NTNU – Trondheim
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Environmental Challenges and Options for Deep-sea Shipping

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24 Augutst 2017

Contents

- Motivation
- Nature of Deep-sea Shipping
- Pollutions from Deep-sea Shipping and Challenges
- Closer Look At Options to Tackle the Challenges
- Pathway to CO_2 reduction and Case Studies
- Summary

Travel and transport

Health risks of shipping pollution have been 'underestimated'

One giant container ship can emit almost the same amount of cancer and asthma-causing chemicals as 50m cars, study finds

Climate change threatens 50 years of progress in global health, st

This article is 8 years old

8,222

John Vidal, environment editor

Thursday 9 April 2009 15.50 BST

90,000 cargo ships travel the world's oceans. Photograph: Peter Maenhoudt/AP

The Guardian (2009)

The Independent (2017)

Air quality on cruise ship deck 'worse than world's most polluted cities', investigation finds

'Each day a cruise ship emits as much particulate matter as a million cars'

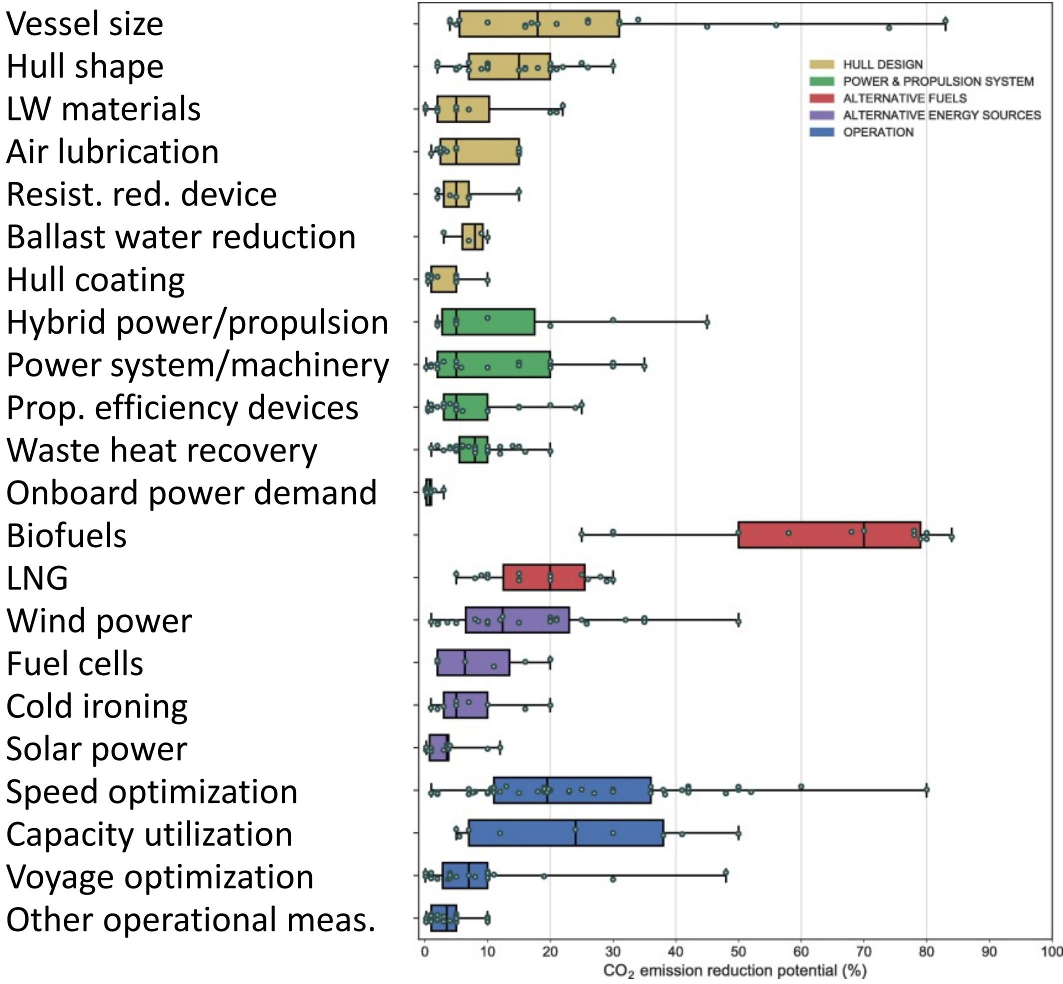
Chloe Farand | Monday 3 July 2017 23:16 BST | 39 comments

좋아요 Click to follow The Independent Online

Passengers sun bathing on the deck of a cruise ship could be exposed to worst air pollution than in some of the world's most polluted cities. Shutterstock

It is possible to reduce emissions per freight transport unit by 75% and above up to 2050

Bouman, E. A., Lindstad, E., Rialland, A. I., & Strømman, A. H. (2017). State-of-the-art technologies , measures , and potential for reducing GHG emissions from shipping – A review. *Transportation Research Part D*, *52*, 408–421.

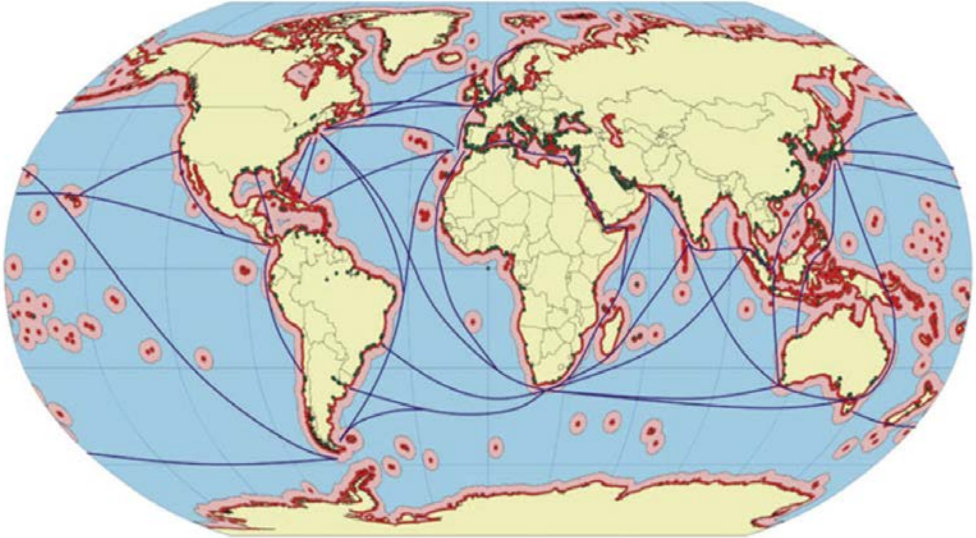


Nature of Deep-Sea Shipping

Deep-sea Shipping

- Deep-sea Shipping
  - Maritime transport of goods on intercontinental routes, crossing oceans, as opposed to short sea shipping




David et. Al. (2015)

Key Figures

- Transportation of **80~90%** world's total commerce in tonnage
- Container liner carry **30%** of global ton-miles, yet **80%** of the total value of shipment
- Longest oil tanker **458.46**m, Longest container ship **400**m, Bulk carrier **363**m, LNG Carrier **345**m
- The biggest engine 14RT-FLEX 96C **80,080** kW
- Responsible for **938MT CO_2** in 2012 (**2.6%** global emissions) and **18.6MT NO_X** (**13%**) and **10.6MT SO_X** (**12%**).

Characteristics of the Market

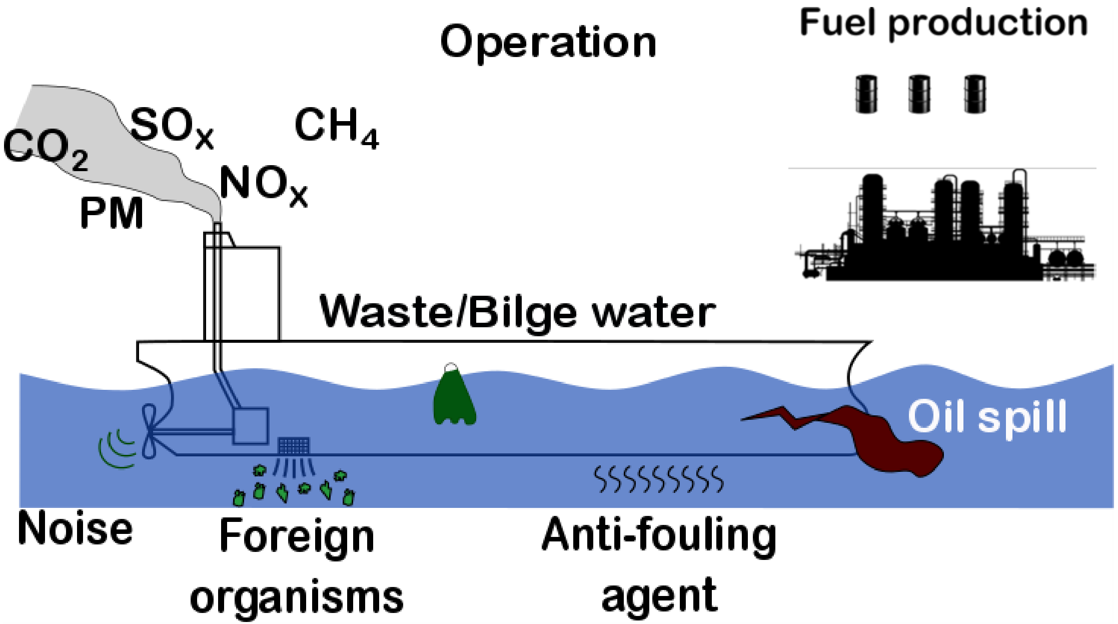
- Market demands driven by macroeconomic trends in global imports and exports
- International competition
- Many players involved
- Conservatisms
- Different type of business
  - Liner (Containers, passengers, vehicles)
  - Chartering (Permanent, Time, Spot)

Characteristics of operation

- Long voyages
- Distinctive operational modes but majority of energy used in the voyages
- Constant speed for its majority of operation
- Risk of being exposed to extreme weather
- Voyages in ballast mode
- Maintenance during the voyage

Pollution from the shipping and challenges

Pollution from Shipping



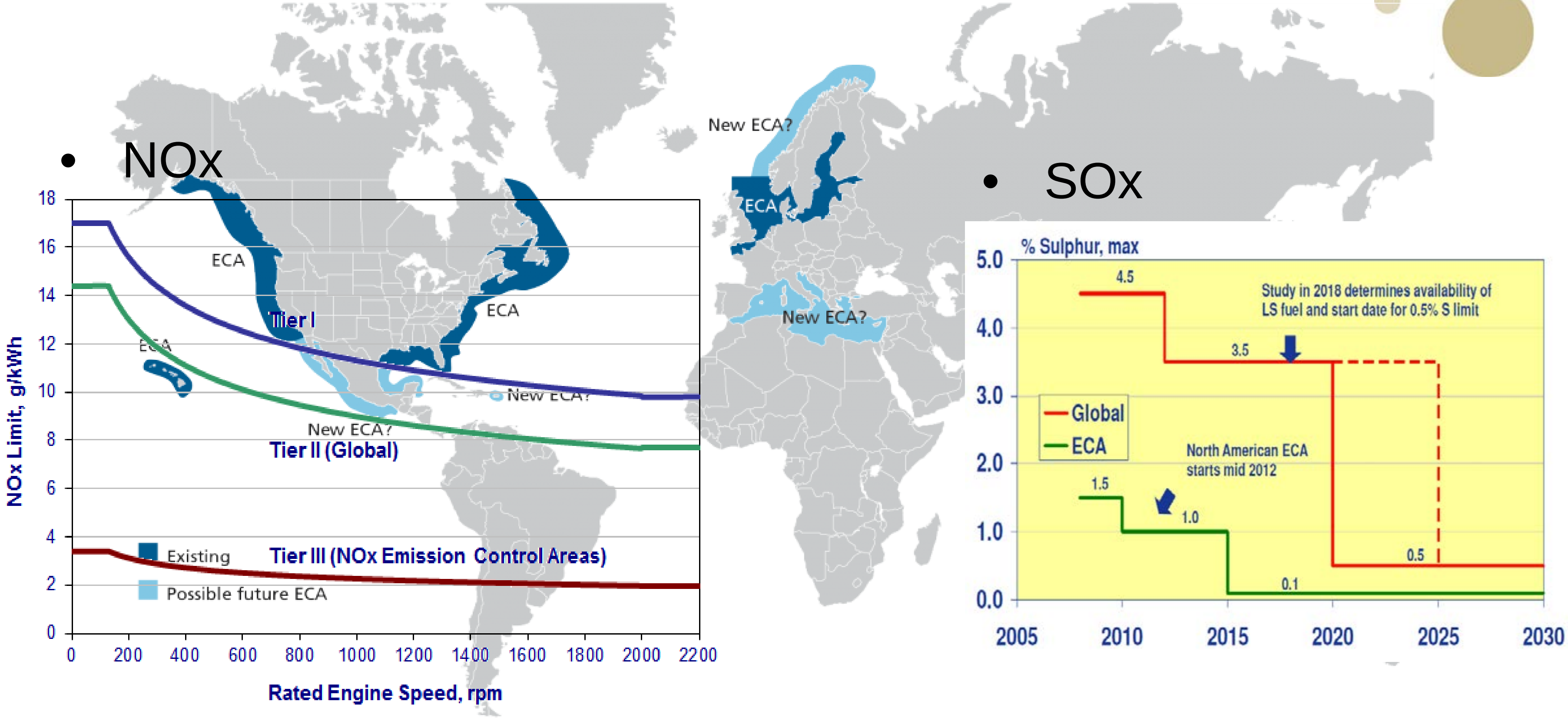
IMO Regulations

IMO Regulations on Water Pollution

- Invasion of foreign species
  - Ballast water convention: Ballast treatment system
  - Bio-fouling convention: Anti-fouling and maintenance practice
- Oil spill
  - MARPOL: Segregated ballast tank and double hull tankers
- Discharge of Sewage / Bilge water
  - Annex IV of MARPOL: Prohibition of discharge of sewage nearby or use of sewage treatment plant
  - MARPOL: Discharge of bilge and cleaning water from COT through oily water separator or oily discharge and monitoring system
- Anti-fouling system
  - Anti-fouling convention: Prohibition of the use of harmful organotin compounds in anti-fouling paints

IMO Regulations on Harmful Gas Emissions

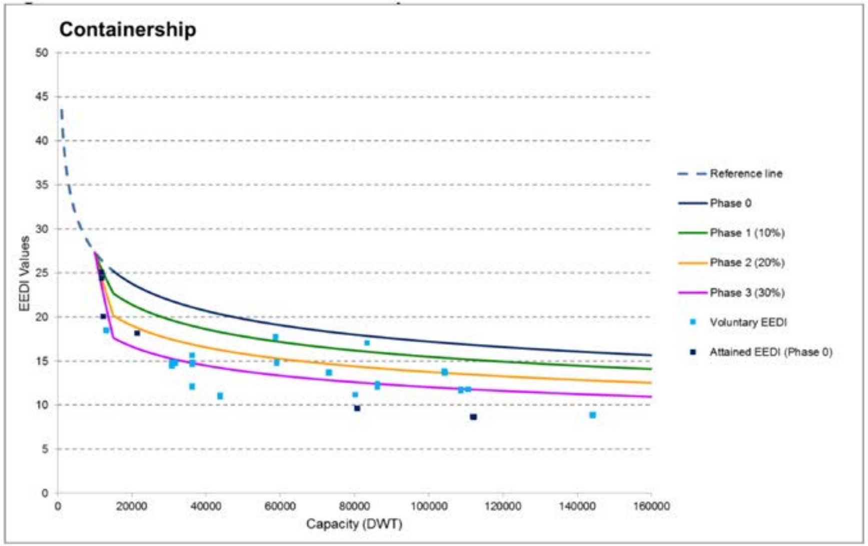
- NOx
- SOx

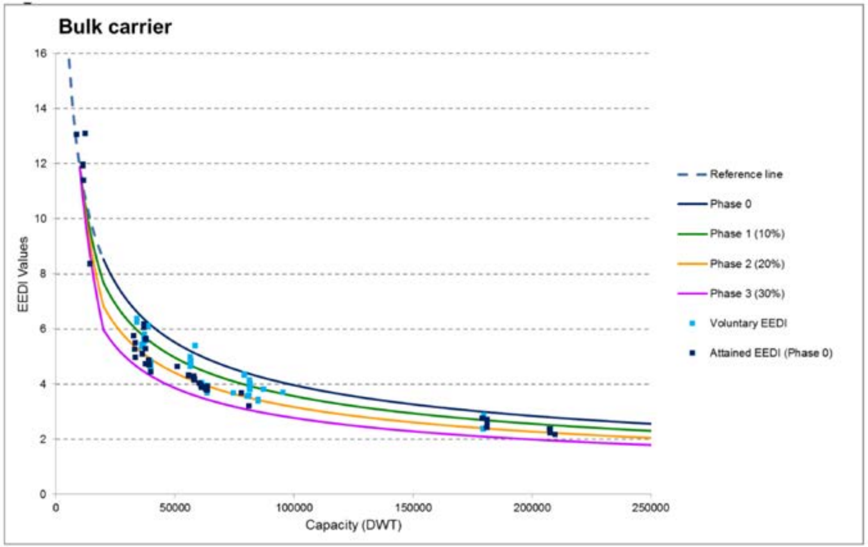


IMO Regulations on CO_2 (Green house gas)

- EEDI

$$\frac{\left(\prod_{j=1}^{n} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} \cdot C_{FME(i)} \cdot SFC_{ME(i)}\right) + \left(P_{AE} \cdot C_{FAE} \cdot SFC_{AE} *\right) + \left(\left(\prod_{j=1}^{n} f_j \cdot \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} \cdot P_{AEeff(i)}\right) C_{FAE} \cdot SFC_{AE}\right) - \left(\sum_{i=1}^{neff} f_{eff(i)} \cdot P_{eff(i)} \cdot C_{FME} \cdot SFC_{ME} **\right)}{f_i \cdot f_c \cdot f_l \cdot Capacity \cdot f_w \cdot V_{ref}}$$

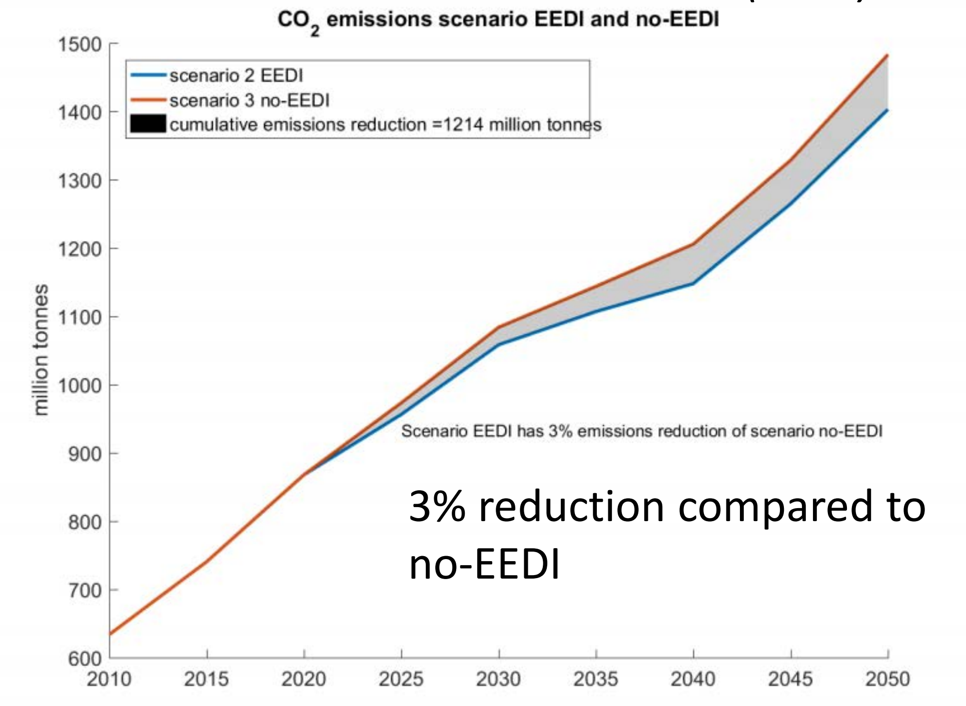




EEDI Database for container ship and buik carrier (from MEPC 68 INF. 13)

Will EEDI solve the GHG challenges?

Smith et al.(2016)



3% reduction compared to no-EEDI

- Limitation
  - Only applies to newbuilds
  - EEDI calculated for a single load case
  - Economic driver to improve fuel efficiency nevertheless

How much is international shipping responsible?

- "Fair share"

> "Shipping will make its fair and proportionate contribution towards realizing the objectives that [the UNFCCC] and the global community pursue"
>
> MEPC 63/5/5, Outcome of the United Nations Climate Change Conference held in Durban, South Africa from 28 November to 11 December 2011, Note by the Secretaria

- How much is fair then?

Smith et al.(2016)

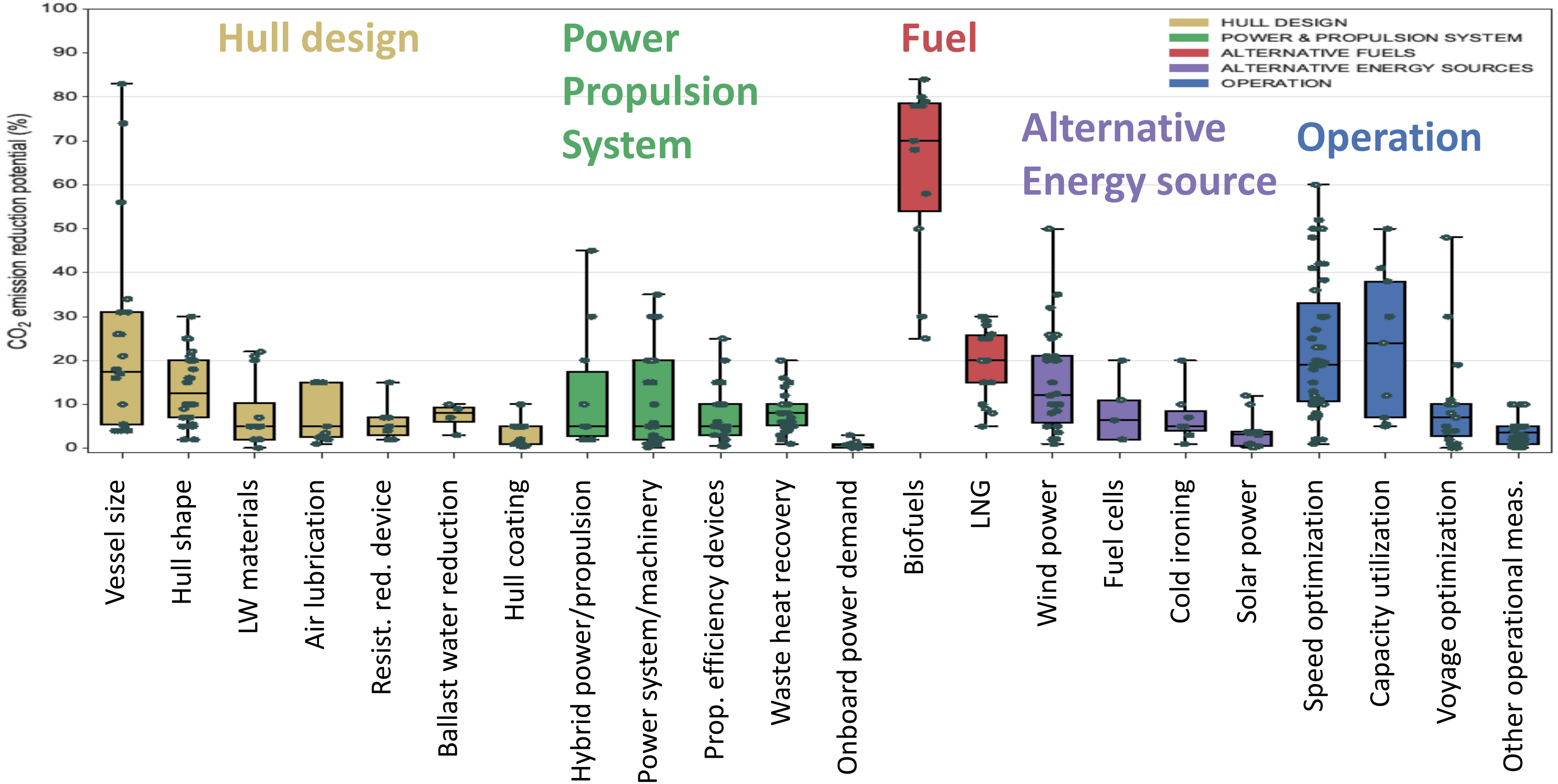
Principle	Stricter	Relaxed
Responsibility	18GT	33GT
Egalitarian	23GT	79.3GT

Responsibility principle: 1.5° target / 2° target

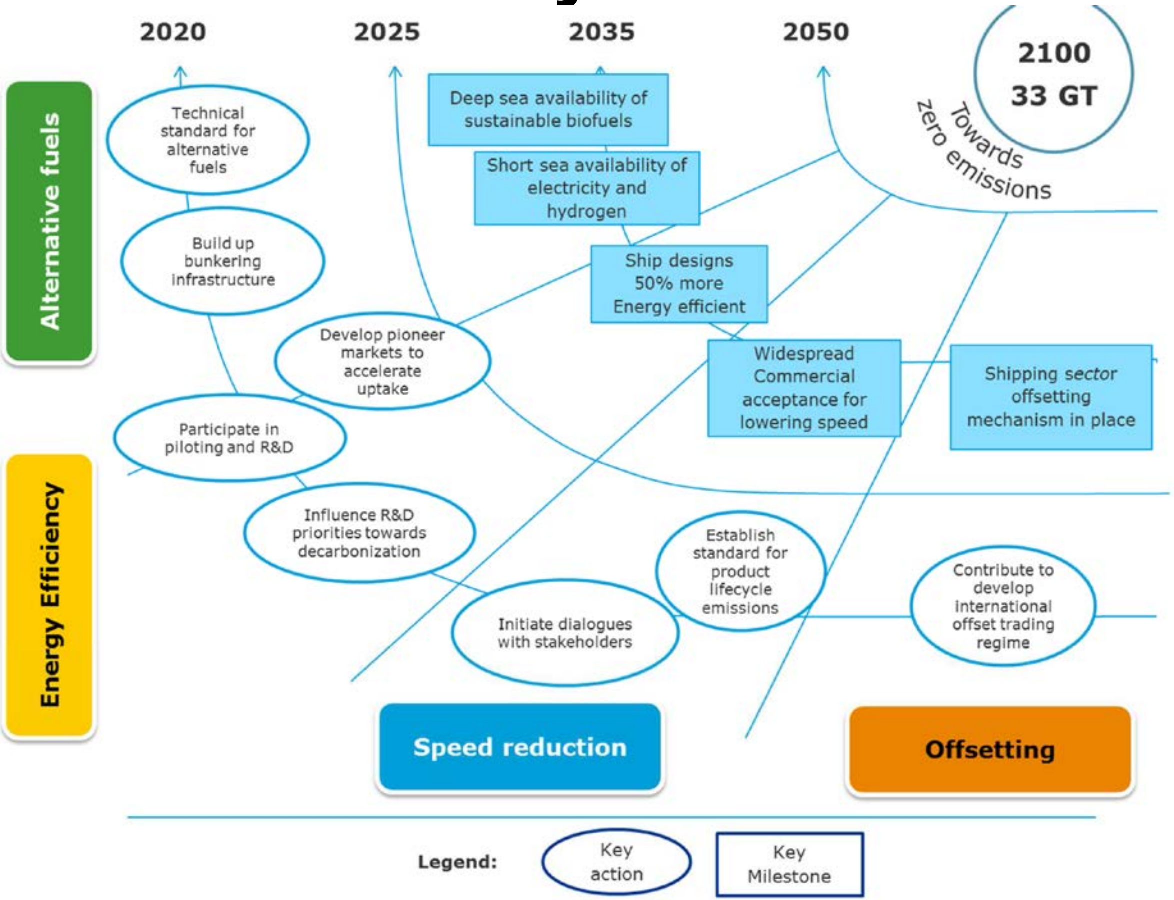
Egalitarian principle: Developed country / Developing country

Options to reduce GHG

Bouman et al.(2017)



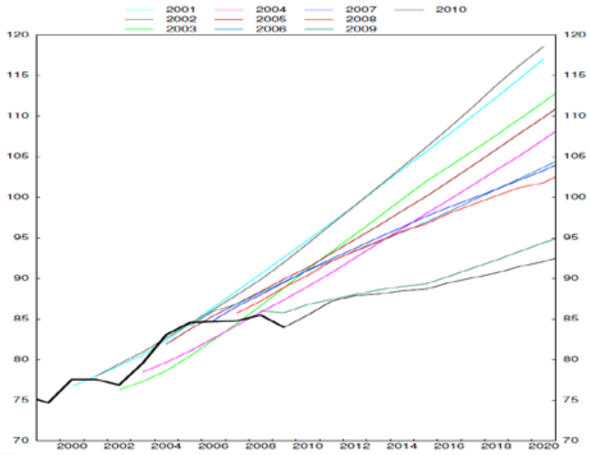
Possible Pathways

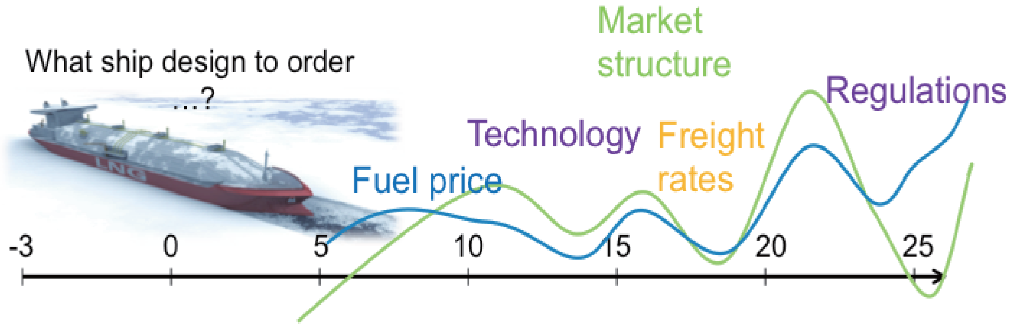


Eide et. al (2017)

Real Challenges

- Complexity
  - Combinations of the options
  - Interaction between the options
  - Operational profiles
  - Market Scenarios
- Uncertainties
  - Fuel price
  - World economy
  - Disruptive technologies
- Long-term horizon for prediction



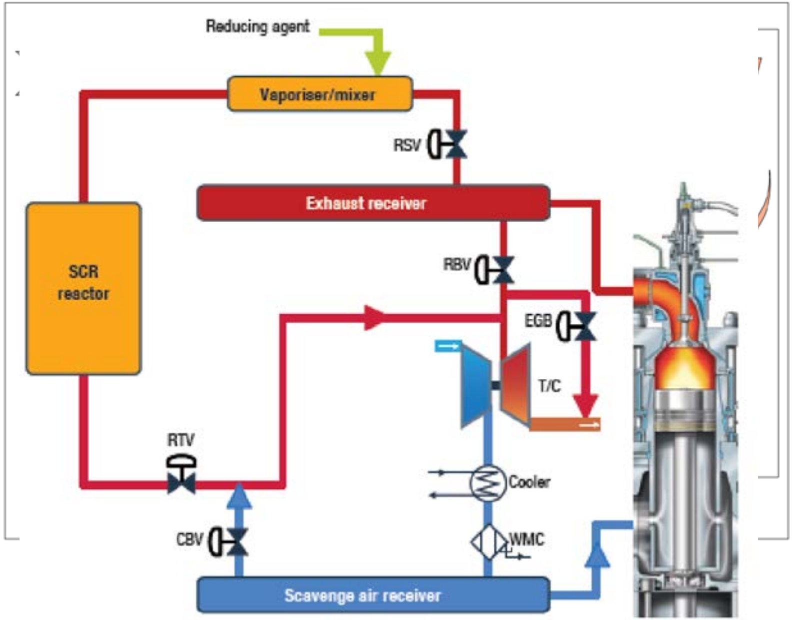


Erikstad et al. (2015)

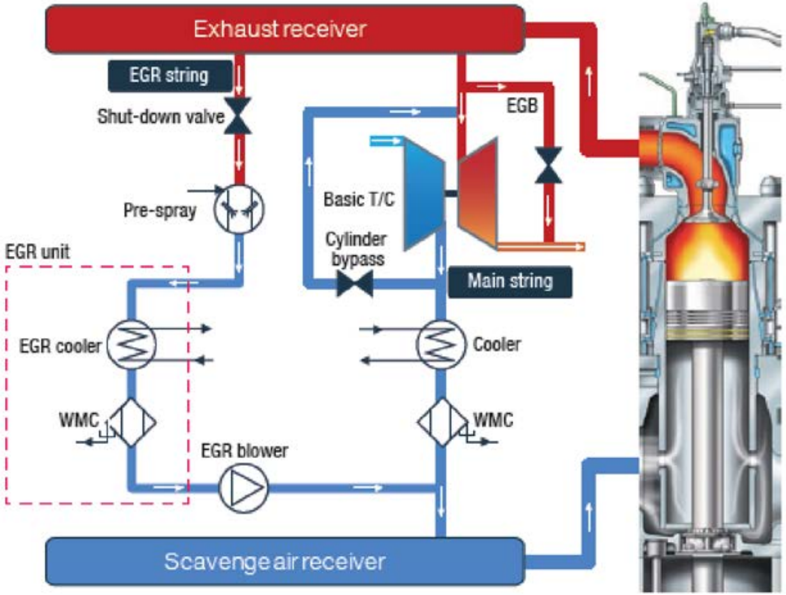
Closer look at the options for Reduction of Gaseous Emissions

Options for NOx emissions

SCR Technology

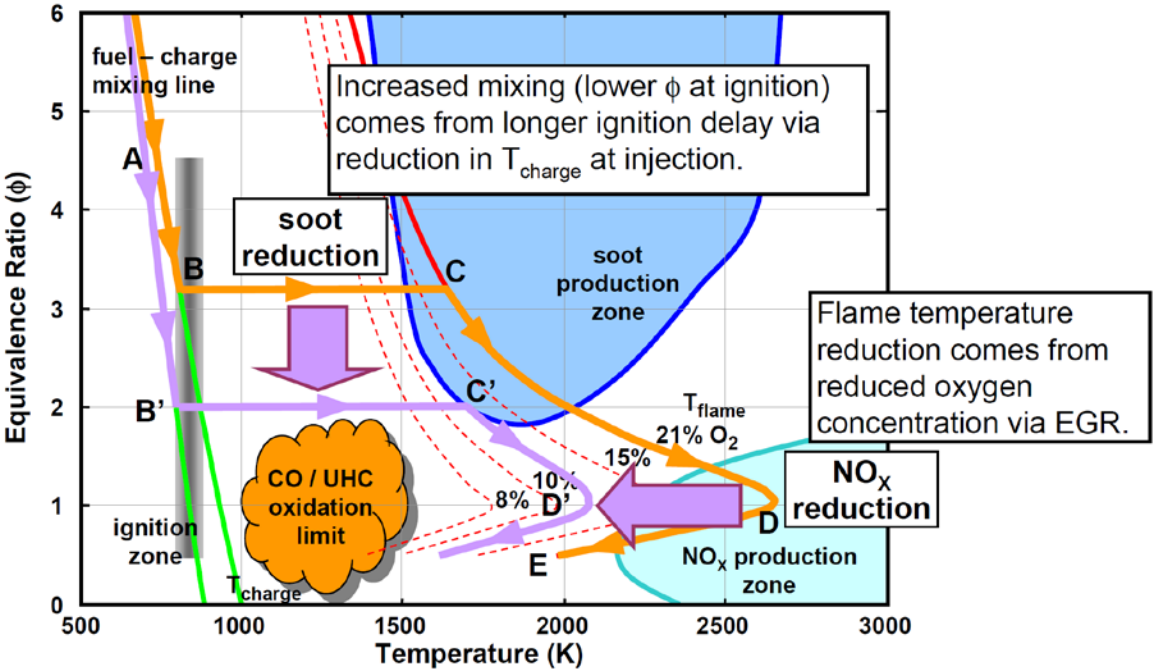


EGR Technology



Options for NOx emissions and Soot

- Engine modification



Fuel injection characteristics

Variable compression ratio

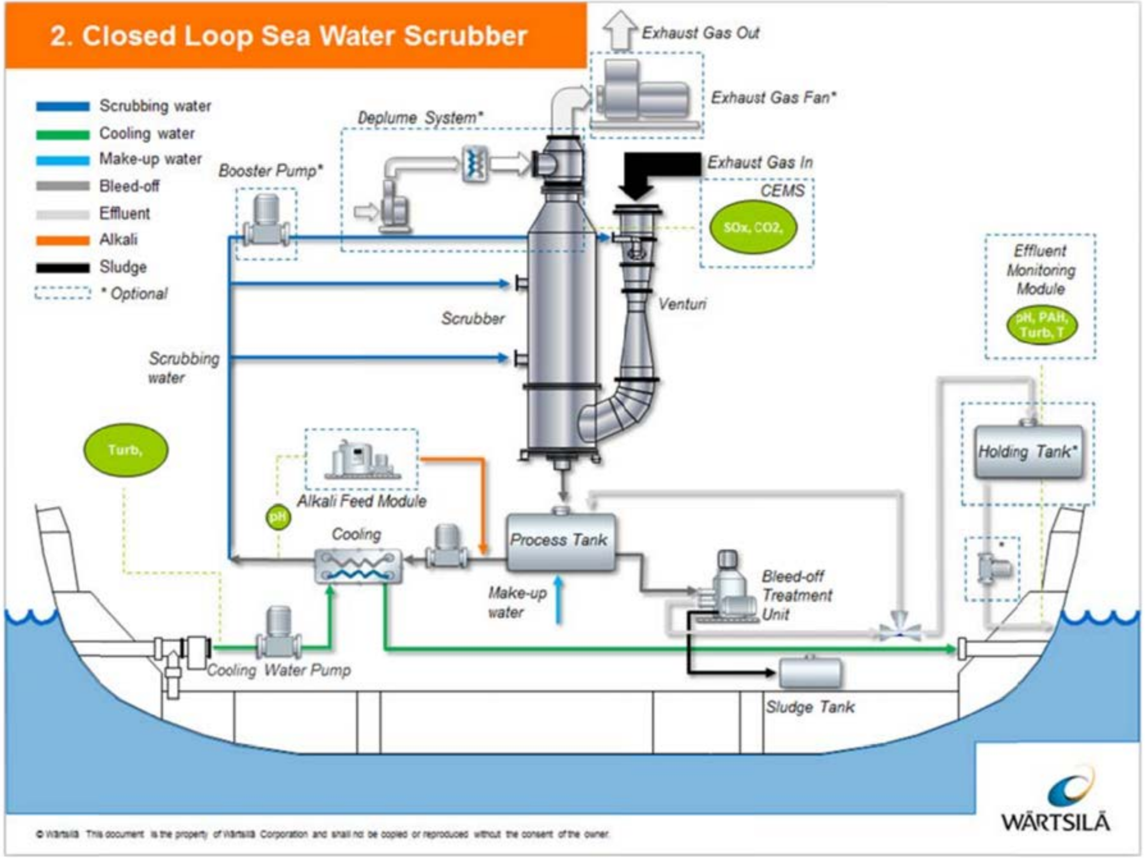
Exhaust gas recirculation

Advanced combustion
 - PCCI, HCCI

Potter, M., & Durrett, R. (2006). Design for compression ignition high-efficiency clean combustion engines. *12th Annual Diesel Engine Emissions Reduction (DEER) Conference*.

Options for SOx Emissions

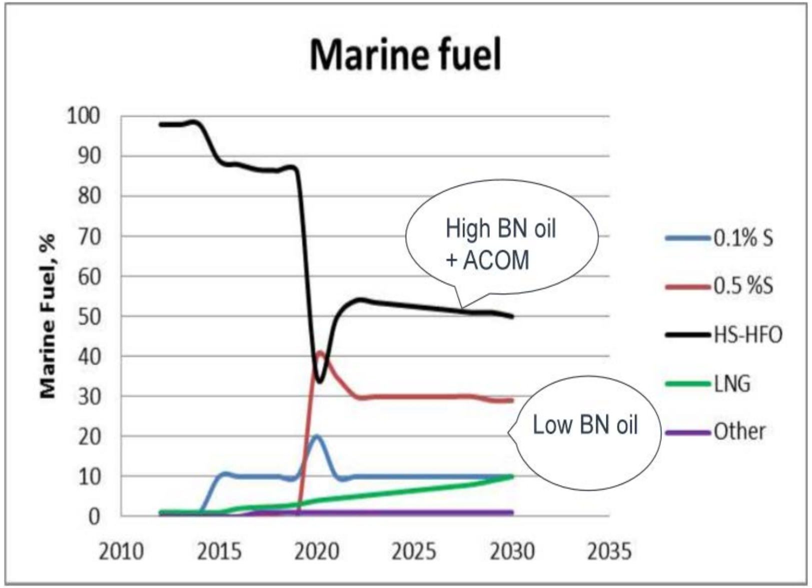
•



Options for emissions from the power system

- Fuel and technology options

Options	HFO	MGO LSHFO	Gas	Surphur free fuel
Scrubber	O			
EGR/SCR	O	O		
2-stage TC	O	O		
DF			O	O



Options for emissions from the power system

- Bio-fuel
  - The biggest question is the availability.
    - Technical, ethical challenge

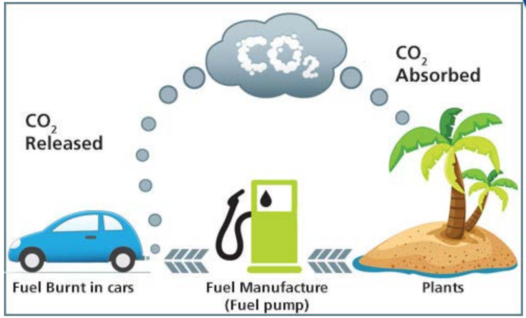


Table 8: Global biomass resource sizes

Source	Definition	Value in 2050	Classification
IEA	Maximum technical potential	1500 EJ	High band
IEA	Low risk potential	475 EJ	Medium band
TIAM-UCL	High scenario	236 EJ	Medium Band
GET Chalmers	Base-case	200 EJ	Medium Band
IEA Roadmap	BLUE Map Scenario	145 EJ	Medium Band
TIAM-UCL	CCC estimate	38 EJ	Low Band
TIAM-UCL	Limited scenario	9 EJ	Low Band

Global supply 500 EJ in 2009

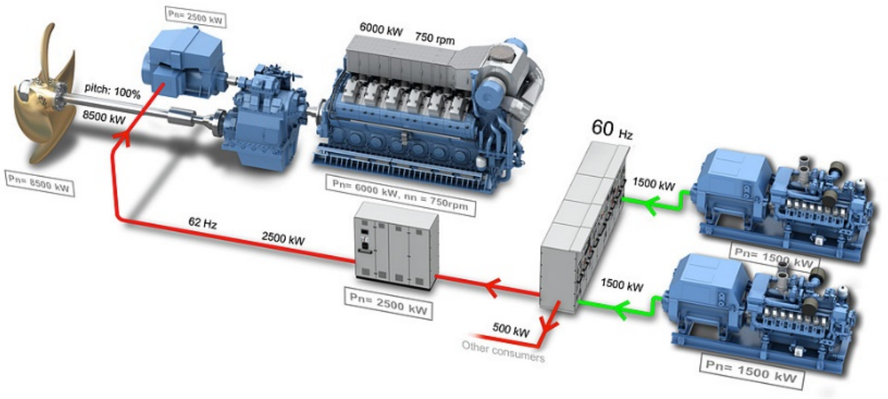
Options for emissions from the power system

- Hybrid Power / Propulsion System

$$P_{\text{prod}} \cong P_{\text{cons}}$$

$$P_{\text{prod}} \cong P_{\text{cons}} + P_{ESS}$$

Spinning reserve
Power smoothing
Load smoothing
Load shifting
Peak shaving



Courtesy of Rolls-Royce (https://www.rolls-royce.com)

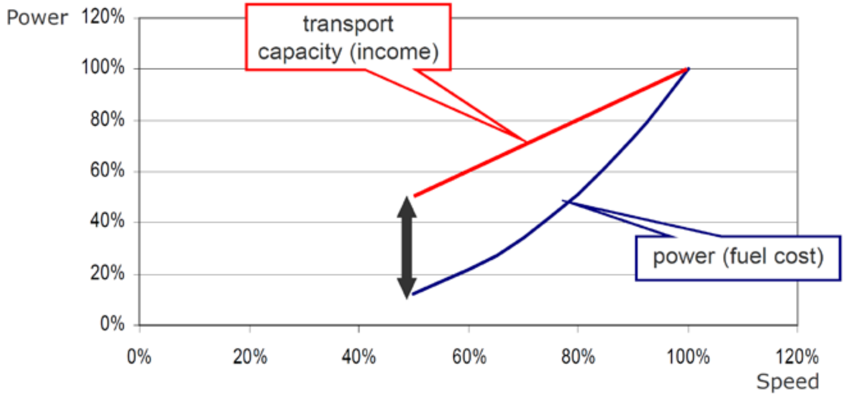
Options for emissions from the hull

- Hull design and resistance reduction measures
  - Larger vessels
  - Slender hulls
  - Reduced block coefficient
  - Air lubrication
  - Energy saving device
    - Fins
    - Pre-swirl device
    - Propeller Boss Cap Fins
    - Propeller duct

Options for emissions from operation

- Reduced speed

$$P_{\text{Prop}} = \frac{\Delta^{2/3} V^3}{C}$$



- Increased utilization
- Larger vessels
- Weather routing
- Alternative sea routes

Options for emissions from business

- Offsetting
  - Buying the carbon offsets from other sector
  - Possible buffer while barriers for other solution are lowered
  - Price trend

Smith et al. (2016)

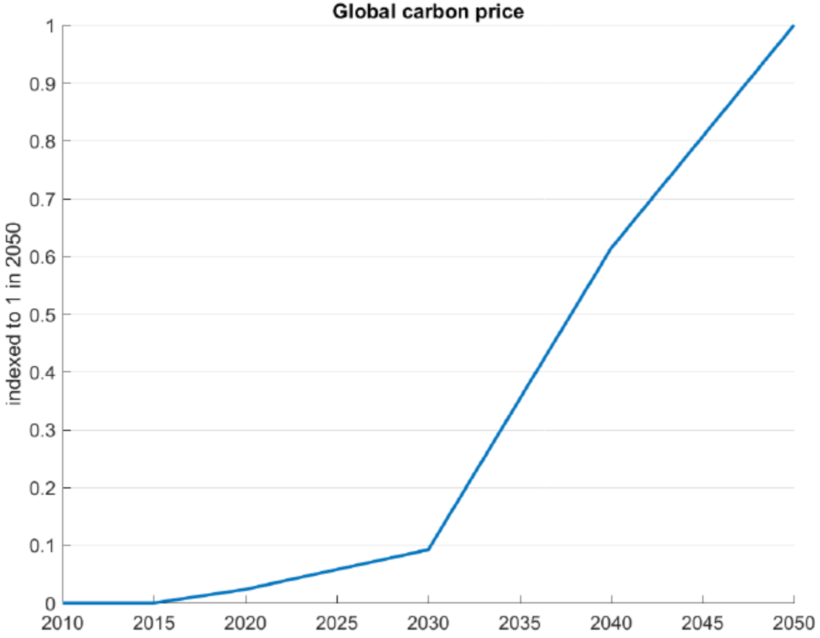


Figure 12: Global carbon price consistent with a 2 degree temperature rise target, as estimated by TIAM UCL

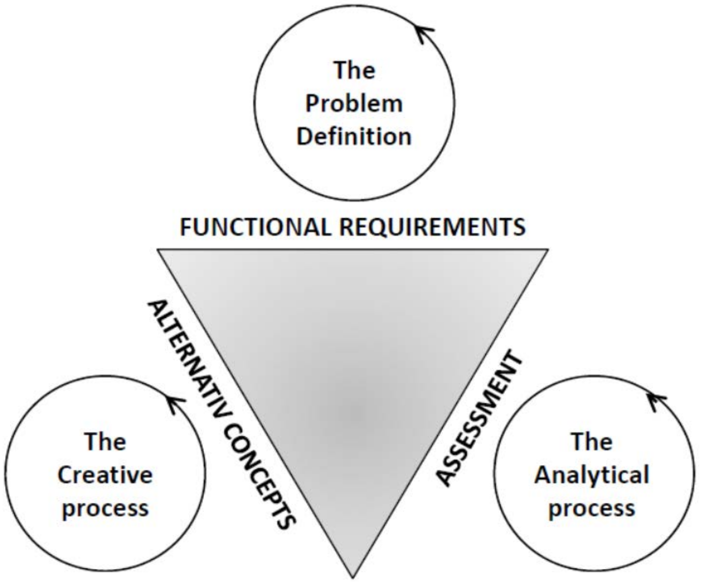
Pathway to CO_2 reduction and Case Studies

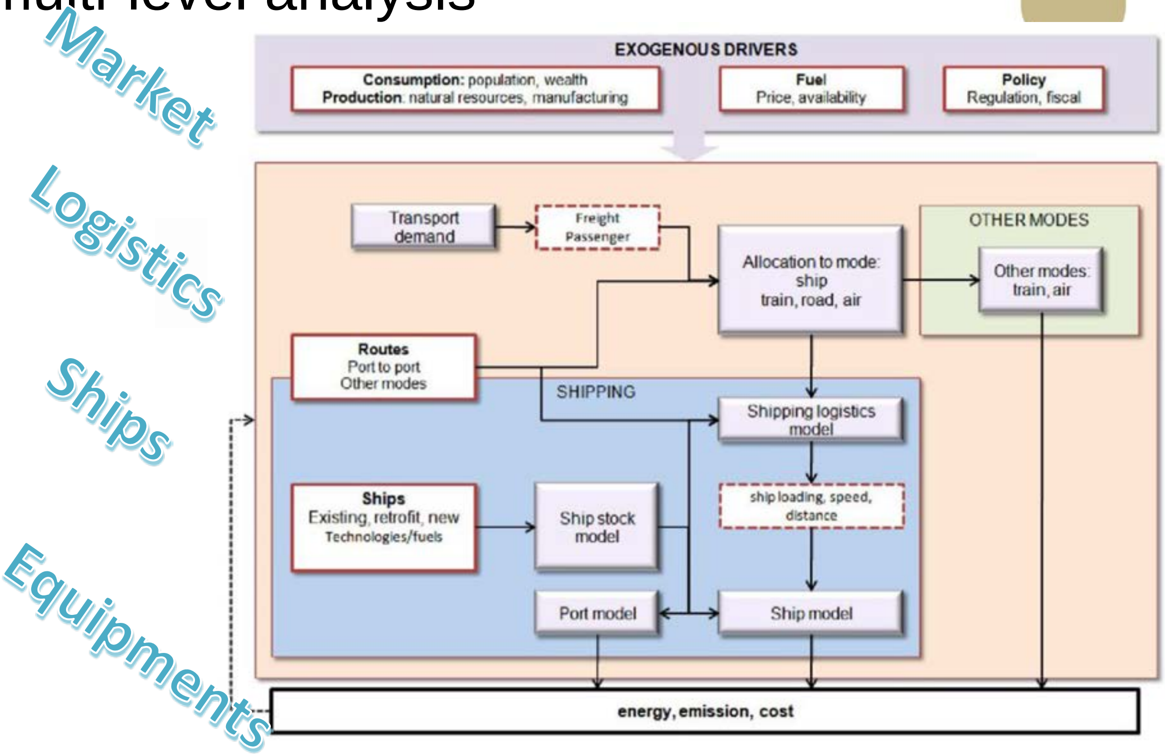
Pathway for CO_2 reduction

- Study status quo in a regular basis
  - IMO GHG Study 2000, 2009, 2014
  - EU, IMO Monitoring, Reporting and Verifiction of fuel consumption
- Develop scenarios and strategies
- Model CO_2 emissions on variousl levels
- Evaluate options
- Apply regulations and strategies

Tools for Analysis and Decision Support

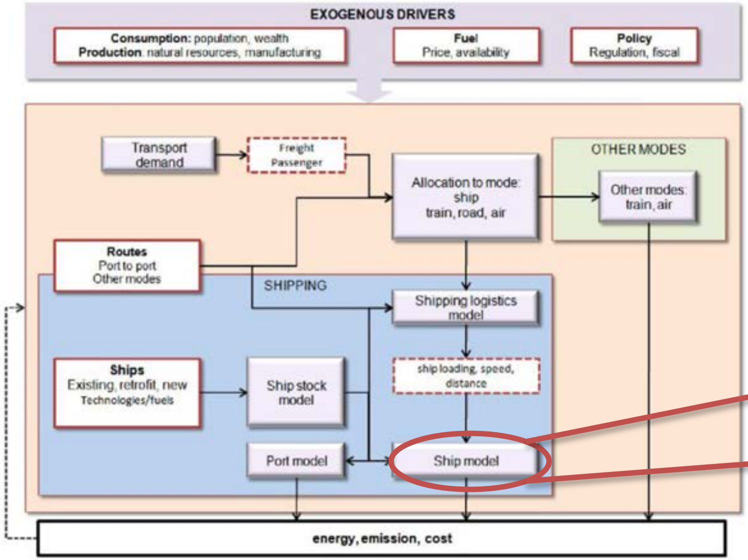
- Design thinking and multi-level analysis



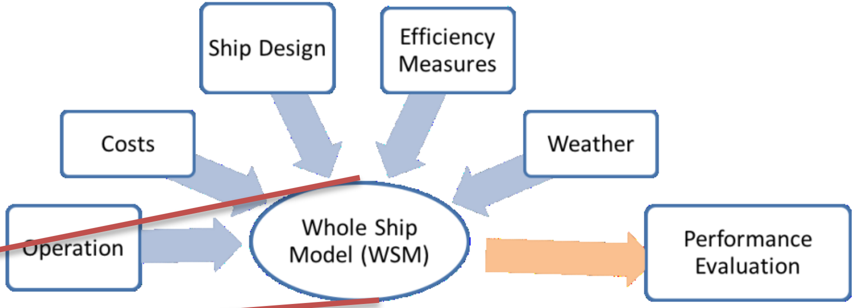


Case Studies - CO2 Emissions from International Shipping (Smith et. al, 2016)

- Models



System dynamics model



Ship Concept Model

Case Studies - CO2 Emissions from International Shipping (Smith et. al, 2016)

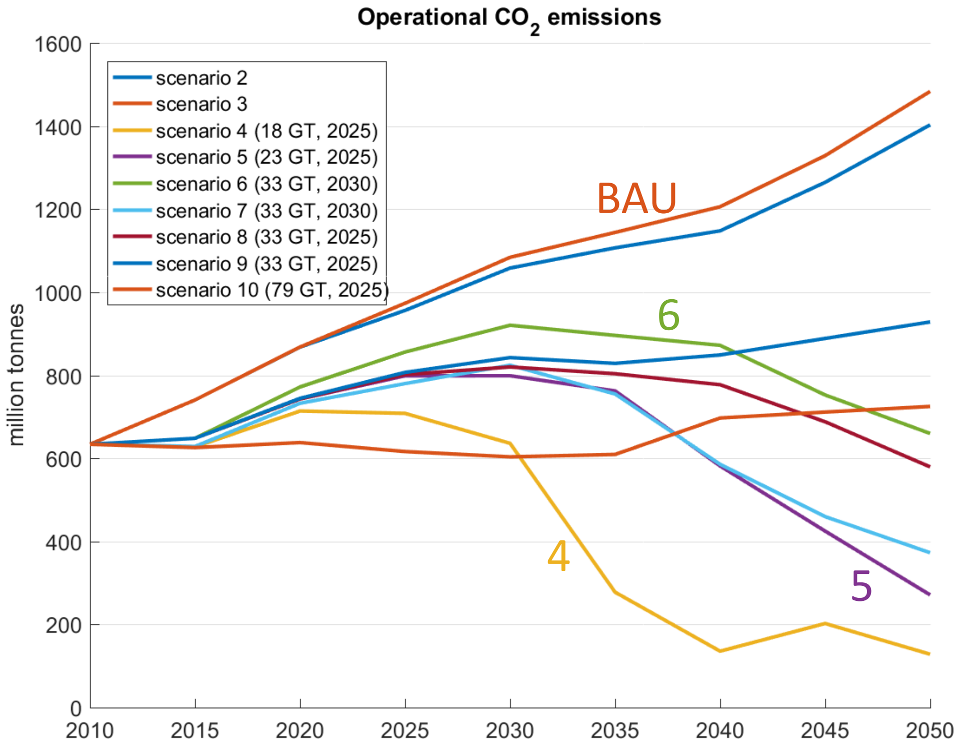
- Possible scenarios

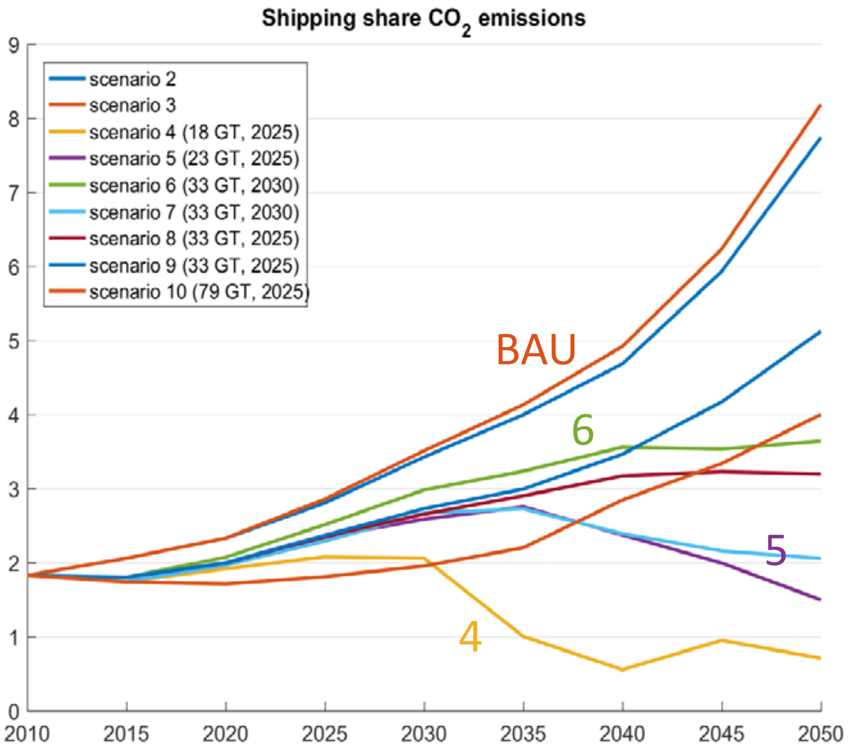
	Regulation Scenario		Techno economic						
	Fair share	Offsets	Fuel options	Fuel price	Biofuel	Speed reduct.	NPV year	Barrier	Tech. cost
BAU	-	-	All fuels except H2	2-degree price	Lower bound	Very limited	3	50%	Full
4	18GT	0	All fuels	2-degree price	Mid-range	Relaxed	3	50%	Full
5	23GT	20%	All fuels	2-degree price	Mid-range	Limited	3	50%	Full
6	33GT	20%	All fuels	2-degree price	Lower-bound	Limited	3	50%	Full

MR Tanker, Panamax BC, 5000TEU Container ship, Very Large Container ship as representative ships

Case Studies - CO2 Emissions from International Shipping (Smith et. al, 2016)

- Results





Case Studies - CO2 Emissions from International Shipping (Smith et. al, 2014)

- Conclusion
  - EEDI alone will hardly be an enough measure to meet the Paris Agreement.
  - The study recommends
    - The net emissions will need to peak in 2025
    - Absolute emission reductions should amount to 400MT by 2050
  - In order to achieve absolute emissions reduction, shipping needs to reduce its average carbon intensity by more than can be achieved through energy efficiency improvements alone

Case studies – Assessment of cost as a function of abatement options (Lindstad, 2015)

- Objective
  - Find a functional relationship between the key parameters (engine size, fuel price, annual fuel consumption in ECA area) and the additional cost for abatement options
- Method

Dataset

- Voyage profile
- Vessel performance curve
- Specific fuel consumption
- Fuel cost
- CAPEX cost for options
- Other operating cost

Models

$$C_a = C^{\mathrm{ECA}} \cdot F^{\mathrm{ECA}} + C^0 \cdot F^0 + C_v^{\mathrm{CAPEX}}$$

$$F^0 = K_f^0 \cdot \left(\sum_{\substack{i=1 \\ ,i \notin \mathrm{ECA}}}^{n} \frac{D_i}{v_i} \cdot P_i \right)$$

$$F^{\mathrm{ECA}} = K_f^{\mathrm{ECA}} \cdot \left(\sum_{\substack{i=1 \\ ,i \notin \mathrm{ECA}}}^{n} \frac{D_i}{v_i} \cdot P_i + T_{lwd} \cdot P_{\mathrm{aux}} \right)$$

$$P_i = \frac{P_s + P_w + P_a}{\eta} + P_{\mathrm{aux}}$$

Case studies – Assessment of cost as a function of abatement options (Lindstad, 2015)

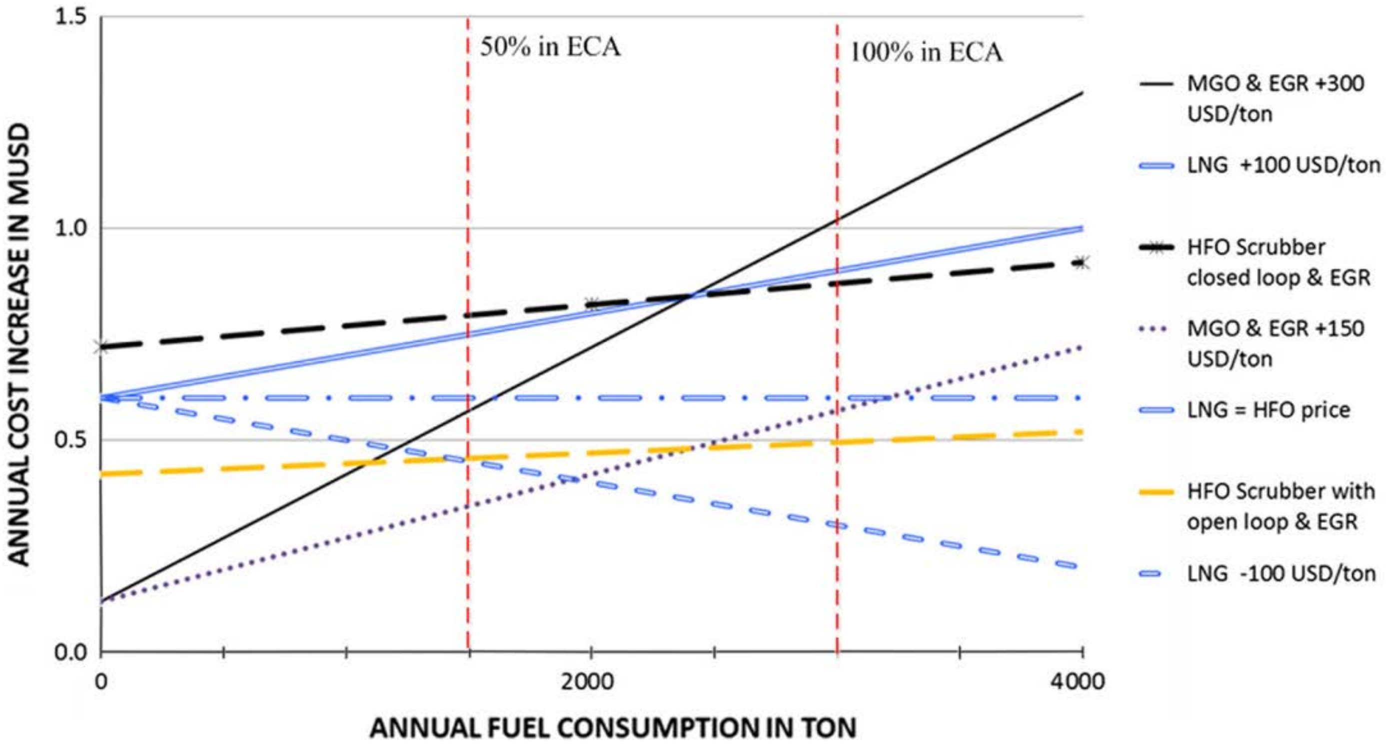
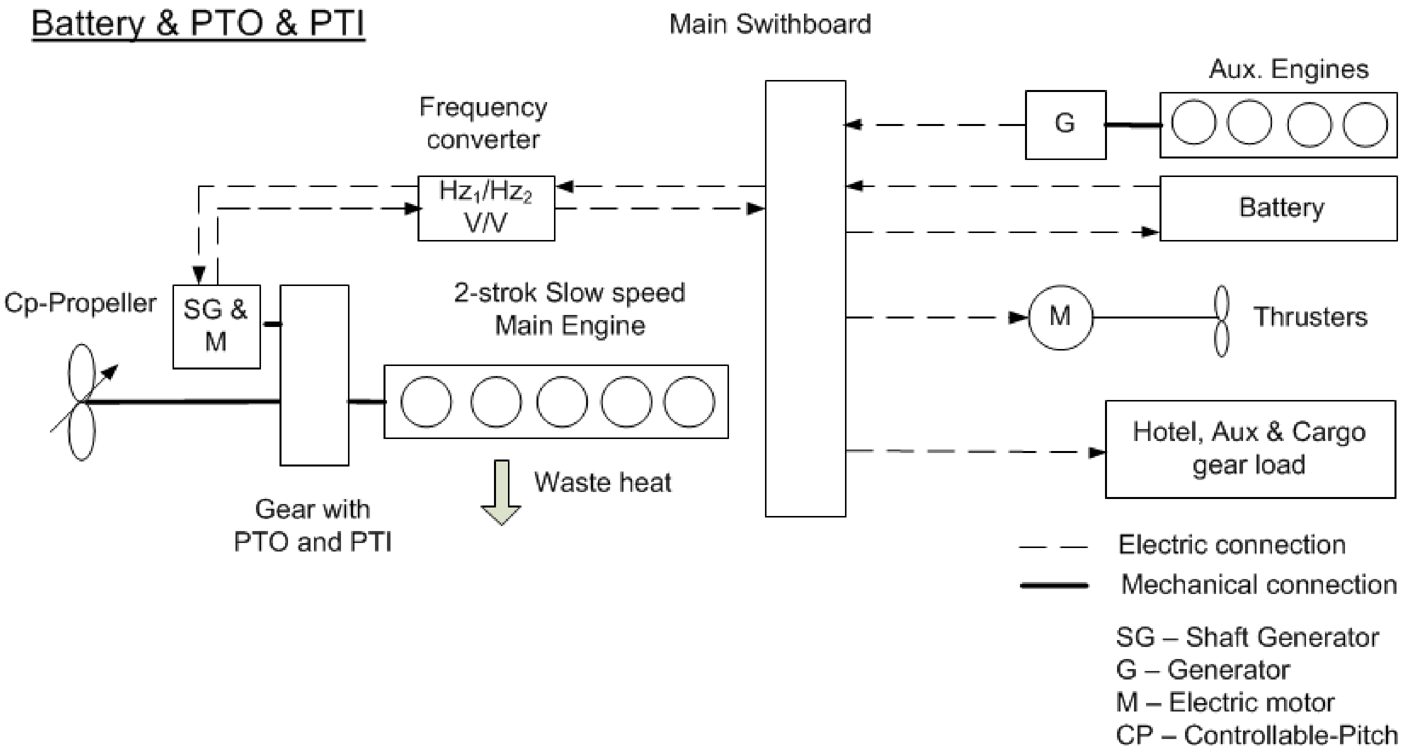


Fig. 3. New-built vessels with 4000 kW engine in Sulfur and Nitrogen ECA.

Case studies – Assessment of cost as a function of abatement options (Lindstad, 2015)

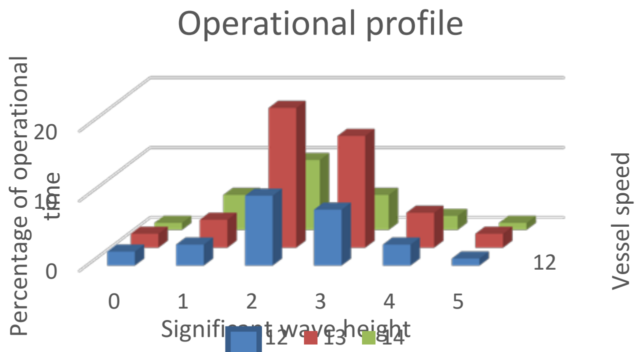
- Conclusion
  - 6 ~ 15% annual cost increase with the best abatement options
  - No single answer for the best option but a function of engine size, annual fuel consumption in ECA and future fuel price
  - Also depends on the regulations development of global sulfur cap

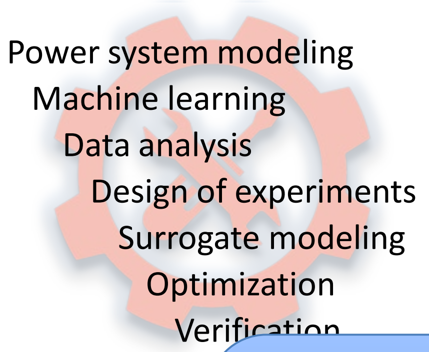
Case studies – Hybrid propulsion system for a VLCC (Alwan et. al, 2017)



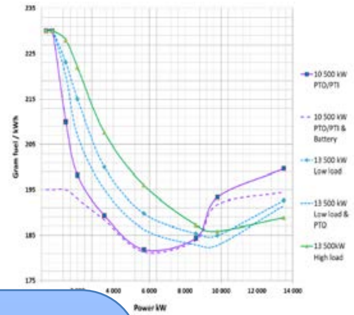
Case studies – Hybrid propulsion system for a VLCC (Alwan et. al, 2017)

Long-term Voyage simulation





Fuel/Emission Calculation



Configuration
Constraints
Objectives
Models

Design of Experiment
Dynamic Performance Simulation
Surrogate Modeling
Optimization
Verification of the result

Power System Design

Case studies – Hybrid propulsion system for a VLCC (Alwan et. al, 2017)

- Results

	Base [kg/m]	Optimum [kg/m]	P_{ME} [MW]	P_{PTI} [MW]	P_{Gen} [MW]	P_{Batt} [MW]
1	0.1641	0.1627 (↓0.85%)	24.93	1.884	1.802	1.079
2	0.1500	0.1492 (↓0.5%)	24.41	2.375	1.641	1.266
3	0.1352	0.1339 (↓0.96%)	23.93	3.554	1.239	2.606

Hs	Scenario 1	Scenario 2	Scenario 3
0 m	5%	5%	5%
1 m	10%	10%	12%
2 m	10%	20%	45%
3 m	55%	55%	28%
4 m	20%	10%	10%

Speed [kts]	Frequency Speed
9	15%
11	50%
13	20%
15	15%

Case studies – Hybrid propulsion system for a VLCC (Alwan et. al, 2017)

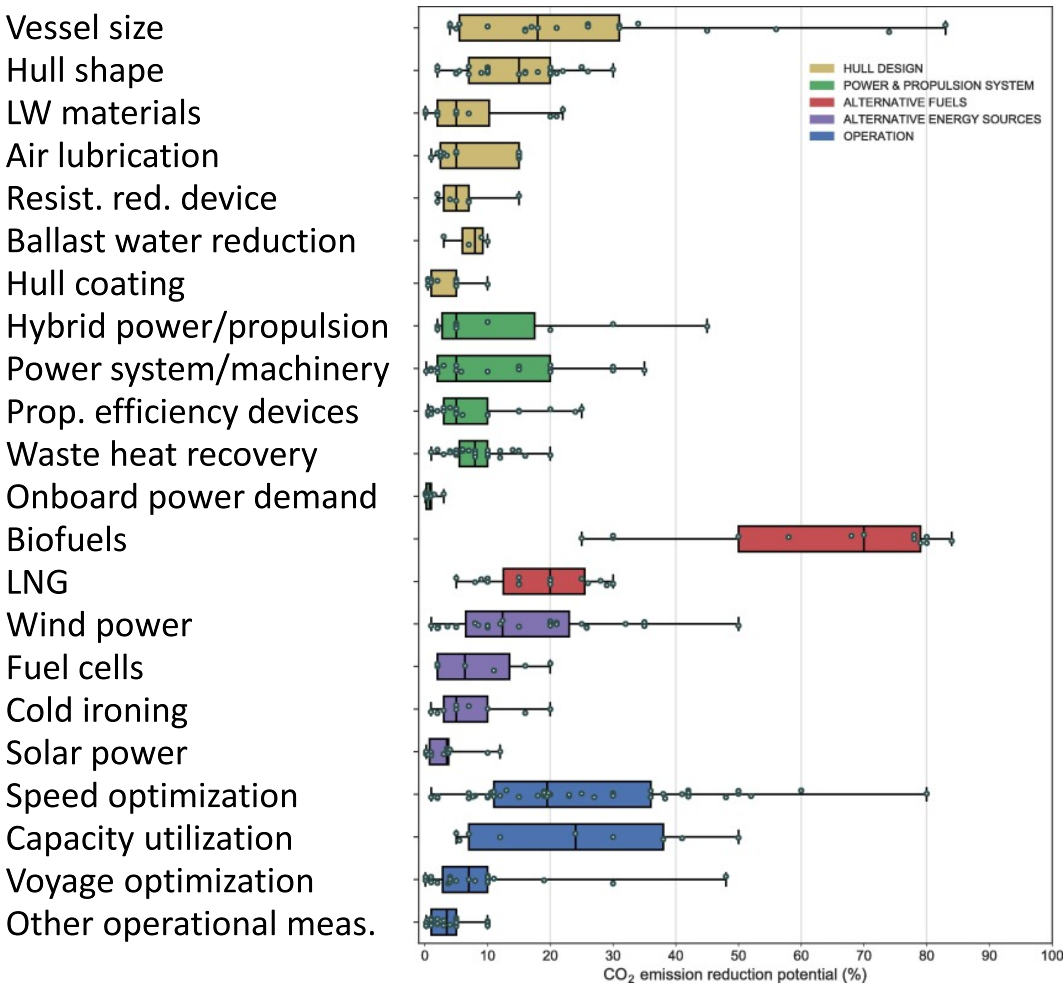
- Conclusion
  - High fidelity simulation models can be used for the design optimization using surrogate modeling framework
  - Metamodels were able to capture the complex physical behavior of the system and understanding parameters relationships
  - Demonstrated ability as a rapid design tool for testing multiple design alternatives and sharing design constraints across subsystems and system boundaries.

Summary

- Deep-sea shipping is a key resource for global economic development.
- Pollutions from the shipping have been urgent problems, and IMO regulations have effectively addressed them.
- Challenges with GHG pose more complex problems with high uncertainties in a long horizon.
- Design thinking and decision support tools with capability of multi-level analysis are necessary to solve the problems.

It is possible to reduce emissions per freight transport unit by 75% and above up to 2050

Bouman, E. A., Lindstad, E., Rialland, A. I., & Strømman, A. H. (2017). State-of-the-art technologies , measures , and potential for reducing GHG emissions from shipping – A review. *Transportation Research Part D*, *52*, 408–421.



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Thank you for your attention.

Questions?