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WELL-TO-WAKE COMPARATIVE ANALYSIS OF FOSSIL AND ALTERNATIVE GREEN FUELS (SINTEF)

WISE USE OF CCS, DAC, AND RENEWABLES TO REACH NET ZERO TRANSPORT BY 2050 (SINTEF & SOLVANG)

Elizabeth Lindstad, SINTEF Ocean

June 20, 2023 – Trondheim

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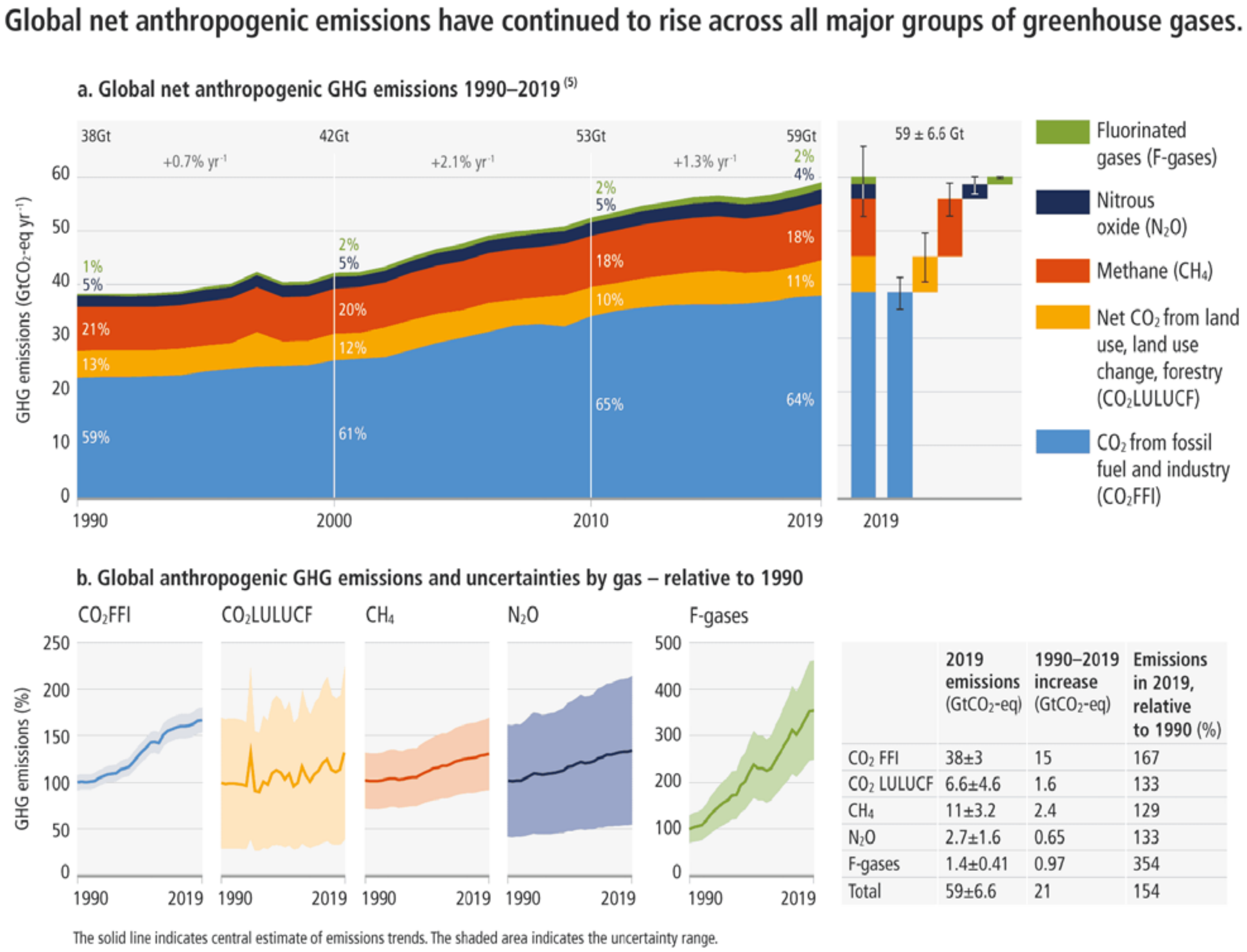
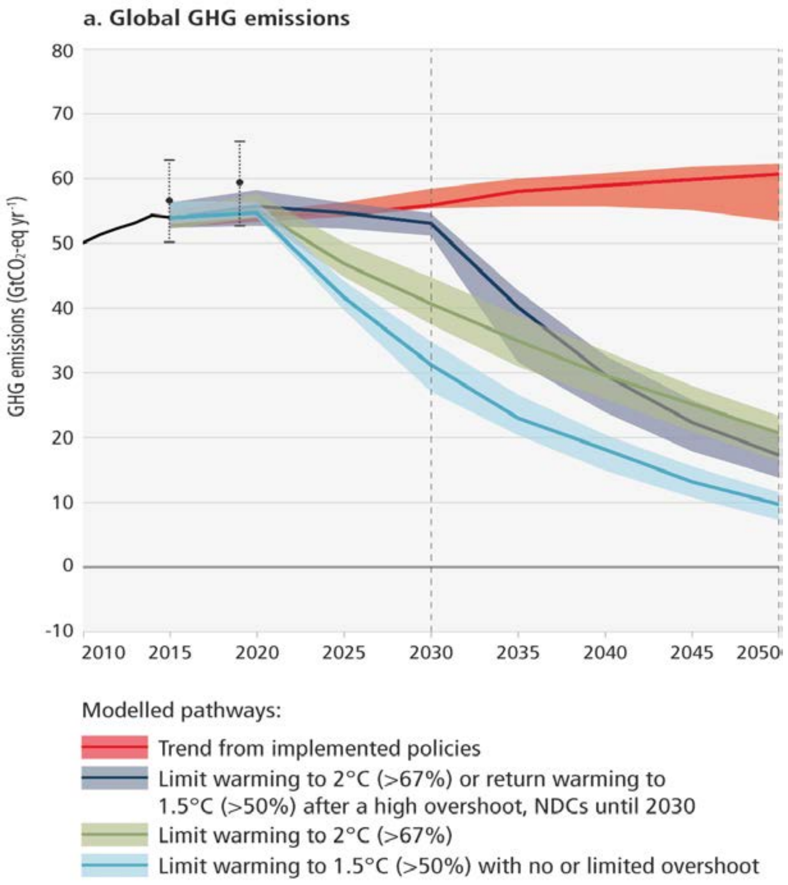
IPCC urges for rapid Global decarbonization



	2019 emissions ($GtCO_2$-eq)	1990–2019 increase ($GtCO_2$-eq)	Emissions in 2019, relative to 1990 (%)
CO_2 FFI	38±3	15	167
CO_2 LULUCF	6.6±4.6	1.6	133
CH_4	11±3.2	2.4	129
N_2O	2.7±1.6	0.65	133
F-gases	1.4±0.41	0.97	354
Total	59±6.6	21	154



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Source: Climate Change 2022: Mitigation of Climate Change (IPCC, 2022), Fig. SPM.1 and SPM.4

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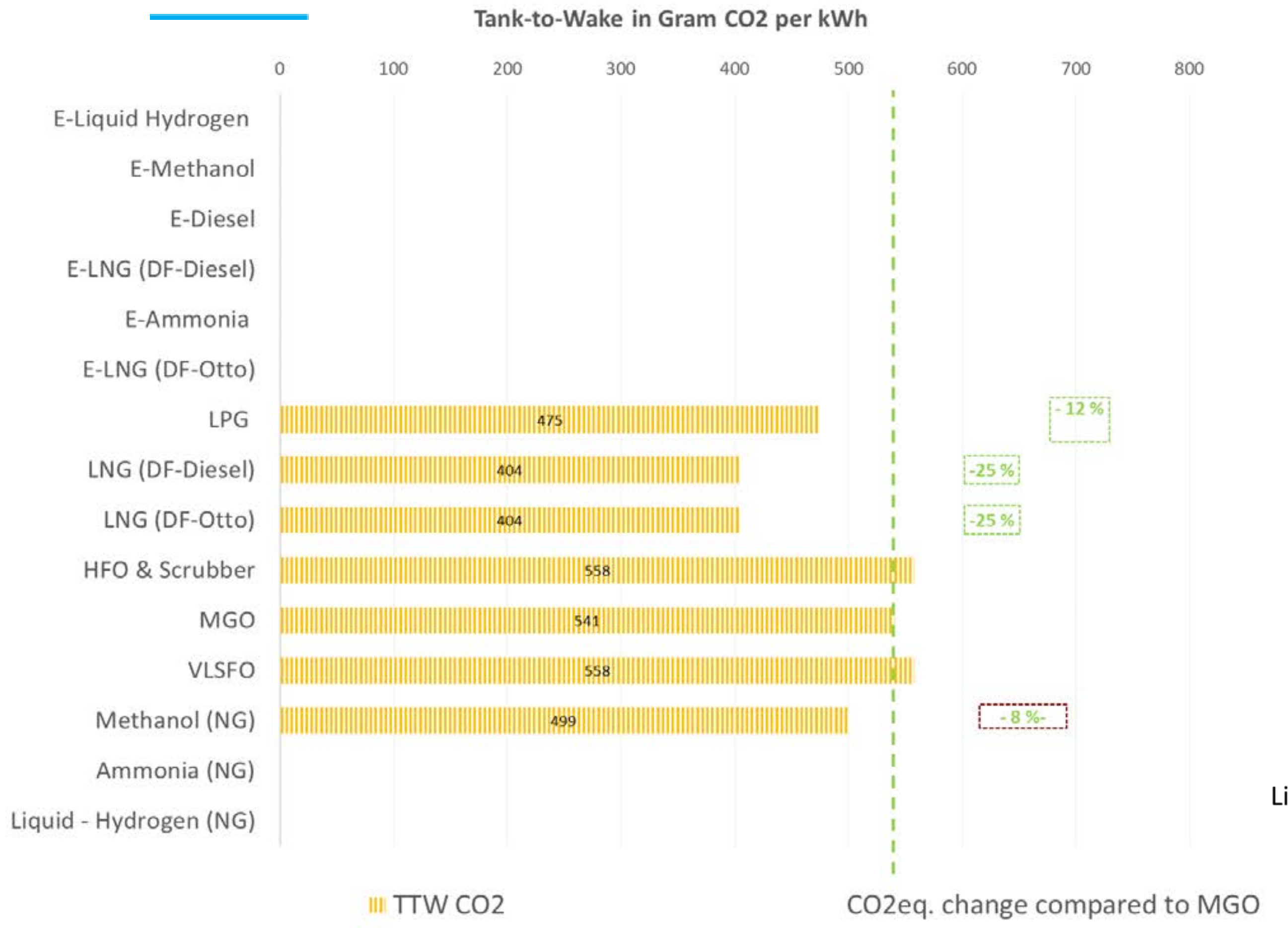
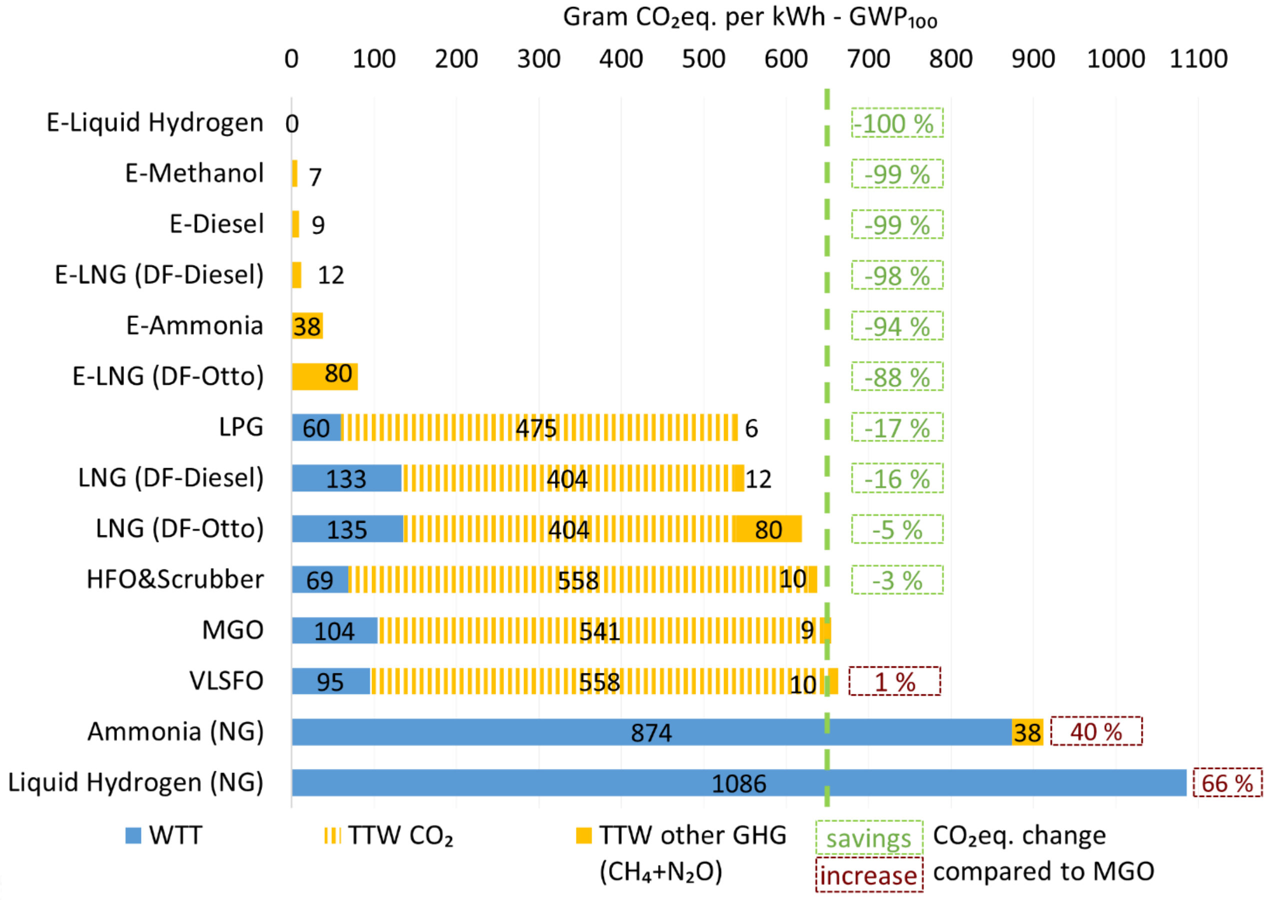
The main motivation for changing IMO legislation from Tank-to-Wake to Well-to-Wake has been to avoid shifting GHG-emissions from shipping to the energy producing sector





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Source: Lindstad, E., Lagemann, B., Rialland, A., Gamlem, G., M., Valland, A. 2021. Reduction of Maritime GHG emissions and the potential role of E-fuels, TRD

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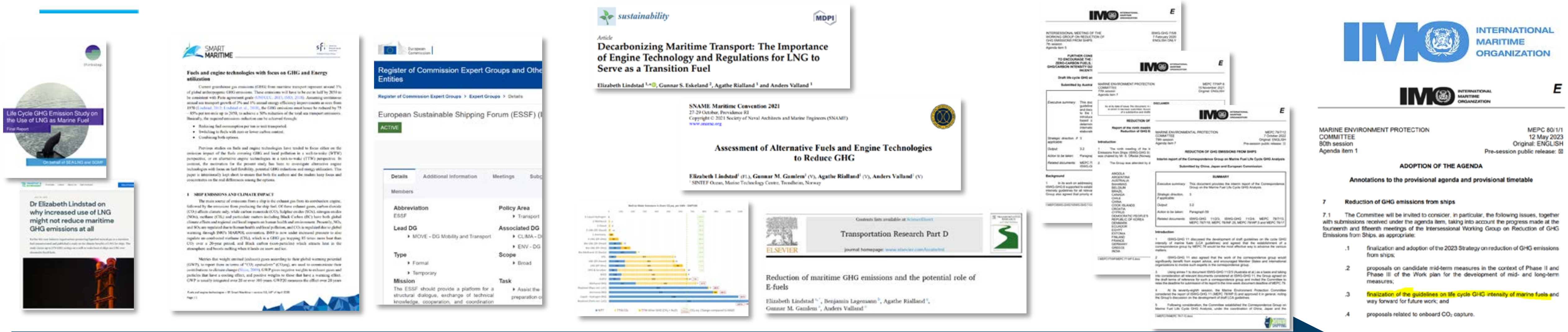
IMO's adoption of guidelines on life cycle GHG intensity of marine fuels and the involvement of Smart Maritime



2019
Questioning
Thinkstep (2019) LCA report om marine fuels.

2020
Smart Maritime WP1 Report on Fuels & engine technologies with focus on GHG and energy utilization

2020-2023
Smart Maritime key contribution to **European Sustainable Shipping Forum – Proposal for Methodology** to calculate the life cycle WTW GHG emissions of marine fuels

2021- 2022
Smart Maritime / SINTEF Publications on WTW LCA of Marine Fuels
+
Continuous dialog with EC ESSF, IMO Correspondance Group on Marine Fuel Life Cycle GHG Analysis.

2021 - 2023
Smart Maritime / SINTEF contribution to dialog on LCA Guidelines at IMO's Intersessional Working Group on Reduction of GHG Emissions from Ships.
MEPCs 76-77-78-79

MEPC80: Adoption of Final Draft LCA Guidelines

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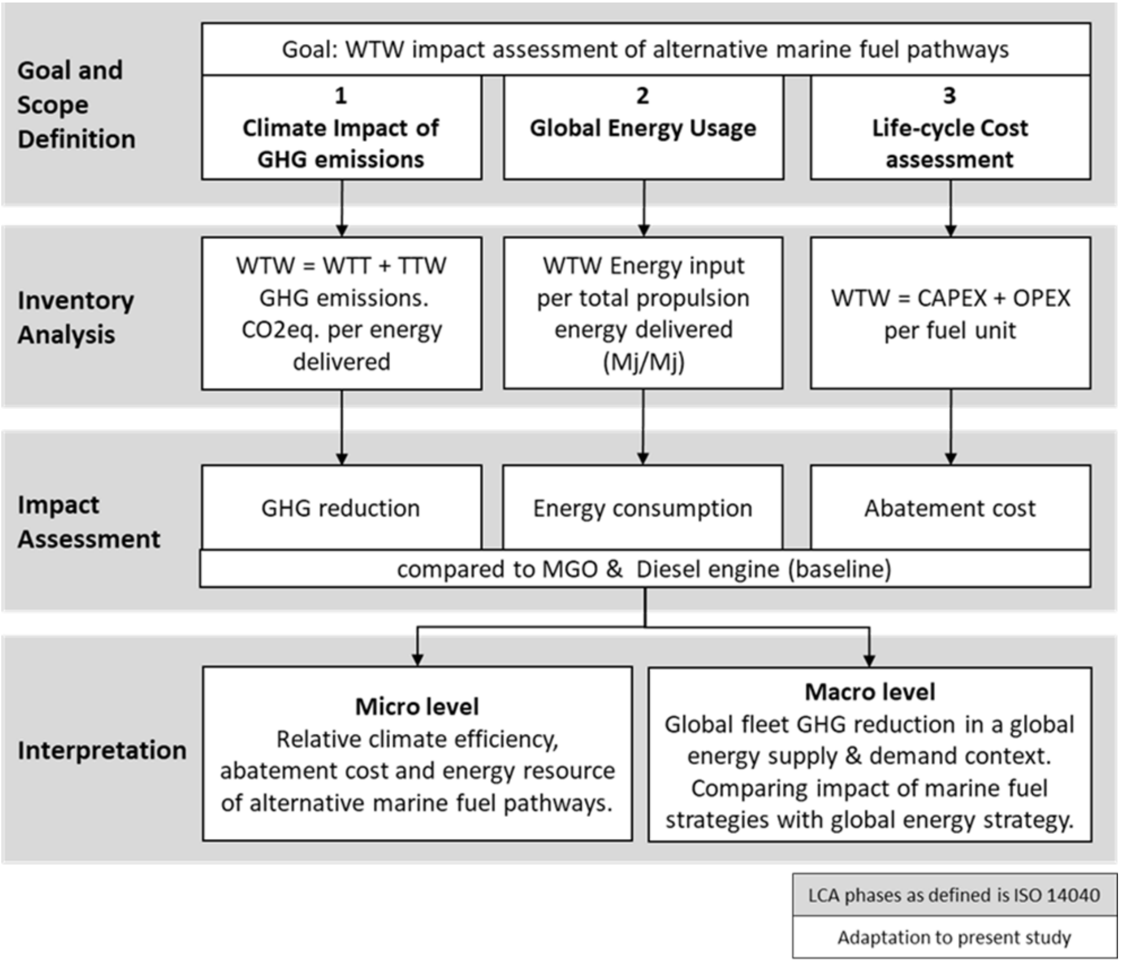
Our methodology for assessing Alternative Fuels & Technologies

To evaluate alternative fuel & technologies options, we compare their:

1-GHG emissions
2-Energy consumption WTW
3-Cost per energy unit delivered for propulsion

which enables a holistic assessment



Source : Lindstad, E., Gamlem, G., Rialland, A., Valland, A, - Assessment of Alternative Fuels and Engine technologies to reduce GHG, SMC-099-2021

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OUR MAIN PUBLICATIONS REGARDING ALTERNATIVE FUELS

Senter for forskningsdrevet innovasjon
Norges forskningsråd

- Lindstad, E., Ask, T.Ø., Cariou, P., Eskeland, G.S., Rialland, A.2023. *Wise use of renewable energy in transport.* Transportation Research Part D: Transport and Environment, 119,103713
- Lagemann, B., Lagouvardou, S., Lindstad, E., Fagerholt, K., Psaraftis, H., N., Erikstad, S.,O. 2023 *Optimal ship lifetime fuel and power system selection under uncertainty*. Transportation Research Part D, 119, 103748
- Lindstad, E., Police, D., Rialland, A., Sandaas, I., Stokke, T., 2022, *Decarbonizing bulk shipping combining ship design and alternative Power.* Ocean Engineering Volume 266, Part 2, 15 December 2022, 11279
- Lagemann, B., Lindstad, E., Fagerholt, K., Rialland, A., Erikstad, S. 2022 *Optimal ship lifetime fuel and power system selection.* Transportation Research Part D, 2022, 102, 103145
- Lindstad, E., Lagemann, B., Rialland, A., Gamlem, G., M., Valland, A. 2021. *Reduction of Maritime GHG emissions and the potential role of E-fuels.* Transportation Research Part D, 2021, 101, 103075
- Lindstad, E., Eskeland, G., S., Rialland, A., Valland, A., *2020 Decarbonizing Maritime Transport: The Importance of Engine Technology and Regulations for LNG to serve as a Transition Fuel*. Sustainability 2020, 12(5), 8793
- Lindstad, E., Rialland, A., 2020 *LNG and Cruise Ships, an Easy Way to Fulfil Regulations—Versus the Need for Reducing GHG Emissions.* Sustainability 2020, 12(5), 2080;
- Lindstad, E., Bø, T., I., 2018. *Potential power setups, fuels and hull designs capable of satisfying future EEDI requirements.* Transportation Research Part D 63 (2018) page 276-290

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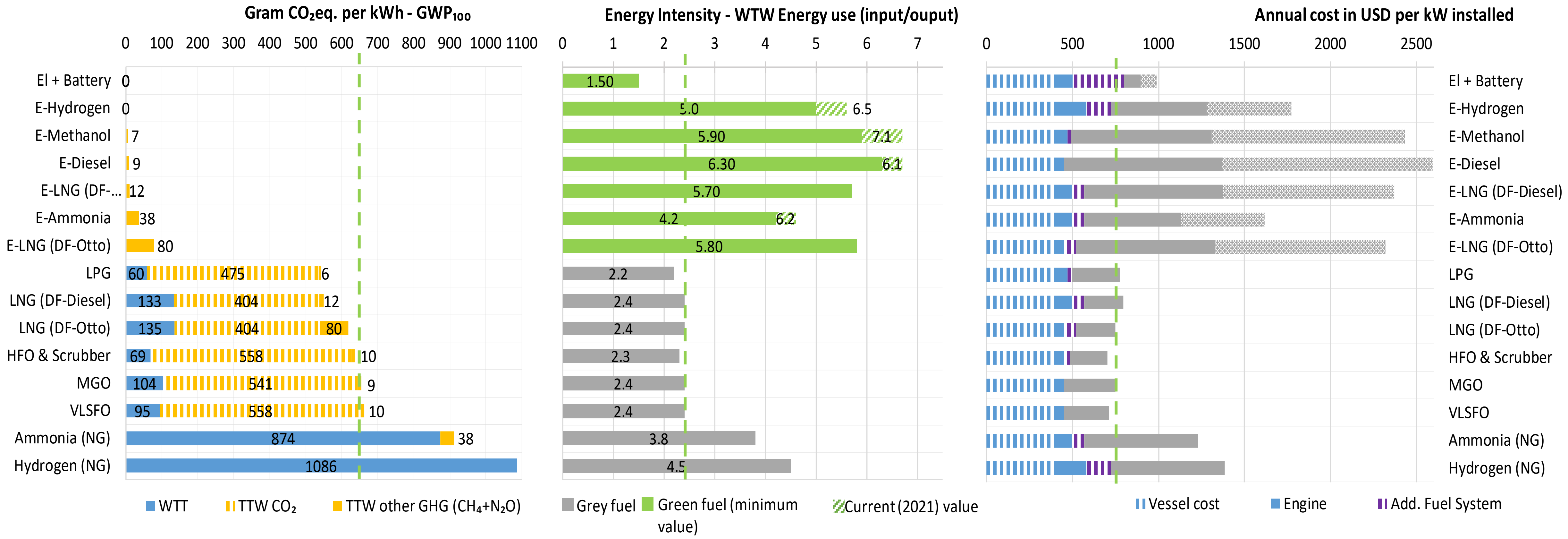
Assessment of fuels based on:
GHG emissions, Energy use, Annual vessel cost



Main Source: Lindstad, E., Lagemann, B., Rialland, A., Gamlem, G., M., Valland, A. 2021. Reduction of Maritime GHG emissions and the potential role of E-fuels, TRD
For cost grey area reflects 20 USD/MWh for renewable electricity, Grey shaded 60 USD/MWh and fossil prices based on 60 USD per barrel (spring 2021)

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Alternative fuels decision-making

Transportation Research Part D 119 (2023) 103748

Contents lists available at ScienceDirect

Transportation Research Part D

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

Optimal ship lifetime fuel and power system selection under uncertainty

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[c] SINTEF Ocean AS, Norway
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ARTICLE INFO

Keywords:
Shipping
Greenhouse gas emissions
Alternative fuels
Stochastic optimization
Flexibility
Retrofit

ABSTRACT

Ship designers face increasing pressure to comply with global emission reduction ambitions. Alternative fuels, potentially derived from bio-feedstock or renewable electricity, provide promising solutions to this problem. The main challenge is to identify a suitable ship power system, given not only uncertain emission requirements but also uncertain fuel and carbon emission prices. We develop a two-stage stochastic optimization model that explicitly considers uncertain fuel and carbon emission prices, as well as potential retrofits along the lifetime. The bi-objective setup of the model shows how the choice of optimal power system changes with reduced emission levels. Methanol and LNG configurations appear to be relatively robust initial choices due to their ability to run on fuel derived from different feedstocks, and their better retrofitt-ability towards ammonia or hydrogen. From a policy perspective, our model provides insight into the effect of the different types of carbon pricing mechanisms on a shipowner's decisions.

Bi-objective, stochastic optimization method

for the selection of alternative fuels and

power systems under uncertainty

Source: Lagemann, B., Lagouvardou, S., Lindstad, E., Fagerholt, K., Psaraftis, H. N., Erikstad, S. O. 2023. "Optimal Ship Lifetime Fuel and Power System Selection Under Uncertainty." Transportation Research Part D: Transport and Environment 119 (2023): 103748.

Inputs and premises

Table 3: Upper and lower bound fuel costs and GWP factors

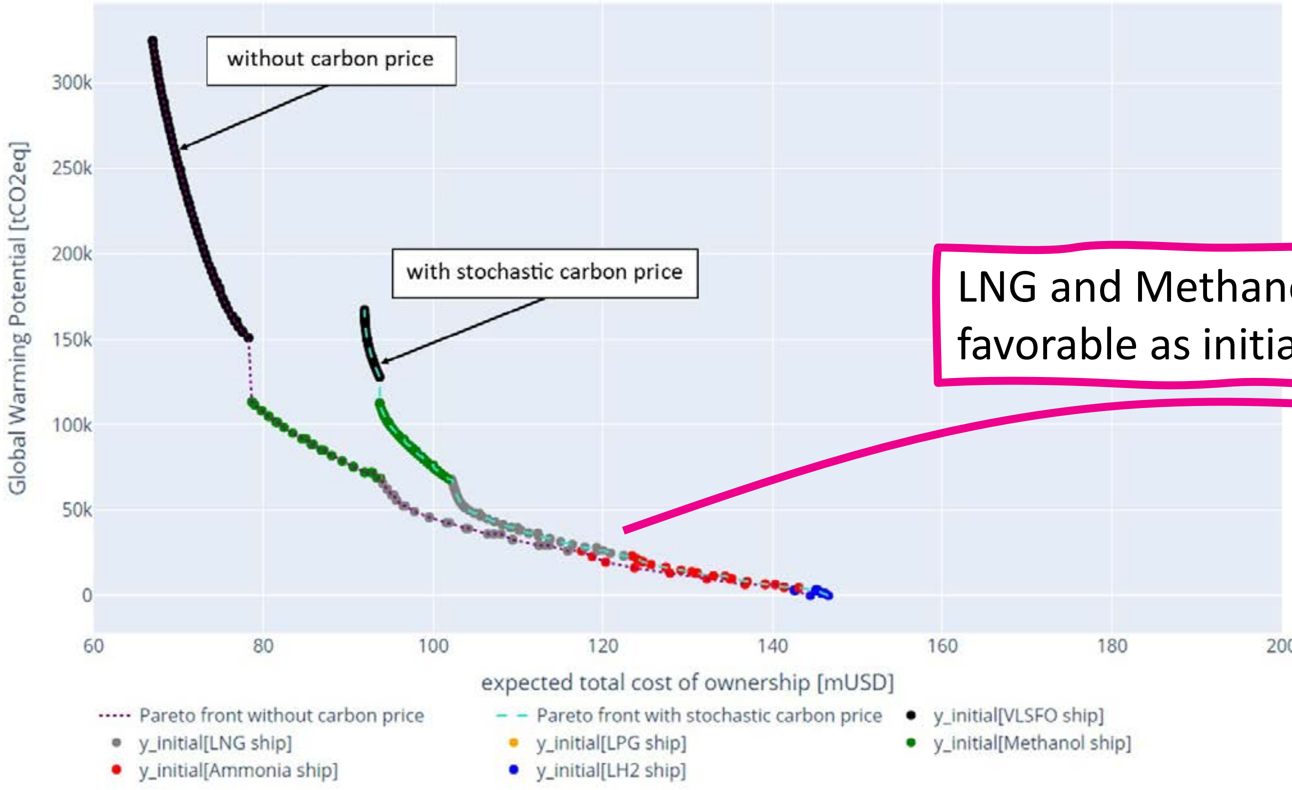
			Environmental impact	Original (Lagemann et al. 2023)		**Changed values**	
Energy carrier	Feed-stock	Fuel label	GWP WTW per fuel energy unit [gCO_{2eq}/kWh]	Upper bound cost [USD/MWh]	Lower bound cost [USD/MWh]	Upper bound cost [USD/MWh]	Lower bound cost [USD/MWh]
Diesel	Fossil	VLSFO	331.6 [1]	95 [2]	38 [2]		
	Bio	bio-Diesel	220.0 [5]	128 [3]	93 [3]		
	electro	e-Diesel	4.5 [1]	**423** [2]	**131** [2]		
Methane	Fossil	LNG	305.4 [1]	81 [2]	32 [2]		
	Bio	bio-LNG	55.7 [1]	119 [3]	89 [3]		
	electro	e-LNG	6.0 [1]	358 [2]	115 [2]		
LPG	Fossil	LPG	267.5 [1]	98.3 [2]	39.3 [2]		
Methanol	Fossil	Methanol	366.1 [1]	210 [2]	90 [2]		
	Bio	bio-Methanol	115.9 [1]	97 [3]	66 [3]		
	electro	e-Methanol	3.5 [1]	385 [2]	116 [2]		
Ammonia	Fossil	Ammonia	106.1 [1], [4]	220 [2], [6]	56 [2], [6]		
	electro	e-Ammonia	19.0 [1]	**220** [2]	**80** [2]	**423** [7]	**131** [7]
Hydrogen	Fossil	LH2	108.7 [1], [4]	245 [2], [6]	55 [2], [6]		
	electro	e-LH2	0.0 [1]	**245** [2]	**79** [2]	**423** [7]	**131** [7]

Sources and comments:
[1] Lindstad et al. (2021a)
[2] Lindstad et al. (2021b)
[3] Korberg et al. (2021)
[4] assuming 80% CCS efficiency
[5] Sustainable Shipping Initiative (2019)
[6] Upper bound 100% of electricity-based pendant, lower bound 70% of electricity-based pendant
[7] **Same as e-Diesel due to additional infrastructural costs**

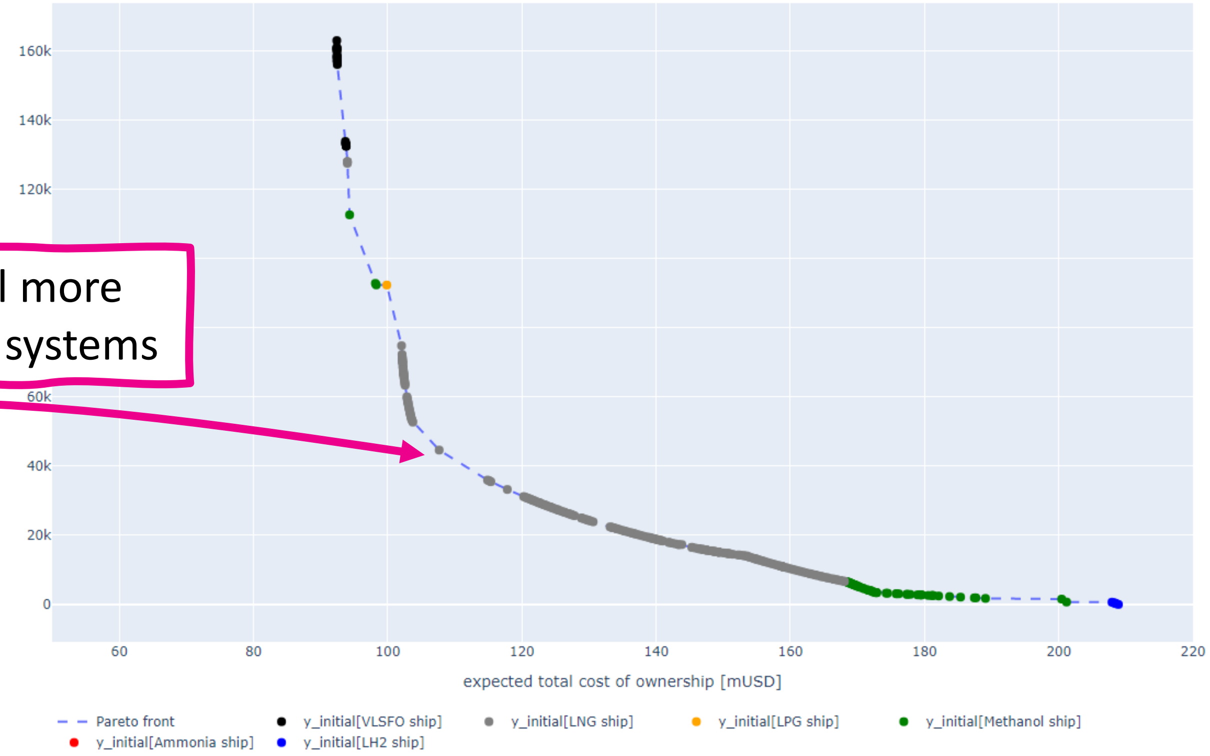
Premises for e-Ammonia and e-LH2 changed: same cost as e-Diesel to account for infrastructural costs

Output

Original costs (Lagemann et al. 2023)



Increased e-fuel costs (LH2, NH3) with stocastic carbon price only



LNG and Methanol more favorable as initial systems

E-Diesel 131-423 [USD/MWh]

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Lagemann, B., Lagouvardou, S., Lindstad, E., Fagerholt, K., Psaraftis, H. N., Erikstad, S. O. 2023. "Optimal Ship Lifetime Fuel and Power System Selection Under Uncertainty." Transportation Research Part D: Transport and Environment 119 (2023): 103748.

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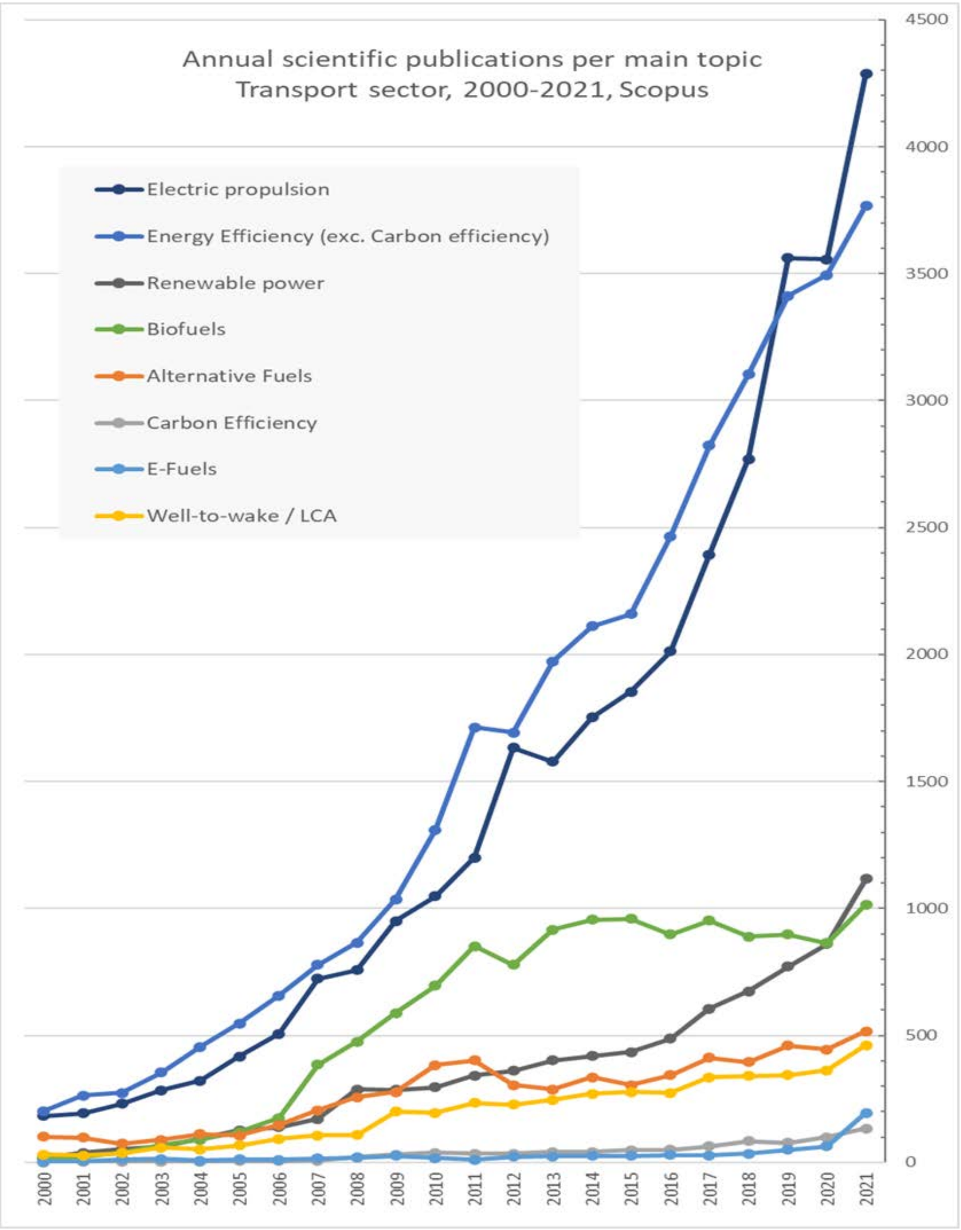
Decarbonization of Transport: a review

- Nearly 50 000 publications from 2000 to 2021.
- Availability of renewable energy at low cost is generally assumed.
- Insufficient attention is given to the impact of transport sectors' decarbonization measures on the energy production sector.
- The studies published, by Lindstad et al. financed by the Smart Maritime project is among the very few studies which investigate not only GHG reduction but also: Energy use, Cost and how fast renewable energy production has to increase to mitigate Global warming.



Source: Lindstad, E., Ask, T, Ø, Cariou, P, Eskeland, G., Rialland, A. 2023. Wise use of Renewable Energy in Transport , Transportation Research Part D.

Wise use of Renewable Energy in Transport

- The Transport sector consumes 25 % of global energy measured Well-to-Wake.
- This study investigates the use of renewable energy for the transport sector, and alternatively within the energy sector.

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Contents lists available at ScienceDirect

Transportation Research Part D

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

Wise use of renewable energy in transport

Elizabeth Lindstad [a,*], Tor Øyvind Ask [b], Pierre Cariou [c], Gunnar S. Eskeland [d], Agathe Rialland [a]

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[b] *Solvang Shipping, Stavanger, Norway*
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A R T I C L E I N F O

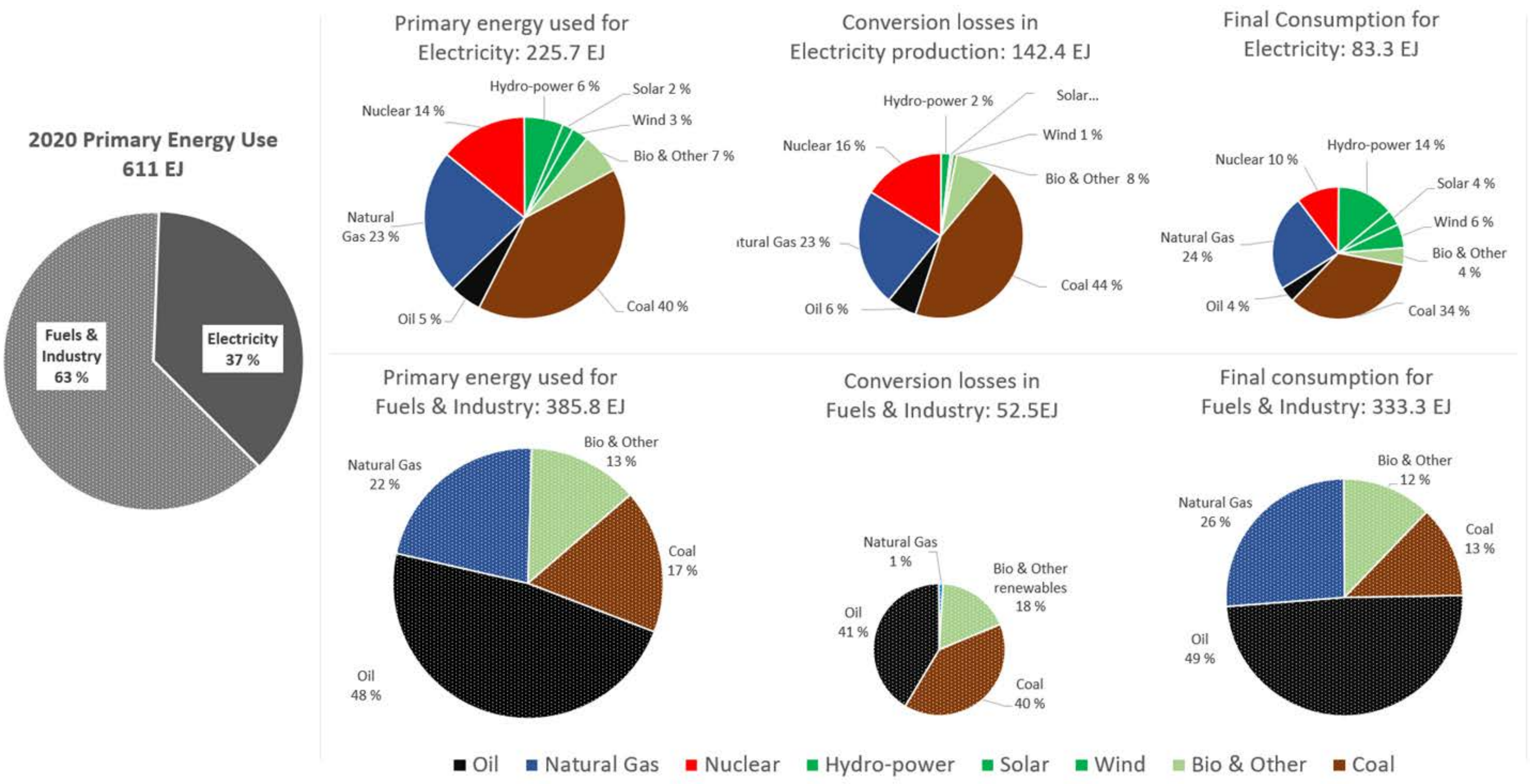
Keywords:
Transport
Alternative Fuels
GHG
Abatement cost
Energy efficiency
IPCC

A B S T R A C T

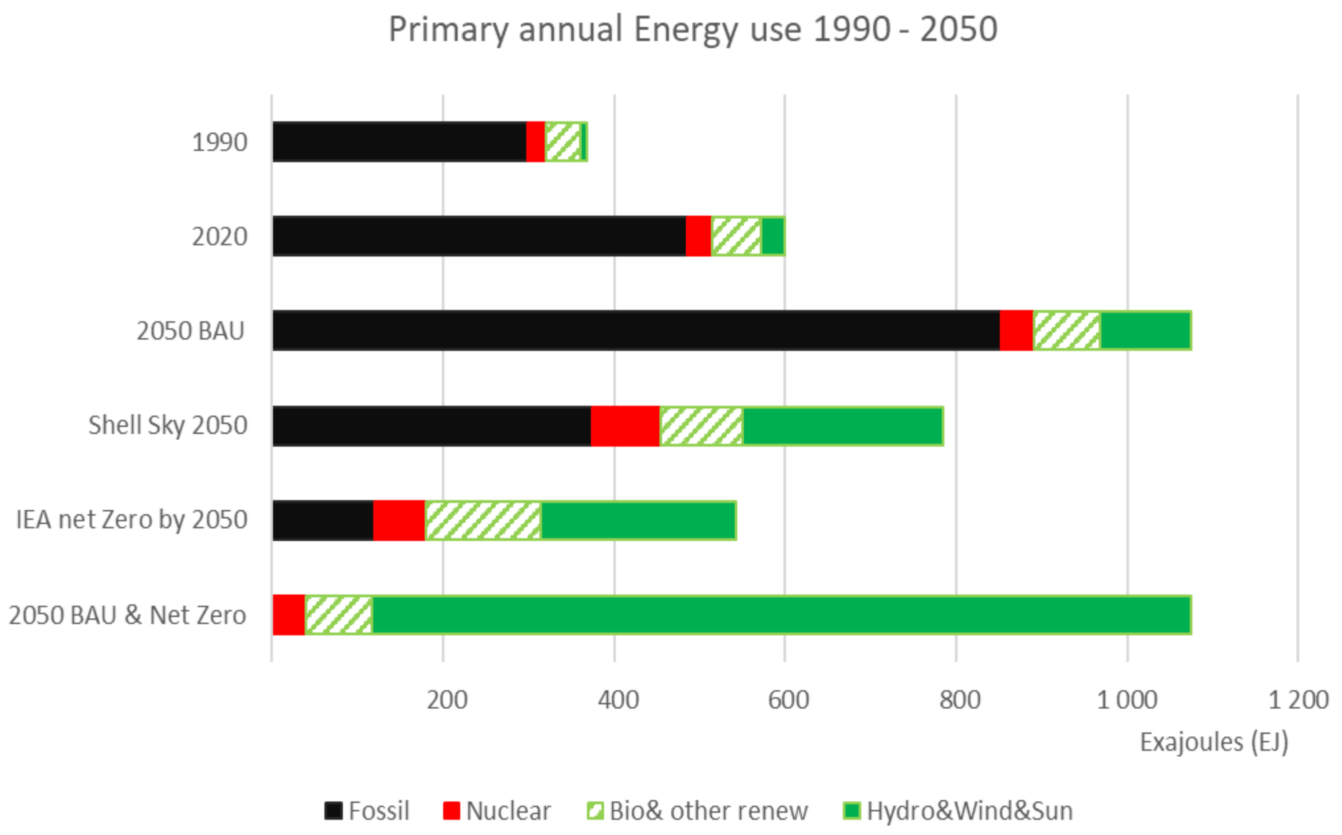
The transport sector accounts for around 25 % of global energy use, considering both fuel production and consumption. To mitigate climate change, a fast decarbonization of transport is therefore often seen as a necessity, as advocated by the International Energy Agency in its *Net Zero by 2050* scenario. In contrast, Shell's *Sky* scenario envisages Net Zero by 2070 by first picking the lowest hanging fruits within all sectors, and hence a much slower de-carbonization of the transport sector. We investigate how renewables, a scarce resource over the next decades, could be used most wisely within the transport sector or alternatively within the energy sector. Our results stress that priority up to 2050 should be: First, to use new renewable energy to replace coal fired electricity production to nearly decarbonize the electricity grid; Second, to gradually electrify road transport; Third, continued use of fossil fuel in shipping and aviation.

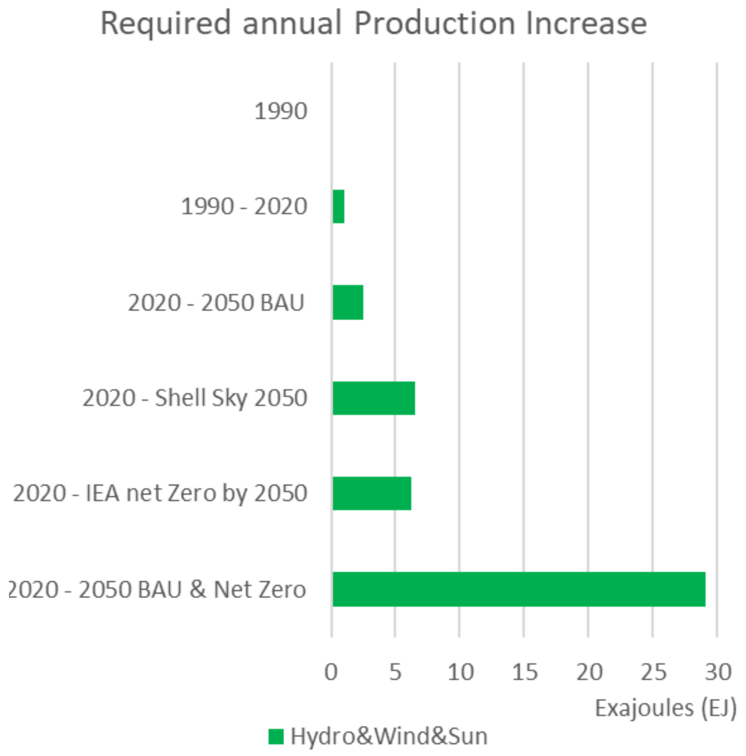
Source: Lindstad, E., Ask, T, Ø, Cariou, P, Eskeland, G., Rialland, A. 2023. Wise use of Renewable Energy in Transport , Transportation Research Part D.

Global Energy (2020) WTW



In a world where all sectors will try to de-carbonize before 2050, a continuous shortage of renewable electricity is likely





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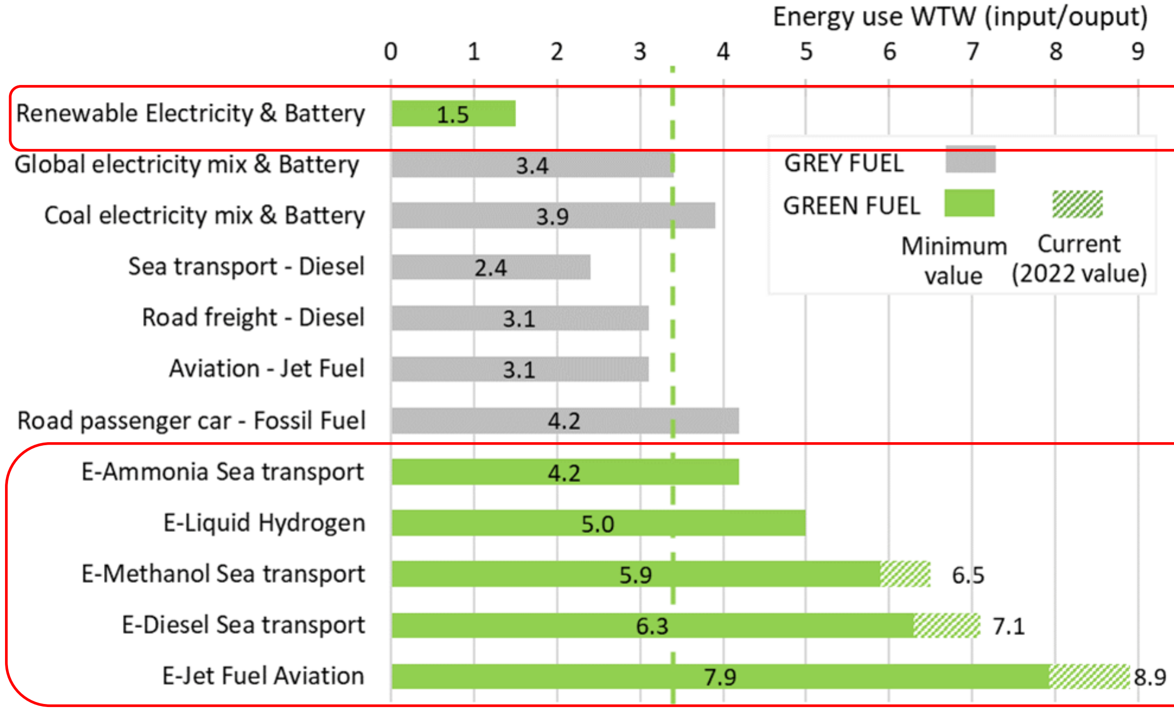
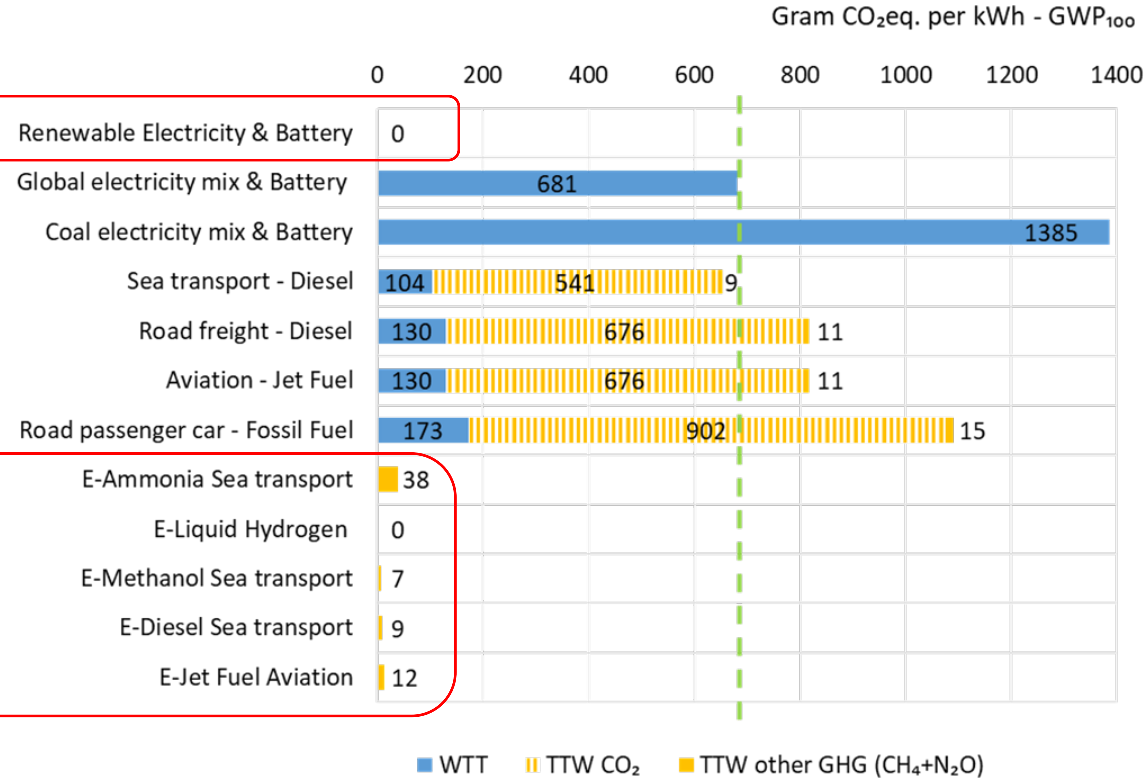
WTW Energy Use and GHG emissions as a function of fuel and transport mode





- Electrification through renewables reduce Global energy use
- Using renewables to produce E-fuels increases Global energy use

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Source: Lindstad, E., Ask, T, Ø, Cariou, P, Eskeland, G., Rialland, A. 2023. Wise use of Renewable Energy in Transport , Transportation Research Part D.

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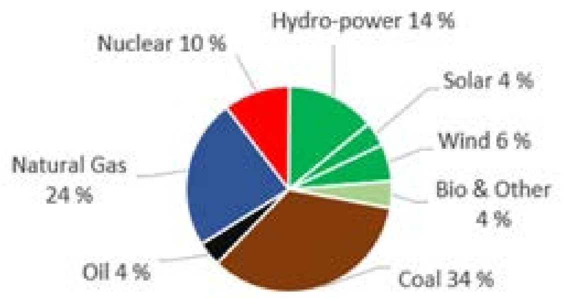
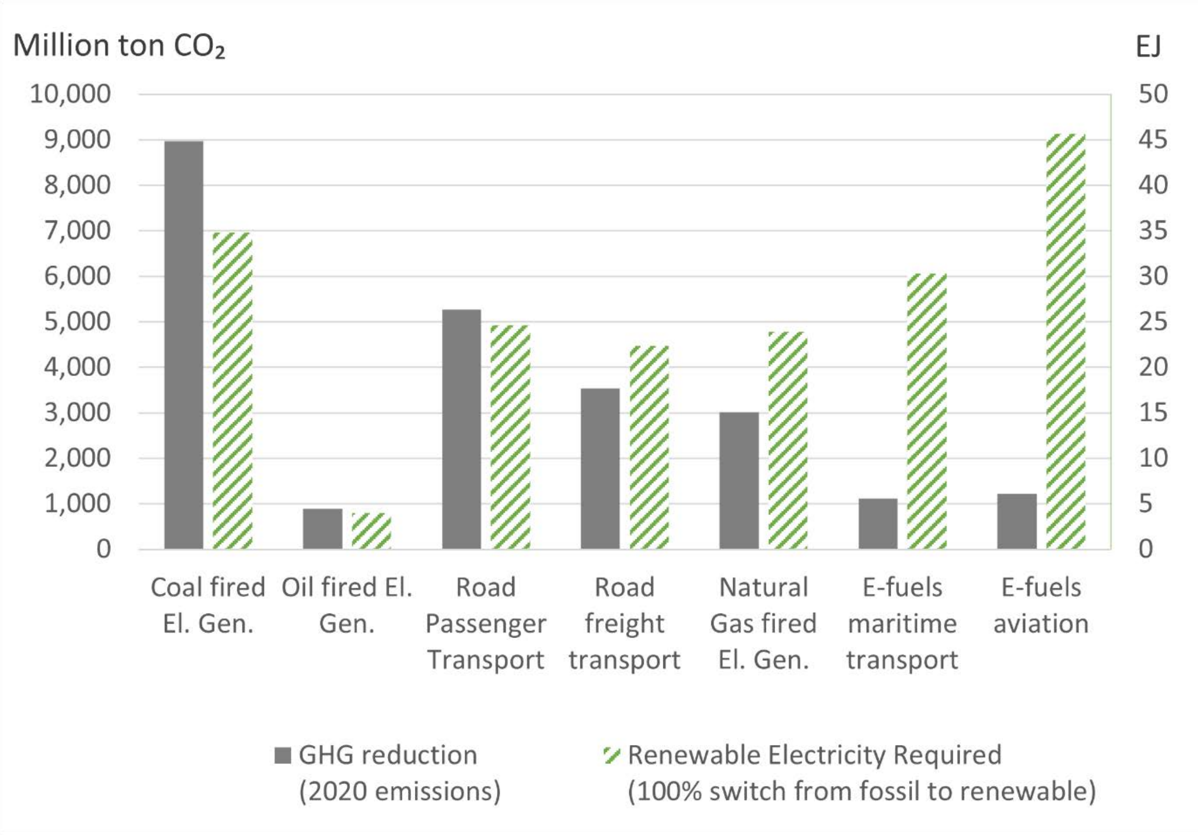
Electrification without decarbonizing the Global electricity generation is not a pathway to Net Zero

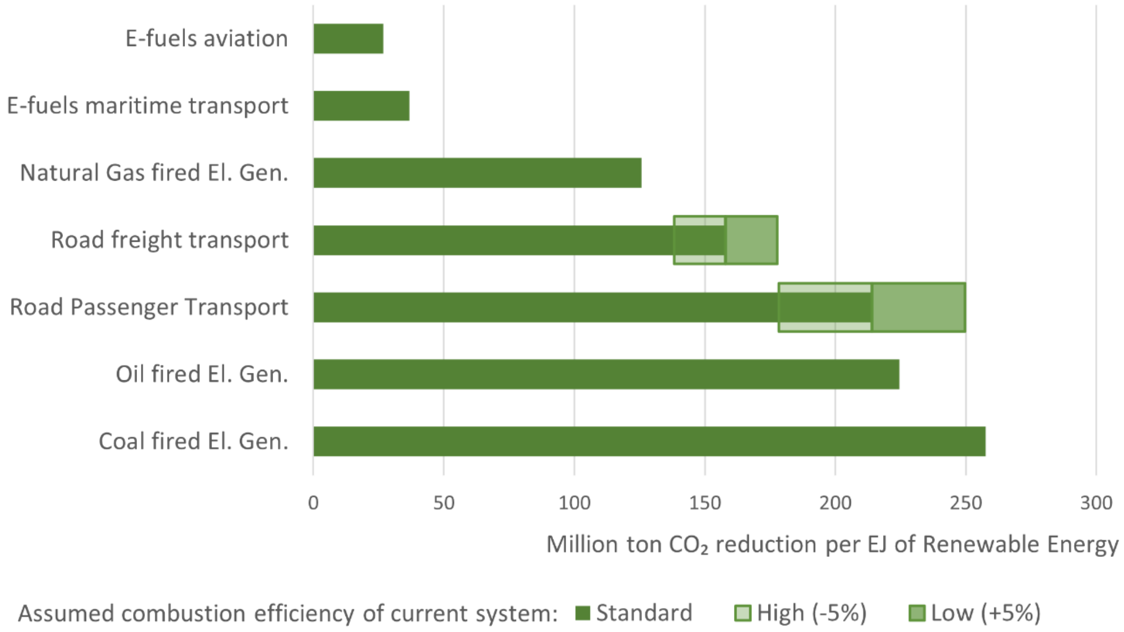


	Primary energy (EJ)	CO_2 Emission Factors	CO_2 Emitted (million ton)	Electricity for final use (EJ)	CO_2 emissions (Gram/kWh)
Hydro-power	14.20			11.61	
Solar	3.87			3.21	
Wind	5.96			4.84	
Bio & Other	14.88			3.52	
Nuclear	31.66			8.70	
Oil	11.57	3.20	884	3.23	985
Natural Gas	52.45	2.40	3 007	19.60	552
Coal	91.11	4.12	8 969	28.55	1 131
Total	225.70		12 860	83.26	556

Source: Lindstad, E., Ask, T, Ø, Cariou, P, Eskeland, G., Rialland, A. 2023. Wise use of Renewable Energy in Transport , Transportation Research Part D.

E-fuels versus decarbonising electricity generation





- Replacing Coal fired Electricity generation gives 7 to 10 times larger GHG reductions than making E-fuels for shipping and aviation

Source: Lindstad, E., Ask, T, Ø, Cariou, P, Eskeland, G., Rialland, A. 2023. Wise use of Renewable Energy in Transport , Transportation Research Part D.

Wise use of Renewable Energy in Transport: Our results stress that priority up to 2050 should be

- First to use new renewable energy to replace coal fired electricity production to nearly fully decarbonize the electricity grid: this gives the largest decarbonisation per unit of renewable energy available;
- Second, to gradually electrify road transport;
- Third, continued use of fossil fuel in maritime shipping and aviation. This late sequencing is due to that a 1.5 degree target does not allow us to make liquid or gaseous E-fuels, since this would deliver 5 to 10 times less decarbonisation per unit of renewable energy compared to if renewables instead are used to replace coal, or road transport fossil fuels.

Wise use of CCS, DAC, and Renewables to reach Net Zero within Transport by 2050

Elizabeth Lindstad[1], Michele Acciaro[3], Tor Øyvind Ask[4] Gunnar S. Eskeland[2], Gunnar Gamlem[1], Benjamin Lagemann[1] ,Agathe Rialland[1],Anders Valland[1]

[1]Sintef Ocean, Trondheim, Norway; [2] NHH, Bergen, Norway [3] Copenhagen Business School [4] Solvang Shipping

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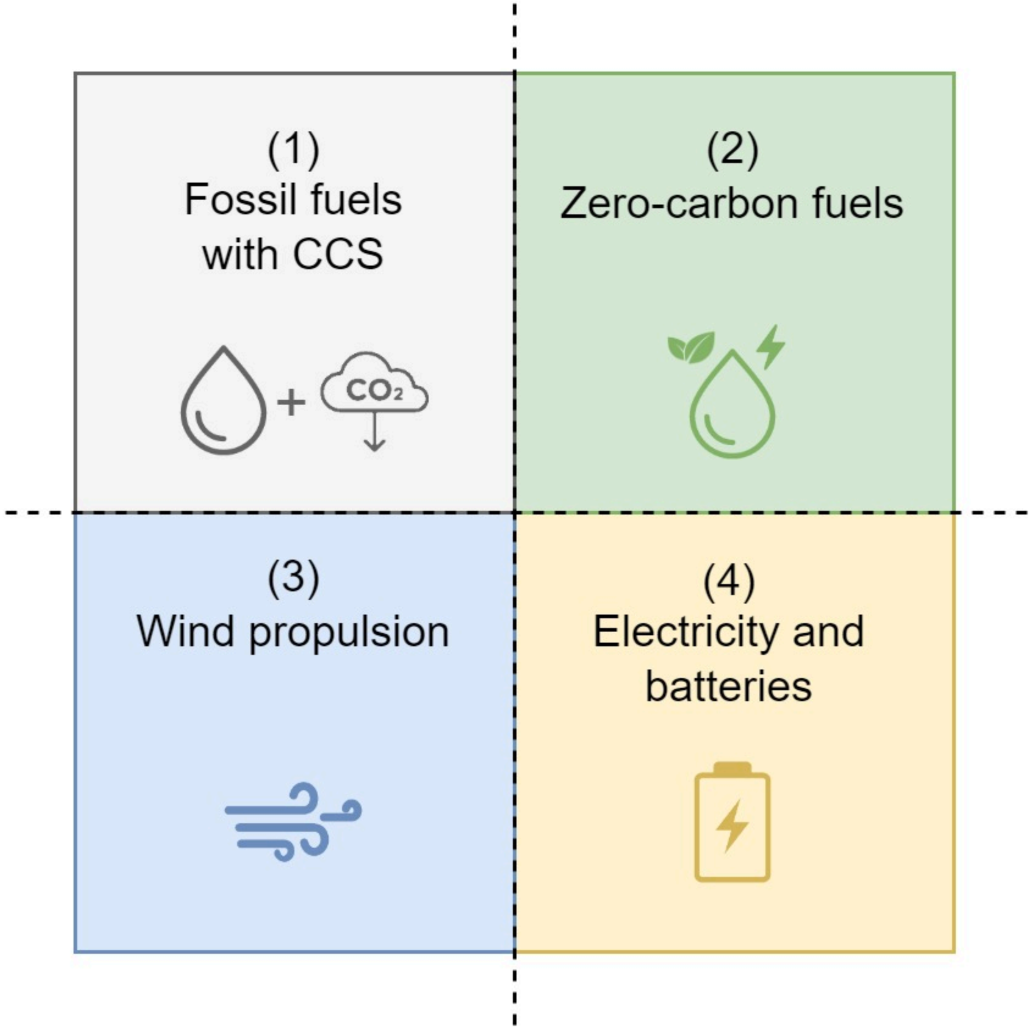
ABSTRACT

With the transport sector representing around 25 % of global energy usage its decarbonization is a core priority to limit global temperature raise to 1.5 to 2 degrees. Building on the constructive role that battery-electric solutions have played in decarbonization in road transport and very short sea shipping applications. The present analysis sheds a critical light on the proposals to extend this role to aviation and shipping with the help of advanced E-fuels made from renewable electricity. We therefor investigate first whether advanced e-fuels, either in the form of E-Hydrogen or E-Ammonia or in the Hydrocarbon form as E-Diesel or E- Methanol represent costlier decarbonization for shipping than Carbon Capture and Storage (CCS) at source, but also than direct air capture (DAC) both for aviation and shipping (DAC). Second, we investigate if CCS as a technology brings us faster to Global Net Zero when applied on hard to abate sectors like maritime and aviation rather than within the electricity production sector.

• Keywords: Net Zero by 2050; Transport; GHG abatement; 1.5 to 2 degrees; IEA; IPCC

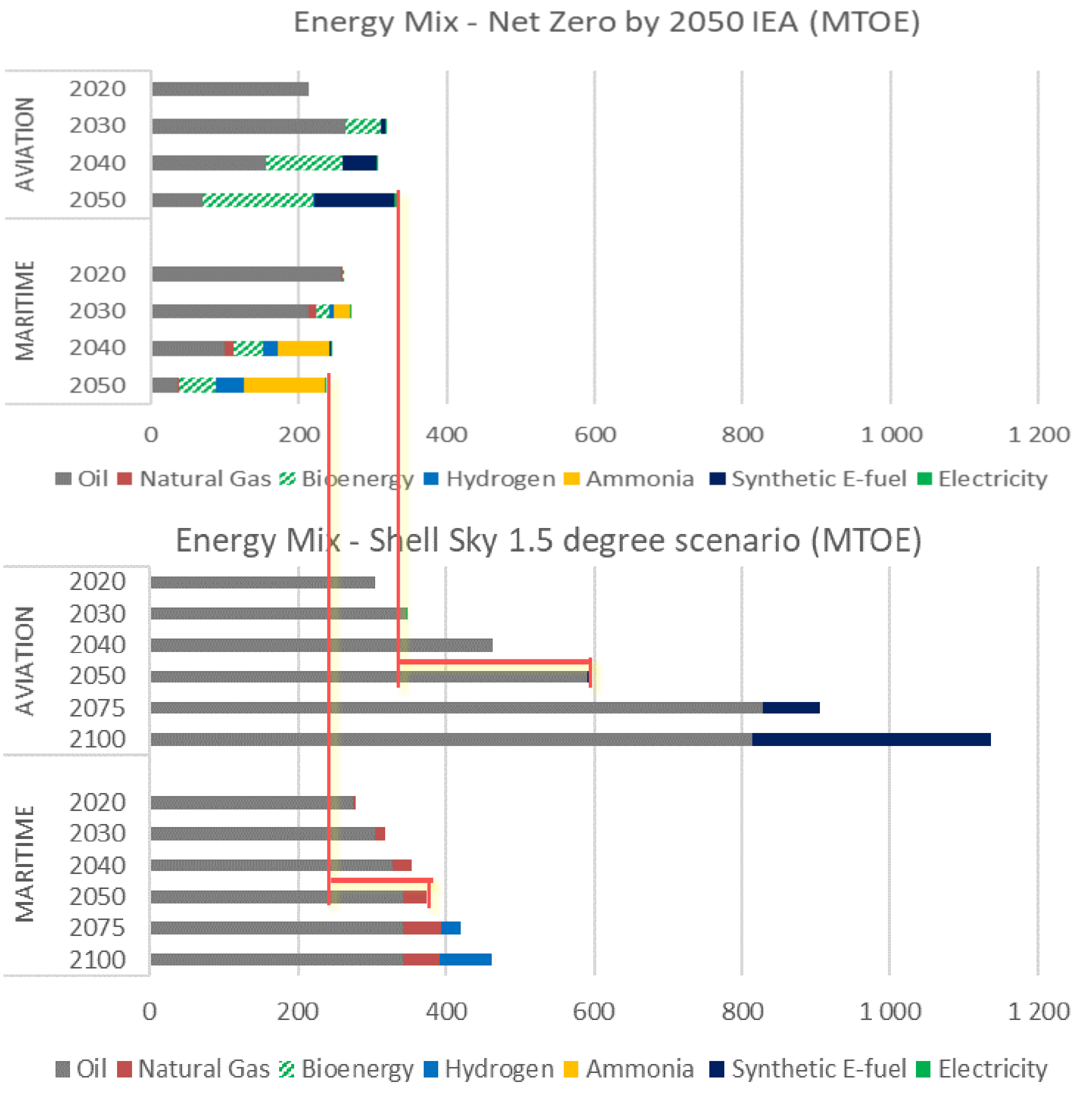
Net Zero by 2050 is reachable in shipping through more than one type of fuels and engine technology

- Fossil fuels with CCS
  - CCS on the vessel
  - DAC (CO2 catch at land from air)
  - CCS at industry plants (emission trading)
- Zero carbon fuels
  - Unconventional (Hydrogen and ammonia)
  - Conventional (E-diesel, E-LNG, E-Methanol)
  - Bio-fuels
- Wind propulsion
  - Wind assisted propulsion
  - Sailing ships
- Electricity and batteries



Hard-to-decarbonise aviation and maritime sector: diverging approaches

- IEA assumes nearly a full decarbonization of Maritime and Aviation by 2050
- Shell assumes that Maritime and Aviation consumption will be mainly fossil-even in 2100
- Shell assumes a large increase in energy use, especially in aviation.
- Lindstad et al 2023 will investigate if CCS or DAC brings us faster to Global Net Zero when applied on hard to abate sectors like maritime and aviation rather than within the electricity production sector



Source: : Lindstad et al. (2021)

IMO LCA WTW Guidelines – if approved at MEPC in July 2023 will equalize CCS and DAC with Zero Carbon E-fuels

CO_{2eq} / $MJ_{(LCV)}$ fuel or electricity

$$GHG_{WtT} = e_{fecu} + e_l + e_p + e_{td} - e_{sca} - e_{ccs}$$

Emissions credit from carbon capture and storage (e_{ccs}), that have not already been accounted for in e_p

CO_2, CH_4, N_2O related to fuel usage (combustion, conversion, fugitive emissions)

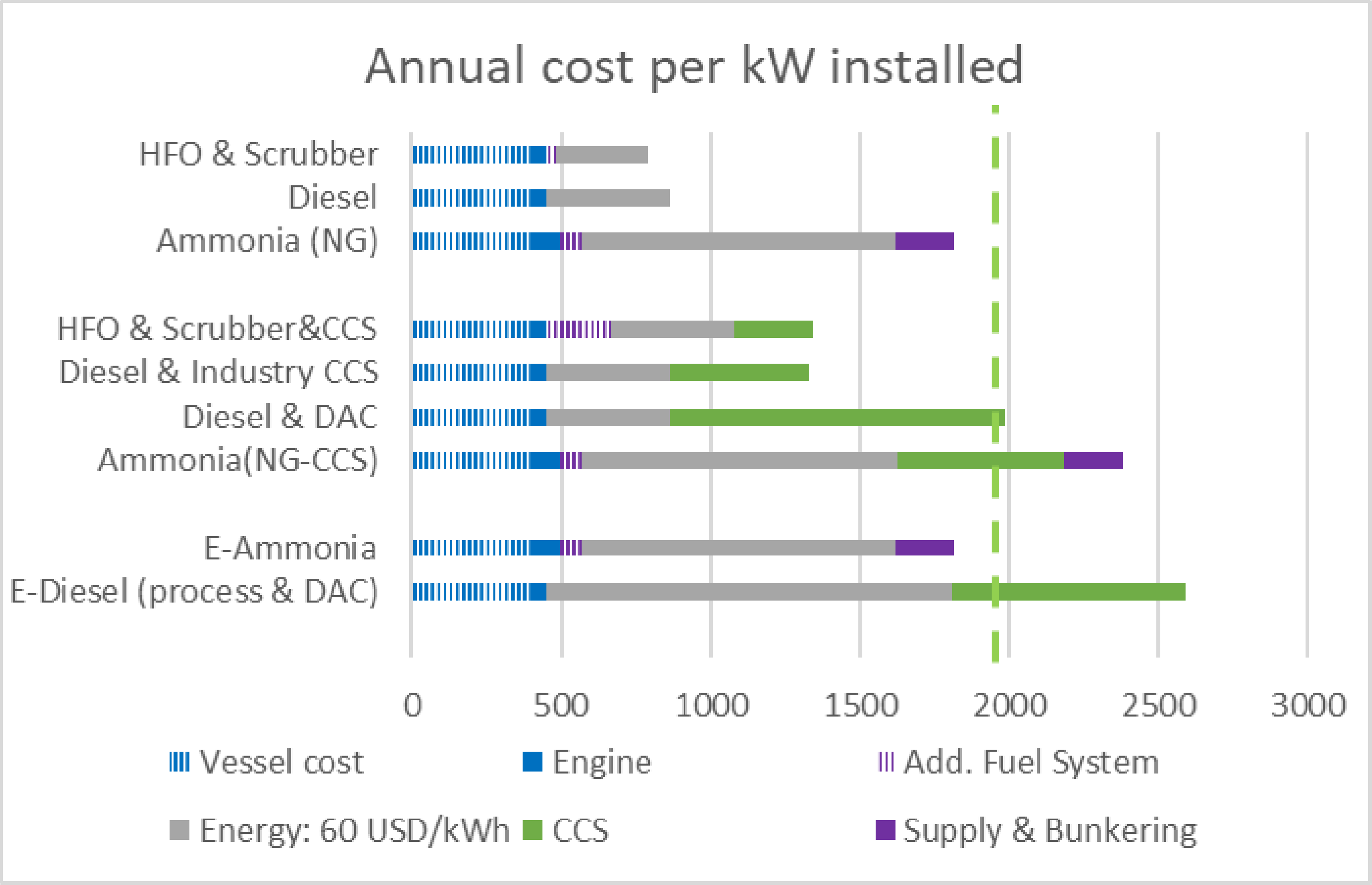
$$GHG_{TtW} = \frac{1}{LCV}\left(\left(1 - \frac{1}{100}\left(C_{slip\_ship} + C_{fug}\right)\right) \times \left(C_{fCO_2} \times GWP_{CO_2} + C_{fCH_4} \times GWP_{CH_4} + C_{fN_2O} \times GWP_{N_2O}\right) + \left(\frac{1}{100}\left(C_{slip\_ship} + C_{fug}\right) \times C_{sfx} \times GWP_{fuelx}\right) - S_{Fc} \times e_c - [S_{Fccu} \times e_{ccu}] - [e_{OCCS}]\right)$$

Emission credit from carbon capture and storage (e_{occs}), where capture of CO_2 occurs onboard

$$GHG_{WtW} = GHG_{WtT} + GHG_{TtW}$$

Source: LCA Guidelines, Correspondance Group on Marine Fuel Life Cycle GHG Analysis, submitted by China, Japan and European Commission (update April 2023)

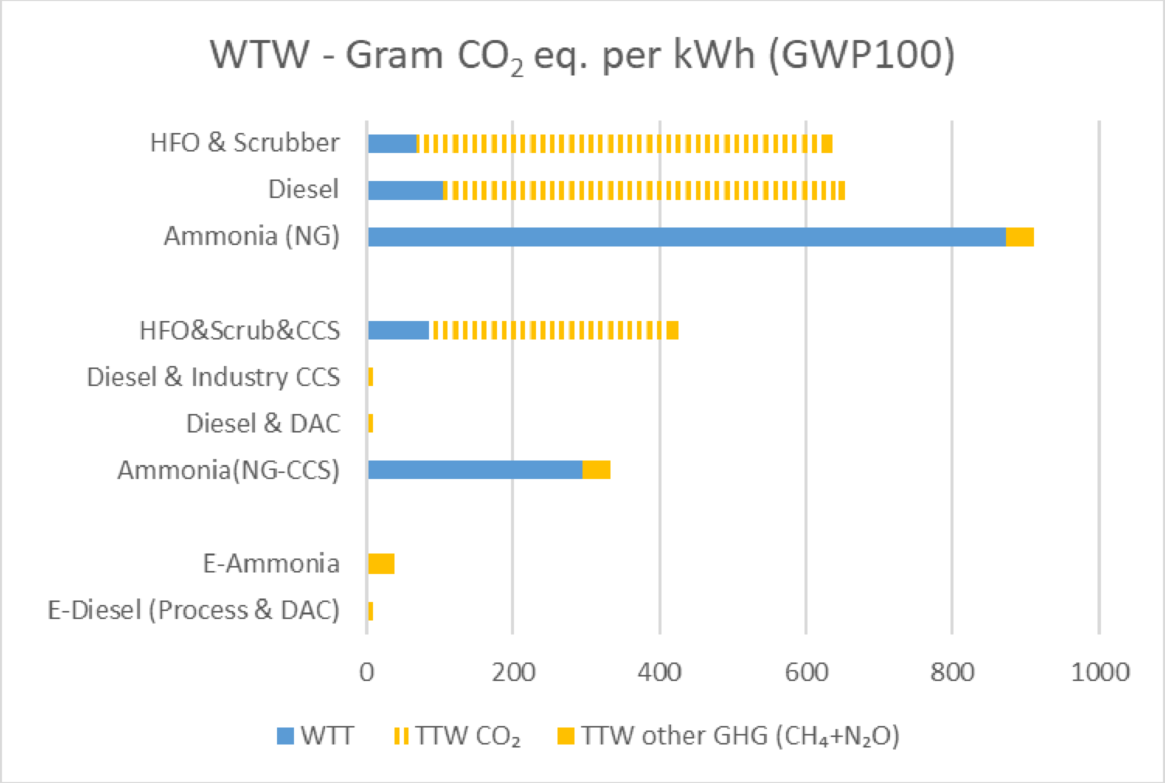
Carbon Capture & Storage versus – E-fuels

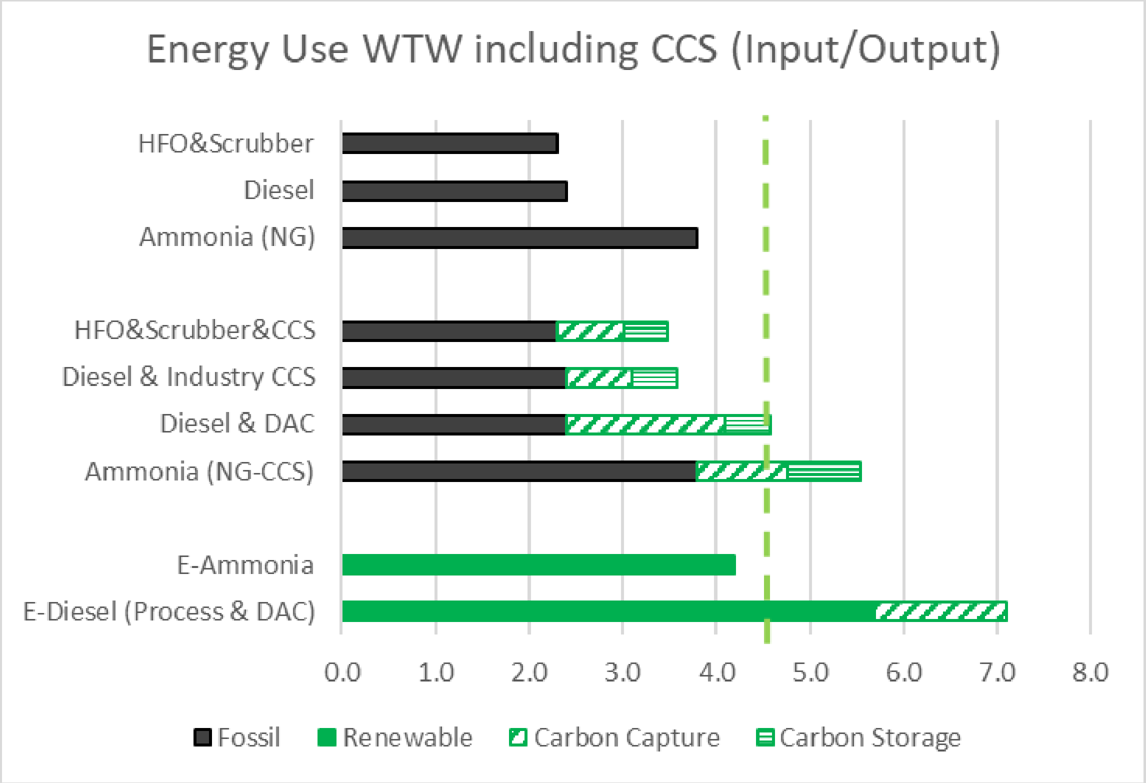


Fuel and Engine types	Annual USD/kW installed	Carbon capture % WTW incl. CCS	Cost per ton of CO2 avoided
HFO & Scrubber&SCC	1 341	41 %	416
Diesel & Industry CCS	1 328	100 %	167
Diesel & DAC	1 989	100 %	406
Ammonia(NG-CCS)	2 382	62 %	882
E-Ammonia	1 818	100 %	624
E-Diesel (process & DAC)	2 593	100 %	696

Source: Lindstad, E. et al 2023. Work in progress – Diesel & DAC and CCS might be adjusted

Carbon Capture & Storage versus – E-fuels





Source: Lindstad, E. et al 2023. Work in progress – Diesel & DAC and CCS might be adjusted

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