Maritime Fuels

Alexandre Szklo /Roberto Schaeffer

Full Prof.

COPPE/UFRJ

2025

cenergia

COPPE

UFRJ

Takeaways

- Brazil has **advantages** to kick off the production of low-emission alternative fuels for maritime transportation
- **For some SBF, logistic challenges** associated to the concentration of **hotspots in countryside areas**
- **Think about multiple hubs and how to deal with uncertainties** (e.g. dual fuel ready orderbooks vs dual fuel vs. retrofit)
- **Green shipping corridors to reduce (share) risks (in the short term) –** e.g. iron ore Brazil
- **E-fuels**: high demand for **materials, energy**, **area** and **water**
- **NH_3 as an e-fuel: +** not drop-in, low density, safety concerns, combustion concerns (N_2O emissions?)
- **Biofuels:** low quality in some cases limits blend, high quality in some cases allows drop-in, some technologies and processes are (are not) developed, i-LUC concerns (we need studies and models)

Takeaways²

- Brazil has **advantages** to kick off the production of low-emission alternative fuels for maritime transportation
- **For some SBF, logistic challenges** associated to the concentration of **hotspots in countryside areas**
- **Think about multiple hubs and how to deal with uncertainties** (e.g. dual fuel ready orderbooks vs dual fuel vs. retrofit)
- **Green shipping corridors to reduce (share) risks (in the short term) –** e.g. iron ore Brazil
- **E-fuels**: high demand for **materials, energy**, **area** and **water**
- **NH_3 as an e-fuel: +** not drop-in, low density, safety concerns, combustion concerns (N_2O emissions?)
- **Biofuels:** low quality in some cases limits blend, high quality in some cases allows drop-in, some technologies and processes are (are not) developed, i-LUC concerns (we need studies and models)

Regarding land use demand (land use change) and even water consumption: all SBFs can face sustainability issues; this is not a challenge exclusive to biofuels. Therefore, LCA criteria that refer to d-LUC should not be specific to biofuels; they should be neutral and account for d-LUC for all SBFs.

The demand for DAC land is enormous, as is the demand for dispersed source land. NH3 is important as a nitrogen fertilizer...

Article https://doi.org/10.1038/s41467-023-41107-x

Global land and water limits to electrolytic hydrogen production using wind and solar resources

Received: 22 March 2023

Accepted: 22 August 2023

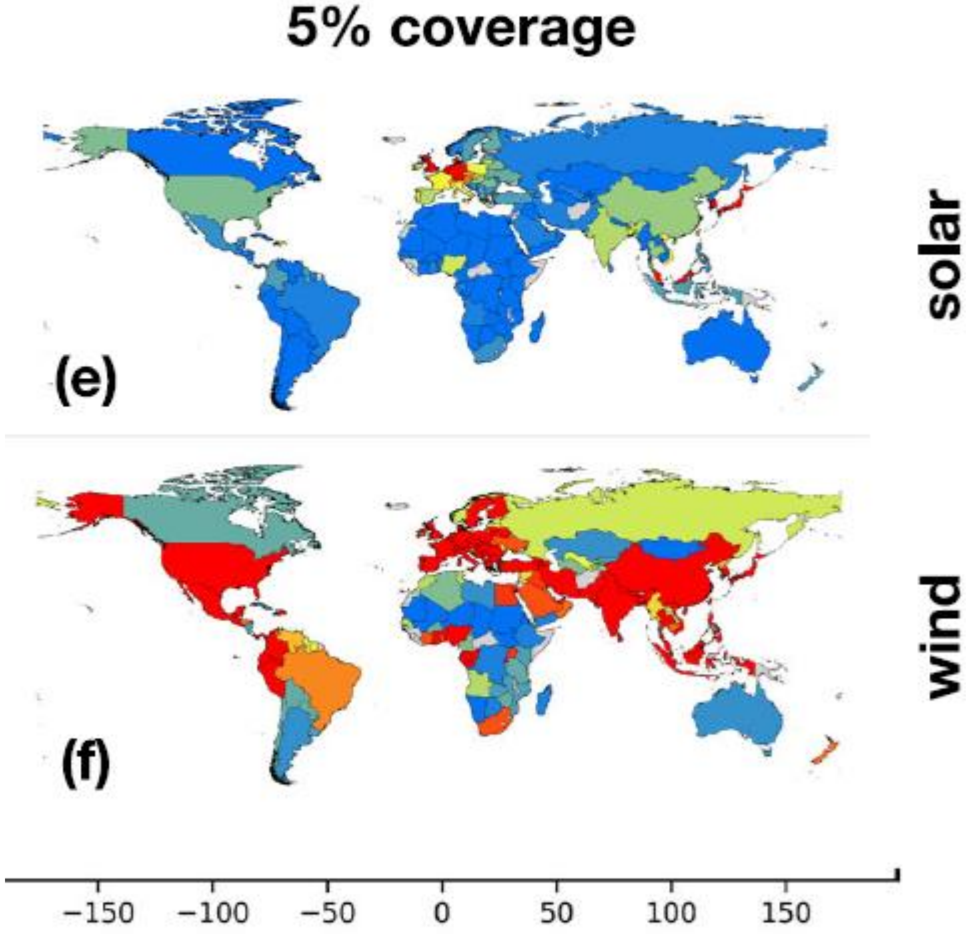
Published online: 08 September 2023

Check for updates

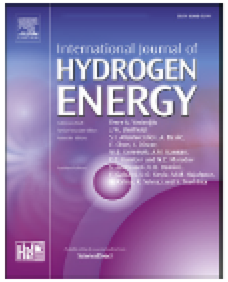
Davide Tonelli[1,2,3], Lorenzo Rosa[3], Paolo Gabrielli[3,4], Ken Caldeira[3,5], Alessandro Parente[2] & Francesco Contino[1]

Proposals for achieving net-zero emissions by 2050 include scaling-up electrolytic hydrogen production, however, this poses technical, economic, and environmental challenges. One such challenge is for policymakers to ensure a sustainable future for the environment including freshwater and land resources while facilitating low-carbon hydrogen production using renewable wind and solar energy. We establish a country-by-country reference scenario for hydrogen demand in 2050 and compare it with land and water availability. Our analysis highlights countries that will be constrained by domestic natural resources to achieve electrolytic hydrogen self-sufficiency in a net-zero target. Depending on land allocation for the installation of solar panels or wind turbines, less than 50% of hydrogen demand in 2050 could be met through a local production without land or water scarcity. Our findings identify potential importers and exporters of hydrogen or, conversely, exporters or importers of industries that would rely on electrolytic hydrogen. The abundance of land and water resources in Southern and Central-East Africa, West Africa, South America, Canada, and Australia make these countries potential leaders in hydrogen export.

https://doi.org/10.1038/s41467-023-41107-x



The sustainability of green hydrogen: An uncertain proposition



L. Cremonese, G.K. Mbungu, R. Quitzow*

Research Institute for Sustainability (RIFS Potsdam), Helmholtz Centre Potsdam, Berliner Strasse 130, 14467 Potsdam, Germany

H I G H L I G H T S

- Production and export of GH raise questions of sustainability and climate justice.
- Land and freshwater availability are key risks for local communities.
- Community engagement is needed to mitigate local environmental risks factors.
- International standards for governance of hydrogen projects are key to sustainability.
- Climate-related risks should be included in sustainability standards.

land

Review

Green Hydrogen Production and Its Land Tenure Consequences in Africa: An Interpretive Review

Uchendu Eugene Chigbu [1,*] and Chigozie Nweke-Eze [2,3]

[1] Faculty of Engineering and the Built Environment, Department of Land and Spatial Sciences, Namibia University of Science and Technology, 13 Jackson Kaujeua Street, Private Bag, Windhoek 13388, Namibia
[2] Integrated Africa Power, Königswinterer Straße 382, 53227 Bonn, Germany; cne@intafripower.de
[3] Institute of Geography, University of Bonn, Meckenheimer Allee 166, 53115 Bonn, Germany
[*] Correspondence: echigbu@nust.na; Tel.: +264-61-207-2470

Part 1a

Background

energies

Article

Biofuels for Maritime Transportation: A Spatial, Techno-Economic, and Logistic A
South Africa, and the USA

Francielle Carvalho [1,*], Joana Portugal-Pereira [1], Martin Ju

Wiley
International Journal of Energy Research
Volume 2025, Article ID 8835499, 16 pages
https://doi.org/10.1155/er/8835499

Research Article

...n Shipping Fuels in Long-Haul

..., [1] Alexandre Szklo, [1] Pedro R. R. Rochedo, [2] and

Cleaner Production Letters 4 (2023) 100028

Energy Policy 160 (2022) 112699

Contents lists available at ScienceDirect

Energy Policy

...page: www.elsevier.com/locate/enpol

WILEY

...ort Mitigation Measures according to their mitigation potentials

..., Alexandre Szklo [b], David Alves Castelo Branco [b]

...) 129385

...Direct

Journal of Cleaner Production

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

...neutral maritime fuels production in Brazil

...theus Poggio, Tainan Nogueira,
...eira, Pedro R.R. Rochedo, Alexandre Szklo,

CellPress OPEN ACCESS

nature climate change

Article https://doi.org/10.1038/s41558-024-01997-1

International shipping in a world below 2 °C

Received: 19 May 2023
Accepted: 26 March 2024
Published online: 22 May 2024
Check for updates

Eduardo Müller-Casseres [1], Florian Leblanc [2,3], Maarten van den Berg [4], Panagiotis Fragkos [5], Olivier Dessens [6], Hesam Naghash [7], Rebecca Draeger [1], Thomas Le Gallic [3,8], Isabela S. Tagomori [4], Ioannis Tsiropoulos [5], Johannes Emmerling [9], Luiz Bernardo Baptista [1], Detlef P. van Vuuren [4,10], Anastasis Giannousakis [5], Laurent Drouet [9], Joana Portugal-Pereira [1,11], Harmen-Sytze de Boer [4], Nikolaos Tsanakas [5], Pedro R. R. Rochedo [12], Alexandre Szklo [1] & Roberto Schaeffer [1]

Artic...
Ev...
Al...
Hua...

[b] PBL Netherlands Environmental Assessment Agency, The Hague, the Netherlands
[c] Faculty of Geosciences, Utrecht University, Utrecht, the Netherlands

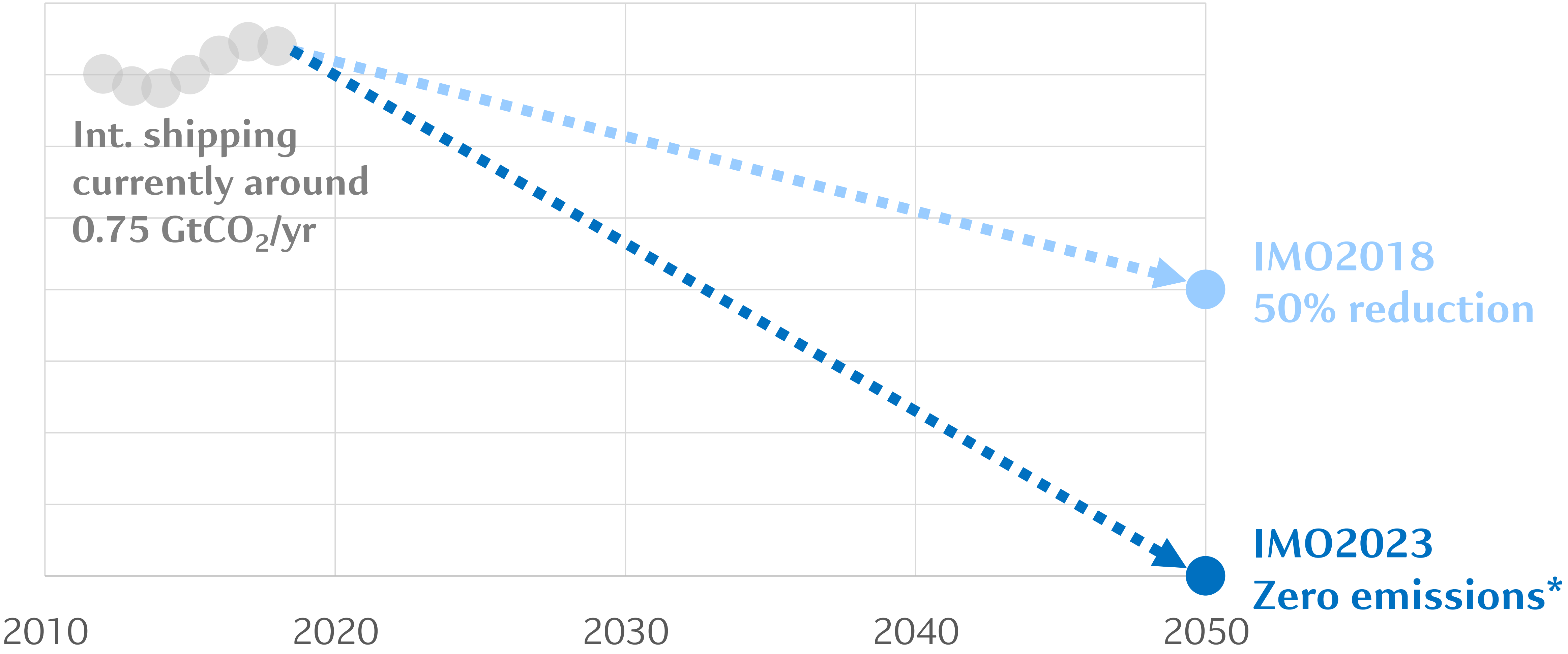
iScience

Article

Are there synergies in the decarbonization of aviation and shipping? An integrated perspective for the case of Brazil

Eduardo Müller-Casseres, [1] Alexandre Szklo, [1] Clarissa Fonte, [1] Francielle Carvalho, [1] Joana Portugal-Pereira, [1,2,3] Luiz Bernardo Baptista, [1] Pedro Maia, [1] Pedro R.R. Rochedo, [1] Rebecca Draeger, [1] and Roberto Schaeffer [1,4,*]

IMO2018 and IMO2023



IMO Mid-Term Measures: Net-Zero Framework (NZF) (MEPC 83)

—

Global Fuel Standard

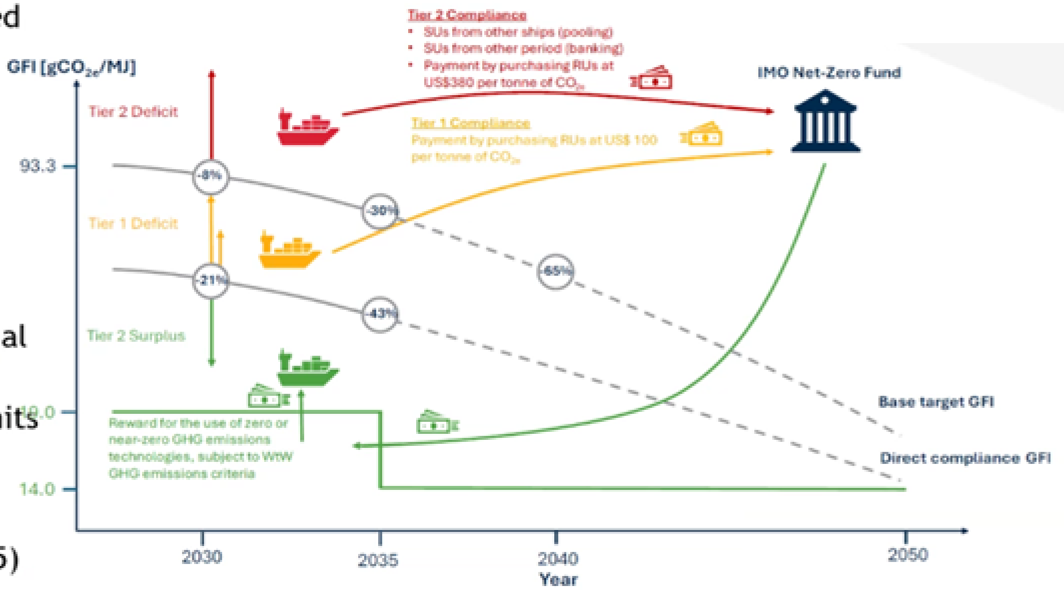
- Annual GHG Fuel Intensity (GFI) reduction required
- Based on Well-to-Wake lifecycle emissions
- Applies at the individual ship level

Compliance & Pricing

- Attained GFI compared to two thresholds:
  - ✓ Base Target (Tier 2): Baseline compliance
  - ✓ Direct Target (Tier 1): High-Exceedance
- Ships exceeding thresholds must purchase Remedial Units (RUs)
- Ships below the Direct Target generate Surplus Units (SUs)

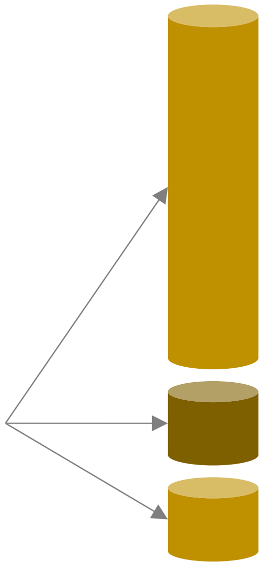
Fuel Incentives

- Fuels ≤19 gCO_2eq/MJ (pre-2035) or ≤14 (post-2035) may earn ZNZ rewards
- Only certified fuels are eligible (via SFCS)

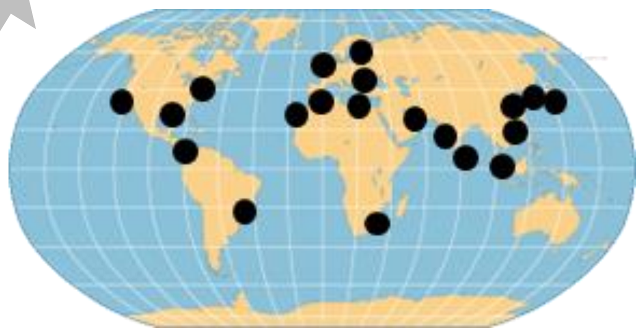


However...

Crude oil
~170 EJ/yr



Int. shipping
~9 EJ/yr



Fuelling hubs
Homogeneous industry
Low price fossil fuel

	Production maturity	Applicability	Energy density	Safety and toxicity
Alcohols	+	0	0	+
Ammonia	0	−	−	−
Hydrogen	0	−	x	−
Natural gas	+	0	0	0
Synthetic liquids	−	+	+	+
Vegetable oils	+	0	+	+

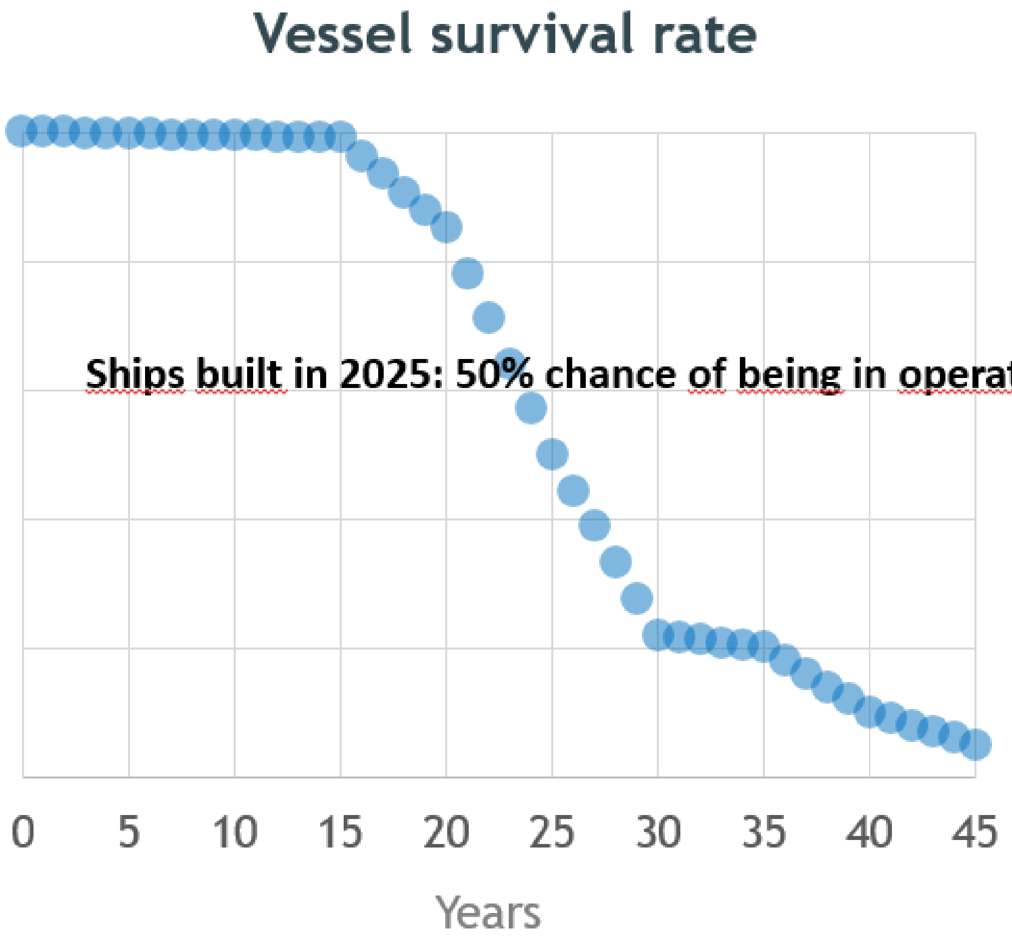
In contrast...

Eduardo Müller-Casseres et al. 2024

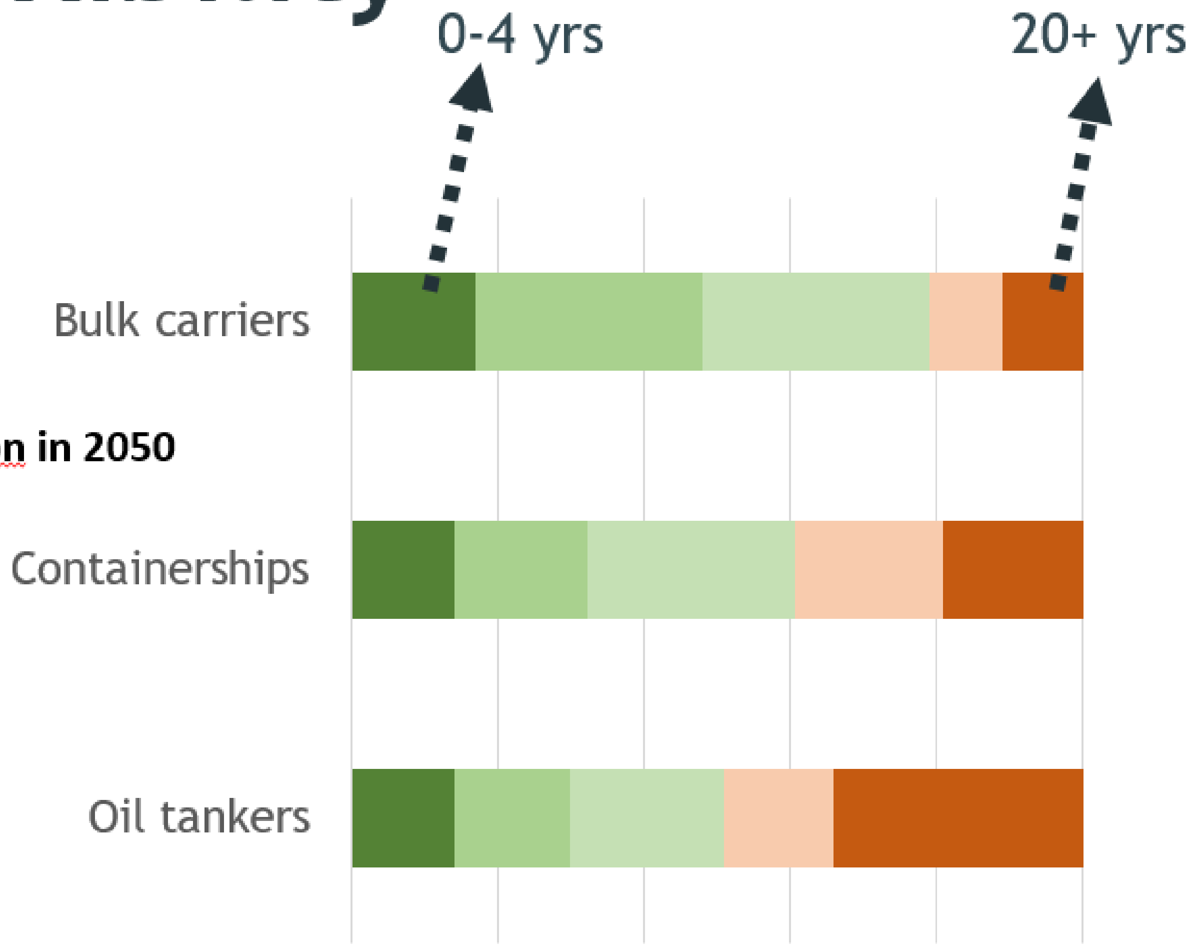
Status in 2023/2025

- The world maritime fleet consisted ≈ 105 x 10^3 vessels with a total cargo capacity of approximately 2.3 billion metric-tons (UNCTAD, 2023)
- Vessels consumption ≈ 14 EJ in 2018: HFO (65%), MDO/MGO (31%), LNG (4%), MeOH (0.02%) (Faber et al., 2020)
- China: 40% of global shipping activity related to fuels and heavy industry + major port operator (20% of world containers in just 3 ports)

Technological inflexibility



Ships built in 2025: 50% chance of being in operation in 2050

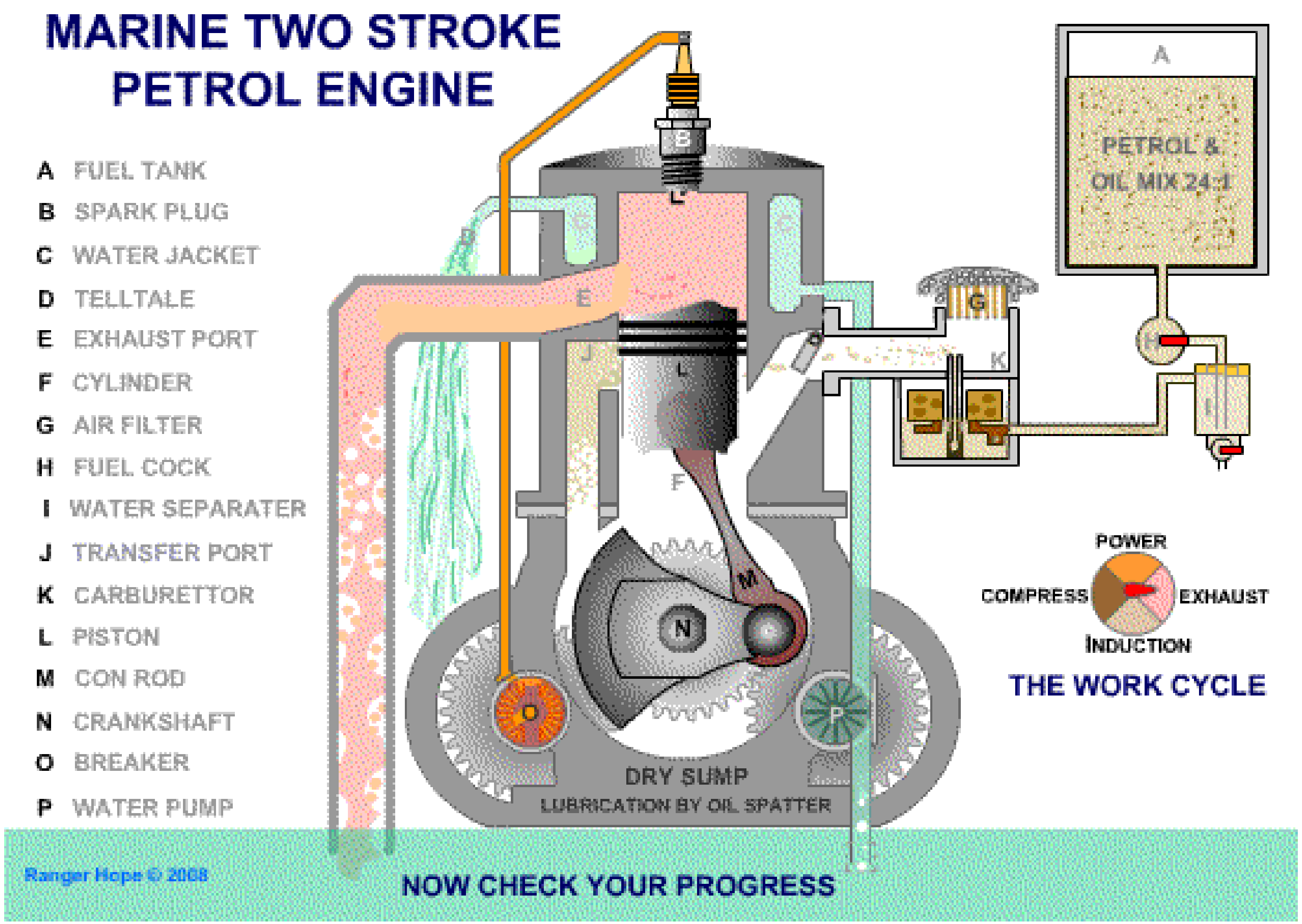


Eduardo Müller-Casseres et al. 2024

- Globally, 1/3 of fleet is older than 15 years
- The average global fleet age in 2024 is 12.5 years (can be higher depending on the ship type)
- The pool of yards capable of carrying out fuel retrofit is small, and turnkey retofits are complex requiring capabilities not always available at all yards (skilled workforce + safely handle and deploy alternative fuels)
- In terms of new fleet (orderbook)...

Part 1b

Bunker



MARINE TWO STROKE PETROL ENGINE
A FUEL TANK
B SPARK PLUG
C WATER JACKET
D TELLTALE
E EXHAUST PORT
F CYLINDER
G AIR FILTER
H FUEL COCK
I WATER SEPARATER
J TRANSFER PORT
K CARBURETTOR
L PISTON
M CON ROD
N CRANKSHAFT
O BREAKER
P WATER PUMP
PETROL & OIL MIX 24:1
DRY SUMP
LUBRICATION BY OIL SPATTER
POWER
COMPRESS
EXHAUST
INDUCTION
THE WORK CYCLE
Ranger Hope © 2008
NOW CHECK YOUR PROGRESS

ISO

Regulation 18

Fuel oil availability and quality

Regulation 18.3 reads as follows:

> "Fuel oil for combustion purposes delivered to and used on board ships to which this Annex applies shall meet the following requirements."

Interpretation

13.1 A fuel oil which is a blend of not more than 30% by volume of biofuel should meet the requirements of regulation 18.3.1 of MARPOL Annex VI. A fuel oil which is a blend of more than 30% by volume of biofuel should meet the requirements of regulation 18.3.2 of MARPOL Annex VI. For the purposes of this interpretation, a biofuel is a fuel oil which is derived from biomass and hence includes, but is not limited to, processed used cooking oils, fatty-acid-methyl-esters (FAME) or fatty-acid-ethyl-esters (FAEE), straight vegetable oils (SVO), hydrotreated vegetable oils (HVO), glycerol or other biomass to liquid (BTL) type products. The Product Name, as entered onto the bunker delivery note, should be of sufficient detail to identify whether, and to what extent, a biofuel is blended into the product as supplied.

Regulation 18.3.2.2 reads as follows:

> "fuel oil for combustion purposes derived by methods other than petroleum refining shall not cause an engine to exceed the applicable NO_X emission limit set forth in paragraphs 3, 4, 5.1.1 and 7.4 of regulation 13."

- Iso 8217 … biofuels. Blends o… plugging point for …
- Marpol 2… ee, at its seventy-… ation 18.3 of MARP…

Part 1c

SBF

- What about maritime **Biodiesel** (almost all FAME) by 2030? 1.8 billion liters (0.06 EJ), driven by ReFuelEU Maritime legislation.

- **What about NH_3**? Market = 188.4 Mt in 2024 (production capacity of around 190 Mt, = 42 Mt). By 2030: 207 Mt. More than 80% as fertiliser. As a fuel, almost zero.

- **What about** H_2 **(needed for e-fuels and NH_3)**? Market in 2024 ≈ 12 EJ (97 Mt). Low-emissions hydrogen, made from fossil fuels with CCUS, from bioenergy or through electrolysis, makes up less than 1% of global supply. Natural gas with CCUS was the source for most low-emissions hydrogen produced in 2024, while electrolytic hydrogen made up less than 0.1%.

Groups

Group 1: Distilled Biofuels

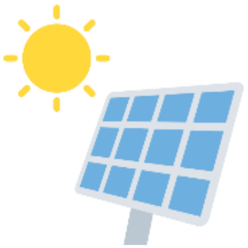
- SVO
- Biodiesel
- HVO
- HDPO
- FT-diesel
- ATD

Group 2: Alcohol and liquefied gases

- Bio-LNG
- Biomethanol
- Bioethanol

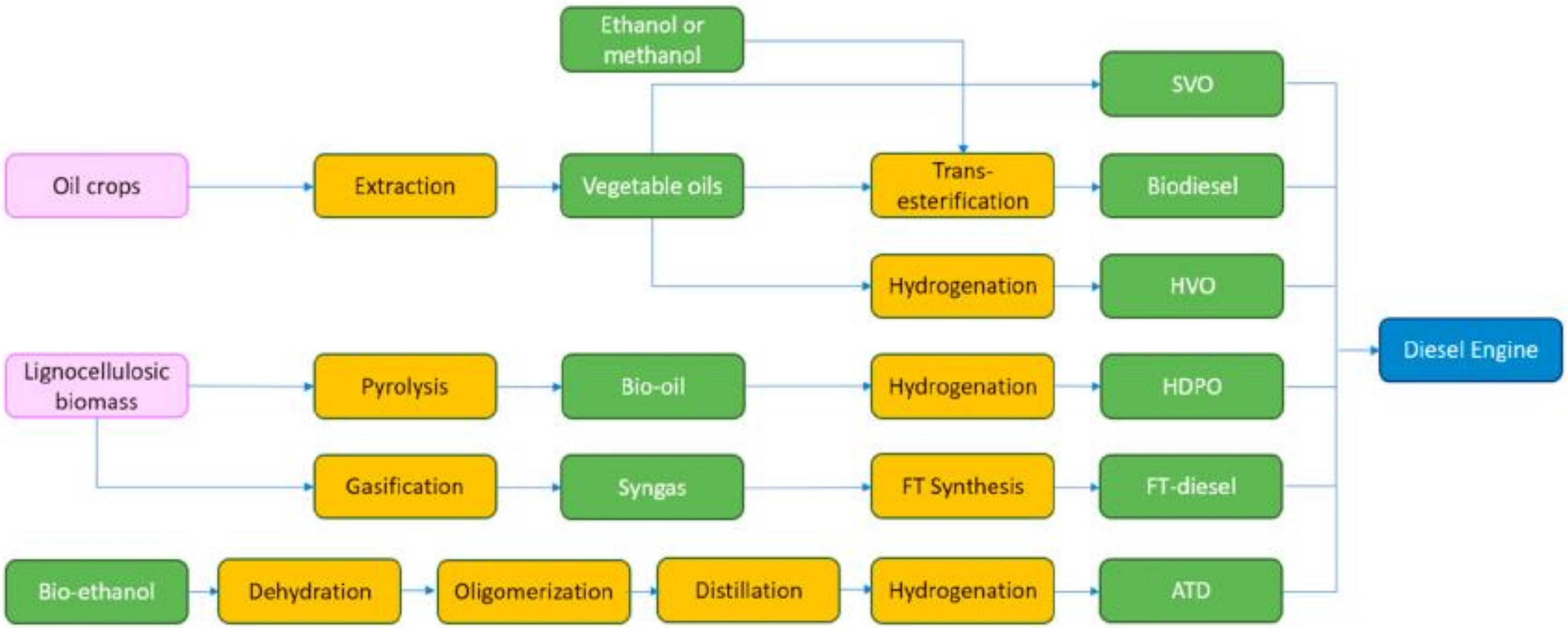
Group 3: Hydrogen-based fuels

- Green H_2
- Green NH_3
- e-diesel
- e-LNG
- e-methanol



Icons: freepik/flaticon

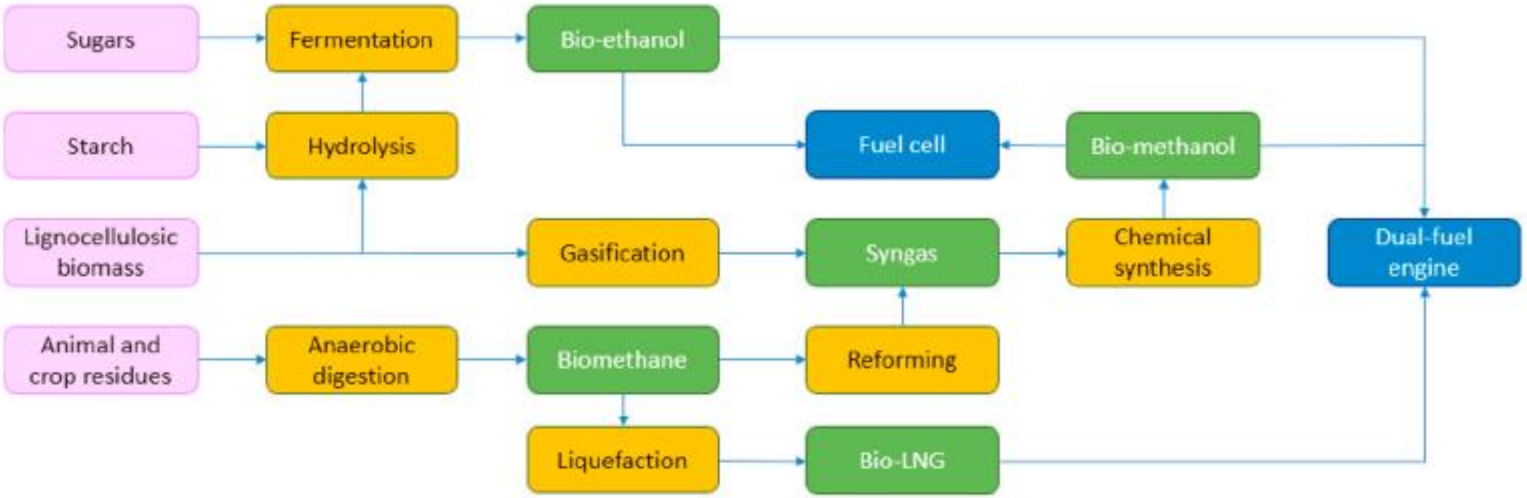
Distilled Fuels
GROUP 1



(a)

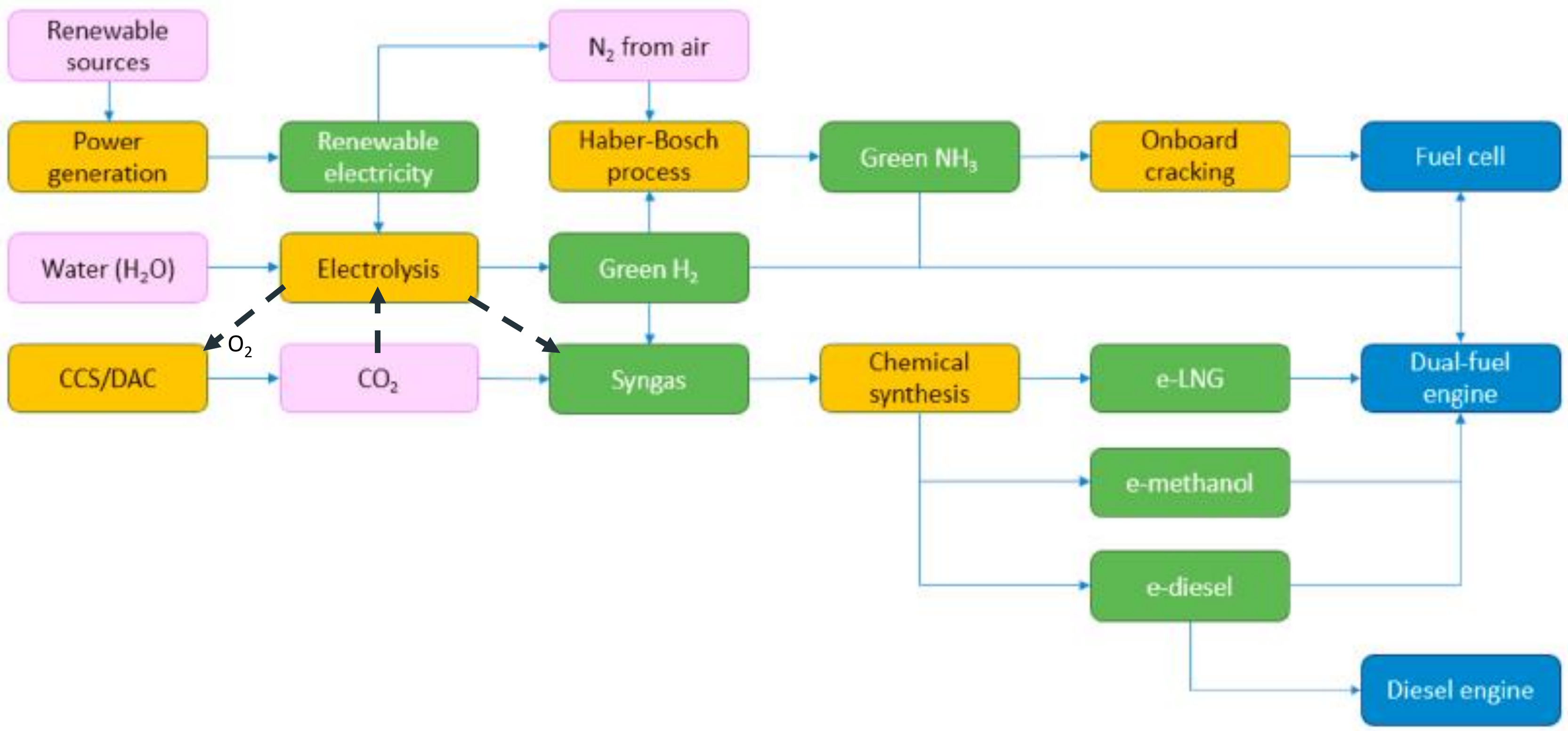
Alcohols and gases

GROUP 2



E-fUELS

GROUP 3



Co-electrolysis, oxyfuel capture...

Part 1d

Comparison

Criteria for comparative analysis

AVAILABILITY	APPLICABILITY	TECHNOLOGICAL MATURITY
Feedstock and production infrastructure	Existing fleet and bunkering infrastructure	Readiness level (production and use)
ENERGY DENSITY	**ECONOMIC**	**SAFETY**
Requirement of space for fuel storage	LCOE - fuel, bunkering and ship modifications	Safety in operation and toxicity
STANDARDS	**LOCAL SUSTAINABILITY**	**GLOBAL SUSTAINABILITY**
Existence of standards and certifications	Air pollutant emissions, impacts on water	Direct and indirect GHG emissions

- Technical
- Economic
- Environmental

Icons: freepik/flaticon

Operational safety

MGO
- Flammable liquid and vapour
- Toxic to aquatic life
- Aspiration hazards

LNG
- Highly flammable gas
- Cryogenic gas risks

Hydrogen
- Highly flammable gas
- Cryogenic gas risks

Biomethanol
- Highly flammable liquid and vapour
- Toxic if swallowed or in contact with skin

Ammonia
- Flammable gas
- Gas under pressure
- Toxic, skin burns
- Toxic to aquatic life

Applicability

Fuel Property	Heating Value	Volumetric Density	Energy Density	Viscosity at 40 °C	Acidity	Flash Point	Self-Ignition Temperature	Aromaticity Index (CCAI)
Unit	MJ/kg	kg/m³	MJ/m³	mm/s²	Mg KOH/g	°C	°C	-
HFO	40.0 [a]	991 [a]	39,640	380 [i]	2.5 [i]	>60 [i]	407 [p]	856.5 [u]
MGO	42.0 [a]	890 [a]	37,380	3.5 [i]	0.5 [i]	>60 [i]	257 [q]	808.1 [u]
LNG	50.0 [b]	415 [b]	20,750	-	-	−188 [b]	537 [o]	-
Biodiesel	37.1[c]	885 [c]	32,833.5	4–6 [j]	0.052–0.295 [m]	>93 [c]	374–449 [r]	822.6 [u]
SVO	37–39.62 [a]	900–930 [a]	33,300–36,847	14–40 [k]	0.02–20 [n]	>400 [k]	405 [s]	836.6–878.7 [u]
HVO	44.1 [d]	780 [d]	34,398	3 [d]	-	99 [d]	204 [o]	738.4 [u]
HPO	28.9 [e]	1150 [h]	33,235	9 [h]	21.3–76.1 [h]	53–101 [h]	340 [t]	1076 [u]
Ammonia	18.6 [g]	758 [g]	14,101	-	-	132 [o]	630 [o]	-
Methanol	20.1 [f]	798 [f]	16,040	0.58 [l]	-	12 [f]	470 [o]	837.6 [u]

Journal of
Marine Science and Engineering

Article

Evaluating the Readiness of Ships and Ports to Bunker and Use Alternative Fuels: A Case Study from Brazil

Huang Wei [1], Eduardo Müller-Casseres [1], Carlos R. P. Belchior [2] and Alexandre Szklo [1,*]

Criteria	LNG	Biodiesel	SVO	HVO	HPO	Methanol	Ammonia
Energy density HFO/fuel	1.91	1.21	1.19–1.08	1.15	1.19	2.47	2.81
Bunkering readiness	Already worldwide established	Adaptation to biodiesel properties, narrow shaped tanks, constant cleaning	Procedures are similar to HFO bunkering	Procedures are similar to MDO bunkering	Urge of development all bunkering process	Under establishment, ventilation reinforcement	Ammonia bunkering is already performed in the chemical industry
Material compatibility	Aluminium and stainless steel	Stainless steel or zinc reinforcement	Stainless or mild steel if coated with zinc silicate	No changes are needed	Stainless steel	Stainless or austenitic manganese steel	Stainless steel
Storage tanks	Double-walled, cryogenic storage (−162°), 10 bar pressure, inert	Isolated from machinery	Isolated from machinery, coated with vegetable oil inert material	Constant maintenance to avoid water contamination	Isolated from machinery, coated with biomass oil inert material	Double-walled, detection system to leakages	Double-walled, isolated from machinery, pressure of 8.6 bar
Engine feed	Double-walled, Ventilation reinforcement, 10 bar feed pressure	Filtering, constant maintenance	Pre-heating (67 to 78 °C), filtering, constant maintenance	No changes are needed	Pre-heating, piping designed to not block solid particles, filtering	Double-walled, ventilation reinforcement, pressure of 10 bar	Double-walled, ventilation reinforcement
Engine option	Dual fuel	Diesel engine	Diesel engine	Diesel engine	Diesel engine	Dual fuel	Fuel cell (dual-fuel is also an option)
Safety	Cryogenic and flammable	Low temperature use restricted due to low pour point, low toxicity	Low toxicity	Low toxicity	Low toxicity	Highly toxic and flammable	Highly toxic and flammable
TRL	9	7	5	5	2	7	5

Journal of Marine Science and Engineering

Article

Evaluating the Readiness of Ships and Ports to Bunker and Use Alternative Fuels: A Case Study from Brazil

Huang Wei [1], Eduardo Müller-Casseres [1], Carlos R. P. Belchior [2] and Alexandre Szklo [1,*]

Part 2a

Georeferenced analysis and
Life cycle assessment of selected fuels

6-steps

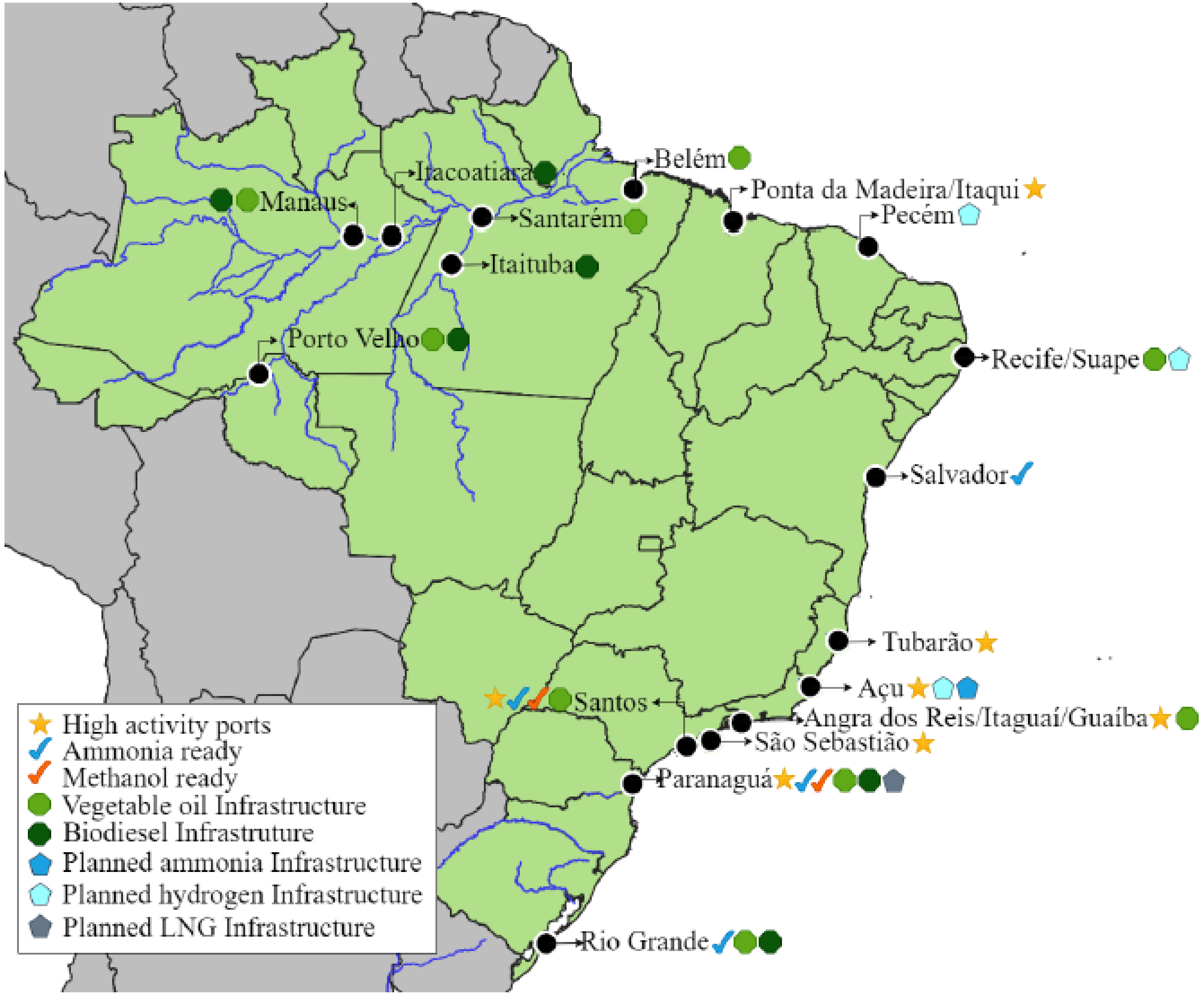
Geogra
modelling
feeds

al potential
mates

TJ/yr

Modell
maritime t

on to current
ker fuel
umption



Feedstocks and energy resources

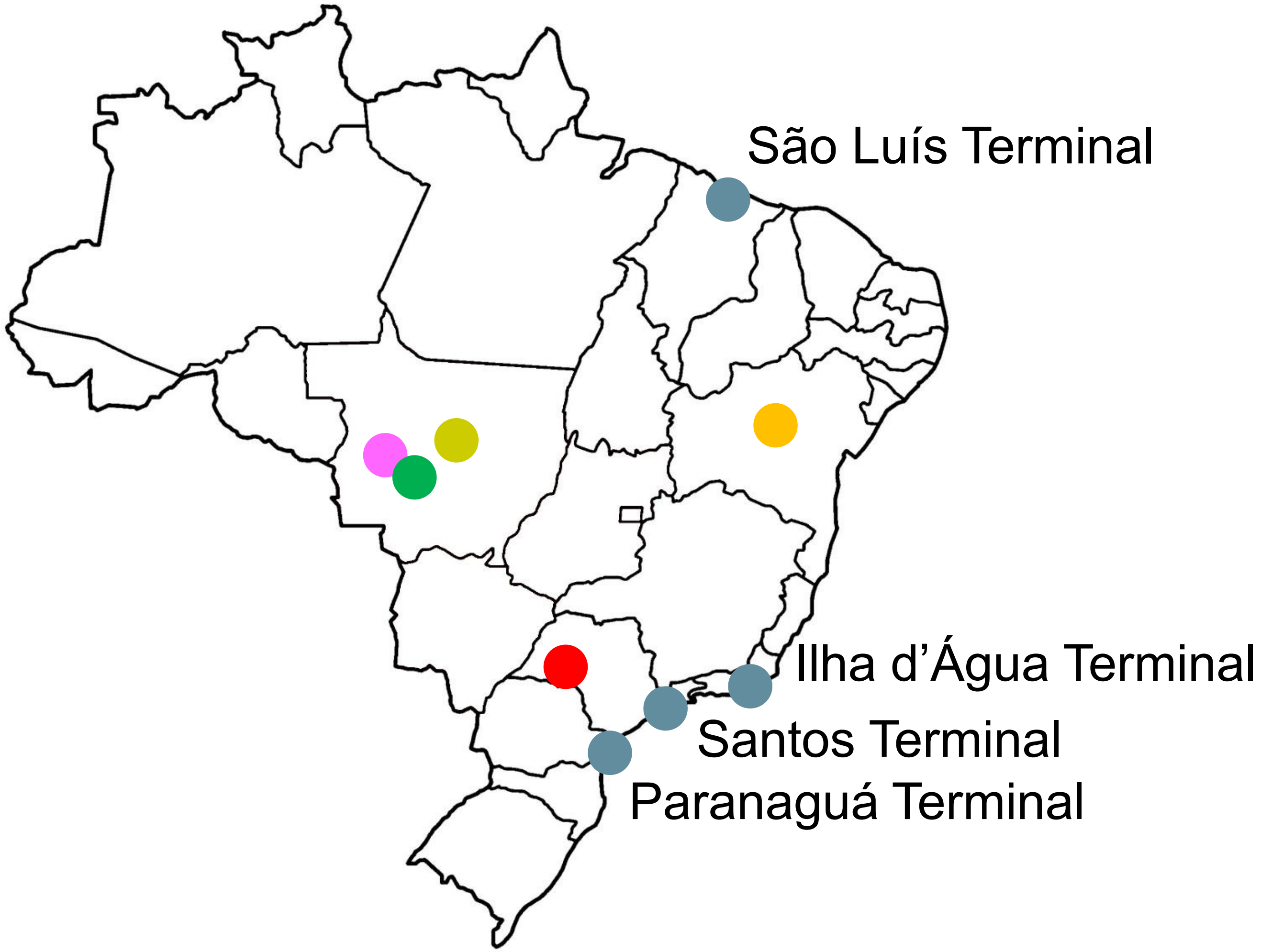
SVO/HVO	FT-diesel	Bio-CH_3OH	e-diesel
○ **Soybean** oil	○ **Sugarcane** straw and bagasse	○ **Rice** straw/husk	○ **Solar** irradiation
○ **Corn** oil	○ **Soybean** straw	○ **Soybean** straw	○ **Water** (H_2O)
○ **Cotton** oil	○ **Corn** stover	○ **Corn** stover	○ **Sodium** hydroxide
○ **Sunflower** oil	○ **Wheat** straw	○ **Wheat** straw	○ **Calcium** carbonate
○ **Peanut** oil	○ **Eucalyptus/Pinus** residues and cuts	○ **Vinasse**	○ Natural **gas** (CH_4)
○ **Mammon** oil	○ **Forest extraction** residues and cuts	○ Animal **manure**	○ **Oxygen** (O_2)
		○ **MSW**	
		○ Sewage **sludge**	

HVO Hotspots

PRODUCTION POTENTIAL (TJ/year)

● *Soybean oil*	6,500
● *Corn oil*	2,000
● *Cotton oil*	1,200
● *Peanut oil*	470
● *Sunflower oil*	160
● *Mammon oil*	23
Total HVO	***9,800** TJ/yr*
Fuel oil*	***24,900** TJ/yr*

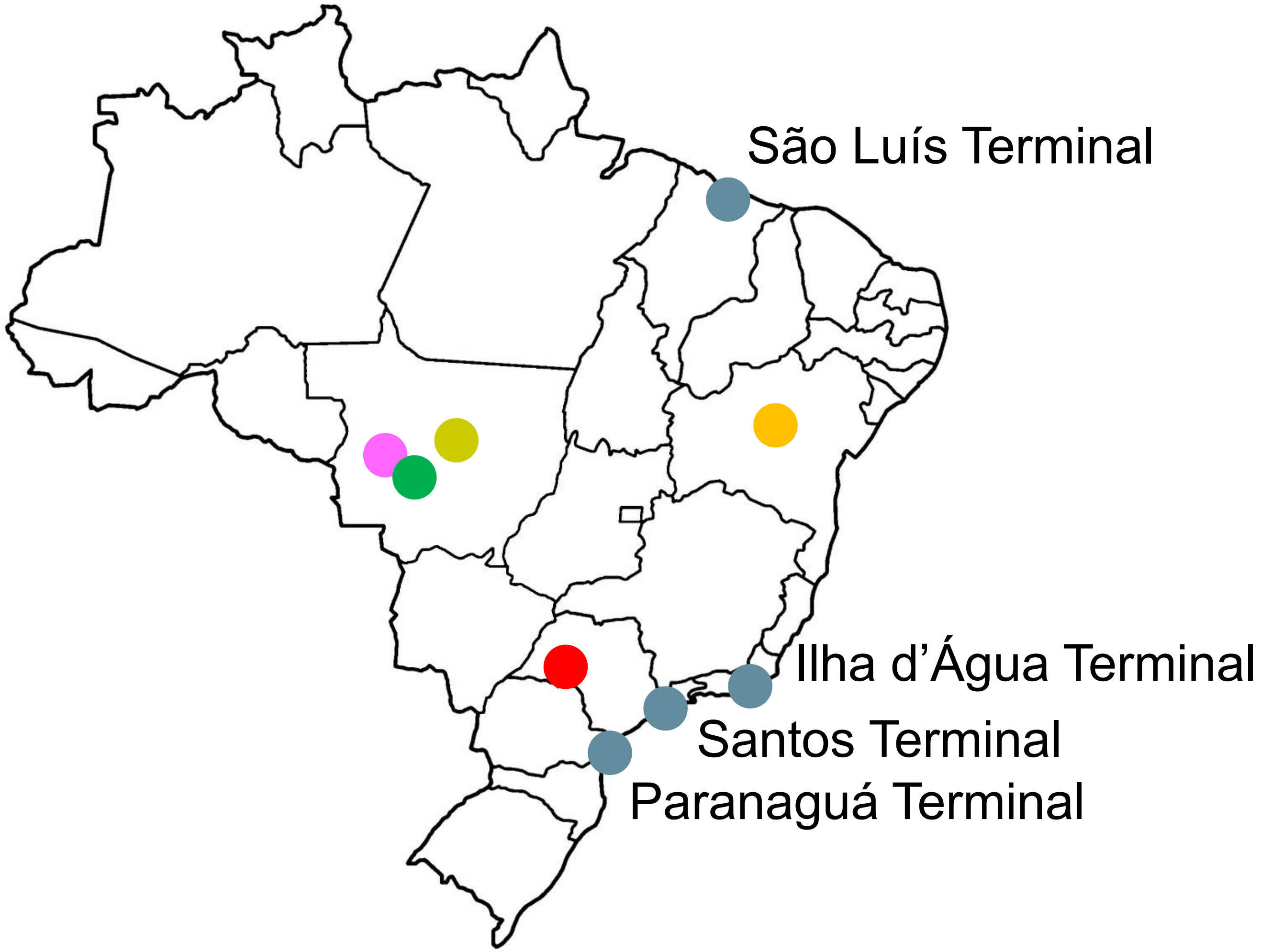
*Average fuel oil production in a Brazilian oil refinery



SVO/HVO hotspots are far from closest terminals

	Terminal	d (km)
Soybean	Santos	1,467
Corn	Santos	1,466
Cotton	Paranaguá	1,592
Peanut	Paranaguá	401
Sunflower	Paranaguá	1,521
Mammon	São Luís	930

Feasible?



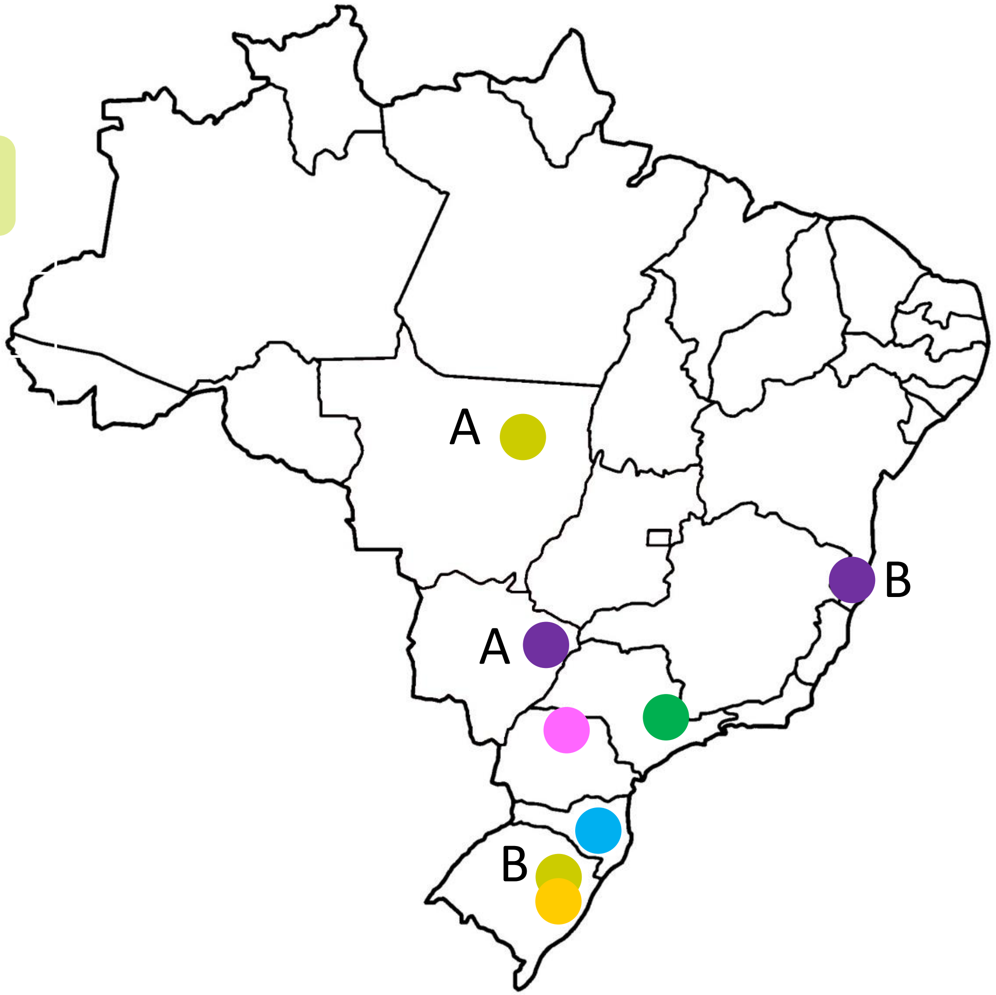
FT-diesel Hotspots

PRODUCTION POTENTIAL (TJ/year)

Sugarcane	23,600
Soybean A	13,700
Soybean B	11,500
Corn	7,100
Wheat	1,100
Eucalyptus A	12,700
Eucalyptus B	9,400
Pinus	10,700
Forest Extraction	530
Fuel oil*	***24,900** TJ/yr*

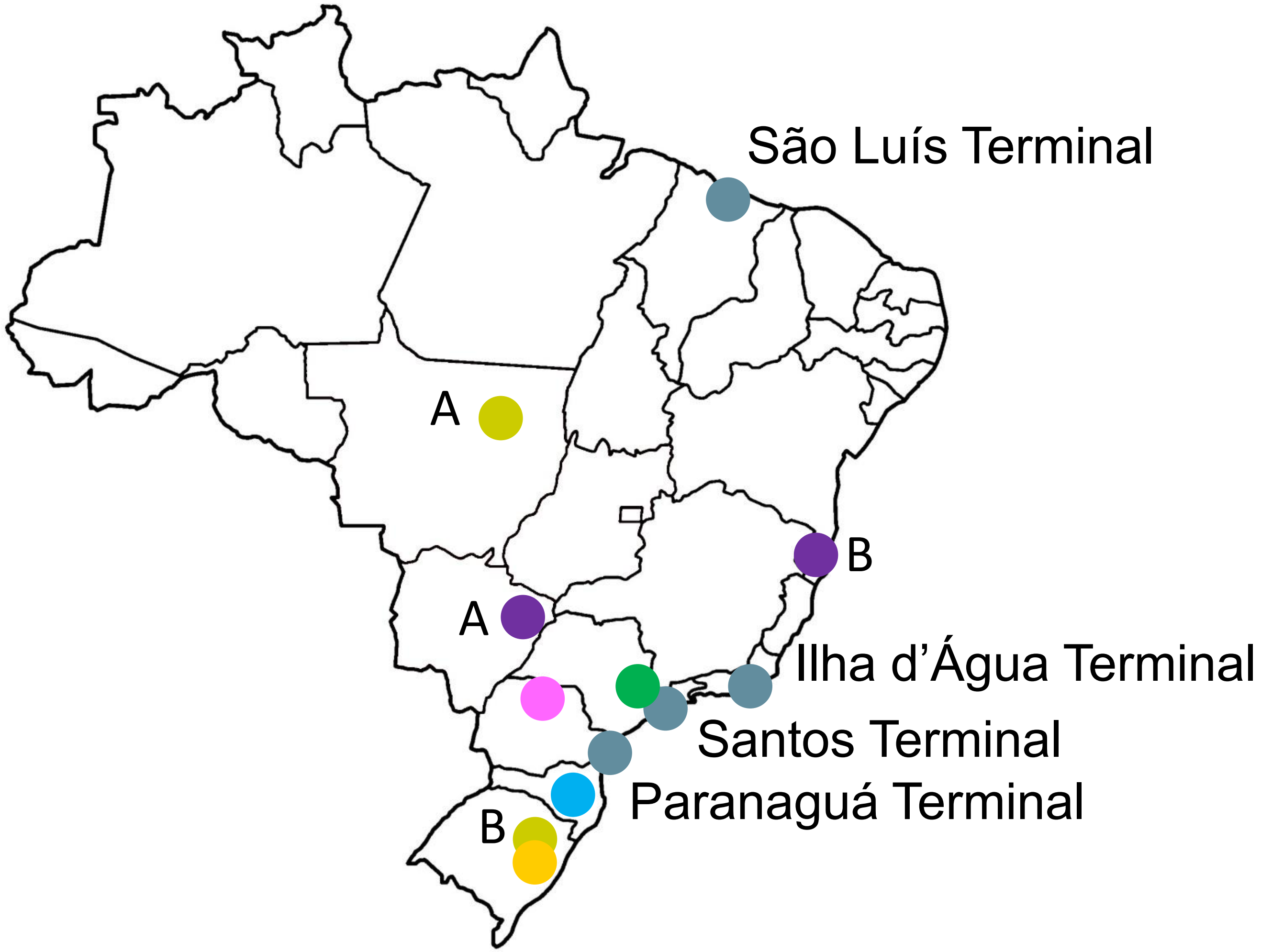
60%

*Average fuel oil production in a Brazilian oil refinery



FT-diesel hotspots in south and southeast regions are close to terminals

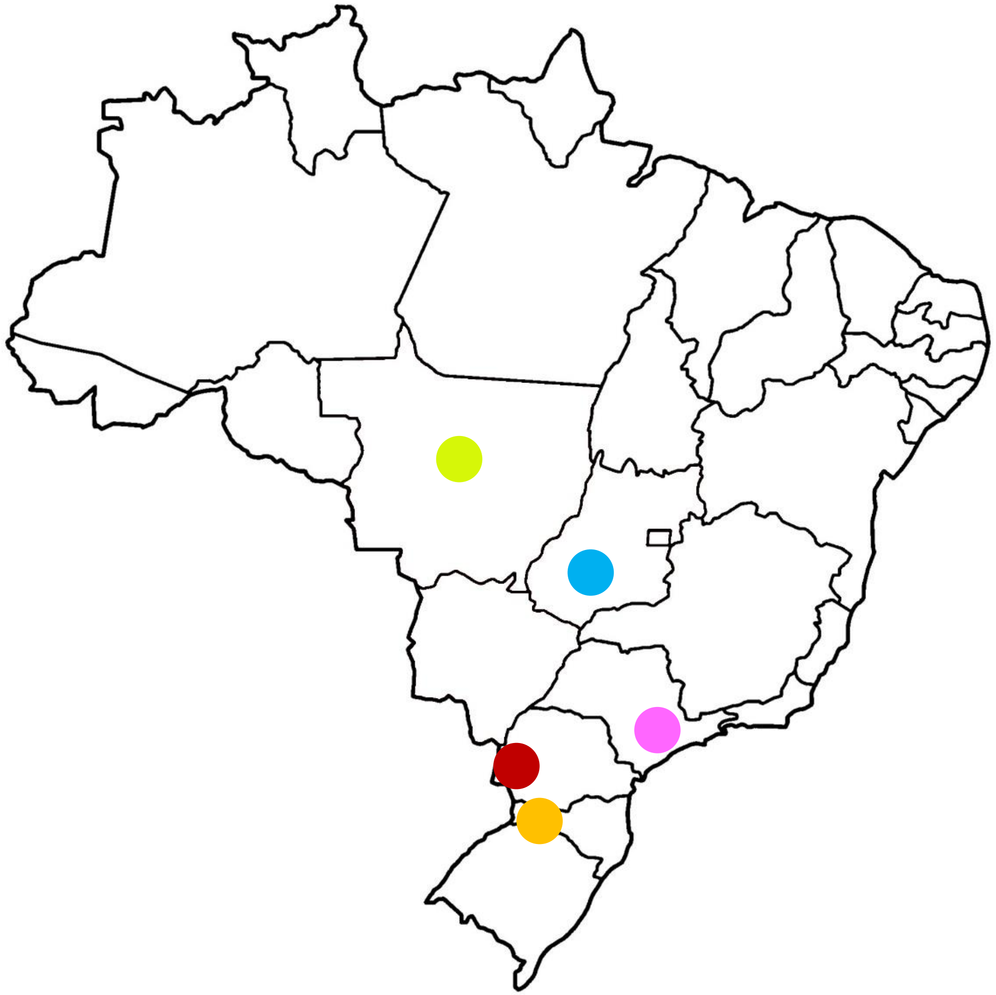
	Terminal	d (km)
Sugarcane	Santos	151
Soybean A	São Luís	1,352
Soybean B	Paranaguá	474
Corn	São Luís	1,346
Wheat	Paranaguá	413
Eucalyptus A	Paranaguá	636
Eucalyptus B	Ilha d'Água	611
Pinus	Paranaguá	265
Forest Extraction	Paranaguá	505



Bio-methanol hotspots

PRODUCTION POTENTIAL (TJ/year)

● *Hotspot PR*	50,900
● *Hotspot GO*	35,800
● *Hotspot MT*	74,500
● *Hotspot SC*	35,100
● *Hotspot SP*	11,900
Fuel oil*	***24,900** TJ/yr*

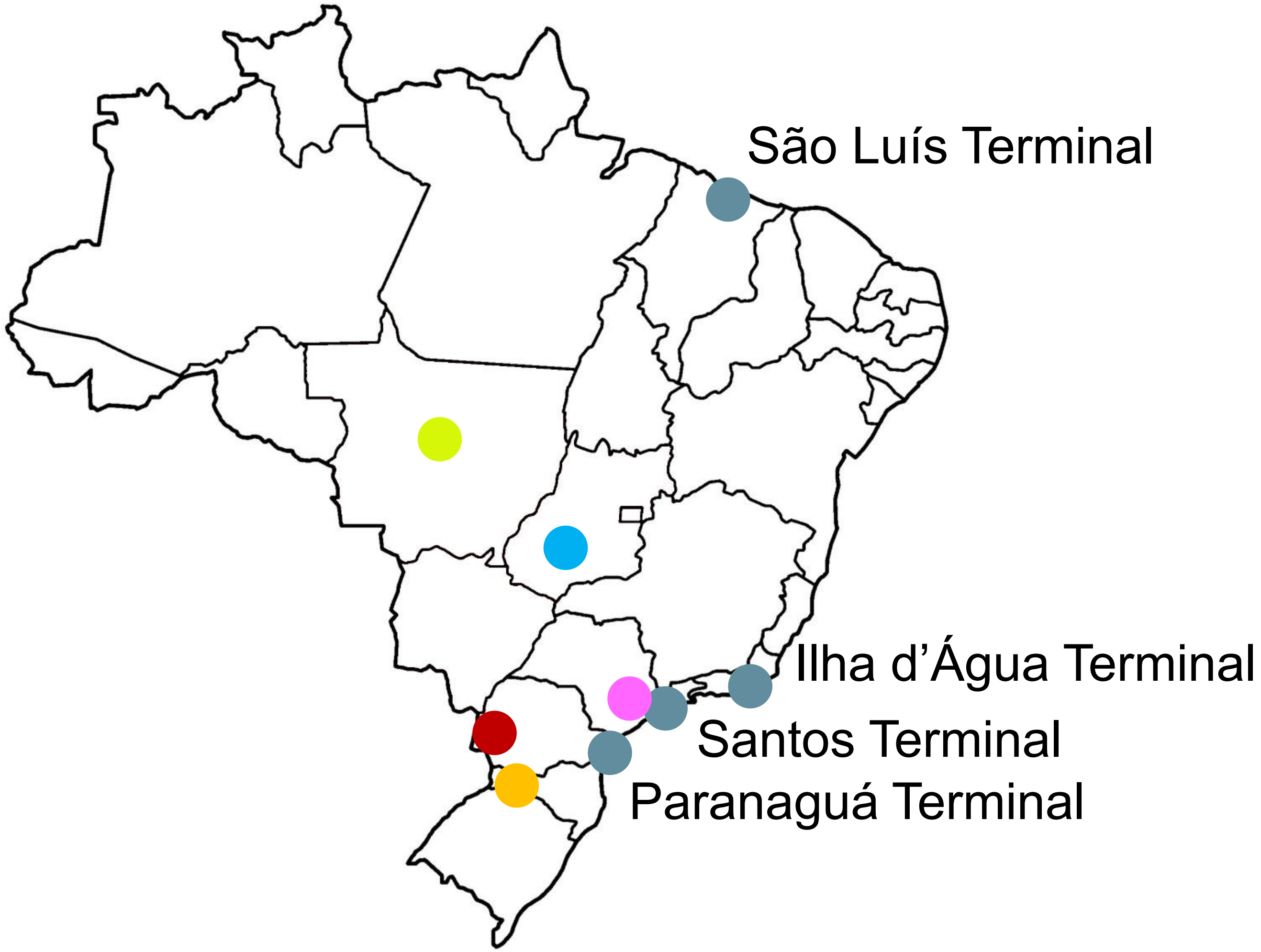


*Average fuel oil production in a Brazilian oil refinery

Bio-methanol hotspots in south and southeast regions are close to terminals

	Terminal	d (km)
● *Hotspot PR*	Paranaguá	530
● *Hotspot GO*	Santos	860
● *Hotspot MT*	Santos	1,590
● *Hotspot SC*	Paranaguá	440
● *Hotspot SP*	Santos	51

Only MSW and sewage sludge



Electrodiesel Hotspots

PRODUCTION POTENTIAL (TJ/year)

- *Hotspot SP* 2,400
- *Hotspot BA* 2,270
- *Hotspot AL* 1,920

Total e-diesel **6,600** *TJ/yr*

Fuel oil* ***24,900*** *TJ/yr*

Hotspots → Proximity to chlorine/caustic soda plants

15 tonnes of NaOH per TJ

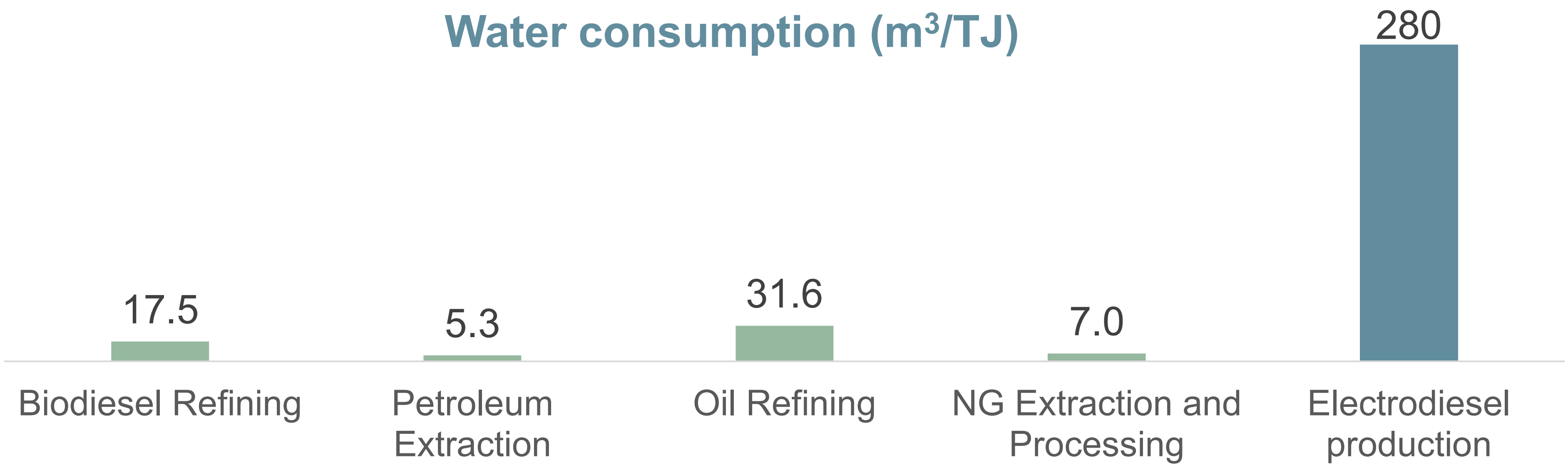
*Average fuel oil production in a Brazilian oil refinery

Electrodiesel Hotspots are close to terminals

	Terminal	d (km)
• *Hotspot SP*	Paranaguá	475
	Santos	20
	Ilha d'Água	495
• *Hotspot BA*	São Luís	1,560
• *Hotspot AL*	São Luís	1,615

But electrodiesel production demands too much water…

Water demand | ≈ 1,800 m^3/day | ≈ 280 m^3/TJ



Icons: freepik/flaticon

... and land.

Required area | ≈ 10 km^2 | ≈ 4300 m^2/(TJ/year)

100 MW-PV power plant (**70 km^2**)

Takeaways

- Brazil has **advantages** to kick off the production of low-emission alternative fuels for maritime transportation
- **For some SBF, logistic challenges** associated to the concentration of **hotspots in countryside areas**
- **Think about multiple hubs and how to deal with uncertainties** (e.g. dual fuel ready orderbooks vs dual fuel vs. retrofit)
- **Green shipping corridors to reduce (share) risks (in the short term) –** e.g. iron ore Brazil
- **E-fuels**: high demand for **materials, energy**, **area** and **water**
- **NH_3 as an e-fuel: +** not drop-in, low density, safety concerns, combustion concerns (N_2O emissions?)
- **Biofuels:** low quality in some cases limits blend, high quality in some cases allows drop-in, some technologies and processes are (are not) developed, i-LUC concerns (we need studies and models)

Tks

cenergia COPPE UFRJ