CARBON LIMITS

Agora Industry

Agora Energiewende

Support on regulatory approach for LCH in the EU

June 2024

Photo by Valdemaras D. on Unsplash

CARBON LIMITS

This study has been prepared for Agora Energiewende and Agora Industry.

Disclaimer

This document was developed to provide support on the regulatory approach for LCH in the EU. The slide deck is based on the findings and analysis done on emission factor intensities in different case studies and assessing the MRV requirements along the value chains assessed as part of this study. Carbon Limits provides analytical support to inform on up-to date technological developments and readiness and economics around (partly) fossil-based hydrogen production pathways.

Prepared by: Carbon Limits AS

Authors: Malavika Venugopal, Fanny Lagrange, Lauren Selleck and Gaelle Cauchois

Version: Final

June 2024

Carbon Limits AS
@CarbonLimitsAS

CJ Hambros plass 2
0164 Oslo
Norge

+47 988 457 930
www.carbonlimits.no

Agora Energiewende

Agora Industry

Introduction

With the delegated acts discussing a minimum threshold for greenhouse gas (GHG) savings from recycled carbon fuels and specifying a methodology for evaluating GHG savings from renewable liquid and gaseous fuels of non-biological origin (RFNBOs) in EU (2023) 1185, and the Delegated act establishing a Union methodology defining detailed rules for RFNBOs production (EU (2023) 1184), in tandem with the Renewables Directive (RED), the European Union has laid out the prerequisites for classifying hydrogen as renewable. Consequently, this framework also establishes criteria for the renewable hydrogen targets outlined in the RED.

However, the picture is less clear when it comes to fossil based/mixed/biomass-based produced hydrogen. With the final methodologies and production criteria for "low carbon hydrogen" imminent, this project aimed to receive analytical support to inform on up-to date technological developments and readiness and economics around (partly) fossil-based hydrogen production pathways.

Objectives of the project

To deliver a comprehensive slide deck with

Section 1	overview of methane (CH_4) and carbon-dioxide (CO_2) intensity for H_2 used in the EU, produced domestically or imported using 5 case studies
Section 2	high level assessment of value chain actors and state of the art of Monitoring, Reporting and Verification (MRV) for estimating CH4 and CO2 emissions along the natural gas value chain

Table of contents

CARBON LIMITS

LCH Case studies assessed

CARBON LIMITS

5 case studies covering different production modes

Case 1: LNG imported from the US to Germany – production of blue H_2 with imported LNG. CO_2 is transported to Norway for storage.

Case 2: Gas imported from Algeria to Germany via pipeline – production of blue H_2 in Germany. CO_2 is transported to Norway for storage.

Case 3: Blue H_2 is produced in Norway (with domestic gas produced), with CO_2 stored in Norway and H_2 transported by offshore pipeline to Germany.

Case 4: Biogas based H_2 production in Germany, with CO_2 transported to Norway for storage.

Case 5: Green hydrogen produced in the US and exported as green ammonia by ship to Germany. Re-converted to hydrogen in Germany.

Task 1

Assessment of emission factors for 5 case studies.

Objectives of Task 1

CARBON LIMITS

This section focusses on Task 1 – its results, the methodology and assumptions applied for estimating the emission factors (EF). Detailed methodology for EF estimations can be found in the Annex.

The EFs were estimated for 2 scenarios.

Scenario 1: Current emissions EF

Represents the current best understanding level of emissions. Scenario 1 presents the average emissions and EF per country, and the EF is considered as flat through the study period until 2050

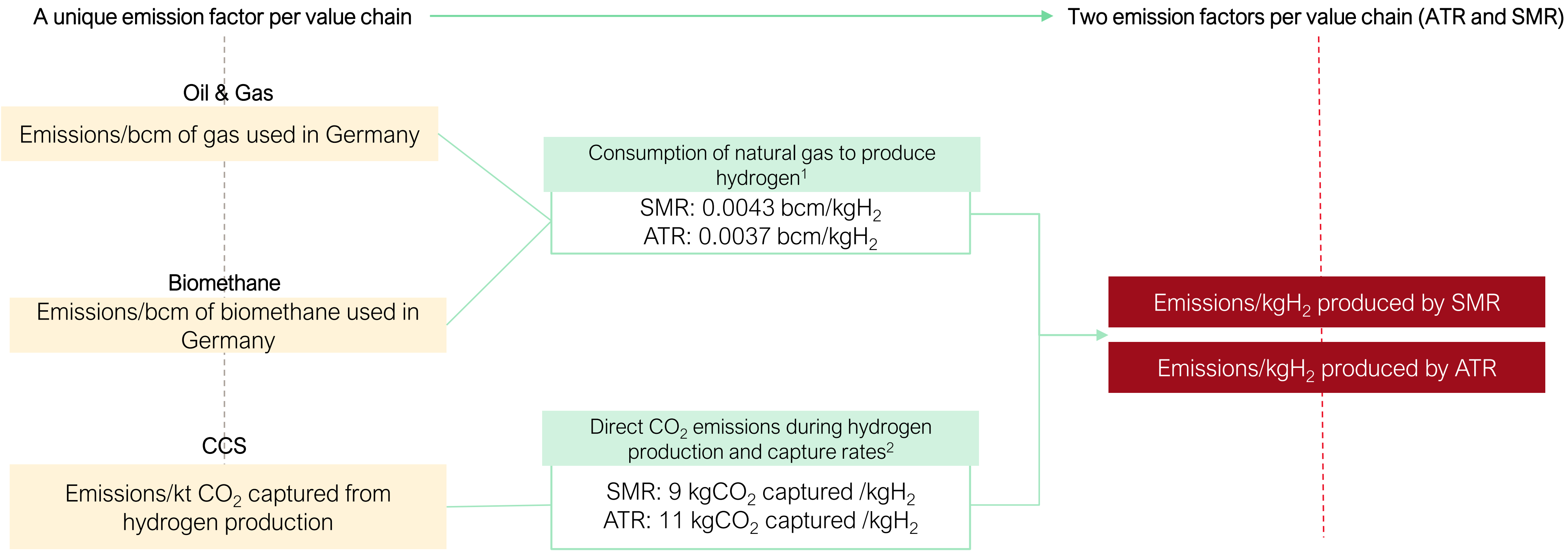
Scenario 2: EF with Best Available Technologies (BAT)

Represents the EF which could be achieved assuming BAT deployment by a certain year. A minimum of ten years is assumed to reach this BAT scenario.

For more details on the methodology applied for each scenario in each case study, see the Annex.

Emission factors units

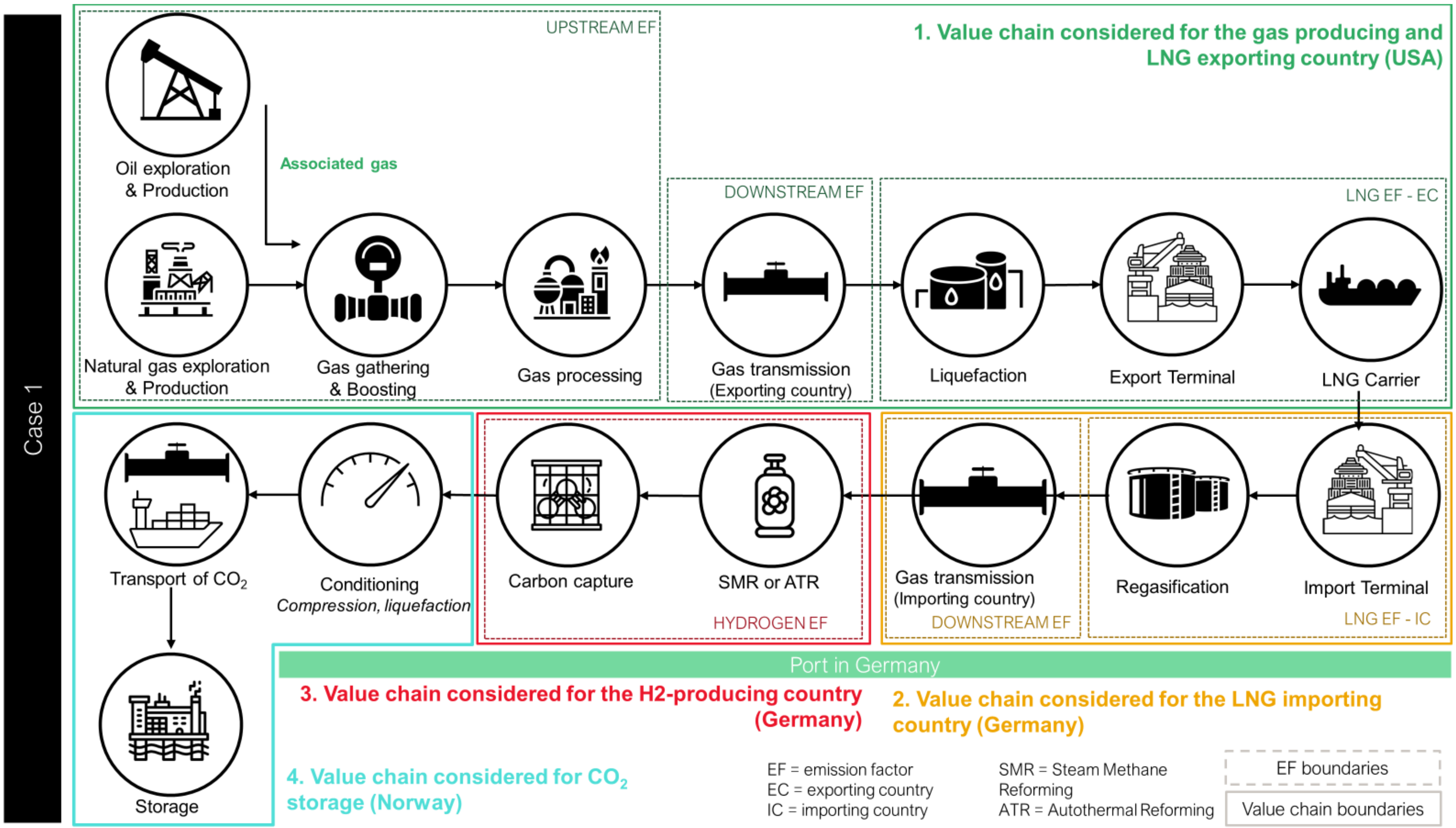
- Emission factors for this task are provided in three forms:
  - $kgCH_4$emitted/kgH_2 produced
  - $kgCO_2$emitted/kgH_2 produced
  - $kgCO_{2eq}$emitted/kgH_2 produced (summary slide) – with GWP 20 and GWP 100[3]. These emission factors are compared to 3.38 $kgCO_{2eq}$emitted/kgH_2 which corresponds to the greenhouse gas savings threshold at least 70% from January 2021, as stated out in the RED II[4].
- The following conversion steps were applied to obtain results in the aforementioned units.



[1]Based on data used in Deloitte's HyPE model: 48 and 41 kWh of natural gas consumed/kgH_2 produced by SMR and ATR respectively
[2]Assuming a capture rate of 90% for SMR and 95% for ATR based on Deloitte's HyPE model assumptions. For direct CO_2 emissions, see the methodology used for emissions from H_2 production.
[3] GWP 100 = 25 and GWP 20 = 84 have been compared, respectively based on the assumption on the Directive (EU) 2018/2001 and AR5 (IPCC)
[4] Renewable Energy – Recast to 2030 (RED II) - European Commission (europa.eu)

Case 1

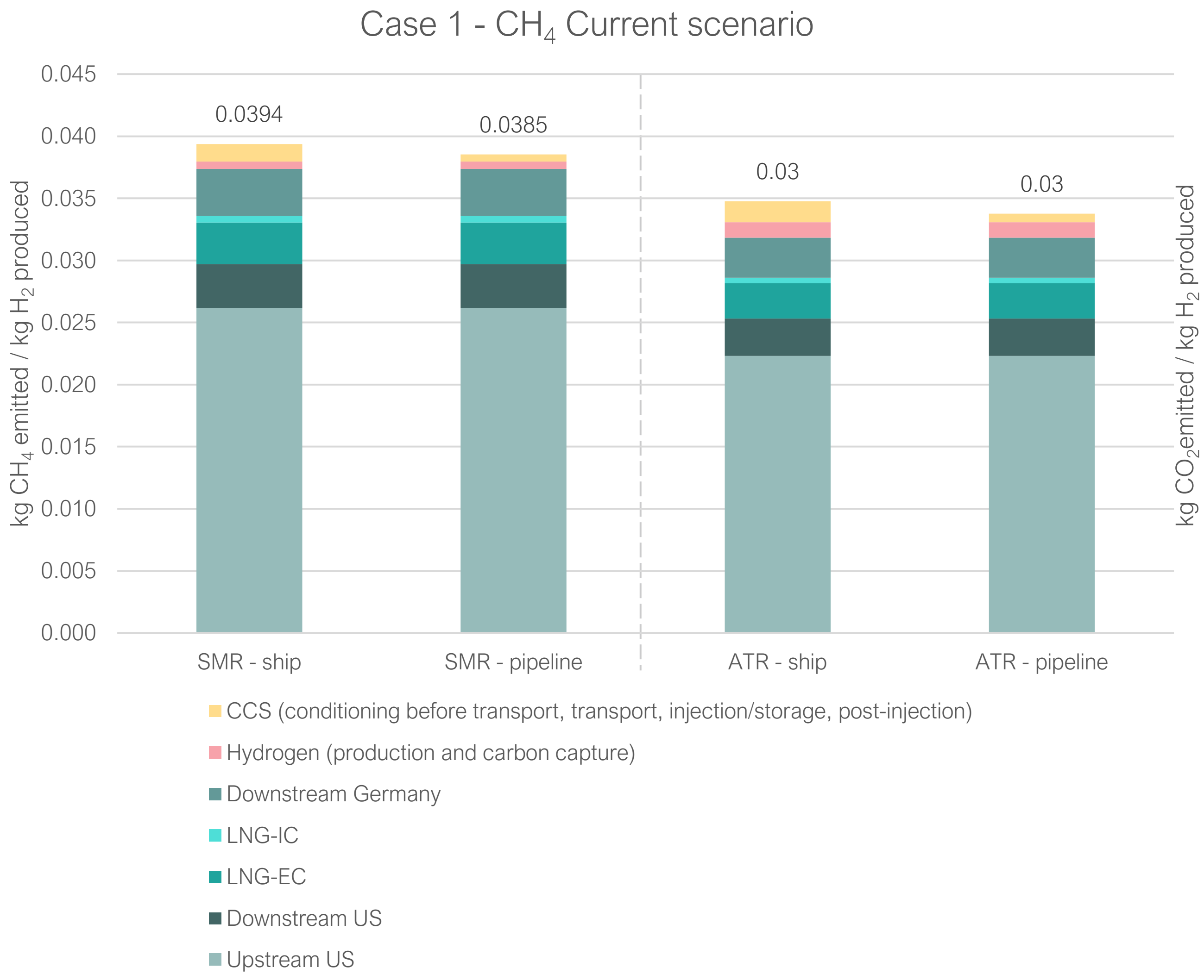
LNG imported from the US to Germany – production of blue H_2 with imported LNG. CO_2 is transported to Norway for storage

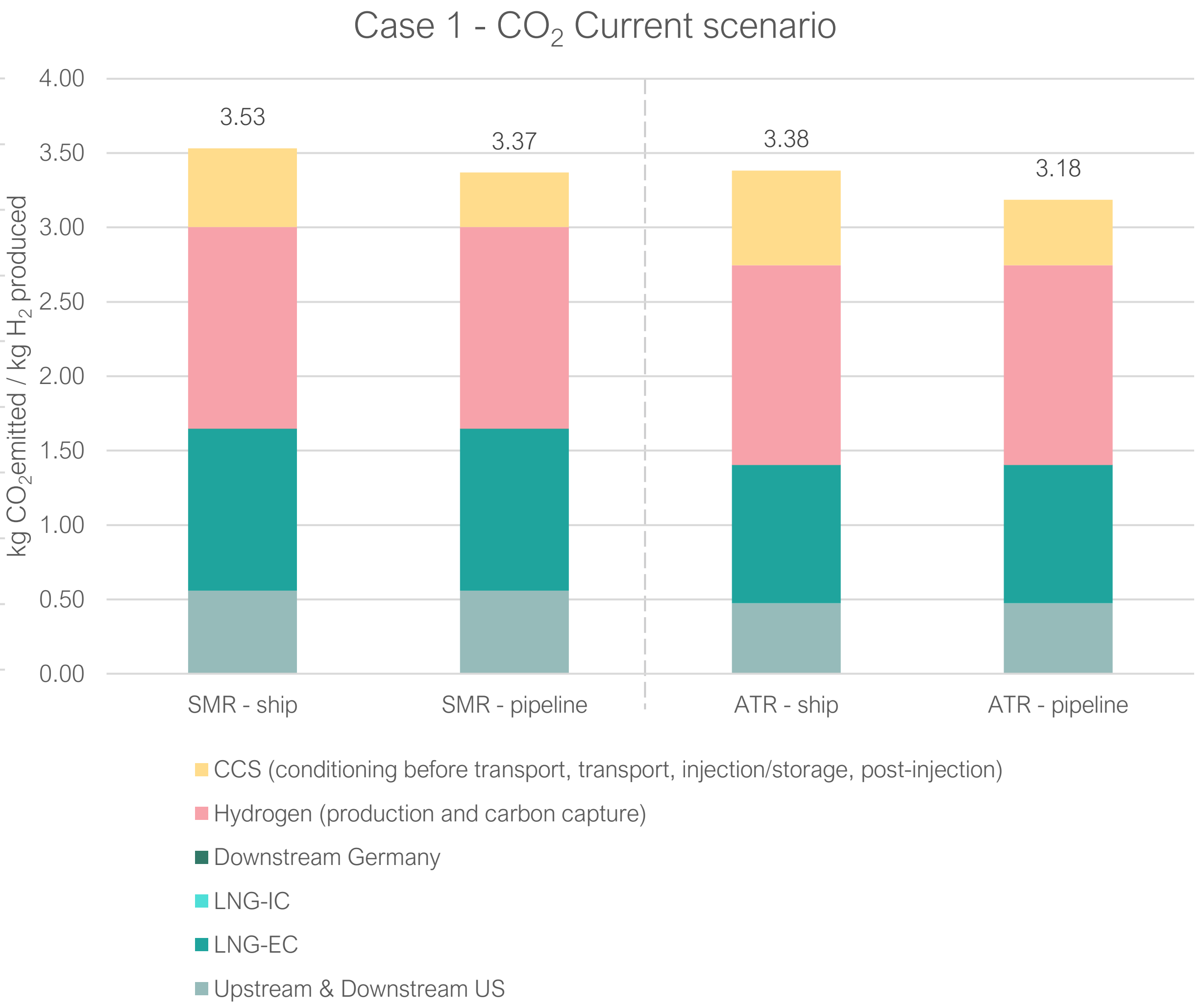

Case 1
UPSTREAM EF
1. Value chain considered for the gas producing and LNG exporting country (USA)
Oil exploration & Production
Associated gas
Natural gas exploration & Production
Gas gathering & Boosting
Gas processing
DOWNSTREAM EF
Gas transmission (Exporting country)
LNG EF - EC
Liquefaction
Export Terminal
LNG Carrier
Transport of CO_2
Conditioning
Compression, liquefaction
Carbon capture
SMR or ATR
HYDROGEN EF
Gas transmission (Importing country)
DOWNSTREAM EF
Regasification
Import Terminal
LNG EF - IC
Storage
Port in Germany
3. Value chain considered for the H2-producing country (Germany)
2. Value chain considered for the LNG importing country (Germany)
4. Value chain considered for CO_2 storage (Norway)
EF = emission factor
EC = exporting country
IC = importing country
SMR = Steam Methane Reforming
ATR = Autothermal Reforming
EF boundaries
Value chain boundaries

Case 1 EF summary for current scenario

CARBON LIMITS

In kg emissions / kg H_2 produced

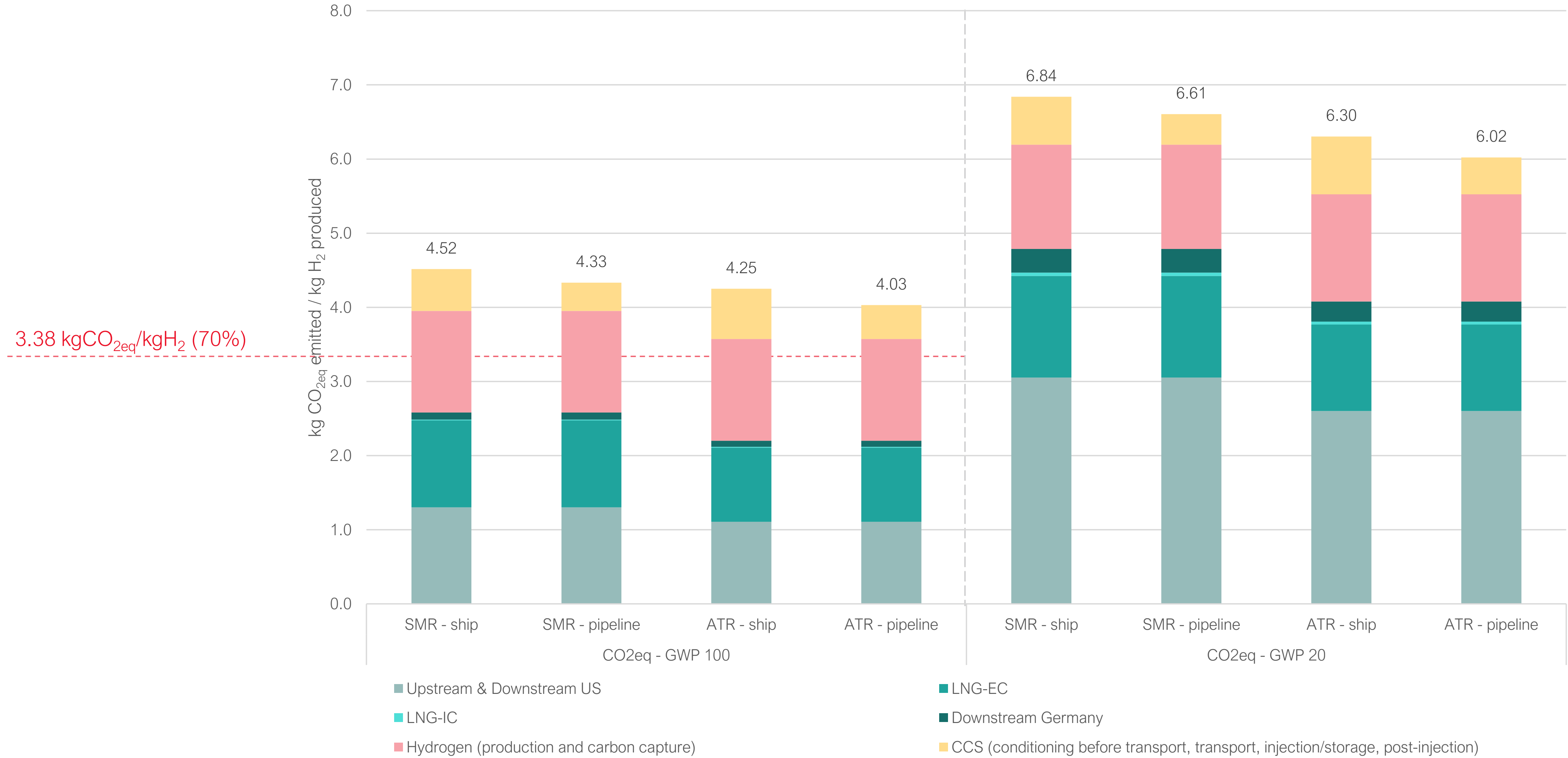




Case 1 EF summary for current scenario

CARBON LIMITS

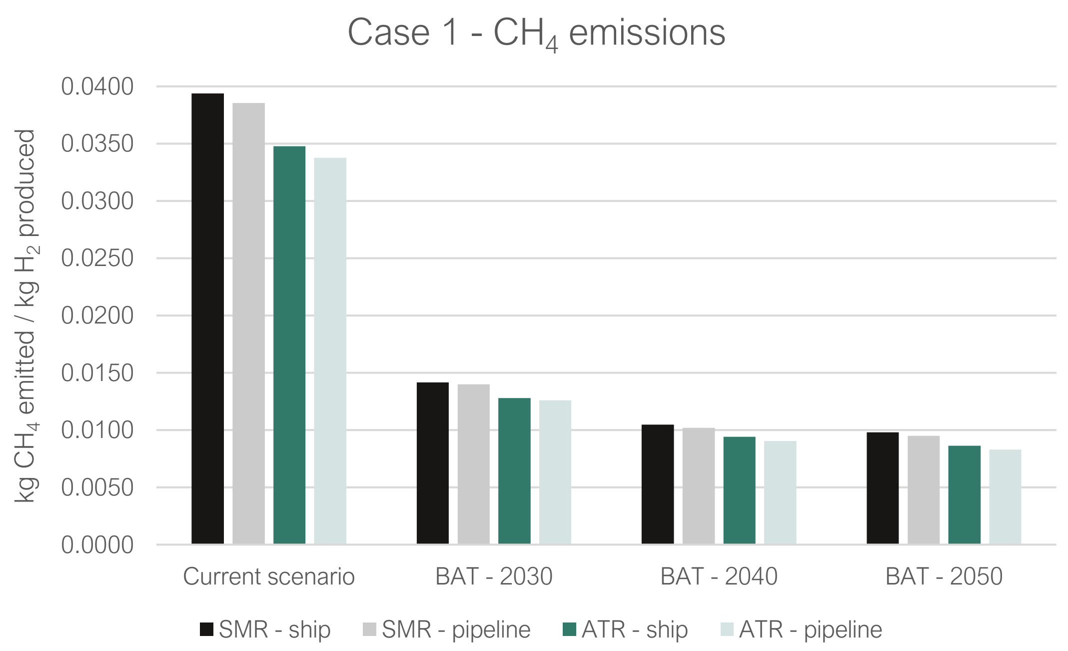
In kg CO_{2e} / kg H_2 produced – using GWP 20 and GWP 100

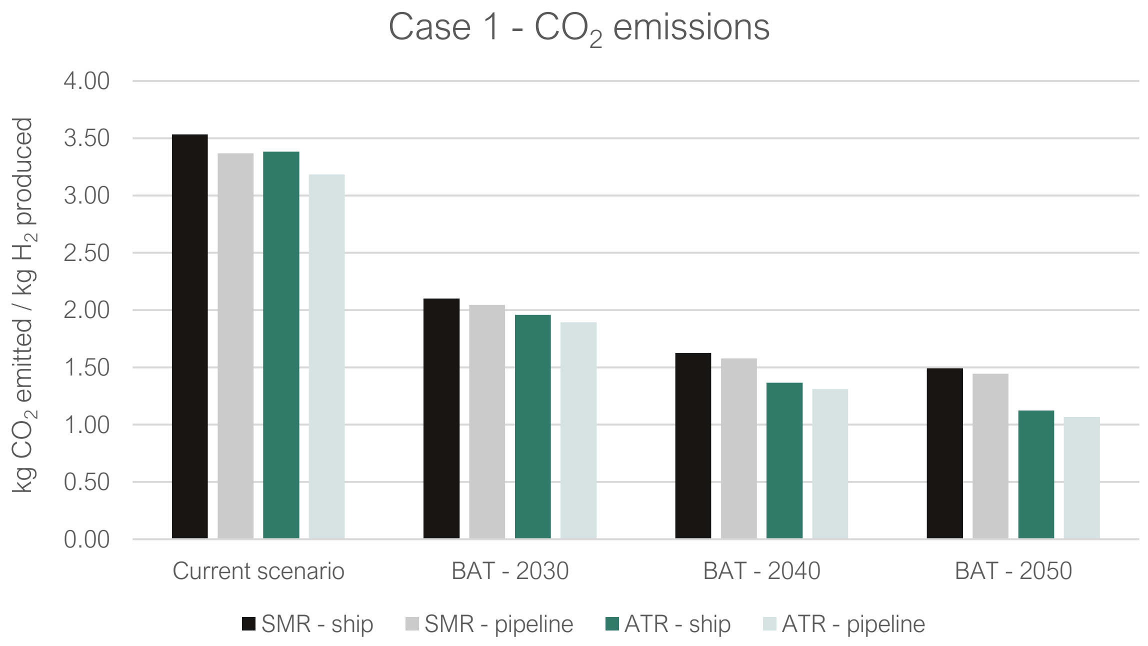


GWP 100 = 25 and GWP 20 = 84 have been compared, respectively based on the assumption on the Directive (EU) 2018/2001 and AR5 (IPCC)

Case 1 EF summary for BAT scenario

In kg emissions / kg H_2 produced



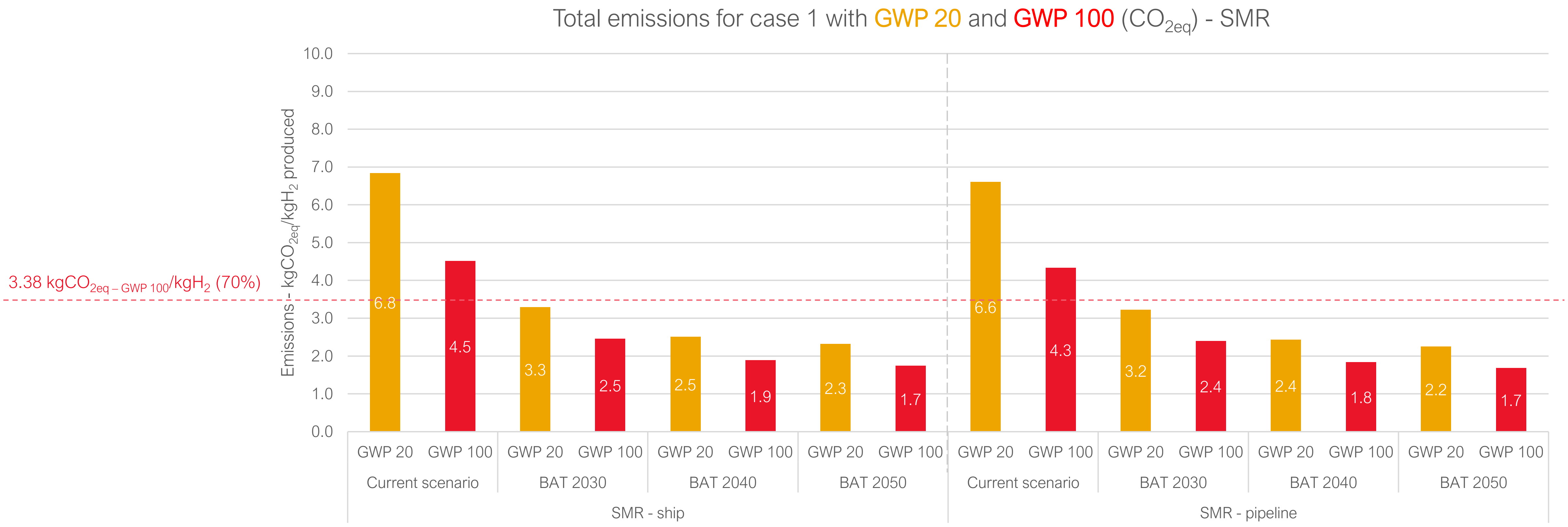


SMR – ship: Hydrogen is produced by Steam Methane Reforming and the captured CO_2 is transported by ship
SMR – pipeline: Hydrogen is produced by Steam Methane Reforming and the captured CO_2 is transported by pipeline

ATR – ship: Hydrogen is produced by Autothermal Reforming and the captured CO_2 is transported by ship
ATR – pipeline: Hydrogen is produced by Autothermal Reforming and the captured CO_2 is transported by pipeline

Case 1 EF summary for current and BAT scenario – SMR production

In kg CO_{2e} / kg H_2 produced – using GWP 20 and GWP 100



SMR – ship: Hydrogen is produced by Steam Methane Reforming and the captured CO_2 is transported by ship
SMR – pipeline: Hydrogen is produced by Steam Methane Reforming and the captured CO_2 is transported by pipeline

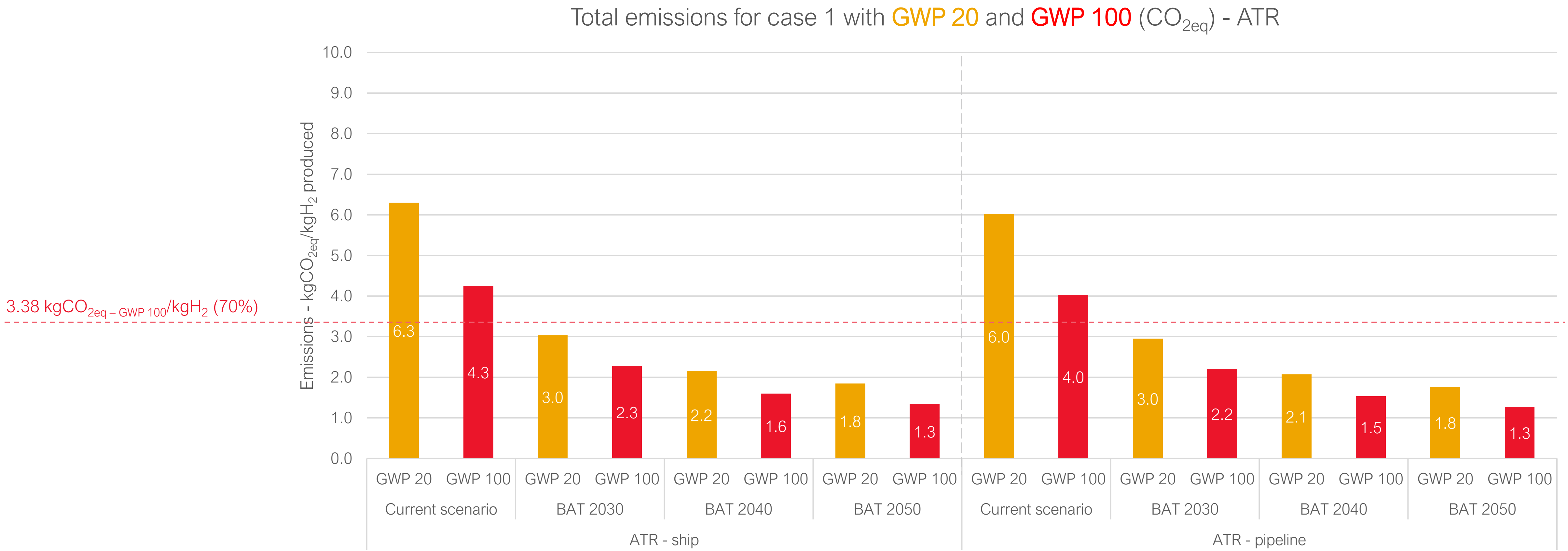
- The EF estimated in the current emissions scenario is higher than the 70% threshold (3.38kgCO_{2eq}/kgH_2) using both GWP 20 and GWP 100.
- For SMR production with both ship and pipeline transport of CO_2, the value chain presented in Case 1 is within the 70% threshold (3.38kgCO_{2eq}/kgH_2) in the BAT scenario within 2030, when using both GWP 20 and GWP 100.
- However emissions estimated using both GWP 20 and GWP 100 are within this threshold from 2040, if BAT technologies are applied for emissions reduction.

GWP 100 = 25 and GWP 20 = 84 have been compared, respectively based on the assumption on the Directive (EU) 2018/2001 and AR5 (IPCC)

Case 1 EF summary for current and BAT scenario – ATR production

CARBON LIMITS

In kg CO_{2e} / kg H_2 produced – using GWP 20 and GWP 100



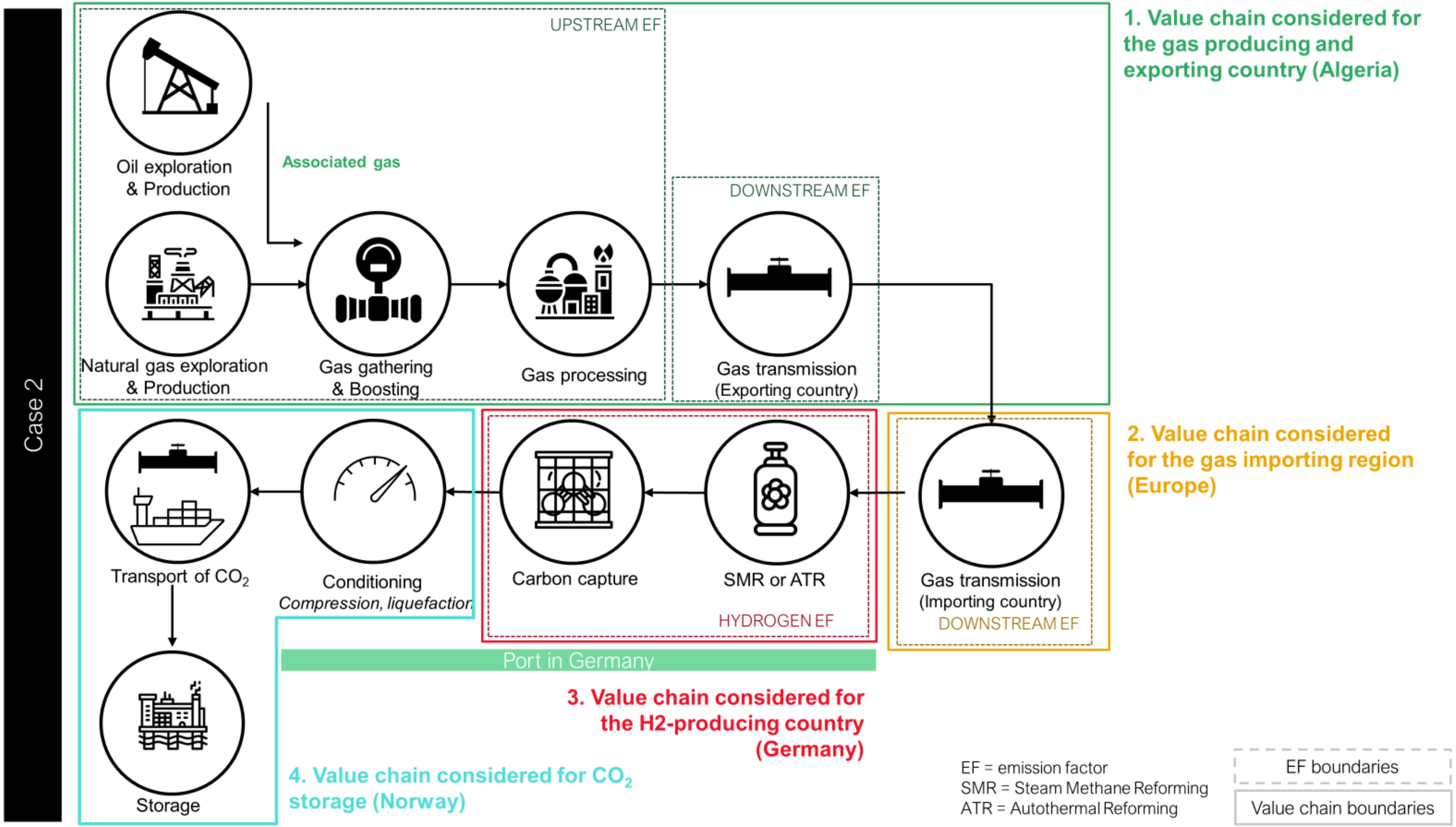
ATR – ship: Hydrogen is produced by Autothermal Reforming and the captured CO_2 is transported by ship
ATR – pipeline: Hydrogen is produced by Autothermal Reforming and the captured CO_2 is transported by pipeline

- The EF in the current emissions scenario is higher than the 70% threshold (3.38kgCO_{2eq}/kgH_2) using both GWP 20 and GWP 100.
- For ATR production with both ship and pipeline transport of CO_2, the value chain presented in Case 1 is within the 70% threshold (3.38kgCO_{2eq}/kgH_2) in the BAT scenario within 2030.
- It should be noted that, depending on the GWP considered and the year of analysis, ATR has between 6% to 24% lower EF than SMR for case 1.

GWP 100 = 25 and GWP 20 = 84 have been compared, respectively based on the assumption on the Directive (EU) 2018/2001 and AR5 (IPCC)

Case 2

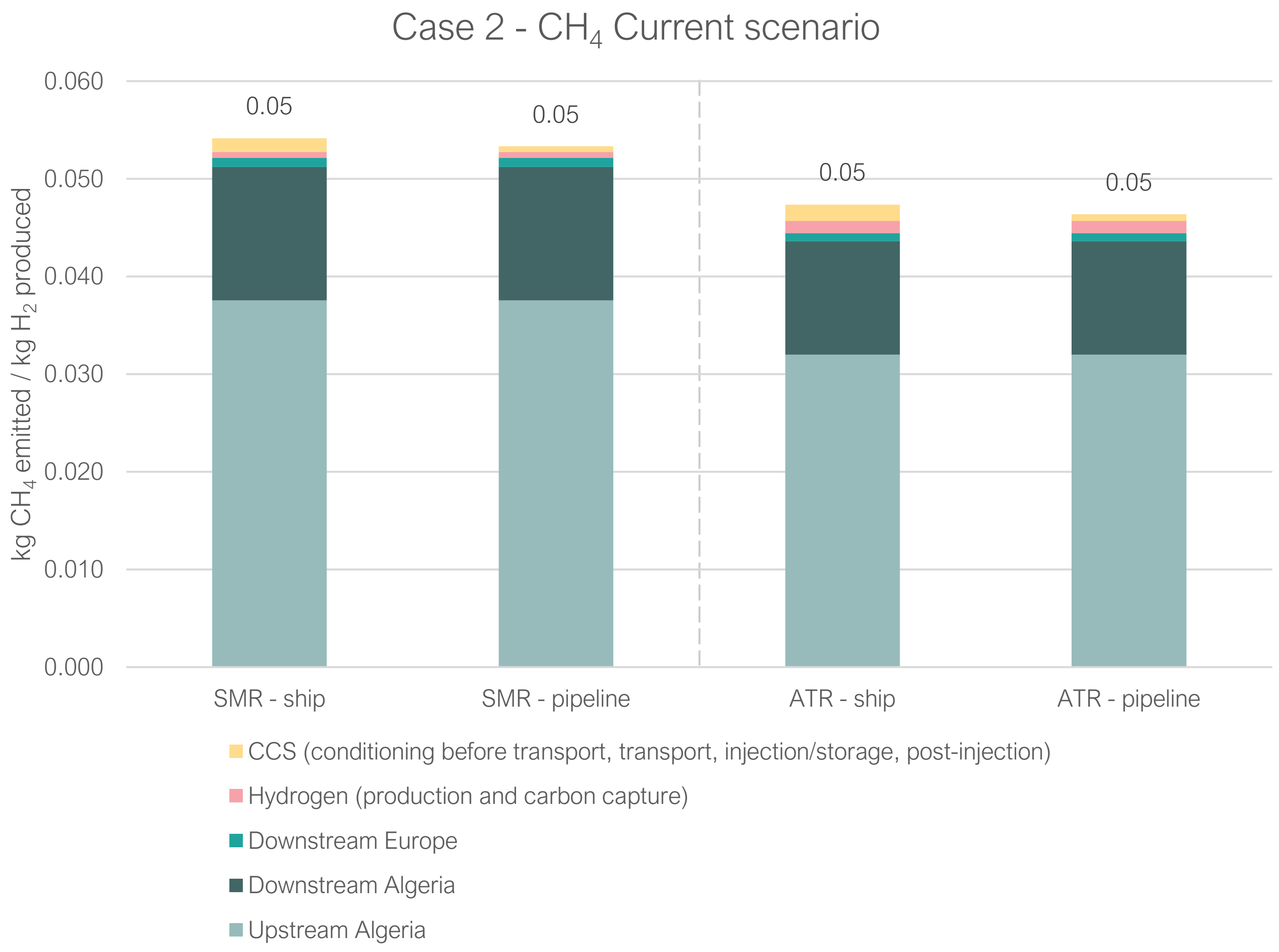
Gas imported from Algeria to Germany via pipeline – production of blue H_2 in Germany. CO_2 is transported to Norway for storage.

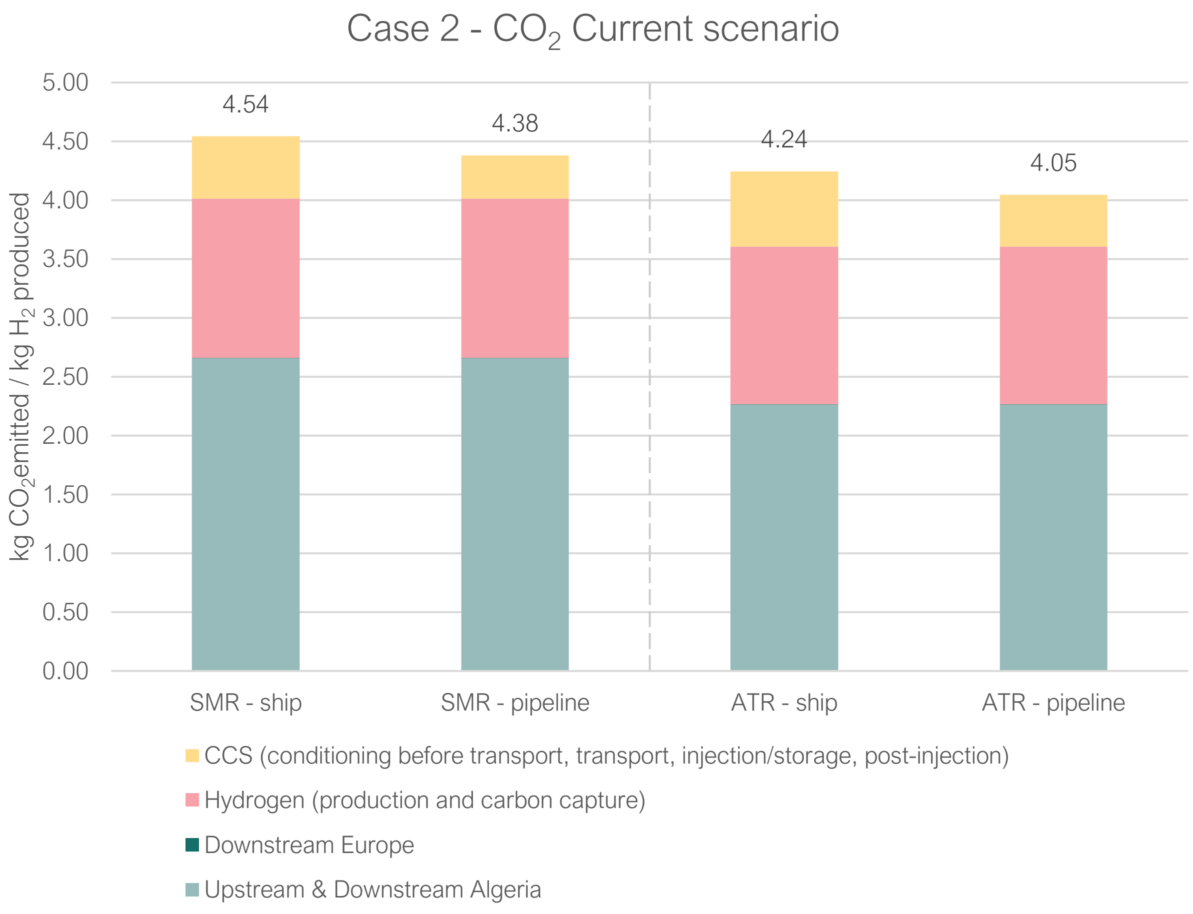

Case 2
UPSTREAM EF
Oil exploration & Production
Associated gas
Natural gas exploration & Production
Gas gathering & Boosting
Gas processing
DOWNSTREAM EF
Gas transmission (Exporting country)
1. Value chain considered for the gas producing and exporting country (Algeria)
Transport of CO_2
Conditioning
Compression, liquefaction
Carbon capture
SMR or ATR
HYDROGEN EF
Gas transmission (Importing country)
DOWNSTREAM EF
2. Value chain considered for the gas importing region (Europe)
Port in Germany
Storage
3. Value chain considered for the H2-producing country (Germany)
4. Value chain considered for CO_2 storage (Norway)
EF = emission factor
SMR = Steam Methane Reforming
ATR = Autothermal Reforming
EF boundaries
Value chain boundaries

Case 2 EF summary for current scenario

CARBON LIMITS

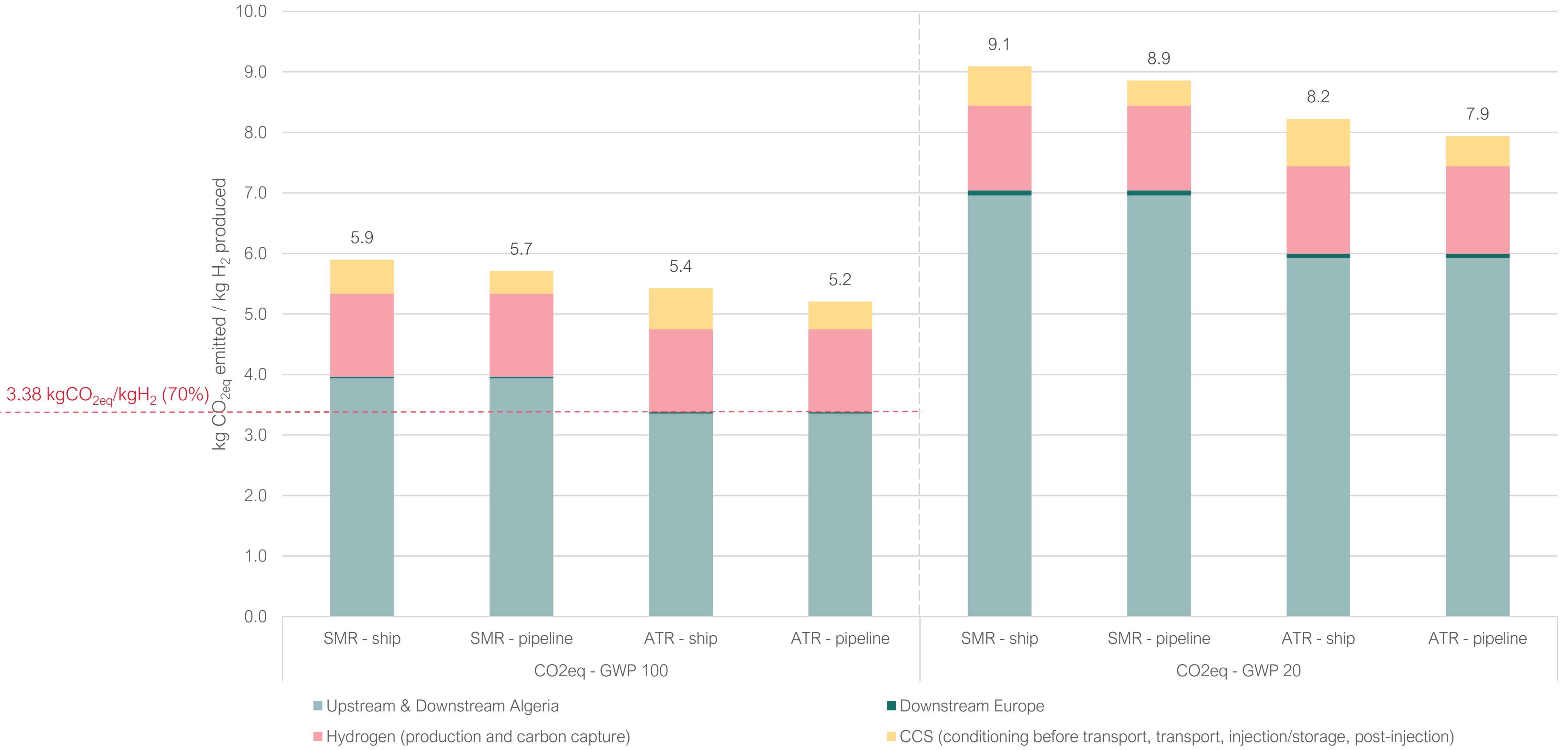
In kg emissions / kg H_2 produced





Case 2 EF summary for current scenario

In kg CO_{2e} / kg H_2 produced – using GWP 20 and GWP 100

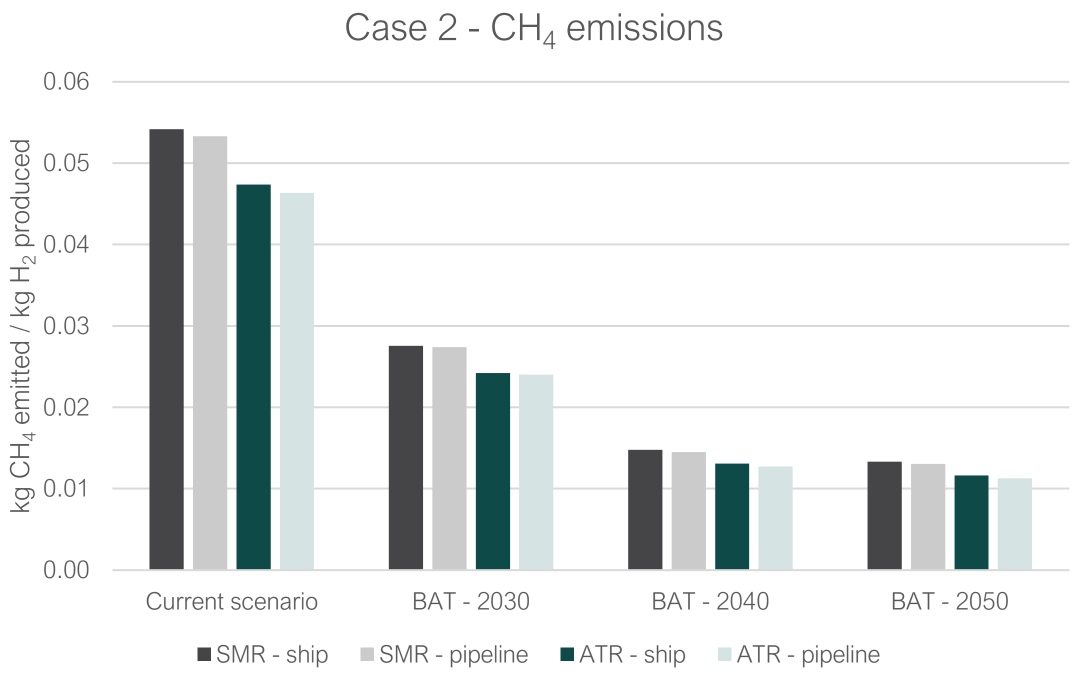


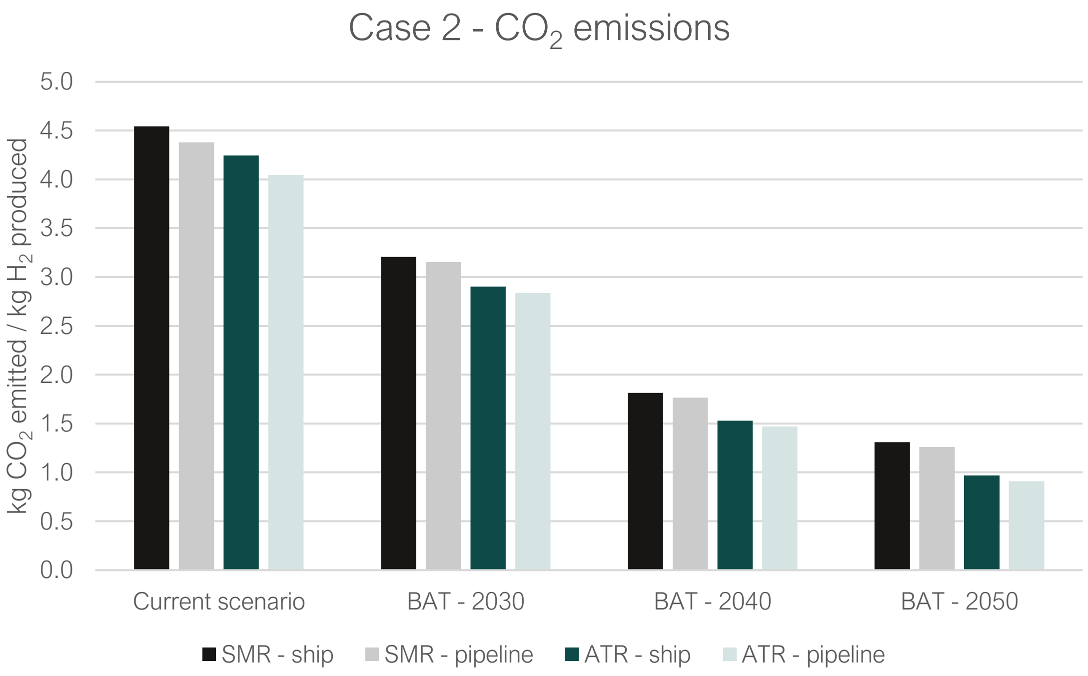
GWP 100 = 25 and GWP 20 = 84 have been compared, respectively based on the assumption on the Directive (EU) 2018/2001 and AR5 (IPCC)

CARBON LIMITS

Case 2 EF summary for BAT scenario

In kg emissions / kg H_2 produced





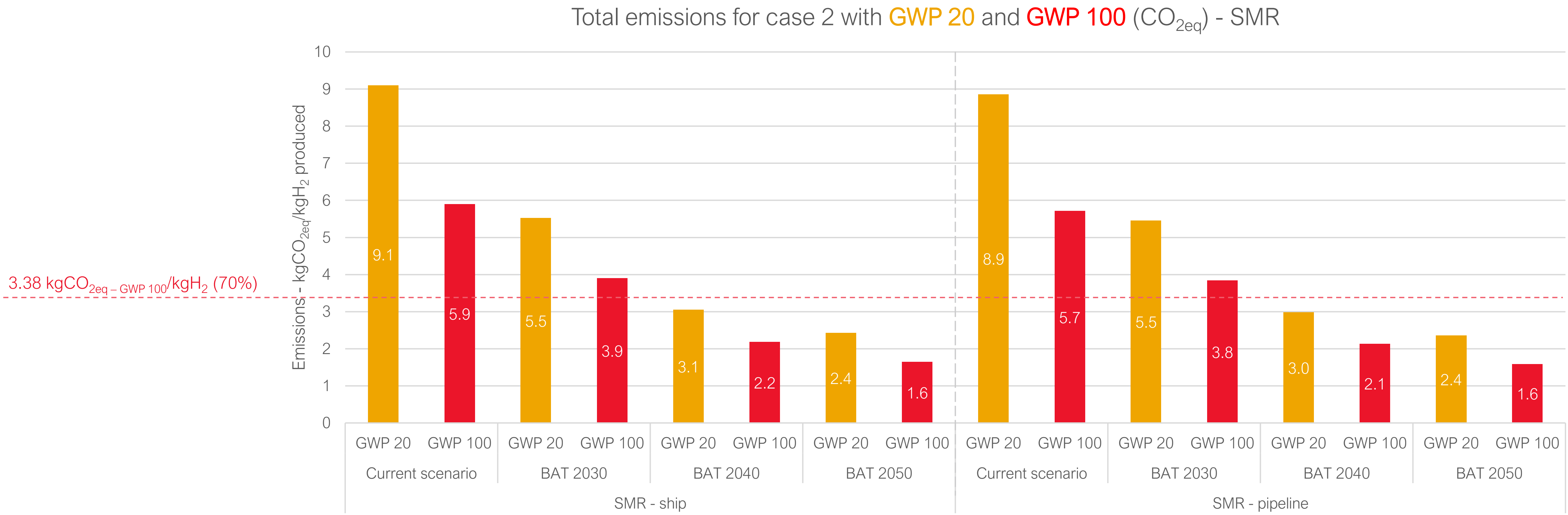
SMR – ship: Hydrogen is produced by Steam Methane Reforming and the captured CO_2 is transported by ship
SMR – pipeline: Hydrogen is produced by Steam Methane Reforming and the captured CO_2 is transported by pipeline

ATR – ship: Hydrogen is produced by Autothermal Reforming and the captured CO_2 is transported by ship
ATR – pipeline: Hydrogen is produced by Autothermal Reforming and the captured CO_2 is transported by pipeline

Case 2 EF summary for current and BAT scenario – SMR production

CARBON LIMITS

In kg CO_{2e} / kg H_2 produced – using GWP 20 and GWP 100



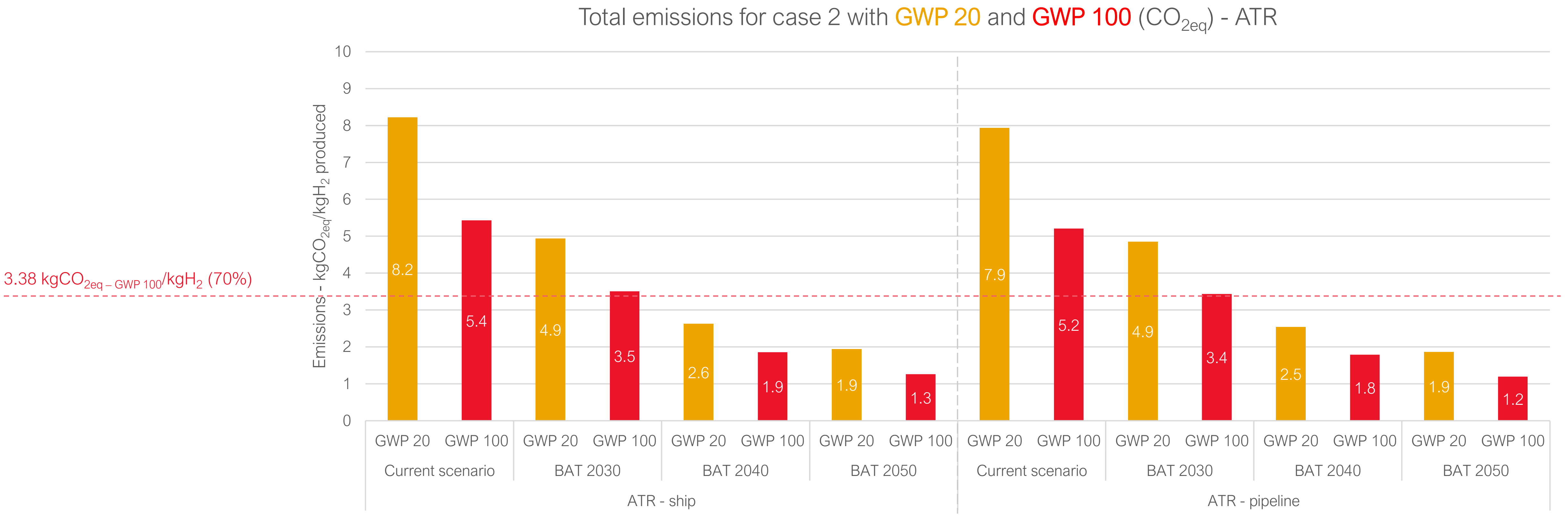
SMR – ship: Hydrogen is produced by Steam Methane Reforming and the captured CO_2 is transported by ship
SMR – pipeline: Hydrogen is produced by Steam Methane Reforming and the captured CO_2 is transported by pipeline

- The EF in the current emissions scenario is higher than the 70% threshold (3.38kgCO_{2eq}/kgH_2) using both GWP 20 and GWP 100.
- Unlike Case 1, the value chain in Case 2 has an EF higher than the 70% threshold (3.38kgCO_{2eq}/kgH_2) in BAT scenario in 2030, a decrease below the threshold is only visible from 2040 BAT scenario for both GWP values

GWP 100 = 25 and GWP 20 = 84 have been compared, respectively based on the assumption on the Directive (EU) 2018/2001 and AR5 (IPCC)

Case 2 EF summary for current and BAT scenario – ATR production

In kg CO_{2e} / kg H_2 produced – using GWP 20 and GWP 100



ATR – ship: Hydrogen is produced by Autothermal Reforming and the captured CO_2 is transported by ship
ATR – pipeline: Hydrogen is produced by Autothermal Reforming and the captured CO_2 is transported by pipeline

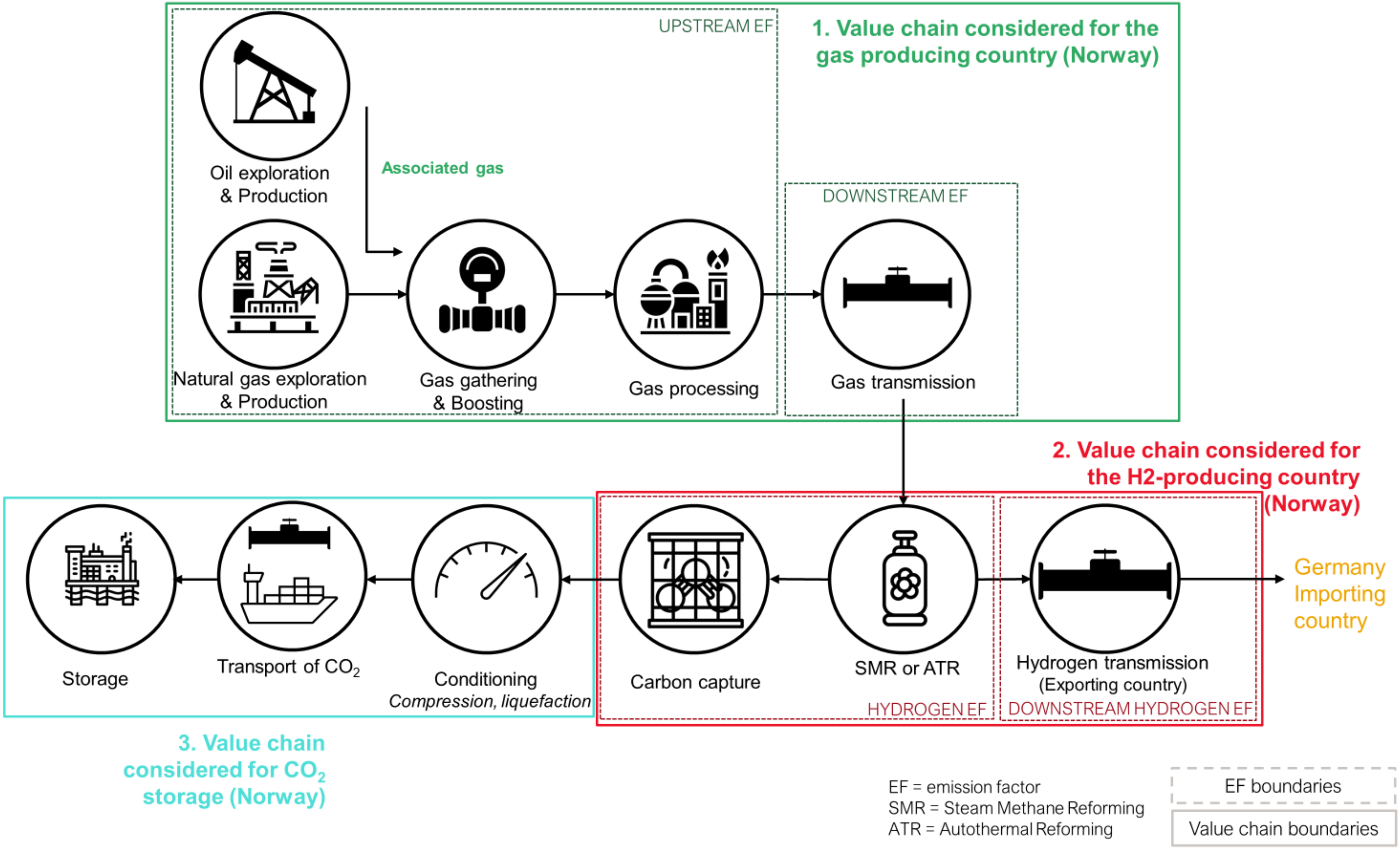
- The EF in the current emissions scenario is higher than the 70% threshold (3.38$kgCO_{2eq}/kgH_2$) using both GWP 20 and GWP 100.
- Unlike Case 1, the value chain in Case 2 has an EF higher than the 70% threshold (3.38$kgCO_{2eq}/kgH_2$) in BAT scenario in 2030.
- However emissions estimated using both GWP 20 and GWP 100 are below this threshold from 2040, if BAT technologies are applied for emissions reduction.
- It should be noted that, depending on the GWP considered and the year of analysis, ATR has between 8% to 25% lower EF than SMR for case 2.

GWP 100 = 25 and GWP 20 = 84 have been compared, respectively based on the assumption on the Directive (EU) 2018/2001 and AR5 (IPCC)

Case 3

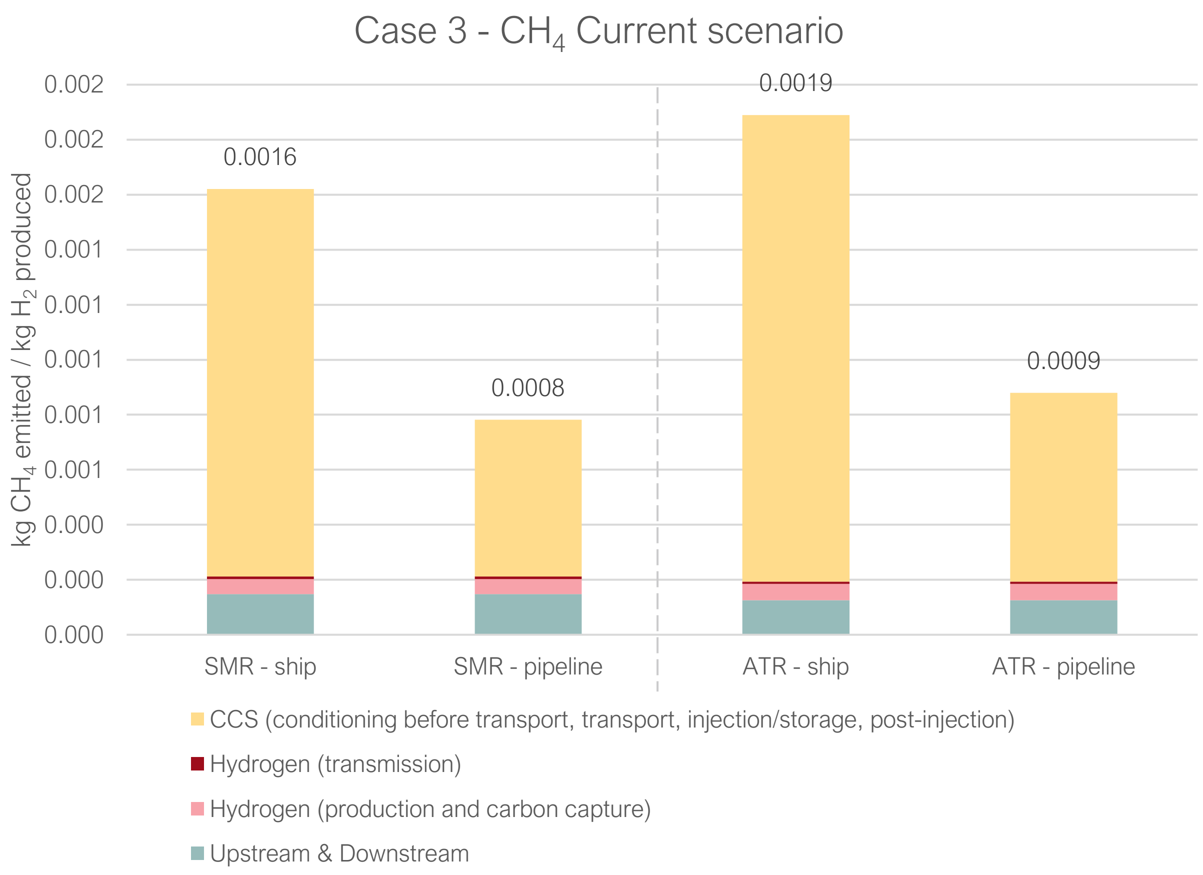
Blue H_2 is produced in Norway (with domestic gas produced), with CO_2 stored in Norway and H_2 transported by offshore pipeline to Germany.

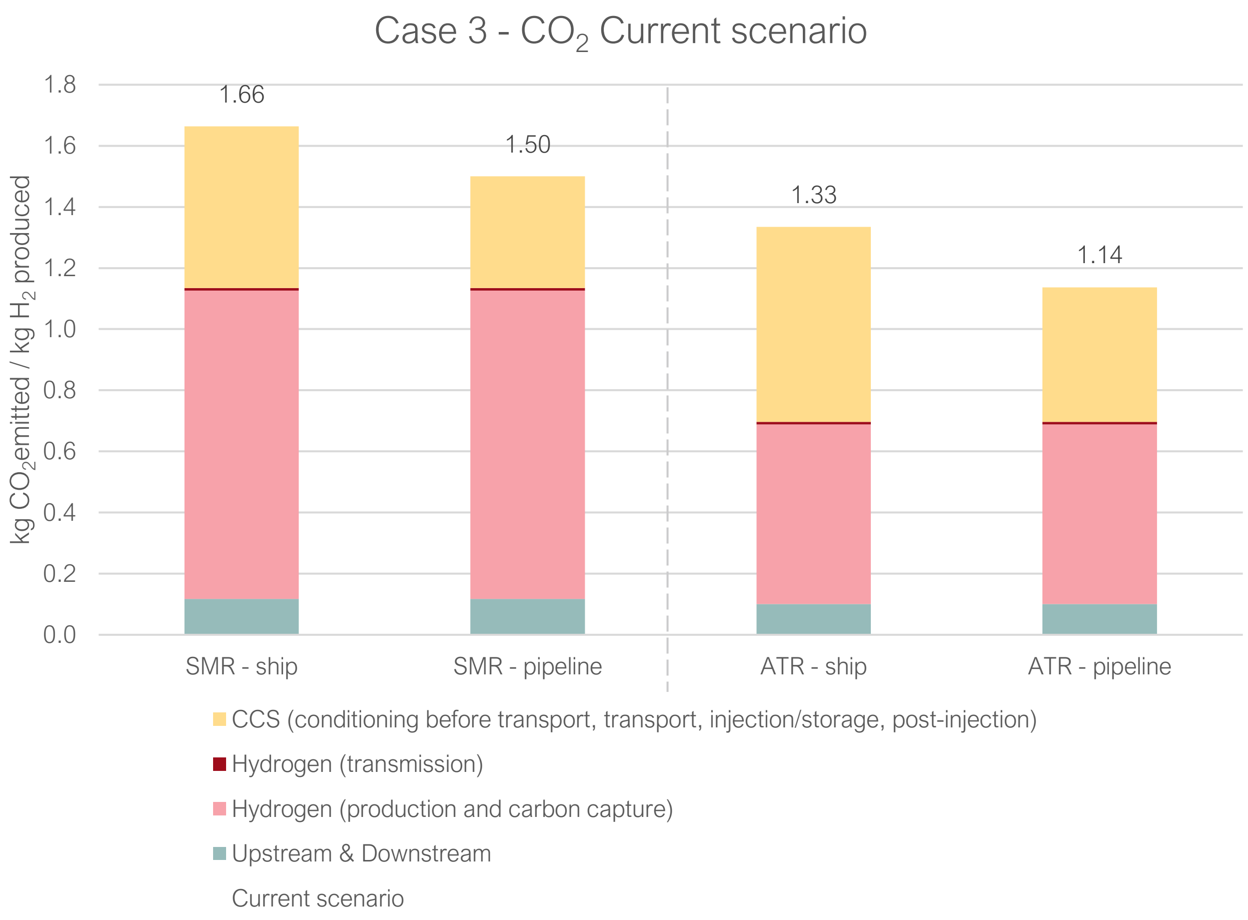
Case 3


UPSTREAM EF
1. Value chain considered for the gas producing country (Norway)
Oil exploration & Production
Associated gas
Natural gas exploration & Production
Gas gathering & Boosting
Gas processing
DOWNSTREAM EF
Gas transmission
2. Value chain considered for the H2-producing country (Norway)
Storage
Transport of CO_2
Conditioning
Compression, liquefaction
Carbon capture
SMR or ATR
Hydrogen transmission (Exporting country)
Germany Importing country
HYDROGEN EF
DOWNSTREAM HYDROGEN EF
3. Value chain considered for CO_2 storage (Norway)
EF = emission factor
SMR = Steam Methane Reforming
ATR = Autothermal Reforming
EF boundaries
Value chain boundaries

Case 3 EF summary for current scenario

In kg emissions / kg H_2 produced





Case 3 EF summary for current scenario

CARBON LIMITS

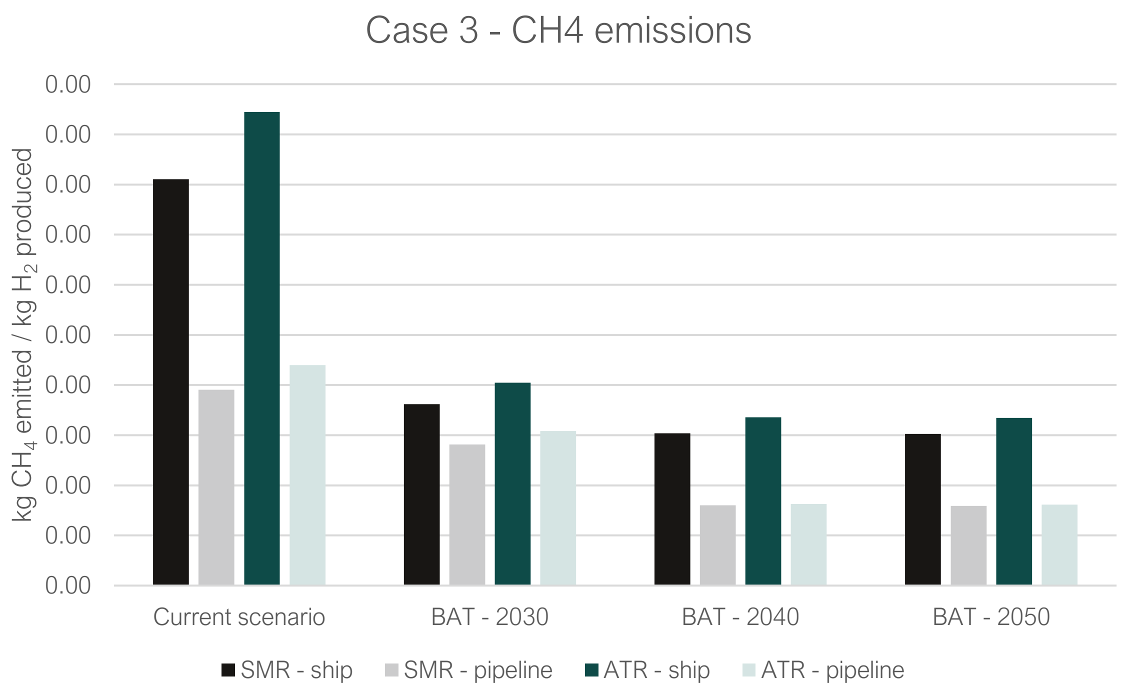
In kg CO_{2e} / kg H_2 produced – using GWP 20 and GWP 100

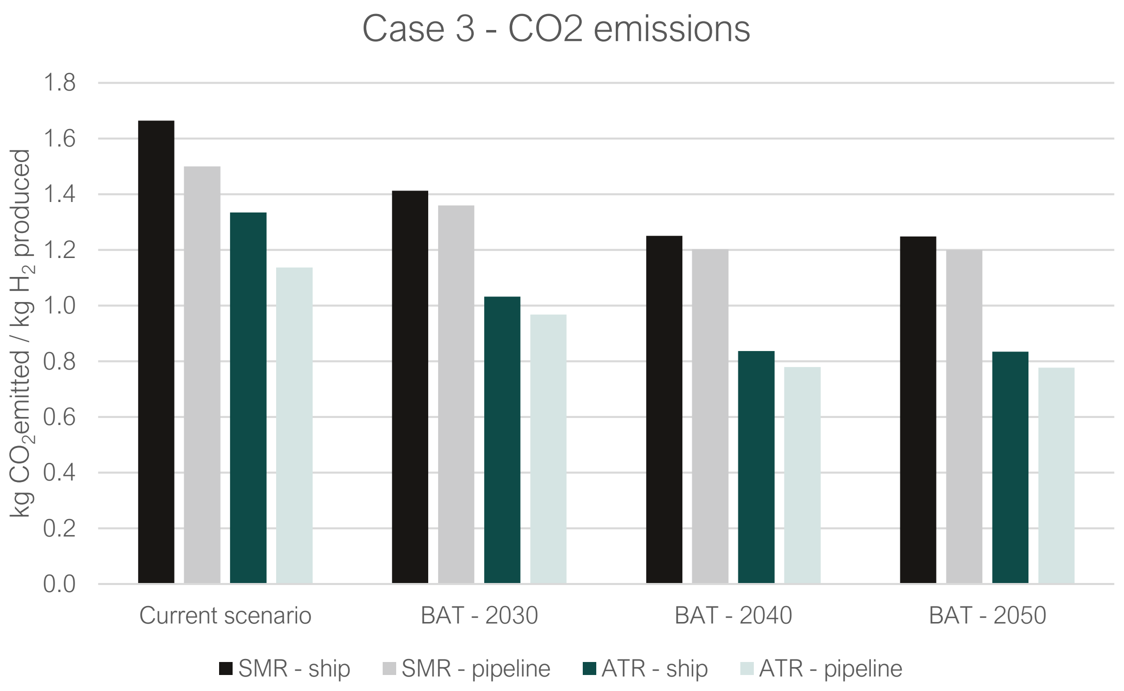
GWP 100 = 25 and GWP 20 = 84 have been compared, respectively based on the assumption on the [Directive (EU) 2018/2001](#) and [AR5 (IPCC)](#)

Case 3 EF summary for BAT scenario

CARBON LIMITS

In kg emissions / kg H_2 produced



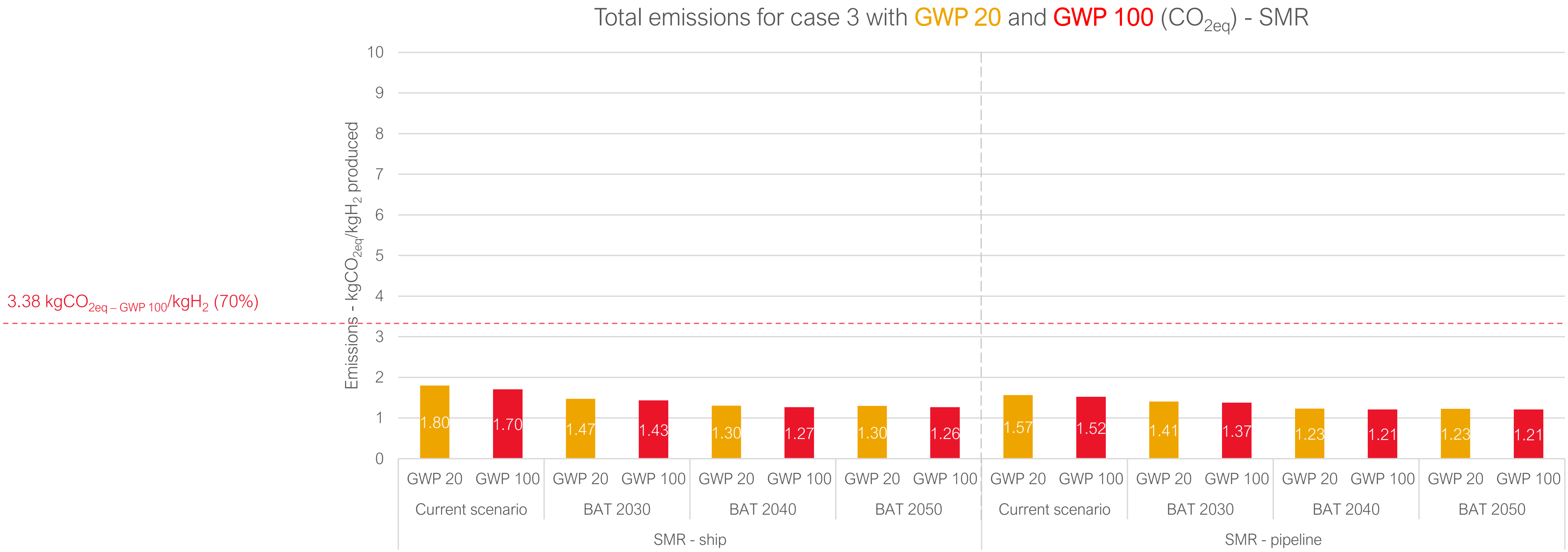


SMR – ship: Hydrogen is produced by Steam Methane Reforming and the captured CO_2 is transported by ship
SMR – pipeline: Hydrogen is produced by Steam Methane Reforming and the captured CO_2 is transported by pipeline

ATR – ship: Hydrogen is produced by Autothermal Reforming and the captured CO_2 is transported by ship
ATR – pipeline: Hydrogen is produced by Autothermal Reforming and the captured CO_2 is transported by pipeline

Case 3 EF summary for current and BAT scenario – SMR production

In kg CO_{2e} / kg H_2 produced – using GWP 20 and GWP 100



SMR – ship: Hydrogen is produced by Steam Methane Reforming and the captured CO_2 is transported by ship
SMR – pipeline: Hydrogen is produced by Steam Methane Reforming and the captured CO_2 is transported by pipeline

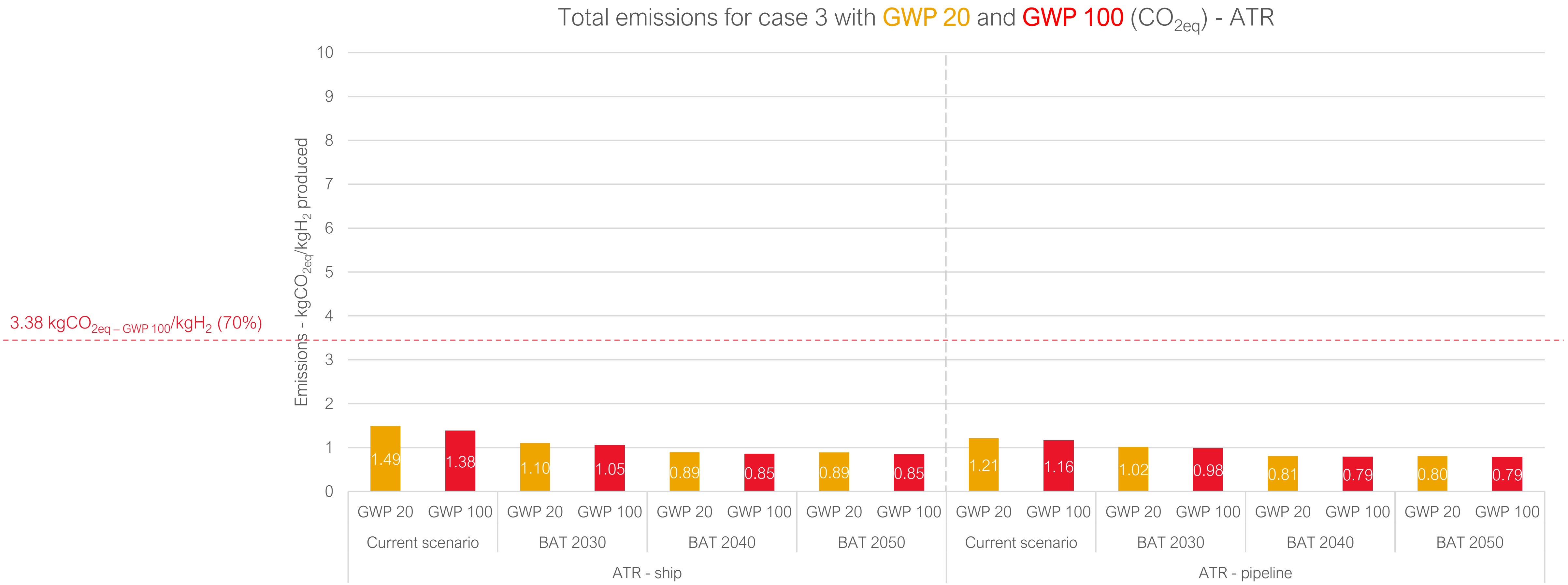
- The estimated EF in Case 3 is much lower than the 70% threshold (3.38kgCO_{2eq}/kgH_2) in all the scenarios.
- Therefore, it is possible today to obtain blue hydrogen within this threshold.

GWP 100 = 25 and GWP 20 = 84 have been compared, respectively based on the assumption on the Directive (EU) 2018/2001 and AR5 (IPCC)

Case 3 EF summary for current and BAT scenario – ATR production

CARBON LIMITS

In kg CO_{2e} / kg H_2 produced – using GWP 20 and GWP 100



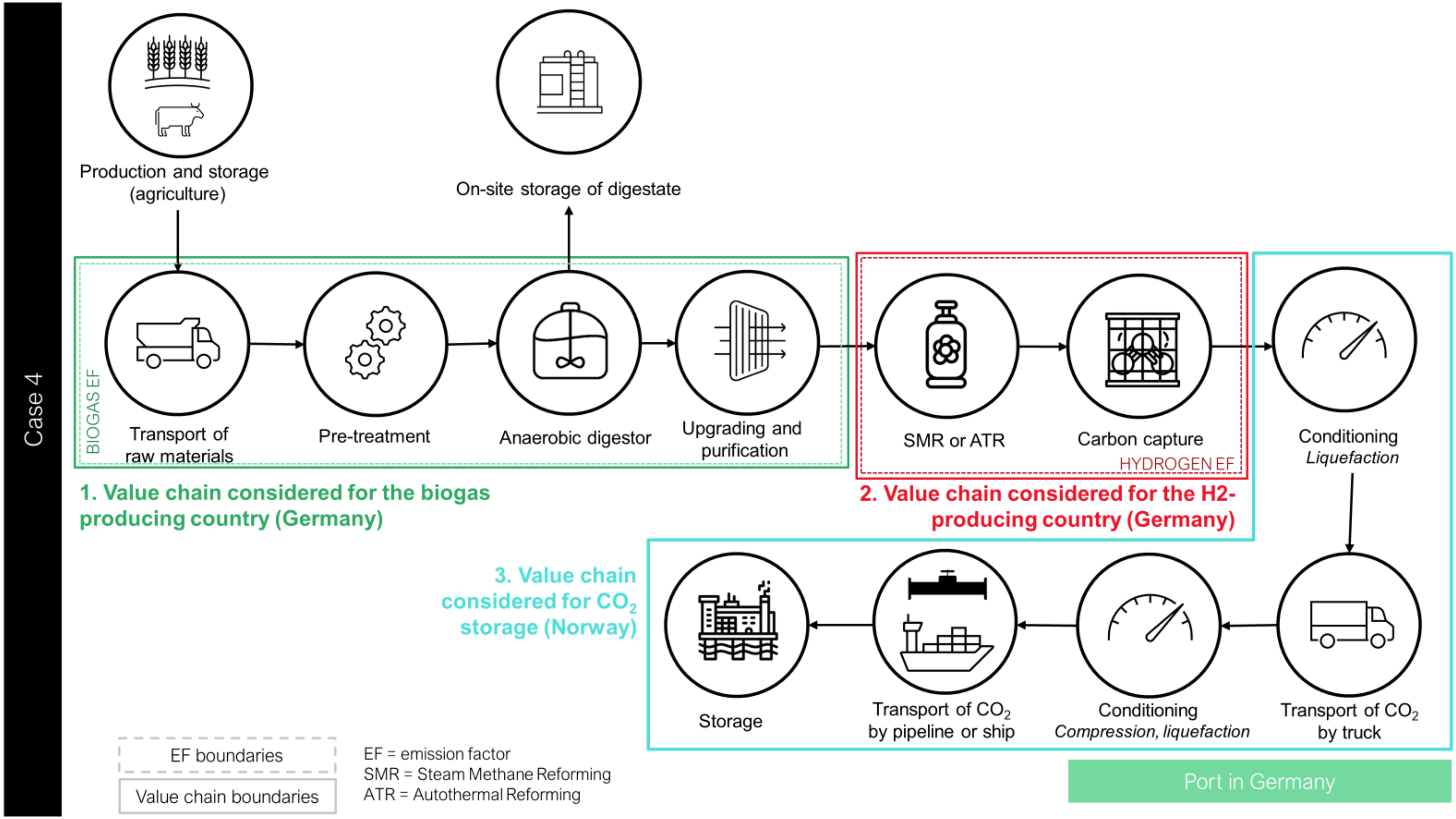
ATR – ship: Hydrogen is produced by Autothermal Reforming and the captured CO_2 is transported by ship
ATR – pipeline: Hydrogen is produced by Autothermal Reforming and the captured CO_2 is transported by pipeline

- The estimated EF in Case 3 is much lower than the 70% threshold (3.38kgCO_{2eq}/kgH_2) in all the scenarios. Therefore, it is possible today to obtain blue hydrogen within this threshold.
- It should be noted that, depending on the GWP considered and the year of analysis, ATR has between 17% to 35% lower EF than SMR for case 3

GWP 100 = 25 and GWP 20 = 84 have been compared, respectively based on the assumption on the Directive (EU) 2018/2001 and AR5 (IPCC)

Case 4

Biogas-based H_2 production in Germany, with CO_2 transported to Norway for storage.


Case 4
Production and storage (agriculture)
On-site storage of digestate
BIOGAS EF
Transport of raw materials
Pre-treatment
Anaerobic digestor
Upgrading and purification
SMR or ATR
Carbon capture
HYDROGEN EF
Conditioning
Liquefaction
1. Value chain considered for the biogas producing country (Germany)
2. Value chain considered for the H2-producing country (Germany)
3. Value chain considered for CO_2 storage (Norway)
Storage
Transport of CO_2 by pipeline or ship
Conditioning
Compression, liquefaction
Transport of CO_2 by truck
Port in Germany
EF boundaries
Value chain boundaries
EF = emission factor
SMR = Steam Methane Reforming
ATR = Autothermal Reforming

Note on biogenic and non biogenic emission assumptions

CARBON LIMITS

General assumptions

- Biogenic CO_2 emissions from the use of biofuels are not accounted for (part of the CO_2 cycle).
- Only non-biogenic (or fossil) CO_2 emissions are accounted for.
- As per IPCC[1], biogenic CH_4 emissions from the production of biofuels (e.g., biomethane in case 4) are accounted for.

Case 4 – Biomethane production in Germany

- Pre-storage of manure: biomethane emissions from manure are accounted for

- Anaerobic digestion and upgrading plant:
    - Heat and electricity consumption
        - Only biogenic emissions from the use of their own biogas, hence non-biogenic CO_2 emissions are zero – in the current scenario. The biogenic CO_2 emissions are not accounted for, as explained in General Assumptions above.
        - For the BAT scenario, the capture of the biogenic CO_2 emissions leads to negative emissions.
    - Leakage – only direct biogenic CH_4 emissions from the anaerobic digestor or upgrading plant are included.

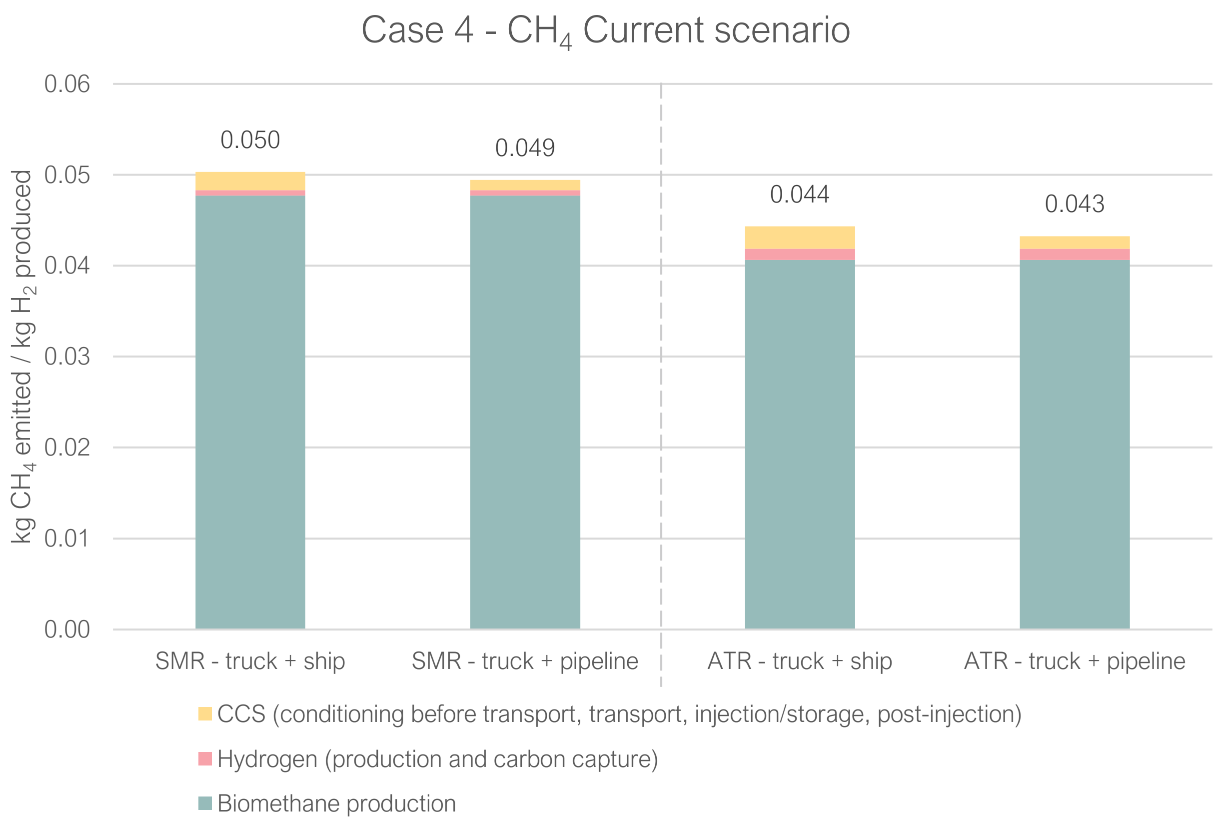
- Hydrogen plant:
    - Leakage – only direct biogenic CH_4 emissions from the hydrogen plant are included.
    - No CO_2 biogenic emissions – since this would be linked to the use of biomethane (part of the CO_2 cycle).
    - However, the capture of these emissions leads to negative emissions in the current and BAT scenarios.

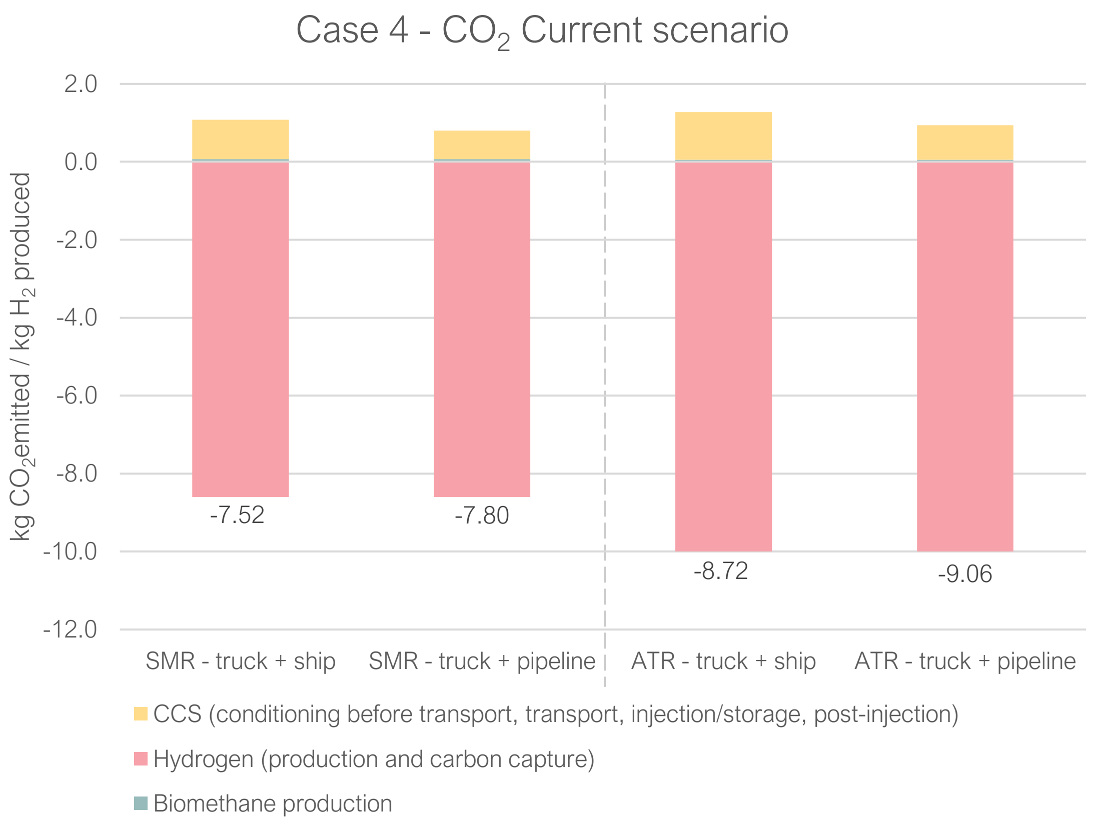
[1] About non-fossil CO_2 from manure pre-storage: "This chapter provides guidance on methods to estimate emissions of methane from Enteric Fermentation in livestock, and methane and nitrous oxide emissions from Manure Management. CO_2 emissions from livestock are not estimated because annual net CO_2 emissions are assumed to be zero – the CO_2 photosynthesized by plants is returned to the atmosphere as respired CO_2. A portion of the C is returned as CH_4 and for this reason CH_4 requires separate consideration." (CHAPTER 1 (iges.or.jp))

Case 4 EF summary for current scenario

CARBON LIMITS

In kg emissions / kg H_2 produced

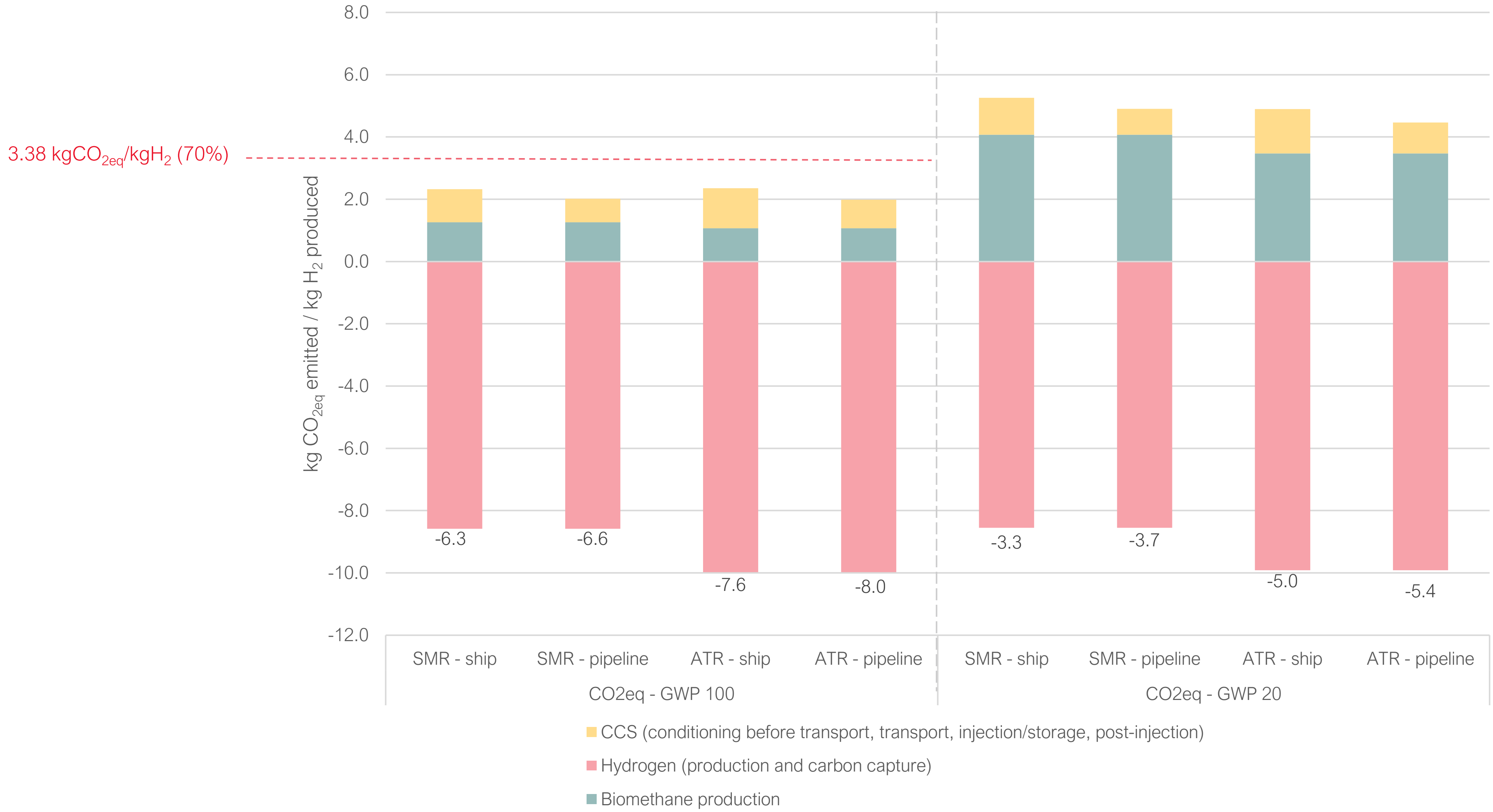




Case 4 EF summary for current scenario

CARBON LIMITS

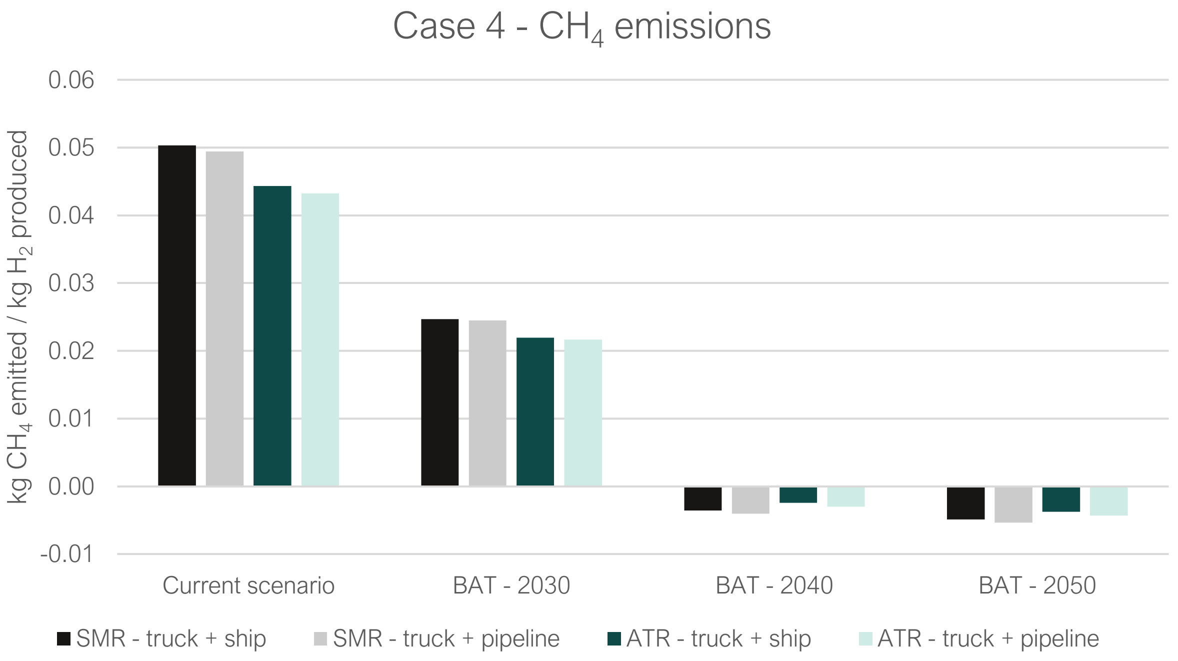
In kg CO_{2e} / kg H_2 produced – using GWP 20 and GWP 100

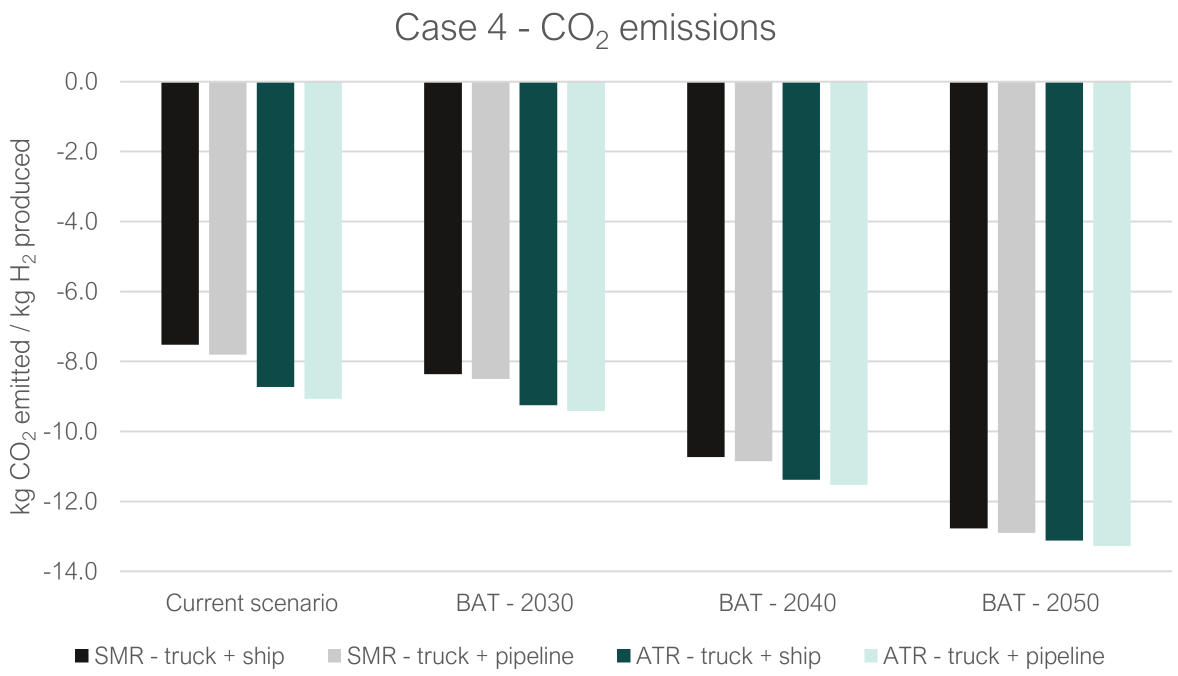


GWP 100 = 25 and GWP 20 = 84 have been compared, respectively based on the assumption on the Directive (EU) 2018/2001 and AR5 (IPCC)

Case 4 EF summary for BAT scenario

In kg emissions / kg H_2 produced





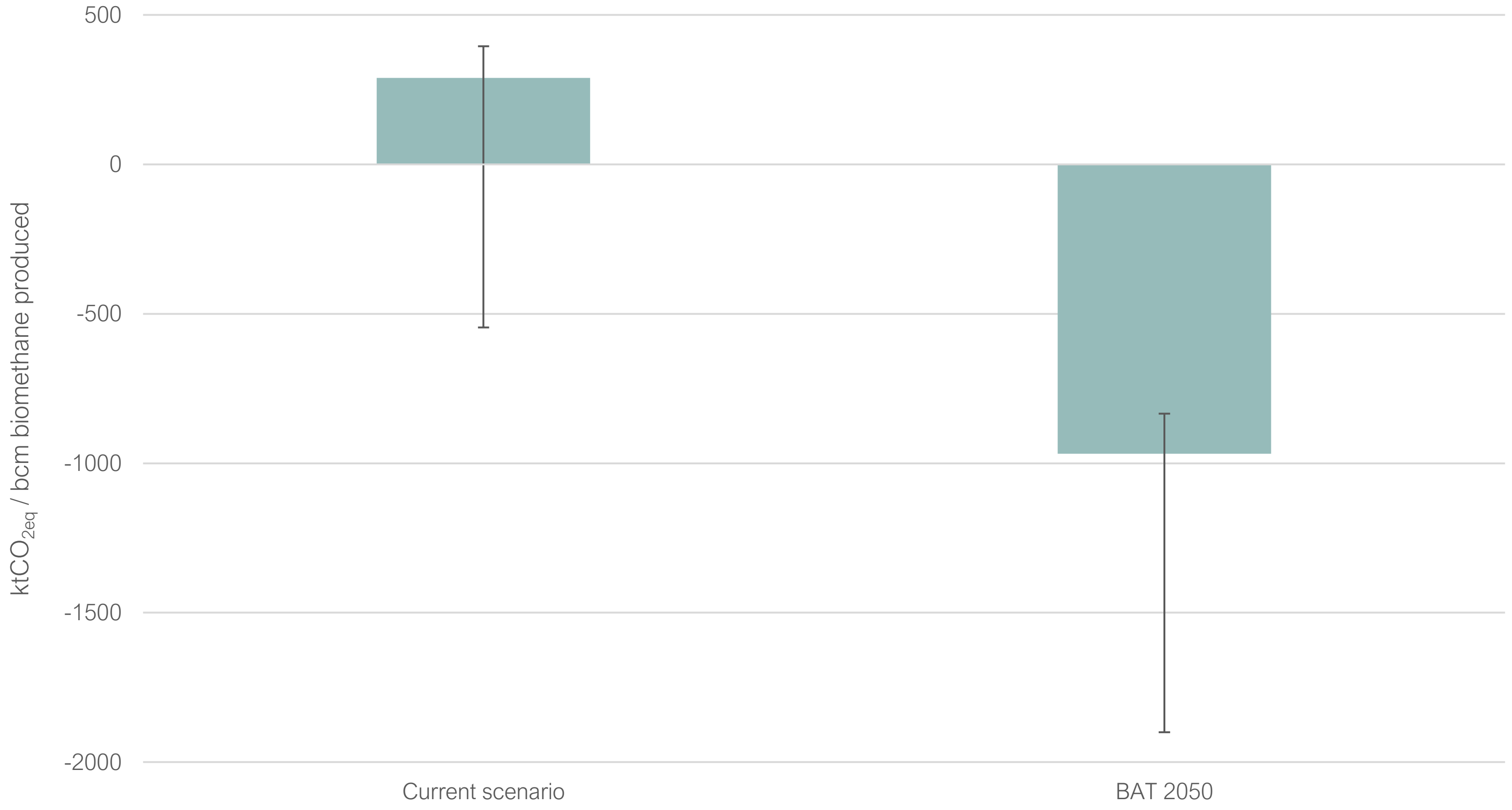
SMR – truck + ship: Hydrogen is produced by Steam Methane Reforming and the captured CO_2 is transported by truck then ship
SMR – truck + pipeline: Hydrogen is produced by Steam Methane Reforming and the captured CO_2 is transported by truck then by pipeline

ATR – truck + ship: Hydrogen is produced by Autothermal Reforming and the captured CO_2 is transported by truck then by ship
ATR – truck + pipeline: Hydrogen is produced by Autothermal Reforming and the captured CO_2 is transported by truck then by pipeline

In Case 4, H_2 production using biomethane can lead to negative emissions. Two main reasons can explain these negative emissions:
(i) The capture of non-fossil CO_2 emissions at the anaerobic digestion, upgrading plants (biomethane production) and at the hydrogen plant.
(ii) The avoided non-fossil CH_4 emissions when producing biomethane from manure instead of storing it.

Case 4 – Sensitivity on feedstock use

In $ktCO_{2eq - GWP\ 100}$ / bcm biomethane produced



To understand the impacts of biomass used on the EF of biomethane, sensitivity analyses were done using different shares of feedstock. The sensitivity line (in black) represent extreme cases where either only maize or only manure is used.

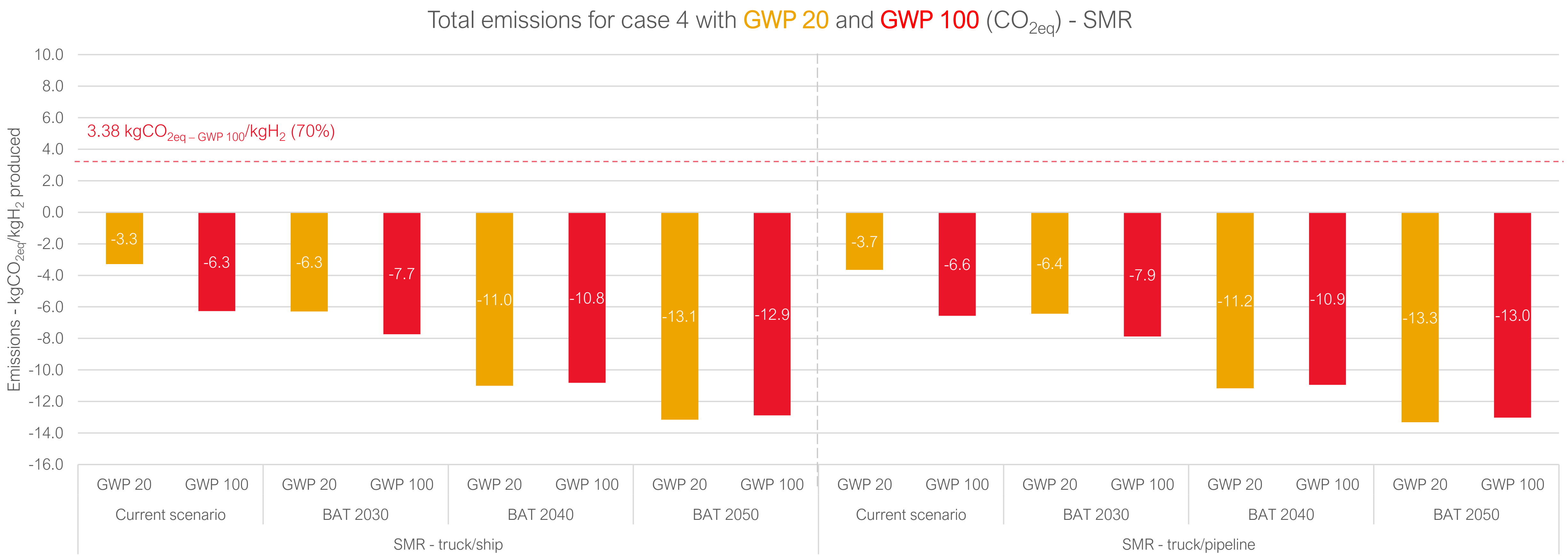
All in all, the use of manure leads to less emissions than the use of maize. Indeed, if the manure is not used to produce biomethane, it would have been stored and have emitted a huge amount of methane. Therefore, using 100% manure in the current scenario would lead to negative emissions compared to a reference scenario with storage of manure.

Feedstock	Min	Max
Maize	0%	100%
Manure	100%	0%

Regulating the feedstock (e.g.,100% manure), in addition to implementing BAT, could lead to an additional 74% reduction in total CO_{2eq} emissions by 2050. Reducing maize could be an effective measure if implemented alongside BAT: this measure alone would reduce emissions by 51% less than the BAT considered in this assessment.

Case 4 EF summary for current and BAT scenario – SMR production

In kg CO_{2e} / kg H_2 produced – using GWP 20 and GWP 100



*To note tha N_2O emissions are not considered here, only CH_4 and CO_2.

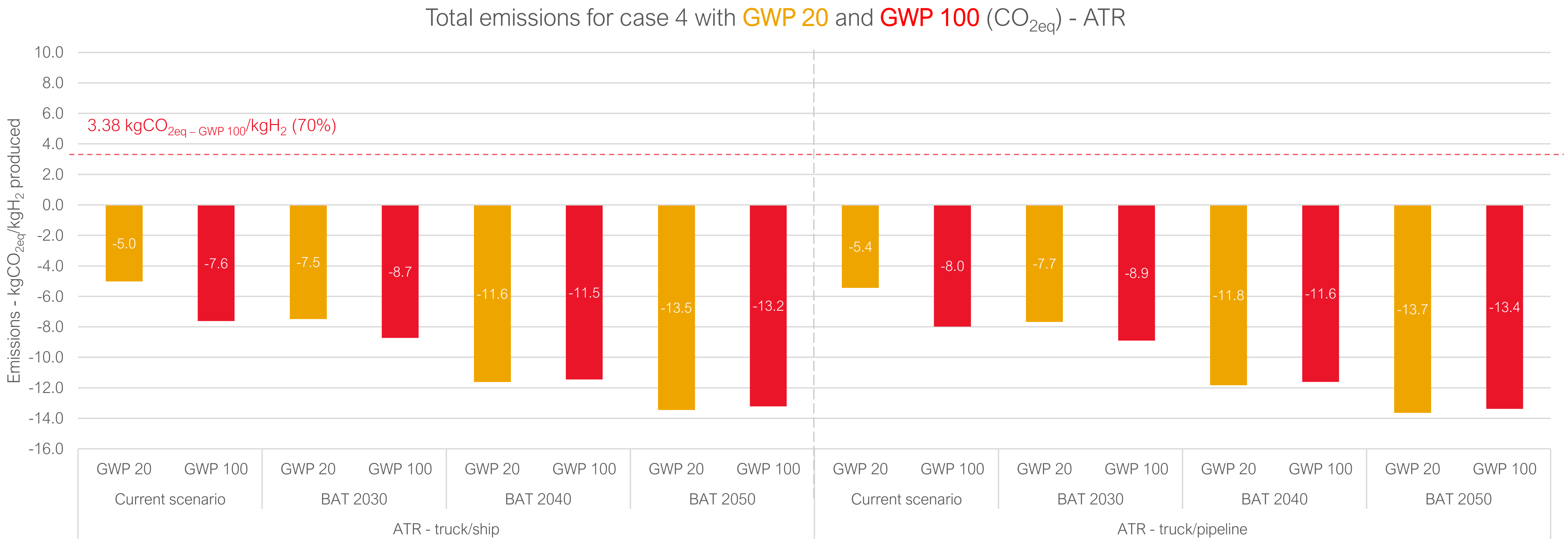
SMR – truck + ship: Hydrogen is produced by Steam Methane Reforming and the captured CO_2 is transported by truck then ship
SMR – truck + pipeline: Hydrogen is produced by Steam Methane Reforming and the captured CO_2 is transported by truck then by pipeline

- In all scenarios, Case 4, or H_2 production using biomethane can lead to negative emissions. Thus, the 70% threshold (3.38kgCO_{2eq}/kgH_2) is achieved.

GWP 100 = 25 and GWP 20 = 84 have been compared, respectively based on the assumption on the Directive (EU) 2018/2001 and AR5 (IPCC)

Case 4 EF summary for current and BAT scenario – ATR production

In kg CO_{2e} / kg H_2 produced – using GWP 20 and GWP 100



To note tha N_2O emissions are not considered here, only CH_4 and CO_2.

ATR – truck + ship: Hydrogen is produced by Autothermal Reforming and the captured CO_2 is transported by truck then by ship
ATR – truck + pipeline: Hydrogen is produced by Autothermal Reforming and the captured CO_2 is transported by truck then by pipeline

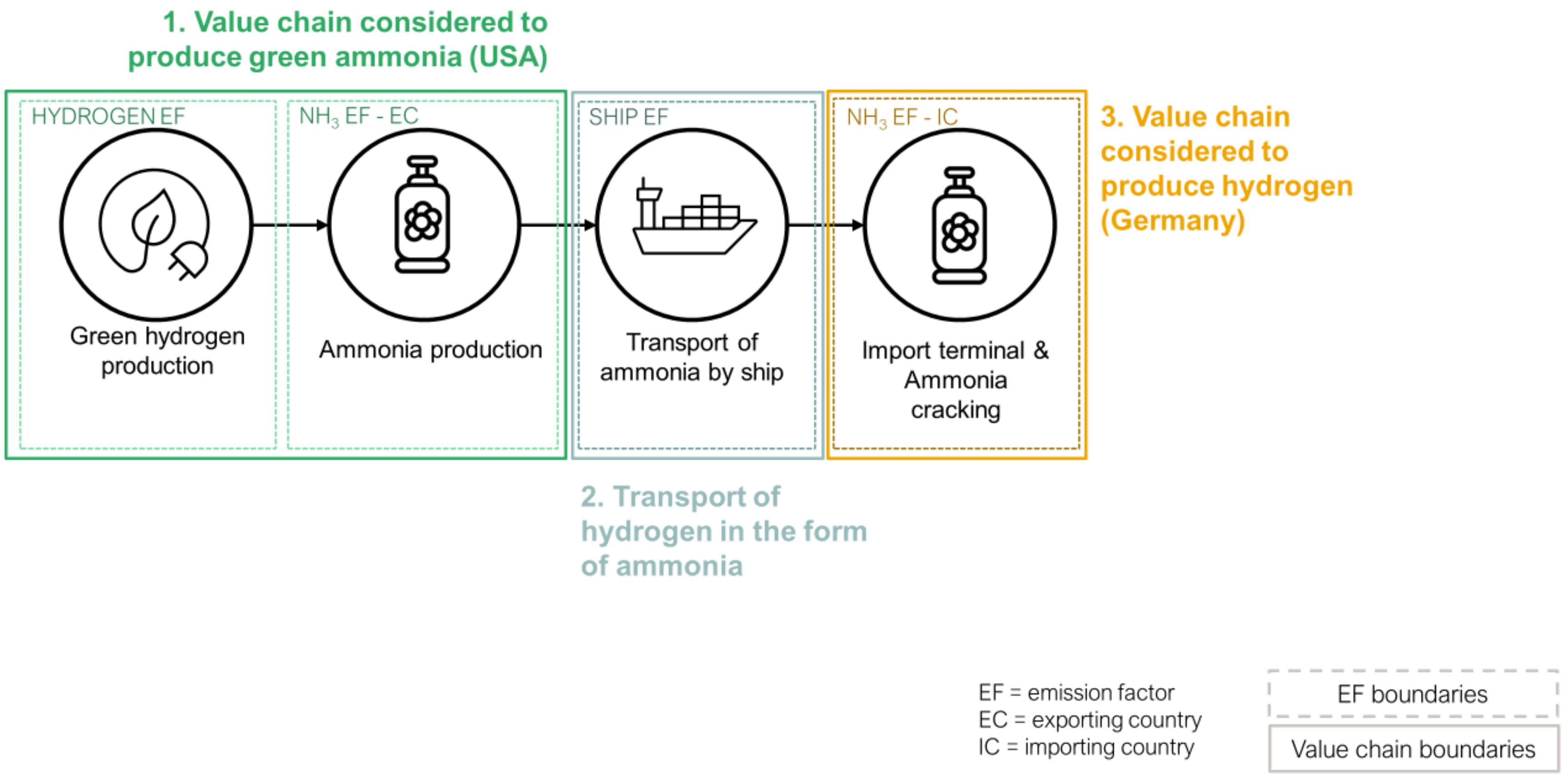
- In all scenarios, Case 4, or H_2 production using biomethane can lead to negative emissions. Thus, the 70% threshold (3.38kgCO_{2eq}/kgH_2) is achieved.
- It should be noted that, depending on the GWP considered and the year of analysis, ATR has up to 25% lower EF than SMR for case 4.

GWP 100 = 25 and GWP 20 = 84 have been compared, respectively based on the assumption on the Directive (EU) 2018/2001 and AR5 (IPCC)

Case 5

Green hydrogen is produced in the US and exported as green ammonia by ship to Germany. Re-converted to hydrogen in Germany.

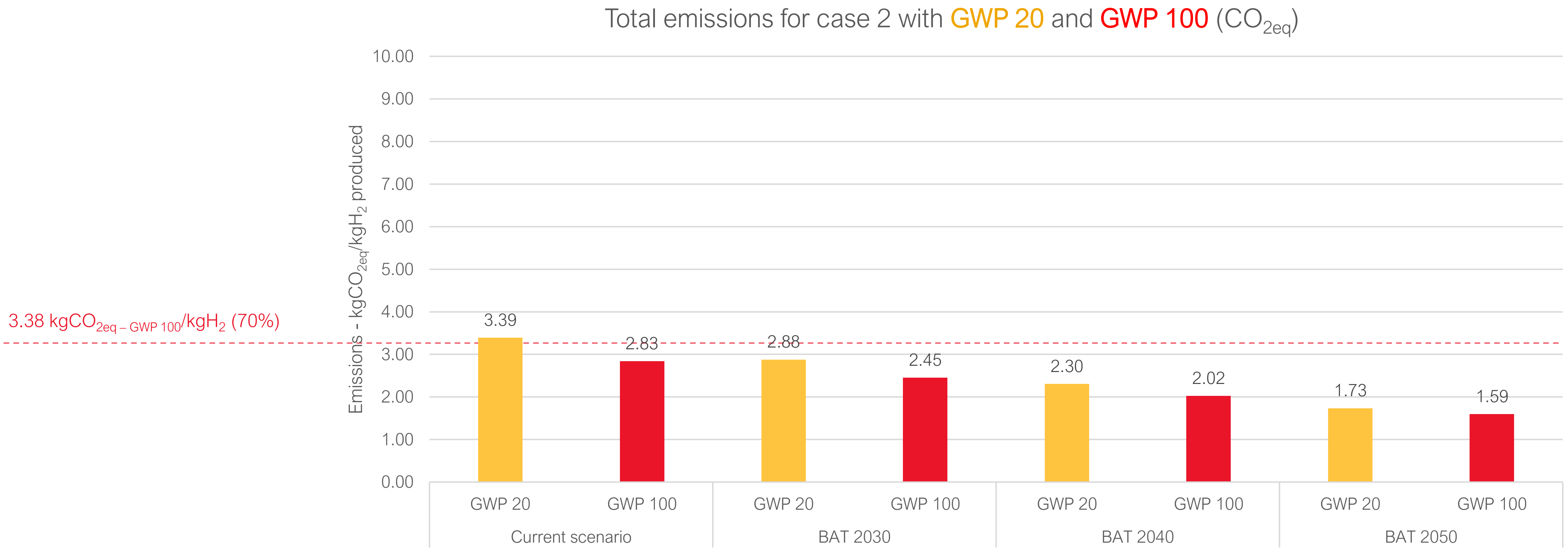
Case 5


1. Value chain considered to produce green ammonia (USA)
HYDROGEN EF
Green hydrogen production
NH_3 EF - EC
Ammonia production
SHIP EF
Transport of ammonia by ship
NH_3 EF - IC
Import terminal & Ammonia cracking
3. Value chain considered to produce hydrogen (Germany)
2. Transport of hydrogen in the form of ammonia
EF = emission factor
EC = exporting country
IC = importing country
EF boundaries
Value chain boundaries

Case 5 EF summary for current and BAT scenario

CARBON LIMITS

In kg CO_{2e} / kg H_2 produced – using GWP 20 and GWP 100

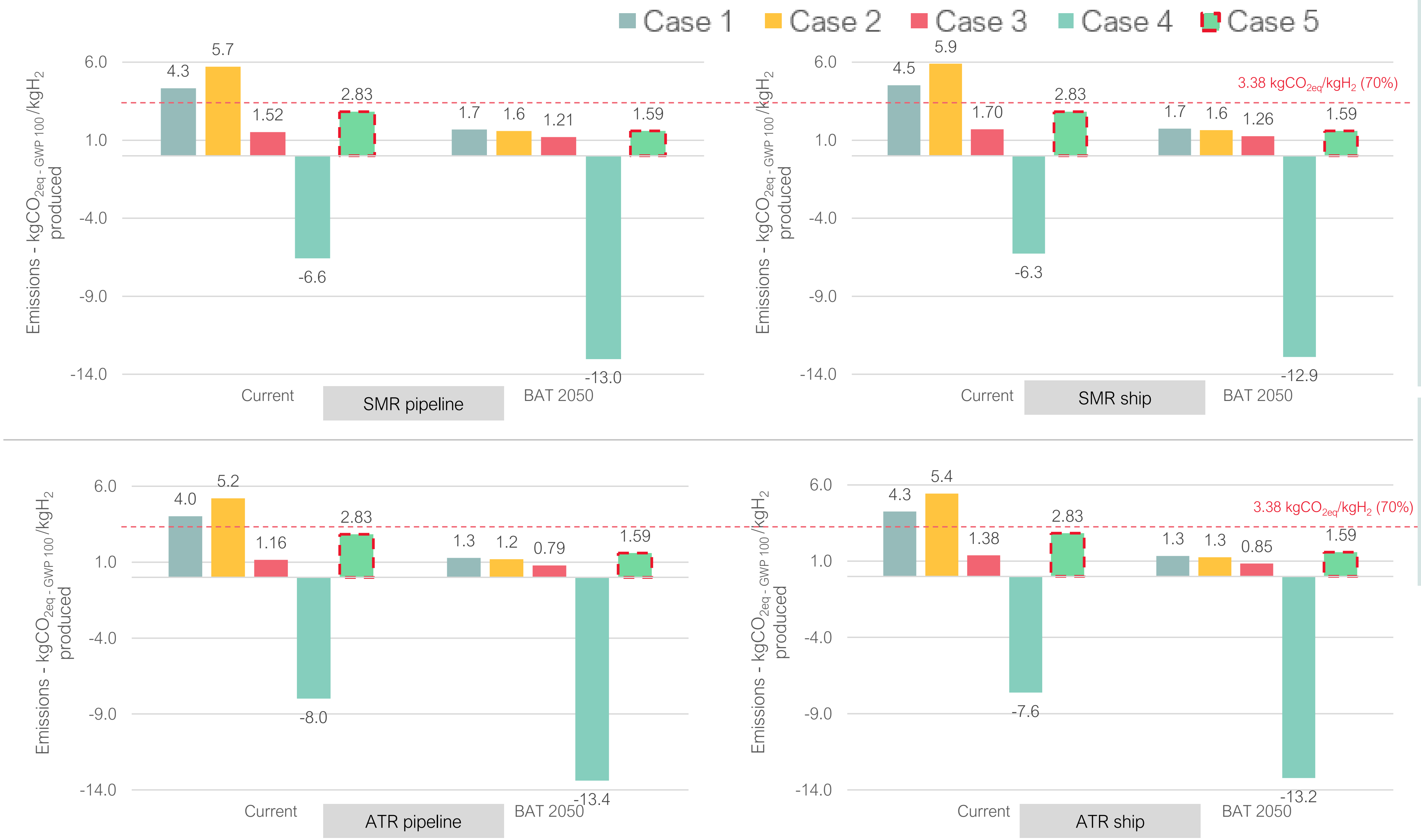


*To note that NH_3 and H_2 emissions are not considered here, only CH_4 and CO_2.

- The EF in the current emissions scenario is already lower than the 70% threshold (3.38$kgCO_{2eq}/kgH_2$) using both GWP 20 and GWP 100.

GWP 100 = 25 and GWP 20 = 84 have been compared, respectively based on the assumption on the Directive (EU) 2018/2001 and AR5 (IPCC)

Summary of EF from all case studies for current scenario and BAT - 2050



The results from the 5 case studies show the importance of applying BAT abatement options for reducing the EF of fossil-based H_2.

However, the production of **blue H_2 in Norway** (*Case 3*), the production of blue H_2 in Germany using **biomethane** (*Case 4*) and the **green H_2 produced in the USA and transported in the form of ammonia** (*Case 5)* already meets the 70% target of 3.38 $kgCO_{2eq}/kgH_2$.

In general, ATR technology has a lower EF as compared to SMR technology.

The transport of CO_2 also plays a role in the overall EF associated with fossil-based H_2.

It is to be noted that Case 5 is green H_2 case, hence there is no differenciation between SMR and ATR. The values have been added to all the graphs for comparison, but there is not differenciation between the four graphs for Case 5.

Task 2

High level assessment of value chain actors and state of the art MRV

Objectives of Task 2

CARBON LIMITS

The following sections provide an overview along the blue and green hydrogen value chain of:

- Stakeholders which could be involved in emissions abatement efforts. Many stakeholders exist along these value chains, but the focus is placed on stakeholders which could have a significant influence (financially, operationally, legally, etc.) on emissions mitigation.
- Available monitoring, reporting, and verification (MRV) frameworks, certification schemes, or other relevant regulations and initiatives for emissions abatement. These can aid stakeholders in monitoring and reducing value chain emissions.
- An overview of the primary abatement opportunities for methane and carbon dioxide at each segment of the value chain. These lists are non-exhaustive and present only the most effective or common options for emissions abatement.

The intent of identifying the most prominent value chain actors and outlining the best available methods by which they could monitor and reduce greenhouse gas emissions is to understand the pathways for generating low-carbon hydrogen and assess what gaps or obstacles exist in this area.

Value chain actor analysis

Value chain actors

There is an extensive list of stakeholders involved along the oil and gas, biogas, hydrogen, and CCS value chains. Many stakeholders are involved with only a portion of the value chain, while other actors are involved more extensively. Stakeholders can be as broad as entire companies, institutions, or regulatory bodies, and as granular as community members and company employees. For the purposes of this study, the following slides focus on three general stakeholder groups:

- Direct emitters: These are companies who are typically directly responsible for the majority of greenhouse gas emissions in their segment of the value chain (using an operators approach). They are releasing emissions as an immediate result of their operations.
- Indirect emitters: These companies are responsible for a smaller volume of emissions in their segment of the value chain. These emissions are typically an indirect result of value chain operations.
- Stakeholders that could influence emissions MRV: These stakeholders are not responsible for emissions within this particular value chain. However, they could have a strong influence on the value chain emissions in the sense that they could affect the development and usage of emissions MRV guidance and regulation.

The following slides present the most relevant stakeholders within each group and illustrate the extent of their influence along the value chain. The "Oil and natural gas" slide presents stakeholders for Case Studies 1-3. The "Biogas" slide presents stakeholders for Case Study 4, and the "Ammonia" slide corresponds to Case Study 5.

Oil and natural gas: value chain stakeholders

CARBON LIMITS

	UPSTREAM OIL AND GAS	DOWNSTREAM OIL AND GAS	LIQUEFIED NATURAL GAS (LNG)			HYDROGEN	DOWNSTREAM HYDROGEN	CARBON CAPTURE, TRANSPORT, AND STORAGE		
	Oil and natural gas exploration and production, gathering/ boosting, processing	Gas transmission	LNG - EC: Liquefaction and export	LNG: LNG Carrier	LNG - IC: Import terminal and regasification	Steam or autothermal reforming	Hydrogen transmission	Carbon capture and conditioning	Transport of CO2	Storage
Direct emitters	Onshore and offshore producers	Gas pipeline operators	LNG plant operators	LNG carrier operators	LNG plant operators	Hydrogen plant operators; CO2 capture site operators	Hydrogen pipeline operators	CO2 capture site operators	CO2 shipping companies; CO2 pipeline operators	Storage site operators
	Electricity providers* (Upstream oil and gas to LNG - EC)				Electricity providers* (LNG - IC to Carbon capture and conditioning)					
Indirect emitters	O&G technology and material providers** (Upstream oil and gas to LNG - IC)					Hydrogen technology providers (Hydrogen to Downstream hydrogen)				
		Pipeline technology and material providers	Terminal operators	Tanker owners; Maritime service providers	Terminal operators		Pipeline technology and material providers	CO2 capture technology providers	Pipeline technology and material providers	
	LNG importers (responsible for reporting value chain emissions using EU-equivalent MRV standards under EU Methane Import Standard) (Upstream oil and gas to LNG - IC)									
Stakeholders that could influence emissions MRV			Port regulators	Maritime regulators	Port regulators					
	Financial institutions and investors (all segments)									
	Environmental and social organizations (all segments)									
	Local, regional, and national governments, regulators, and licensing bodies*** (all segments)									

* In the respective country where the value chain segment is occurring.

** I.e. processing and liquefaction technology, storage tank and tanker providers

*** I.e. land management, environmental, and energy agencies

Biogas: value chain stakeholders

CARBON LIMITS

BIOGAS					HYDROGEN	CARBON CAPTURE, TRANSPORT, AND STORAGE		
Agricultural production and storage	Transport of raw materials	Pre-treatment	Anaerobic digestion, on-site storage of digestate	Upgrading and purification	Steam or autothermal reforming	Carbon capture and conditioning	Transport of CO2 by truck and pipeline	Storage

Direct emitters

- Biomass suppliers and traders (Agricultural production and storage; Transport of raw materials; Pre-treatment)
- Biomass farmers and producers (Agricultural production and storage)
- Shipping and transport companies (Transport of raw materials)
- Biomass processing companies (Pre-treatment)
- Biogas plant operators (Anaerobic digestion, on-site storage of digestate; Upgrading and purification)
- Hydrogen plant operators (Steam or autothermal reforming)
- CO2 capture site operators (Steam or autothermal reforming; Carbon capture and conditioning)
- CO2 shipping companies (Transport of CO2 by truck and pipeline)
- CO2 pipeline operators (Transport of CO2 by truck and pipeline; Storage)
- Storage site operators (Storage)
- Electricity providers* (Agricultural production and storage through Carbon capture and conditioning)

Indirect emitters

- Agricultural sector (Agricultural production and storage through Upgrading and purification)
- Biogas technology and material providers (Pre-treatment through Upgrading and purification)
- Hydrogen technology providers (Steam or autothermal reforming)
- CO2 capture technology providers (Carbon capture and conditioning)
- Truck and pipeline technology and material providers (Transport of CO2 by truck and pipeline)

Stakeholders that could influence emissions MRV

- Financial institutions and investors
- Environmental and social organizations
- Local, regional, and national governments, regulators, and licensing bodies***

* In the respective country where the value chain segment is occurring.

** I.e. processing and liquefaction technology, storage tank and tanker providers

*** I.e. land management, environmental, and energy agencies

Ammonia: value chain stakeholders

CARBON LIMITS

	AMMONIA			HYDROGEN
	Green hydrogen production	Ammonia production	Transport of ammonia by ship	Import terminal and ammonia cracking*
Direct emitters	Hydrogen plant operators	Ammonia producers	Shipping and transport companies	Hydrogen plant operators
	Electricity providers*			Electricity providers*
Indirect emitters	Hydrogen technology providers		Tanker owners	Hydrogen technology providers
			Maritime service providers	Terminal operators
Stakeholders that could influence emissions MRV			Maritime regulators	Port regulators
	Financial institutions and investors			
	Environmental and social organizations			
	Local, regional, and national governments, regulators, and licensing bodies***			

* In the respective country where the value chain segment is occurring.

** I.e. processing and liquefaction technology, storage tank and tanker providers

*** I.e. land management, environmental, and energy agencies

State-of-the-art MRV

Monitoring, reporting, and verification (MRV)

Various voluntary and mandatory monitoring, reporting, and verification (MRV) standards exist to facilitate emissions accounting along the blue hydrogen value chain. These standards and frameworks vary in their requirements, value chain coverage, granularity of detail, and participation rates, but serve a similar purpose: to facilitate emissions monitoring and reduction practices.

Although some frameworks are more widely used or commonly recognized than others, there is no MRV framework that serves as the singular industry standard for methane and carbon dioxide monitoring at any point along the value chains considered in this study. And despite the abundance of frameworks, certain gaps exist – for example, agriculture and biogas are not currently included in MRV standards for regulatory compliance.

In addition to these MRV standards, a number of certification mechanisms exist for different parts of the value chains considered herein. Certifications indicate a company's adherence to certain emissions intensity standards. These mechanisms also sometimes consider other benchmarks such as biomass sustainability requirements.

Finally, there are many other regulations and initiatives which are not directly related to emissions quantification but remain highly relevant for any entity looking to quantify and reduce emissions along the hydrogen value chain. These regulations and initiatives are international (EU-wide or global) and are aimed at promoting large-scale emissions reductions.

The following slides provide an overview of the most relevant standards, frameworks, regulations, and initiatives, illustrating which section(s) of the value chain they apply to. Further details are subsequently provided on each item to clarify their purpose and extent, as well as highlight any pertinent limitations.

Natural gas, hydrogen, and CCS: value chain benchmarking frameworks

CARBON LIMITS

- Upstream O&G (exploration/ production, gathering/ boosting, processing)
- Gas transmission
- LNG: Liquefaction and export
- LNG: LNG Carrier
- LNG: Import terminal and regasification
- Steam or autothermal reforming
- Hydrogen transmission
- Carbon capture and conditioning
- Transport of CO2
- Storage

Voluntary methodologies for emissions monitoring and reporting

- Oil and Gas Methane Partnership (CH4 only)
- ISO/TS 19870: 2023
- ISO/TR 27915: 2017
- Statement of Greenhouse Gas Emissions (LNG only)
- Verra CCS Methodology Framework
- GIIGNL (International Group of Liquefied Natural Gas Importers) (LNG only)
- Puro.earth Geologically Stored Carbon Methodology (only relevant for CCS in biogas value chain)
- Veritas/GTI Energy (CH4 only)
- American Petroleum Institute Compendium
- Drax/Stockholm Exergi Methodology
- Greenhouse Gas Protocol

Compliance standard methodologies for emissions monitoring and reporting

- USEPA Greenhouse Gas Reporting Program Subpart W (only applies to value chain segments within the US)
- EU Maritime MRV (ships only)
- Guidelines for emissions reporting (Norway)
- EU Maritime MRV
- (Provisional agreement on) EU Methane Emissions Reduction in the Energy Sector (EEA only)
- EU Emissions Trading System

Note: Sources are listed on the MRV focus slides in the Annex

Natural gas, hydrogen, and CCS: value chain certification frameworks

Value chain stages: Upstream O&G (exploration/ production, gathering/ boosting, processing) | Gas transmission | LNG: Liquefaction and export | LNG: LNG Carrier | LNG: Import terminal and regasification | Steam or autothermal reforming | Hydrogen transmission | Carbon capture and conditioning | Transport of CO2 | Storage

Emissions reduction certification schemes

- Oil and Gas Methane Partnership Gold Standard (CH4 only) — Upstream O&G to LNG: Import terminal and regasification
- MiQ — Upstream O&G to LNG: Import terminal and regasification
- Statement of Greenhouse Gas Emissions (LNG only) — Upstream O&G to LNG: Import terminal and regasification
- CertifHy — Steam or autothermal reforming to Hydrogen transmission
- GWKHV (Germany) — Steam or autothermal reforming to Hydrogen transmission
- CEN-EN 16325 (pending hydrogen revision) — Steam or autothermal reforming
- EU Carbon Removal Certification Framework (only relevant for CCS in biogas value chain) — Carbon capture and conditioning to Storage
- Verra Verified Carbon Standard — Carbon capture and conditioning to Storage
- Puro.earth CO2 Removal Certificates (only relevant for CCS in biogas value chain) — Carbon capture and conditioning to Storage

Other relevant regulations and initiatives

- EU Methane Import Standard (only applies to fossil fuels imported into the EU) — Upstream O&G to LNG: Import terminal and regasification
- EU CCS Directive — Carbon capture and conditioning to Storage
- EU Taxonomy on Sustainable Finance (EEA countries only) — Upstream O&G to Storage
- Global Methane Pledge (US, Germany, Norway only) — Upstream O&G to Storage
- Zero Routine Flaring Initiative (US, Germany, Norway only) — Upstream O&G to LNG: Import terminal and regasification
- Global Methane Initiative (US, Germany, Norway only) — Upstream O&G to LNG: Import terminal and regasification

Note: Sources are listed on the MRV focus slides in the Annex

Hydrogen via biogas: value chain benchmarking frameworks

CARBON LIMITS

	Agricultural production and storage, transport of raw materials	Pre-treatment	Anaerobic digestion and on-site storage of digestate	Upgrading and purification	Steam or autothermal reforming	Hydrogen transmission*
Voluntary methodologies for emissions monitoring and reporting	Drax/Stockholm Exergi Methodology (spans Agricultural production through Upgrading and purification)				ISO/TS 19870: 2023 (spans Steam or autothermal reforming through Hydrogen transmission)	
	Greenhouse Gas Protocol (spans entire value chain)					
Compliance standard methodologies for emissions monitoring and reporting						

Note: Sources are listed on the MRV focus slides in the Annex

* Methodologies for the remainder of the value chain (carbon capture through storage) are provided on the "Natural gas, hydrogen, and CCS" slides.

Hydrogen via biogas: value chain certification frameworks

CARBON LIMITS

Value chain stages:

- Agricultural production and storage, transport of raw materials
- Pre-treatment
- Anaerobic digestion and on-site storage of digestate
- Upgrading and purification
- Steam or autothermal reforming
- Hydrogen transmission*

Emissions reduction certification schemes

- International Sustainability & Carbon Certification (ISCC)
- dena (Germany Energy Agency) Biogas Register
- Red Cert
- Germany's GWKHV
- CertifHy
- CEN-EN 16325 (pending hydrogen revision)
- DNV-SE-0654

Other relevant regulations and initiatives

- EU Taxonomy on Sustainable Finance
- EU Renewable Energy Directive (RED) III
- Global Methane Pledge
- Global Methane Initiative

Note: Sources are listed on the MRV focus slides in the Annex

* Certification schemes, regulations, and initiatives for the remainder of the value chain (carbon capture through storage) are provided on the "Natural gas, hydrogen, and CCS" slide.

Ammonia: MRV frameworks, certification schemes, and other initiatives

CARBON LIMITS

	Green hydrogen production	Ammonia production	Transport via ship	Import and cracking
Voluntary methodologies for emissions monitoring and reporting		ISO/TS 19870: 2023		
		Ammonia Energy Association Ammonia Certification System		
	Greenhouse Gas Protocol			
Compliance standard methodologies for emissions monitoring and reporting			EU Maritime MRV	
Emissions reduction certification schemes	DNV-SE-0654			
		Ammonia Energy Association Ammonia Certification System		
Other relevant regulations and initiatives			International Maritime Organization (IMO) IGC/IGF Codes and MARPOL	
			ABS Requirements for Ammonia Fueled Vessels	
			Bureau Veritas' Ammonia-Fuelled Ships: Tentative Rules	
			IMO Strategy on Reduction of GHG Emissions from Ships	

Note: Sources are listed on the MRV focus slides in the Annex

A note on Guarantees of Origin

Guarantees of origin (GOs) facilitate and incentivize the use of renewable and low-carbon energy. CEN-EN 16325, the European standard for GOs for electricity, is currently being revised to include GOs for heating, cooling, and gaseous energy carriers (including hydrogen). However, Hydrogen Europe highlights potential risks with the current approach, including the theoretical possibility of using biomethane GOs in place of low-carbon hydrogen GOs and potentially “greenwashing” hydrogen produced with natural gas. They therefore recommend an entirely separate GO system for hydrogen that can be tradeable between EU member states and ultimately established on a global level. GOs for low-carbon hydrogen should also account for the location of the electricity or other energy source used to produce the hydrogen, as this can ultimately affect the carbon intensity of the hydrogen.

Other challenges in the GO space currently include, but are not limited to:

- Currently, there are various GO schemes which have been established to verify blue and green hydrogen but these have not yet been formally recognized as compliant with RED. CertifHy is one such scheme which has applied for formal recognition under the EU system, but approval is still pending. This poses a challenge to stakeholders looking to align with RED and related regulations but do not currently have a reliable method for doing so.
- Different definitions of system boundaries (for example, certificates under Netherland’s hydrogen GO scheme are only valid within the country whereas CertifHy applies across EEA countries and ultimately plans to expand internationally)
- Differing GHG accounting methodologies
- Varying definitions of what constitutes a “Renewable Fuel of Non-Biological Origin” (RFNBO) like hydrogen (i.e. Denmark’s green hydrogen GO scheme does not perfectly align with EU rules)

To generate reliable and consistent GOs for green or blue hydrogen, the entire value chain – starting from energy production and transport through to the delivery of low carbon hydrogen – should be verified in a standardized manner.

Sources	
European Commission	Association of Issuing Bodies
Hydrogen Insight	Hydrogen Europe
Science Direct	Fortum

MRV – in conclusion (1)

Due to the growing number of regulations surrounding emissions mitigation and reduction, as well as increasing consumer and public interest in low-emission alternatives, a number of methodologies and standards for emissions monitoring, reporting, and verification have materialized in recent years. Some of these frameworks are mandated by governments and other regulatory bodies, such as the US Environmental Protection Agency's Greenhouse Gas Reporting Program or the EU Emissions Trading System. Others, like the Greenhouse Gas Protocol or the Oil and Gas Methane Partnership (OGMP) 2.0 Framework, are voluntary. Many certification schemes also exist to verify that companies, facilities, or products are in alignment with these mandatory or voluntary standards. These voluntary frameworks and certification schemes allow companies to publicly signal their emission reduction efforts and commitments.

In many cases, many frameworks exist for emissions monitoring within a value chain segment. This is especially true for the oil and gas sector, which is a prominent focus in the emissions reduction arena. As such, there is often no singular framework that can be broadly recommended for monitoring these value chain segments. For example, the OGMP 2.0 Framework is the best option for oil and gas companies looking to monitor their methane emissions. OGMP is led by the United Nations Environment Programme (and therefore is well-recognized globally), aligns with incoming EU methane regulations, and its participants represent nearly 40% of global oil and gas production. However, OGMP only covers methane emissions, meaning that companies looking to monitor other GHG emissions may require a separate framework such as the American Petroleum Institute's Compendium of GHG Emissions Methodologies. The Statement of Greenhouse Gas Emissions Methodology could also be used, but only for LNG cargoes.

MRV – in conclusion (2)

Although MRV frameworks are abundant in the oil and gas sector, there are fewer for biogas, hydrogen, and CCS. For example, the ISO technical specification ISO/TS 19870:2023 may be the best available voluntary guideline for emissions accounting for hydrogen production and transmission processes, although hydrogen production is also monitored under the EU Emissions Trading System. Several certification systems exist for biogas, but there are a limited number of voluntary MRV frameworks that can be used for this value chain, and biogas is generally excluded from regulatory compliance frameworks as it is considered a "zero-emission" product.

There is also some remaining ambiguity around third-party verification. Many certification schemes require verification by an independent third party, while others, like OGMP, are currently based on self-reporting without requiring an external audit. Even among schemes that require third-party verification, the procedures and standards around how the verification is done can vary. Third-party verification requirements should be evaluated further to support the development of effective verification schemes. For example, better standardization of what verification entails, how much it costs and who should pay, and how thorough the verification steps are (i.e., if a certification is company-wide, what percentage of their sites should be verified) could facilitate more reliable certification processes.

Overall, the ever-growing focus on emissions monitoring and reduction has led to an increasing number of emission monitoring methodologies, regulations, technologies, and initiatives. The list presented here is not exhaustive, and it is likely that more will continue to emerge. Many of these frameworks build on each other and are compatible with one another, but there is currently no singular preferred choice for emissions MRV at any part of the blue hydrogen value chain.

CH_4 and CO_2 abatement options

an overview

Abatement options - Introduction

CARBON LIMITS

Abatement options for methane (CH_4) and carbon dioxide (CO_2) in the oil and gas sector, biogas, hydrogen (H_2) production, and carbon capture and storage (CCS) value chains are crucial for reducing the emission intensity of blue H_2 and biomethane-based H_2 production. While the strategies for abatement depend on existing practices in the field of operation, most sites can address emissions through technological advancements and behavioral improvements.

Given the vast array of abatement options for CH_4 and CO_2, this task focuses on identifying the main abatement options rather than creating an exhaustive list. Developing a comprehensive list requires lower granularity (e.g., at the site level, state level, etc.) based on existing regulations.

The slides in this section highlight key abatement options along the value chains of natural gas, H_2, CCS, and biogas. These options include:

- Technological Improvements: Implementing advanced technologies to reduce emissions at various stages of production and processing.
- Behavioural Improvements: Encouraging best practices and operational changes to minimize emissions.

By focusing on these key abatement strategies, we aim to provide a clear and practical approach to reducing CH_4 and CO_2 emissions across these critical sectors.

CH_4 abatement: Gas value chain

Mitigation option	Description	Upstream (exploration/ production, gathering/ boosting, processing)	Gas transmission	Liquefaction and export terminal	LNG carrier	Import terminal and regasification	Behaviour- or technology-based?
Early replacement of devices	Replacement of high-bleed devices with low-bleed.	X					Behaviour
Pump replacement	Replacement of pumps which use fossil fuels to operate (i.e. pneumatic pumps) with electric pumps or solar pumps.	X					Technology
Compressor seal/rod replacement	Old, worn compressor parts can lead to increased emissions. Wet seals can also be degassed or replaced with dry seals.	X	X				Technology
Replacement with instrument air systems	Pumps and controllers which use natural gas as an energy source can be replaced with instrument air systems, which pressurize ambient air to perform the same functions without emitting methane.	X					Technology
Replacement with electric motors	Even low-bleed devices are a source of emissions. Electric motors can instead be used in pneumatic devices as well as in engines used for drilling and well completion operations.	X					Technology
Installation of vapour recovery units	Vapour recovery units (VRUs) capture emissions which accumulate in equipment.	X					Technology
Blowdown capture	Equipment is depressurized by performing gas blowdowns. Instead of venting/flaring excess gas, it can be captured during blowdown events for onsite reuse or sale.	X	X				Behaviour and technology
Flare installation	Flaring is not a zero-emissions solution but is preferrable to venting excess gas as it reduces the amount of methane released to the atmosphere.	X		X			Technology
Plunger installation	Plunger lifts improve the efficiency of liquid unloading events while reducing methane emissions.	X					Technology
Leak detection and repair	Fugitive leaks are identified and addressed in a process referred to as leak detection and repair (LDAR). This can be done in several ways with a variety of technologies.	X	X	X	X	X	Behaviour and technology

Sources

Methane abatement options – Methane Tracker 2020 – Analysis - IEA

CO_2 abatement: Gas value chain

Mitigation option	Description	Upstream (exploration/ production, gathering/ boosting, processing)	Gas transmission	Liquefaction and export terminal	LNG carrier	Import terminal and regasification	Behaviour- or technology-based?
Flare mitigation	Although gas flaring reduces atmospheric methane emissions, it emits less potent greenhouse gases including carbon dioxide. To reduce flaring emissions, excess gas should be utilized (onsite or sold to the market) to the extent possible.	X					Technology
Energy efficiency	Many processes (gas turbines, diesel engines, compressors, drivers, etc.) throughout the oil and gas value chain use fuel to generate energy. Improving the energy efficiency of these processes (for example, via heat recovery) can mean less fuel is required to generate heat and power, resulting in lower emissions.	X	X	X	X	X	Technology
Electrification and renewable energy	Instead of generating heat and power onsite using combustion processes, companies can reduce reliance on fuel by switching to using electricity from the grid or renewable energy (including biogas). An issue with this option is that it requires a reliable supply of electricity or renewable energy.	X	X	X	X	X	Technology
Carbon capture and storage	Due to the relatively low volumes of CO2 produced in the value chain, carbon capture and storage is generally not a preferred mitigation option for oil and gas. However, CCS can be a viable option for the acid gas removal process (when CO2 is removed from gas to meet market specifications). Since CO2 separation is an inherent part of this process, CCS on acid gas removal units can be feasible and low-cost. This is occurring at the Sleipner field in Norway.	X		X		X	Technology

Sources

International Energy Agency

CH_4 abatement: H_2 and CCS

Mitigation option	Description	Steam or autothermal reforming	Hydrogen transmission	Carbon capture and conditioning	Transport of CO2	Storage	Behaviour- or technology-based?
Waste heat recovery	Excess heat from different processes can be recovered and reused for heat or electricity purposes, lowering the amount of fossil fuels required to power these processes.	X		X			Technology
Energy efficiency	Improving the energy efficiency of various processes (for example, via heat recovery) can mean less fuel is required to generate heat and power, resulting in lower emissions.	X	X	X	X		Technology
Renewable energy use (including bioenergy)	Using renewable or low-carbon energy to power various processes can reduce reliance on fossil fuels.	X	X	X	X	X	Technology
Leak detection and repair	Fugitive leaks are identified and addressed in a process referred to as leak detection and repair (LDAR). This can be done in several ways with a variety of technologies.	X	X	X	X		Behaviour and technology
Route optimization	Optimizing the route used for transporting CO2 from the capture site to the storage site (for example, via source-sink matching) can reduce the emissions associated with transportation.				X		Behaviour

CO_2 abatement: H_2 and CCS

Mitigation option	Description	Steam or autothermal reforming	Hydrogen transmission	Carbon capture and conditioning	Transport of CO2	Storage	Behaviour- or technology-based?
Waste heat recovery	Excess heat from different processes can be recovered and reused for heat or electricity purposes, lowering the amount of fossil fuels required to power these processes.	X		X			Technology
Energy efficiency	Improving the energy efficiency of various processes (for example, via heat recovery) can mean less fuel is required to generate heat and power, resulting in lower emissions.	X	X	X	X		Technology
Renewable energy use (including bioenergy)	Using renewable or low-carbon energy to power various processes can reduce reliance on fossil fuels.	X	X	X	X	X	Technology
Carbon capture and storage	Carbon capture and storage (CCS) can be implemented on processes that generate large amounts of point-source CO2. Carbon dioxide emissions are captured and stored in underground geological formations.	X			X (onboard CCS for ships)		Technology
Emissions recovery	Gaseous CO2 in transport vessels or temporary onshore storage vessels can be reliquefied and piped to the CO2 storage site.	X	X		X	X (in case of intermediate onshore storage)	Technology
Leak detection and repair	Fugitive leaks are identified and addressed in a process referred to as leak detection and repair (LDAR). This can be done in several ways with a variety of technologies.	X	X	X	X	X	Behaviour and technology
Electrification	Instead of generating heat and power onsite using combustion processes, companies can reduce reliance on fuel by switching to using electricity from the grid – but only applicable of grid EF is less than EF of fuel used on site	X	X	X	X		Technology
Route optimization	Optimizing the route used for transporting CO2 from the capture site to the storage site (for example, via source-sink matching) can reduce the emissions associated with transportation.				X		Behaviour

CH_4 abatement: biogas

Mitigation option	Description	Agricultural production and storage, transport of raw materials	Pre-treatment	Anaerobic digestion and on-site storage of digestate	Upgrading and purification	Behaviour- or technology-based?
Feedstock supply management	Installation of covers and methane recovery systems in manure storage pits to mitigate methane emissions. Optimization storage time and conditions of feedstock to avoid the feedstock to enter anaerobic decomposition before the digestion stage.	X	X			Behaviour and technology
Leak detection and repair	Fugitive leaks are identified and addressed in a process referred to as leak detection and repair (LDAR). This can be done in several ways with a variety of technologies.			X	X	Behaviour and technology
Flaring	Flaring of vented biogas or biomethane, which turns into CO_2 emissions and lowers the short-term global warming effect of the released gas.			X	X	Technology
Waste heat recovery	Recovery of heat generated during anaerobic digestion and storage of digestate to supply the biodigester and biogas facilities with heat if natural gas or biogas/biomethane was primarily used to generate heat.			(X)		Technology
Energy efficiency	Improvement of the combustion efficiency of different engines through optimization or replacement can reduce methane slip if those engines are running on natural gas/biomethane (truck, excavator, compressor).	(X)	(X)	(X)	(X)	Technology
Electrification	Substitution with electric machinery and equipment will reduce methane slip if the machinery and equipment is running on natural gas or biomethane.	(X)	(X)	(X)	(X)	Technology
Sustainable feedstock production	The use of sustainable feedstocks (such as residues and other waste products), as well as adherence to sustainability requirements set forth in the EU Renewable Energy Directive and other regulations (such as the Land Use, Land Use Change and Forestry regulation) help to ensure that emissions have been minimized in the feedstock growth, harvesting, and storage processes.	X				Behaviour and technology

(X) – applies to value chain only if biogas or natural gas is used as the process fuel.

Sources

European Biogas Association

Ecohz

IEA Bioenergy

CO_2 abatement: biogas

Mitigation option	Description	Agricultural production and storage, transport of raw materials	Pre-treatment	Anaerobic digestion and on-site storage of digestate	Upgrading and purification	Behaviour- or technology-based?
Carbon capture and storage (CCUS)	CO_2 emissions from the upgrading process can be captured to be permanently stored in products or underground geological formations.				X	Technology
Waste heat recovery	Recovery of heat generated during anaerobic digestion and storage of digestate to supply the biodigester and biogas facilities to reduce consumption of external energy input.		X	X	X	Technology
Electrification	Substitution with electric machinery and equipment will reduce CO2 emissions if the electricity grid has a lower CO_2 intensity than the fuel previously used.	(X)	(X)	(X)	(X)	Technology
Renewable energy use (including bioenergy)	Using renewable or low-carbon energy to power various processes can reduce CO_2 emissions from fuel combustion in various processes (transport, heating, compression).	X	X	X	X	Technology
Energy efficiency	Energy efficiency improvement of machinery of equipment to reduce the energy required.	X	X	X	X	Technology
Leak detection and repair	Fugitive leaks are identified and addressed in a process referred to as leak detection and repair (LDAR). This can be done in several ways with a variety of technologies.			X	(X)	Behaviour and technology
Sustainable feedstock production	The use of sustainable feedstocks (such as residues and other waste products), as well as adherence to sustainability requirements set forth in the EU Renewable Energy Directive and other regulations (such as the Land Use, Land Use Change and Forestry regulation) help to ensure that emissions have been minimized in the feedstock growth, harvesting, and storage processes.	X				Behaviour and technology

(X) – applicable under certain circumstances

Sources

European Biogas Association

Ecohz

IEA Bioenergy

Ammonia: mitigation to prevent leakage

When ammonia is transported as a maritime cargo, ships should be designed in accordance with the International Maritime Organization (IMO) *International Code for Construction and Equipment of Ships Carrying Liquefied Gases in Bulk* (IGC Code), which is required under the International Convention for the Safety of Life at Sea (SOLAS). This code provides standards and specifications for designing and constructing ships in a way that mitigates risks related to the liquefied gases (or certain other substances) that it is transporting. These include risks to the ship, humans, and the environment. The following are design aspects and situations that the IGC Code covers (this list is non-exhaustive):

- Ship survival capability, and emergency situations such as collisions or strandings and subsequent uncontrolled releases
- Ship arrangements
- Cargo containment, pressure/temperature control, and atmosphere control
- Material specifications
- Filling limits

Similarly, the International Convention for the Prevention of Pollution from Ships (MARPOL) stipulates regulations that reduce pollution of the sea and air by marine vessels. Vessel design, construction, and operation should be in compliance with these conventions and codes in order to minimize as much as possible potential environmental harm.

Sources and links
International Maritime Organization (1, 2, 3)
American Bureau of Shipping
Bureau Veritas (1, 2)
Witherbys

Conclusions on the high-level value chain assessments

When it comes to emissions monitoring and reduction along the blue and green hydrogen value chains, the picture is not always crystal clear. The different value chain segments often have overlapping stakeholders – this might dilute the responsibility of emissions mitigation, but it also presents the opportunity for synergy between value chain actors. In terms of MRV frameworks and certification schemes, the situation varies. For some value chain segments, like the production of oil and gas, there is an abundance of frameworks and schemes. This offers extensive coverage, but it is not always clear which option is the best for a given situation. For other segments, such as hydrogen production, the options are more limited. Emissions abatement is more straightforward: there is a range of mature technologies available for minimizing emissions along the value chain. However, the feasibility of each option must be assessed on a case-by-case basis to maximize the environmental and economic benefits.

Despite some uncertainties, the foundation for producing, monitoring, and verifying low-carbon hydrogen is already strong, and it is likely that the sector will continue to experience technological advances and regulatory/voluntary framework developments as global efforts to meet climate targets continue.

Annex

Deloitte's HyPe model

CARBON LIMITS

Results from Task 1 are also feeding into Deloitte's HyPe model, including:

- CO_2 and CH_4 EF along the natural gas value chain
- CO_2 and CH_4 EF along the biomethane value chain

In this context, underlying assumptions were synchronized between Task 1 modeling and the HyPe model:

- Capture rates considered
- Natural gas and electricity consumption to produce hydrogen using SMR or ATR
- Direct CO_2 emissions during hydrogen production using SMR or ATR

Brief note on enhanced oil recovery (EOR)

Direct effect of captured carbon used for EOR

CARBON LIMITS

About 90% - 95% of the CO_2 injected for EOR could be trapped within the formation, which leads to **associated storage**[1]

However, the goals of EOR and CCS are quite different.

CCS goals:
Store as much CO_2 as possible – decarbonize!

Can be incentivised using taxes, carbon markets...

≠

O&G goals:
- Buy as little CO_2 as possible, which leads to "store as little CO_2 as possible"
- Increase oil production, make money, produce more oil

Side effects
- Oil production increase
- Upstream and downstream methane emissions increase (including emissions from combustion of the final product)
- More potential emission sources are added to the value chain (e.g.,gas separation of gas to recover CO_2 that has not been trapped and reuse it)

/!\ Risk of double counting emission reductions: either claimed by the hydrogen plant OR by the O&G company

Sources and links

Frontiers

Direct effect of captured carbon used for EOR

CARBON LIMITS

CO_2-EOR EF

CO_2-EOR generates additional emissions compared to a typical CCS project.

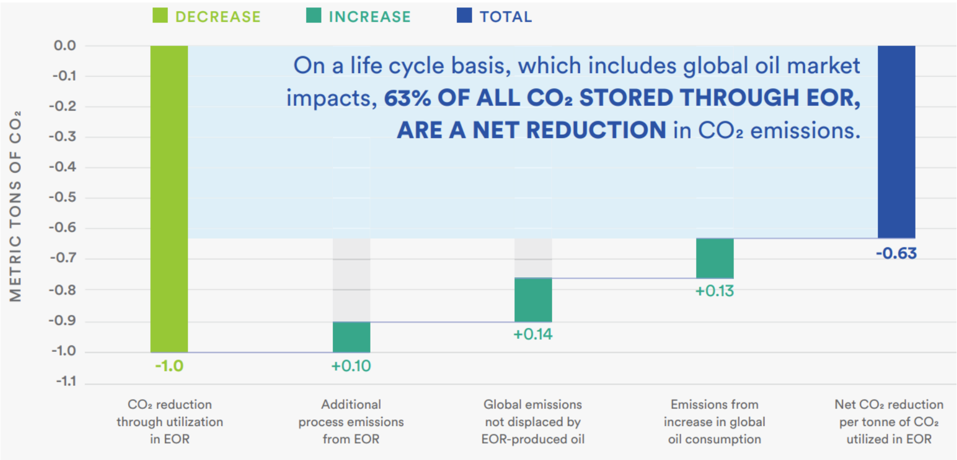


Figure 1. Net CO_2 emissions per tonne of CO_2 stored through EOR [1]

CCS EF

Based on our analysis, between **90% and 97%** of all CO_2 captured through a typical CCS project is a net reduction in CO_2 emissions. In the Northern Lights project, it corresponds to 97% *[2]*.

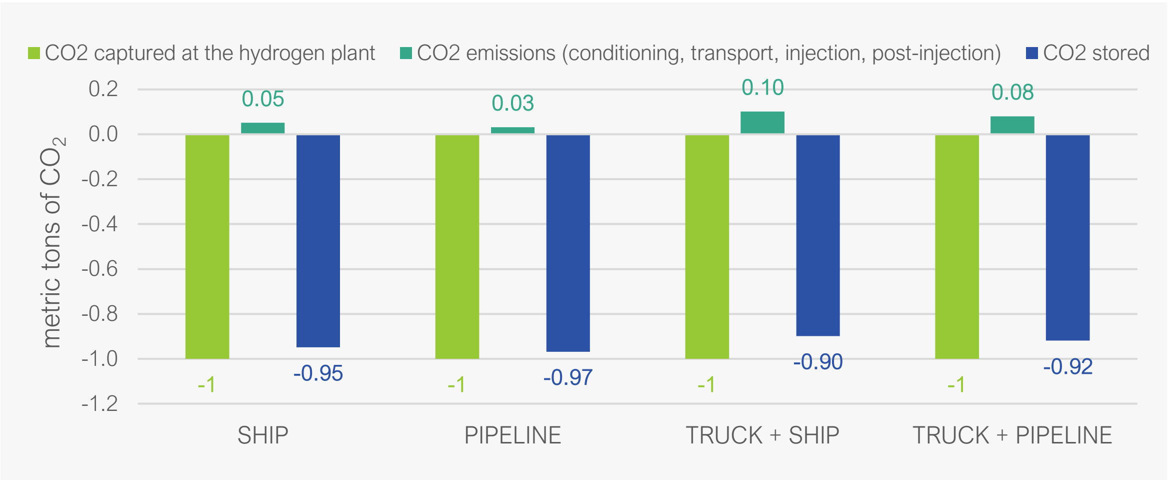


Figure 2. Net CO_2 emissions per tonne of CO_2 stored through CCS

Sources and links

[1] CATF. Does not include CH4 emissions. Included in the LCA: impacts of potential increase in oil consumption, injection, EOR operations

[2] Northern Lights

Detailed results for Case 1 – Case 5

Case 1

LNG imported from the US to Germany – production of blue H_2 with imported LNG. CO_2 is transported to Norway for storage

1. USA CH_4 emissions

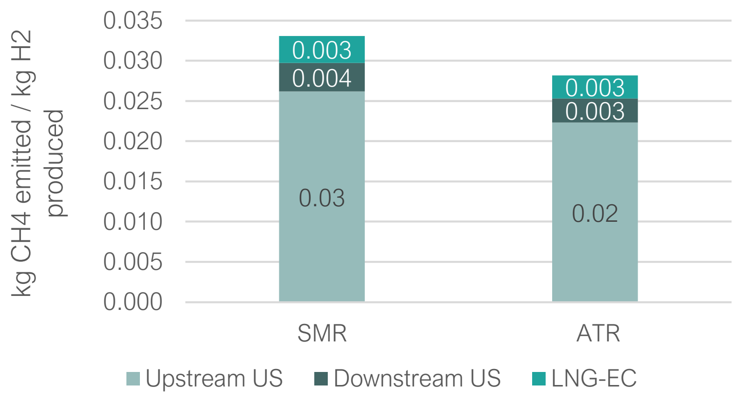
LNG exporter

Source selection*

Priority I - Emissions reported in any recent academic paper representative of the country (with peer review)

**See methodology slides in Annex*

CH_4 emissions along the gas value chain



Unit: kg CH_4/kg H_2	SMR	ATR
Upstream	0.03	0.02
Downstream	0.004	0.003
LNG – EC	0.003	0.003
Total	**0.033**	**0.028**

The unit of EF is per kg of blue hydrogen produced either by Steam Methane Reforming (SMR) or Auto-Thermal Reforming (ATR)

Upstream and transmission EF

- Different academic papers were considered, and the selection is based on the following criteria:
  - Academic paper representative of the country based on a large measurement sample with peer review.
  - US specific – since the Permian basin behaved differently than other basins, academic papers only based on this region were eliminated.
  - Input emissions data less than 5 years old (from 2019).
  - Emissions for the entire oil and gas value chain – not only production.

  Emissions within <5% of the IEA reported emissions and higher than UNFCCC emissions which is consistent with most academic papers. Hence, Shen et al. (2022) is the chosen source.

- Shen et al. (2022) provides estimates based on measurement carried out between March 2018 and February 2020. Only total emissions from the US oil and gas sector is provided.
  - Alvarez et al. (2018, data for 2015) has thus been leveraged and use to split total oil and gas emissions into production, gathering, processing, transmission and storage and local distribution categories.
  - Oil & gas emission are split using the energy ratio of oil & gas produced in the country
  - CH_4 from Associated Gas (APG) was estimated as a share of the oil production emission using the relative energy content of the associated gas.

Liquefaction EF

- Roman-White et al. (2021), an academic paper based on Cheniere data for 2018 and data for most recent years published by Cheniere have been considered. No significant difference is noted; hence, the academic paper is the chosen source.

LNG Carrier EF

- Paul Balcombe et al. (2022) is the only academic paper estimating CH_4 and CO_2 emissions from LNG carriers.

Information used	Source and link
Volume of oil and gas produced, Volume of oil and gas imported, Same source was used to estimate the energy ratio of oil and gas produced	Energy Institute 2023 - data for 2019
Upstream emissions, Transmission emissions	Sources considered: IEA Methane Tracker 2022, UNFCCC 2021/EPA GHGI 2022, Alvarez et al. (2018), Zhang et al. (2020), Rutherford et al. (2021), O'Rourke et al. (2020), Veefkind et al. (2022), Sherwin et al. (2024), Omara et al. (2022), Schneising et al. (2020). Chosen source: Shen et al. (2022) - emissions data for 2019
Volume of APG produced in the country	EIA report
Methane emissions from LNG Carrier and the corresponding quantity of LNG delivered	Paul Balcombe et al. (2022)
Methane emissions from LNG Liquefaction and corresponding activity data (volume of gas liquefied)	Sources considered: Cheniere (2023) - data for 2019, Roman-White et al. (2021) – based on Cheniere data for 2018 Chosen source: Roman-White et al. (2021) – based on Cheniere data for 2018

1. USA CO_2 emissions

LNG exporter

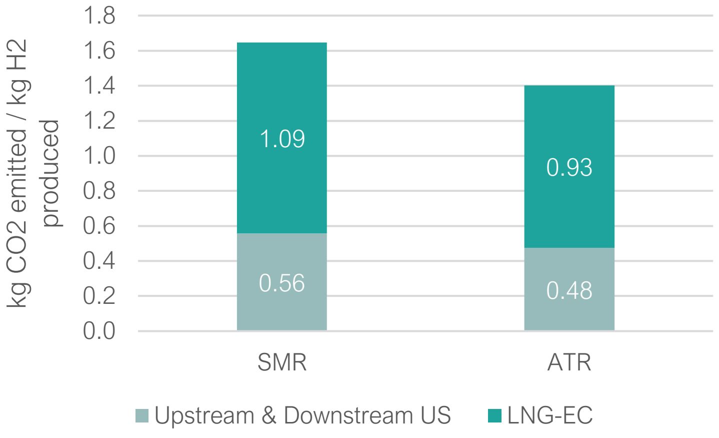
Source selection*

Flaring | **Energy use** | **CO_2 venting (e.g., AGR)**

Priority I - Recent tier 2 or tier 3 reported emissions data by the country

See methodology slides in Annex

CO_2 emissions along the gas value chain



Unit: kt CO_2/kt H_2	SMR	ATR
Upstream & Downstream	0.56	0.48
LNG – EC	1.09	0.93
Total	1.65	1.40

The unit of EF is per kg of blue hydrogen produced either by Steam Methane Reforming (SMR) or Auto-Thermal Reforming (ATR)

CO_2 emissions (flaring, CO_2 venting, energy use)

- Different sources were considered. Since GHGRP provides tier 2 or 3 flaring emissions, this is the chosen source.
- Energy use - GHGRP was the only source providing carbon dioxide emissions from energy use in the upstream and transmission segments of oil and gas production.

Liquefaction EF

- Roman-White et al. (2021), an academic paper based on Cheniere data for 2018 and data for most recent years published by Cheniere have been considered. No significant difference is noted; hence, the academic paper is the chosen source.

LNG Carrier EF

- Paul Balcombe et al. (2022) is the only academic paper estimating CH4 and CO2 emissions from LNG carriers, hence, the chosen source.

Information used	Source and link
Volume of oil and gas produced, Volume of oil and gas imported, Same source was used to estimate the energy ratio of oil and gas produced	Energy Institute 2023 - data for 2019
Flaring emissions, CO_2 venting emissions, Energy use emissions	Sources considered: GHGRP EPA, VIIRS data, UNFCCC Chosen source: GHGRP EPA – data for 2019
Volume of APG produced in the country	EIA report
Carbon dioxide emissions from LNG Carrier and the corresponding quantity of LNG delivered	Paul Balcombe et al. (2022)
Carbon dioxide emissions from LNG Liquefaction and corresponding activity data (volume of gas liquefied)	Sources considered: Cheniere (2023) - data for 2019, Roman-White et al. (2021) Chosen source: Roman-White et al. (2021)

2. Germany CH_4 emissions

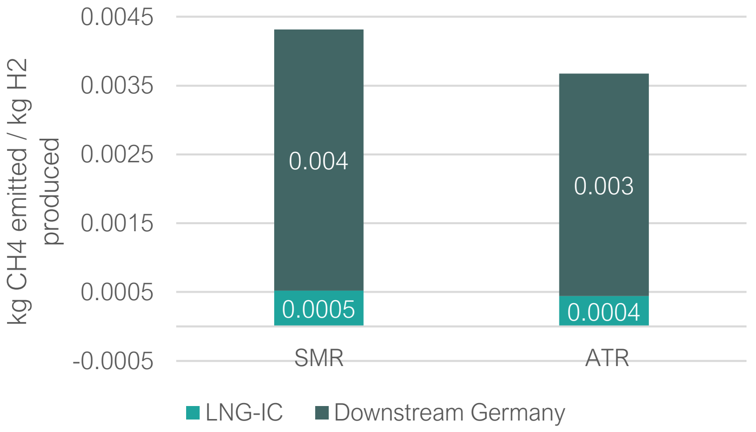
LNG importer

Source selection*

Priority II - Recent tier 2 or tier 3 reported emissions data by the country (NIR and UNFCCC)

**See methodology slides in Annex*

CH_4 emissions along the gas value chain



Unit: kg CH_4/kg H_2	SMR	ATR
LNG - IC	5E-4	4E-4
Downstream	0.004	4E-4
Total	0.0043	0.0037

The unit of EF is per kg of blue hydrogen produced either by Steam Methane Reforming(SMR) or Auto-Thermal Reforming (ATR)

Transmission EF

- For transmission, the national inventory report (UNFCCC) was prioritized over IEA.

LNG Regasification EF

- For regasification, Marcogas and Roman-White's academic papers are the considered sources. Marcogas provides European specific estimate whereas Roman-White et al. consider an LNG trip from the US to China where the regasification might be different than in Germany. Hence, Marcogas is the chosen source.
- A proportional relationship has been assumed between the LNG-related emissions and LNG imported into the region.

Information used	Source and link
Volume of gas produced, Volume of gas imported (pipeline, LNG)	Energy Institute 2023 - data for 2021
Transmission emissions	UNFCCC 2021 – data for 2021
LNG terminal and regasification	Source considered: Marcogas LNG Terminals report 2018, Roman-White et al. (2021) Chosen source: Marcogas LNG Terminals report 2018

2. Germany CO_2 emissions

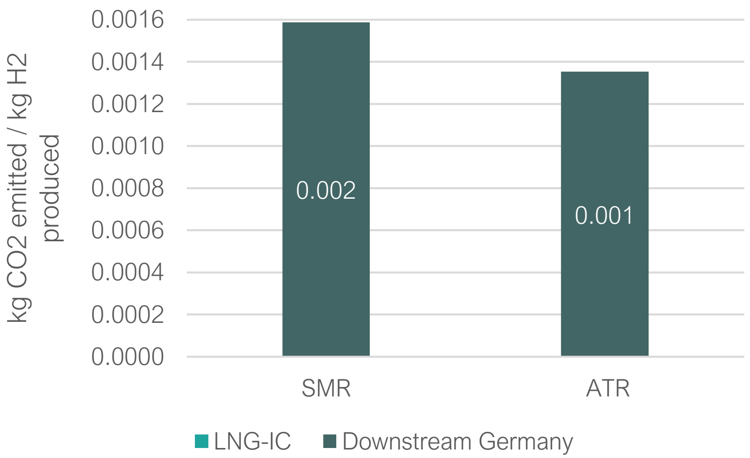
LNG importer

Source selection

Flaring | Energy use | CO_2 venting (e.g., AGR)

Priority I - Recent tier 2 or tier 3 reported emissions data by the country

CO_2 emissions along the gas value chain



kg CO_2/kg H_2	SMR	ATR
LNG - IC	2.2E-8	1.87E-8
Downstream	0.002	0.001
Total	**0.002**	**0.001**

The unit of EF is per kg of blue hydrogen produced either by Steam Methane Reforming(SMR) or Auto-Thermal Reforming (ATR)

Transmission EF

- For transmission, the national inventory reports (UNFCCC) were prioritized.

LNG Regasification EF

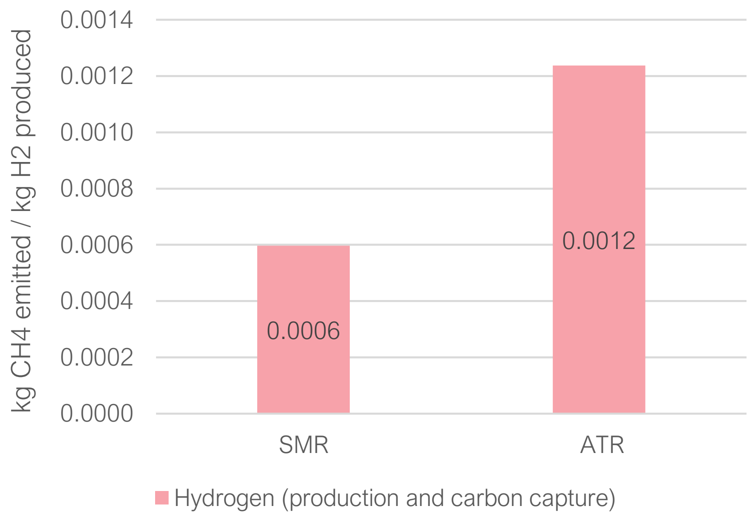
- For regasification, Roman-White's academic papers is the only relevant source available, hence the chosen source.

Information used	Source and link
Volume of gas produced, Volume of gas imported (pipeline, LNG)	Energy Institute 2023 - data for 2021
Transmission emissions	UNFCCC 2021 – data for 2021
LNG terminal and regasification	Roman-White et al. (2021)

3. Germany – CH_4 emissions

Hydrogen production

CH_4 emissions during H_2 production & CO_2 capture



Unit: kg CH_4/kg H_2	SMR	ATR
Total	6E-4	1.2E-3

The unit of EF is per kt of blue hydrogen produced either by Steam Methane Reforming (SMR) or Auto-Thermal Reforming (ATR)

Direct emissions (hydrogen production + CO_2 capture)
- Given the limited data available for SMR and ATR with CCS, the EcoInvent emission factor for SMR without CCS is extrapolated.

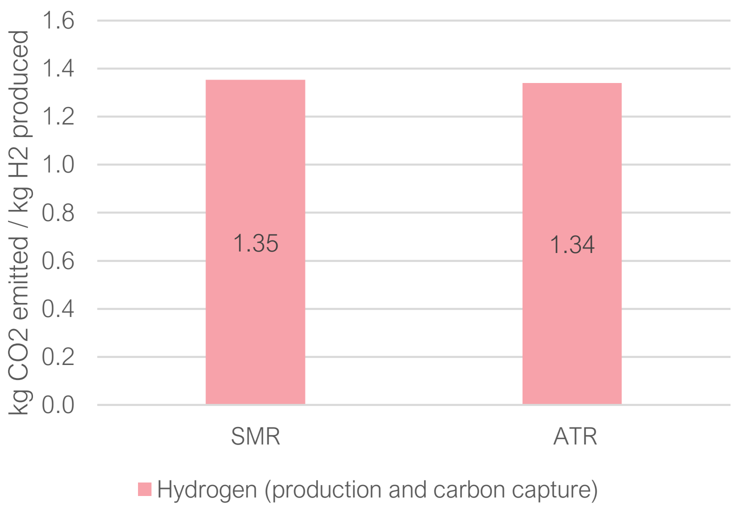
Electricity consumption
- Electricity consumption provided by Deloitte's HyPE model assumptions for both SMR with CCS and ATR with CCS.
- The GHG Delegated Act is used for the electricity intensity of generated electricity in Germany. EcoInvent is used to split the intensity between methane and carbon dioxide.

Information used	Source and link
CO_2 emissions during hydrogen production with CCS, Electricity consumption	Deloitte
Emission factor for the production of electricity based on the production mix in Germany	GHG Delegated Act, Table A: Delegated regulation - 2023/1185 - EN - EUR-Lex (europa.eu)
CH_4/CO_2 split, Electricity intensity of the Norwegian production mix, Methane emissions during hydrogen production with SMR without CCS	EcoInvent database
Energy use for the compression of hydrogen	Kanz O. et al, 2023 : Life-cycle global warming impact of hydrogen transport through pipelines from Africa to Germany (rsc.org)

3. Germany – CO_2 emissions

Hydrogen production

CO_2 emissions during H_2 production & CO_2 capture



Unit: kg CO_2/kg H_2	SMR	ATR
Total	1.35	1.34

The unit of EF is per kt of blue hydrogen produced either by Steam Methane Reforming (SMR) or Auto-Thermal Reforming (ATR)

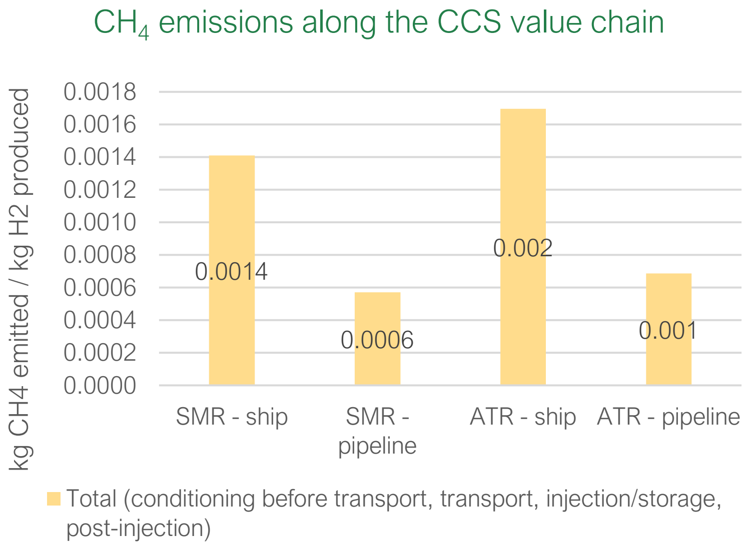
Direct emissions (hydrogen production + CO_2 capture)
- Direct CO_2 emissions provided by Deloitte's HyPE model assumptions for both SMR with CCS and ATR with CCS
- 90% capture rate for SMR and 95% capture rate for ATR

Electricity consumption
- Electricity consumption provided by Deloitte's HyPE model assumptions for both SMR with CCS and ATR with CCS.
- The GHG Delegated Act is used for the electricity intensity of generated electricity in Germany. EcoInvent is used to split the intensity between methane and carbon dioxide.

Information used	Source and link
CO_2 emissions during hydrogen production with CCS, Electricity consumption	Deloitte's HyPE model assumptions
Emission factor for the production of electricity based on the production mix in Germany	GHG Delegated Act, Table A: Delegated regulation - 2023/1185 - EN - EUR-Lex (europa.eu)
CH_4/CO_2 split, Electricity intensity of the Norwegian production mix	EcoInvent database
Energy use for the compression of hydrogen	Kanz O. et al, 2023 : Life-cycle global warming impact of hydrogen transport through pipelines from Africa to Germany (rsc.org)

4. Germany / Norway – CH_4 emissions

CCS – CO_2 conditioning, transport and storage



Unit: kg CH_4/kg H_2	SMR - ship	SMR - pipeline	ATR – ship	ATR - pipeline
Total	0.0014	0.0006	0.0017	0.0007

The unit of EF is per kg of blue hydrogen produced either by Steam Methane Reforming (SMR) or Auto-Thermal Reforming (ATR)

Conditioning of CO_2 before transport (liquefaction, compression)

- The electricity intensity for Germany from the GHG Delegated Act (gCO_{2eq} /MJ) is used and EcoInvent is used to split the total intensity between methane and carbon dioxide.
- Jackson et al, 2018 provide the energy consumption for compression (pipeline), and Jackson et al, 2019 for liquefaction (ship, truck)

Transport of CO_2

- Ship - Northern Light carbon footprint is used to estimate CO_{2eq} and the EcoInvent database is used to split the emissions between methane and carbon dioxide.
- Pipeline - Zero emissions assumed for the transport by pipeline

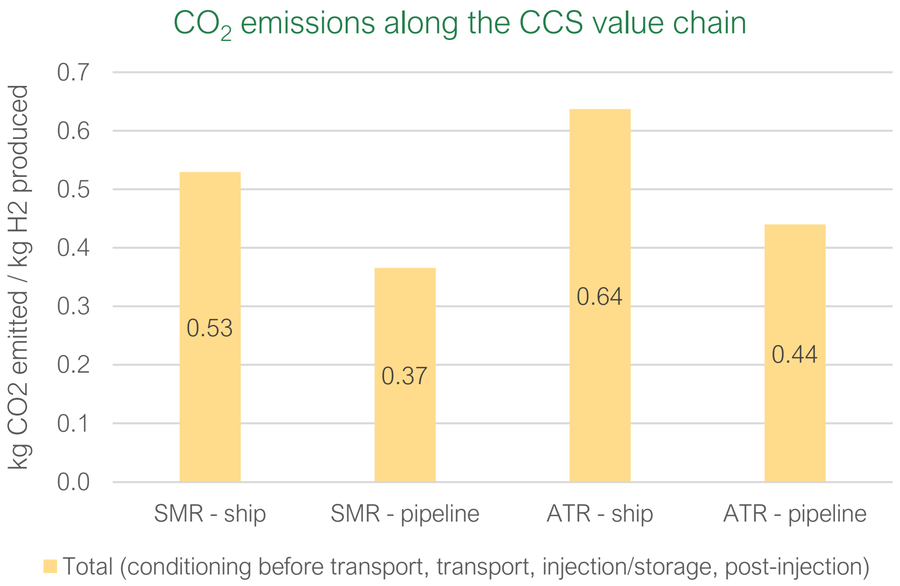
Storage/Injection and post-injection

- Northern Light carbon footprint is used to estimate CO_{2eq} and the EcoInvent database is used to split the emissions between methane and carbon dioxide.

Information used	Source and link
Emission factor for the production of electricity based on the production mix in Germany	GHG Delegated Act, Table A: Delegated regulation - 2023/1185 - EN - EUR-Lex (europa.eu)
CH_4/CO_2 split	EcoInvent database
Energy consumption of compression	Jackson et al, 2018
Energy consumption of liquefaction	Jackson et al., 2019
Emission from transportation by ship, storage, injection and post-injection	Northern Light: Report-Carbon-footprint-of-the-Northern-Lights-JV-co2-transport-and-storage-value-chain.pdf (norlights.com)

4. Germany / Norway – CO_2 emissions

CCS – CO_2 conditioning, transport and storage



Unit: kg CO_2/kg H_2	SMR - ship	SMR - pipeline	ATR – ship	ATR - pipeline
Total	0.53	0.37	0.64	0.44

The unit of EF is per kg of blue hydrogen produced either by Steam Methane Reforming(SMR) or Auto-Thermal Reforming (ATR)

Conditioning of CO_2 before transport (liquefaction, compression)

- The electricity intensity for Germany from the GHG Delegated Act (gCO_{2eq} /MJ) is used and EcoInvent is used to split the total intensity between methane and carbon dioxide.
- Jackson et al, 2018 provide the energy consumption for compression (pipeline), and Jackson et al, 2019 for liquefaction (ship, truck)

Transport of CO_2

- Ship - Northern Light carbon footprint is used to estimate CO_{2eq} and the EcoInvent database is used to split the emissions between methane and carbon dioxide.
- Pipeline - Zero emissions assumed for the transport by pipeline

Storage/Injection and post-injection

- Northern Light carbon footprint is used to estimate CO_{2eq} and the EcoInvent database is used to split the emissions between methane and carbon dioxide.

Information used	Source and link
Emission factor for the production of electricity based on the production mix in Germany	GHG Delegated Act, Table A: Delegated regulation - 2023/1185 - EN - EUR-Lex (europa.eu)
CH_4/CO_2 split	EcoInvent database
Energy consumption of compression	Jackson et al, 2018
Energy consumption of liquefaction	Jackson et al., 2019
Emission from transportation by ship, storage, injection and post-injection	Northern Light: Report-Carbon-footprint-of-the-Northern-Lights-JV-co2-transport-and-storage-value-chain.pdf (norlights.com)

Estimating CH_4 emissions in the BAT scenario

- For estimating the emissions from the BAT scenario, EF from the current scenario is used as the baseline, followed by applying some emission reduction trajectories along the different parts to the value chain.
- The solutions applied are country specific – all solutions are based on existing abatement potentials, and employ realistic assumptions on the year of implementation.

Natural gas production in the USA
- Upstream - OGCI industry target used
- Transmission
  - IEA downstream potential abatement reduction used
  - Downstream abatement potential split between transmission and distribution based on the share of emissions from Alvarez et al 2018.

LNG export (liquefaction and shipping) in the USA
- LNG liquefaction – comparison between Cheniere (USA) (Roman-White et al, 2021) and Hammerfest (Norway). Lower emissions are observed at the Norwegian plant which is considered as our Best Available Technology.
- LNG Carrier – Carbon Limits internal LNG Carrier model is used based on BAT assumptions (e.g., low emissions from engine, low BOG, no BOK leakage)

LNG import (unloading and regasification) in Germany
- Already very little emissions – BAT scenario already reached in the current scenario.

Transmission in Germany
- The average EF used for Europe is compared to the German EF. The lowest is assumed to be reached by 2030 and the median European EF is assumed to be reached by 2040.

Hydrogen production and CO_2 capture
- No more coal in the German electricity production mix. The second lowest electricity intensity provided by the GHG Delegated Act is used (France): the lowest intensity is observed in Sweden which does not apply to Germany due to the high share of hydro in the electricity production mix.
- Capture rates: same as current scenario

CCS
- Conditioning before transport – No more coal in the German electricity production mix. The second lowest electricity intensity provided by the GHG Delegated Act is used (France): the lowest intensity is observed in Sweden which does not apply to Germany due to the high share of hydro in the electricity production mix.
- Transport – use of bioLNG + bioCCS on the ship
- Storage and injection – already very little emissions – same as current scenario

Information used	Source and link
OGCI methane intensity targets	Learn about Reducing methane emissions - OGCI
IEA methane abatement potential	Methane Tracker – Data Tools – IEA, data for 2021
Mitigation potential for energy use and CO2 venting	Carbon Limits for CATF/CAELP done for US
LNG liquefaction	Roman-White et al. (2021) / Feltspesifikke utslippsrapporter for 2021 - Offshore Norge

Estimating CO_2 emissions in the BAT scenario

- For estimating the emissions from the BAT scenario, EF from the current scenario is used as the baseline, followed by applying some emission reduction trajectories along the different parts to the value chain.
- The solutions applied are country specific – all solutions are based on existing abatement potentials, and employ realistic assumptions on the year of implementation.

Natural gas production in the USA
- Flaring – assumed that the best practices for flaring were not implemented everywhere. Hence, the minimum EF between the assessed countries (i.e., Norway) is considered as the BAT.
- Energy use – assumed that CCS or electrification can be applied. Hence, an 80% reduction is applied (see methodology)
- CO_2 venting – assumed that CCS on AGR units is not applied everywhere. Hence, an 87% reduction is applied (see methodology)

LNG export (liquefaction and shipping) in the USA
- LNG liquefaction – comparison between Cheniere (USA) (Roman-White et al, 2021) and Hammerfest (Norway). Lower emissions are observed at the Norwegian plant which is considered as our Best Available Technology.
- LNG Carrier – Carbon Limits internal LNG Carrier model is used based on BAT assumptions (e.g., low emissions from engine, low BOG, no BOK leakage)

LNG import (unloading and regasification) in Germany
- Already very little emissions – BAT scenario already reached in the current scenario.

Transmission in Germany
- The average EF used for Europe is compared to the German EF. The lowest is assumed to be reached by 2030 and the median European EF is assumed to be reached by 2040.

Hydrogen production and CO_2 capture
- No more coal in the German electricity production mix. The second lowest electricity intensity provided by the GHG Delegated Act is used (France): the lowest intensity is observed in Sweden which does not apply to Germany due to the high share of hydro in the electricity production mix.
- Capture rates: same as current scenario

CCS
- Conditioning before transport – No more coal in the German electricity production mix. The second lowest electricity intensity provided by the GHG Delegated Act is used (France): the lowest intensity is observed in Sweden which does not apply to Germany due to the high share of hydro in the electricity production mix.
- Transport – bioCCS on the ship and bioLNG
- Storage and injection – already very little emissions – same as current scenario

Information used	Source and link
IEA methane abatement potential	Methane Tracker – Data Tools – IEA, data for 2021
Mitigation potential for energy use and CO2 venting	Carbon Limits for CATF/CAELP done for US
LNG liquefaction	Roman-White et al. (2021) / Feltspesifikke utslippsrapporter for 2021 - Offshore Norge
Emission factor for the production of electricity based on the production mix in Germany and France	GHG Delegated Act, Table A: Delegated regulation - 2023/1185 - EN - EUR-Lex (europa.eu)

Case 2

Gas imported from Algeria to Germany via pipeline – production of blue H_2 in Germany. CO_2 is transported to Norway for storage.

1. Algeria - CH_4 emissions

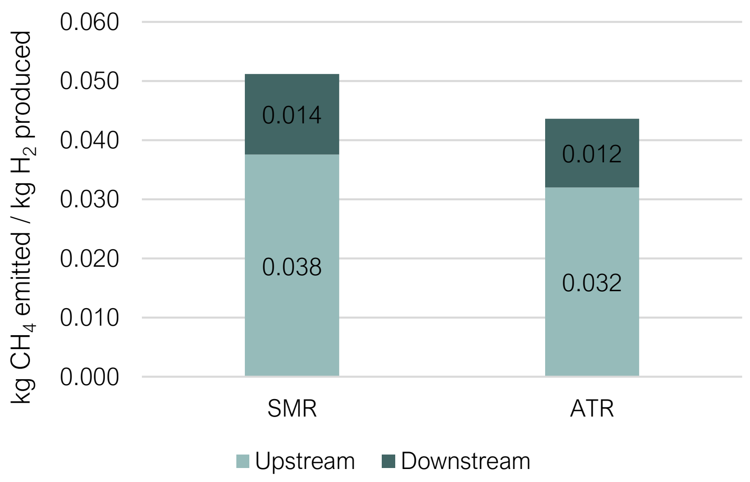
Gas exporter via pipeline

Source selection*

Priority III - Emissions reported by the IEA Methane Tracker 2022

See methodology slides in Annex

CH_4 emissions along the gas value chain



Unit: kg CH_4/kg H_2	SMR	ATR
Upstream	0.038	0.032
Downstream	0.014	0.012
Total	**0.051**	**0.044**

The unit of EF is per kt of blue hydrogen produced either by Steam Methane Reforming(SMR) or Auto-Thermal Reforming (ATR)

Upstream EF

- In the absence of an academic paper with local measurement on a representative sample, and in the absence of a tier 2 or 3 inventory, IEA was selected as the source of information.

Transmission EF

- Since IEA do not split downstream emissions between transmission and distribution and that, based on Carbon Limits expertise and in a comparison with other countries, the distribution estimate may be on the low side, the National Inventory Report (NIR) of Algeria was used for the transmission EF.

- When only combined data is available on CH_4 emissions along the oil & gas value chain, they are split using the energy ratio of oil & gas produced in the country
- CH_4 from Associated Gas (APG) was estimated as a share of the oil production emission using the relative energy content of the associated gas.

Information used	Source and link
Volume of oil and gas produced, Volume of oil and gas consumed, Same source was used to estimate the energy ratio of oil and gas produced	Energy Institute 2023 - data for 2021
Upstream emissions	IEA Methane Tracker 2022 – data for 2021
Transmission emissions	NIR of Algeria (2023) – data for 2020
Volume of APG produced in the region (Africa)	IEA Report, 2020 – data for 2019

1. Algeria – CO_2 emissions

Gas exporter via pipeline

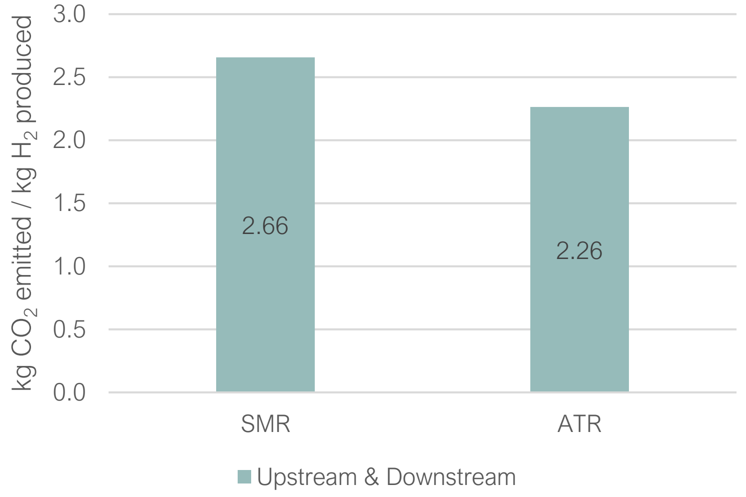
Source selection*

Flaring | Energy use | CO_2 venting (e.g., AGR)

Priority III
Emissions reported by OCI+

*See methodology slides in Annex

CO_2 emissions along the gas value chain



Unit: kg CH_4/kg H_2	SMR	ATR
Upstream & Downstream	2.66	2.26

The unit of EF is per kg of blue hydrogen produced either by Steam Methane Reforming (SMR) or Auto-Thermal Reforming (ATR)

Total EF

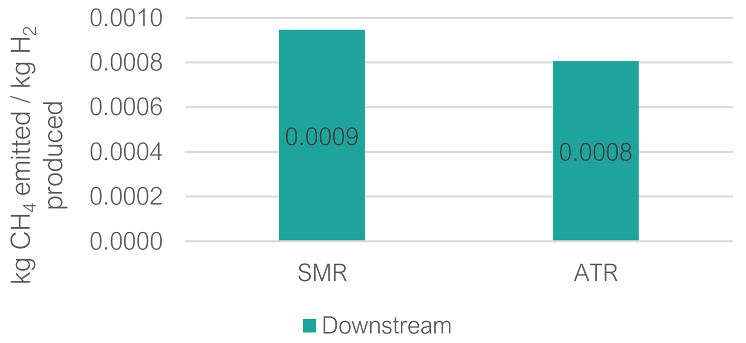
- In the absence of national data regarding carbon dioxide emissions from energy use, total CO_2 emissions from the OCI+ database have been used.
- OCI+ provides emissions of CO_2 per MJ of natural gas per field. A weighted average by production of gas per field is performed.

Information used	Source and link
Volume of oil and gas produced, Volume of oil and gas consumed, Same source was used to estimate the energy ratio of oil and gas produced	Energy Institute 2023 - data for 2021 and 2020
Flaring emissions	Source considered: IEA Methane Tracker 2022 – data for 2021
Energy use emissions	Source considered: Initial National Communication to the UNFCCC from Qatar
CO_2 venting emissions	Source considered: NIR of Algeria (2023) – data for 2020
Total CO_2 emissions from natural gas activities	Source used: Oil Climate Index plus Gas (rmi.org)
Volume of APG produced in the region (Africa)	IEA Report, 2020 – data for 2019

2. Europe – CH_4 and CO_2 emissions

Gas importer

CH_4 emissions along the gas value chain



Unit: kg CH_4/kg H_2	SMR	ATR
Downstream	0.0009	0.0008

The unit of EF is per kg of blue hydrogen produced either by Steam Methane Reforming (SMR) or Auto-Thermal Reforming (ATR)

Source selection*

Priority II - Recent tier 2 or tier 3 reported emissions data by the country (NIR and UNFCCC)

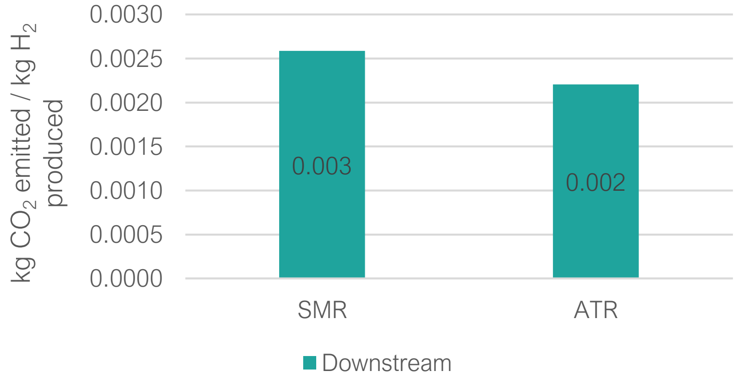
**See methodology slides in Annex*

Transmission EF

- For transmission, the national inventory report (UNFCCC) was prioritized over IEA for each European country.
- Since the pipeline from Algeria to Germany goes through different European countries, an average EF is calculated.

Information used	Source and link
Volume of gas produced, Volume of gas imported (pipeline, LNG)	Energy Institute 2023 - data for 2021
(1) Transmission emissions	UNFCCC 2021

CO_2 emissions along the gas value chain



Unit: kg CO_2/kg H_2	SMR	ATR
Downstream	0.003	0.002

The unit of EF is per kg of blue hydrogen produced either by Steam Methane Reforming (SMR) or Auto-Thermal Reforming (ATR)

Source selection*

Flaring | Energy use | CO_2 venting (e.g., AGR)

Priority I - Recent tier 2 or tier 3 reported emissions data by the country

**See methodology slides in Annex*

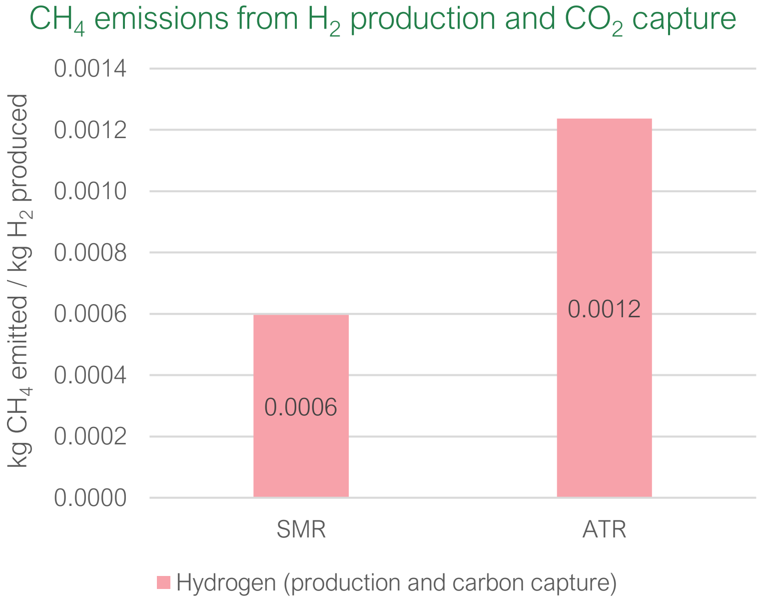
Transmission EF

- For transmission, the national inventory reports (UNFCCC) were prioritized.
- Since the pipeline from Algeria to Germany goes through different European countries, an average EF is calculated.

Information used	Source and link
Volume of gas produced, Volume of gas imported (pipeline, LNG)	Energy Institute 2023 - data for 2021
Transmission emissions	UNFCCC 2021

3. Germany – CH_4 emissions

Hydrogen production



Unit: kg CH_4/kg H_2	SMR	ATR
Total	0.0006	0.0012

The unit of EF is per kg of blue hydrogen produced either by Steam Methane Reforming (SMR) or Auto-Thermal Reforming (ATR)

Direct emissions (hydrogen production + CO_2 capture)

- Given the limited data available for SMR and ATR with CCS, the EcoInvent emission factor for SMR without CCS is extrapolated.

Electricity consumption

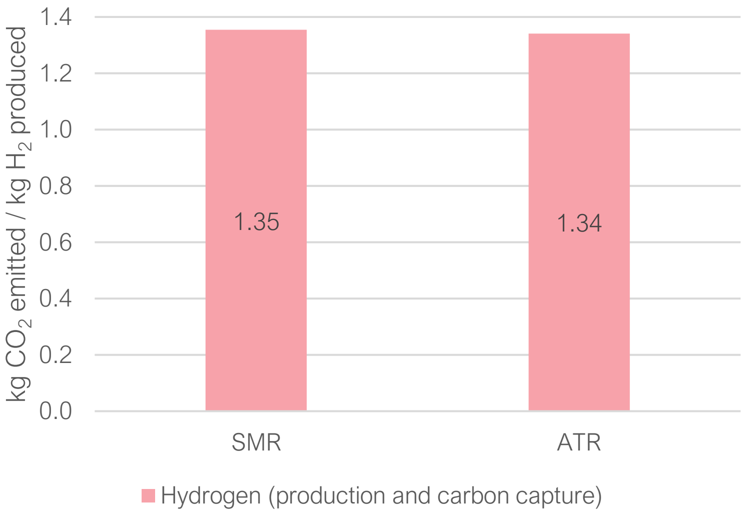
- Electricity consumption provided by Deloitte's HyPE model assumptions for both SMR with CCS and ATR with CCS.
- The GHG Delegated Act is used for the electricity intensity of generated electricity in Germany. EcoInvent is used to split the intensity between methane and carbon dioxide.

Information used	Source and link
CO_2 emissions during hydrogen production with CCS, Electricity consumption	Deloitte's HyPE model assumptions
Emission factor for the production of electricity based on the production mix in Germany	GHG Delegated Act, Table A: Delegated regulation - 2023/1185 - EN - EUR-Lex (europa.eu)
CH_4/CO_2 split, Electricity intensity of the Norwegian production mix, Methane emissions during hydrogen production with SMR without CCS	EcoInvent database
Energy use for the compression of hydrogen	Kanz O. et al, 2023 : Life-cycle global warming impact of hydrogen transport through pipelines from Africa to Germany (rsc.org)

3. Germany – CO_2 emissions

Hydrogen production

CO_2 emissions from H_2 production and CO_2 capture



Unit: kg CH_4/kg H_2	SMR	ATR
Total	1.35	1.34

The unit of EF is per kt of blue hydrogen produced either by Steam Methane Reforming (SMR) or Auto-Thermal Reforming (ATR)

Direct emissions (hydrogen production + CO_2 capture)

- Direct CO_2 emissions provided by Deloitte's HyPE model assumptions for both SMR with CCS and ATR with CCS
- 90% capture rate for SMR and 95% capture rate for ATR

Electricity consumption

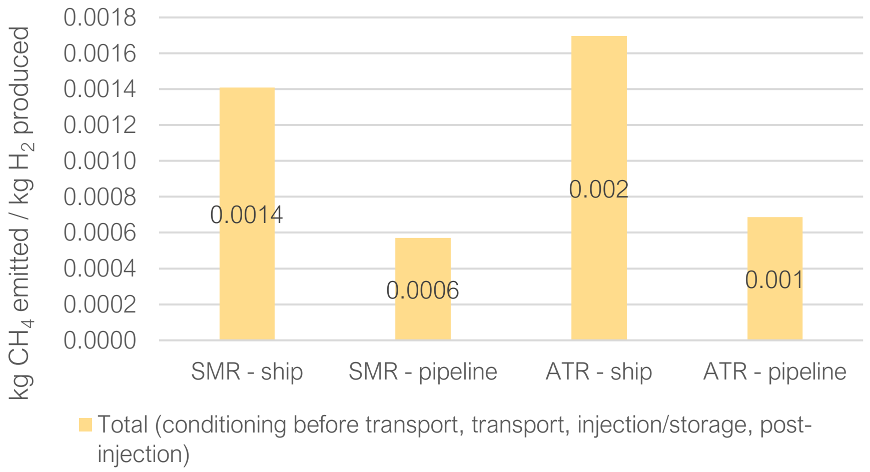
- Electricity consumption provided by Deloitte's HyPE model assumptions for both SMR with CCS and ATR with CCS.
- The GHG Delegated Act is used for the electricity intensity of generated electricity in Germany. EcoInvent is used to split the intensity between methane and carbon dioxide.

Information used	Source and link
CO_2 emissions during hydrogen production with CCS, Electricity consumption	Deloitte's HyPE model assumptions
Emission factor for the production of electricity based on the production mix in Germany	GHG Delegated Act, Table A: Delegated regulation - 2023/1185 - EN - EUR-Lex (europa.eu)
CH_4/CO_2 split, Electricity intensity of the Norwegian production mix	EcoInvent database
Energy use for the compression of hydrogen	Kanz O. et al, 2023 : Life-cycle global warming impact of hydrogen transport through pipelines from Africa to Germany (rsc.org)

4. Germany / Norway – CH_4 emissions

CCS – CO_2 conditioning, transport and storage

CH_4 emissions along the CCS value chain



Unit: kg CH_4/kg H_2	SMR - ship	SMR - pipeline	ATR – ship	ATR - pipeline
Total	0.0014	0.0006	0.0017	0.0007

The unit of EF is per kg of blue hydrogen produced either by Steam Methane Reforming (SMR) or Auto-Thermal Reforming (ATR)

Conditioning of CO_2 before transport (liquefaction, compression)
- The electricity intensity for Germany from the GHG Delegated Act (gCO_{2eq} /MJ) is used and EcoInvent is used to split the total intensity between methane and carbon dioxide.
- Jackson et al, 2018 provide the energy consumption for compression (pipeline), and Jackson et al, 2019 for liquefaction (ship, truck)

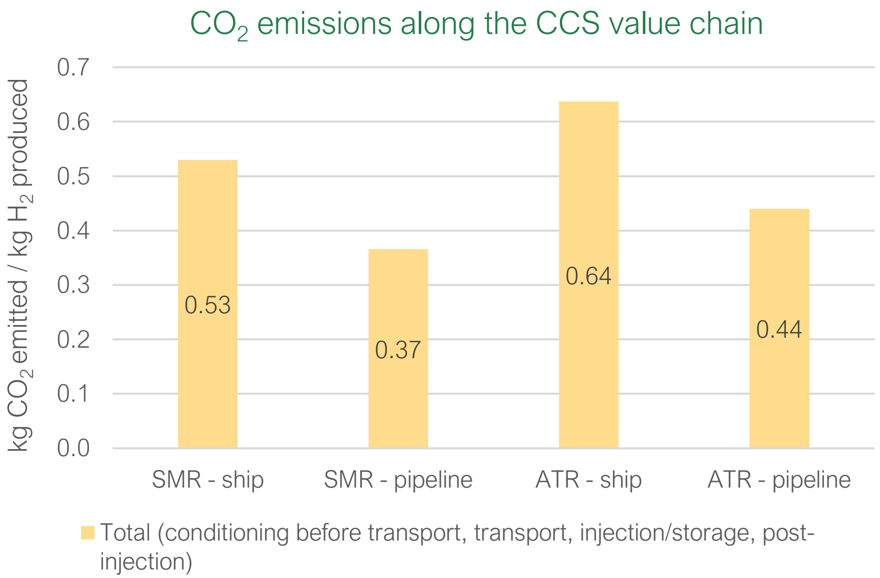
Transport of CO_2
- Ship - Northern Light carbon footprint is used to estimate CO_{2eq} and the EcoInvent database is used to split the emissions between methane and carbon dioxide.
- Pipeline - Zero emissions assumed for the transport by pipeline

Storage/Injection and post-injection
- Northern Light carbon footprint is used to estimate CO_{2eq} and the EcoInvent database is used to split the emissions between methane and carbon dioxide.

Information used	Source and link
Emission factor for the production of electricity based on the production mix in Germany	GHG Delegated Act, Table A: Delegated regulation - 2023/1185 - EN - EUR-Lex (europa.eu)
CH_4/CO_2 split	EcoInvent database
Energy consumption of compression	Jackson et al, 2018
Energy consumption of liquefaction	Jackson et al., 2019
Emission from transportation by ship, storage, injection and post-injection	Northern Light: Report-Carbon-footprint-of-the-Northern-Lights-JV-co2-transport-and-storage-value-chain.pdf (norlights.com)

4. Germany / Norway – CO_2 emissions

CCS – CO_2 conditioning, transport and storage



Unit: kg CH_4/kg H_2	SMR - ship	SMR - pipeline	ATR – ship	ATR - pipeline
Total	0.53	0.37	0.64	0.44

The unit of EF is per kg of blue hydrogen produced either by Steam Methane Reforming(SMR) or Auto-Thermal Reforming (ATR)

Conditioning of CO_2 before transport (liquefaction, compression)
- The electricity intensity for Germany from the GHG Delegated Act (gCO_{2eq} /MJ) is used and EcoInvent is used to split the total intensity between methane and carbon dioxide.
- Jackson et al, 2018 provide the energy consumption for compression (pipeline), and Jackson et al, 2019 for liquefaction (ship, truck)

Transport of CO_2
- Ship - Northern Light carbon footprint is used to estimate CO_{2eq} and the EcoInvent database is used to split the emissions between methane and carbon dioxide.
- Pipeline - Zero emissions assumed for the transport by pipeline

Storage/Injection and post-injection
- Northern Light carbon footprint is used to estimate CO_{2eq} and the EcoInvent database is used to split the emissions between methane and carbon dioxide.

Information used	Source and link
Emission factor for the production of electricity based on the production mix in Germany	GHG Delegated Act, Table A: Delegated regulation - 2023/1185 - EN - EUR-Lex (europa.eu)
CH_4/CO_2 split	EcoInvent database
Energy consumption of compression	Jackson et al, 2018
Energy consumption of liquefaction	Jackson et al., 2019
Emission from transportation by ship, storage, injection and post-injection	Northern Light: Report-Carbon-footprint-of-the-Northern-Lights-JV-co2-transport-and-storage-value-chain.pdf (norlights.com)

Estimating CH_4 emissions in the BAT scenario

- For estimating the emissions from the BAT scenario, EF from the current scenario is used as the baseline, followed by applying some emission reduction trajectories along the different parts to the value chain.
- The solutions applied are country specific – all solutions are based on existing abatement potentials, and employ realistic assumptions on the year of implementation.

Natural gas production in Algeria

- Upstream – emissions based on the IEA abatement potential are higher than the OGCI target. Conservative assumption that the BAT scenario in Algeria corresponds to the highest EF between IEA and OGCI. Hence, IEA is the chosen source, assumed achieved by 2030 and OGCI intensity target achieved by 2040 and 2050.
- Transmission
  - IEA downstream potential abatement reduction used
  - Downstream abatement potential split between transmission and distribution based on the share of emissions from the national inventory report (Tier 1).

Transmission in Europe

- The average EF used for Europe is compared to the German EF. The lowest is assumed to be reached by 2030 and the median European EF is reached by 2040.

Hydrogen production and CO_2 capture

- No more coal in the German electricity production mix. The second lowest electricity intensity provided by the GHG Delegated Act is used (France): the lowest intensity is observed in Sweden which does not apply to Germany due to the high share of hydro in the electricity production mix.
- Same capture rates as in the current scenario

CCS

- Conditioning before transport – No more coal in the German electricity production mix. The second lowest electricity intensity provided by the GHG Delegated Act is used (France): the lowest intensity is observed in Sweden which does not apply to Germany due to the high share of hydro in the electricity production mix.
- Transport –bioLNG use + bioCCS on the ship
- Storage and injection – already very little emissions – same as current scenario

Information used	Source and link
OGCI targets	Learn about Reducing methane emissions - OGCI
IEA abatement potential	Methane Tracker – Data Tools – IEA, data for 2021
Emission factor for the production of electricity based on the production mix in Germany and France	GHG Delegated Act, Table A: Delegated regulation - 2023/1185 - EN - EUR-Lex (europa.eu)
Mitigation potential for energy use and CO2 venting	Carbon Limits for CATF/CAELP done for US
LNG liquefaction	Roman-White et al. (2021) / Feltspesifikke utslippsrapporter for 2021 - Offshore Norge

Case 2

Estimating CO_2 emissions in the BAT scenario

- For estimating the emissions from the BAT scenario, EF from the current scenario is used as the baseline, followed by applying some emission reduction trajectories along the different parts to the value chain.
- The solutions applied are country specific – all solutions are based on existing abatement potentials, and employ realistic assumptions on the year of implementation.

Natural gas production in Algeria

- Flaring – since OCI+ uses VIIRS data to estimate CO_2 emissions from flaring, this dataset has been used to extract flare emissions from total CO_2 emissions, assuming 10% of CO_2 emissions are attributable to the gas value chain and 90% to the oil value chain. Then, it is assumed that the best practices for flaring were not implemented. Hence, the minimum EF between the assessed countries (i.e., Norway) is considered the BAT.
- For the rest (energy use and CO_2 venting), it is assumed that CCS, electrification can be applied. Hence, an 80% reduction is applied (see methodology).

Transmission in Europe

- The average EF used for Europe is compared to the German EF. The lowest is assumed to be reached by 2030 and the median European EF is reached by 2040.

Hydrogen production and CO_2 capture

- No more coal in the German electricity production mix. The second lowest electricity intensity provided by the GHG Delegated Act is used (France): the lowest intensity is observed in Sweden which does not apply to Germany due to the high share of hydro in the electricity production mix.
- Same capture rates as in the current scenario

CCS

- Conditioning before transport – No more coal in the German electricity production mix. The second lowest electricity intensity provided by the GHG Delegated Act is used (France): the lowest intensity is observed in Sweden which does not apply to Germany due to the high share of hydro in the electricity production mix.
- Transport – bioCCS on the ship and bioLNG
- Storage and injection – already very little emissions – same as current scenario

Information used	Source and link
OGCI targets	Learn about Reducing methane emissions - OGCI
IEA abatement potential	Methane Tracker – Data Tools – IEA, data for 2021
Emission factor for the production of electricity based on the production mix in Germany and France	GHG Delegated Act, Table A: Delegated regulation - 2023/1185 - EN - EUR-Lex (europa.eu)
Mitigation potential for energy use and CO2 venting	Carbon Limits for CATF/CAELP done for US
LNG liquefaction	Roman-White et al. (2021) / Feltspesifikke utslippsrapporter for 2021 - Offshore Norge

Case 3

Blue H_2 is produced in Norway (with domestic gas produced), with CO_2 stored in Norway and H_2 transported by offshore pipeline to Germany.

1. Norway – CH_4 emissions

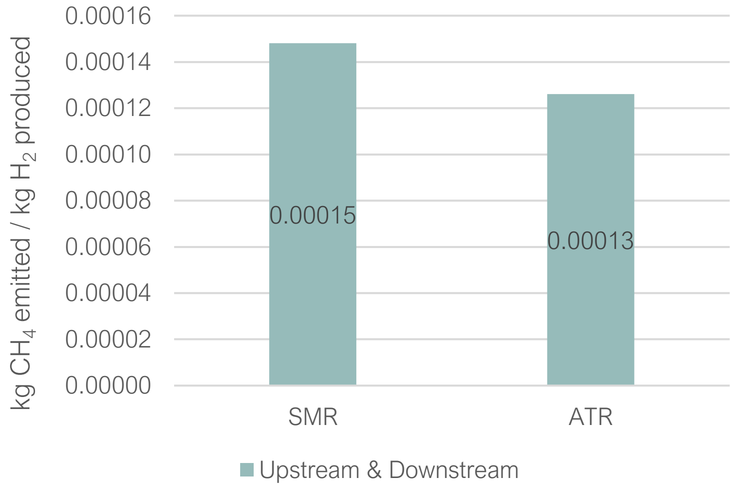
Gas producer

Source selection*

Priority II - Recent tier 2 or tier 3 reported emissions data by the country (e.g., NIR, UNFCCC)

See methodology slides in Annex

CH_4 emissions along the gas value chain



Unit: kg CH_4/kg H_2	SMR	ATR
Upstream & Downstream	1.5E-4	1.3E-4

The unit of EF is per kg of blue hydrogen produced either by Steam Methane Reforming (SMR) or Auto-Thermal Reforming (ATR)

Upstream and transmission EF

- The inventory from the Norwegian Petroleum Directorate (NPD) has been chosen as the main source as they follow a transparent and country-specific methodology based on a source-by-source assessment.

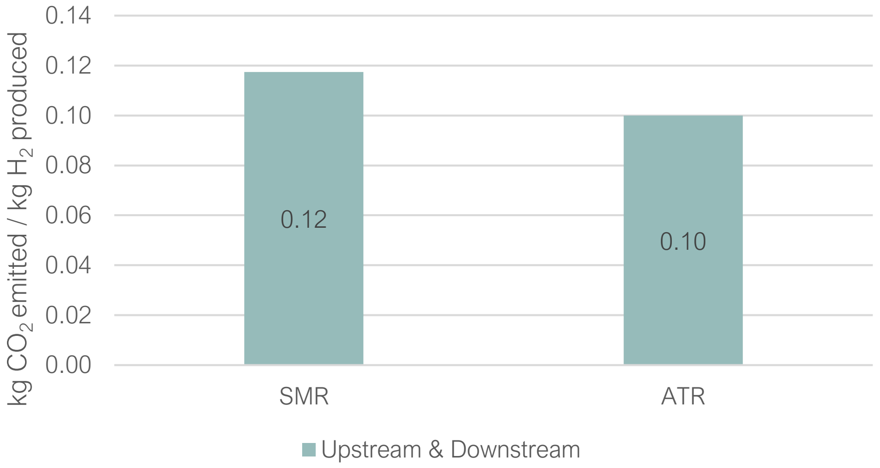
- Emissions from gas production include “fugitive emissions and cold venting” and “combustion”. Emissions attributable to the oil production include “Loading” and “Storage”.
- CH_4 from Associated Gas (APG) was estimated as a share of the oil production emission using the relative energy content of the associated gas. For the calculation, we use oil and gas production by facility, assuming that when oil production was negligible gas production was only non-associated gas.

Information used	Source and link
Volume of oil and gas produced	Energy Institute 2023 - data for 2021
Upstream emissions, Transmission emissions	Sources considered: UNFCCC 2021 (2022, data for 2021), IEA Methane Tracker (2022, data for 2021) , Norsk Olje og Gass (2022, data for 2021) / Source-by-source methodology Chosen source: Norsk Olje og Gass (2022, data for 2021) / Source-by-source methodology
Volume of APG produced in the country	Norwegian Petroleum, data for 2021

1. Norway – CO_2 emissions

Gas producer

CO_2 emissions along the gas value chain



Unit: kg CH_4/kg H_2	SMR	ATR
Upstream & Downstream	0.12	0.10

The unit of EF is per kg of blue hydrogen produced either by Steam Methane Reforming(SMR) or Auto-Thermal Reforming (ATR)

Source selection*

Flaring	Energy use	CO_2 venting (e.g., AGR)

Priority I
Recent tier 2 or tier 3 reported emissions data by the country

Upstream and transmission EF

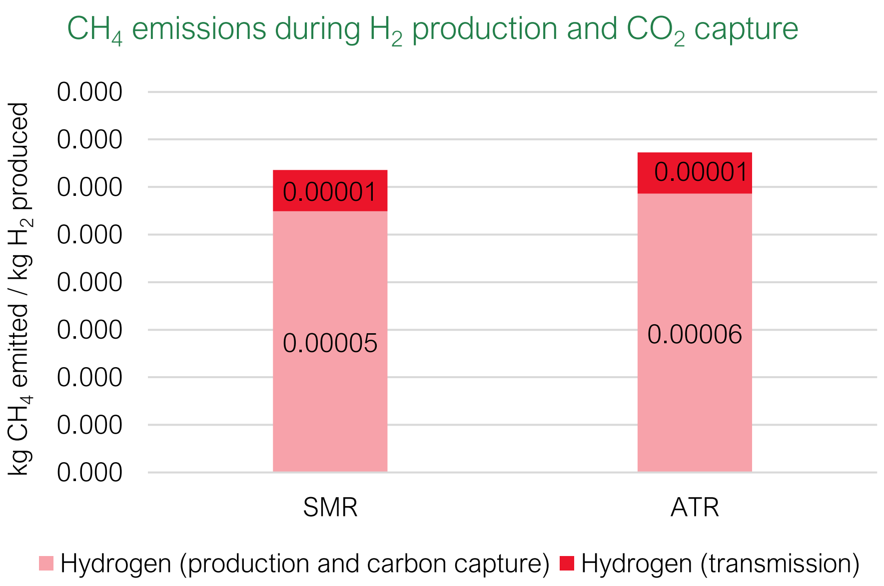
- The inventory from the Norwegian Petroleum Directorate (NPD) has been chosen as the main sources as they follow a transparent and country specific methodology based on a source-by-source assessment.
- Emissions are split between oil and gas using the gas-to-oil energy ratio.

Information used	Source and link
Volume of oil and gas produced	Energy Institute 2023 - data for 2021
Upstream emissions, Transmission emissions	Sources considered: UNFCCC 2021 (2022, data for 2021), Norsk Olje og Gass (2022, data for 2021) / Source-by-source methodology Chosen source: Norsk Olje og Gass (2022, data for 2021) / Source-by-source methodology

**See methodology slides in Annex*

2. Norway – CH_4 emissions

Hydrogen production



Unit: kg CH_4/kg H_2	SMR	ATR
Hydrogen production and carbon capture	5.5E-5	5.9E-5
Hydrogen transmission	8.7E-6	8.7E-6
Total	**6.4E-5**	**6.7E-5**

The unit of EF is per kg of blue hydrogen produced either by Steam Methane Reforming (SMR) or Auto-Thermal Reforming (ATR)

Direct emissions (hydrogen production + CO_2 capture)

- Given the limited data available for SMR and ATR with CCS, the EcoInvent emission factor for SMR without CCS is extrapolated.

Electricity consumption

- Electricity consumption provided by Deloitte's HyPE model assumptions for both SMR with CCS and ATR with CCS.
- The electricity intensity of generated electricity in Norway from EcoInvent is used.

Conditioning of hydrogen for transportation (compression)

- Kanz O. et al, 2023 provide the consumption of electricity to compress hydrogen for pipeline transport. We assume it applies to the transport between Norway and Germany, assuming a 100-km-length offshore pipeline. EcoInvent is used to estimate the electricity intensity based on the Norwegian production mix.

Transport of hydrogen by pipeline

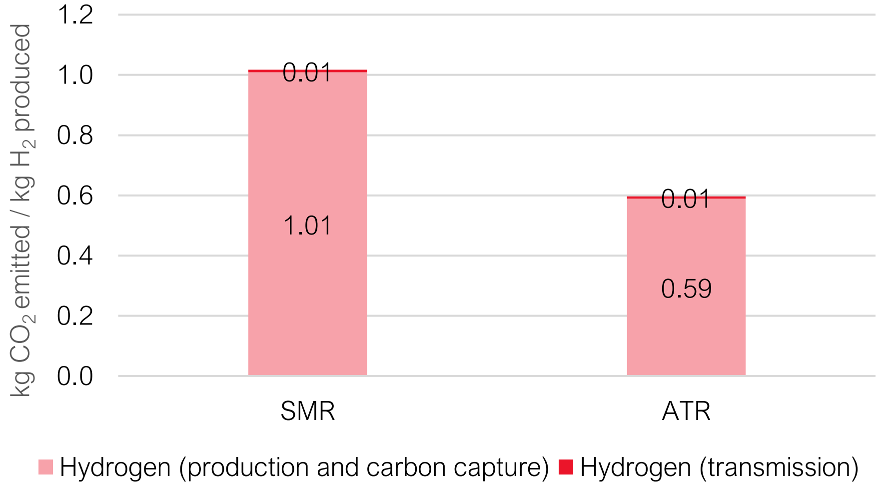
- Zero emissions assumed during the transport by pipeline.

Information used	Source and link
CO_2 emissions during hydrogen production with CCS, Electricity consumption	Deloitte's HyPE model assumptions
CH_4/CO_2 split, Electricity intensity of the Norwegian production mix	EcoInvent database
Energy use for the compression of hydrogen	Kanz O. et al, 2023 : Life-cycle global warming impact of hydrogen transport through pipelines from Africa to Germany (rsc.org)

2. Norway – CO_2 emissions

Hydrogen production

CO_2 emissions along H_2 production and CO_2 capture



Unit: kg CH_4/kg H_2	SMR	ATR
Hydrogen production and carbon capture	1.01	0.59
Hydrogen transmission	0.01	0.01
Total	**1.02**	**0.60**

The unit of EF is per kg of blue hydrogen produced either by Steam Methane Reforming (SMR) or Auto-Thermal Reforming (ATR)

Direct emissions (hydrogen production + CO_2 capture)
- Direct CO_2 emissions provided by Deloitte's HyPE model assumptions for both SMR with CCS and ATR with CCS
- 90% capture rate for SMR and 95% capture rate for ATR

Electricity consumption
- Electricity consumption provided by Deloitte's HyPE model assumptions for both SMR with CCS and ATR with CCS.
- The electricity intensity of generated electricity in Norway from EcoInvent is used.

Conditioning of hydrogen for transportation (compression)
- Kanz O. et al, 2023 provide the consumption of electricity to compress hydrogen for pipeline transport. We assume it applies to the transport between Norway and Germany, assuming a 100-km-length offshore pipeline. EcoInvent is used to estimate the electricity intensity based on the Norwegian production mix.

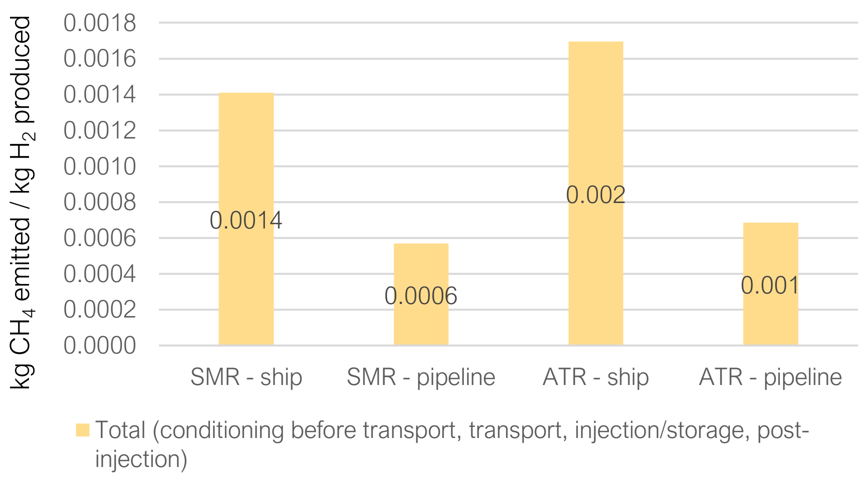
Transport of hydrogen by pipeline
- Zero emissions assumed during the transport by pipeline.

Information used	Source and link
CO_2 emissions during hydrogen production with CCS, Electricity consumption	Deloitte's HyPE model assumptions
Total emissions during hydrogen production with CCS	Oni et al, 2022: Comparative assessment of blue hydrogen from steam methane reforming, autothermal reforming, and natural gas decomposition technologies for natural gas-producing regions - ScienceDirect
CH_4/CO_2 split, Electricity intensity of the Norwegian production mix	EcoInvent database
Energy use for the compression of hydrogen	Kanz O. et al, 2023 : Life-cycle global warming impact of hydrogen transport through pipelines from Africa to Germany (rsc.org)

3. Germany / Norway – CH_4 emissions

CCS – CO_2 conditioning, transport and storage

CH_4 emissions along the CCS value chain



Unit: kg CH_4/kg H_2	SMR - ship	SMR - pipeline	ATR – ship	ATR - pipeline
Total	0.0014	0.0006	0.0017	0.0007

The unit of EF is per kt of blue hydrogen produced either by Steam Methane Reforming (SMR) or Auto-Thermal Reforming (ATR)

Conditioning of CO_2 before transport (liquefaction, compression)

- The electricity intensity for Germany from the GHG Delegated Act (gCO_{2eq} /MJ) is used and EcoInvent is used to split the total intensity between methane and carbon dioxide.
- Jackson et al, 2018 provide the energy consumption for compression (pipeline), and Jackson et al, 2019 for liquefaction (ship, truck)

Transport of CO_2

- Ship - Northern Light carbon footprint is used to estimate CO_{2eq} and the EcoInvent database is used to split the emissions between methane and carbon dioxide.
- Pipeline - Zero emissions assumed for the transport by pipeline

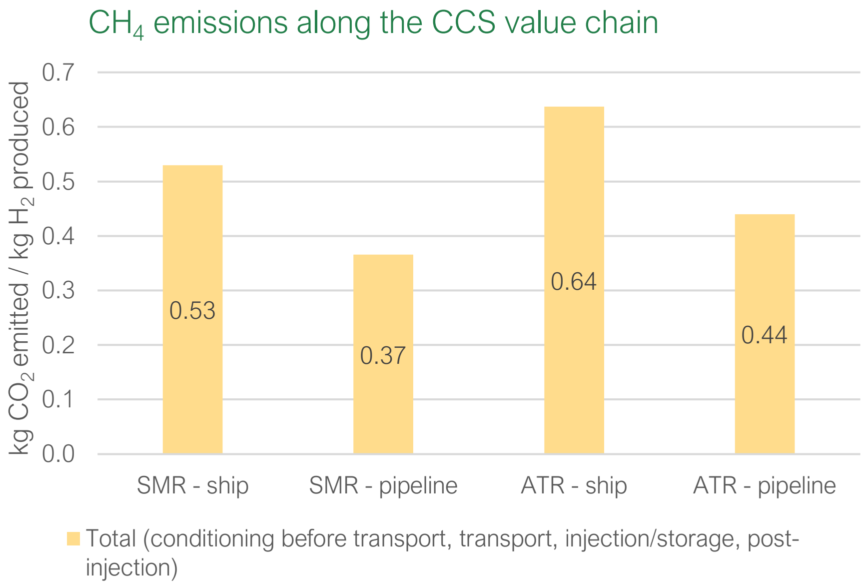
Storage/Injection and post-injection

- Northern Light carbon footprint is used to estimate CO_{2eq} and the EcoInvent database is used to split the emissions between methane and carbon dioxide.

Information used	Source and link
Emission factor for the production of electricity based on the production mix in Germany	GHG Delegated Act, Table A: Delegated regulation - 2023/1185 - EN - EUR-Lex (europa.eu)
CH_4/CO_2 split	EcoInvent database
Energy consumption of compression	Jackson et al, 2018
Energy consumption of liquefaction	Jackson et al., 2019
Emission from transportation by ship, storage, injection and post-injection	Northern Light: Report-Carbon-footprint-of-the-Northern-Lights-JV-co2-transport-and-storage-value-chain.pdf (norlights.com)

3. Germany / Norway – CO_2 emissions

CCS – CO_2 conditioning, transport and storage



Unit: kg CH_4/kg H_2	SMR - ship	SMR - pipeline	ATR – ship	ATR - pipeline
Total	0.53	0.37	0.64	0.44

The unit of EF is per kg of blue hydrogen produced either by Steam Methane Reforming (SMR) or Auto-Thermal Reforming (ATR)

Conditioning of CO_2 before transport (liquefaction, compression)

- The electricity intensity for Germany from the GHG Delegated Act (gCO_{2eq} /MJ) is used and EcoInvent is used to split the total intensity between methane and carbon dioxide.
- Jackson et al, 2018 provide the energy consumption for compression (pipeline), and Jackson et al, 2019 for liquefaction (ship, truck)

Transport of CO_2

- Ship - Northern Light carbon footprint is used to estimate CO_{2eq} and the EcoInvent database is used to split the emissions between methane and carbon dioxide.
- Pipeline - Zero emissions assumed for the transport by pipeline

Storage/Injection and post-injection

- Northern Light carbon footprint is used to estimate CO_{2eq} and the EcoInvent database is used to split the emissions between methane and carbon dioxide.

Information used	Source and link
Emission factor for the production of electricity based on the production mix in Germany	GHG Delegated Act, Table A: Delegated regulation - 2023/1185 - EN - EUR-Lex (europa.eu)
CH_4/CO_2 split	EcoInvent database
Energy consumption of compression	Jackson et al, 2018
Energy consumption of liquefaction	Jackson et al., 2019
Emission from transportation by ship, storage, injection and post-injection	Northern Light: Report-Carbon-footprint-of-the-Northern-Lights-JV-co2-transport-and-storage-value-chain.pdf (norlights.com)

Estimating CH_4 emissions in the BAT scenario

- For estimating the emissions from the BAT scenario, EF from the current scenario is used as the baseline, followed by applying some emission reduction trajectories along the different parts to the value chain.
- The solutions applied are country specific – all solutions are based on existing abatement potentials, and employ realistic assumptions on the year of implementation.

Natural gas production and transmission in Norway

- The OGCI target is higher than the current methane intensity in Norway. Same as the current scenario.

Hydrogen production and CO_2 capture

- Same as the current scenario

CCS

- Conditioning before transport – No more coal in the German electricity production mix. The second lowest electricity intensity provided by the GHG Delegated Act is used (France): the lowest intensity is observed in Sweden which does not apply to Germany due to the high share of hydro in the electricity production mix.
- Transport –bioLNG use + bioCCS on the ship
- Storage and injection – already very little emissions – same as current scenario

Information used	Source and link
OGCI targets	Learn about Reducing methane emissions - OGCI
Emission factor for the production of electricity based on the production mix in Germany and France	GHG Delegated Act, Table A: Delegated regulation - 2023/1185 - EN - EUR-Lex (europa.eu)

Estimating CO_2 emissions in the BAT scenario

- For estimating the emissions from the BAT scenario, EF from the current scenario is used as the baseline, followed by applying some emission reduction trajectories along the different parts to the value chain.
- The solutions applied are country specific – all solutions are based on existing abatement potentials, and employ realistic assumptions on the year of implementation.

Natural gas production and transmission in Norway

- Assumed that the best practices for flaring are already implemented and that the best available technologies are already implemented. Same as the current scenario.

Hydrogen production and CO_2 capture

- Same as current scenario

CCS

- Conditioning before transport – No more coal in the German electricity production mix. The second lowest electricity intensity provided by the GHG Delegated Act is used (France): the lowest intensity is observed in Sweden which does not apply to Germany due to the high share of hydro in the electricity production mix.
- Transport – bioCCS on the ship and bioLNG
- Storage and injection – already very little emissions – same as current scenario

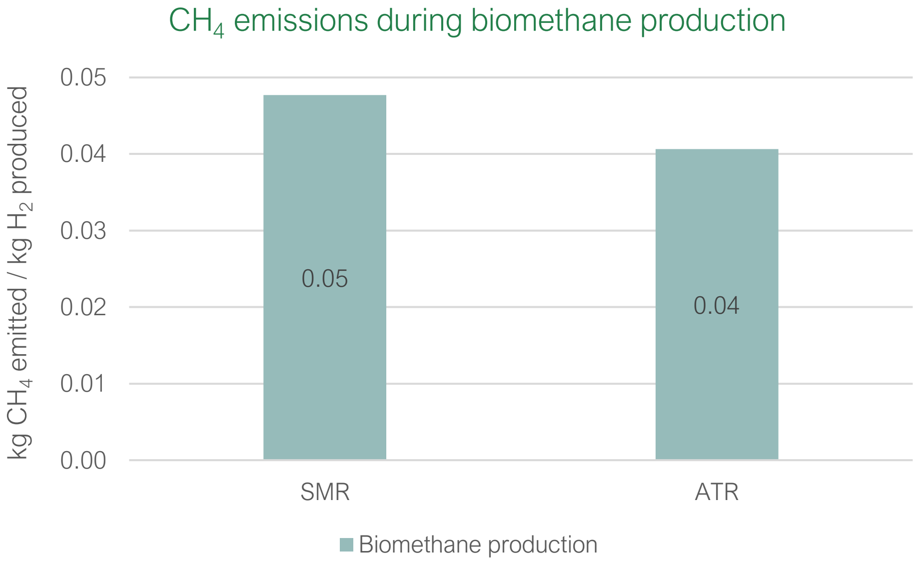
Information used	Source and link
OGCI targets	Learn about Reducing methane emissions - OGCI
Emission factor for the production of electricity based on the production mix in Germany and France	GHG Delegated Act, Table A: Delegated regulation - 2023/1185 - EN - EUR-Lex (europa.eu)

Case 4

Biogas-based H_2 production in Germany, with CO_2 transported to Norway for storage.

1. Germany – CH_4 emissions

Biomethane production



Unit: kg CH_4/kg H_2	SMR	ATR
Total	0.05	0.04

The unit of EF is per kt of blue hydrogen produced either by Steam Methane Reforming SMR) or Auto-Thermal Reforming (ATR)

General assumptions

- Based on the FNR report, it was assumed that the two main feedstocks to produce biomethane in Germany are maize (50%) and cattle slurry (50%).
- Emissions related to the production of biomethane (from the transport of raw materials to the upgrading) are compared to a reference scenario in which we only consider emissions related to the storage of manure (for more than 7 days) (only methane emissions).

Transport of raw materials

- The raw materials were assumed to be transported over 25 km between the farm and the biogas plant with an EURO6 20-ton truck.
- Based on the FNR report, 5% of fuels consumed in the transport sector in 2018 were biofuels. It was assumed that it is still the case in 2021 and emissions related to the consumption of biofuels are not considered.
- Emissions from EcoInvent were used.

Pre-storage

- No emissions related to the storage of maize.
- Based on DBFZ (2021), emissions related to the storage of manure before utilization for biogas production are estimated for manure stored for less than 7 days.
- Rösemann et al., 2019 paper on emissions from German agriculture between 1990 and 2019 is used to estimate non-fossil methane emissions.

Anaerobic digestion

- No fossil emissions – assuming that anaerobic digestion plants directly use their biogas/biomethane, no fossil fuels
- Many sources agree on 1% methane leakage from the digestor; hence, this methane intensity is used.

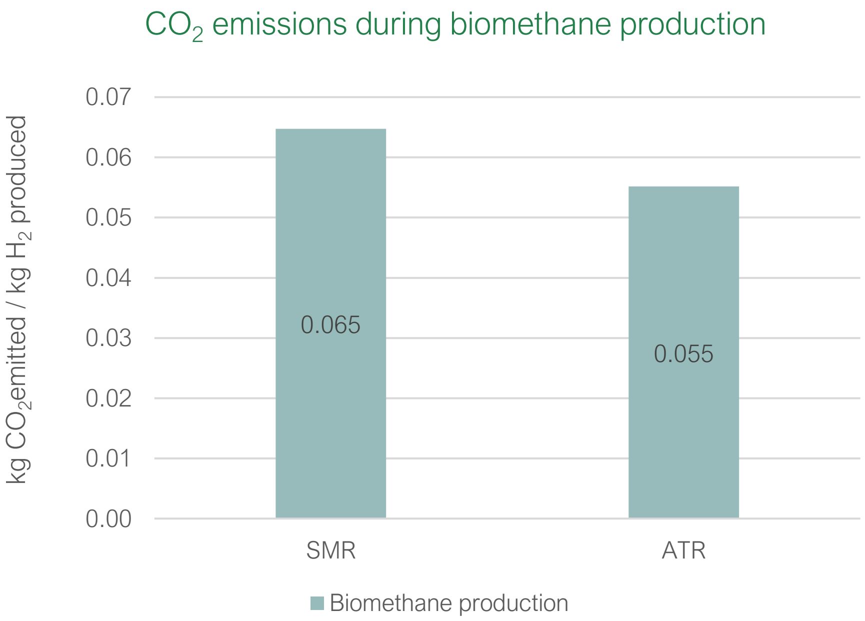
Upgrading

- No fossil emissions – assuming that anaerobic digestion plants directly use their biogas/biomethane, no fossil fuels.
- Based on the FNR report and emission data available in academic papers, amino washing, and swing adsorption are the two main upgrading processes considered. The FNR report is used to estimate non-fossil methane emissions using a weighted average of the two main upgrading processes considered.

Information used	Source and link
Reference scenario – storage of manure	pdf (europa.eu)
Fuel consumption in the transport sector, Feedstock to produce biomethane, Biogas yield per feedstock and its methane content	FNR - Bioenergy in Germany Facts and Figures 2020 (fnr.de), data for 2018
Methane loss during upgrading	Sources considered: LCA-gas-EU-white-paper-A4-v5.pdf (theicct.org). Chosen source: FNR - Bioenergy in Germany Facts and Figures 2020 (fnr.de)
Methane emission factor for a freight transport in Europe, Emission factor of biogas purification to biomethane by swing adsorption or amino washing	EcoInvent
Storage period of manure before utilization for biogas production in Germany	DBFZ (2021) - Schumacher_2021.pdf (dbfz.de)
MCF value of 0.017 m3/m3, B0 in pre-storage emissions	Rösemann et al., 2019 - https://literatur.thuenen.de/digbib_extern/dn063510.pdf
Methane leakage from digestor (1%)	“KTBL (2016), BACHMAIER and GRONAUER (2007), BÖRJESSON and BERGLUND (2007), GÄRTNER et al. (2008) and ROTH et al. (2011). In 2016 the Federal Environment Agency pulished a study that, too, is based on a leakage rate of 1 % (UBA, 2016a).” - Rösemann et al., 2019 - https://literatur.thuenen.de/digbib_extern/dn063510.pdf Zhou Y. et al, 2021 - LCA-gas-EU-white-paper-A4-v5.pdf (theicct.org)

1. Germany – CO_2 emissions

Biomethane production



Unit: kg CH_4/kg H_2	SMR	ATR
Total	0.065	0.055

The unit of EF is per kt of blue hydrogen produced either by Steam Methane Reforming (SMR) or Auto-Thermal Reforming (ATR)

General assumptions

- Based on FNR report, it was assumed that the two main feedstocks to produce biomethane in Germany are maize (50%) and cattle slurry (50%).
- Emissions related to the production of biomethane (from the transport of raw materials to the upgrading) are compared to a reference scenario in which we only consider emissions related to the storage of manure (for more than 7 days) (only methane emissions).

Transport of raw materials

- The raw materials were assumed to be transported over 25 km between the farm and the biogas plant with an EURO6 20-ton truck.
- Based on the FNR report, 5% of fuels consumed in the transport sector in 2018 were biofuels. It was assumed that it is still the case in 2021 and emissions related to the consumption of biofuels are not considered.
- Emissions from EcoInvent were used.

Pre-storage

- No CO_2 emissions

Anaerobic digestion

- No fossil emissions – assuming that anaerobic digestion plants directly use their biogas/biomethane, no fossil fuels
- Non-fossil CO_2 emissions (from biogas leakages from agricultural feedstocks) are not included – "CO_2 emissions from livestock are not estimated because annual net CO_2 emissions are assumed to be zero – the CO_2 photosynthesized by plants is returned to the atmosphere as respired CO_2. A portion of the C is returned as CH_4 and for this reason, CH_4 requires separate consideration." (IPCC 2006)

Upgrading

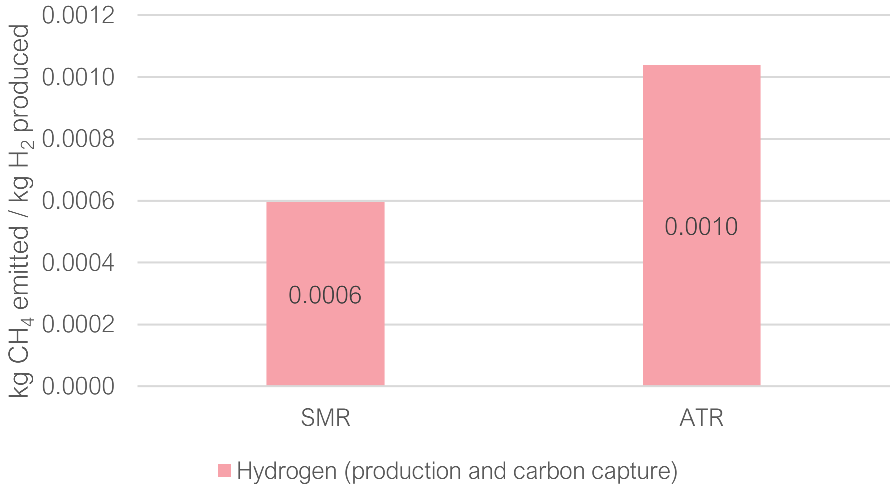
- Fossil CO_2 emissions – no emission considered, assuming that anaerobic digestion plants directly use their biogas/biomethane, no fossil fuels
- Non-fossil CO_2 emissions (from biogas leakages from agricultural feedstocks) are not included – "CO_2 emissions from livestock are not estimated because annual net CO_2 emissions are assumed to be zero – the CO_2 photosynthesized by plants is returned to the atmosphere as respired CO_2. A portion of the C is returned as CH_4 and for this reason, CH_4 requires separate consideration." (IPCC 2006)

Information used	Source and link
Reference scenario – storage of manure	pdf (europa.eu)
Carbon dioxide emission factor for a freight transport in Europe	EcoInvent
Non-fossil CO_2 emissions	IPCC 2006 – Volume 4, Chapter 10 - CHAPTER 1 (iges.or.jp)

2. Germany – CH_4 emissions

Hydrogen production

CH_4 emissions during H_2 production and CO_2 capture



Unit: kg CH_4/kg H_2	SMR	ATR
Total	0.0006	0.0010

The unit of EF is per kt of blue hydrogen produced either by Steam Methane Reforming(SMR) or Auto-Thermal Reforming (ATR)

Direct emissions (hydrogen production + CO_2 capture)

- Given the limited data available for SMR and ATR with CCS, the EcoInvent emission factor for SMR without CCS is extrapolated.

Electricity consumption

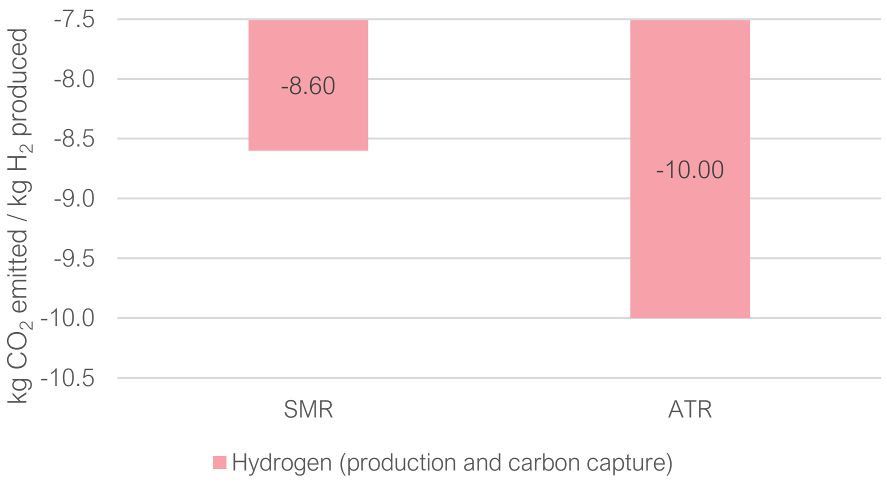
- Electricity consumption provided by Deloitte's HyPE model assumptions for both SMR with CCS and ATR with CCS.
- The GHG Delegated Act is used for the electricity intensity of generated electricity in Germany. EcoInvent is used to split the intensity between methane and carbon dioxide.

Information used	Source and link
CO_2 emissions during hydrogen production with CCS, Electricity consumption	Deloitte's HyPE model assumptions
Emission factor for the production of electricity based on the production mix in Germany	GHG Delegated Act, Table A: Delegated regulation - 2023/1185 - EN - EUR-Lex (europa.eu)
CH_4/CO_2 split, Electricity intensity of the Norwegian production mix, Methane emissions during hydrogen production with SMR without CCS	EcoInvent database
Energy use for the compression of hydrogen	Kanz O. et al, 2023 : Life-cycle global warming impact of hydrogen transport through pipelines from Africa to Germany (rsc.org)

2. Germany – CO_2 emissions

Hydrogen production

CO_2 emissions during H_2 production and CO_2 capture



Unit: kg CH_4/kg H_2	SMR	ATR
Total	-8.60	-10.00

The unit of EF is per kg of blue hydrogen produced either by Steam Methane Reforming (SMR) or Auto-Thermal Reforming (ATR)

Direct emissions (hydrogen production + CO_2 capture)

- Direct CO_2 emissions provided by Deloitte's HyPE model assumptions for both SMR with CCS and ATR with CCS
- 90% capture rate for SMR and 95% capture rate for ATR

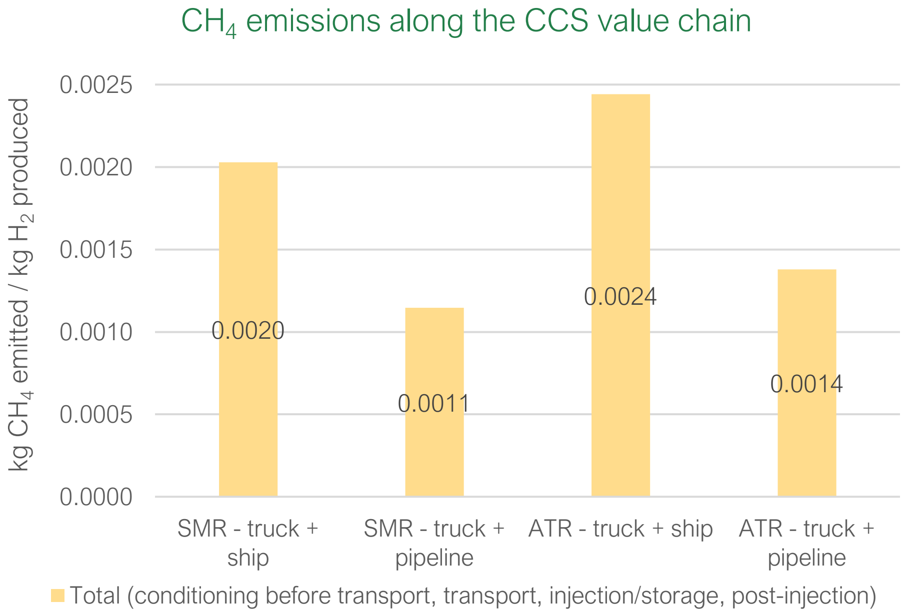
Electricity consumption

- Electricity consumption provided by Deloitte's HyPE model assumptions for both SMR with CCS and ATR with CCS.
- The GHG Delegated Act is used for the electricity intensity of generated electricity in Germany. EcoInvent is used to split the intensity between methane and carbon dioxide.

Information used	Source and link
CO_2 emissions during hydrogen production with CCS, Electricity consumption	Deloitte's HyPE model assumptions
Emission factor for the production of electricity based on the production mix in Germany	GHG Delegated Act, Table A: Delegated regulation - 2023/1185 - EN - EUR-Lex (europa.eu)
CH_4/CO_2 split, Electricity intensity of the Norwegian production mix	EcoInvent database
Energy use for the compression of hydrogen	Kanz O. et al, 2023 : Life-cycle global warming impact of hydrogen transport through pipelines from Africa to Germany (rsc.org)

3. Germany / Norway – CH_4 emissions

CCS – CO_2 conditioning, transport and storage



Unit: kg CH_4/kg H_2	SMR - ship	SMR - pipeline	ATR – ship	ATR - pipeline
Total	2E-3	1.1E-3	2.4E-3	1.4E-3

The unit of EF is per kg of blue hydrogen produced either by Steam Methane Reforming (SMR) or Auto-Thermal Reforming (ATR)

Conditioning of CO_2 before transport (liquefaction, compression)

- The electricity intensity for Germany from the GHG Delegated Act (gCO_{2eq}/MJ) is used and EcoInvent is used to split the total intensity between methane and carbon dioxide.
- Jackson et al, 2018 provide the energy consumption for compression (pipeline), and Jackson et al, 2019 for liquefaction (ship, truck)

Transport of CO_2

- Truck – Based on the FNR report, 5% of fuels consumed in the transport sector in 2018 were biofuels. It was assumed that it is still the case in 2021 and emissions related to the consumption of biofuels are not considered. Emissions from EcoInvent were used.
- Ship - Northern Light carbon footprint is used to estimate CO_{2eq} and the EcoInvent database is used to split the emissions between methane and carbon dioxide.
- Pipeline - Zero emissions assumed for the transport by pipeline

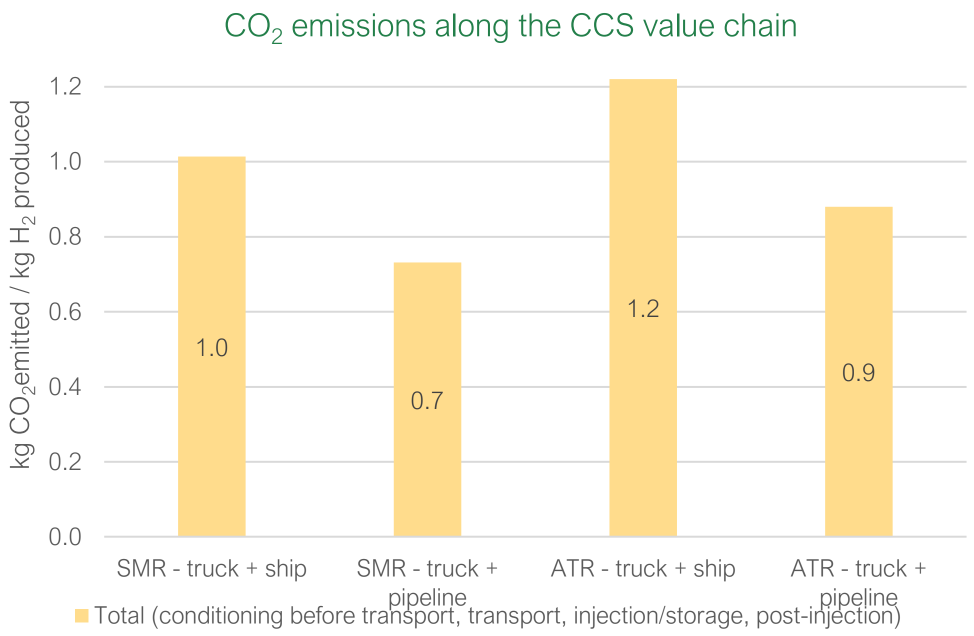
Storage/Injection and post-injection

- Northern Light carbon footprint is used to estimate CO_{2eq} and the EcoInvent database is used to split the emissions between methane and carbon dioxide.

Information used	Source and link
Emission factor for the production of electricity based on the production mix in Germany	GHG Delegated Act, Table A: Delegated regulation - 2023/1185 - EN - EUR-Lex (europa.eu)
CH_4/CO_2 split, Truck emissions	EcoInvent database
Fuel consumption in the transport sector	FNR - Bioenergy in Germany Facts and Figures 2020 (fnr.de), data for 2018
Energy consumption of compression	Jackson et al, 2018
Energy consumption of liquefaction	Jackson et al., 2019
Emission from transportation by ship, storage, injection and post-injection	Northern Light: Report-Carbon-footprint-of-the-Northern-Lights-JV-co2-transport-and-storage-value-chain.pdf (norlights.com)

3. Germany / Norway – CO_2 emissions

CCS – CO_2 conditioning, transport and storage



Unit: kg CH_4/kg H_2	SMR - ship	SMR - pipeline	ATR – ship	ATR - pipeline
Total	1.0	0.7	1.2	0.9

The unit of EF is per kg of blue hydrogen produced either by Steam Methane Reforming (SMR) or Auto-Thermal Reforming (ATR)

Conditioning of CO_2 before transport (liquefaction, compression)

- The electricity intensity for Germany from the GHG Delegated Act (gCO_{2eq}/MJ) is used and EcoInvent is used to split the total intensity between methane and carbon dioxide.
- Jackson et al, 2018 provide the energy consumption for compression (pipeline), and Jackson et al, 2019 for liquefaction (ship, truck)

Transport of CO_2

- Truck – Based on the FNR report, 5% of fuels consumed in the transport sector in 2018 were biofuels. It was assumed that it is still the case in 2021 and emissions related to the consumption of biofuels are not considered. Emissions from EcoInvent were used.
- Ship - Northern Light carbon footprint is used to estimate CO_{2eq} and the EcoInvent database is used to split the emissions between methane and carbon dioxide.
- Pipeline - Zero emissions assumed for the transport by pipeline

Storage/Injection and post-injection

- Northern Light carbon footprint is used to estimate CO_{2eq} and the EcoInvent database is used to split the emissions between methane and carbon dioxide.

Information used	Source and link
Emission factor for the production of electricity based on the production mix in Germany	GHG Delegated Act, Table A: Delegated regulation - 2023/1185 - EN - EUR-Lex (europa.eu)
CH_4/CO_2 split, Truck emissions	EcoInvent database
Fuel consumption in the transport sector	FNR - Bioenergy in Germany Facts and Figures 2020 (fnr.de), data for 2018
Energy consumption of compression	Jackson et al, 2018
Energy consumption of liquefaction	Jackson et al., 2019
Emission from transportation by ship, storage, injection and post-injection	Northern Light: Report-Carbon-footprint-of-the-Northern-Lights-JV-co2-transport-and-storage-value-chain.pdf (norlights.com)

Estimating CH_4 emissions in the BAT scenario

- For estimating the emissions from the BAT scenario, EF from the current scenario is used as the baseline, followed by applying some emission reduction trajectories along the different parts to the value chain.
- The solutions applied are country specific – all solutions are based on existing abatement potentials, and employ realistic assumptions on the year of implementation.

Biogas production

- The reference scenario is still the same.
- Transport of raw materials – GHG reduction based on CO_2 emission standards for trucks.
- Pre-storage – the manure stored is covered and the gas is captured with a 90% capture rate.
- Anaerobic digestion and upgrading – the lowest value in the literature is assumed to be reached by 2040.

Hydrogen production and CO_2 capture

- No more coal in the German electricity production mix. The second lowest electricity intensity provided by the GHG Delegated Act is used (France): the lowest intensity is observed in Sweden which does not apply to Germany due to the high share of hydro in the electricity production mix.
- Same capture rates as in the current scenario

CCS

- Conditioning before transport – No more coal in the German electricity production mix. The second lowest electricity intensity provided by the GHG Delegated Act is used (France): the lowest intensity is observed in Sweden which does not apply to Germany due to the high share of hydro in the electricity production mix.
- Transport by ship – bioLNG use + bioCCS on the ship
- Transport by truck - GHG reduction based on CO_2 emission standards for trucks
- Storage and injection – already very little emissions – same as current scenario

Information used	Source and link
CO_2 emission standards for trucks	Heavy-duty vehicles: Council and Parliament reach a deal to lower CO2 emissions from trucks, buses and trailers - Consilium (europa.eu)
Fuel consumption in the transport sector	FNR - Bioenergy in Germany Facts and Figures 2020 (fnr.de), data for 2018
Emission factor for the production of electricity based on the production mix in Germany and France	GHG Delegated Act, Table A: Delegated regulation - 2023/1185 - EN - EUR-Lex (europa.eu)
Anaerobic digestion	Source considered: Lantz, EcoInvent Chosen source: Lantz, M. (2017). Hållbarhetskriterier för biogas: En översyn av data och metoder. Miljö- och energisystem, LTH, Lunds universitet. Uppsatsmall (lu.se)
Upgrading	Sources considered: Lantz 2017 and LCA-gas-EU-white-paper-A4-v5.pdf (theicct.org) and EcoInvent Chosen source: Lantz, M. (2017). Hållbarhetskriterier för biogas: En översyn av data och metoder. Miljö- och energisystem, LTH, Lunds universitet. Uppsatsmall (lu.se)

Estimating CO_2 emissions in the BAT scenario

- For estimating the emissions from the BAT scenario, EF from the current scenario is used as the baseline, followed by applying some emission reduction trajectories along the different parts to the value chain.
- The solutions applied are country specific – all solutions are based on existing abatement potentials, and employ realistic assumptions on the year of implementation.

Biogas production

- The reference scenario is still the same.
- Transport of raw materials – GHG reduction based on CO_2 emission standards for trucks
- Pre-storage – still no emissions
- Anaerobic digestion and upgrading – non-fossil CO_2 emissions are not included in the current scenario. It was assumed that in the BAT scenario, these emissions were captured with a 90% capture rate by 2050 and used (e.g., in greenhouses near the biogas plant) which led to negative emissions compared to the reference scenario in which no CO_2 emissions were released.

Hydrogen production and CO_2 capture

- No more coal in the German electricity production mix. The second lowest electricity intensity provided by the GHG Delegated Act is used (France): the lowest intensity is observed in Sweden which does not apply to Germany due to the high share of hydro in the electricity production mix.
- Same capture rates as in the current scenario

CCS

- Conditioning before transport – No more coal in the German electricity production mix. The second lowest electricity intensity provided by the GHG Delegated Act is used (France): the lowest intensity is observed in Sweden which does not apply to Germany due to the high share of hydro in the electricity production mix.
- Transport by ship – bioCCS on the ship and bioLNG
- Transport by truck - GHG reduction based on CO_2 emission standards for trucks
- Storage and injection – already very little emissions – same as current scenario

Information used	Source and link
CO_2 emission standards for trucks	Heavy-duty vehicles: Council and Parliament reach a deal to lower CO2 emissions from trucks, buses and trailers - Consilium (europa.eu)
Fuel consumption in the transport sector	FNR - Bioenergy in Germany Facts and Figures 2020 (fnr.de), data for 2018
Emission factor for the production of electricity based on the production mix in Germany and France	GHG Delegated Act, Table A: Delegated regulation - 2023/1185 - EN - EUR-Lex (europa.eu)
Anaerobic digestion	Source considered: Lantz, EcoInvent Chosen source: Lantz, M. (2017). Hållbarhetskriterier för biogas: En översyn av data och metoder. Miljö- och energisystem, LTH, Lunds universitet. Uppsatsmall (lu.se)
Upgrading	Sources considered: Lantz 2017 and LCA-gas-EU-white-paper-A4-v5.pdf (theicct.org) and EcoInvent Chosen source: Lantz, M. (2017). Hållbarhetskriterier för biogas: En översyn av data och metoder. Miljö- och energisystem, LTH, Lunds universitet. Uppsatsmall (lu.se)

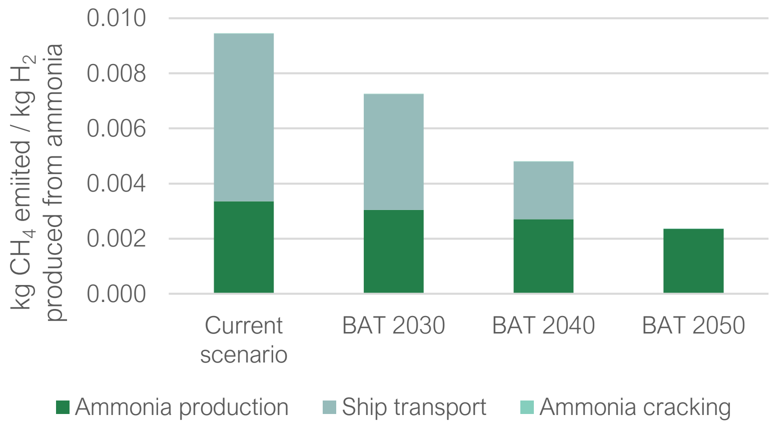
Case 5

Green hydrogen is produced in the US and exported as green ammonia by ship to Germany. Re-converted to hydrogen in Germany.

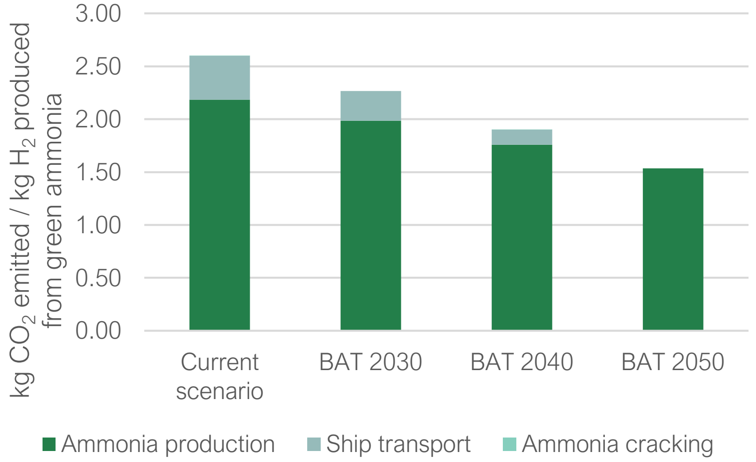
Case 5 – CH_4 and CO_2 emissions

Direct ammonia and hydrogen emissions are not considered in this analysis.

CH_4 emissions along the hydrogen value chain



CO_2 emissions along the hydrogen value chain



Green hydrogen production
- Based on the Delegated Acts of RFNBO, zero emissions are assumed.

Ammonia production in the USA
- Included: emissions from Haber Bosch production and nitrogen separation from air.
- Current scenario: EcoInvent is used for the electricity intensity generated in the US.
- BAT scenario: 0% of the electricity used is lost by heat (e.g., used to pre-heat the feed). The lowest value of electricity consumption in the literature is used.

Transport of ammonia by ship
- Transport of ammonia by ship is assumed similar to the transport of LNG by ship (boil-off rates, fuel used) in the current scenario. In the BAT scenario, biofuels are used (non-fossil CO_2 and CH_4 emissions are not accounted in this analysis) and the boil-off is captured and reliquefied.

Ammonia cracking in Germany
- Heat is produced from the imported green ammonia.
- Current scenario: the heat is produced from natural gas. The GHG Delegated Act is used for the electricity intensity of generated electricity in Germany. EcoInvent is used to split the intensity between methane and carbon dioxide.
- BAT scenario: No more coal in the German electricity production mix. The second lowest electricity intensity provided by the GHG Delegated Act is used (France): the lowest intensity is observed in Sweden which does not apply to Germany due to the high share of hydro in the electricity production mix.

Assumed that 0.18 kg H_2 produced per kg NH_3.

Information used	Source and link
Emission factor for the production of electricity based on the production mix in Germany or France	GHG Delegated Act, Table A: Delegated regulation - 2023/1185 - EN - EUR-Lex (europa.eu)
CH_4/CO_2 split, Electricity intensity of the US production mix	EcoInvent database
Production of ammonia	Sources considered: 2023.03_H2Europe_Clean_Ammonia_Report_DIGITAL_FINAL.pdf (hydrogeneurope.eu), IEAGHRassumptions_final.pdf, Blue and green ammonia production: A techno-economic and life cycle assessment perspective - ScienceDirect Chosen source: (current scenario) JRC Publications Repository - Environmental life cycle assessment (LCA) comparison of hydrogen delivery options within Europe (europa.eu) (BAT): IRENA_Global_Trade_Hydrogen_2022.pdf
Renewable energies production in the USA	EIA projects that renewable generation will supply 44% of U.S. electricity by 2050 - U.S. Energy Information Administration (EIA)
Production of hydrogen from ammonia	2023.03_H2Europe_Clean_Ammonia_Report_DIGITAL_FINAL.pdf (hydrogeneurope.eu)

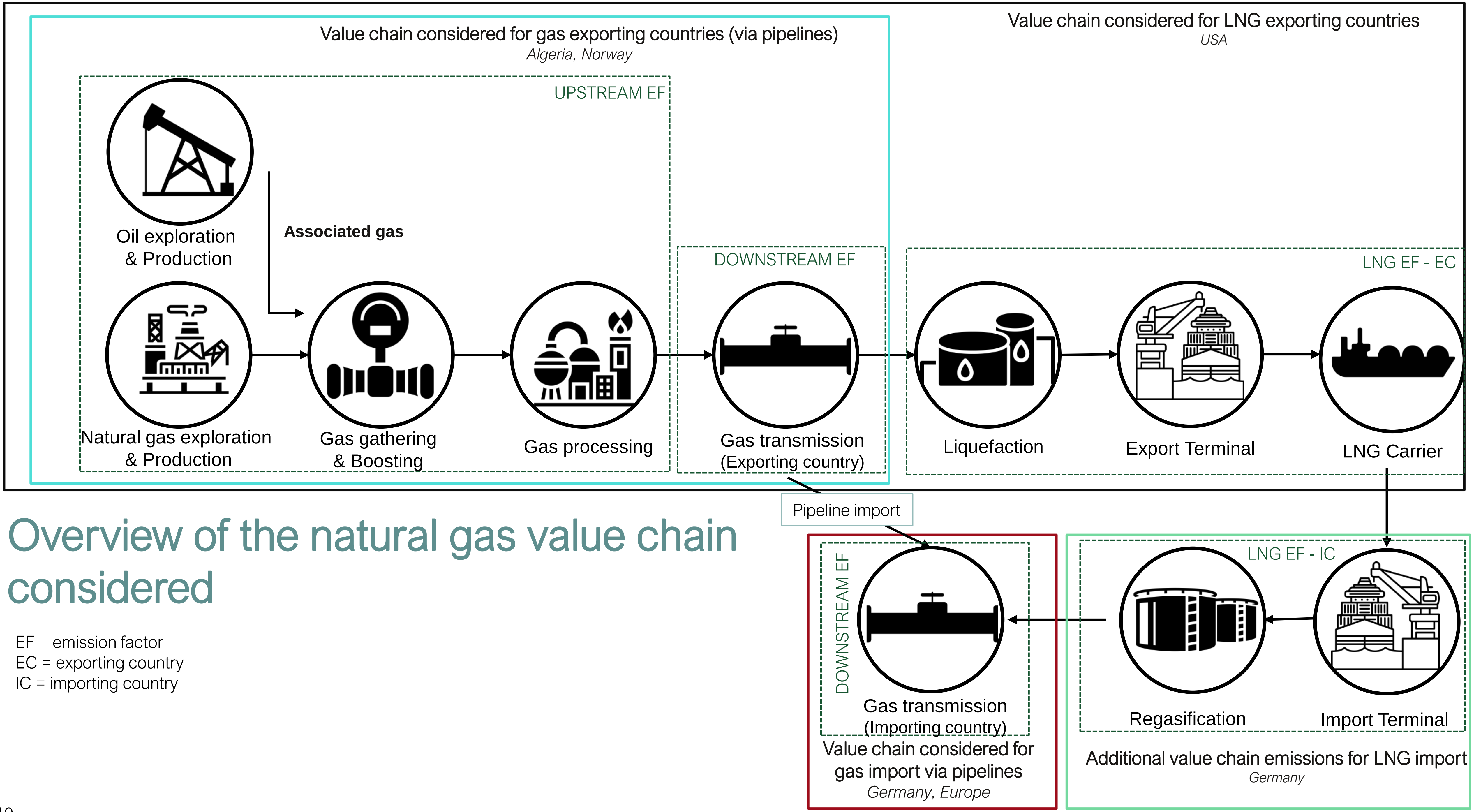
Methodology for emission factor estimations

Methodology – Current scenario

1. Gas value chain

Overview of the natural gas value chain considered

EF = emission factor
EC = exporting country
IC = importing country



A. Formula for emission factor (EF)

CARBON LIMITS

- An EF is essentially the total emissions from a particular process divided by the associated activity data. As such, emissions and activity data are estimated for calculating the EF for each step along the value chain.
- EFs for methane (CH_4) and carbon dioxide (CO_2) are estimated separately, before converting to CO_{2e}[1]

$$EF = \frac{Emissions\ from\ the\ process}{Activity\ Data\ for\ the\ process}$$

[1]GWP 100 = 28 and GWP 20 = 84 have been compared, based on the AR5 (IPCC)

B. Estimation of activity data for gas value chain

CARBON LIMITS

- Different activity data are used for estimating EF in exporting and importing countries.
- Activity data for upstream = total gas volume produced
- Activity data for downstream would be the sum of the total volume of gas imported and of the volume of gas produced in the country

Activity data description | Source of information for the activity data

For exporting countries

Calculations*
Volume of associated gas produced (bcm)
+
Volume of non-associated gas produced (bcm)
Energy Institute

Calculations*
Volume of total gas produced (bcm)

Used as activity data for EF for upstream

For importing countries

Energy Institute
Volume of total gas imported (bcm)
+
Volume of total gas produced (bcm)

Used as activity data for EF for transmission

Energy Institute – Statistical Review of World Energy: Resources and data downloads | Statistical Review of World Energy (energyinst.org)
*See next slide

B. Estimation of activity data for gas value chain

CARBON LIMITS

- Both associated gas and non-associated gas are considered in the assessment of EF.

  Total natural gas production = Non-associated gas production + Associated gas production

- Non-associated gas is natural gas produced in dedicated gas wells, with little liquid production. Associated gas is natural gas produced from oil wells.
- Associated gas can be used locally, reinjected into the well, vented, flared or exported as marketable natural gas and thus joins the natural gas value chain. Hence. methane emissions related to associated gas production must be considered.

Volume of non-associated gas produced (bcm) - V_{nonAPG}

- The volume of associated gas produced for each country is provided directly by the Energy Institute.

Volume of associated gas (APG) produced (bcm) - V_{APG}

- The following equation is used to estimate V_{APG} : $V_{APG} = V_{nonAPG} * APG_{\%} / (1 - APG_{\%})$
- $APG_{\%}$ corresponds to the APG to total gas ratio $V_{nonAPG} / (V_{APG} + V_{nonAPG})$ and is estimated by country based as follows:

Ex: USA

Priority I
$APG_{\%}$ directly provided at country level

Data on the production from different wells in Norway is used to estimate V_{APG}, assuming that facilities producing less than 5 Mm^3 of oil are gas wells and that the gas production from other wells (i.e., oil wells) is associated gas.

Ex: Norway

Priority II
Estimation based on national data

$$APG_{\%NORWAY} = 1 - \frac{V_{nonAPG\,NORWAY}(Mm3\ oil\ equivalent)}{V_{nonAPG\,NORWAY} + V_{APG\,NORWAY}(Mm3\ oil\ equivalent)}$$

Ex: Algeria

Priority III
Estimation based on regional data

$$APG_{\%ALGERIA} = \frac{APG\ used\ in\ the\ African\ region\ (bcm)}{APG\ used\ in\ the\ African\ region(bcm) + Non\ associated\ gas\ produced\ in\ the\ African\ region(bcm)}$$

V_{nonAPG}: Energy Institute – Statistical Review of World Energy: Resources and data downloads | Statistical Review of World Energy (energyinst.org)
V_{APG}: (for the USA) Associated gas contributes to growth in U.S. natural gas production - Today in Energy - U.S. Energy Information Administration (EIA) (for Norway) Historical production on the NCS - Norwegianpetroleum.no (norskpetroleum.no) (for Algeria/Africa) APG used: https://www.iea.org/commentaries/putting-gas-flaring-in-the-spotlight / Non associated gas produced in the region: Energy Institute – Statistical Review of World Energy

C.1.a. Estimating methane emissions (upstream)

CARBON LIMITS

- Estimating emissions from the gas value chain have similar steps in all countries, with a few variations depending on the type of information obtained from the different sources. Case specific differences have been highlighted in the results section of Task 1; this methodology section provides an overall methodology applied for estimations.
- The total upstream emissions is the sum of emissions from associated and non-associated gas production. Estimation of these emissions are presented below.

1. Estimation of upstream methane emissions

1.1. Estimating upstream non-associated gas emissions

For the selected source, all methane emissions linked to the production, gathering, boosting and processing of natural gas* have been added together.

1.2. Estimating upstream associated gas emissions

For the selected source, all methane emissions linked to the production of oil* have been added together ($Emissions_{oil}$). Then, the emissions are split between oil and associated gas based on the APG to oil ratio ($APG\text{-}to\text{-}oil_{\%}$):

$$Emissions_{APG} = Emissions_{oil} * APG\text{-}to\text{-}oil_{\%}$$

$$APG\text{-}to\text{-}oil_{\%} = \frac{\text{APG produced (EJ)}}{\text{APG produced (EJ) + Oil produced (EJ)}}$$

Where APG produced is estimated similarly – same formula, same sources - to V_{APG} used for the activity data and Oil produced is provided directly by the Energy Institute.

Energy Institute – Statistical Review of World Energy: Resources and data downloads | Statistical Review of World Energy (energyinst.org)

*In the case where oil and gas emissions are not split (e.g., Examples: "Other – oil and gas"/"Ultra-emitters" IEA categories , some UNFCCC categories, academic paper where emissions from oil and gas are not split), the gas-to-oil energy ratio is used: Total natural gas produced (EJ)/(Total natural gas produced (EJ) + Oil produced (EJ)) using the Energy Institute data.

C.1.b. Estimating methane emissions (downstream)

CARBON LIMITS

- **Pipeline** - The total downstream emissions is a sum of emissions during transmission in the exporting country and in the importing country.
- **LNG** - The total downstream emissions is a sum of emissions during transmission and liquefaction in the exporting country, LNG shipping, LNG unloading and regasification and transmission in the importing country.

2. Estimation of downstream methane emissions

2.1. Estimating transmission emissions

For the selected source, it corresponds to emissions reported under the category "Transmission and storage emissions".

2.2. Estimating LNG related emissions *(liquefaction, shipping, unloading and regasification)*

LNG related data are directly provided separately for "liquefaction", "shipping" and "unloading and regasification" by three different sources. It can be provided directly in the form of an emission factor or in the form of emissions along with the corresponding activity data.

C.1.c. Selecting sources for methane emissions data

CARBON LIMITS

- Country specific academic papers, national inventories and IEA methane tracker data are assessed to estimate the methane emissions along gas value chain.
- While some countries have extensive research on methane emissions, others have very limited data available.
- Different priorities were established for selecting the sources, along with a decision tree to make the final decision on source choice.

Ex: USA

Priority I

Emissions reported in any recent academic paper representative of the country (with peer review)

Ex: Norway, Germany, Europe, Algeria (transmission)

Priority II

Recent tier 2 or tier 3 reported emissions data by the country (NIR and UNFCCC)

Ex: Algeria (upstream)

Priority III

Emissions reported by the IEA Methane Tracker 2022

Assessment of academic papers:

- Measurement performed on local facilities?
- Data been published in the past 5 years?
- Data established based on a large sample size (representative of the full population)?
- Were there top-down measurements applied to validate the data?

Level of granularity:

- Are the oil and gas emissions split?
- Are the upstream emissions separated from downstream emissions?
- Are the transmission emissions separated from distribution emissions?

Compare sources based on above questions, and identify the best source, on a case-by-case basis.

Note: (i) for the LNG part of the value chain, emissions reported by industry representatives of the country/region have also been considered (ii) data from company reports to OGMP are not considered because the granularity level doesn't match

C.2.a. Estimating carbon dioxide emissions

CARBON LIMITS

- Estimating emissions from the gas value chain have similar steps in all countries, with a few variations depending on the type of information obtained from the different sources. Case-specific differences have been highlighted in the results section of Task 1; this methodology sections provides an overall methodology applied for estimations.
- For carbon dioxide emissions, data can be split between upstream and downstream emissions or between flaring, energy use and venting (from acid gas removal units).
- Thus, for the selected sources, carbon dioxide emissions from natural gas production and transmission are added up.
- If the emissions are not split between oil and gas, similarly to methane emissions, the gas-to-oil ratio is used except for flares for which only 10% is attributable to the total gas and 90% to oil.
- LNG carbon dioxide emissions estimation are following the same methodology as methane emissions.

Energy Institute – Statistical Review of World Energy: Resources and data downloads | Statistical Review of World Energy (energyinst.org)

In the case where oil and gas emissions are not split the gas-to-oil energy ratio is used: Total natural gas produced (EJ)/(Total natural gas produced (EJ) + Oil produced (EJ)) using the Energy Institute data.

C.2.b. Selecting sources for carbon dioxide emissions data

CARBON LIMITS

Flaring	Energy use	CO_2 venting (e.g., acid gas recover (AGR))
Ex: Norway, USA, Germany, Europe	*Ex: Norway, USA, Germany, Europe*	*Ex: Norway, USA, Germany, Europe*
Priority I Recent tier 2 or tier 3 reported emissions data by the country	**Priority I** Recent tier 2 or tier 3 reported emissions data by the country	**Priority I** Recent tier 2 or tier 3 reported emissions data by the country
Priority II VIIRS flaring data	**Priority II** Recent tier 1 reported emissions data by the country	**Priority II** Recent tier 1 reported emissions data by the country

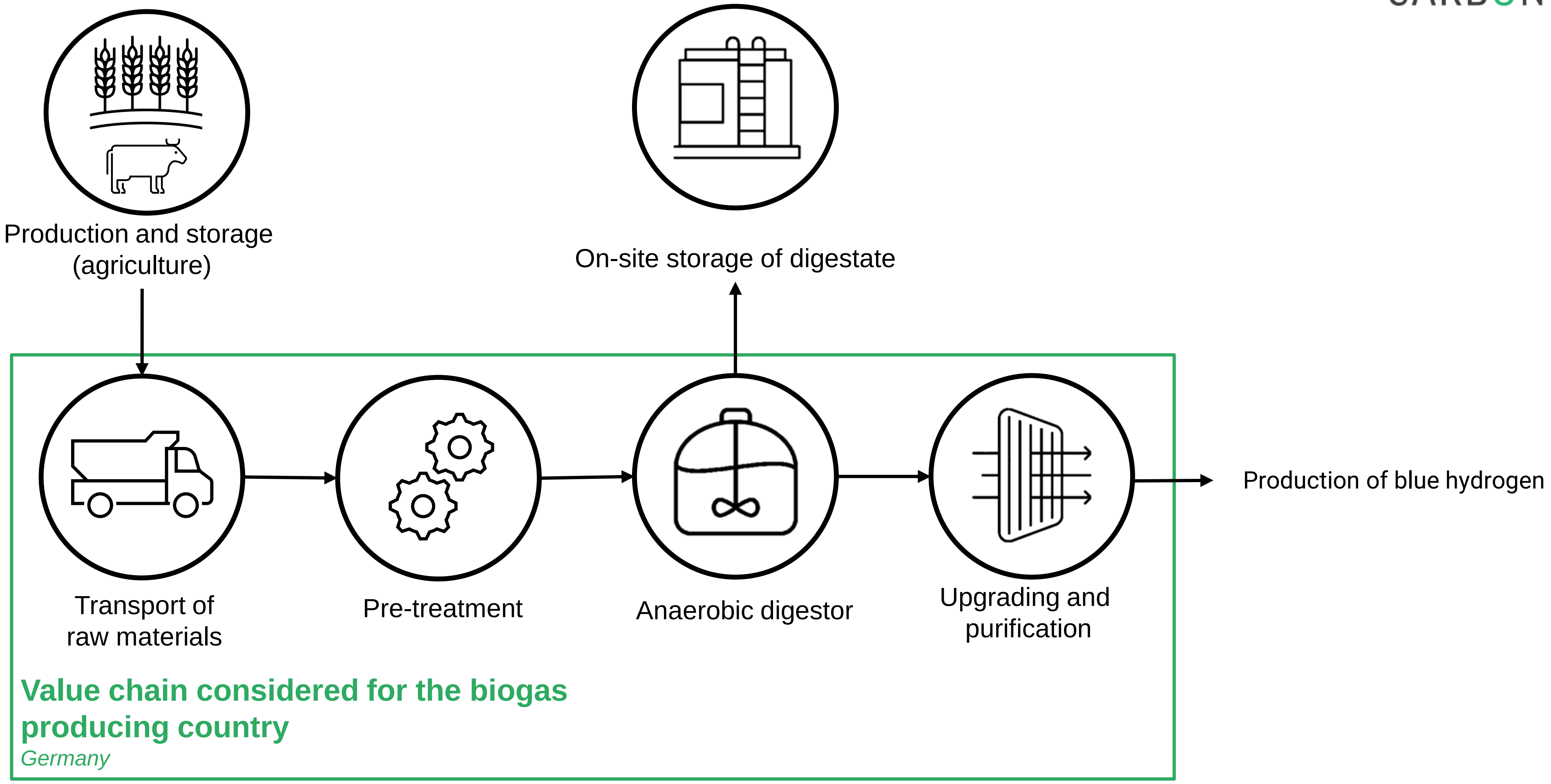
Ex: Algeria

Priority III
Emissions reported by OCI+

Note: For the LNG part of the value chain, emissions reported by industry representatives of the country/region have also been considered.

Methodology – Current scenario

2. Biogas production



Overview of biogas value chain considered

Biogas production – general assumptions

CARBON LIMITS

Feedstock	Maize (energy crop) and cattle slurry (livestock manure) as the main feedstocks (assumed 50% each) Bioenergy in Germany Facts and Figures 2020 (fnr.de) To note that the Land Use Change is not taken into account here.
Upgrading process	Pressure swing adsorption and amine scrubbing are considered here – based on the availability of emission data and the type of biomethane upgrading processes in Germany Bioenergy in Germany Facts and Figures 2020 (fnr.de)
Reference scenario	The biogas production scenario is compared to a reference scenario (only storage of manure which is not used) – if the biomethane production process (from transport of raw materials to upgrading) generates less emissions than the reference scenario, it leads to negative emissions. The reference scenario is determined as mentioned in european regulation and correspond to 54 $kgCO_{2eq}$ emitted per ton of manure pdf (europa.eu)

Biogas production - emissions

	Transport of raw materials	Pre-storage	Pre-treatment and anaerobic digestion	Upgrading
CO_2 fossil / CH_4 fossil	EcoInvent *Assuming a distance of 25 km between the farm and the biogas production plant*	No fossil emissions	No fossil emissions – anaerobic digestion and upgrading plants usually use their produced biomethane.	
CO_2 non-fossil	5% biofuels – non-fossil emissions related to the burning of biofuels are not included	No CO_2 non-fossil emissions	No non-fossil CO_2 emissions (IPCC 2006)	
CH_4 non-fossil		See below: (2) / (1)	1% methane loss- based on several sources	Weighted average of methane loss per upgrading process considered (see assumptions)

(1) **Production of biomethane from cattle slurry** (bcm biomethane/kg cattle slurry) = Biogas yield from catlle slurry (bcm biogas/kg cattle slurry) * Methane content (%)

(2) **Emissions of methane from cattle slurry storage** (kgCH_4 emitted/kg cattle slurry) = Emissions of methane from cattle slurry storage (kgCH_4 emitted/kg VS) * A

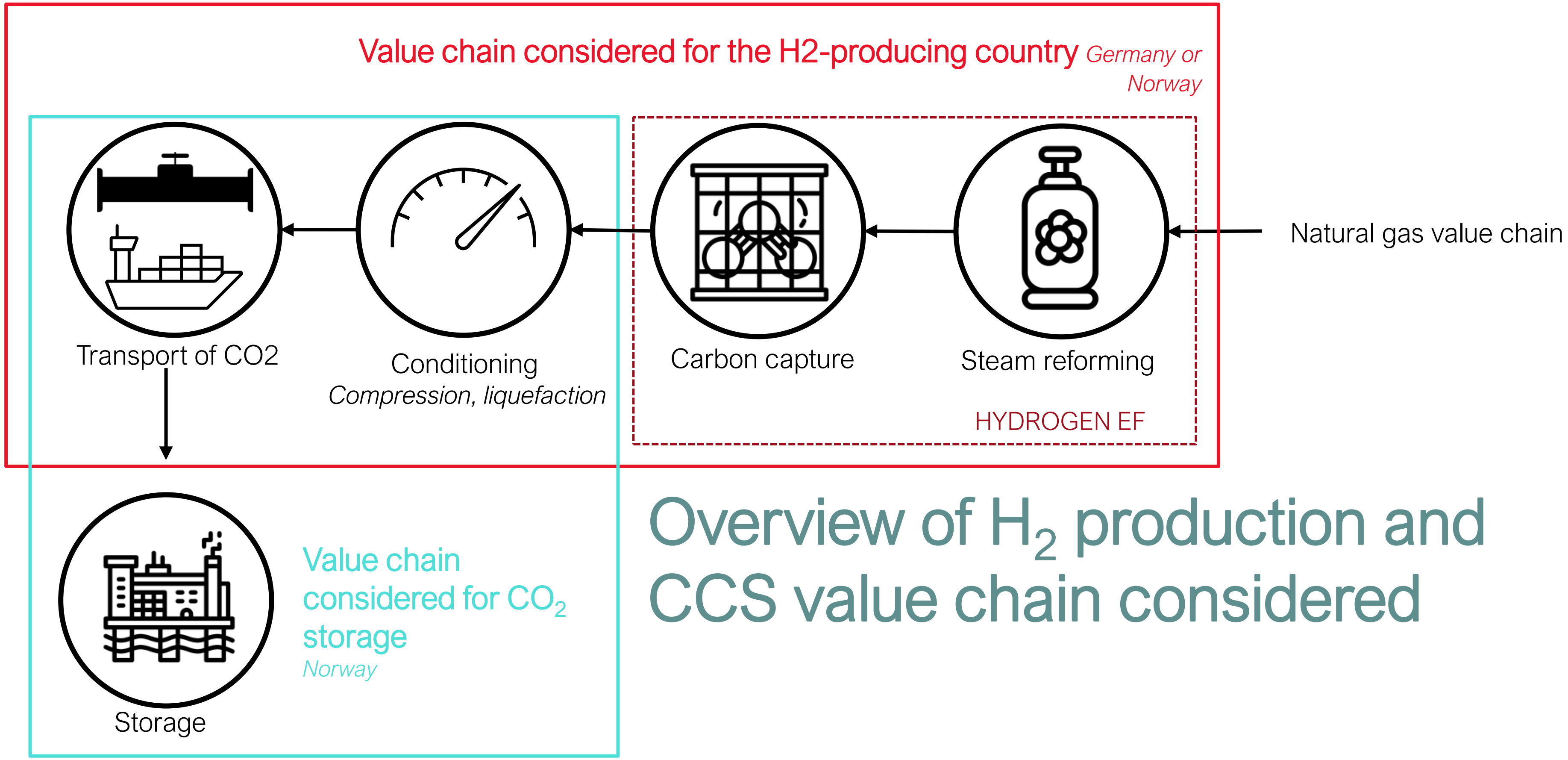
Where:
- Emissions of methane from cattle slurry storage (kgCH_4 emitted/kg VS) = B_0 * MCF, with:
  - B_0 (maximum methane production capacity of manure)= 0.23 m^3 CH_4/kgVS (Rösemann et al., 2019)
  - MCF (methane conversion factor) = 0.017 m^3/m^3 (Rösemann et al., 2019)
  - Methane density: 667 kt/bcm
- A is a conversion factor based on the % of VS in dry matter (70-80%, Cárdenas et al., 2021) and the % dry matter in slurry (14%, Alan Rotz, 2017)

IPCC 2006 – Volume 4, Chapter 10 - "CO_2 emissions from livestock are not estimated because annual net CO_2 emissions are assumed to be zero – the CO_2 photosynthesized by plants is returned to the atmosphere as respired CO_2. A portion of the C is returned as CH_4 and for this reason, CH_4 requires separate consideration." *(IPCC 2006. Volume 4, Chapter 10)*

Rösemann et al., 2019 - https://literatur.thuenen.de/digbib_extern/dn063510.pdf
Cárdenas et al., 2021 - https://doi.org/10.1016/j.wasman.2020.12.026
Alan Rotz, 2017 - https://doi.org/10.3168/jds.2017-13272

Methodology – Current scenario

3. Hydrogen and CCS value chain



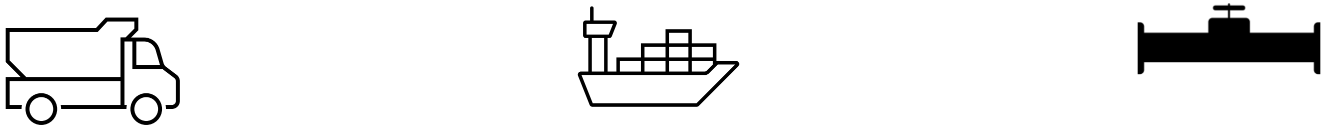
Overview of H_2 production and CCS value chain considered

Hydrogen related emissions

CARBON LIMITS

	CO_2 emissions	CH_4 emissions
Direct emissions *Leakage, natural gas consumption*	From Deloitte's HyPE model assumptions. For Case 4, since biomethane is used, CO_2 emissions are biogenic and are not accounted for. However, the capture of these emissions leads to negative emissions.	EcoInvent for SMR without CCS – extrapolated to SMR with CCS and ATR with CCS based on the natural gas used (kWh) for each process
Electricity production	Electricity consumption: from Deloitte's HyPE model assumptions 1. Production in Germany: Emissions (CO_{2eq}): GHG Delegated Act for Germany-split between CH_4 and CO_2 using EcoInvent 2. Production in Norway: Emissions (CH_4, CO_2): EcoInvent for Norway	

CCS related emissions



	Truck	Ship	Pipeline	Source
Conditioning before transportation	**Emissions from electricity production** $kgCO_2$ and CH_4/kWh of electricity - German production mix			GHG Delegated Act
	Liquefaction Electricity need in kWh/tCO_2 compressed		**Compression** Electricity need in kWh/tCO_2 compressed	Academic papers
Transport	**EcoInvent** Assuming 85 km	**Northern Light emission in CO_{2eq}** – split based on EcoInvent Included: operation (ship fuel consumption, process emissions, grid electricity)	**No emissions**	EcoInvent
Injection/Storage	**Not relevant**	**Northern Light emission in CO_{2eq}** – split based on EcoInvent Included: injection (use of vessel, grid electricity, other process emissions) and post injection (use of vessel)	**Northern Light emission in CO_{2eq}** – split based on EcoInvent Included: injection and post injection (use of vessels)	EcoInvent

Conditioning before transport: Jackson et Brodal (2018), Jackson and Brodal (2019)
Emissions from transport and injection/storage: Report-Carbon-footprint-of-the-Northern-Lights-JV-co2-transport-and-storage-value-chain.pdf (norlights.com)
GHG Delegated Act: Delegated regulation - 2023/1185 - EN - EUR-Lex (europa.eu)

Methodology – BAT scenario

1. Gas value chain

A.1. Calculation of methane emission factors for BAT scenario

Where IEA emissions are chosen

Algeria

Option 1: Use abatement values from IEA & estimate emission reduction potential in 2030 and 2040 – apply reduction% to EFs

Assumption: Abatement options at no net-cost are achieved by 2030, positive net-cost options are achieved by 2040

Option 2: Use OGCI industry target for upstream CH_4 emissions for all countries

Selection Criteria

Q1.1. Is the upstream EF for IEA < upstream EF set by industries?

Yes → **A1.1.** Use industry set EF for upstream. Use IEA EF for downstream. By 2050, all countries are to achieve industry target EF (0.9 kt CH_4/bcm)

No → **A1.2.** Use IEA EF for both upstream & downstream emissions. By 2050, all countries are to achieve industry target EF (0.9 kt CH_4/bcm)

Industry Target[1] (upstream EF)

Kt CH4 per bcm	
1.2	2040
0.9	2050

For LNG Liquefaction

Comparison between different liquefaction facilities: lowest emissions

For LNG Carriers

Boil-off rate based on new ship performances, engine: HPDF/slow speed/two-stroke (0.20gCH4/kWh), BOG to fuel (90%), 0%BOG leaked [based on Carbon Limits' LNG carrier model]

For LNG Regasification

Current scenario

[1]Adjusted, based on: Learn about Reducing methane emissions - OGCI

A.2. Calculation of methane emission factors for BAT scenario

Where non - IEA emission sources are chosen

Countries with same methodology:
Norway, USA, Germany

Upstream EF

Q1.1. Is the upstream EF for the country < upstream EF set by industries?

- Yes → **A1.1.** Upstream EF for the country remains the same as in the current scenario
- No → **A1.2.** Use upstream EF set by industries

Downstream EF

Q2.1. Do the major gas pipeline operators in the country have emission reduction targets for downstream gas?

- Yes → **A2.1.** Use the downstream reduction target set by the local company
- No → **A2.2.** Use downstream abatement options from IEA to estimate downstream EF

Industry Target[1] (upstream EF)

2030	2040	2050
1.2 Kt CH4 per bcm	1.02 Kt CH4 per bcm	0.9 Kt CH4 per bcm

[1]Adjusted, based on: Learn about Reducing methane emissions - OGCI

B. Calculation of CO_2 emission factors for BAT scenario

CARBON LIMITS

Flaring EF

Q1.1. Are best practices for flaring implemented in the country?

- Yes → **A1.1.** Upstream EF for the country remains the same as in the current scenario
- No → **A1.2.** Reduce the current flaring EF to the best among the different countries

Combustion EF

Q1.1. Can CCS or electrification be applied?

- Yes → **A1.1.** Reduce the current combustion EF by 80%[1]
- No → **A2.2.** Upstream EF for the country remains the same as in the current scenario

CO_2 venting/Acid Gas Removal EF

Q1.1. Is CCS on AGR units applied?

- Yes → **A1.1.** Reduce the current venting EF by 87%[1]
- No → **A1.2.** Upstream EF for the country remains the same as in the current scenario

<u>Total CO2 EF</u> = Flaring EF + Combustion EF + CO2 venting EF

Q1.2. Is CO_2 EF for Norway $<$ CO_2 EF for the country?

- Yes → **A2.1.** Use calculated EF[1] for 2040 and Norway for 2050
- No → **A2.2.** Use Norway EF for 2040 and calculated EF[1] for 2050

[1]Carbon Limits for CATF/CAELP done for US

Methodology – BAT scenario

2. Biogas production

Biogas production - emissions

	Transport of raw materials	Pre-storage	Pre-treatment and anaerobic digestion	Upgrading
CO_2 fossil CH_4 fossil	EcoInvent *Assuming a distance of 25 km between the farm and the biogas production plant*	No fossil emissions	No fossil emissions – anaerobic digestion and upgrading plants usually use their produced biomethane.	
CO_2 non-fossil	GHG reduction based on CO_2 emission standards for trucks	No CO_2 non-fossil emissions	No non-fossil CO_2 emissions (IPCC 2006) accounted in the current scenario. In the BAT scenario, 90% of these emissions are assumed to be captured by 2050 (with a linear increase from 2030 to 2050), which leads to negative emissions	
CH_4 non-fossil		The manure stored is covered and the gas is captured with a 90% capture rate by 2040 and 95% by 2050	The lowest value in the litterature = BAT, assuming it involves the capture of biogas/biomethane	

IPCC 2006 – Volume 4, Chapter 10 - "CO_2 emissions from livestock are not estimated because annual net CO_2 emissions are assumed to be zero – the CO_2 photosynthesized by plants is returned to the atmosphere as respired CO_2. A portion of the C is returned as CH_4 and for this reason, CH_4 requires separate consideration." *(IPCC 2006. Volume 4, Chapter 10)*

Methodology – BAT scenario

3. Hydrogen value chain

Hydrogen related emissions

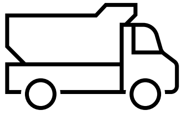
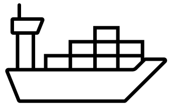
CARBON LIMITS

	CO_2 emissions	CH_4 emissions
Direct emissions *Leakage, natural gas consumption*	Capture rates: same as current scenario	
Electricity production	Electricity consumption: from Deloitte's HyPE model assumptions 1. Production in Germany: Emissions (CO_{2eq}): GHG Delegated Act German production mix without coal (French mix as an approximation – intensity fron the GHG Delegated Act)-split between CH_4 and CO_2 using EcoInvent 2. Production in Norway: Same as current scenario	

Methodology – BAT scenario

4. CCS value chain

CCS related emissions

			
Conditioning before transportation	**Emissions from electricity production** $kgCO_2$ and CH_4/kWh of electricity - German production mix without coal (French mix as an approximation – intensity fron the GHG Delegated Act)		
	Liquefaction Electricity need in kWh/tCO_2 compressed – *Same as the current scenario*		**Compression** Electricity need in kWh/tCO_2 compressed – *Same as the current scenario*
Transport	**EcoInvent** Assuming 85 km	**Northern Light emission in CO_{2eq}** – bioCCS on the ship, use of bioLNG → assuming a reduction of 70%	**No emissions**
Injection/Storage	**Not relevant**	**Northern Light emission in CO_{2eq}** – *Same as the current scenario*	**Northern Light emission in CO_{2eq}** – *Same as the current scenario*

GHG Delegated Act: Delegated regulation - 2023/1185 - EN - EUR-Lex (europa.eu)

Methane emissions factor for other countries

From Hydrogen4Europe

Key takeaways

- The information in the slides in this section provide upstream methane emission factors for different countries from a previous study.
- Only data shared in the public reports of the study are presented hereafter.
- It only includes the methane emission factor.

Key result from the Nature publication "The impact of methane leakage on the role of natural gas in the European energy transition"

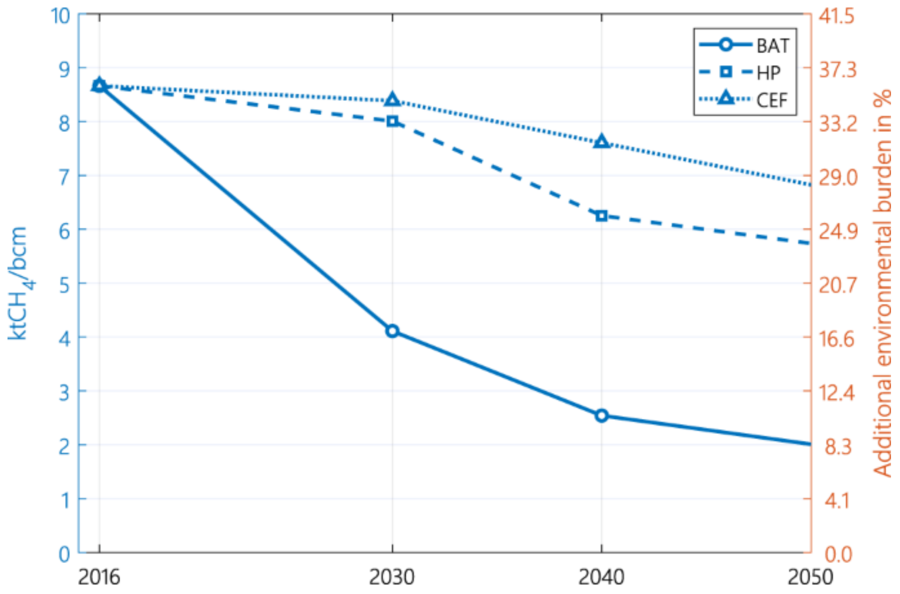


Fig: Methane intensity of natural gas consumed in Europe for each methane emission scenario[1].

In all three scenarios the EF drops progressively until 2050. The methane EF in the BAT scenario is respectively 70% and 65% lower than the 2050 EF in the CEF and HP scenarios. The BAT scenario sees the sharpest decrease in methane's additional environmental burden by 2050. These results show that there is significant room for further methane emission reduction (BAT), more than what is envisaged under the existing policy framework (HP).

BAT stands for the best available technology scenario,
HP stands for the harmonised pledges scenario and
CEF stands for the current emission factors scenario

Sources: (1) Hydrogen4EU - 2022 edition / (2) The impact of methane leakage on the role of natural gas in the European energy transition | Nature Communications
Current emission factor (CEF): current best understanding of emissions / Harmonized pledges (HP): abatement of methane emissions based on announced policies / BAT (Best Available Technologies): "abatement of methane emissions if oil and gas industry pursues all necessary efforts to deploy BAT and rapidly reduce emissions"

Implementing BAT and having stricted methane emission regulations can have drastic impact on upstream EF among gas/LNG exporting countries.

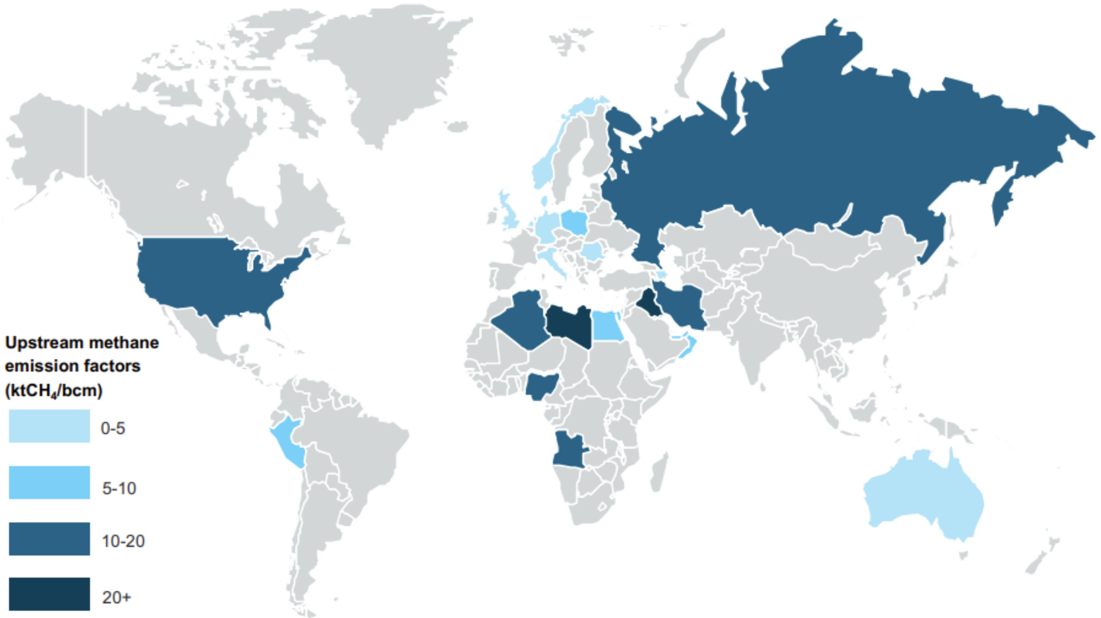


Fig: Upstream methane emissions of gas producing countries[2].

Upstream methane emission factors vary vastly between the countries assessed. Hence having a standardized value for upstream methane emissions will not account for the differences in emission abatement practices in the different countries.

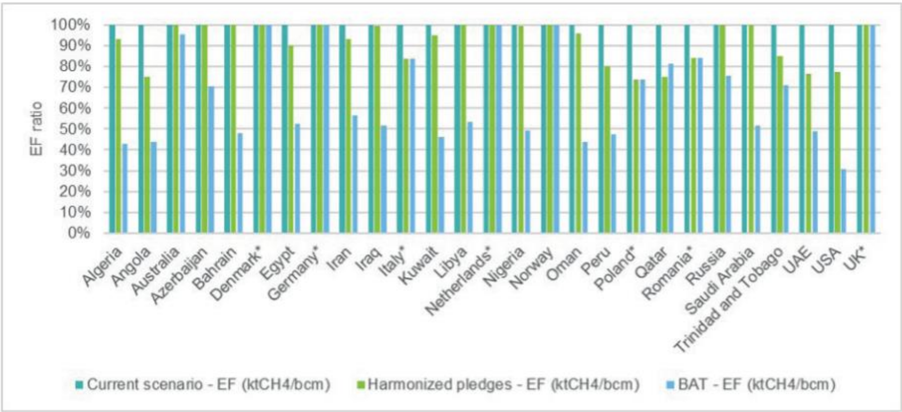
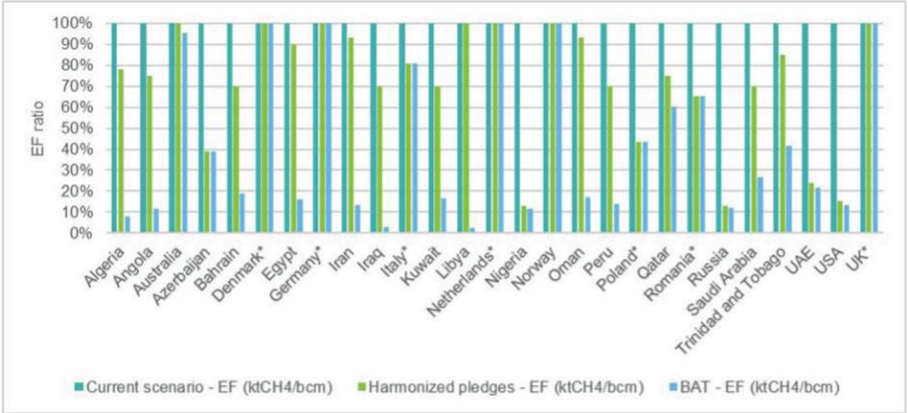


Fig: Comparison of emission factors (upstream, transmission and distribution without including LNG) between three methane emission cases in 2030[2].



*Note: * refers to the emission factors that include distribution.*

Source: Hydrogen4EU

Fig: Comparison of emission factors (upstream, transmission and distribution without including LNG) between three methane emission cases in 2050[2].

Sources: (1) Hydrogen4EU - 2022 edition / (2) The impact of methane leakage on the role of natural gas in the European energy transition | Nature Communications
Current emission factor (CEF): current best understanding of emissions / Harmonized pledges (HP): abatement of methane emissions based on announced policies / BAT (Best Available Technologies): "abatement of methane emissions if oil and gas industry pursues all necessary efforts to deploy BAT and rapidly reduce emissions"

MRV descriptions

American Bureau of Shipping Requirements for Ammonia Fueled Vessels

Other relevant regulations & initiatives

The ABS Requirements outline how to design and construct ammonia-fueled ships to mitigate potential human or environmental risks (as well as vessel damage) in accordance with standards specified in the *International Code of Safety for Ships Using Gases or other Low-Flashpoint Fuels* (IGF Code; see IMO slide for more detail). The ABS requirements apply to ships of all sizes. The focus of this document is generally around immediate risks, such as those related to ammonia spills or gas releases, instead of indirect risks like overall GHG emissions. However, the requirements do note that venting is generally not allowed except in safety or emergency situations.

Sources and links
American Bureau of Shipping

Ammonia Energy Association (AEA) Ammonia Certification System

AMMONIA ENERGY ASSOCIATION

Voluntary methodologies

Certification schemes

The AEA's Ammonia Certification System is currently **under development**. The framework is intended to help **ammonia producers measure and report the GHG emissions** associated with their product, covering everything upstream of and including the production of ammonia, but **not its transport and distribution**. The certification system intends to include a carbon intensity methodology, which is why it is considered here as both a voluntary methodology and a certification scheme.

Sources and links
Ammonia Energy Association (1, 2)

API Compendium of GHG Emissions Methodologies for the Natural Gas and Oil Industry

American Petroleum Institute

Voluntary methodologies

The American Petroleum Institute (API) Compendium is a comprehensive **compilation of commonly-used GHG emission estimation methodologies** for the natural gas and oil sector, including methodologies for LNG and CCS. **MiQ's** standards often reference this Compendium.

Sources and links
API

Bureau Veritas' Ammonia-Fuelled Ships: Tentative Rules

Similarly to the requirements set forth by the American Bureau of Shipping, Bureau Veritas's Tentative Rules for Ammonia-Fuelled Ships specify **design and construction requirements for ammonia-fueled ships** in accordance with the (IMO) *International Code of Safety for Ships Using Gases or other Low-Flashpoint Fuels* (IGF Code). This document also places a **focus on immediate risks**, such as those related to ammonia spills or gas releases, instead of indirect risks like overall GHG emissions.

Other relevant regulations & initiatives

Sources and links

Bureau Veritas

CertifHy

Certification schemes

The CertifHy scheme is managed by a consortium led by HINICIO, comprised of the Association of Issuing Bodies (AIB), GREXEL, Ludwig Bölkow System Technik (LBST), CEA, and TÜV SÜD and financed by the EU Clean Hydrogen Partnership. The voluntary scheme issues **guarantees of origin for green hydrogen** (produced from renewable energy including wind, solar, hydro, and biomass) **and low-carbon hydrogen** (produced from non-renewable energy including nuclear or fossil energy with CCS). Both types of hydrogen must have a carbon intensity of **60% below that of SMR** hydrogen*, and this **target will increase** over time. The guarantees of origin disclose the energy source, plant information, time of production, **GHG intensity**, and issuing date. Their carbon footprint document provides a general overview of how to calculate the carbon footprint of the hydrogen's core energy input that may be produced from various energy sources (i.e. biomethane from various feedstocks). The calculation is based on emission factors.

CertifHy currently only applies to countries in the EEA but is **intended to be expanded internationally**. The scheme uses officially-approved certification bodies that meet a set of standards. Currently, recognized certification bodies include TÜV SÜD (Germany) and Bureau Veritas (Norway).

*This value corresponds to an approximate emission factor between 4.37 kg CO_2eq/kg H_2 (using an energy density of 120 MJ/kg) and 5.10 CO_2eq/kg H_2 (using an energy density of 142 MJ/kg). These exceed the emission factor set forth by the delegated acts defining renewable hydrogen within the EU. However, as CertifHy has stated its intent to increase this target over time, and as the scheme has applied to be recognized as a voluntary scheme under RED, it can be assumed that the carbon intensity reduction target will be updated to align with EU standards.

Sources and links	
CertifHy (1, 2, 3, 4, 5)	TÜV SÜD
World Bank	European Commission
Waterstof Net	The Physics Factbook

dena (German Energy Agency) Biogas Register

The German Energy Agency, dena (Deutsche Energie-Agentur), developed a biogas register in collaboration with companies from the biogas/biomethane industry. The Biogas Register allows producers to **verify the quantity and quality** of biomethane that is used in Germany's natural gas grid. To be verified by the register, **plants must be inspected** by an environmental assessor or auditor.

Certification schemes

Sources and links
dena
Biogas Register (1, 2)

DNV-SE-0654

Validation of attribute claims for low carbon and renewable hydrogen and ammonia

Certification service specification

DNV has published a service specification detailing how they can **verify hydrogen producers' compliance with different standards**, including RED and the EU Taxonomy. The specification outlines DNV's compliance verification process for the **production and distribution of low-carbon hydrogen and ammonia**. This specification references **ISOs 14064-3 and 14067**, among others.

Sources and links
DNV
Dr. Thomas Koller on LinkedIn

EU Carbon Removal Certification Framework (CRCF)

European Commission

Certification schemes

The EU CRCF is a **voluntary framework** for certifying carbon removals within the EEA, including permanent removals, carbon farming and carbon storage in products, and carbon storage in long-lasting products. Removals are considered high-quality if they meet certain QU.A.L.ITY criteria: quantification, additionality, long-term storage, and sustainability. Audits and certifications will be conducted by Member-state-approved certification bodies.

The final text of the CRCF was adopted in April 2024. The framework is expected to enter into force by the **end of 2024**, but it is likely that **methodologies** under the framework **will not be available until 2026** at the earliest. The existing framework proposal states that in order to be conservative in emissions and removals estimates, they "should be based on an appropriate combination of on-site measurements with remote sensing or modelling according to rules set out in the appropriate certification methodology."

Sources and links
European Commission (1, 2)
Sebastian Manhart on LinkedIn
Inside Energy and Environment
Carbon Gap

EU CCS Directive

European Commission

Other relevant regulations & initiatives

The CCS Directive is the EU's legal framework for **environmentally safe geological CO2 storage** in EEA countries over the entire lifetime of a storage site. It largely focuses on the storage of CO2 in geological formations within the EU but also covers parts of the capture and transport sectors as well. Under this directive, geological CO2 storage is only permitted if it can be shown that there is **no risk of leakage or damage** to human health or the environment.

Sources and links
European Commission

EU Emissions Trading System (ETS)

European Commission

Compliance methodologies

The ETS is a **mandatory cap-and-trade system** which places an annually decreasing cap on GHG emissions for certain sectors within the EEA. Companies get **emission allowances** to use or trade on the market.

Starting in 2026, the ETS will cover **CH4 and nitrous oxide in addition to CO_2**. From 2027, the ETS will also include offshore ships above 5000 GT (currently it only applies to cargo and passenger ships above 5000 GT). Bio-CO_2 is not included in the ETS.

The ETS regulation explicitly includes a section including GHG emissions from CO_2 capture activities, CO_2 pipeline transport for geological storage, as well as from geological storage (from both injection activities and leakage) in Annex IV. It also covers fossil-based hydrogen production.

Sources and links
European Commission (1, 2, 3, 4)
DNV

(Provisional agreement on) EU Methane Emissions Reduction in the Energy Sector

European Commission

Compliance methodologies

In November 2023, the EU Council and Parliament reached a provisional agreement for a regulation on **tracking and reducing fossil-based energy sector methane emissions** in the EEA. The regulation, which is **built on the OGMP 2.0 framework**, includes MRV requirements for source-level emissions including from non-operated assets; mitigation requirements are also included. The agreement is pending formal adoption.

Sources and links
European Commission (1, 2)

EU Methane Import Standard

European Commission

Starting at the end of 2024, **importers of fossil fuel to the EEA will be required to report their methane emissions**. By 2027, they will be required to show that **EU-equivalent methane MRV standards** were used (see slide on “(Provisional agreement on) EU Methane Emissions Reduction in the Energy Sector"), and by 2030 a **methane intensity import standard** will be enacted.

Other relevant regulations & initiatives

The MRV proposals **build on OGMP 2.0 framework**. According to Emils Lagzdins, Senior Policy Officer at IOGP Europe, around 115 companies have begun participating in OGMP 2.0 in the last couple of years in anticipation of these EU methane regulations.

Sources and links
European Commission (1, 2)
Industrial Decarbonization Network

EU Monitoring, Reporting and Verification (MRV) Maritime Regulation

European Commission

Compliance methodologies

The EU Monitoring, Reporting and Verification (MRV) Maritime Regulation is a regulatory framework intended to **monitor GHG emissions from shipping activities** within the EEA. Operators of ships subject to the regulation must report their GHG emissions (CO2, CH4, and N2O), among other information.

The regulation applies to **passenger and commercial cargo ships from all countries** that travel to or from EEA ports. Currently, the regulation generally applies to ships above 5,000 gross tonnage, with some exceptions. In 2025, the regulation will extend to offshore ships as well as cargo ships between 400 - 5000 gross tonnage.

Sources and links
DNV (1, 2)

EU Renewable Energy Directive (RED) III and CEN-EN-16325

European Commission

Other relevant regulations & initiatives

The EU's Renewable Energy Directive (RED) III aims to **promote clean energy use** in all economic sectors and **requires 42.5% of EU energy consumption to be renewable by 2030**. The directive defines which energy sources count towards this target. RED defines GHG emissions for biofuels as including extraction/cultivation emissions, carbon stock change emissions, processing, transport, and distribution emissions, fuel emissions, CCS emissions savings, and more. The **Commission Delegated Regulation (CDR) 2023/1185** further establishes the methodology for evaluating these emissions reductions.

RED also requires that Member States verify **renewable fuels such as biogas and hydrogen using Guarantees of Origin (GO)** per European Standard CEN-EN 16325, which outlines the requirements for GOs of electricity from all energy sources. This standard is currently being revised to **also include GOs for heating, cooling, and gaseous energy carriers.** This includes **specific provisions for hydrogen GOs**, such as additional application information (a simplified energy flow diagram with various process parts labeled), input sources and types, verification of an application for registration of a production device, and verification of consumption and production declarations. Hydrogen Europe states that there are risks with the current approach, including the theoretical possibility of using biomethane GOs instead of low-carbon hydrogen GOs. They therefore recommend an entirely differentiated GO system for hydrogen that can be tradeable between EU member states and ultimately established on a global level. GOs for low-carbon hydrogen should also account for the location of the electricity or other energy source used to produce the hydrogen, as this can ultimately affect the carbon intensity of the hydrogen.

To meet GO requirements, Member States appoint and operate Issuing Bodies to issue GOs; these bodies can be general or location-specific organizations. The **Association of Issuing Bodies** (AIB), which currently has 37 members from 30 European countries, has implemented the **European Energy Certificate System** (EECS).

The EECS aligns different GO registries and thus allows the exchange of GOs between Member States, allowing for reliable, efficient, and standardized GO transfers between Member States. In Norway, the issuing body is Statnett. In Germany, it is the Umweltbundesamt (German Environment Agency). Germany is one of a few countries which currently have GO issuing systems for biogas.

Sources and links	
European Commission (1, 2, 3, 4, 5, 6)	Cerqlar
PtX Hub	Statnett
European Biogas Association	Energy Track & Trace
Ecohz	Grexel
IEA	Entsog
Association of Issuing Bodies (1, 2, 3, 4, 5, 6)	Hydrogen Europe
Fortum	

EU Taxonomy on Sustainable Finance

European Commission

Other relevant regulations & initiatives

The EU Taxonomy was developed to provide a **standardized classification system** to define "sustainable" activities within the EEA which are considered to contribute to EU sustainability objectives. Emissions under the taxonomy are calculated according to the EU ETS benchmark methodologies.

Hydrogen manufacturing is considered sustainable under the Taxonomy if the following requirements are met:

- Direct emissions should not exceed 5.8 t CO2e/ton hydrogen
- Electricity use for electrolytic hydrogen should not exceed 58 MWh/ton hydrogen
- Average carbon intensity of the electricity used should be at or below 100 g CO2e/kWh

Carbon capture and storage can be eligible as a sustainable activity under any other Taxonomy activity, if it meets two conditions: the CCS project must allow the Taxonomy activity to meet its emissions intensity threshold, and the transport & storage components must be considered sustainable themselves under Taxonomy criteria.

Biogas is also included as providing a substantial contribution to climate change mitigation and adaptation, either via production of electricity, heating/cooling, and power from bioenergy or by manufacture of biogas/biofuels.

Sources and links
European Commission
OECD iLibrary
University of Agder
Global CCS Institute

Gas-Wärme-Kälte-Herkunftsnachweisregister-Verordnung (GWKHV)

Deutscher Bundestag

Certification schemes

In January 2024, the German government passed the Gas-Wärme-Kälte-Herkunftsnachweisregister-Verordnung (GWKHV) ("Gas-Heat-Cooling Proof of Origin Register Ordinance") based on the country's Herkunftnachweisregistergesetz (Guarantee of Origin Register Act). The GWKHV establishes a **register of origin for gas, heating, cooling, and hydrogen**, providing a way for suppliers to demonstrate their climate-neutral energy production. The ordinance differentiates between different "colors" of hydrogen (blue – steam reforming, turquoise - pyrolysis, orange – biomass). The environmental agency (Umweltbundesamt) reviews submitted data and may require third-party expert verification.

The final text of the ordinance was published on April 25, 2024. For biomass-based hydrogen, the regulation states that the type of biomass used, as well as an assessment of whether it meets German biomass sustainability requirements, should be provided.

The register is expected to be operational in 2025.

Sources and links
Bundesministerium für Wirtschaft und Klimashutz
IHK
Goldenstein-Kanzlei
Bundesministerium der Justiz (1, 2)

GIIGNL

GIIGNL is an organisation supporting global LNG activities. It has 94 members representing the LNG industry from around the world in the Americas, Asia and Europe.

GIIGNL's framework for MRV of emissions from LNG and for emissions offsets is intended to, among other things, **outline best practices for emissions MRV** and offsetting and help generate **consistent and reliable GHG footprints for LNG cargos**. The framework covers the entire LNG value chain.

This framework had 85 participants in 2023 with low growth (1%) from 2022 to 2023.

Voluntary methodologies

Sources and links
GIIGNL (1, 2)
Oxford Energy
Highwood Emissions Management (1, 2)
HC Group

Global Methane Initiative

The Global Methane Initiative aims to **reduce barriers to methane recovery and use** by providing technical support for methane-to-energy projects in the oil and gas, biogas, and coal mine sectors. Of the countries considered in this analysis, Norway, Germany, and the US are participants in the Global Methane Initiative.

Other relevant regulations & initiatives

Sources and links
Global Methane Initiative

Global Methane Pledge

The Global Methane Pledge was launched at COP26 in an effort to reduce global methane emissions. Pledge **participants endeavour to collectively reduce global methane emissions** at least 30% from 2020 levels by 2030. This target focuses on global emissions reductions rather than just reducing emissions at the national level. The GMP has over 155 participants, including the US, Germany, and Norway.

Other relevant regulations & initiatives

Sources and links
Global Methane Pledge

Greenhouse Gas Protocol (GHG-P)

The Greenhouse Gas Protocol (GHG-P) provides a **standard to help public and private entities**, such as companies, organizations, jurisdictions, and agencies, **develop a GHG inventory**. Their guidance includes corporate standards (i.e. corporate-level, product-level, and project-level emissions inventories), as well as various standards for countries and cities (i.e. for mitigation goals, policies, city-wide GHG accounting). Currently, a "Land Sector and Removals Standard" is under development.

The GHG-P standards are high-level, but their *Product Life Cycle Accounting and Reporting Standard* is theoretically applicable to any product (good or service). This makes it the only methodology covered here that could be applied to the **entire low-carbon hydrogen value chain**. However, the high-level nature of this protocol means that it would only be recommended in the **absence of more industry-specific and granular standards** (i.e., OGMP or the ISO hydrogen technologies standard)

GREENHOUSE GAS PROTOCOL

Voluntary methodologies

Sources and links
GHG Protocol (1, 2)
Ecohz

International Maritime Organization IGC and IGF Codes and MARPOL

Other relevant regulations & initiatives

The International Maritime Organization's (IMO) *International Code for Construction and Equipment of Ships Carrying Liquefied Gases in Bulk* (IGC Code) regulates carriers of liquefied gas and certain other substances, and therefore **regulates ammonia when it is transported as maritime cargo** instead of as a fuel. The IGC Code requires these carriers to meet certain design and construction standards in order to **prevent potential harm to the vessel, people, and the environment**.

The IGC Code prohibits the use of ammonia as fuel in liquefied gas carriers. However, other vessels may use ammonia as fuel in accordance with alternative design requirements which meet the *International Code of Safety for Ships Using Gases or other Low-Flashpoint Fuels* (IGF Code).

The IGC Code and IGF Code are mandatory regulations under the IMO's International Convention for the Safety of Life at Sea (SOLAS). The focus of SOLAS is safety; however, the IMO's International Convention for the Prevention of Pollution from Ships (MARPOL) regulates the **pollution of the sea and air by marine vessels.**

Sources and links
International Maritime Organization (1, 2, 3)
American Bureau of Shipping
Bureau Veritas (1, 2)
Witherbys

International Maritime Organization (IMO) Strategy on Reduction of GHG Emissions from Ships

Other relevant regulations & initiatives

The most recent version of this IMO standard was adopted in 2023. The standard sets emissions reduction targets (among other related targets) for international shipping activities; it also outlines options for reducing GHG emissions in the short, medium, and long term, and how the IMO Committee can help its member countries achieve these goals.

Sources and links
IMO (1, 2)

International Sustainability & Carbon Certification (ISCC) Sustainability Test Certificates

International Sustainability & Carbon Certification

Certification schemes

The ISCC certification, which is recognized by the EU, **ensures compliance with the sustainability and GHG emissions savings criteria** laid out in the Renewable Energy Directive, including both biomass and biofuel requirements. The GHG emissions calculation is based either on conservative default values provided in the Renewable Energy Directive (RED) or "actual values" calculated based on methodologies defined in RED and in the ISCC document EU 205 – Greenhouse Gas Emissions. ISCC's GHG Emissions document considers emissions based on RED, and therefore includes emissions from the cultivation of biomass, transport and distribution, processing, and more. Third-party certification bodies, which are approved by ISCC, conduct verification and issue certificates.

Sources and links
ISCC (1, 2, 3)
Magnus Commodities

ISO 14064-3:2019

Greenhouse Gases - Part 3: Specification with Guidance for the Verification and Validation of Greenhouse Gas Statements

Voluntary methodologies

This ISO standard outlines requirements for **verification of GHG statements** attributed to an organization, project, or product.

Sources and links
ISO

ISO 14067

Greenhouse gases - Carbon footprint of products - Requirements and guidelines for quantification

This standard from the International Organization for Standardization (ISO) establishes guidelines for **quantifying and reporting the carbon footprint** of products. The standard is consistent with the ISO life cycle assessment (LCA) standards ISO 14040 and ISO 14044.

Voluntary methodologies

Sources and links

ISO

ISO/TR 27915:2017

Carbon dioxide capture, transportation and geological storage

Voluntary methodologies

This ISO technical report, while not a standard in itself, is a reference for potential future standards related to the **quantification and verification of GHG emissions from CCS activities** (as well as verification of captured and stored CO2 volumes). It covers current methodologies and requirements for quantification of captured, transported, and geologically stored CO2, as well as other GHG emissions from CCS project activities.

Sources and links

ISO

ISO/TS 19870:2023

Hydrogen technologies

This ISO technical specification outlines the methodologies for generating **GHG inventories for hydrogen production, conditioning, and transport**. This includes emissions from "production, transport and cracking of **ammonia** as a hydrogen carrier." It sets guidelines for determining the carbon footprint of hydrogen throughout the technology's lifecycle. This technical specification is expected to be turned into a complete ISO standard sometime this year (2024).

Voluntary methodologies

Sources and links
ISO (1, 2)
Green Hydrogen Organisation

MiQ

Certification schemes

MiQ performs **emissions certification** for natural gas facilities at the **asset level**. This is in contrast to OGMP, which certifies at a company level – MiQ's "Minimum Reconciliation Requirements" are also **more flexible** than that of OGMP's. For onshore and offshore production, MiQ covers **methane intensity, company practices, and monitoring technology deployment**, and the assets are graded on a scale of A-F. Emissions quantification can be performed using direct measurement techniques or via indirect methods such as emission factors, engineering calculations, and modeling. MiQ uses experienced third-party auditors to assess sites on an annual basis.

Methane standards exist for onshore and offshore production; gathering, boosting, processing; transmission & storage; and LNG. The carbon intensity standard is based on a summation of emission sources as defined in the 2021 API Compendium of Greenhouse Gas (GHG) Emissions Methodologies.

MiQ's participant growth rate was 29% between 2022 and 2023. Currently, all MiQ-certified facilities are located **in the United States.**

MiQ differs to OGMP Gold Standard in several ways, such as:

- Coverage of multiple GHGs
- More flexible requirements
- Asset-level certification

Sources and links
MiQ (1, 2, 3, 4, 5)
Highwood Emissions Management (1, 2)
Oxford Energy

In March 2023, the MiQ certification began covering **carbon dioxide and nitrous oxide** in addition to **methane**.

Norwegian guidelines for emissions reporting

Miljø-direktoratet

OFFSHORE NORGE

Compliance methodologies

These guidelines were developed to aid **Norwegian petroleum operators** in reporting their emissions to the Norwegian Environment Agency and Offshore Norge, to ensure consistency in reporting. The relevant guidelines include:

- Guidelines for reporting from offshore petroleum activities (Miljødirektoratet)
- Recommended guidelines for discharge and emission reporting, and Appendix B - Handbook for quantifying direct methane and NMVOC emissions (Offshore Norge)

The latter guidelines from Offshore Norge are intended to supplement the guidelines from Miljødirektoratet (the Norwegian Environment Agency).

Sources and links
Offshore Norge
Miljødirektoratet
IEA

OGMP

Voluntary methodologies | Certification schemes

Oil And Gas Methane Partnership 2.0

The Oil and Gas Methane Partnership (OGMP) 2.0 is a voluntary global partnership aiming to reduce **methane** emissions from the **oil and gas sector**, led by **UNEP** and joined by oil and gas companies representing **over 35% of the world's oil and gas production**. As part of OGMP, companies are to self-report annually their methane emissions according to a detailed and transparent reporting framework. In exchange, companies **publicly underline** their commitment toward methane emissions reporting and reductions. OGMP does not cover other GHGs besides methane.

As per OGMP 2.0, member companies seeking to acquire a "Gold Standard" certification shall report their methane emissions following the highest reporting standards. They are also required to develop and submit a methane emissions reduction plan and a 3-year roadmap detailing how they will reach this goal.

Achieving **OGMP Gold Standard** allows companies to publicly signal their ongoing efforts to transparently report and reduce methane emissions from their operations and positions them as front-runners in that arena. There are 5 levels of reporting within OGMP, and Gold Standard is achieved by meeting Level 4/5 reporting for operated assets within 3 years and for non-operated assets within 5 years. Default and measured values can both be used in OGMP reporting, but it affects the level – for example, a default emission factor would typically reflect Level 3 reporting while a measured value would meet Level 4 requirements.

OGMP performs review and verification of implementation plans and other documentation. However, they do not require the use of independent auditors.

OGMP is the leading standard for oil and gas methane reporting.

There are currently 140 participants in OGMP.

OGMP had an 86% participant growth rate between 2022 and 2023 – significantly higher than its competitors.

Anticipated future EU methane MRV standards are built on OGMP framework.

Sources and links
OGMP (1, 2, 3)
CCAC
Highwood Emissions Management (1, 2)
Industrial Decarbonization Network

Puro.earth Geologically Stored Carbon Methodology and CORC

Voluntary methodologies | Certification schemes

Puro.earth is a carbon crediting platform for engineered carbon **removals** (ECRs). Their Puro Standard establishes a framework for **certifying ECRs** with their CO2 Removal Certificates, or CORC. The Puro Standard Geologically Stored Carbon Methodology provides guidelines for **quantifying net CO2 removal impact from CCS activities** over the project lifetime (and thus inherently includes guidelines on quantifying CCS project emissions). Methodology compliance is verified by independent auditors.

Sources and links
Puro.earth (1, 2)

REDcert

Certification schemes

REDcert-EU is a sustainability certification scheme intended to demonstrate that the **biomass and biofuel sustainability requirements set forth in the EU Renewable Energy Directive** (RED) have been met and to ensure reliable, accurate methods are used for calculating GHG emissions savings from biofuels. Emissions under REDcert, similar to ISCC, can be based either on conservative default values provided in RED or "actual values" calculated based on methodologies defined in RED. Because emissions are evaluated based on RED, the REDcert should include emissions from the cultivation of biomass, transport and distribution, processing, and more. REDcert-EU is a globally leading certification scheme for biomass and biofuels. Independent third-party certification bodies verify compliance with REDcert requirements.

Sources and links
REDcert (1, 2, 3)
GUTcert

SGE

Voluntary methodologies

Certification schemes

The Statement of Greenhouse Gas Emissions (SGE) Methodology, created by QatarEnergy, Pavilion Energy, and Chevron, is intended to help quantify GHG emissions (using direct measurements and/or default values) associated with **delivered LNG cargo from production to import terminal delivery and unloading.** The methodology covers Scope 1, 2, and 3 emissions, basing Scope 3 emissions quantification on lifecycle accounting methods. Third-party verification is required by the scheme, and a statement is provided for each delivered cargo. Each statement requires cargo details, GHG data, and verification information.

SGE, unlike GIIGNL, does not allow the use of offsets. Further differences between the two methodologies are described by Rogier Beaumont of Pavilion Energy below.

SGE vs. GIIGNL:

"We see the SGE Methodology as complementary to [GIIGNL's] in the way that GIIGNL's efforts describe very well the broader context on what can be considered a carbon neutral LNG cargo. On the other hand, [the SGE] methodology goes into more details on the 'how' when it comes to specifically developing a statement for GHG emissions on a per cargo basis. Essentially, the SGE Methodology is more of a handbook for practical step-by-step application by industry players." – Rogier Beaumont, Pavilion Energy

Sources and links
Oxford Energy
Highwood Emissions Management (1, 2)
IPIECA
HC Group
Pavilion Energy

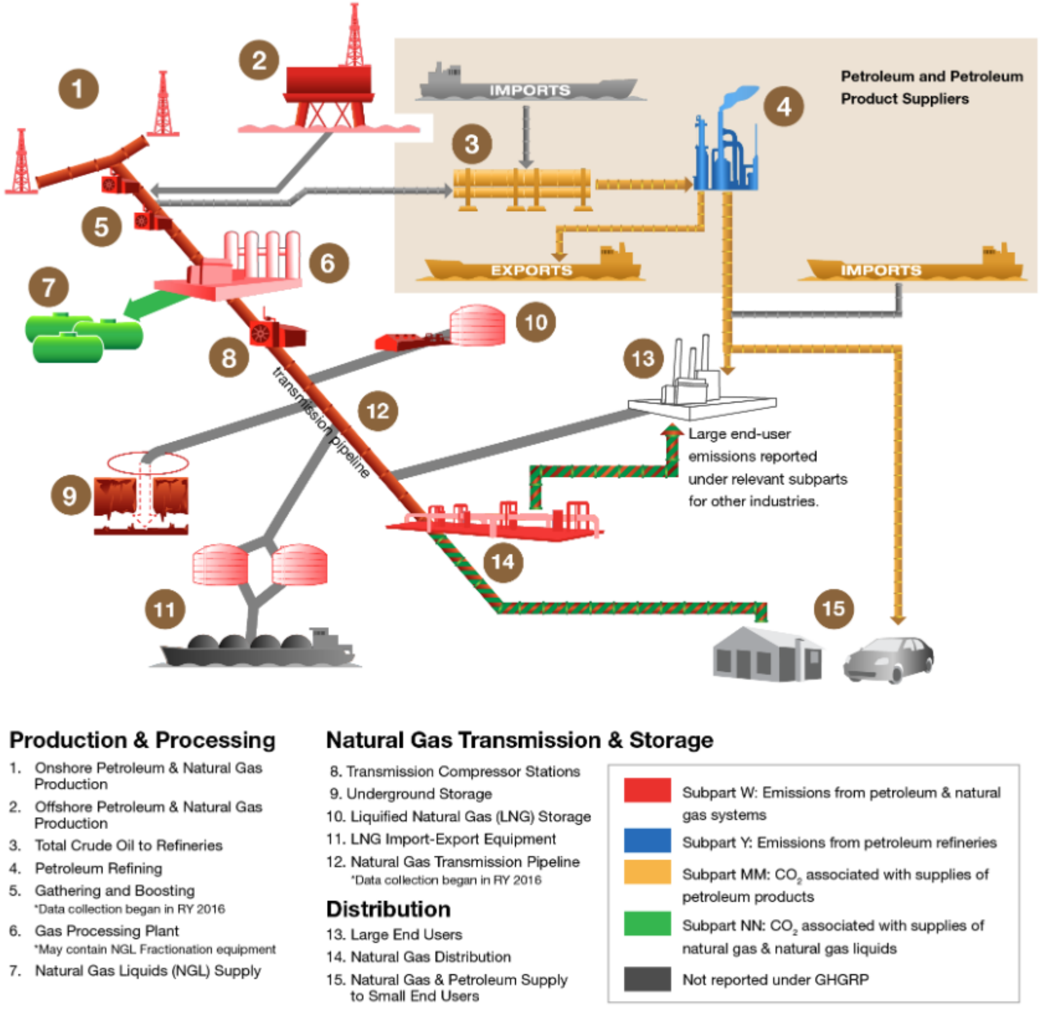
USEPA Greenhouse Gas Reporting Program (GHGRP)

Compliance methodologies

The United States Environmental Protection Agency (USEPA) Greenhouse Gas Reporting Program (GHGRP) is a national program requiring **monitoring and reporting of emissions data** (along with other information) from certain operations within the US. The program currently applies to around 8,000 facilities in the country. Applicable facilities can be determined using the EPA's info sheet.

Subpart W of the program requires **operators of petroleum or natural gas facilities that emit >25,000 Mt CO2e** annually to collect and report GHG emissions data, adhering to quality assurance and other specified procedures. The Subpart W value chain extends from petroleum/natural gas production through natural gas distribution but does not cover LNG import/export equipment (including liquefaction/storage equipment). The data is posted publicly.

Subpart Y covers emissions from petroleum refineries, Subpart MM covers CO2 emissions associated with supplies of petroleum products, and Subpart NN covers CO2 associated with supplies of natural gas and natural gas liquids.



Source: EPA

Sources and links

USEPA (1, 2, 3)

Verra CCS Methodology Framework and Verified Carbon Standard

Voluntary methodologies

Certification schemes

Verra is an organization which develops and manages internationally-recognized, high-integrity standards related to climate and sustainability. Currently, Verra is developing a CCS Methodology Framework which sets criteria and procedures for **emissions quantification for carbon capture, transport, and storage** activities. Verra's Verified Carbon Standard (VCS) is a certification mechanism to generate carbon credits for offsetting emissions. Independent third-party validation/verification bodies (VVBs), approved by Verra, provide certification under the VCS.

Sources and links
Verra (1, 2, 3, 4, 5)

Veritas (GTI Energy)

VERITAS

Voluntary methodologies

Veritas, GTI Energy's **methane** emissions **measurement and verification initiative**, uses both site-level and source-level protocols that include measurement, reconciliation, emission intensity, value chain summation, and assurance methodologies. These protocols have incorporated feedback from a wide range of stakeholders and been refined to improve their consistency, usability, and reliability. Protocols exist **for upstream, midstream, and distribution.**

The **source-level methodologies**, published in February 2024, provide details on how companies can perform site measurements and reconciliation to help meet OGMP 2.0 Level 5 requirements. The methodologies only cover methane emissions, and not other GHGs.

In this way, the Veritas protocols **facilitate a transparent and accurate certification process** (via OGMP or other certification bodies) – but Veritas does not provide the certification themselves.

Sources and links
GTI Energy (1, 2)
USEPA
Highwood Emissions Management

Zero Routine Flaring (ZRF) Initiative

THE WORLD BANK

Other relevant regulations & initiatives

The Zero Routine Flaring (ZRF) Initiative was launched by the World Bank to commit governments and companies to **ending routine flaring by 2030**. Participants must annually report their flaring activities and progress, and monitoring also occurs via government/company reports and satellite observations. The Initiative promotes collaboration between participants to improve available solutions. Of the countries considered in this analysis, Norway, Germany, and the US are participants in the ZRF.

Sources and links
World Bank