectancy n divided by the number of week in a year (22)

$$C^{K^V} = \sum_{r \in \mathcal{R}} \sum_{v \in \mathcal{V}_r} m_{r,v} p_v^V \frac{r^K}{1 - (1 + r^K)^{-n_v^V}} * \frac{1}{52.1429} \tag{22}$$

We use the same method for **vessel**, **fuel** and **measures** investment

[5] Faber, J., Wang, H., Nelissen, D., Russell, B., & St Amand, D. (2011). Marginal abatement costs and cost effectiveness of energy-efficiency measures [MARINE ENVIRONMENT PROTECTION COMMITTEE, 62nd session, Agenda item 5, MEPC 62/INF.7, 8 April 2011, ENGLISH ONLY].

[6] Faber, J., Hanayama, S., Zhang, S., & Pereda, P. (2021). *Fourth imo greenhouse gas study* (tech. rep. No. 4). International Maritime Organization. London.

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Routes I

- 6 CMA CGM routes (times, ships, ports via *cma-cgm.fr*, distance via *sea-route.com*)
- **Single type** of vessels accepted by route

Route	**Duration** *in days*	**Vessels** *number*	**Port** *calls*	**Vessels** *type*
r	$T0_r^{tot}$	m_v^0	N_r	$v \in \mathcal{V}_r$
FAL1	98	14	12	Large
FAL3	84	14	11	Large
EPIC	63	13	15	Medium
BEX	70	14	14	Medium
BEX2	70	11	12	Small
MEX	91	15	17	Large

Table: Route characteristics

Routes II

Figure: French Asia Line 1 route (late 2023)

Vessels

- Base fleet: 81 vessels
- **3 types** : small, medium , large

Operational cost, port entrance fee, berthing time and cost from Herrera Rodriguez et al., 2022 in 2024US$. vessel price from VesselsLink, 2024

Vessel type	Capacity	Operating cost	Port-entrance fee	Bething time	Berthing cost	Price
	TEU	*$M/year*	*$/port calls*	*hour/TEU*	*$/hour*	*$M*
v	cap_v	c_v^{opr}	c_v^{entr}	tp_v^{ber}	c_v^{ber}	p_v^V
Small	8000	4.79	10,373	0.008	2518.95	120
Medium	12000	6.29	13,831	0.007	4678.05	170
Large	18000	7.79	18,442	0.006	5877.55	210

Table: Cost data by vessel type

Fuel Data

We consider 6 types of fuel:

- **Very Low Sulfur Fuel Oil (VLSFO)**: Used as a base fuel, common in maritime shipping.
- **Methanol (MeOH):** A lower carbon fuel option with a moderate emission factor.
- **Dual Fuel Liquified Natural Gas - Otto Method (LNG-Otto)**: Utilizes pre-mixed LNG and air, ignited by a spark or small diesel pilot.
- **Dual Fuel Liquified Natural Gas - Diesel Method (LNG-Diesel)**: Injects LNG at high pressure with compression ignition.
- **Liquified Natural Gas Lean Burn Spark-Ignited (LBSI)**: Operates on a lean air-fuel mixture.
- **Hydrogen Internal Combustion Engine (H2-ICE)**: Zero-carbon option

Fuel Type	ME emission factor	OE emission factor	ME fuel price	OE fuel price
	g^{CO_2} / g^{fuel}	g^{CO_2} / g^{fuel}	$2024/mt	$2024/mt
f	ε_f^{me}	ε_f^{oe}	p_f^{Fme}	p_f^{Foe}
VLSFO	3.114	3.114	554.0	554.0
MeOH	4.375	4.375	340.0	340.0
LNG-Otto	2.752	2.750	668.5	668.0
LNG-Diesel	2.769	2.750	671.7	668.0
LBSI	2.750	2.750	668.0	668.0
H2-ICE	0.000	0.000	4000.0	4000.0

Table: Emission factor and fuel price by fuel type and engine type

Measures

Groups	Abatement technologies	$\hat{n}$	m
Group 1 : *Main engine improvements*	Main Engine Tuning Common-rail Electronic engine control	Θ_1	*met* *cr* *eec*
Group 2 : *Auxiliary systems*	Frequency converters Speed control of pumps and fans	Θ_2	*fc* *scpf*
Group 3	Steam plant operation improvements	Θ_3	*spoi*
Group 4 : *Waste heat recovery*	Waste heat recovery Exhaust gas boilers on auxiliary engines	Θ_4	*whr* *egbae*
Group 5 : *Propeller improvements*	Propeller-rudder upgrade Propeller upgrade (nozzle, tip winglet) Propeller boss cap fins Contra-rotating propeller	Θ_5	*pru* *pu* *pbcf* *crp*
Group 6 : *Propeller maintenance*	Propeller performance monitoring Propeller polishing	Θ_6	*ppm* *pp*
Group 7	Air lubrication	Θ_7	*al*
Group 8	Low-friction hull coating	Θ_8	*lfhc*
Group 9 : *Hull maintenance*	Hull performance monitoring Hull brushing Hull hydro-blasting Dry-dock full blast	Θ_9	*hpm* *hb* *hhb* *ddfb*
Group 10	Optimization water flow hull openings	Θ_{10}	*owfho*
Group 11	Super light ship	Θ_{11}	*sls*
Group 12	Reduced auxiliary power demand (low energy lighting etc.)	Θ_{12}	*rapd*

Table: Energy savings technologies groups and index

Demand

- **Data Availability**: Specific demand data for each port pair was not available.
- **Approach Taken**:
  - Utilized round-trip duration provided by CMA CGM and base fleet data.
  - Assumed an average operational speed of 16.5 knots for each route.
- **Methodology**:
  - Formulated a maximization model for total demand over a week.
  - Aligned demand per port pair with typical vessel operations.
  - Ensured the calculated demand was consistent with operational constraints.
- **Objective Function**:
  - Maximized total annual demand while maintaining vessel speed and fleet composition.

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Introduction to Results

Solver Used

- **GAMS** software with the **Standard Branch and Bound (SBB)** solver.
- Solved using a **Mixed Integer Non-Linear Programming** approach.

Table: Scenario list

`BASE`	No energy-saving measures, no fuel
`OF`	Only alternative fuels
`MAT_1`	Energy-saving measures and fuels already available (Maturity = 1)
`MAT_2`	Energy-saving measures and fuels available in 5 years (Maturity $\leq$ 2)
`MAT_3`	Energy-saving measures and fuels available in 10 years (Maturity $\leq$ 3)
`MAT_4`	Energy-saving measures and fuels available in 20 years (Maturity $\leq$ 4)

Base and MAT_1 Scenario Comparison

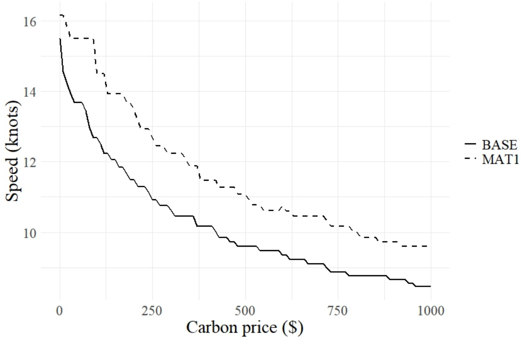

Figure: Average speed in knots in BASE and MAT_1 scenarios

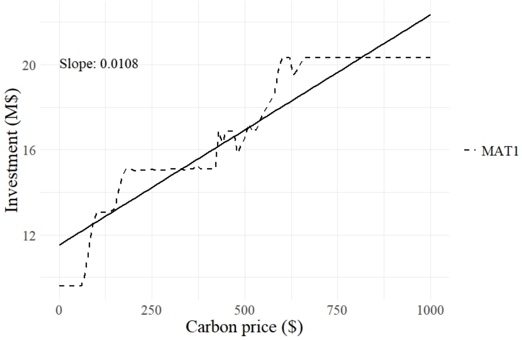

Figure: Average investment in energy-saving measures by vessel in MAT_1 scenario

- Between BASE and MAT_1 scenarios, average speed difference is 1.44 knots (14% decrease).
- The MAT_1 scenario shows that energy-saving investments start at $0 carbon price.
- Investment in measures grows by $108k per dollar of carbon price, with a slowdown between $150 and $400 carbon price.

Investment by Vessel Type in `MAT_1` Scenario

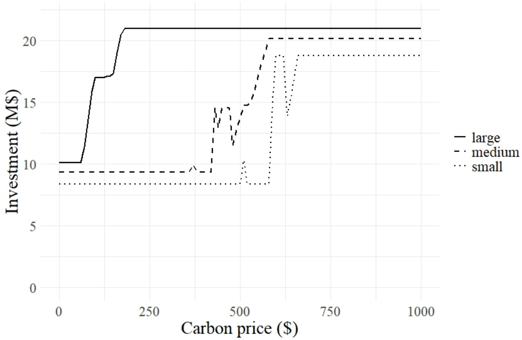

Figure: Investment in energy-saving measures by vessel type in `MAT_1` scenario

- Larger vessels attract higher investments due to high fuel consumption and high investment cost
- This preference for larger vessels is evident in fleet expansion and investment trends.

Alternative Fuels in OF Scenario

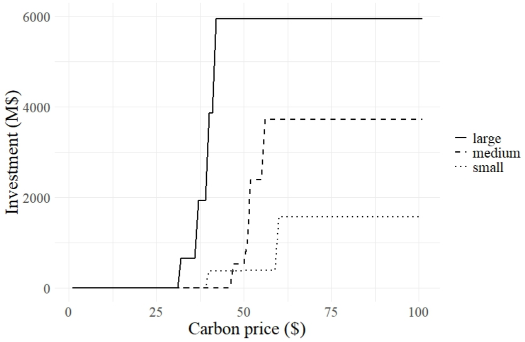

Figure: Investment in alternative fuels by vessel type in OF scenario

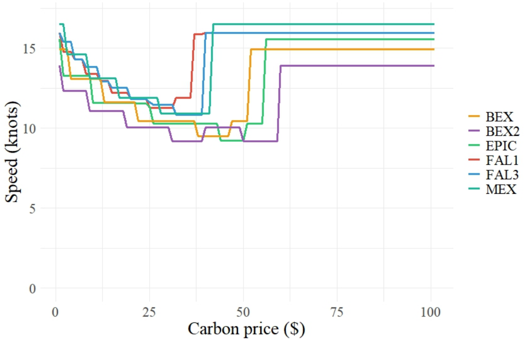

Figure: Speed by route in OF scenario

- In the OF scenario, alternative fuels are adopted at carbon prices $300/tCO2 and higher.
- LNG and hydrogen are the first alternative fuels adopted, with larger vessels transitioning first.
- Routes with alternative-fuel ships show higher speeds than those with high-emission fuels.

Investment in Alternative Fuels in MAT_2-MAT_4 Scenarios

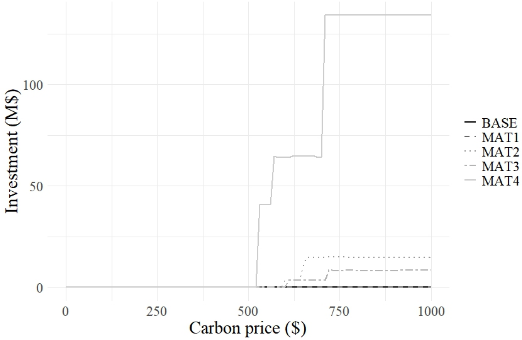

Figure: Average investment in alternative fuel for a single vessel in each scenario

- Investment in alternative fuels intensifies with the maturity of energy-saving measures.
- In MAT_3, investment in energy-saving measures limits the transition to alternative fuels.
- The threshold for fuel adoption rises to $500/tCO2 when energy-saving measures are in place.

Carbon Emissions in Different Scenarios

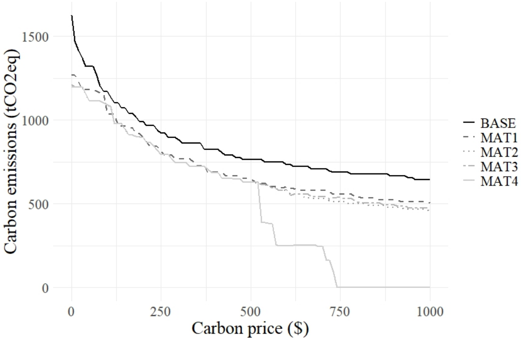

Figure: Average GHG emissions by vessel in each scenario

- The adoption of hydrogen results in zero carbon emissions in the `MAT_4` scenario.
- While alternative fuels reduce emissions, their impact is limited until the most mature fuels (e.g., hydrogen) are adopted.

Thank you for your attention !

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