LIFE CYCLE ASSESSMENT (LCA) OF (E-/BIO-) METHANOL & (E-/GREY-/BLUE-) AMMONIA

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COMMISSIONED BY CMA CGM

2025

PRESENTATION OUTLINE

1. INTRODUCTION
2. EMISSIONS SCOPE REGULATIONS & METHODOLOGY
3. FUEL PRODUCTION SCENARIOS AND ASSESSMENTS
4. SHIP TRANSPORT ASSESSMENT
5. LCA TAKE AWAY MESSAGES

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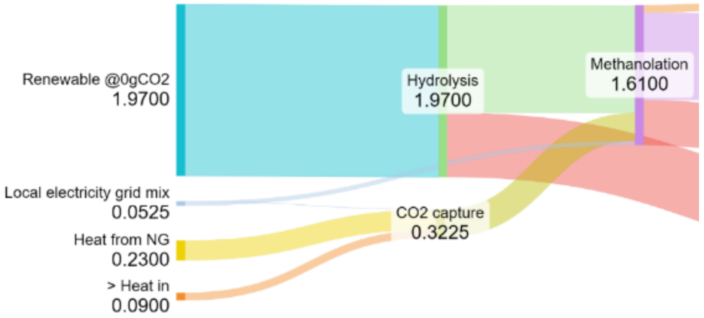
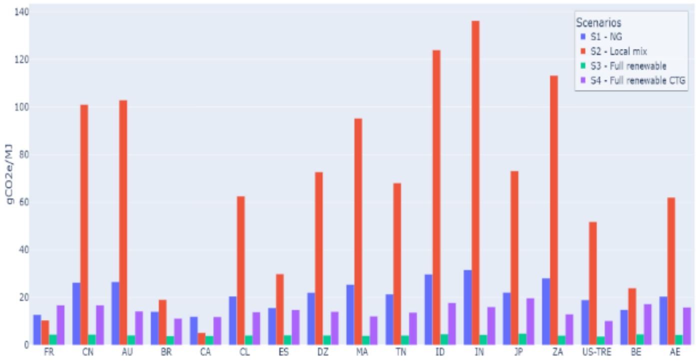
INTRODUCTION: LCA ON METHANOL AND AMMONIA PRODUCTION

Product	Feedstock scenario	Production scenario
Methanol	H2 from Electrolysis (e-)	• **3 time horizons** (2025,2035,2050) • **17 production locations** considered. • Transport and bunkering in **Rotterdam or Singapore**. • **Different energy source** scenarios (NG, grid or RE powered). • **Fuel Well to Wake scope (gCO2e/MJ)**, with or without infrastructure footprint. • **Container unit transportation work Well to Wake scope (gCO2e/TEUkm).**
	Biomass based (bio-)	
Ammonia	H2 from electrolysis (e-)	
	H2 from Methane Reforming (grey-/blue-)	





Key results include:

- Energy flow analyses
- Detailed GHG contribution analysis
- Prospective results

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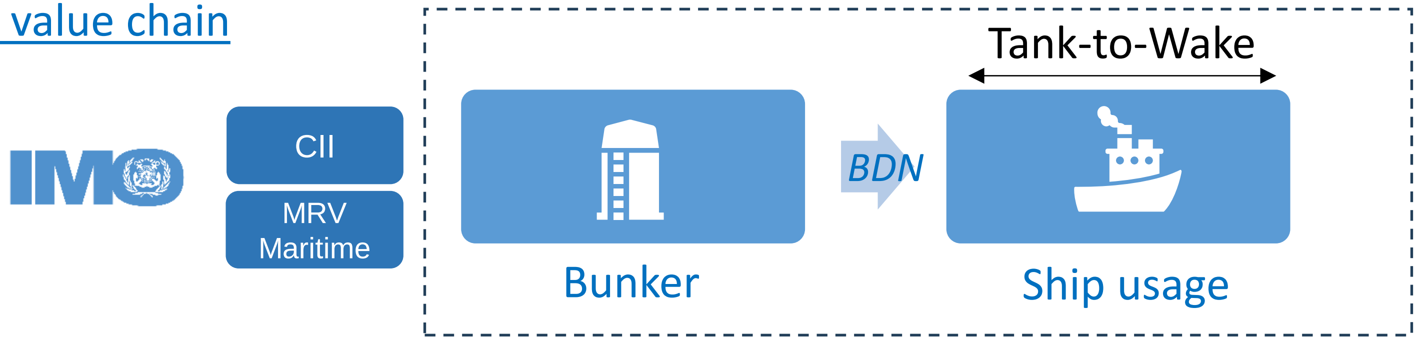
REGULATIONS GHG METHODOLOGIES & SUSTAINABLE CRITERIA ASSESSMENT

Current shipping value chain



IMO

CII

MRV Maritime

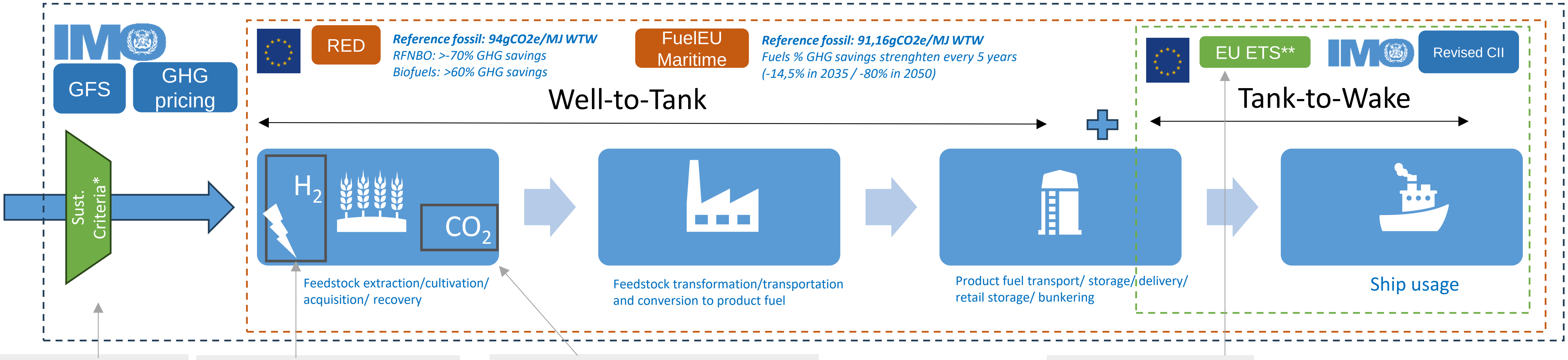
Tank-to-Wake

BDN

Bunker

Ship usage

Future shipping value chain



IMO

GFS

GHG pricing

Sust. Criteria*

RED

Reference fossil: 94gCO2e/MJ WTW
RFNBO: >-70% GHG savings
Biofuels: >60% GHG savings

FuelEU Maritime

Reference fossil: 91,16gCO2e/MJ WTW
Fuels % GHG savings strenghten every 5 years
(-14,5% in 2035 / -80% in 2050)

Well-to-Tank

EU ETS**

IMO

Revised CII

Tank-to-Wake

H_2

CO_2

Feedstock extraction/cultivation/ acquisition/ recovery

Feedstock transformation/transportation and conversion to product fuel

Product fuel transport/ storage/ delivery/ retail storage/ bunkering

Ship usage

*LCA indicators for sustainability (quanti. or quali.). **Yet to be defined.***

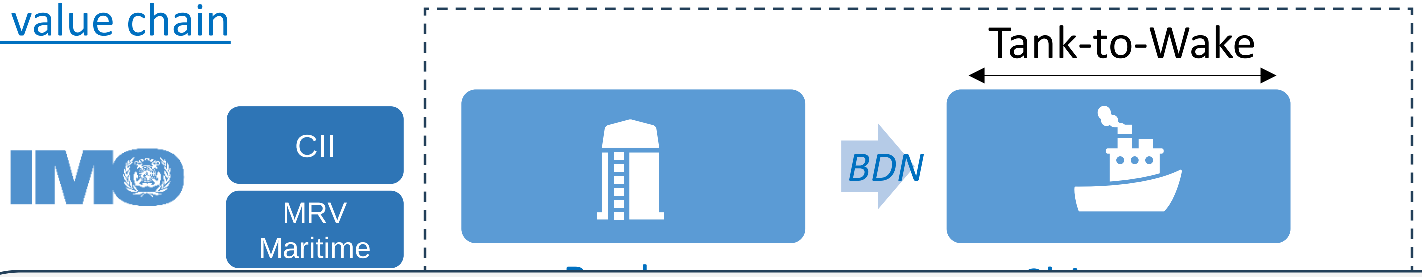
*Renewable electricity **is set to 0 gCO2e/MJ** (RED RFNBO DA Annexes)*

*CO2 captured **allows to offset TtW emissions**.*
Remains the emissions for CO2 capture.

CH4 and N2O emissions to be considered after 2026

REGULATIONS GHG METHODOLOGIES & SUSTAINABLE CRITERIA ASSESSMENT

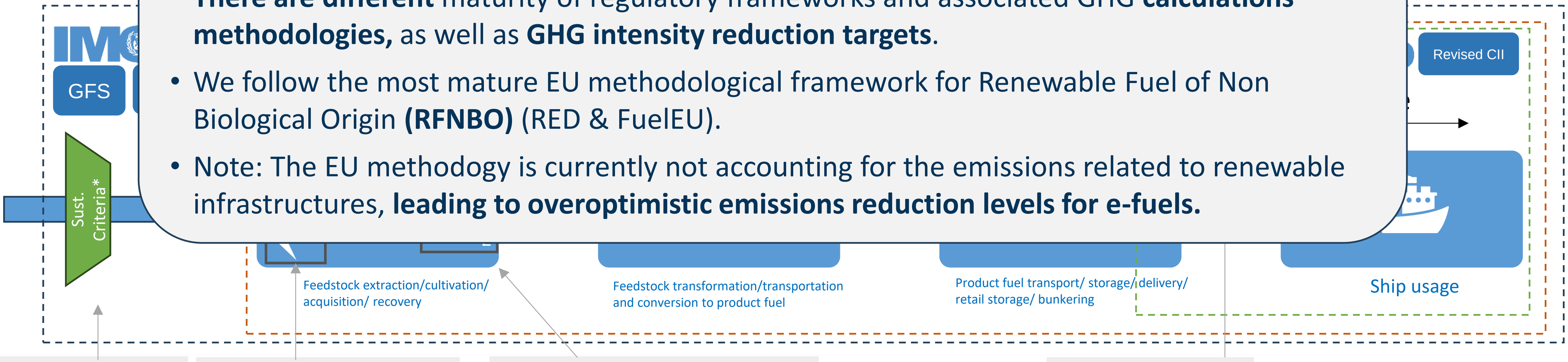
Current shipping value chain



Key messages

- We must now account for measuring GHG emissions from **Well to Wake.**
- **There are different** maturity of regulatory frameworks and associated GHG **calculations methodologies,** as well as **GHG intensity reduction targets**.
- We follow the most mature EU methodological framework for Renewable Fuel of Non Biological Origin **(RFNBO)** (RED & FuelEU).
- Note: The EU methodogy is currently not accounting for the emissions related to renewable infrastructures, **leading to overoptimistic emissions reduction levels for e-fuels.**

Future shipp



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CH4 and N2O emissions to be considered after 2026

PRESENTATION OUTLINE

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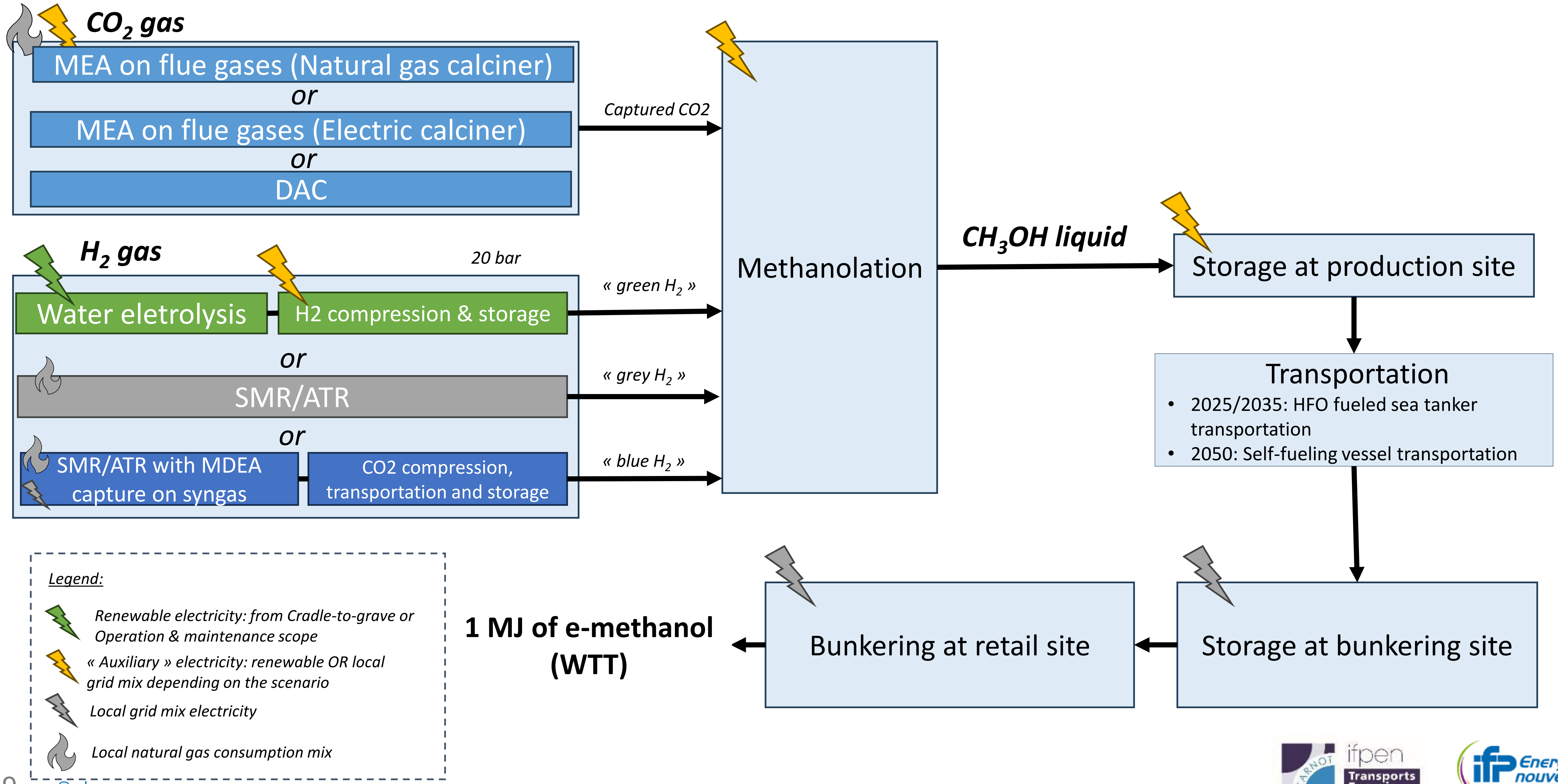
METHANOL

LCA FUEL PRODUCTION SCENARIOS AND ASSESSMENTS

E-METHANOL VIA METHANOLATION: WTT SCOPE OF MODELLING



CO_2 gas

MEA on flue gases (Natural gas calciner)

or

MEA on flue gases (Electric calciner)

or

DAC

Captured CO2

H_2 gas

20 bar

Water eletrolysis

H2 compression & storage

« green H_2 »

or

SMR/ATR

« grey H_2 »

or

SMR/ATR with MDEA capture on syngas

CO2 compression, transportation and storage

« blue H_2 »

Methanolation

CH_3OH liquid

Storage at production site

Transportation
- 2025/2035: HFO fueled sea tanker transportation
- 2050: Self-fueling vessel transportation

Storage at bunkering site

Bunkering at retail site

1 MJ of e-methanol (WTT)

Legend:

⚡ *Renewable electricity: from Cradle-to-grave or Operation & maintenance scope*

⚡ *« Auxiliary » electricity: renewable OR local grid mix depending on the scenario*

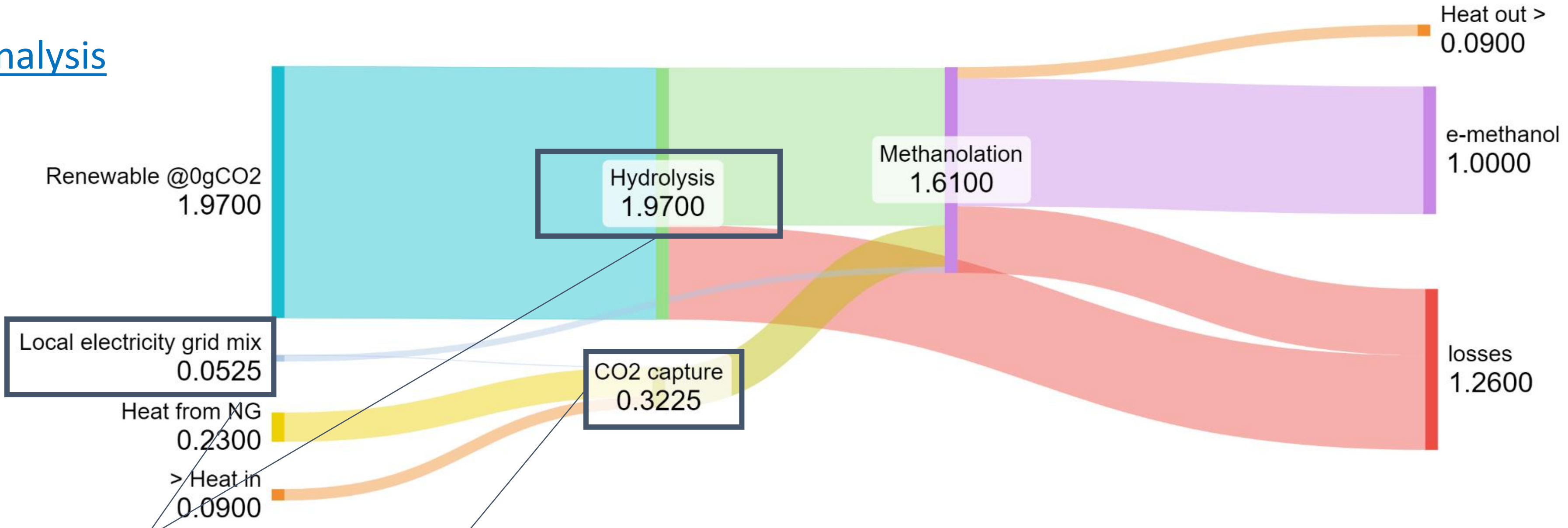
⚡ *Local grid mix electricity*

🔥 *Local natural gas consumption mix*

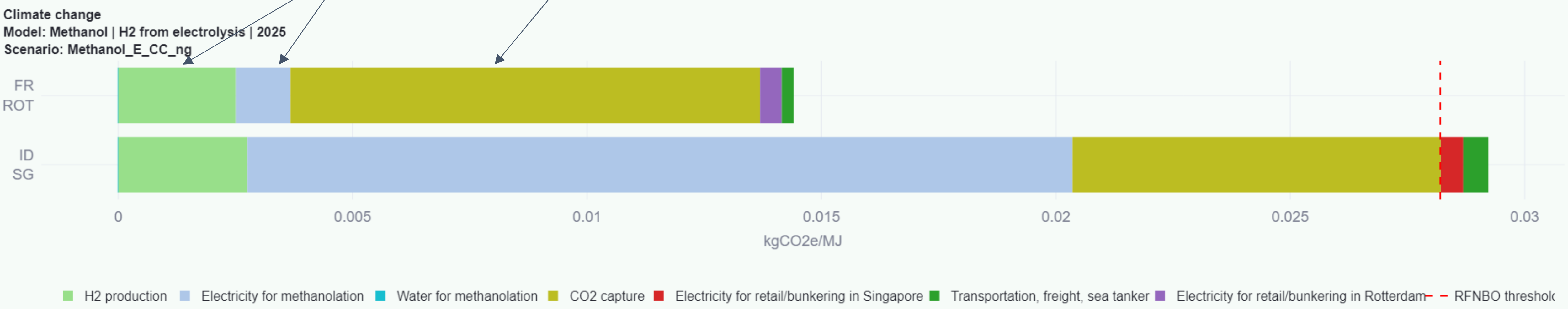
E-METHANOL VIA NATURAL GAS POWERED CO2 CAPTURE

Energy flow analysis

The methodology proposed by International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) includes scope 1 & 2 emissions for H2 production. Thus considered zero for green H2. This standard is used by IEA, RED and probably future IMO guidelines.



GHG analysis



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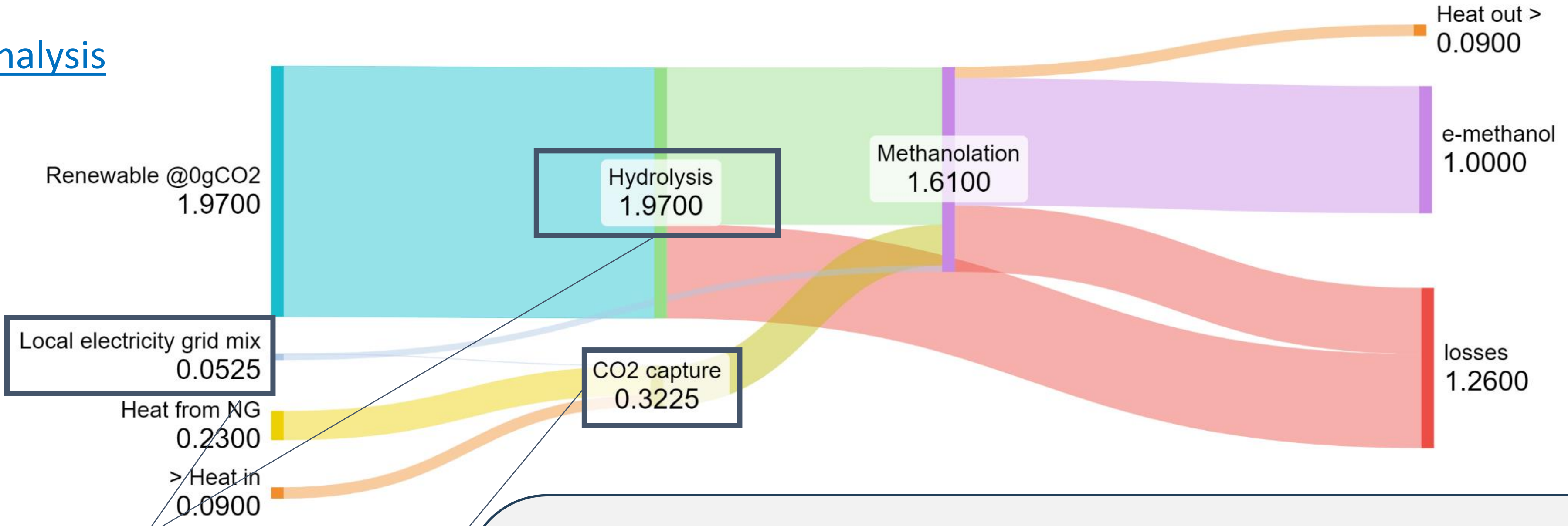
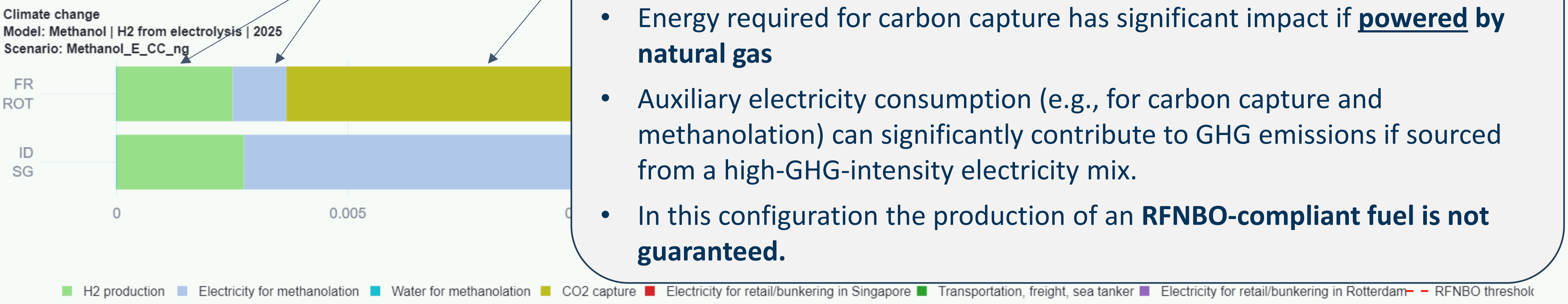


GHG analysis

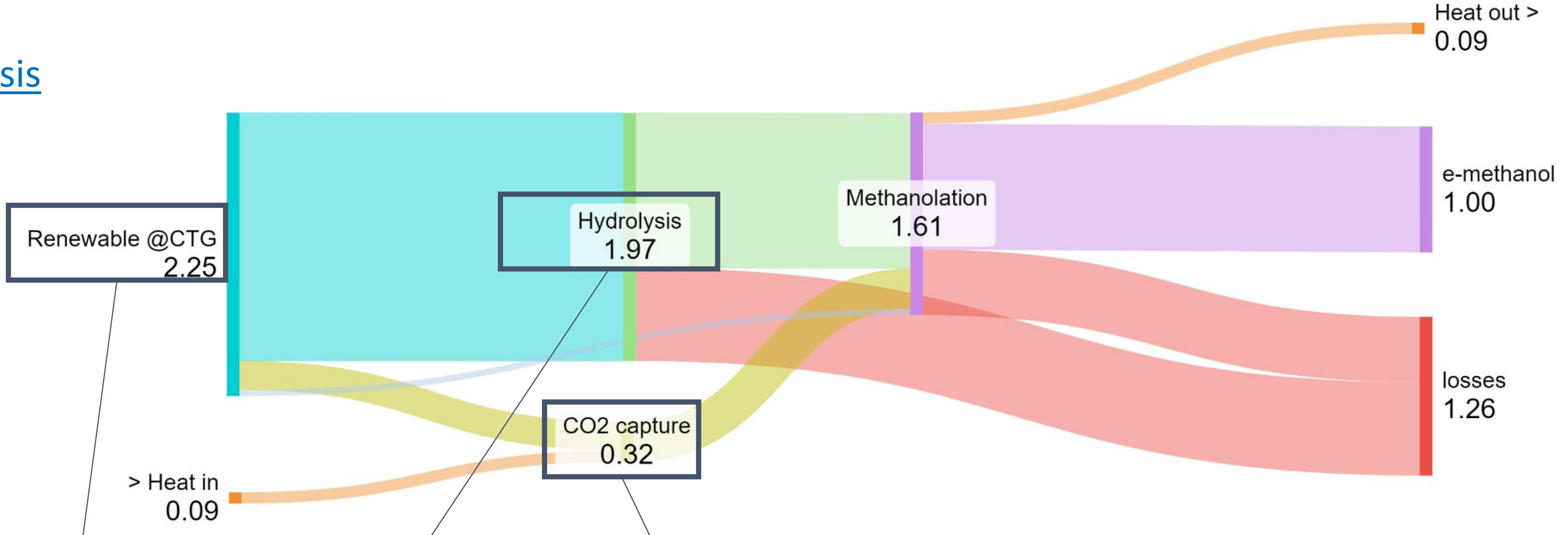


Key messages

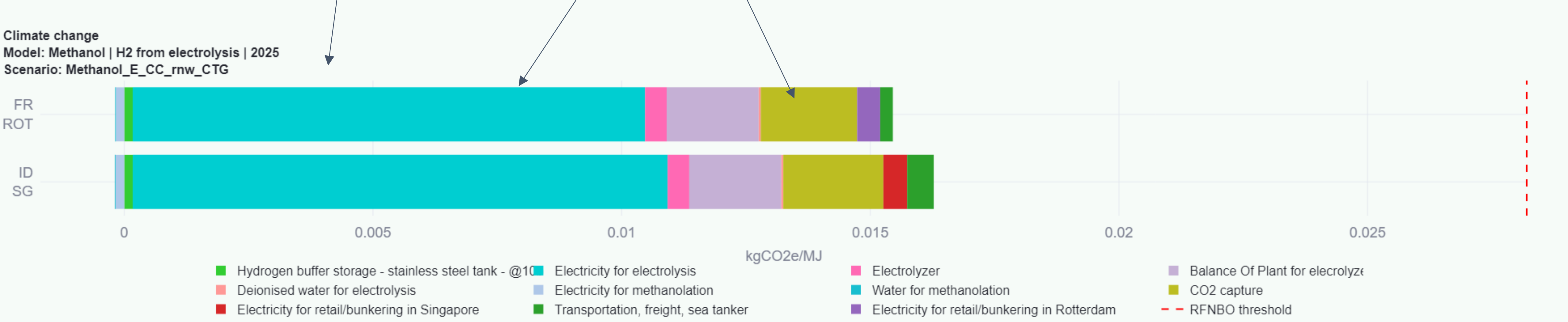
- Energy required for carbon capture has significant impact if **powered by natural gas**
- Auxiliary electricity consumption (e.g., for carbon capture and methanolation) can significantly contribute to GHG emissions if sourced from a high-GHG-intensity electricity mix.
- In this configuration the production of an **RFNBO-compliant fuel is not guaranteed.**

E-METHANOL VIA ELECTRICITY POWERED CO2 CAPTURE

Energy flow analysis

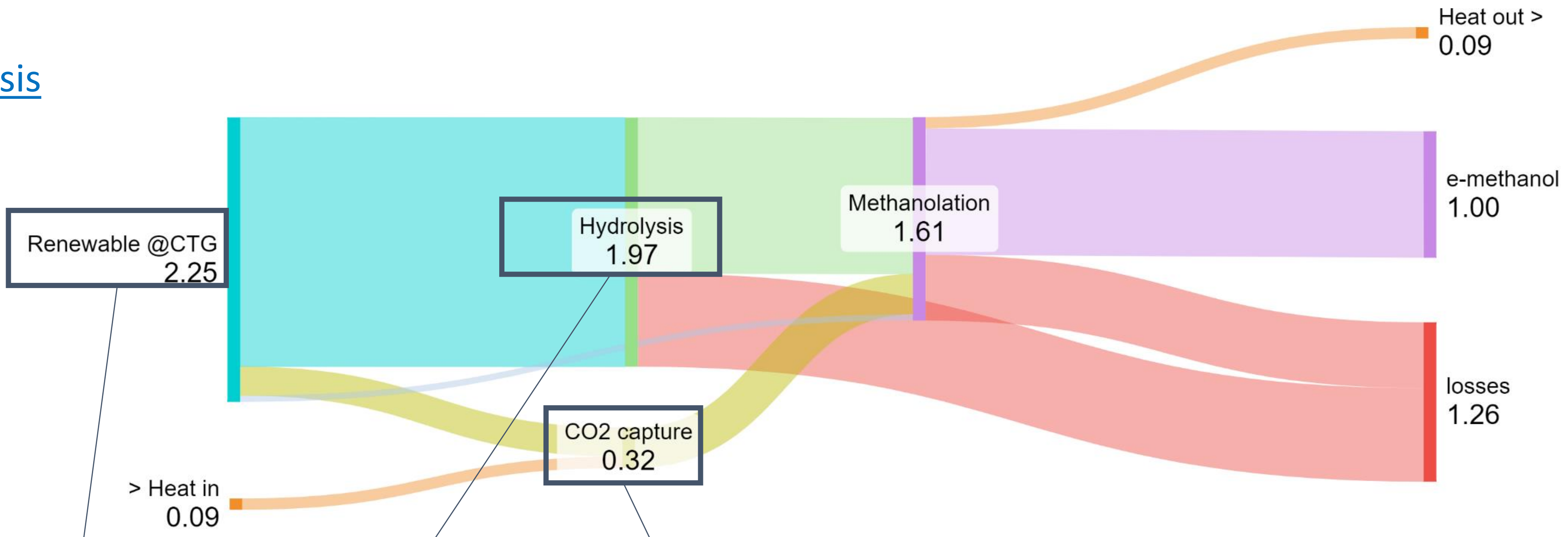


GHG analysis

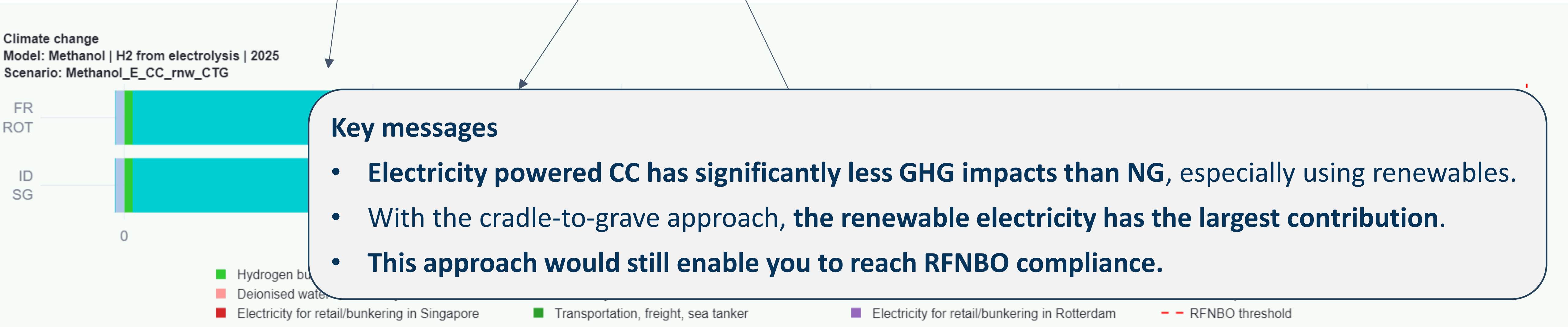

Climate change
Model: Methanol | H2 from electrolysis | 2025
Scenario: Methanol_E_CC_rnw_CTG

E-METHANOL VIA ELECTRICITY POWERED CO2 CAPTURE

Energy flow analysis



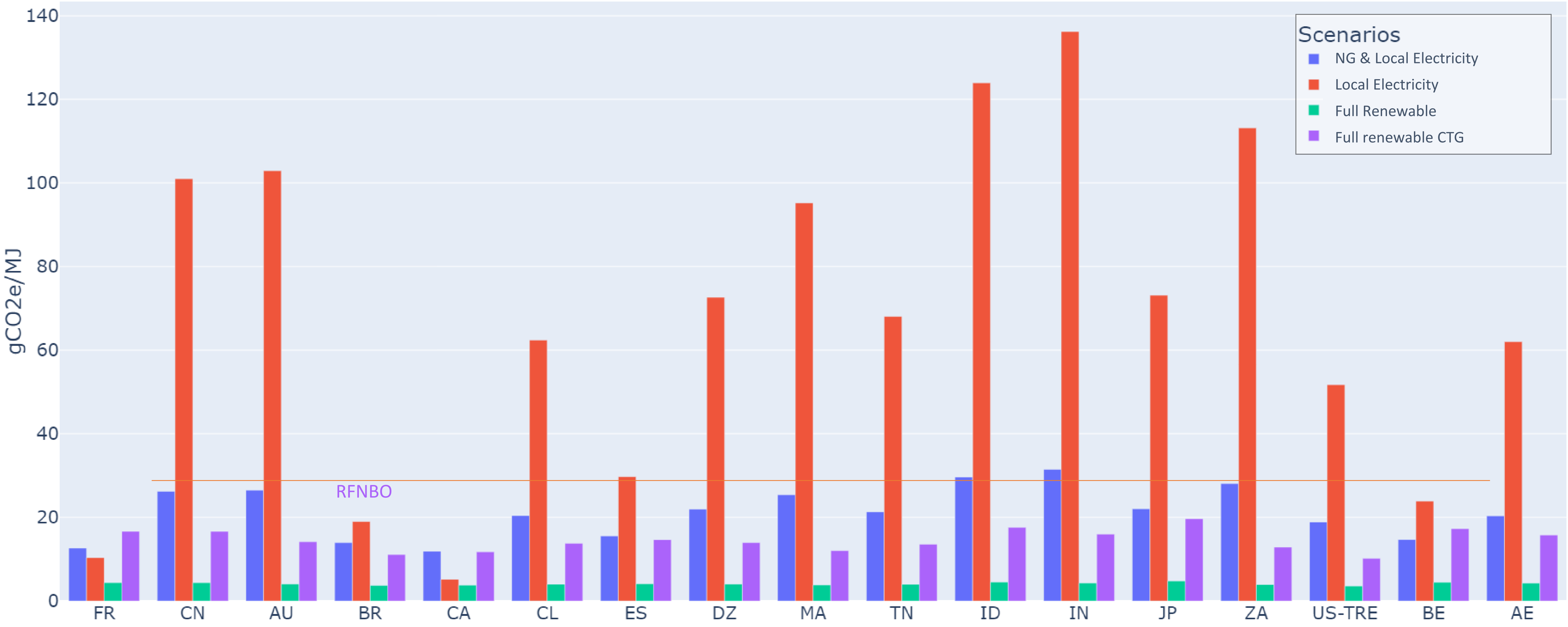
GHG analysis



Key messages

- **Electricity powered CC has significantly less GHG impacts than NG**, especially using renewables.
- With the cradle-to-grave approach, **the renewable electricity has the largest contribution**.
- **This approach would still enable you to reach RFNBO compliance.**

GHG EMISSIONS OF E-METHANOL WTW WITHOUT T&C, BY REGION AND CONFIGURATION SCENARIO



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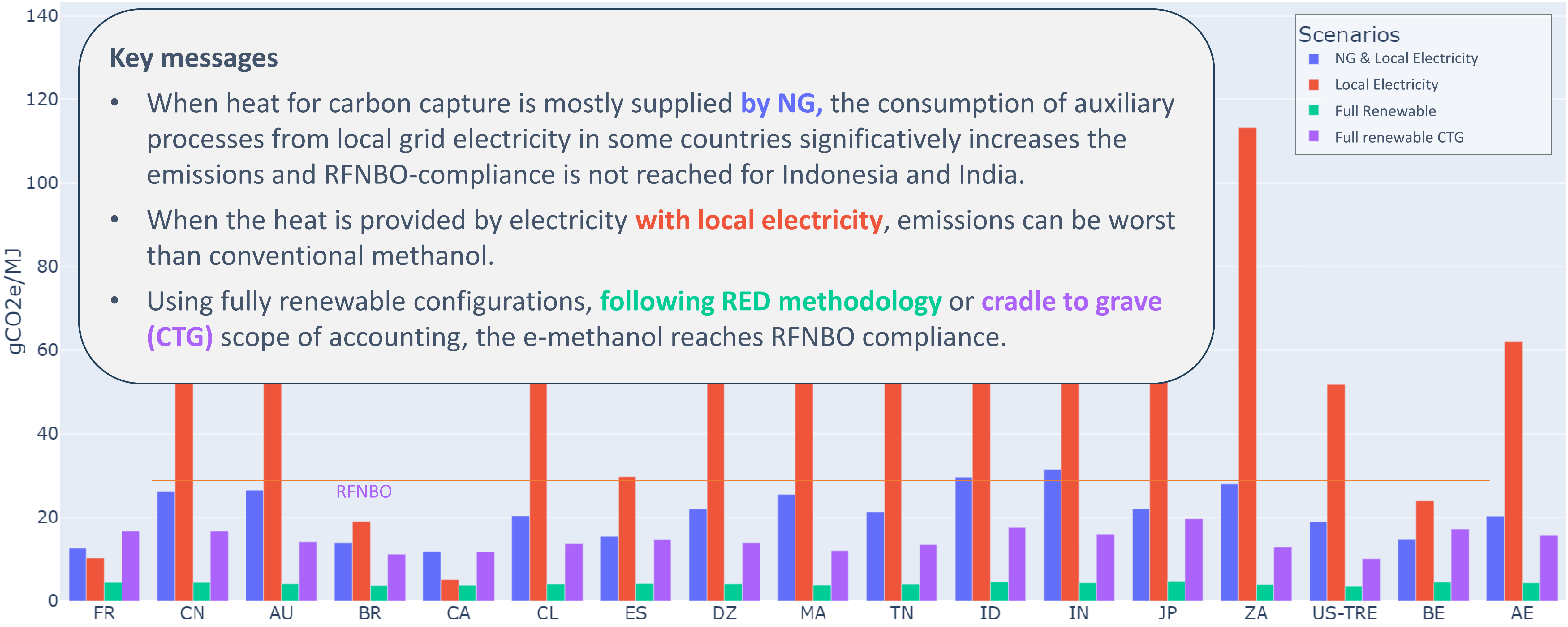
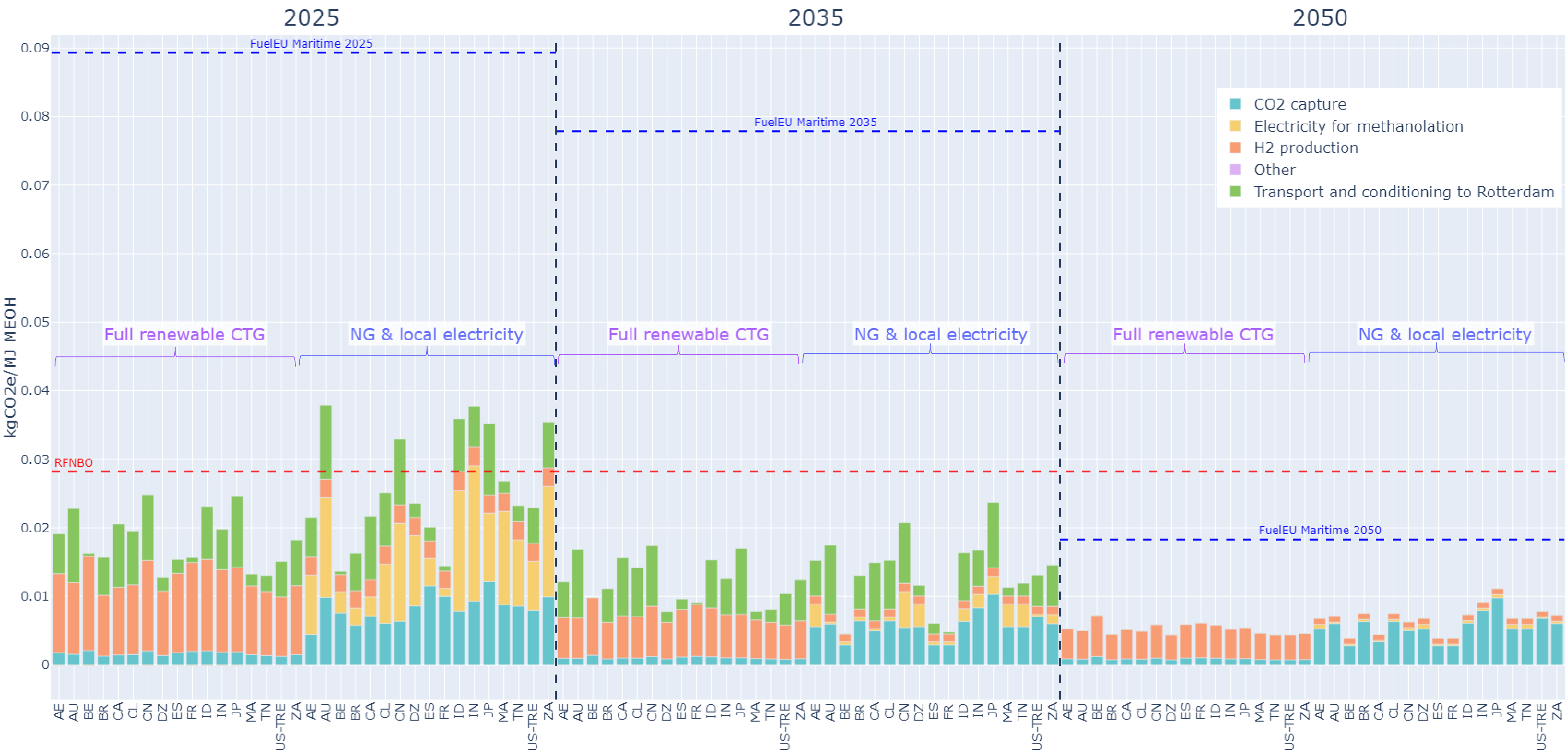


Key messages

- When heat for carbon capture is mostly supplied **by NG,** the consumption of auxiliary processes from local grid electricity in some countries significatively increases the emissions and RFNBO-compliance is not reached for Indonesia and India.
- When the heat is provided by electricity **with local electricity**, emissions can be worst than conventional methanol.
- Using fully renewable configurations, **following RED methodology** or **cradle to grave (CTG)** scope of accounting, the e-methanol reaches RFNBO compliance.

E-METHANOL SUMMARY PROSPECTIVE RESULTS BY LOCATION

Prospective results for e-methanol produced (with Transport and Conditioning to Rotterdam for bunkering)



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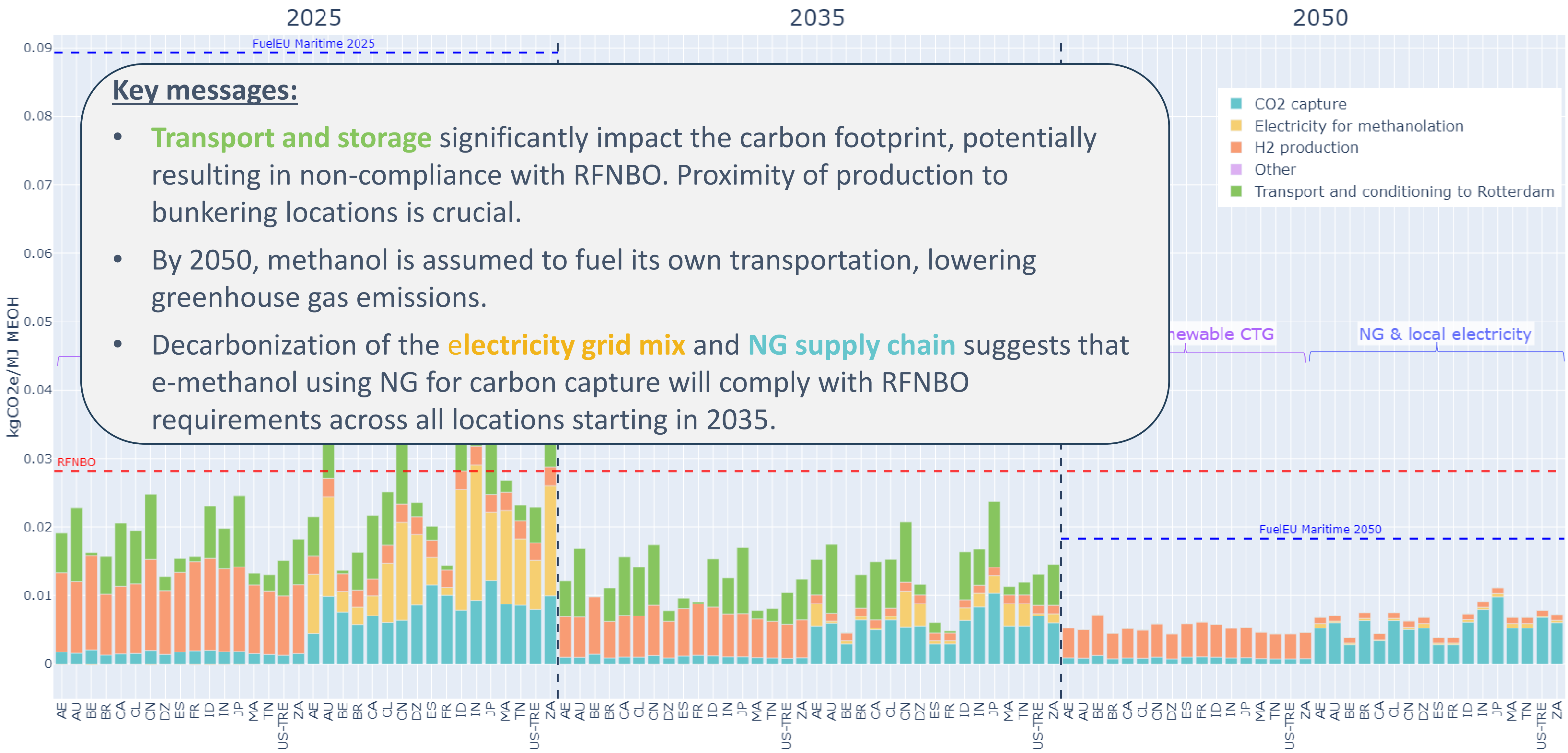

Key messages:

- **Transport and storage** significantly impact the carbon footprint, potentially resulting in non-compliance with RFNBO. Proximity of production to bunkering locations is crucial.
- By 2050, methanol is assumed to fuel its own transportation, lowering greenhouse gas emissions.
- Decarbonization of the **electricity grid mix** and **NG supply chain** suggests that e-methanol using NG for carbon capture will comply with RFNBO requirements across all locations starting in 2035.

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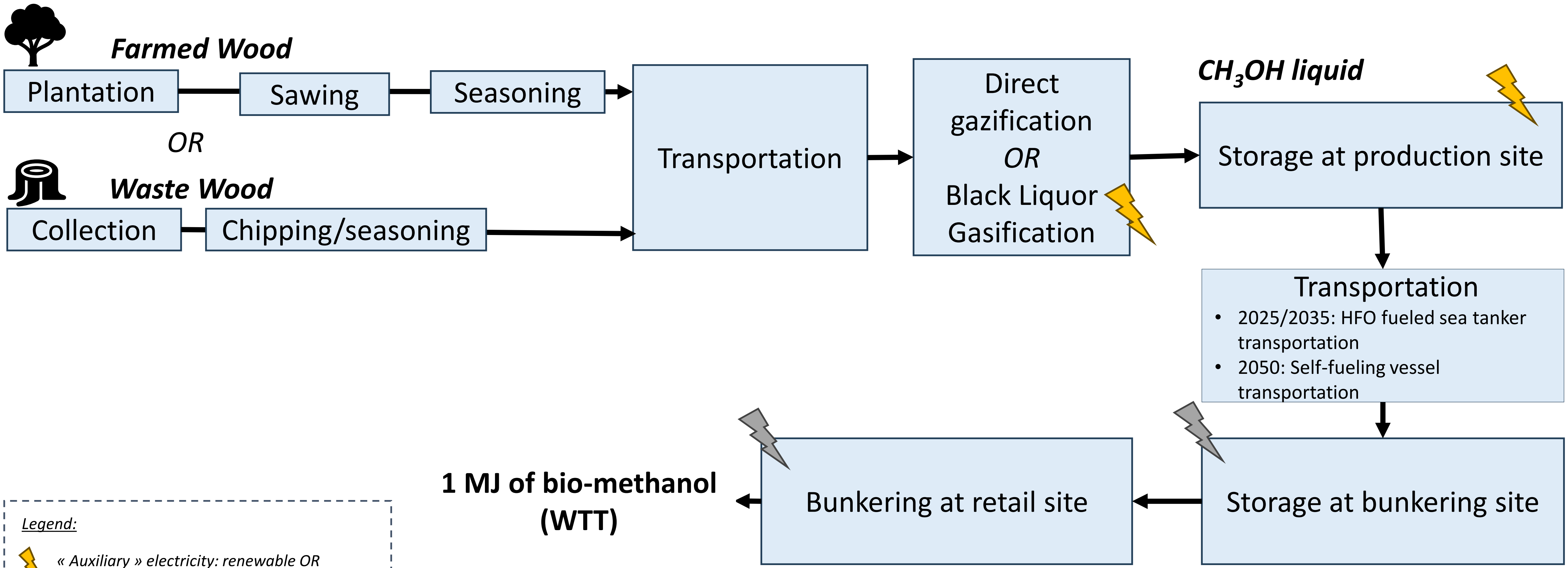
BIO-METHANOL VIA GASIFICATION: WTT SCOPE OF MODELLING



Farmed Wood

Plantation → Sawing → Seasoning

OR

Waste Wood

Collection → Chipping/seasoning

Transportation

Direct gazification *OR* Black Liquor Gasification

CH_3OH liquid

Storage at production site

Transportation
- 2025/2035: HFO fueled sea tanker transportation
- 2050: Self-fueling vessel transportation

Storage at bunkering site

Bunkering at retail site

1 MJ of bio-methanol (WTT)

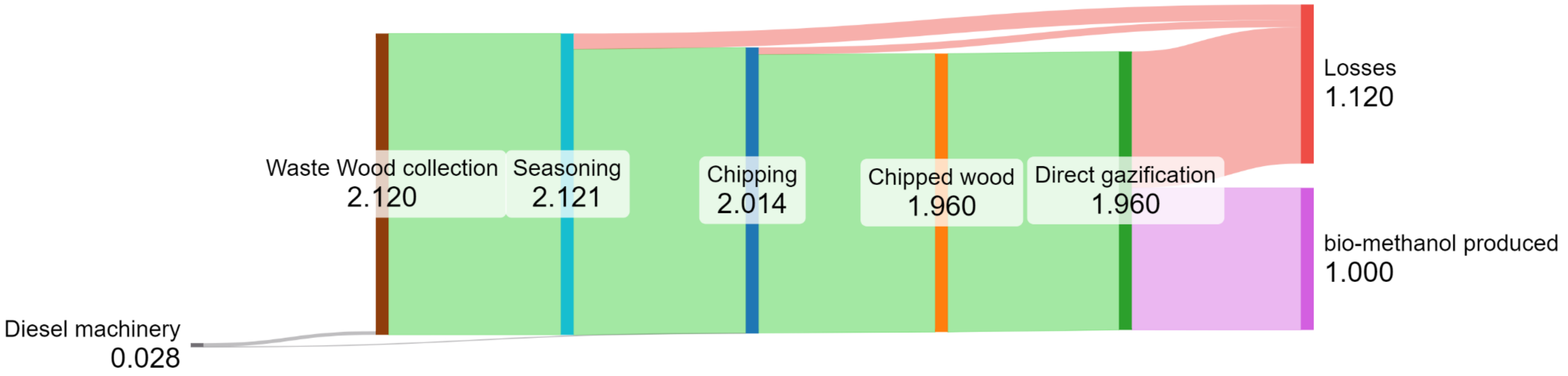
Legend:

⚡ *« Auxiliary » electricity: renewable OR local grid mix depending on the scenario*

⚡ *Local grid mix electricity*

BIO-METHANOL VIA DIRECT GASIFICATION OF WASTE WOOD

Energy flow analysis



GHG analysis

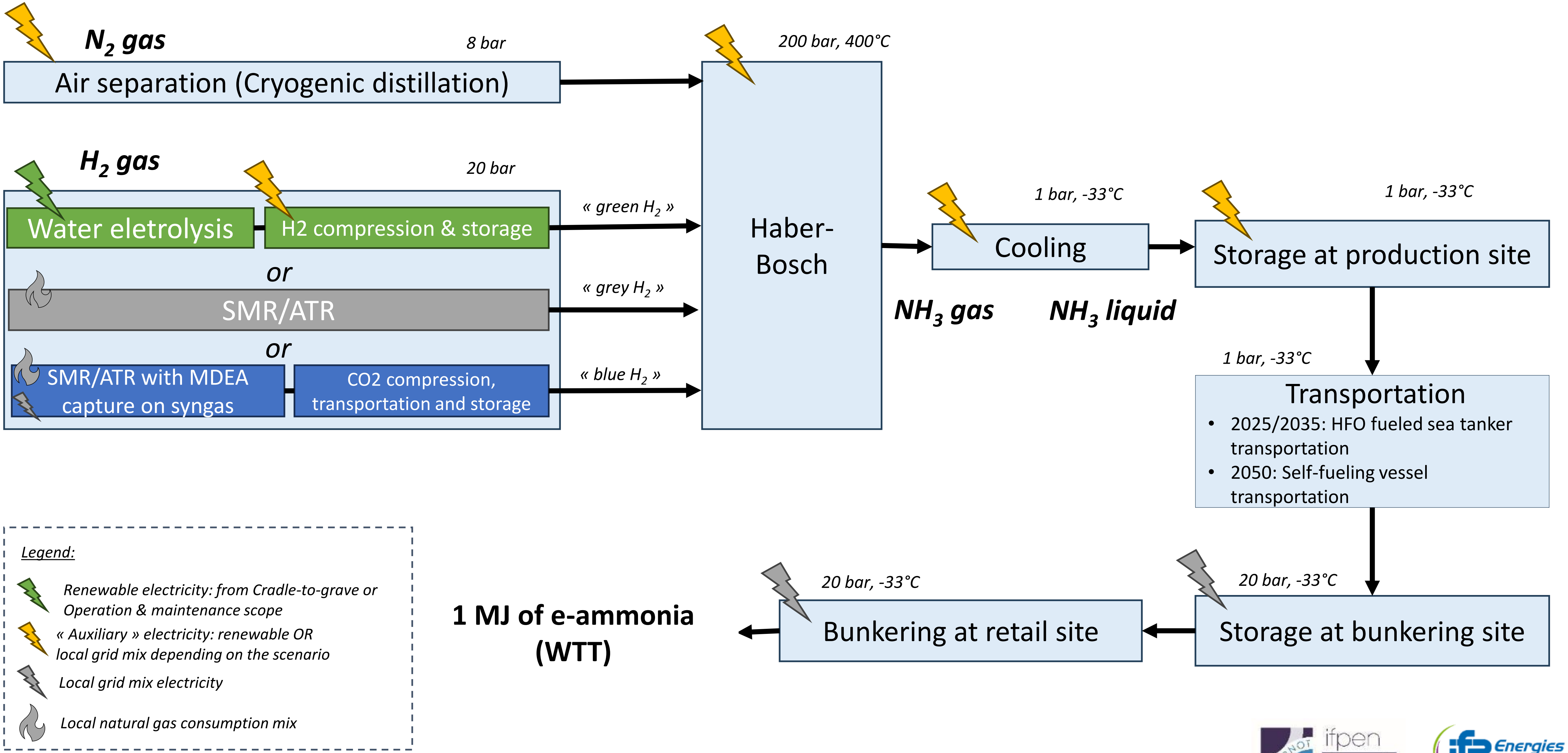
Key messages

- Supply chain for waste wood and gasification efficiency losses are the most important contributors.
- RED compliance is met in all regions reaching **(~95% GHG reduction)**

AMMONIA

LCA FUEL PRODUCTION SCENARIOS AND ASSESSMENTS

E-AMMONIA WTT SCOPE OF MODELLING



N_2 gas

8 bar

Air separation (Cryogenic distillation)

H_2 gas

20 bar

Water eletrolysis

H2 compression & storage

« green H_2 »

or

SMR/ATR

« grey H_2 »

or

SMR/ATR with MDEA capture on syngas

CO2 compression, transportation and storage

« blue H_2 »

200 bar, 400°C

Haber-Bosch

NH_3 gas

1 bar, -33°C

Cooling

NH_3 liquid

1 bar, -33°C

Storage at production site

1 bar, -33°C

Transportation

- 2025/2035: HFO fueled sea tanker transportation
- 2050: Self-fueling vessel transportation

20 bar, -33°C

Storage at bunkering site

20 bar, -33°C

Bunkering at retail site

1 MJ of e-ammonia (WTT)

Legend:

Renewable electricity: from Cradle-to-grave or Operation & maintenance scope

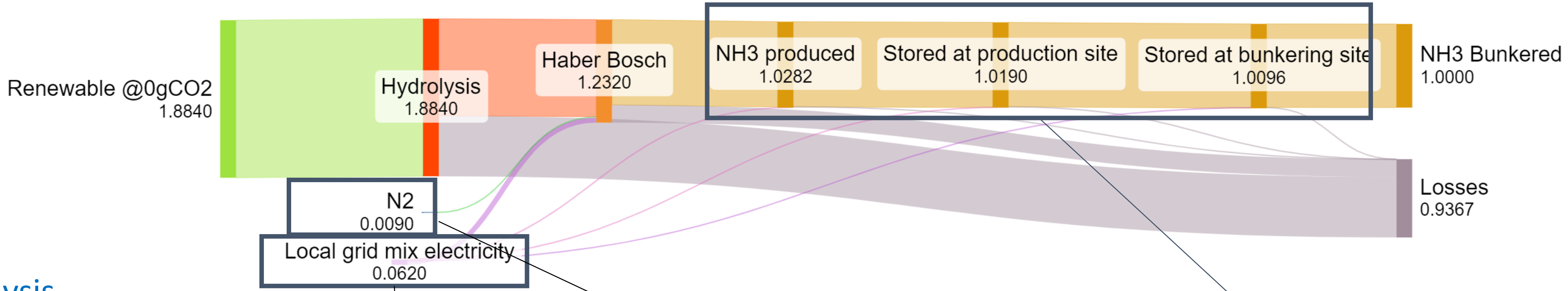
« Auxiliary » electricity: renewable OR local grid mix depending on the scenario

Local grid mix electricity

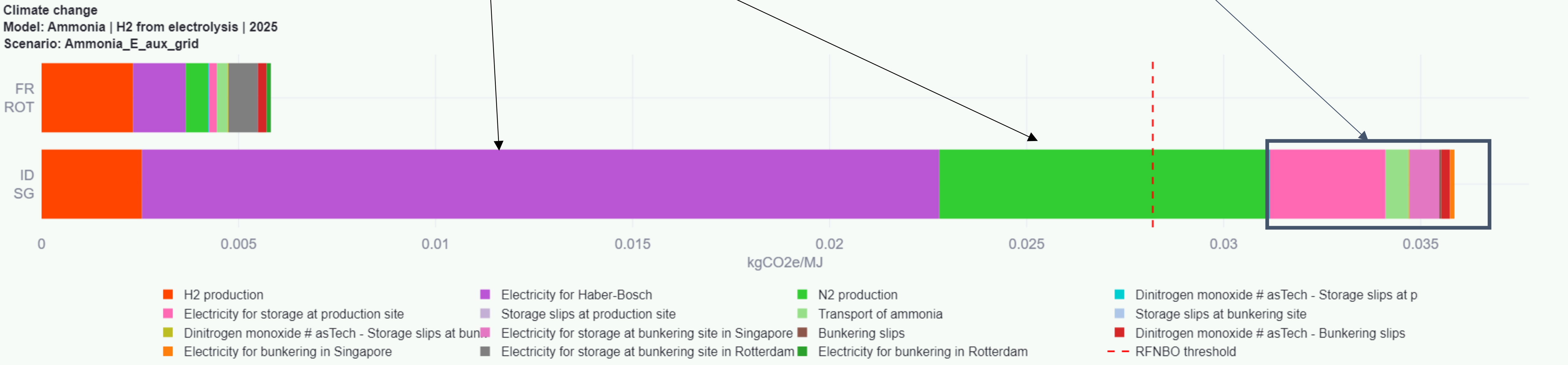
Local natural gas consumption mix

E-AMMONIA VIA LOCAL GRID ELECTRICY FOR AUXILIARY PROCESSES

Energy flow analysis

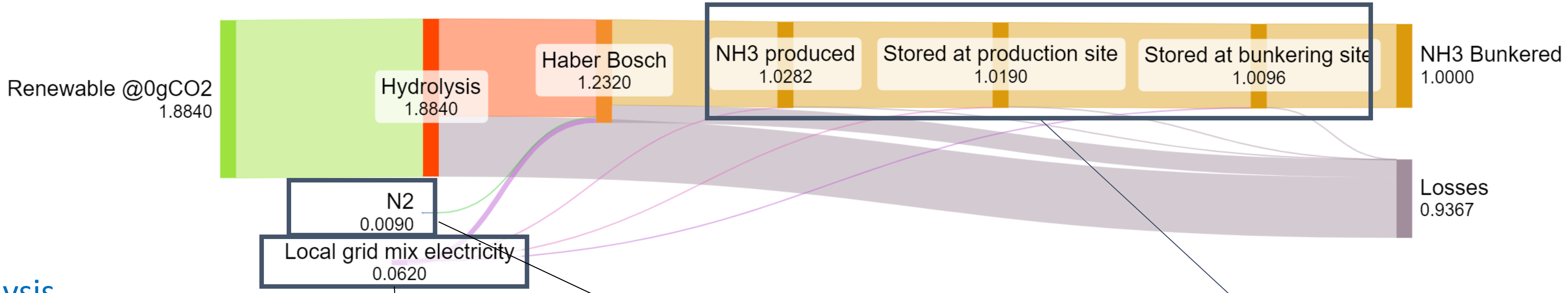


GHG analysis

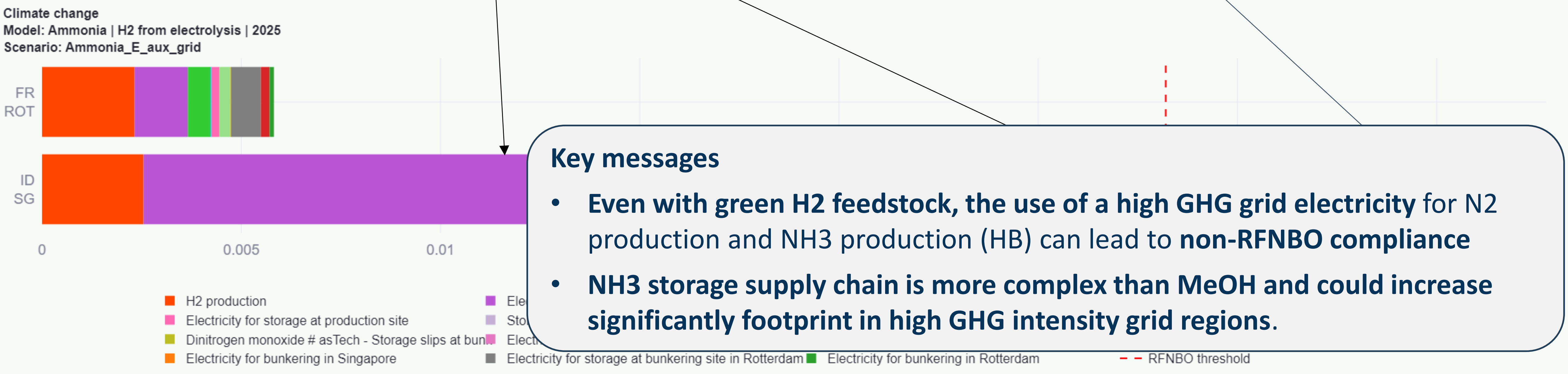


E-AMMONIA VIA LOCAL GRID ELECTRICY FOR AUXILIARY PROCESSES

Energy flow analysis



GHG analysis

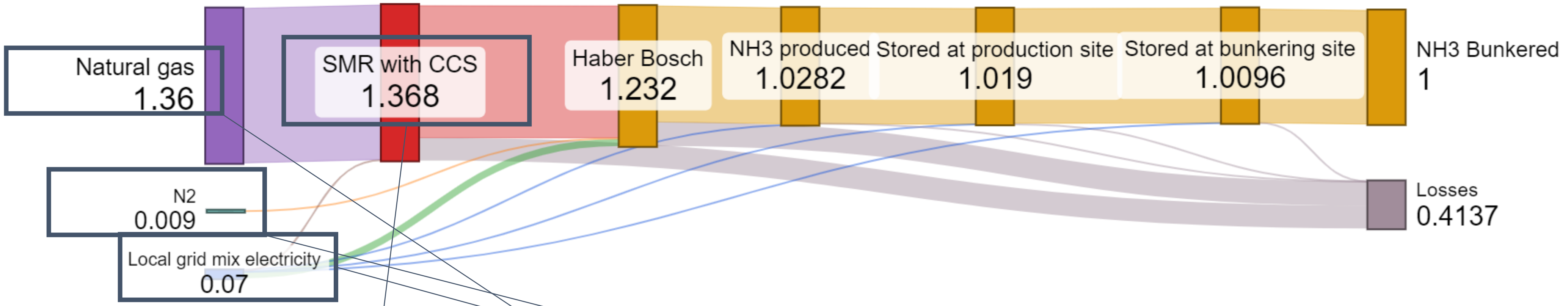


Key messages

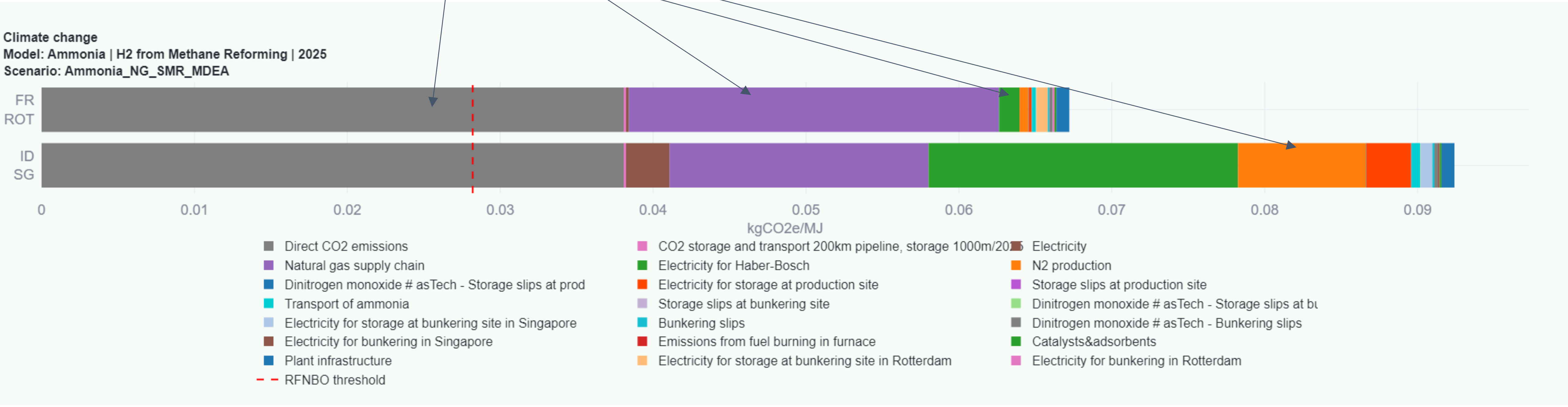
- **Even with green H2 feedstock, the use of a high GHG grid electricity** for N2 production and NH3 production (HB) can lead to **non-RFNBO compliance**
- **NH3 storage supply chain is more complex than MeOH and could increase significantly footprint in high GHG intensity grid regions.**

BLUE-AMMONIA VIA H2 FROM SMR+CCS AND LOCAL GRID MIX FOR AUXILIARY PROCESSES

Energy flow analysis

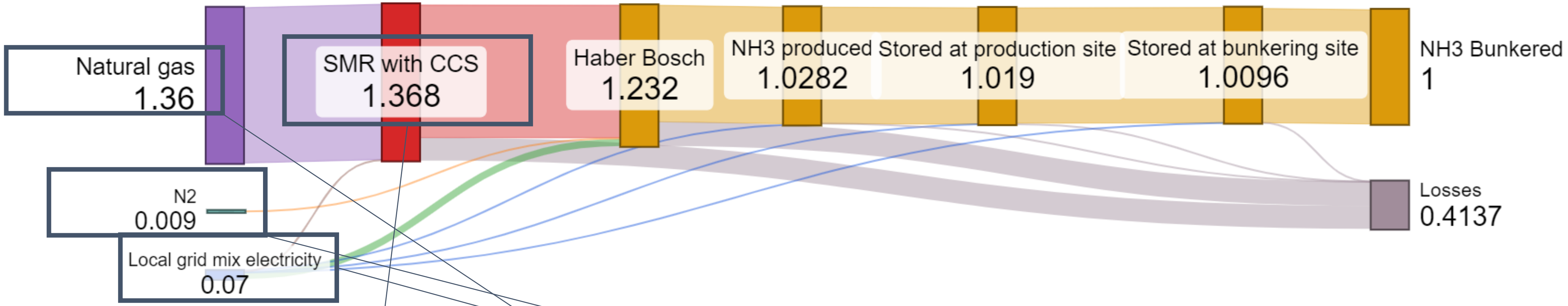


GHG analysis

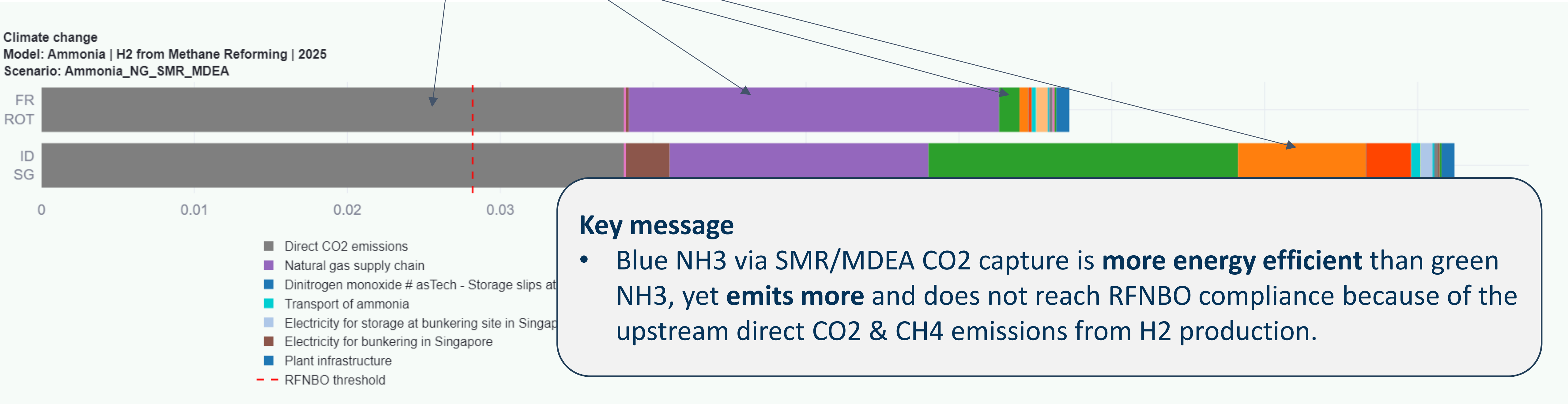


BLUE-AMMONIA VIA H2 FROM SMR+CCS AND LOCAL GRID MIX FOR AUXILIARY PROCESSES

Energy flow analysis



GHG analysis

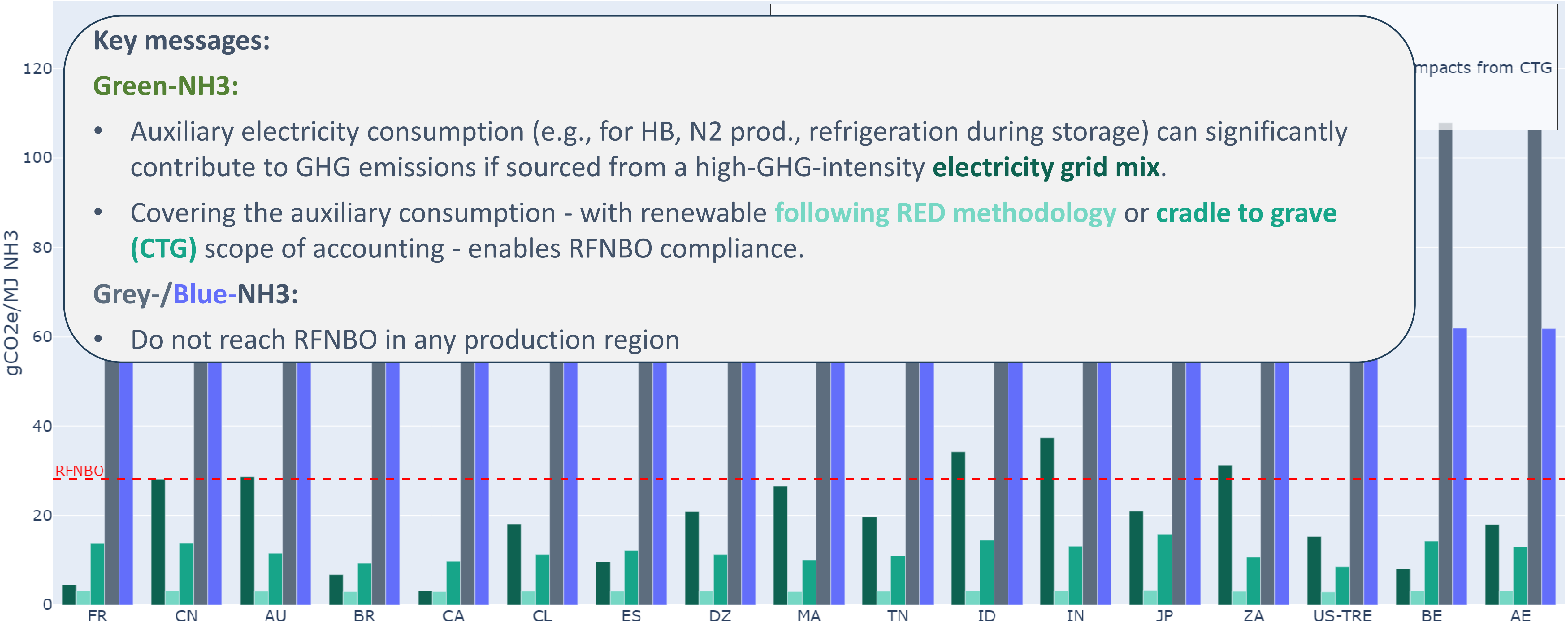


Key message

- Blue NH3 via SMR/MDEA CO2 capture is **more energy efficient** than green NH3, yet **emits more** and does not reach RFNBO compliance because of the upstream direct CO2 & CH4 emissions from H2 production.

GHG EMISSIONS OF AMMONIA WTW WITHOUT T&C, BY REGION AND CONFIGURATION SCENARIO

GHG EMISSIONS OF AMMONIA WTW WITHOUT T&C, BY REGION AND CONFIGURATION SCENARIO



Key messages:

Green-NH3:

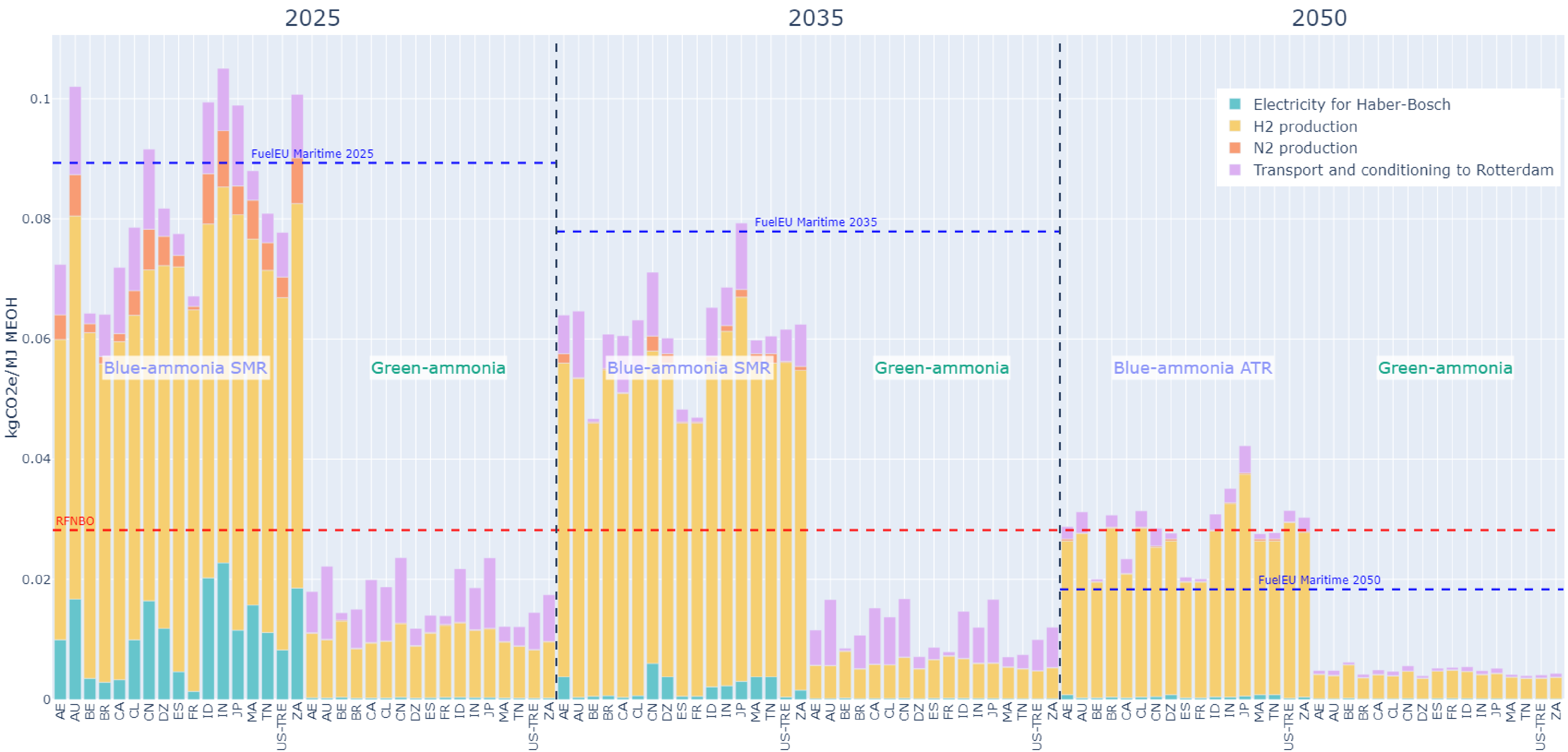
- Auxiliary electricity consumption (e.g., for HB, N2 prod., refrigeration during storage) can significantly contribute to GHG emissions if sourced from a high-GHG-intensity **electricity grid mix**.
- Covering the auxiliary consumption - with renewable **following RED methodology** or **cradle to grave (CTG)** scope of accounting - enables RFNBO compliance.

Grey-/Blue-NH3:

- Do not reach RFNBO in any production region

GREEN AND BLUE NH3 SUMMARY PROSPECTIVE RESULTS BY LOCATION

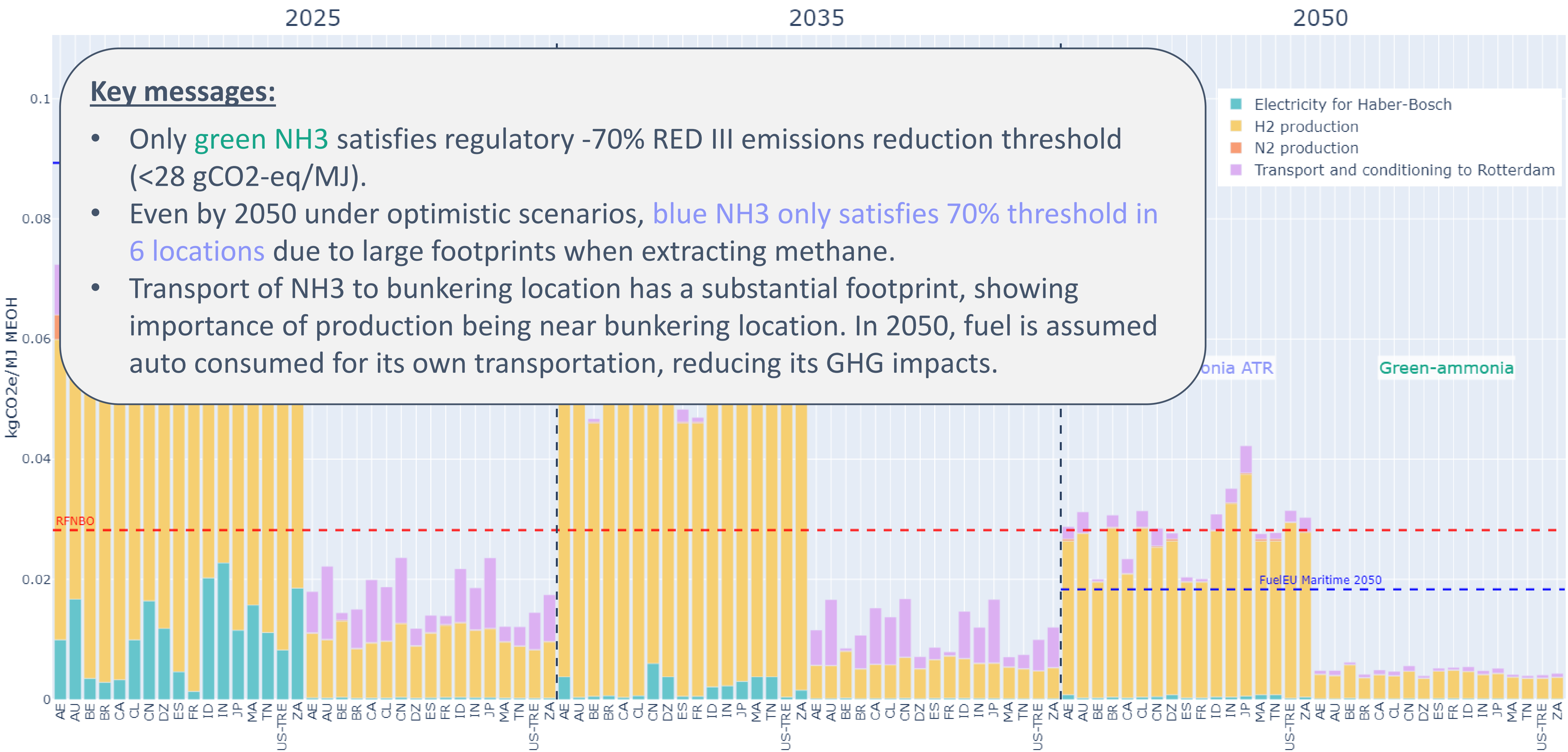
Prospective results for green and blue ammonia produced (with Transport and Conditioning to Rotterdam for bunkering)



Note – For Green-Ammonia, GHG emissions scope shown below: cradle-to-grave (whole scope) while regulatory accounting (FuelEU Maritime) is Well-to-Wake (smaller scope)

GREEN AND BLUE NH3 SUMMARY PROSPECTIVE RESULTS BY LOCATION

Prospective results for green and blue ammonia produced (with Transport and Conditioning to Rotterdam for bunkering)



Key messages:

- Only green NH3 satisfies regulatory -70% RED III emissions reduction threshold (<28 gCO2-eq/MJ).
- Even by 2050 under optimistic scenarios, blue NH3 only satisfies 70% threshold in 6 locations due to large footprints when extracting methane.
- Transport of NH3 to bunkering location has a substantial footprint, showing importance of production being near bunkering location. In 2050, fuel is assumed auto consumed for its own transportation, reducing its GHG impacts.

Note – For Green-Ammonia, GHG emissions scope shown below: cradle-to-grave (whole scope) while regulatory accounting (FuelEU Maritime) is Well-to-Wake (smaller scope)

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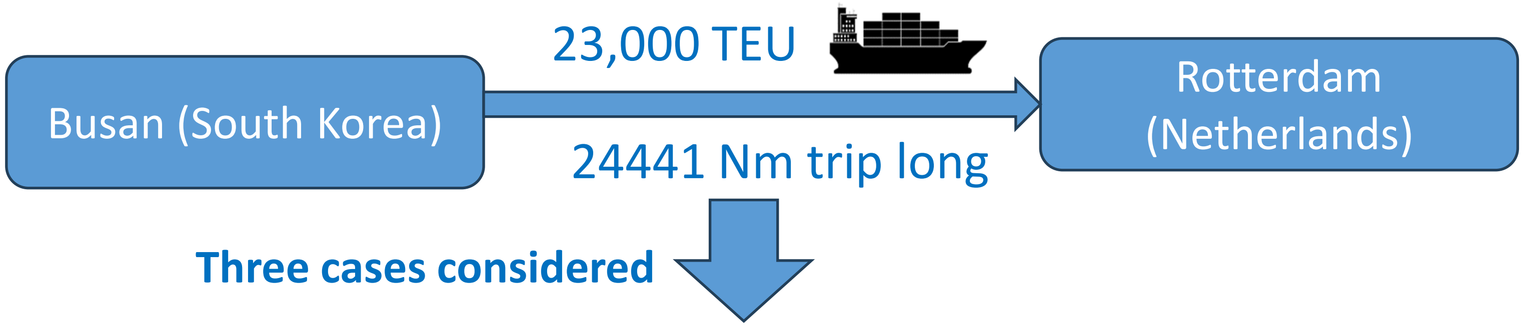
4. **SHIP TRANSPORT ASSESSMENT**
5. LCA TAKE AWAY MESSAGES

FUEL USE FOR SHIP TRANSPORTATION SCENARIOS

CHANGE OF FUNCTIONAL UNIT CO2EQ / TEU.KM



Busan (South Korea)

23,000 TEU

24441 Nm trip long

Rotterdam (Netherlands)

Three cases considered

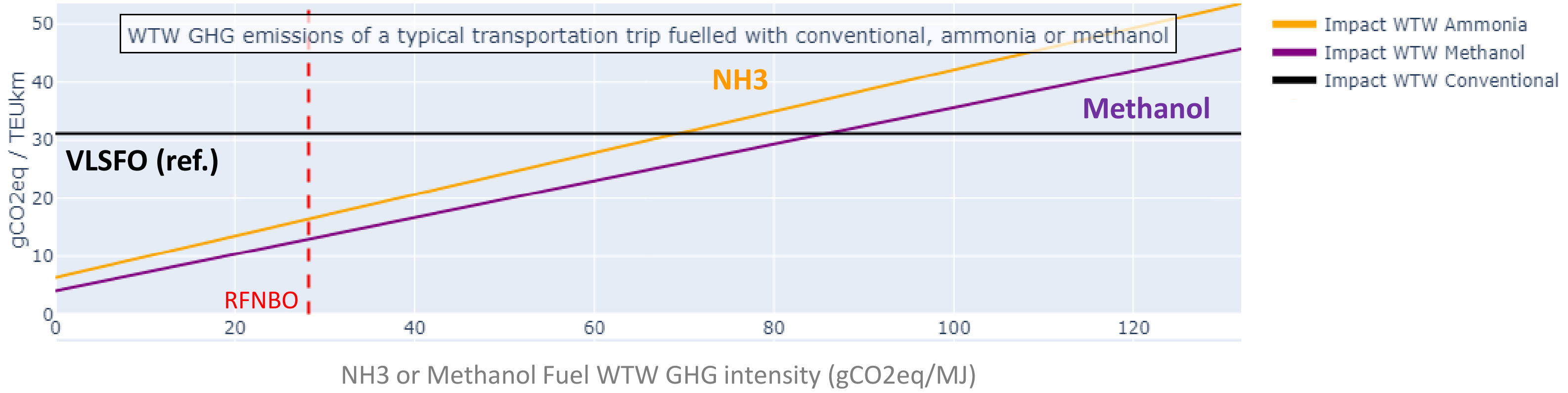
	Reference scenario	**Methanol scenario**	**Ammonia scenario**
Fuels used	VLSFO, MDO	13% pilot fuel (VLSO & MDO) 87% MeOH -> 102 GWh	13% pilot fuel (VLSO & MDO) 87% NH3 -> 115 GWh
GHG intensity	31.18 gCO2eq/TEU.km	**Results will depend on the GHG intensity of the fuel, thus its production scenario.**	

⚠ Note on data:

23,000 TEU Methanol and Ammonia ships do not currently exist. Our ship models rely on the most up-to-date engine model data, which includes test bed results for methanol engine (currently operational) and maker simulations for ammonia engine. However, for the sake of baseline comparison, the same engine configuration (size and number) has been selected. This results in non-optimal configurations for emissions, especially for NH3, where auxiliaries emit significant amounts of particularly N2O.

COMPARISON OF AMMONIA METHANOL AND VLSFO

Fuel GHG intensity VS Container transportation work GHG intensity summations (1st graph) and scenario distributions for NH3 (2nd graph) and MeOH (3rd) - **Scenario: 2025**



1st graph:

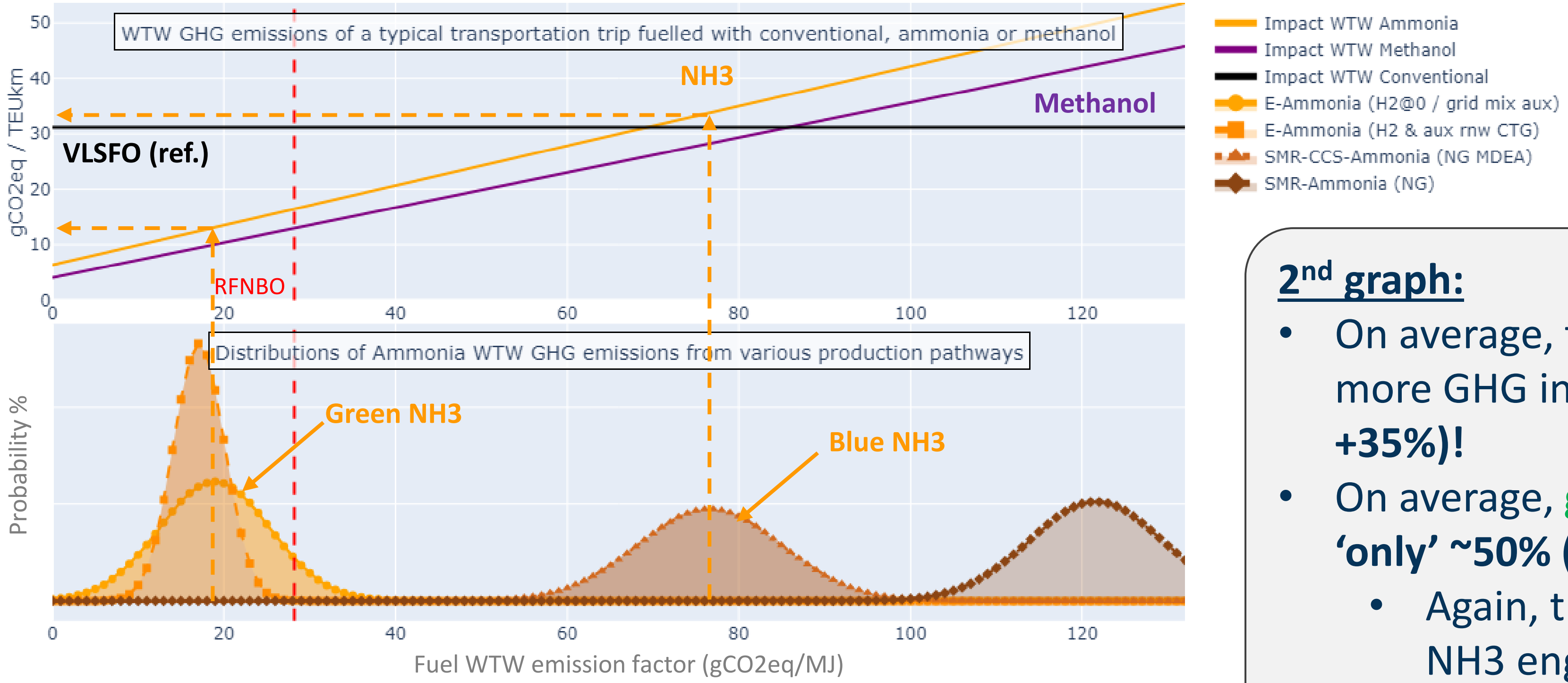
- For a given fuel emission factor (x-axis), transportation work with **NH3 is more GHG intensive** (y-axis) than with Methanol due to
  - **Lower engine efficiency** (i.e. more energy consumed per unit of output power), partly due to a non-optimized engine size and architecture).
  - Higher needs of (fossil VLSFO) **pilot fuel consumption** to ignite the combustion
  - **N_2O emissions**, a powerful greenhouse gas

➔ Engine development, ship architecture, and including a PTO to reduce N2O will improve the overall picture.

➔ The use of cleaner pilot fuel will also reduce the gap between ammonia and methanol in term of emissions, while incurring additional costs and competing with decarbonisation of VLSFO.

COMPARISON OF AMMONIA METHANOL AND VLSFO

Fuel GHG intensity VS Container transportation work GHG intensity summations (1st graph) and scenario distributions for NH3 (2nd graph) and MeOH (3rd) - Scenario: 2025



2nd graph:

- On average, transportation work with blue NH3 is more GHG intensive **than VLSFO (range of -20% to +35%)!**
- On average, green NH3 **reduces GHG emissions by ‘only’ ~50% (range of 35-85%) compared to VLSFO.**
    - Again, this highlights the need for R&D on NH3 engines, vessel architecture optimisation + the need of cleaner pilot fuel.
    - Loopholes in the regulatory accounting (not accounting for the infrastructure) leads to “a feeling of better outcome” than stated here.

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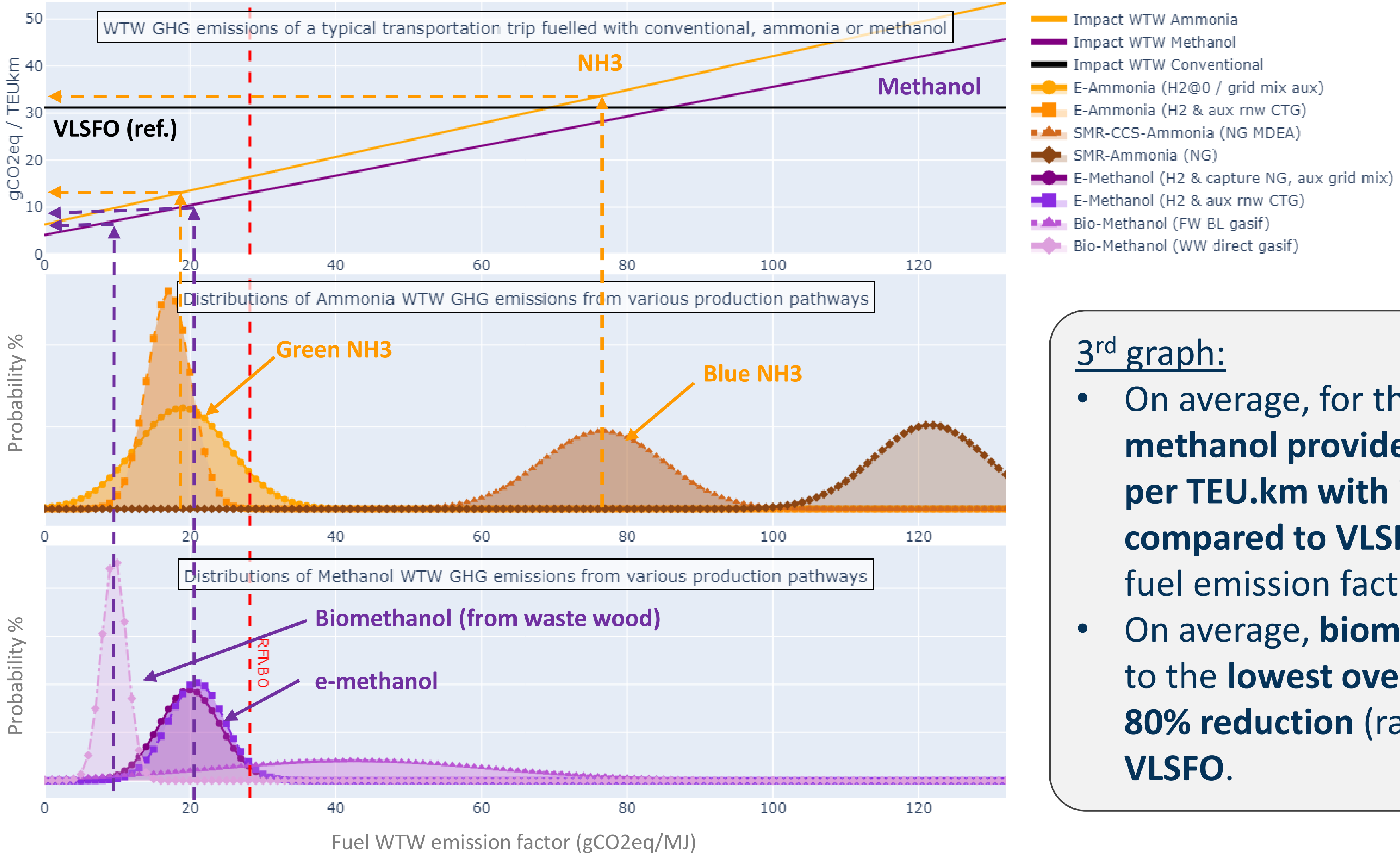
COMPARISON OF AMMONIA METHANOL AND VLSFO

Fuel GHG intensity VS Container transportation work GHG intensity summations (1st graph) and scenario distributions for NH3 (2nd graph) and MeOH (3rd) - Scenario: 2025



3rd graph:

- On average, for this baseline comparison, **e-methanol provides lower overall WTW emissions per TEU.km with 70% reduction** (range 60-80%) **compared to VLSFO**, despite slightly higher WTW fuel emission factor than NH3.
- On average, **biomethanol from waste wood** leads to the **lowest overall WTW GHG emissions with 80% reduction** (range 75-85%) **compared to VLSFO**.

PRESENTATION OUTLINE

1. INTRODUCTION
2. EMISSIONS SCOPE REGULATIONS & METHODOLOGY
3. FUEL PRODUCTION SCENARIOS AND ASSESSMENTS
4. SHIP TRANSPORT ASSESSMENT
5. LCA TAKE AWAY MESSAGES

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LCA TAKE AWAY MESSAGES (1/2)

Regulations & methodologies

- With RED methodology, **the molecules derived from green H2 show a significant GHG reduction potential (~90% vs RED fossil reference).** Loopholes in this methodology, currently not accounting for the emissions related to renewables infrastructure, lead to **overoptimistic emissions reduction levels for e-fuels.**
- **Considering the Cradle-to-Grave scope, they can achieve ~80% reduction potential (still passing RFNBO threshold).**

Comparisons of fuels

Overall, **Ammonia and Methanol products have similar order of magnitude of WTW GHG results.** However, lower ammonia engine efficiency results in higher overall WTW **GHG emissions at transportation trip level.**

Ammonia

- **Blue NH3 is not fit for decarbonization,** it emits more overall WTW GHG emissions per TEU.km than VLSFO, on average.
- **E-NH3 is fit for decarbonization** but it provides only **~50% reduction** (range 35-85%) in overall GHG emissions, on average
  - Highlighting need for R&D on NH3 engines and vessel architecture optimisation to improve this figure.

Methanol

- **Biomethanol is fit for decarbonization,** providing **80% reduction** (range 75-85%) in overall GHG emissions, on average.
  - Providing that it is produced with the appropriate bio-feedstock… and that it is available.
- **E-methanol is fit for decarbonization,** providing **70% reduction** (range 60-80%) in overall GHG emissions, on average.
  - … but it is **hard to produce** (requires capture of biogenic CO2).

LCA TAKE AWAY MESSAGES (2/2)

Comparisons of production regions

- **Transportation and storage** of finished product to the bunkering site has **a significant impact**.
- However, depending on the scenario of production chosen, fuels produced in regions **far from bunkering sites, but with a low-carbon electricity grid, may have lower GHG intensity than those produced nearby with high-carbon grid mixes**.
- Similarly, for products derived from reformed methane (grey or blue) hydrogen, **the natural gas supply chain GHG intensity has a significant impact on the finished product.**

Prospective results

- GHG impacts are expected to decrease with years (overall global economy decarbonation, technological improvements of electrolyzers etc.).
- Using the produced fuel for its own transportation enables to significatively reduce the final impacts of the WTW product.
- Even by 2050 under optimistic scenarios, **blue NH3 only satisfies 70% threshold in 6 out of 17 considered locations** due to large footprints when **extracting methane.**

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