SOx regulation - Intended and unintended consequences

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SINTEF

Outline of presentation

- Development of GDP, trade, energy consumption and maritime transport 1970 – 2012
- Shipping emissions and legislation
- The climate effect from shipping
- Hybridization might reduce the environmental problems with low power operations
- Assessment of cost as a function of abatement options in maritime emission control areas.
- Continued use of Heavy Fuel Oil at high seas might maintain the cooling effect of shipping and maritime transport

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Routledge
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Opportunities for increased profit and reduced cost and emissions by service differentiation within container liner shipping

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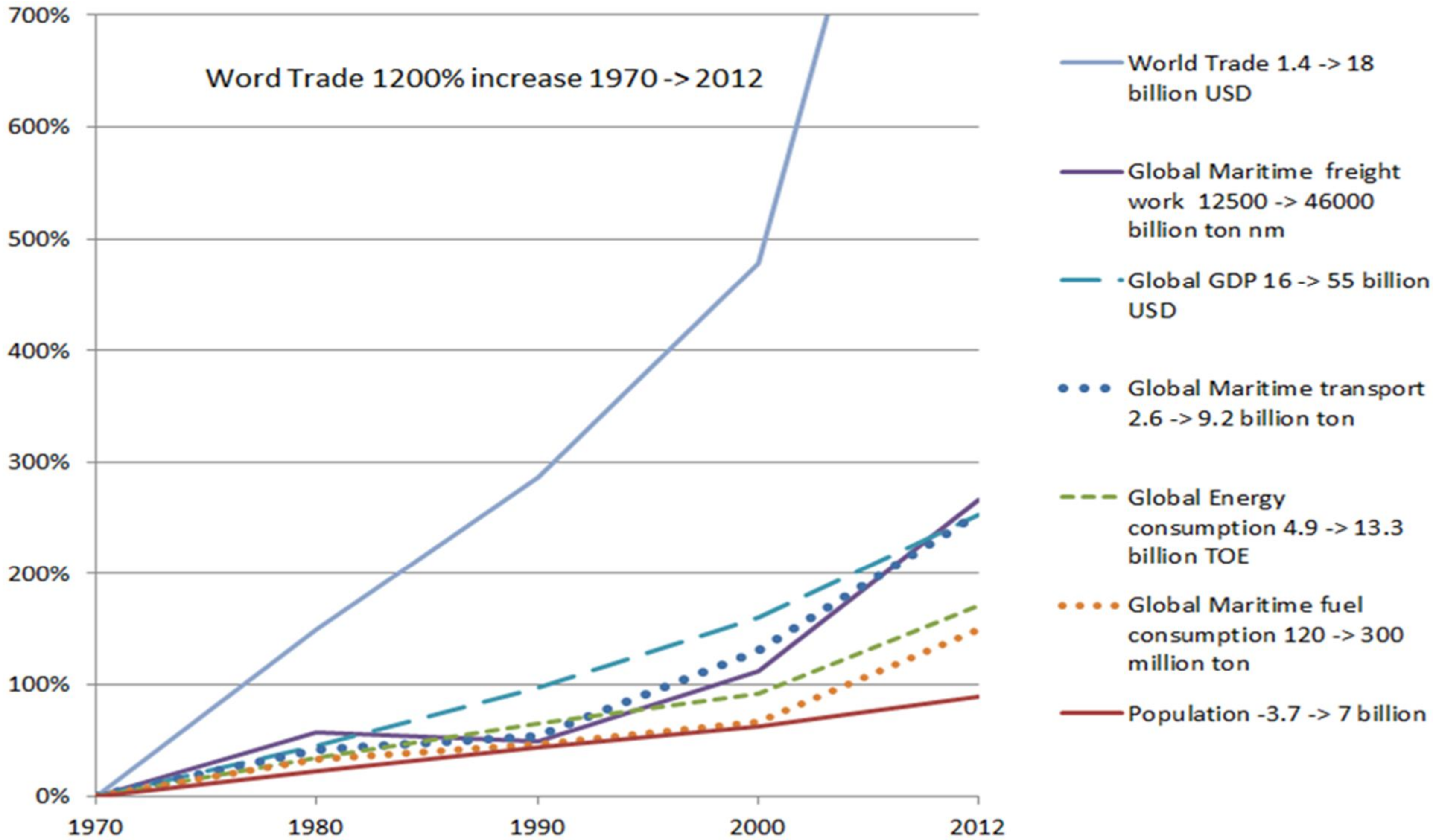
This paper investigates opportunities for increased profit and reduced emissions and cost by service differentiation within container shipping. Traditionally the strategy among the container lines has been profit maximization by utilizing economies of scale through the building of larger and faster vessels. In 2008, the financial crisis in combination with higher fuel prices put an end to this progress and in today's market operators are basically trying to survive by providing standardized services at the lowest possible cost. This study investigates alternative strategies and the results indicate that container lines should provide two different services instead of one

Globalization: fuel consumption in maritime transport has increased less than ton-miles, less than tons moved, and less than world trade, however the main source of the reduction is economies of scale



Source: UNCTAD 2014; IEA 2014; Lindstad 2013; Eskeland and Lindstad 2015

Global fleet 2007 – 2012 (IMO 2014 & IMO 2009 GHG Study)

Vessel type	Number of vessels 2007	Number of vessels 2012	Average vessel size in dwt 2007	Average vessel size in dwt 2012	Design Speed 2007	Design Speed 2012	Average Speed 2007	Average Speed 2012	CO2 2007 IMO 2009 GHG-Study	CO2 2007	CO2 2012	Change in CO2 2007 - 2012
			ton	ton	knots	knots	knots	knots	ton	ton	ton	%
Dry Bulk	7 523	10 395	52 500	68 600	14.1	14.8	12.2	11.5	170 000	179 000	166 000	-7%
General Cargo	17 280	16 486	4 600	5 300	12.1	12.5	10.0	9.3	93 000	100 000	70 000	-30%
Container	4 398	5 132	34 200	41 600	20.3	21.3	16.3	14.6	241 000	206 000	205 000	
Reefer	1 226	1 090	5 400	5 700	16.2	16.2	16.3	13.4	19 000	20 500	18 000	-12%
RoRo & Vehicle	2 410	2 585	7 200	7 600	16.3	16.3	15.0	15.0	42 000	56 000	56 000	
OilTanker-mainly crude > 80' dwt	1 569	1 991	176 500	183 500	15.5	15.7	13.8	11.9	91 000	106 000	80 000	-25%
OilTankers-mainly product < 80'dwt	5 390	5 404	9 800	13 300	12.3	12.4	10.6	9.4	54 000	44 000	45 000	2%
Chemicals	3 868	4 935	15 800	18 000	13.4	13.6	12.1	11.1	53 000	58 000	55 000	-5%
LNG & LPG	1 368	1 612	22 800	27 600	14.9	15.6	13.1	12.9	38 000	32 000	50 000	56%
RoPax	2 784	2 867	1 400	1 600	17.9	16.6	13.8	10.7	61 000	46 000	32 000	-30%
Totals Cargo Vessels	47 816	52 497	22 500	30 800	14.1	14.6	12.0	11.1	862 000	847 500	777 000	-8%
Ferry-Pax only	3 019	3 152	100	170	23.5	22.6	18.7	13.8	17 000	19 200	12 000	-38%
Cruise	489	520	3 200	3 700	17.0	17.2	12.5	12.0	19 000	34 000	35 500	4%
Yacht	1 162	1 750	80	170	17.1	16.5	12.6	10.7	2 500	3 300	3 500	6%
Offshore	5 204	6 480	1 600	1 700	13.4	13.8	9.7	8.0	20 000	36 000	28 000	-22%
Service	17 808	18 064	490	540	12.0	12.0	8.7	7.5	52 000	53 600	34 000	-37%
Fishing	23 643	22 130	240	180	11.8	11.5	9.7	7.4	63 000	86 100	51 500	-40%
Other	1 169	3 008	1 100	60	11.3	12.7	8.7	7.3	10 500	15 300	7 500	-51%
Totals Other Vessels	52 494	55 104	480	530	12.9	12.9	10.0	8.1	184 000	247 500	172 000	-31%
Totals All Vessels	100 310	107 601	11 000	15 300	13.5	13.7	10.9	9.5	1046 000	1095 000	949 000	-13%

Key fleet and operational drivers 2007-2012 – Own analysis to understand the IMO 2014 GHG study

Vessel type	Average vessel size in dwt		Freight work		Market share of freight work		DWT Capacity increase at equal speeds 2007-2012	Emission change due to reduced sea speeds	Emission change due to EOS	Emission Change due to change of fleet mix	CO2 - per ton nm		Change in CO2 per ton nm 2007 - 2012	Change in CO2 if operated at design speed 2007 - 2012
	2007	2012	2007	2012	2007	2012					2007	2012		
	ton		Billion ton nm								Gram/ton nm			
Dry Bulk	52 500	68 600	16 000	20 000	39.0%	41.7%	81%	-12%	-8.5%		10.4	8.4	-19%	1%
General Cargo	4 600	5 300	2 400	2 300	5.9%	4.8%	2%	-14%	-4.6%		36.5	30.0	-18%	2%
Container	34 200	41 600	7 500	9 000	18.3%	18.8%	42%	-20%	-6.3%		30.5	23.0	-25%	3%
Reefer	5 400	5 700	250	225	0.6%	0.5%	-6%	-32%	-1.8%		121.2	80.4	-34%	-2%
RoRo	7 200	7 600	500	550	1.2%	1.1%	13%	0%	-1.8%		101.6	99.8	-2%	-2%
OilTanker-mainly crude > 80' dwt	176 500	183 500	9 500	10 000	23.2%	20.8%	32%	-26%	-1.3%		10.9	8.0	-27%	1%
OilTankers-mainly product < 80'dwt	9 800	13 300	1 700	2 000	4.1%	4.2%	36%	-21%	-9.7%		31.4	22.3	-29%	-9% (1)
Chemicals	15 800	18 000	1 900	2 300	4.6%	4.8%	45%	-15%	-4.2%		30.0	24.3	-19%	-1%
LNG & LPG	22 800	27 600	1 100	1 500	2.7%	3.1%	43%	-3%	-6.2%		36.6	33.4	-9%	3%
RoPax	1 400	1 600	150	125	0.4%	0.3%	18%	-40%	-4.3%		439.2	252.8	-42%	-18% (2)
Totals Cargo Vessel	22 500	30 800	41 000	48 000	100%	100%	50%	-16%	-5.5%	-4.5%	20.7	16.2	-25%	

(1) 35 % increase in size (2) 25 % decrease of average speed

Shipping represents a significant share of the global NOx and the SOx emissions

- Measured in million ton
  - CO_2 1 050 (2007) – 950 (2012)
  - NOx 25 (2007) – 19 (2012)
  - SO_2 15 (2007) – 11 (2012)

- Measured as % of global total
  - NOx 12.5% (2007) – 15% (2012)
  - SO_2 7% (2007) – 13% (2012)
  - CO_2 3.3% (2007) – 2.7%(2012)

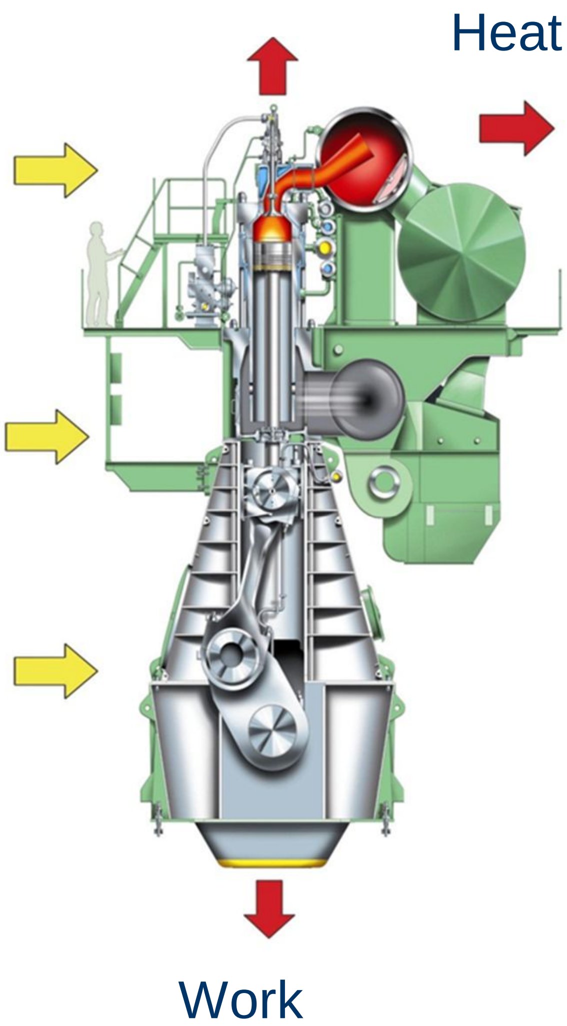
Sources - IMO 2009 GHG study: and IMO 2014 GHG study

Basic Combustion engine – and input and output when engine is adjusted to produce power without any focus on emissions

Air
8.5 kg/kWh
21% O_2
79% N_2

Fuel
175 g/kWh
97% HC
3% S

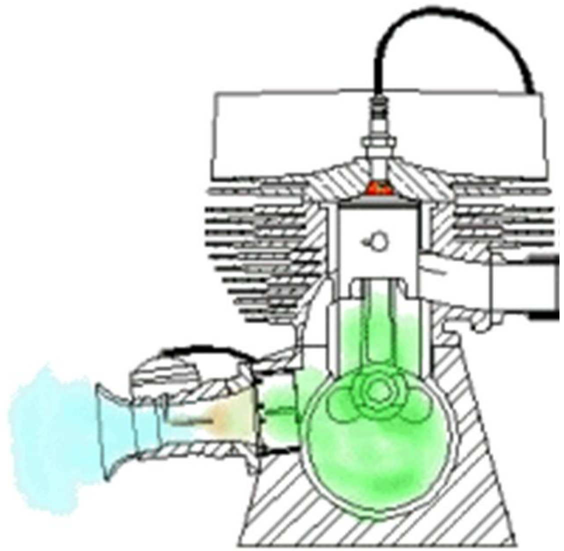
Lube
1 g/kWh
97% HC
2.5% CA
0.5% S



Exhaust gas
75.8% N_2
13.0% O_2
5.35% H_2O
94.15% in Subtotal

5.2% CO_2
0.25% NOx = 22 g/kwh (Tier 1 =17)
0.15 % SO_2
0.045 % HC
0.015 % CO
5.66 % in Subtotal

BC - Black Carbon
$PM_{2.5}$ - Particles
Other
0.19 % in Subtotal



Source: Input figures and drawing from Man B & W, animation from wikipedia.org

Current Emissions regulation (MARPOL annex VI)

- Current emissions regulations provide limits for SOx and NOx, for health and environmental reasons (Tier I,II,III) , Sulphur ECA and for CO_2 to mitigate global warming (EEDI)
- Counterintuitively, the NOx and the SOx emissions mitigate against global warming , while the unregulated emissions, i.e. BC and CH_4 contribute to global warming.
- From an environmental viewpoint one of the challenges with the current IMO legislation is that it assumes medium to high power operations under test bench conditions

Global Warming Potential – CO2 eq.

- Since the impact of each emission species depends strongly on where a vessel operates, region-specific Global Warming Potential (GWP) characterizations are needed to more accurately quantify the climate impact of each emission species.
- Emission metrics such as GWP, with emission impacts expressed as "*CO_2 equivalents*" have become the common currency to benchmark and communicate the relative and absolute contributions to climate change of emissions of different substances (Shine, 2009).
- The GWP integrates radiative forcing from a pulse up to the chosen time horizon which in a sense constitutes a memory of the earlier short lived forces.
- GWP is usually integrated over 20, 100 or 500 years consistent

The climate effects from shipping arise from

- CO_2 including CO which has a warming effect
- CH_4 which has a warming effect
- BC which has a warming effect
- N_2O which has a warming effect
- NO_x, which results in the production of tropospheric O_3 (positive RF) and a reduction of ambient $CH_{4,}$ which has a cooling effect
- SOx (sulphate particles) which has a cooling effect
- OC which has a cooling effect
- Formation or change in low-level clouds which has a cooling effect

Source: Source:, IPCC 2013. *FIFTH ASSESSMENT REPORT OF THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE*. www.ippc.ch; *IMO 2009 GHG study*

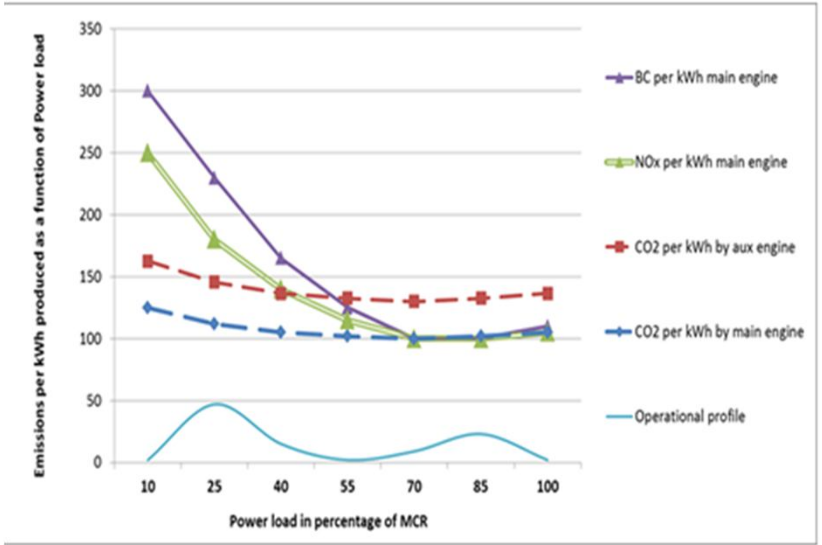
Global Warming Potential (kg-CO2-equivalents)

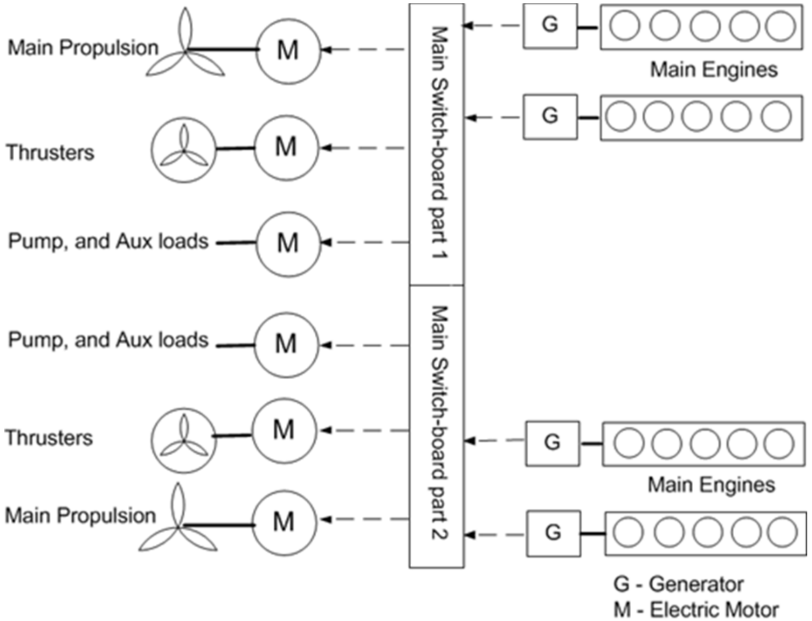
Emission type	CO_2	BC	CH_4	CO	N_2O	NOx	SO_2	OC
GWP_{20} World factors	1	1200	85	5.4	264	-15.9	-141	-240
GWP_{20} Arctic factors	1	6200	85	5.4	264	-31	-47	-151
GWP_{100} World factors	1	345	30	1.8	265	-11.6	-38	-69
GWP_{100} Arctic factors	1	1700	30	1.8	265	-25	-13	-43

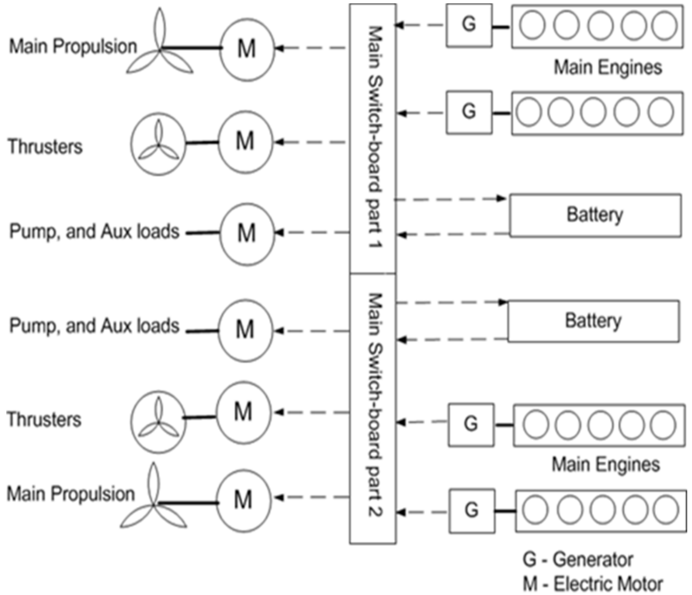
Source:, IPCC 2013. *FIFTH ASSESSMENT REPORT OF THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE.* www.ippc.ch

Hybridization is one option to partly solve the environmental problem with low power operations

Emissions as a function of power outake

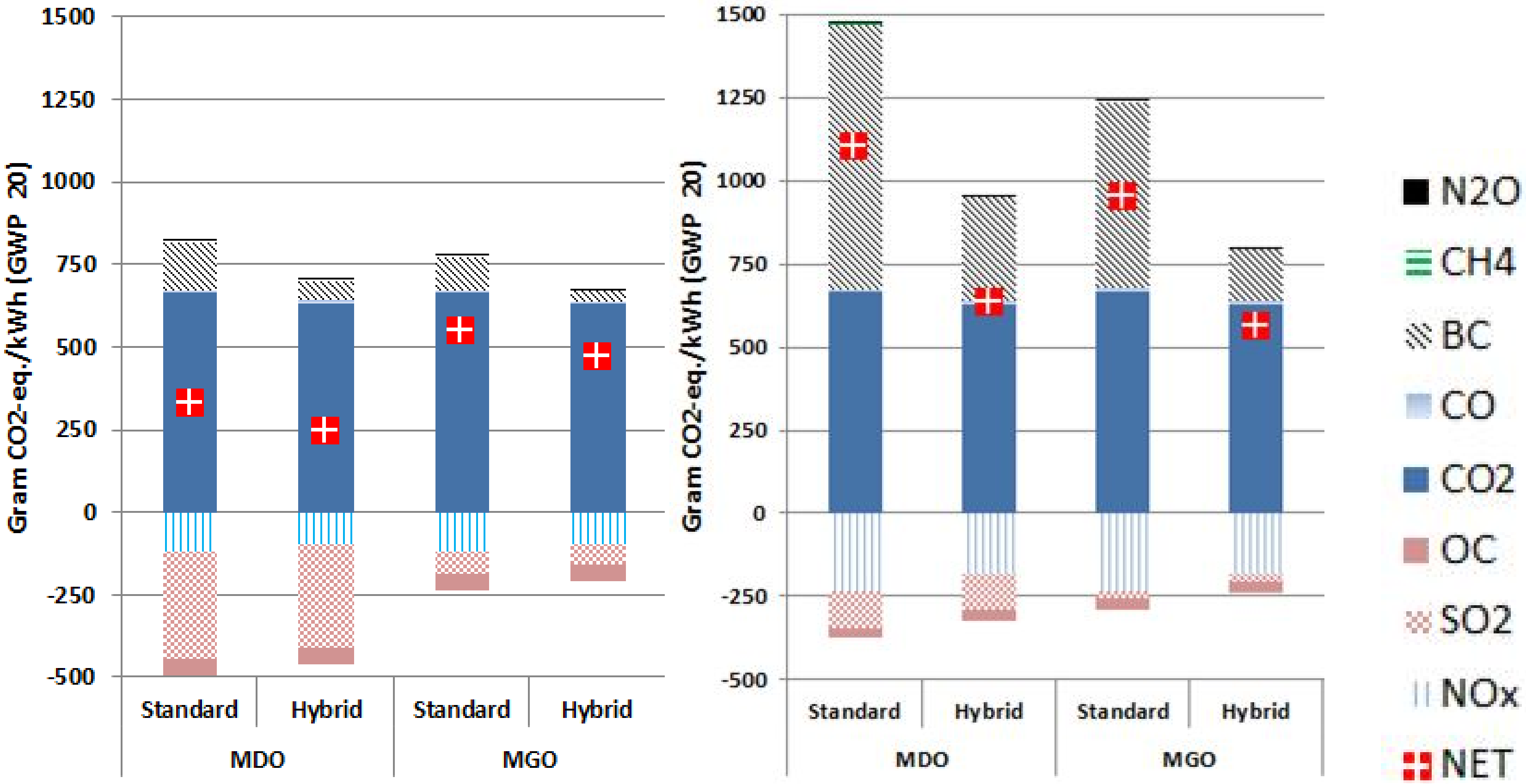






Source: Lindstad, H., Sandaas, S. 2014 Emission and Fuel Reduction for Offshore Support Vessels through Hybrid Technology. SNAME Convention, Conference proceedings, Houston, Oct. 2014.

CO2 eq. emissions
North Sea & Gulf of Mexico versus Arctic



Source: Lindstad, H., Sandaas, S. 2014 Emission and Fuel Reduction for Offshore Support Vessels through Hybrid Technology. SNAME Convention, Conference proceedings, Houston, Oct. 2014.

Assessment of cost as a function of abatement options in maritime emission control areas

(Accepted For publication in Transportation Research Part D)

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ABSTRACT

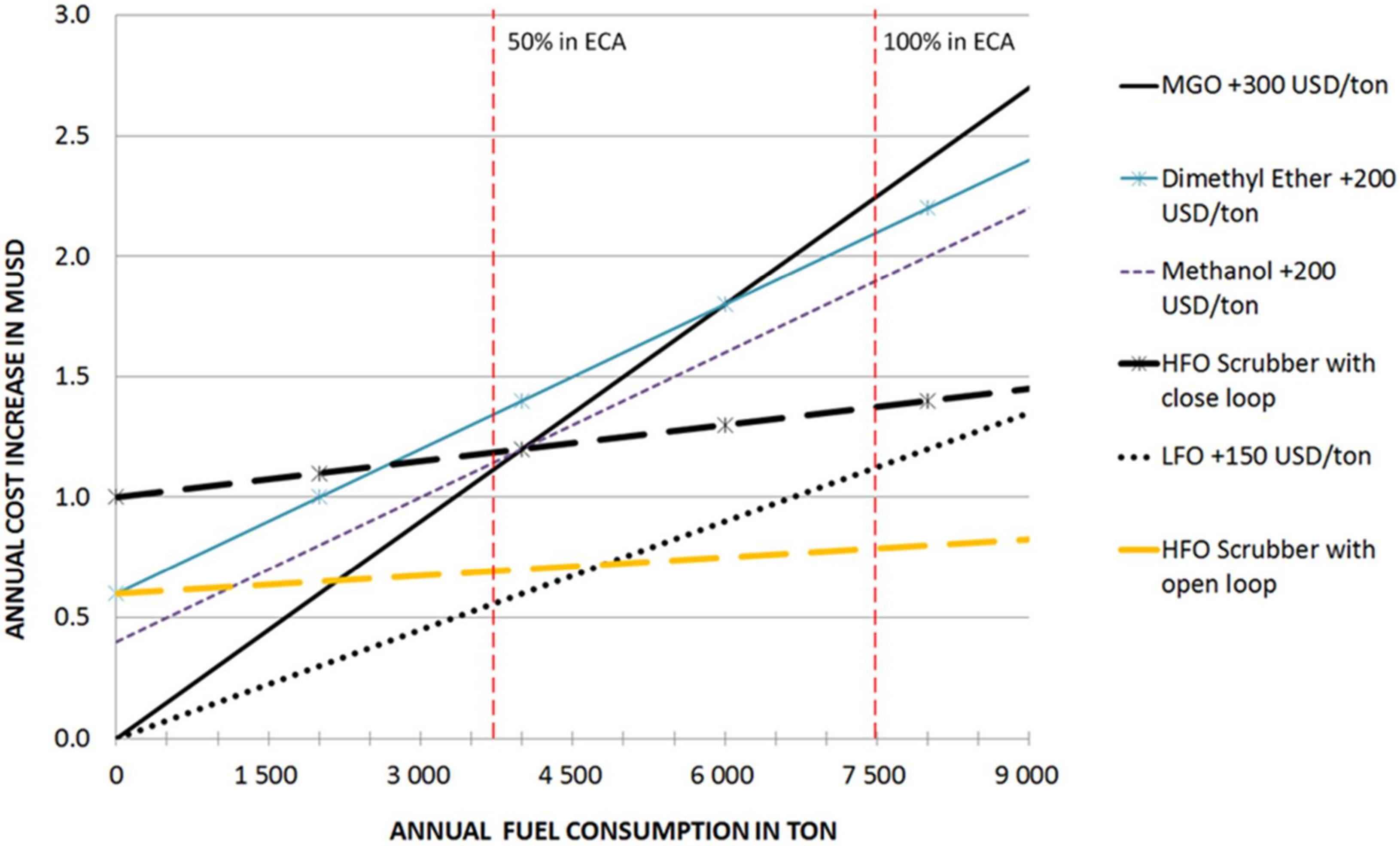
This paper assesses cost as a function of abatement options in maritime emission control areas (ECA). The first regulation of air pollutions from ships which came into effect in the late 1990's was not strict and could easily be met. However the present requirement (2015) for reduction of Sulphur content for all vessels, in combination with the required reduction of nitrogen and carbon emissions for new-built vessels, is an economic and technical challenge for the shipping industry. Additional complexity is added by the fact that the strictest nitrogen regulations are applicable only for new-built vessels from 2016 onwards which shall enter US or Canadian waters. This study indicates that there is no single answer to what is the best abatement option, but rather that the best option will be a function of engine size, annual fuel consumption in the ECA and the foreseen future fuel prices. However a low oil price, favors the options with the lowest capex, i.e. Marine Gas Oil (MGO) or Light Fuel Oil (LFO), while a high oil price makes the solutions which requires higher capex more attractive.

Assessment of cost as a function of abatement options in maritime emission control areas

	Investment cost in million USD (*)		Annual cost increase in million USD			
	12 000 kW power	4 000 kW power	12 000 kW power	4 000 kW power	Fuel price per ton	Additional cost per ton of fuel
MGO high HFO					300	
MGO low HFO					150	
EGR	1.0	1.0	0.12	0.12		
Scrubber open loop	3.0	2.5	0.36	0.30	0	25
Scrubber closed loop	5.0	4.5	0.60	0.54	0	50
LNG (HFO + 100)					100	
LNG (HFO - 0)	9.0	5.0	1.08	0.60	0	
LNG (HFO - 100)					-100	
Methanol	2.0	1.0	0.24	0.12	200	
Methanol conversion to DME	3.0	2.0	0.36	0.24	200	

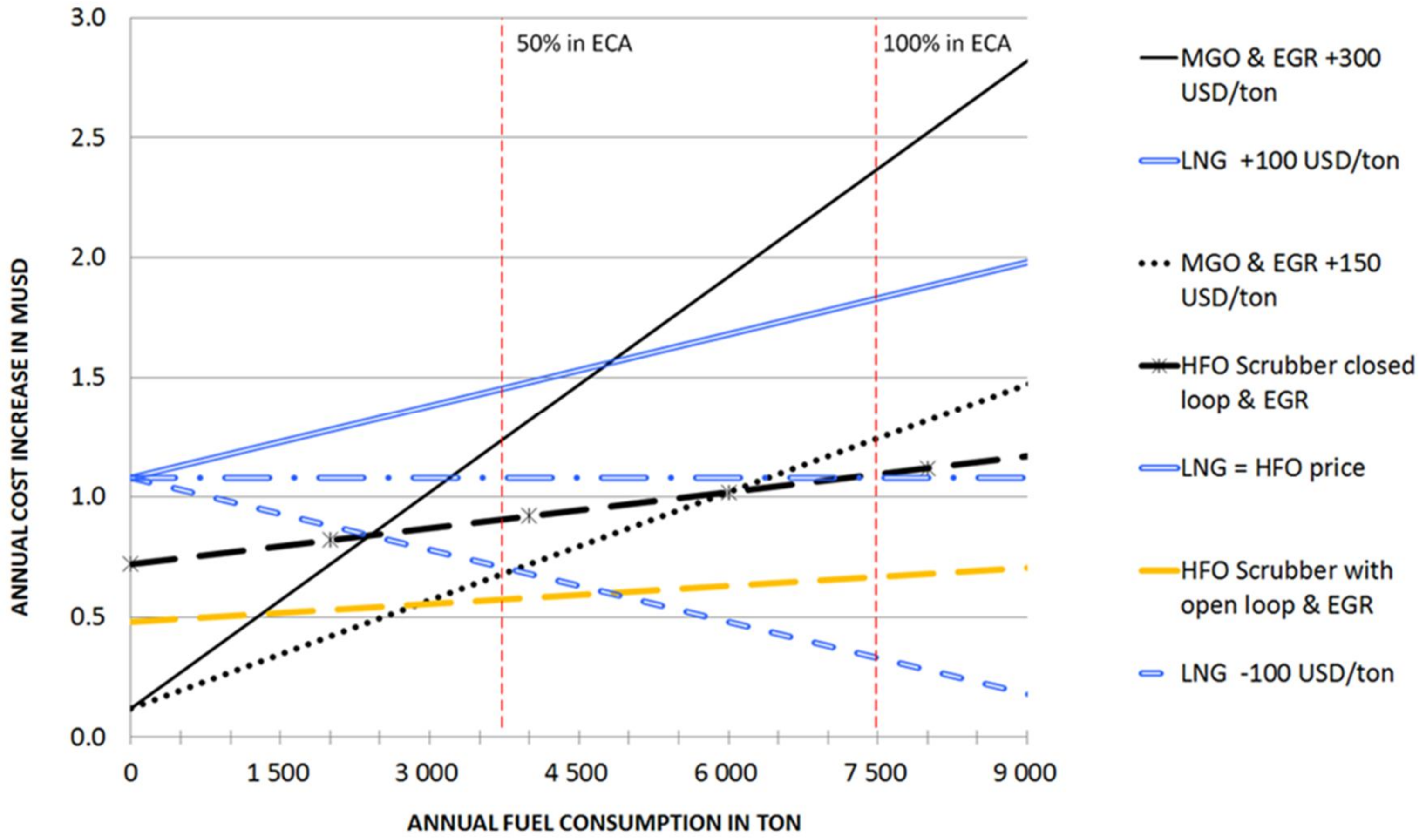
(*) Cost figures based on (DNV, 2013; Einang 2011; Hennie 2012; Man Diesel 2013; Norwegian NOx fond 2014; Ramne, 2011; World maritime news, 2013; Ongoing building projects.

Existing vessels with 12 000 kW engine



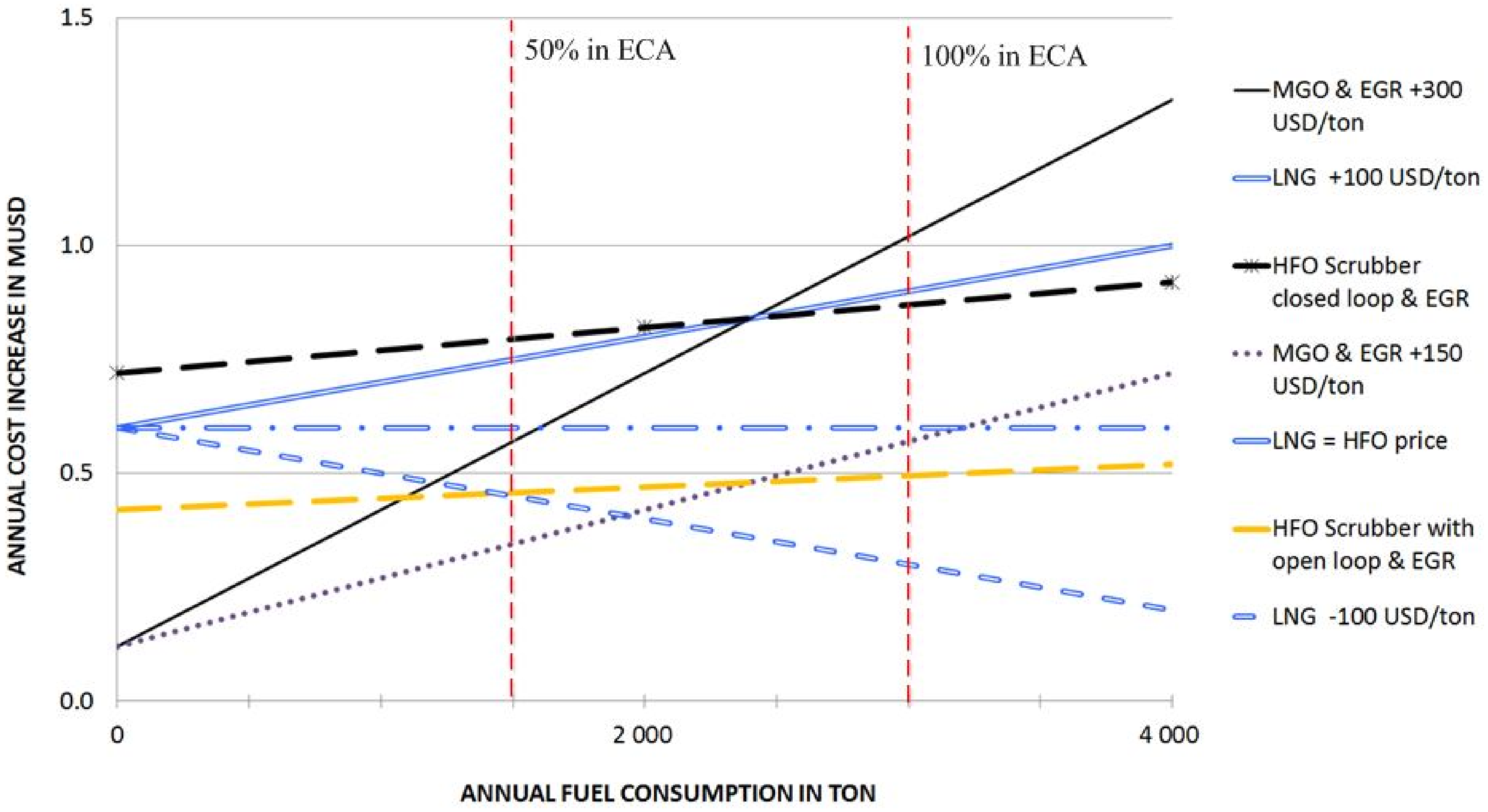
Source: Lindstad, H., Sandaas, I., Strømman, A.H., 2015 *Assessment of cost as a function of abatement options in maritime emission control areas*. Accepted for publication in Transportation Research Part D

New-built vessels with 12 000 kW engine in Sulphur and Nitrogen ECA



Source: Lindstad, H., Sandaas, I., Strømman, A.H., 2015 *Assessment of cost as a function of abatement options in maritime emission control areas*. Accepted for publication in Transportation Research Part D

New-built vessels with 4 000 kW engine in Sulphur and Nitrogen ECA



Source: Lindstad, H., Sandaas, I., Strømman, A.H., 2015 *Assessment of cost as a function of abatement options in maritime emission control areas*. Accepted for publication in Transportation Research Part D

Maritime Shipping and Emissions: A three-layered, damage based approach

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ABSTRACT

An important idea is to shift the policy emphasis in ship design from idealized towards realistic vessel operating conditions. The traditional approach to reducing shipping emissions, based on technical standards, tends to neglect how damages and abatement opportunities vary according to location and operative conditions. Since environmental policy originates in damages relating to ecosystems, and jurisdictions, a three-layered approach is 'natural'; in port, in coastal areas possibly defining an Emission Constraint Area (ECA as in North America or Nordic/Baltic), and open seas, globally. *

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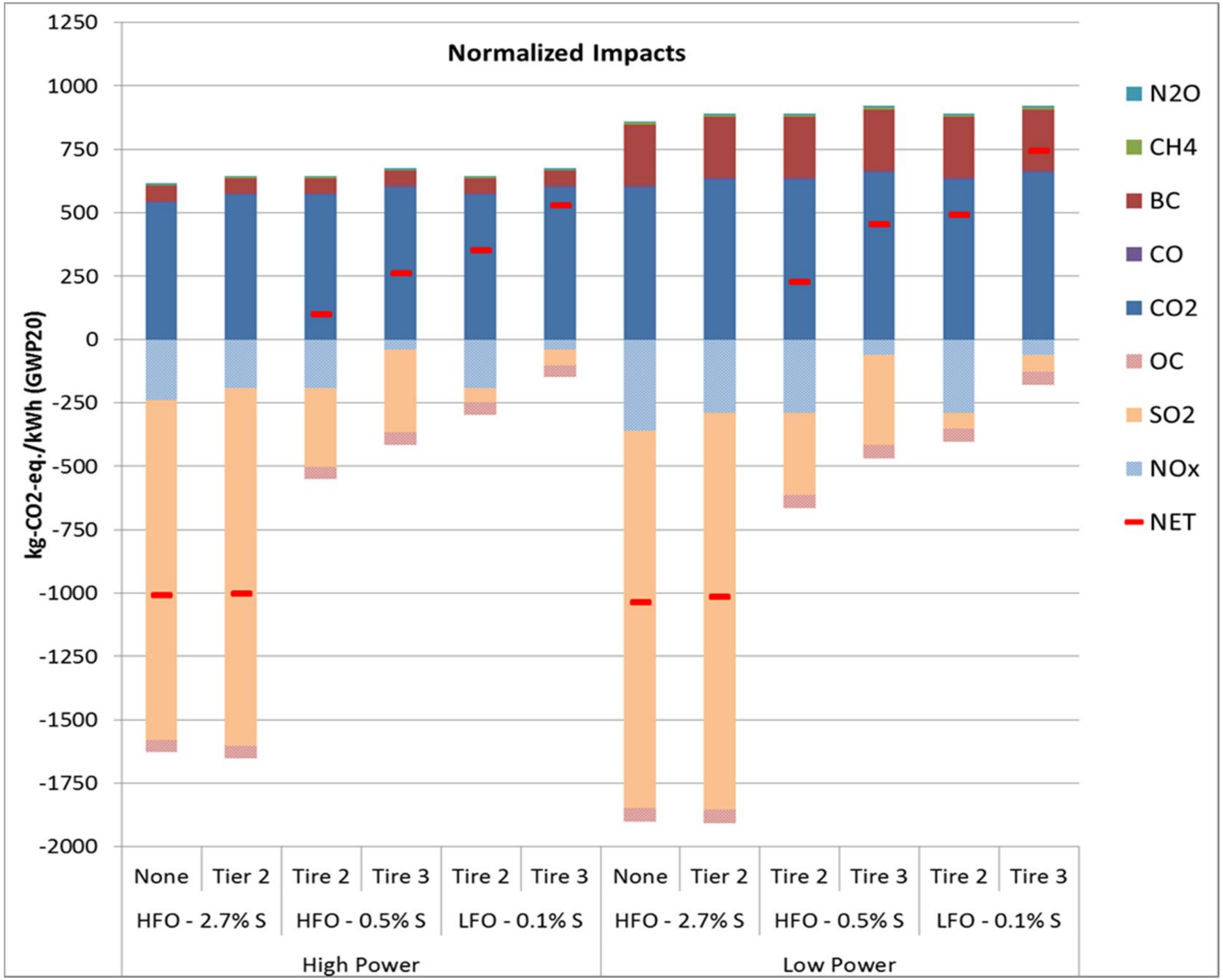
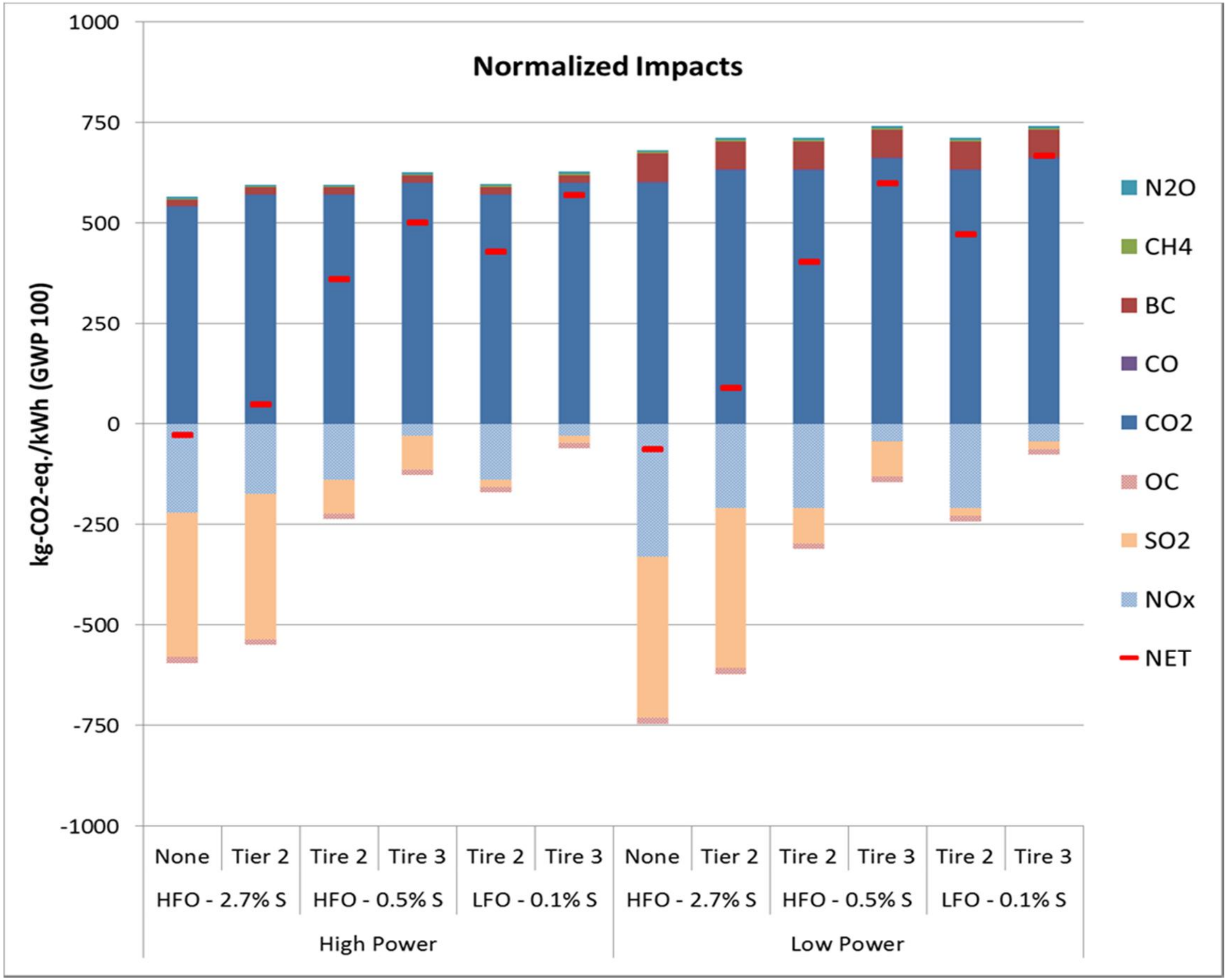
Lindstad, H., Eskeland. G., Psaraftis, H., Sandaas, I., Strømman, A., H., 2015 Maritime Shipping and Emissions: A three-layered, damage based approach. Submitted to Ocean Engineering Journal

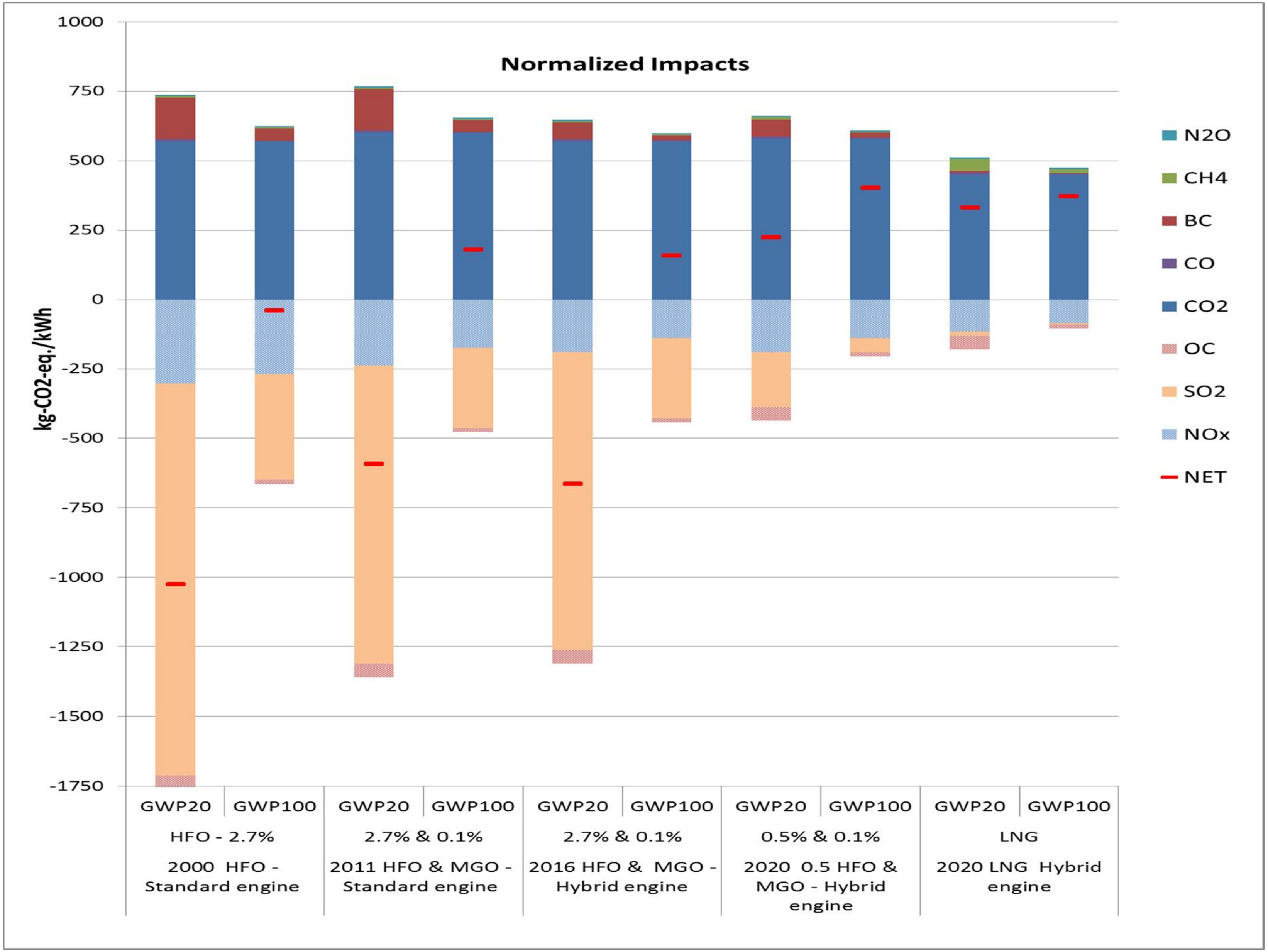
CO2 eq. based on a 20 year time frame (GWP_{20}) per 1000 kWh as a function of power, fuel, and operational area



CO2 eq. based on a 100 year time frame (GWP_{100}) per 1000 kWh as a function of power, fuel, and operational area



Average Global warming impact over 20 and 100-year horizon in kg CO_2-equivalents per 1000 kWh produced (25 % of distance in ECA)



Annual figures for a 17 000dwt vessel with 7 500 kW engine in North Atlantic trades (4000 nm of which 1000nm in ECA)

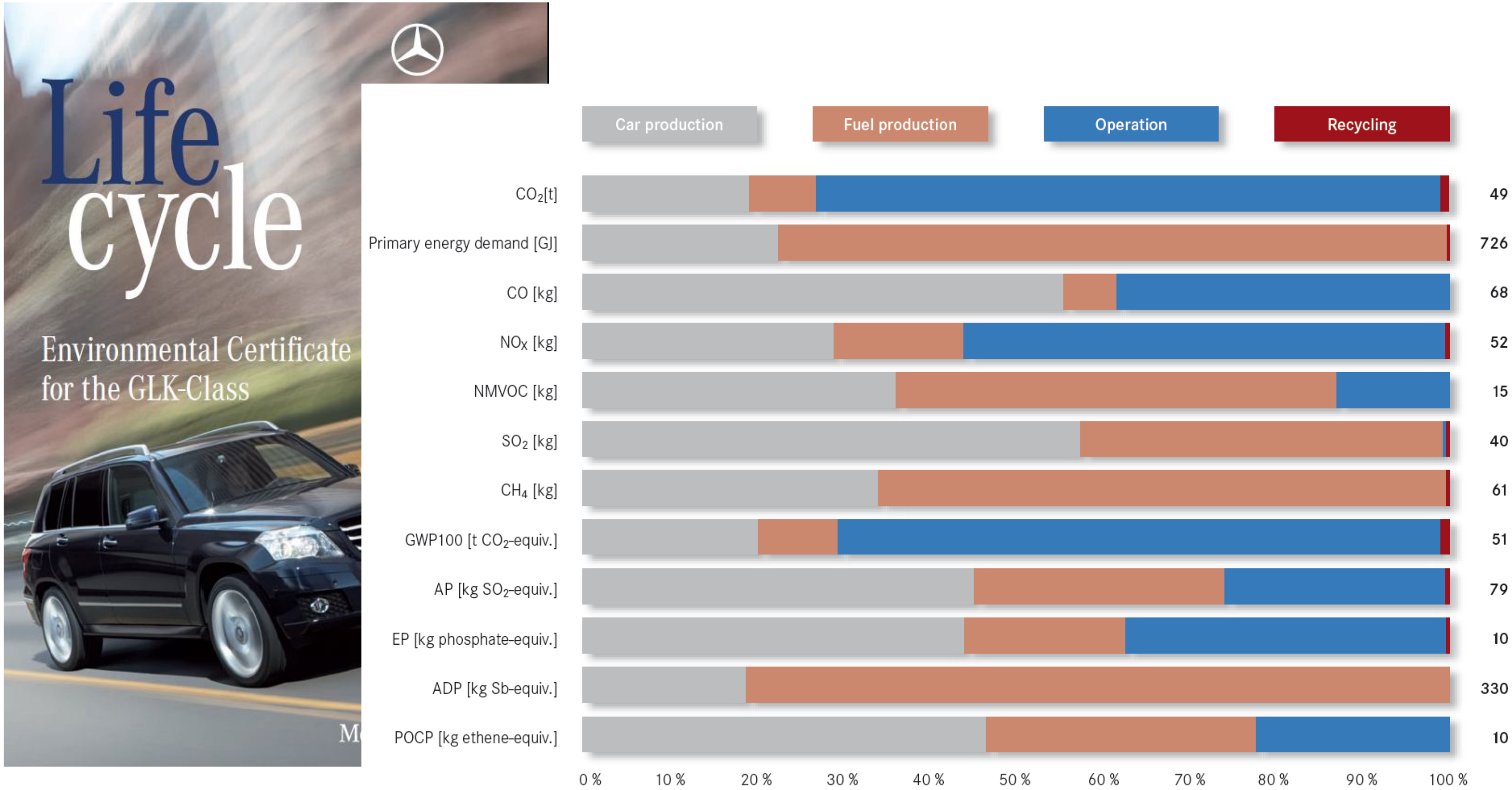
Engine Setup	Built Year	Fuel	Region	NOx Tier	Fuel in ton per voyage	Annual fuel cost 2015	Fuel Cost Increase	GWI_{20} in kg per ton trans-ported	Annual ton CO_2 eq. GWP_{20}	GWI_{100} in kg per ton trans-ported	Annual ton CO_2 eq. GWP_{100}
Standard	2000	2.70%	Atlantic ECA	None	156 51	1 242 000		-1120	- 22 394	-43	- 851
Standard	2011	2.7% 0.1%	Atlantic ECA	Tier 2	165 57	1 503 000	261 000	-646	- 12 923	195	3 904
Hybrid	2016	2.7% 0.1%	Atlantic ECA	Tier 2 Tier 3	156 54	1 422 000	180 000	-726	- 14 523	172	3 449
Standard	2016	2.7% 0.1%	Atlantic ECA	Tier 3	173 57	1 551 000	309 000	-547	- 10 937	327	6 547
Hybrid	2020	0.5% 0.1%	Atlantic ECA	Tier 2 Tier 3	156 54	1 656 000	414 000	245	4 897	439	8 770
Hybrid	2020	LNG	Atlantic ECA	Tier 2 Tier 3	156 54	1 260 000	18 000	418	8 355	430	8 595
Standard	2020	0.5% 0.1%	Atlantic ECA	Tier 3	173 57	1 551 000	309 000	471	9 425	612	12 240

Fuel prices : 2.7 %(HFO)=300 USD/ton; 0.5%(LFO)=375 USD/ton; 0.1(MGO)= 450 USD/ton; LNG =300USD/ton (all fuel prices per TOE); Annual CO_2 emissions only approximately 13 000 tons

It might be that it will be more benefical with the following legislation.

1. Batteries, clean fuels or cold ironing in ports
2. Clean fuels close to land or when extra power is required for loading and discharging
3. Continued use of heavy fuel oil (HFO 2.7%) at deep sea
4. Solutions where NOx is rather maximized than minimized at sea and only minimized close to land and in ports
5. Strict regulation of Black carbon in Artic areas and close to glaciers

Inspiration from the car industry – Our next step will be well to propeller and not only tank to propeller (Application of LCA)



We have already a good start in this domain

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

May 2014

Assessment of profit, cost, and emissions for slender bulk vessel designs

Haakon Lindstad[a,*], Inge Sandaas[c], Sverre Steen[b]

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

April 2012

The importance of economies of scale for reductions in greenhouse gas emissions from shipping

Haakon Lindstad[a,b,*], Bjørn E. Asbjørnslett[a], Anders H. Strømman[a]

JOURNAL OF INDUSTRIAL ECOLOGY

November 2013

RESEARCH AND ANALYSIS

Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack

Environmental Science & Technology

April 2011

ARTICLE

pubs.acs.org/est

Life Cycle Environmental Assessment of Lithium-Ion and Nickel Metal Hydride Batteries for Plug-In Hybrid and Battery Electric Vehicles

Guillaume Majeau-Bettez,[*,†] Troy R. Hawkins,[†] and Anders Hammer Strømman[†]

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

April 2011

Reductions in greenhouse gas emissions and cost by shipping at lower speeds

Haakon Lindstad[a,b,*], Bjørn E. Asbjørnslett[a], Anders H. Strømman[a]

Cost and emissions reductions through hybrid power options for sea going cargo vessels

Power solutions for seagoing vessels have generally been designed and optimized to enable operation at maximum economic speeds based on hydrodynamic considerations, and in addition that vessels have the required power to be seaworthy and maneuverable in rough weather and at any sea state.

There is no-proven methodology available for calculating minimum power, and in this study we make the following assumptions:

- The current installed power reflects what is power is required for bulkers and tankers in survival conditions at high sea states for short periods
- The average required power for a bulker or a tanker at high sea states is 70 % of the current installed power.
- At moderate sea states, 30 – 50 % of current installed power is required for achieving speeds from cost minimizing and upwards
- At calm water, 15 % to 40 % of installed power is required to operate at cost minimizing speeds and upwards

	Installed Power main engines		Average DWT		kW per DWT		Change	Increased Power per dwt
	2010	2015	2010	2015	2010	2015		
	kW	kW	ton	ton	kW/ton	kW/ton		
CONTAINER	23,561	27,688	35,229	44,305	0.669	0.625	93%	
CONT_1_PPAN_up60	56,661	56,626	81,547	93,872	0.695	0.603	87%	
CONT_2_PANA_60	32,121	33,761	48,907	49,867	0.657	0.677	103%	
CONT_3_SPAN_40	21,363	21,818	34,866	34,888	0.613	0.625	102%	
CONT_4_HAND_30	13,040	13,428	21,549	21,655	0.605	0.620	102%	
CONT_5_FEEM_15	7,039	7,203	10,119	10,317	0.696	0.698	100%	
CONT_6_FEED_5	2,366	2,517	3,268	3,710	0.724	0.679	94%	
DRY BULK	8,466	9,516	58,973	69,038	0.144	0.138	96%	
DB_1_BC_CAPE_up_120	16,127	18,165	182,262	195,145	0.088	0.093	105%	
DB_2_BC_CAPE_85_120	12,038	12,735	94,057	97,308	0.128	0.131	102%	
DB_3_BC_PANA_60_85	10,060	10,463	72,785	75,198	0.138	0.139	101%	
DB_4_BC_HANM_35_60	8,427	8,738	47,288	50,175	0.178	0.174	98%	
DB_5_BC_HAND_15_35	6,507	6,288	26,112	27,814	0.249	0.226	91%	
DB_6_BC_COSTAL_0_15	2,151	1,962	5,138	4,921	0.419	0.399	95%	
GAS (LNG & LPG)	10,025	10,759	27,255	29,032	0.368	0.371	101%	
GENERAL CARGO	2,652	2,633	5,671	6,244	0.468	0.422	90%	
GC_1_up15	6,893	7,174	17,165	21,496	0.402	0.334	83%	
GC_2_5_15	3,748	3,584	8,183	8,222	0.458	0.436	95%	
GC_3_to_5	1,143	1,134	2,106	2,160	0.543	0.525	97%	
RO-RO	8,212	8,680	8,651	8,927	0.949	0.972	102%	
GC_RORO_1_up15	14,734	15,107	21,194	21,438	0.695	0.705	101%	
GC_RORO_2_0_15	6,017	6,130	4,910	4,611	1.225	1.329	108%	
CHEMICAL TANKER	4,972	5,282	17,328	19,016	0.287	0.278	97%	
LB_CH_1_up_40	9,677	9,793	48,239	48,532	0.201	0.202	101%	
LB_CH_2_15_40	7,766	7,583	27,035	26,354	0.287	0.288	100%	
LB_CH_3_0_15	2,621	2,710	5,686	5,988	0.461	0.452	98%	
OIL TANKERS	7,348	8,365	56,256	63,998	0.131	0.131	100%	
LB_CRPR_1_TK_ULCC	28,031	28,568	310,665	313,053	0.090	0.091	101%	
LB_CRPR_2_TK_VLCC	20,266	20,363	202,397	197,038	0.100	0.103	103%	
LB_CRPR_3_TK_SUEZ	13,475	13,725	108,853	109,579	0.124	0.125	101%	
LB_CRPR_4_TK_AFRA	12,095	12,333	82,979	78,969	0.146	0.156	107%	
LB_CRPR_5_TK_PANA	10,121	10,073	62,761	61,242	0.161	0.164	102%	
LB_CRPR_6_TK_HAND	2,744	2,690	9,160	8,796	0.300	0.306	102%	
CRUISE	30,606	33,061	4,921	5,264	6.220	6.281	101%	
FERRY_PAXONLY	3,293	2,889	336	251	9.805	11.532	118%	
RO-PAX	7,949	7,432	1,808	1,752	4.396	4.243	97%	
Undefined	7,788	8,916	26,403	33,724	0.295	0.264	90%	

Thank you !

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