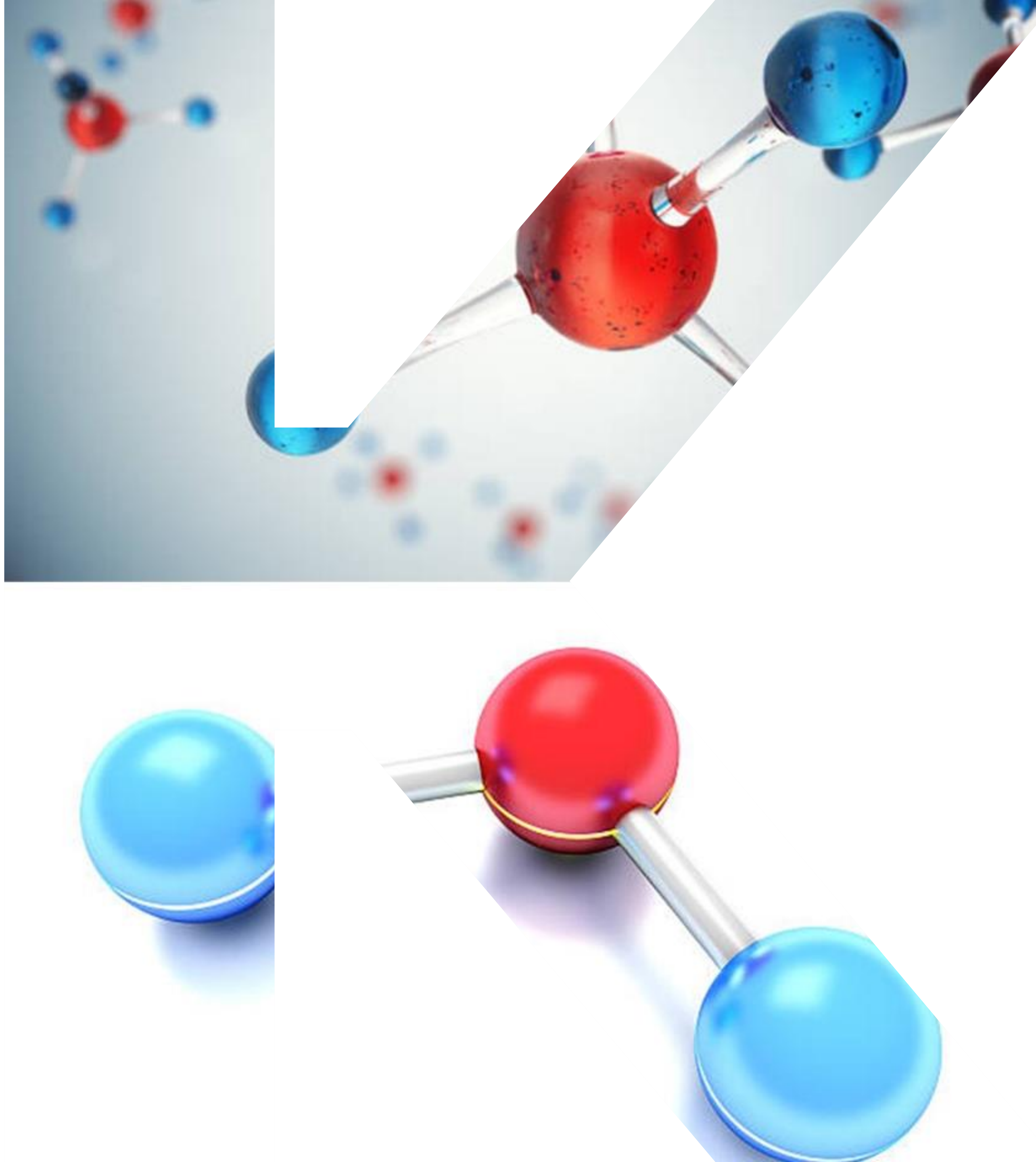
Carbon emissions assessment

Towards accurate control

Vol.1 – Carbon Emissions Management Series

April 2022



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Compiled by the Kearney Energy Transition Institute

Acknowledgements

The Kearney Energy Transition Institute wishes to acknowledge the following people for their review of this FactBook: Philippe Ciais (Associate Director CEA, Laboratoire des Sciences du Climat et de l'Environnement) and Paula Perez Lopez (Centre Observation, Impacts, Energy - MINES ParisTech OIE) as well as Dr. Adnan Shihab Eldin, Claude Mandil, Antoine Rostand, and Richard Forrest, members of the board for the Kearney Energy Transition Institute. The Institute also wishes to thank Christian Lelong form Kayrros for its kind contribution and insights provided for the elaboration of the second chapter of this report. Their review does not imply that they endorse this FactBook or agree with any specific statements herein.

About the FactBook: Carbon emissions management

The FactBook focuses on carbon-based greenhouse gas (GHG) emissions (CO_2 and CH_4) and identifies the gaps and the current knowledge in this field. The FactBook introduces key scientific concepts, such as the global warming potential or the life-cycle assessment that are used to estimate and assess greenhouse gas emissions, together with other potential environmental impacts, from anthropogenic activities at different scales and highlights related uncertainties, providing concrete case analysis across key industrial sectors and energy uses.

About the Kearney Energy Transition Institute

The Kearney Energy Transition Institute is a nonprofit organization that provides leading insights on global trends in energy transition, technologies, and strategic implications for private-sector businesses and public-sector institutions. The Institute is dedicated to combining objective technological insights with economical perspectives to define the consequences and opportunities for decision-makers in a rapidly changing energy landscape. The independence of the Institute fosters unbiased primary insights and the ability to co-create new ideas with interested sponsors and relevant stakeholders.

Authors

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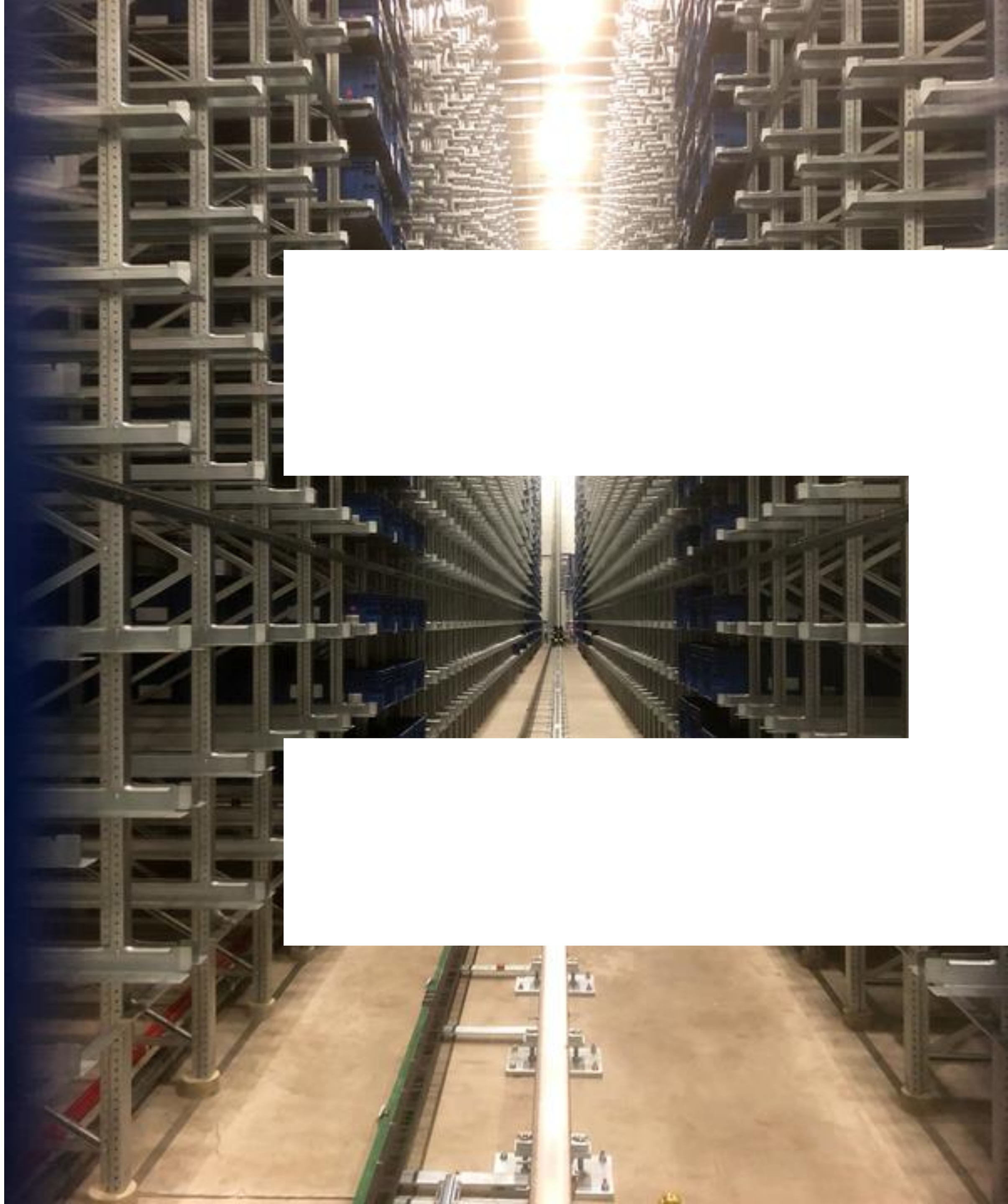
1. The need for carbon emissions management



Climate change mitigation strategies must focus on reducing methane and carbon dioxide emissions

On a global level, the increase of the greenhouse effect is driven by emissions of several gases, about 90 percent of which consist of carbon dioxide (CO_2) and methane (CH_4). The energy sector is by far the largest emitter, as it accounts for more than 40 percent of total GHG emissions (CO_{2eq}).

CO_2 and CH_4 are the main greenhouse gases in the atmosphere, with concentrations respectively equal to 417 ppm and 1.9 ppm. Net carbon fluxes to the atmosphere are decomposed into positive (anthropogenic and natural emissions) and negative (absorption by lands and oceans) contributions.

The amount of carbon in the atmosphere has increased by 30 percent since the pre-industrial era and is growing at a rate of 5.1GtC a year.[1] Burning the same amount of fossil fuels as what has already been extracted since the pre-industrial era would lead to a 2°C increase of surface temperature. Current trends predict a much higher volume of extraction, and fossil reserves are still large enough to release 14 times that amount.

To estimate and compare the impact on climate change of GHG emissions, policymakers use a common metric called CO_2 equivalent, which relies on a comparison of the radiative forcing of a gas with CO_2. The basis is the change of radiative forcing; that is, the unbalance of energy fluxes in the atmosphere caused by emitted GHGs. Methane and carbon dioxide have contributed to 70 percent of total change in radiative forcing since the pre-industrial era.

Two choices must be made when calculating CO_2–eq emissions. The first is the type of metric used and the second is the time scale on which the impact is assessed. There is no single metric and time horizon appropriate for all applications—the choice depends on the purpose. Main recommendations regarding these choices include always specifying the assumptions behind the calculation, using different types of metrics according to their lifetime, and using at least two different time horizons when reporting to understand the implication of choosing another metric.

Recent studies revealed the magnitude of unreported methane emissions on a global level and the importance of reducing them. Those studies better reflect atmospheric dynamics and the impact on temperature change of short-lived components like methane by relying on step-based metrics. Until now, metrics depending on the time-horizon chosen, like the global warming potential (GWP), were used. With a 20-year time frame, GWP show a two orders of magnitude higher impact of CH_4 than of CO_2. With a 100-year time scale, the difference is one order of magnitude lower.

[1] GtC is gigaton of carbon, Friedlingstein et al. 2021
Source: Kearney Energy Transition Institute analysis

What is the anthropogenic increase of greenhouse effect?

Earth’s energy budget viewed from the top of the atmosphere

Incoming solar radiation[1]
(~340 W/m^2)

Emitted infrared radiation
= Outgoing radiation

1 **Initial equilibrium state**
- Incoming and outgoing fluxes balanced
- Global average surface temperature stable

2 **Greenhouse gases are added**
- Instant decrease in emitted infrared radiation
- Positive energy imbalance
- Extra heat retained by the Earth
- Progressive global warming
- Gradual increase in emitted infrared radiation

time

3 **New equilibrium reached**
- Stabilization takes several centuries (climate lag)
- Energy balance back to equilibrium
- New average temperature (increased by ΔT)
- Induced **climate change**[1]

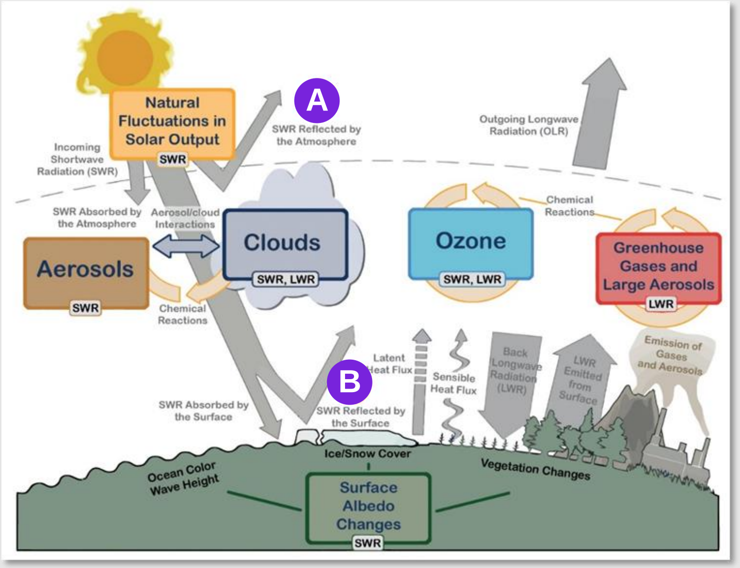
Greenhouse gases

1. Earth also reflects solar radiation through its albedo(≈ 30% of incoming radiation) so only about 70% of incoming short-wave radiation is lost as infra-red radiation.
Climate change refers to a significant change in the statistical distribution of weather patterns over a sustained period, of at least 20-30 years.
Source: Kearney Energy Transition Institute, “Climate Change FactBook - Scientific basis” (2015)

1.1 Overview of the greenhouse effect

The Earth’s energy balance is influenced by the intensity of solar radiation and the properties of its atmosphere, surface and oceans

On the one hand, clouds, aerosols and the surface partially reflect incoming solar radiation and contribute to cooling the Earth



A Atmospheric albedo

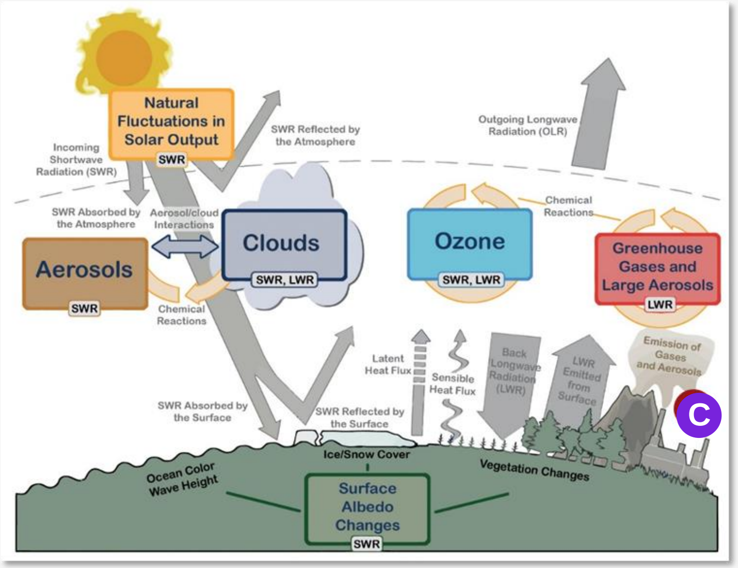
About 30% of solar radiation is reflected into space before it can heat the Earth’s surface.

- **The amount of cloud** cover and its reflectivity are influenced primarily by humidity and atmospheric circulation, which can be affected by human-induced climate change.
- **Aerosols** partly reflect sunlight, generally have a cooling effect and influence albedo and cloud formation as well. Aerosols are small particles in suspension (fossil-fuel combustion, volcano eruptions, dust and sea salt.
- **Black carbon** (smoke, industrial ash, soot) is a dark aerosol with also an important warming effect.

B Surface albedo

- **The ocean and land cover (forests, deserts, ice/snow cover …)** influences surface albedo and is indirectly influenced by human activity through climate change and land-use change.

On the other hand, greenhouse gases partially retain emitted infrared radiation in the lower atmosphere and contribute to warming the surface



C Greenhouse gases (GHGs)

Directly emitted by human activities and natural processes:

- **Carbon dioxide** (CO_2): naturally present in the atmosphere and released by hydrocarbon combustion, deforestation…
- **Methane** (CH_4): naturally present in the atmosphere, and released by human activity (agriculture, waste, fossil-fuels)
- **Nitrous oxide** (N_2O): mostly from the use of fertilizers
- **Fluorinated gases** (F-gas): mostly from the use of refrigeration

Precursors: CO and NOx emitted from incomplete combustion are not GHGs can increase OH radical concentration and thus decrease CH_4

Not directly emitted by human activities

- **Tropospheric Ozone** (O_3): results from the atmospheric oxidation of unburned hydrocarbons
- **Water vapor** (H_2O): naturally present in the lower atmosphere in very large quantities, increases **exponentially with temperature.**

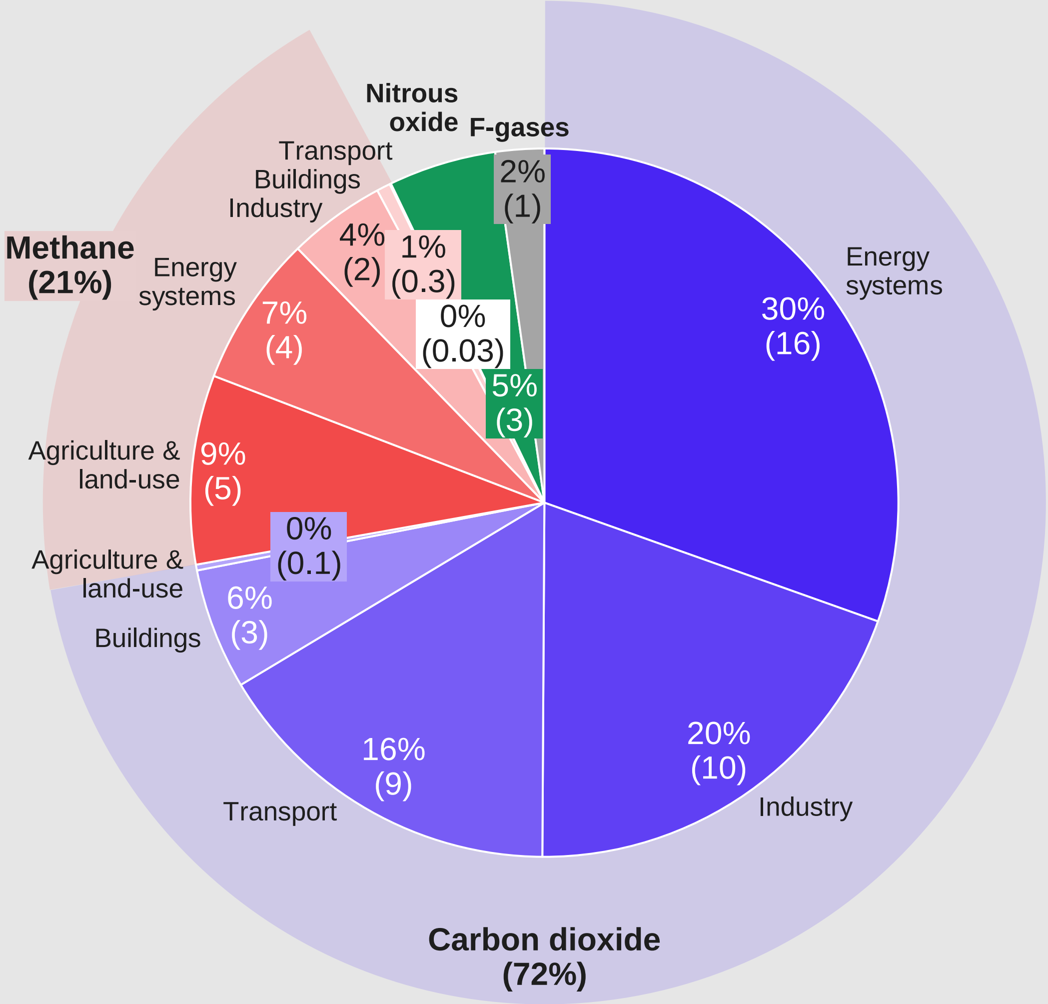
Several gases make up the anthropogenic greenhouse effect, but CO_2 and CH_4 stack up to 93%

Total GHG emissions represented **52.5 $GtCO_2eq$** in 2019, about **48.8 $GtCO_2eq$** from CO_2 and CH_4 emissions

1.2 Overview of global anthropogenic GHG emissions

Global greenhouse gas emissions in 2019

$GtCO_2eq$ and % of total GHG



Note: Graphic uses Global Carbon Project data for global carbon emissions 2021 combined with EDGAR v6.0 split between sectors and uses; Global Methane Budget 2020 for methane emissions by sources and sectors and EDGARv6.0 data (2018) for global CH_4 (GWP-100 (AR6)), N2O and F-gases emissions. AFOLU: Agriculture, Forestry and Other Land Use
Sources: Global Carbon Budget 2021; International Energy Forum Methane Initiative, 2021; Kearney Energy Transition Institute analysis

Carbon dioxide (CO_2, 37.9 $GtCO_2eq$): Fossil fuel use is the primary source of CO_2. But CO_2 can also be emitted from direct land use, land management and land use change, such as through deforestation, land clearing for agriculture, and degradation of soils. Likewise, land remove CO_2 from the atmosphere through reforestation, land management, and changes in environmental drivers. Ocean also removes 1/3 of the fossil-fuel CO_2 emissions.

Methane (CH_4, 10.9 $GtCO_2eq$): Agricultural activities, waste management, fossil fuel extraction and distribution, and biomass burning all contribute to anthropogenic CH_4 emissions.

Nitrous oxide (N_2O, 2.6 $GtCO_2eq$): Agricultural activities, such as fertilizer use, are the primary source of N_2O emissions. Fossil fuel combustion and industry also generates N_2O.

Fluorinated gases (F-gases,1.2 $GtCO_2eq$): Industrial processes, refrigeration, and the use in other industrial sectors contribute to emissions of F-gases, which include hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF6).

Nitrogen trifluoride (NF_3, 2.10^{-3} $GtCO_2eq$) was added as a GHG under the Kyoto Protocol for its second commitment period.

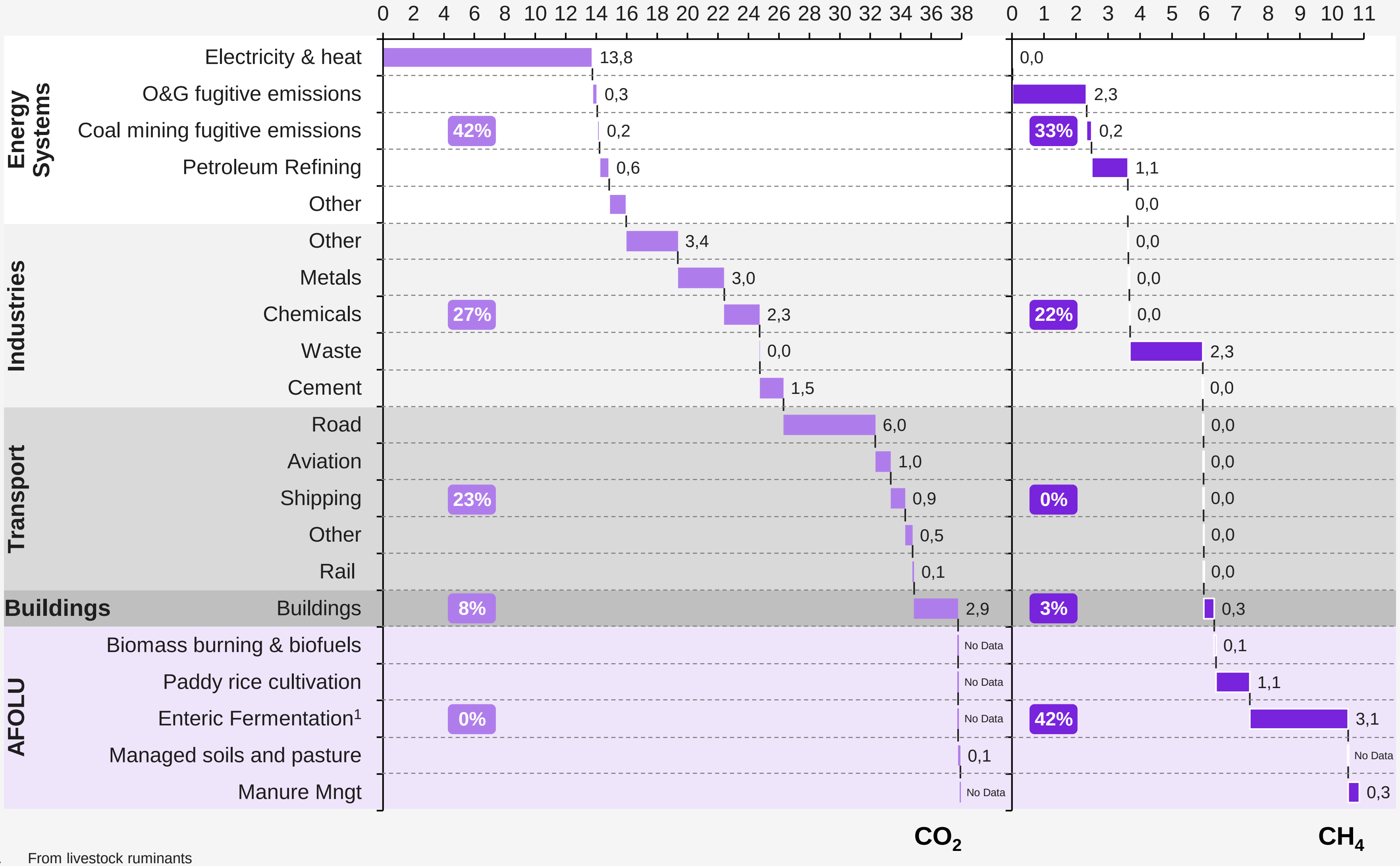
Methane is the second GHG from anthropogenic sources, and is emitted from three major processes: livestock ruminants, waste and oil, gas & coal fugitive emissions

Recent studies demonstrated that coal and Oil & Gas fugitive emissions are largely underestimated compared to national inventories (see Chapter 2)

1.2 Overview of global anthropogenic GHG emissions

Global carbon emissions (CO_2 and CH_4) per sector

$GtCO_2eq$, 2019



1. From livestock ruminants

Note: Graphic uses Global Carbon Project data for global carbon emissions 2021 combined with EDGAR v6.0 split between sectors and uses; Global Methane Budget 2020 for methane emissions by sources and sectors and EDGARv6.0 data (2018) for global CH_4 (GWP-100 (AR4)), N_2O and F-gases emissions. AFOLU: Agriculture, Forestry and Other Land Use, AFOLU inventories report FFCO2 for machinery in agricultural sector which is not the case here.

Sources: Global Carbon Budget 2021; International Energy Forum Methane Initiative, 2021; Kearney Energy Transition Institute analysis

Methane emissions measurement displays important variability but about 60% of methane emissions are from anthropogenic sources

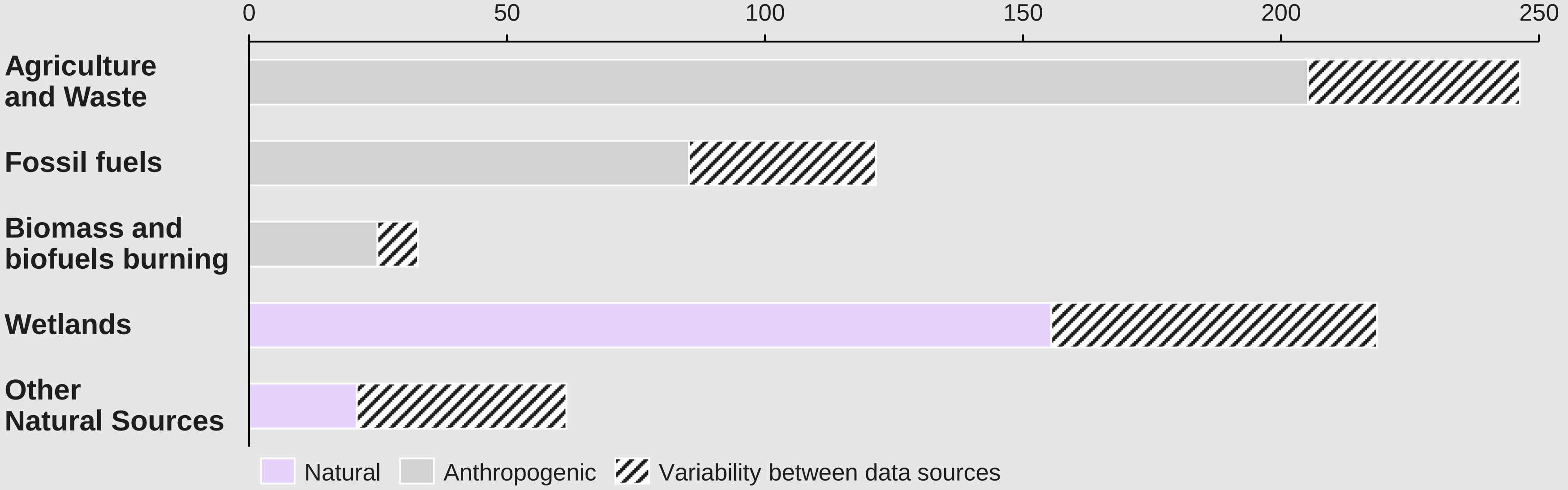
The amount of methane in the atmosphere has more than doubled since pre-industrial times.

Nearly 60% of methane emissions are driven by human activity.

1.2 Overview of global anthropogenic GHG emissions

Natural and anthropogenic sources of methane emissions from Global Carbon Project

Mt CH_4/yr and %, global, 2020, GCP Top-Down Methane Budget



Approximately 40% of global methane emissions come from natural sources, such as wetlands or wildfires. The remaining 60% are anthropogenic, of which the largest sources are:

Agriculture and Waste (45%) is the second methane emissions sector, and the first anthropogenic methane source. Methane emissions from livestock originate mainly from ruminant species (enteric fermentation and manure management (30%)), and from rice cultivation (10%)). Sources of methane emissions are often diffuse in the agriculture sector, which can make measurement, reporting and verification challenging. **Waste.** The main identified sources of methane are emissions in landfill sites, the treatment of sewage sludge, and leaks from biogas plants.

Fossil fuel production and use (20%). Methane leaks come from fossil fuel production sites, transmission systems, ships, and distribution systems. Methane is also vented (released intentionally) into the atmosphere. Even when flared (burnt), carbon dioxide is released, and methane can still escape during flaring as a result of incomplete combustion.

Biomass/biofuels burning (5%). Methane emissions arising from biomass burning are a result of incomplete combustion during large-scale burning of woodlands, savanna (periodically burnt for land clearance), burning of agricultural waste or biomass burning for domestic use.

1. Later reduction is an option to meet a target because of immediate effect 2. In UNFCCC national inventories - fire or biomass burning occurring in managed land are counted as anthropogenic (ie all fires CH_4 emissions are anthropogenic) 3. Other natural sources include: fresh waters, geologic seepage, wild animals, termites, wildfires, permafrost and vegetation

Sources: Global Carbon Budget 2021; International Energy Forum Methane Initiative, 2021; Kearney Energy Transition Institute analysis; Curtailing Methane Emissions from Fossil Fuel Operations, IEA, October 2021; Kearney Energy Transition Institute analysis

Anthropogenic carbon emissions accumulate in the atmosphere and increase the concentration in the atmosphere, land and oceans

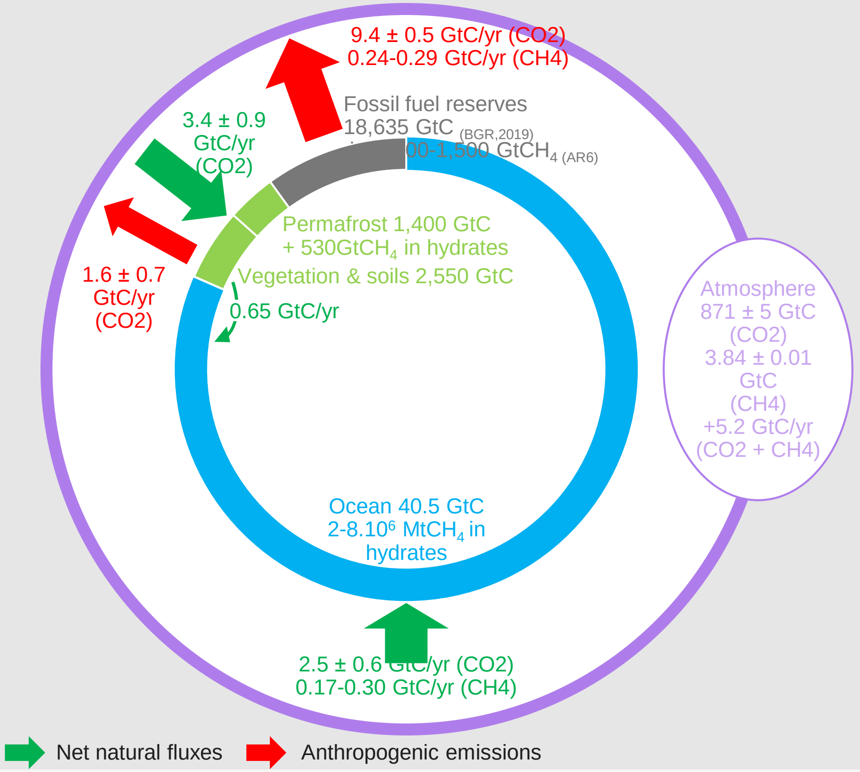
Carbon fluxes here include CO_2 and CH_4 **anthropogenic** (direct human activities since pre-industrial/pre-agricultural time: agriculture, waste-management, fossil-fuel related activities) and **natural** (pre-agricultural emissions even if perturbed by anthropogenic climate change).

Fluxes are mainly estimated from models, while atmospheric growth (5.2 GtC/yr) is estimated from direct concentration measurements.

In the atmosphere, CO_2 is the main carbon bearing trace gas with a concentration of approximatively **417 ppm in January 2022** (mass of 918 GtC). Additional trace gases include CH_4 (~3.7 GtC, 1,909 ppb, end of 2021) and CO (~0.2 GtC).

An amount of less than half of all emissions stays in the atmosphere. **Land and oceans together have a net absorption of ~52% of all emissions, of which 55% is attributed to land and 45% to oceans.**

Global carbon stocks (GtC) and net fluxes (GtC/yr) of CO_2 (2019) and CH_4 (2017), IPCC AR6 Fig.11 & 5.12



Global mean concentrations for CO_2 and CH_4 in 2019 correspond to increases of about 47% and 156%, respectively, above the pre-industrial levels of 1750 (*AR6, Chap5*).

Since the beginning of the industrial era, fossil fuel extraction has resulted in the release of more than 365 GtC stored in fossil fuels to the atmosphere, altering carbon budgets and fluxes. **There is still enough in the fossil reserves to release almost 50 times this amount.**

An increase of 2° in temperature compared with the pre-industrial era corresponds to a stabilized carbon concentration of **450ppm**. **This concentration will already be reached if we extract and emit an amount of carbon equal to less of which has already been released.**

In addition to climate change, higher carbon concentration in the atmosphere is causing fundamental changes in the biogeochemistry of natural reservoirs.

1.3 Overview of global carbon fluxes

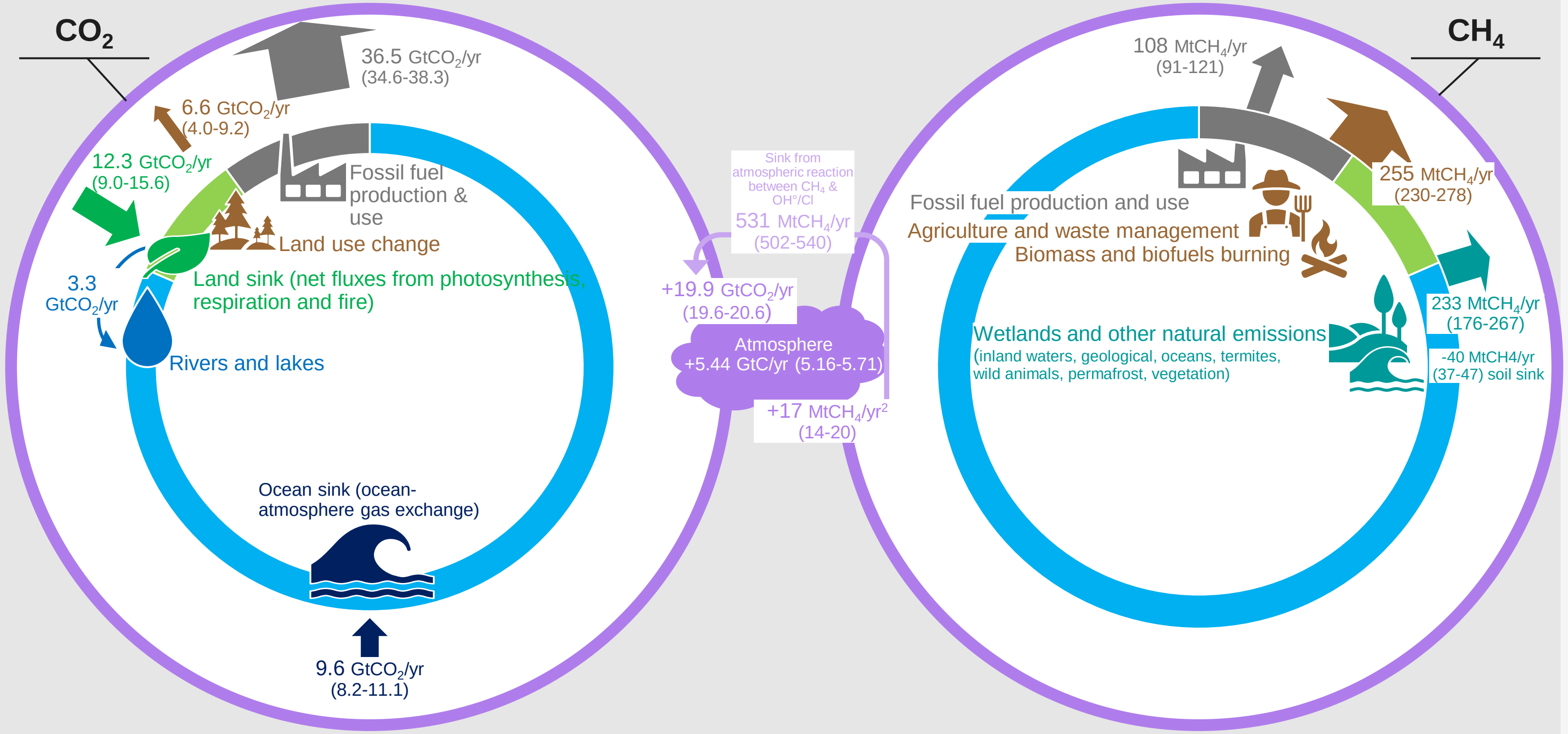
Notes: These numbers may have major uncertainties, but they show the magnitude of anthropogenic activities; (10.03 + 1.99 – 3.22 – 2.62) – 5.89 = 0.25 GtC per year is the budget imbalance between modeled atmospheric uptake and observations. In particular, it captures the uncertainties of models in capturing the observed growth rate.
Here we convert CO2 and CH4 into their equivalent in terms of carbon (C) using 1,3356 gCH_4 = 1 gC and 3,664 gCO_2 = 1 gC
Sources: Saunois & al., Global Carbon Budget 2021 (2020 data for carbon fluxes), AR6 Chapter 5 Fig 5.11 and 5.12 for fluxes and stocks, BGR 2019 for fossil fuels reserves, Kearney Energy Transition Institute analysis

CO_2 is the first green house gas is terms of carbon flux going to the atmosphere

CO_2 source	Estimation method
Fossil fuel	Energy consumption data
Land use, land-use change, and forestry	Bookkeeping approaches using land use emissions models.
Land sink	Global dynamic vegetation models
Ocean sink	Global ocean biochemistry models
Atmospheric growth rate	Direct atmospheric CO_2 concentration measurements

1.3 Overview of global carbon fluxes

Net fluxes of CO_2 ($GtCO_2$/yr, Global Carbon Budget 2019) and CH_4 ($MtCH_4$/yr, Global Methane Budget 2017)



All uncertainties represent ± 1 sigma error (68% chance of being in the range provided).

All CH_4 fluxes and uncertainties are estimated from top-down atmospheric inversions gathering various chemistry-transport models and using in-situ observations and satellite observations (three different retrievals from the JAXA satellite Greenhouse Gases Observing SATellite (GOSAT).

1. This additional amount of CO_2 is included in the observed atmospheric of 19.9 $GtCO_2$/yr but does not appear in the flows. Thus, it is part of the budget imbalance. 2. Global Methane Top-Down Budget 2017. The absolute budget imbalance for CO_2 is |(36.5 + 6.6 + 12.3 – 9.6) – 19.9| = 1.3 $GtCO_2$ per year. The budget imbalance for CH_4 is |(255 + 130 + 108 – 531) – 17| = 55 $MtCH_4$/yr.
Note: 1GtCO2 = 0.273GtC and 1MtCH4 = 0.00075GtC
Sources: Friedlingstein et al. 2020, Jackson et al. 2020 Global Carbon Budget 2020; Saunois et al 2019, Global Methane Budget 2020; Intergovernmental Panel on Climate Change AR5 Gr. I Section 6.1 & Gr. III Section 3.8.3; Kearney Energy Transition Institute analysis

Climate-change mitigation strategies rely metrics to compare the effect of different GHGs

Emission metrics are ways to compare the effect of a greenhouse gas to the effect of CO_2

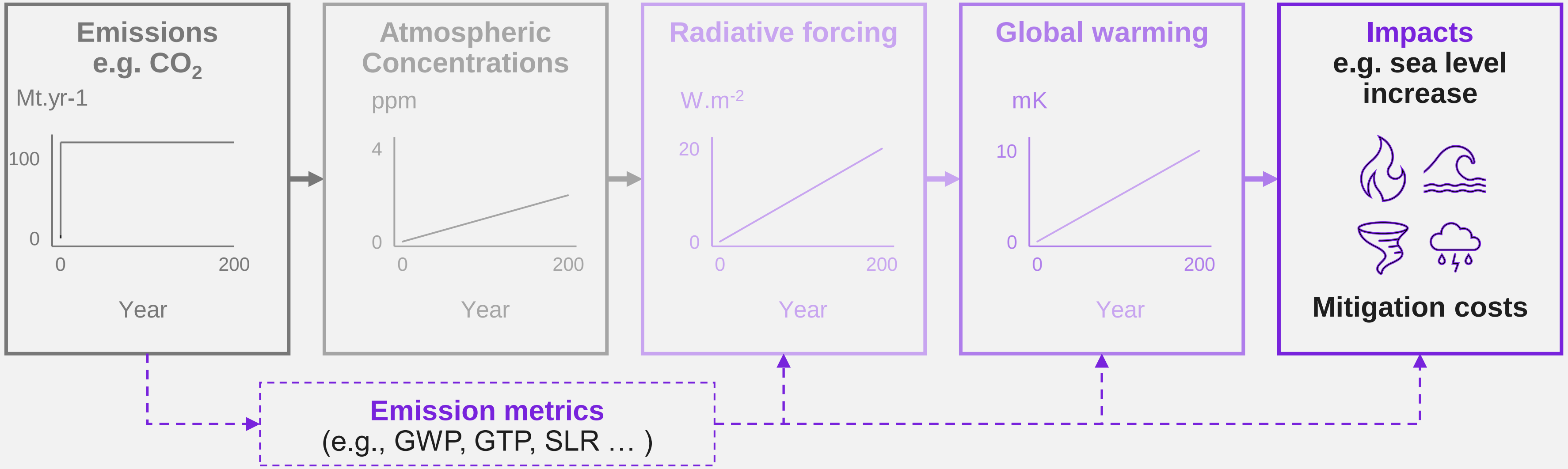
Global environmental policies aim to mitigate climate change and its related impacts on the environment. To do so, policymakers target the **origin of the causal chain: anthropogenic greenhouse gases emissions.** They need to be able to **quantify** the impact on the environment of the emission and the removal of a given quantity of different greenhouse gases. They rely on the use of **emission metrics** (e.g., Global Warming Potential (**GWP**), Global Temperature Potential (**GTP**), Sea Level Rise (SLR), etc.). In order to compare the effect of different gases in order to prioritize mitigation actions. **Policymakers choose the appropriate metrics relative to their policy goals.**

The contribution of GHG emissions to global warming is explained by **radiative forcing**, which is defined as the “change in the net, downward minus upward, radiative flux (expressed in $W.m^2$) at the tropopause or top of the atmosphere due to a change in an external driver of climate change, such as, for example in the change in the concentration of a gas[1], or the output of the sun.”

There are also **indirect** contributions, e.g., linked to carbon cycle and **interactions between gases** in the atmosphere.

Gases have very **different properties**, on which the climate system response to their emissions depend (e.g., lifetime in the atmosphere), which makes the comparison complex and is why metrics are used.

Overall, modelling the successive causal steps is complex, and the design of metrics for specific purpose is the subject of extensive scientific research. Evolution of emission metrics (creation of new ones, improvements of old ones) are reported in the successive IPCC reports, for example the UNFCCC parties agreed for monitoring progress to Paris goals to use GWP100 but have left open the possibility to revise that choice in the future.



1. Or volcano aerosols

Note: Graphics representing the successive steps of the causal chain are taken from simulations from John Lynch et al 2020 Environ. Res. Lett. 15 044023.

Sources: Intergovernmental Panel on Climate Change AR5 (2014) and AR6 (2021); John Lynch et al 2020 Environ. Res. Lett. 15 044023; Kearney Energy Transition Institute analysis

There are a wide variety of emission metrics, which serve different purposes and are constantly revised

Metrics are further defined in the Appendix

Other metrics include, for example, the Absolute Global Precipitation Potential (AGPP, derived from RF and AGTP), the Global Cost Potential (GCP), the Global Damage Potential (GDP, the damage costs to society resulting from an incremental increase in emissions), or the Cost-Effective Temperature Potential (CETP).

1.4 GHG and climate change: key concepts and uncertainties

Metric	Definition	Usefulness or purpose
Radiative forcing (RF) (W.m^{-2})	**Radiative efficiency (W.m^{-2}.ppb^{-1}) is the radiative forcing associated to a unit change of concentration of a given component in the atmosphere.** Change in net downward radiative flux at the tropopause after allowing for stratospheric temperatures to readjust to radiative equilibrium, while holding surface and tropospheric temperatures and state variables fixed at the unperturbed value.	Simple quantitative basis for comparing some aspects of the potential climate response (basis for the calculation of the other metrics) ERF is more accurate than RF, but its calculation is computationally intensive.
Effective RF (ERF) (W.m^{-2})	Change in net downward radiative flux after allowing for atmospheric temperatures, water vapor and clouds to adjust, but with surface temperature or a portion of surface conditions unchanged, due a unit change of concentration of a given component in the atmosphere.	
Absolute Global Warming Potential (AGWP)	Time-integrated RF after an emission pulse of a given component, over a chosen time horizon (e.g., 20/100/500 yrs).	Basis for the calculation of GWP
Global Warming Potential (GWP)	Ratio of AGWP for a given component over AGWP for the reference gas (CO_2). Default metric for transferring emissions of different gases to a common scale, "CO_2 equivalent emissions."	GWP compares the radiative forcing of a given mass of GHGs to the same mass of CO_2 over a specified time. Index of how much energy accumulation could be avoided by avoiding the emission of a unit of a GHG compared to avoiding a unit of CO_2 at a given future point in time.
Absolute Global Temperature Potential (AGTP)	Convolution time integral of RF with a global surface temperature response function, in response to an emission pulse, over a chosen time horizon.	Basis for the calculation of GTP
Global Temperature Potential (GTP)	Ratio of AGTP for a given gas over AGTP for the reference gas CO_2.	Index of how much global warming could be avoided by avoiding the emission of a unit of a short-lived GHG compared with avoiding a unit of CO_2 at a given future point in time
Integrated AGTP (iAGTP or AGTP^S)	Time-integrated AGTP, which is equivalent to a time-integrated radiative forcing due to a step change in the rate of emissions (in contrast to an instantaneous pulse in a given year that is used for AGTP).	Basis for the calculation of CGTP in climate models
Combined GTP (CGTP) (years)	Ratio of AGTP^S for a given gas over AGTP for the reference gas CO_2. (Expressed in years as AGTP^S is a time-integrated AGTP.)	Close approximation of the additional energy accumulation/global warming from a time-series of short-lived GHG emissions; useful scaling for comparing a change in emission rate (in kg.yr^{-1}) of short-lived GHG (e.g. CH_4) with a pulse emission of CO_2 (in kg) Those pulse-step metrics are less dependent on the chosen time horizon for species with lifetimes less than half the time horizon of the metric. They are useful where time dependence of pulse metrics, such as GWP or GTP, complicates their use.
GWP*	Combination of emissions (pulse) and changes in emission levels (step) approaches. The step (or flow or rate) term in GWP* accounts for the impact due a change in short-lived gas emission rate, as in CGTP, but here approximated by the change in emissions over the previous 20 years.	

Sources: Intergovernmental Panel on Climate Change AR5 (2014) and AR6 (2021); Kearney Energy Transition Institute analysis

Prioritizing emissions reduction of a specific GHG is highly dependent on the chosen time horizon and type of emission metric

Choices of time horizon affect the results by a factor of up to ~10. Understanding the differences between types of metrics is necessary to correctly interpret their values, which can vary by a factor of ~200 depending on the type of metric used.

1.4 GHG and climate change: key concepts and uncertainties

Comparison of GHG metrics for different gases and over various time horizons

Global Warming Potential (GWP), Global Temperature Potential (GTP), and Combined GTP

Species	Lifetime (years)	GWP-20	GWP-100	GWP-500	GTP-50	GTP-100	CGTP-50 (years)	CGTP-100 (years)
CO_2	Hundreds[1]	1	1	1	1	1	NA[2]	NA
N_2O	109	273	273	130	290	233	NA	NA
CFC-11	52.0	8321	6226	2093	6351	3536	NA	NA
HFC-134a	14.0	4144	1526	436	733	306	146670	181408
CH_4 - fossil	11.8	82.5	29.8	10.0	13.2	7.5	2823	3531
CH_4 - non fossil	11.8	80.8	27.2	7.3	10.3	4.7	2701	3254

×10

×20

×10

Using a GTP metric with a 50-year time horizon, avoiding emitting a unit of N_2O is ~**20** times more efficient than avoiding emitting a unit of fossil CH_4 in terms of temperature change.

With a 50-year time horizon, the CGTP metric for CH_4 shows that decreasing annual methane emissions rate by a unit is ~**10** times more efficient than avoiding emitting a unit of N_2O.

Once emitted, GHG remain in the atmosphere for a limited time before either transforming by reacting chemically with other species in the atmosphere or being absorbed by the earth's surface or being broken down by radiation. So each gas is characterized by a lifetime. Gases with lifetimes below ~20 years are considered short-lived.

For a given component, GWP (or GTP) indicates how much energy accumulation (or global warming) could be avoided by avoiding a pulse emission of the gas compared to avoiding a unit of CO_2 at a given future point in time (e.g., GWP-20 means Global Warming Potential calculated using a 20-year time horizon). Such pulse-based emission metrics for short-lived GHGs are very sensitive to the choice of time horizon (e.g., for HFC, GWP is divided by ~10 when the time horizon goes from 20 to 500 years).

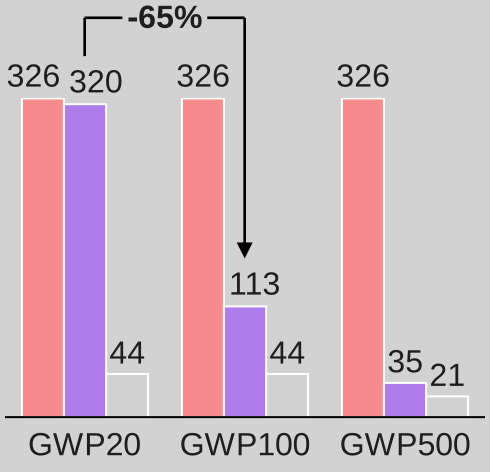
Combined Global Temperature Potential (CGTP) and GWP accounts for differences between short-lived components (e.g., CH_4), and long-lived gas (e.g., CO_2). CGTP take steps (or rates) of emissions as inputs, while GTP and GWP are calculated using emission pulses.

For CH_4, a difference is made between fossil and non-fossil CH_4: metrics for fossil methane account for additional CO_2 created by oxidation of CH_4 in the atmosphere, while for non-fossil sources, this CO_2 compensates for that which was absorbed by biological sources before CH_4 emissions. Therefore, GWP for non-fossil CH_4 is slightly lower than fossil CH_4.

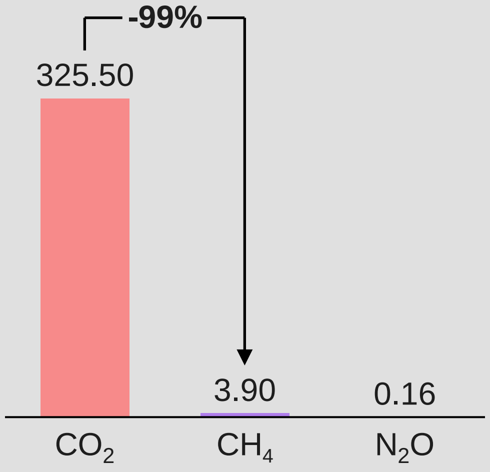
1. There is no specific lifetime for CO_2 since it involves different time scales and processes 2. CGTP is defined in theory for long-lived GHGs, but their value is more uncertain, and they are not used as CGTP is precisely useful to better assess for impacts of short-lived gas emissions.
Sources: Intergovernmental Panel on Climate Change AR5 (2014) and AR6 (2021); Kearney Energy Transition Institute analysis

Traditional CO_2-equivalent emissions have been used to assess the impact of changes in cumulative emissions

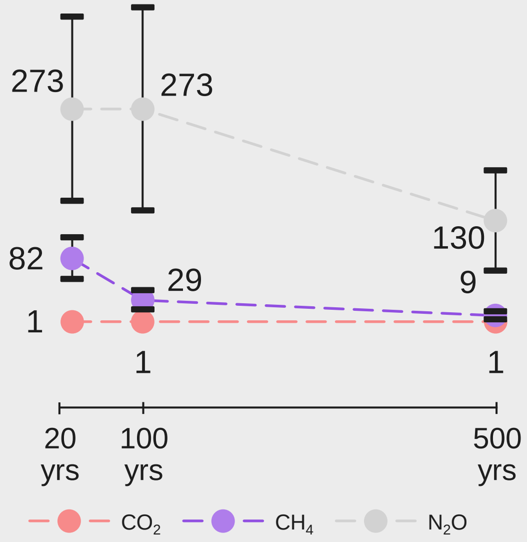
GWP-based CO_2-eq emissions change for three time horizons
2010–2020, $GtCO_2$-eq



Cumulative CO_2, CH_4 and N_2O emissions change
2010–2020, Gt



GWP of CO_2, CH_4, and N_2O for three time horizons with associated uncertainties



Using pulse-based metrics to put changes in cumulative emissions of all gas on a common scale shows a rapid decrease of methane impact.

CO_2-equivalent is a common scale for GHG emissions, which enables policymakers to compare their impact on climate change.

- 1kg CO_2-eq of emitted gas indicates that the emission has the same impact as 1kg of emitted CO_2. CO_2-eq relies on classic metrics, e.g., Global Warming Potential or Global Temperature Potential.

In theory, GWP and GTP metrics are not adapted to cumulative emissions (e.g., over a certain period) since they assess the impact of pulse-emissions. But we can take cumulative emissions as inputs in the CO_2-eq formula, making the approximation that the temperature change scales with cumulative emissions.

- Using GWP20 based CO_2-equivalent values shows that cumulative emissions changes of CH_4 and CO_2 from 2010 to 2020 have similar impacts on the climate, while absolute cumulative change of CH_4 emissions represents only ~1% of one of CO_2.

GWP of a component (and thus CO_2–eq emissions) does not vary much for a time scale shorter than the gas lifetime.

- CH_4 has a lifetime 12 years and N_2O of 109 years. So with a 100-year time horizon, the change in CH_4 emissions has a much lower impact than with a 20-year time horizon, while for N_2O, it is the same.

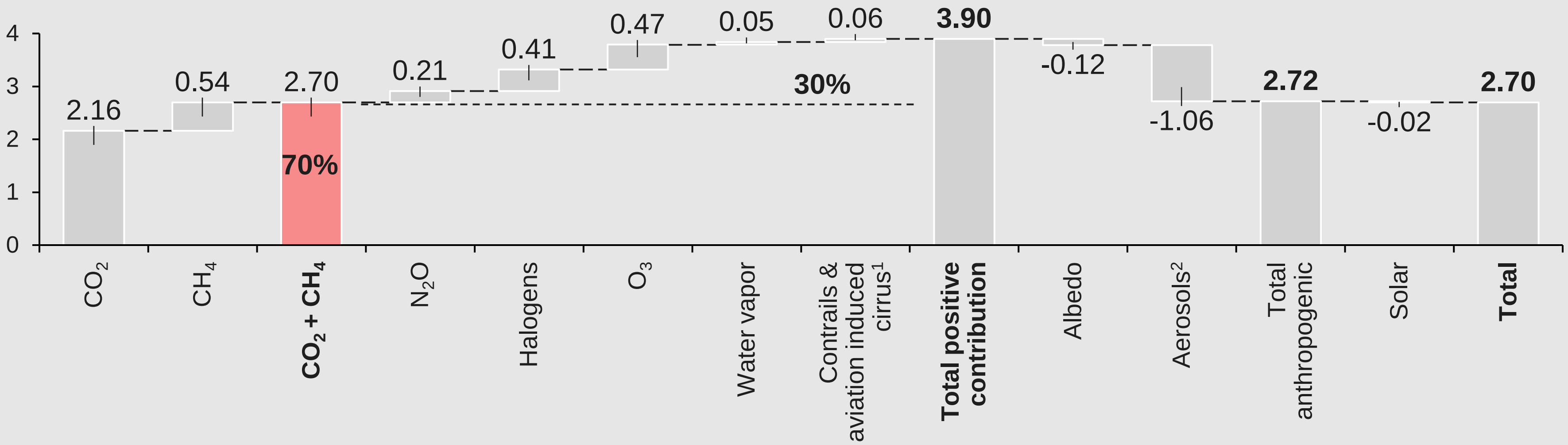
Emission metrics such as GWP vary according to the purpose of the user. Interpretation of CO_2-eq values should consider those uncertainties.

Sources: Global Carbon Project (Global CO_2, CH_4, N_2O budgets 2020), Intergovernmental Panel on Climate Change AR5 (2014) and AR6 (2021), William J Collins et al 2020 Environ. Res. Lett; Lynch et al., 2020; Kearney Energy Transition Institute analysis

In terms of change in radiative forcing since the pre-industrial era, carbon dioxide and methane are the main contributors

Net change in effective radiative forcing by contributing forcing agents (1750–2019)

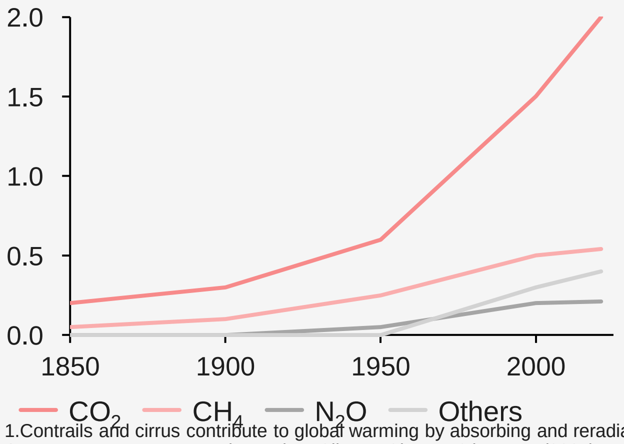
Global, W.m-2



Together, CO_2 and recently emitted CH_4 contribute to ~70% of the positive radiative forcing change due to human activities since the pre-industrial era.

Evolution of radiative forcing from three major well-mixed greenhouse gases (1850–2019)

Global, W.m-2



Among the various metrics that provide estimates of the climate impact of individual factors, radiative forcing (RF) is one of the most widely used one and is the main input for calculating other metrics (e.g., GWP). The net change in radiative forcing from the pre-industrial era is **~2.7 W.m-2.**

RF is due to both natural and anthropogenic agents. An emission pulse of a given component results in additional atmospheric agents (e.g., CO_2, H_2O, O_3 for CH_4). Both the emitted and the resulting agents contribute to RF.

Human activity has caused many changes in different forcing agents in the atmosphere or land surface, especially GHGs and atmospheric aerosols.

RF from well-mixed GHGs (e.g., CO_2, CH_4, N_2O) are determined entirely from observations, while RF from heterogeneously distributed forcing agents (e.g., ozone and aerosols) are derived from chemistry-climate models.

1.Contrails and cirrus contribute to global warming by absorbing and reradiating infrared radiation from Earth 2. Including volcanic activity

Sources: Intergovernmental Panel on Climate Change 6th report (2021); Kearney Energy Transition Institute analysis

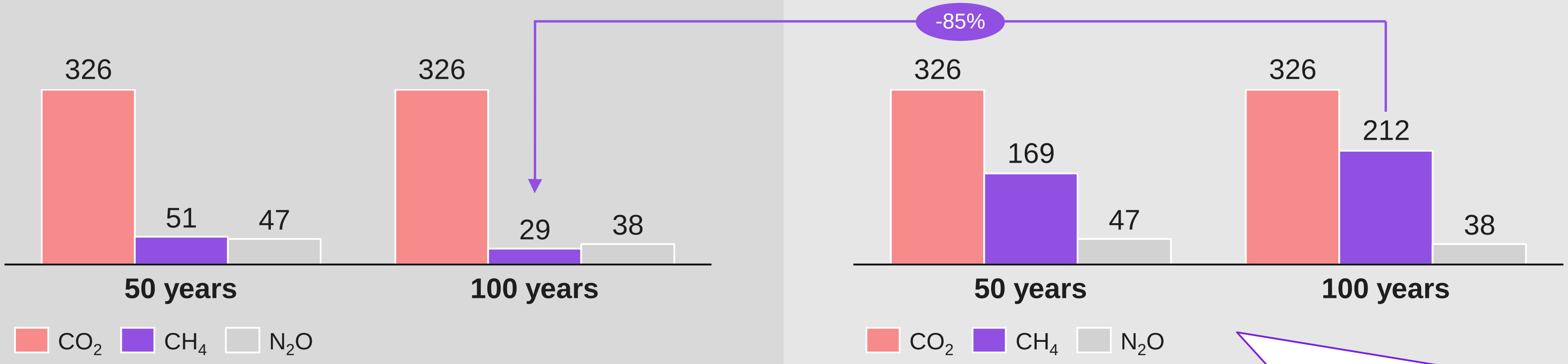
According to the IPCC, new ways of assessing the impact of methane show a greater effect of increased emission rates for long time frames

Step-based emission metrics are more appropriate for assessing the long-term impact of short-lived gas, such as methane. By using the traditional pulse-based metrics, the impact of methane was underestimated by 85%.

1.4 GHG and climate change: key concepts and uncertainties

CO_2-eq emissions change of CO_2, CH_4, and N_2O based on GTP metric using two time-horizons
2010–2020, $GtCO_2$-eq

Cumulative CO_2-eq emissions change based on GTP for CO_2 & N_2O and CGTP for CH_4
2010–2020, $GtCO_2$-eq



Using CGTP gives the closest approximation of global temperature change due to the change in cumulative emissions over that period and shows an underestimation of the impact of CH_4 by ~85% using GTP for a 100-year time horizon.

CO_2-eq methane emissions calculated using CGTP increase with the length of the time frame considered, which reflects the real high impact of constantly increasing emission rates of short-lived components.

A step emission of short-lived GHG (e.g., CH_4) is more comparable to a pulse emission of CO_2. Because CO_2 is a long-lived gas, the change in global temperature due to a pulse emission of CO_2 is constant in time. On the contrary, the effects of a pulse emission of short-lived gas will decrease over time. However, a step change in short-lived GHG emission (change in annual emission rates) that is maintained indefinitely will generate stable changes (because the concentration in the atmosphere will equilibrate).

Short-lived gas emissions expressed with CO_2-eq based on pulse metrics do not reflect their real impact on global warming.

New metrics have therefore been developed, such as the combined metric CGTP, which is based on step emissions. CGTP-based cumulative CO_2-equivalent emissions are calculated as follow:

$$CO_2\text{-eq cumulative emissions change} = CGTP \times \text{Change in emission rate}$$

For a short-lived GHG, a reported change in emission rate should be converted to cumulative CO_2 emission equivalents using CGTP, while for a long-lived GHG, a change in cumulative emissions can be converted to CO_2-eq using pulse metrics such as GTP.

Sources: Global Carbon Project (Global CO_2, CH_4, N_2O budgets 2020), Intergovernmental Panel on Climate Change AR5 (2014) and AR6 (2021), William J Collins et al 2020 Environ. Res. Lett, Lynch et al., 2020; Kearney Energy Transition Institute analysis

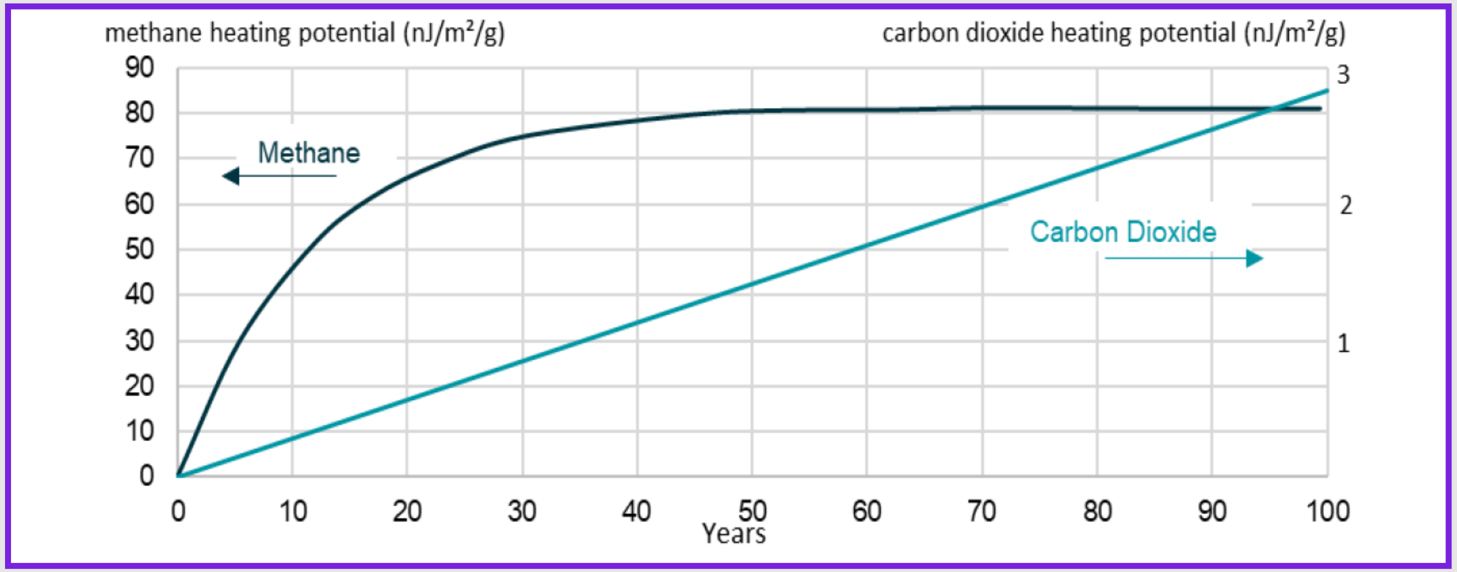
Methane is more efficient at causing global warming than many other gases

Methane's atmospheric lifetime is around 12 years, whereas carbon dioxide lingers for centuries. Hence, a reduction in methane emissions should have an immediate and palpable impact on methane-driven warming.

1.4 Overview of global methane assessment

Absolute global warming potentials of methane and carbon dioxide

To measure the relative climate importance of methane comparing it with carbon dioxide, the International Panel on Climate Change (IPCC) has introduced the concept of **global warming potential** (GWP): Methane global warming potential has been continuously revised and adjusted in each assessment report (AR) from the IPCC, and **it has increased by 33% over 25 years**. The AR6 due for release in 2022 might also give an updated value.



Key insights:

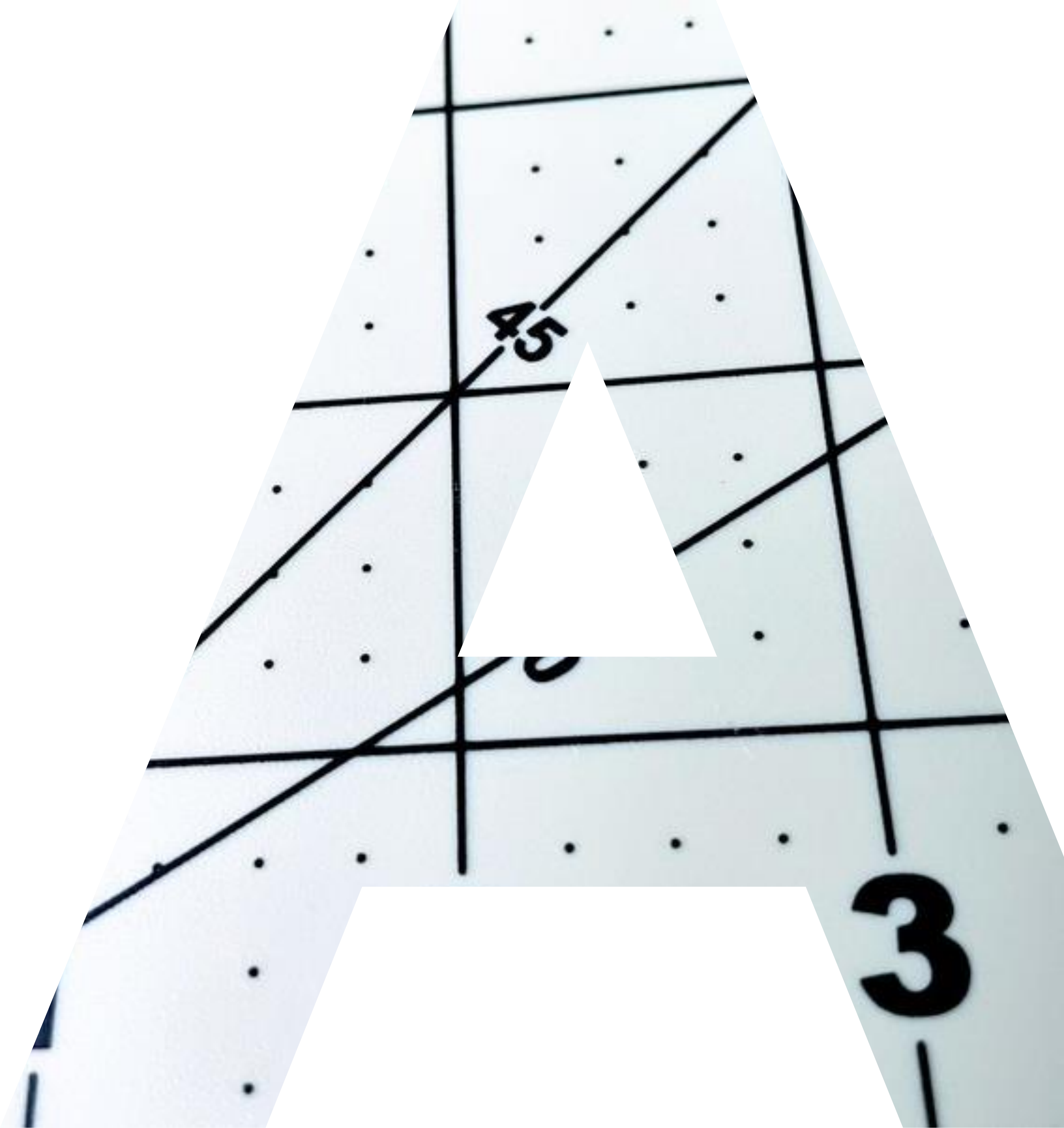
In the first 20 years after being released into the atmosphere, methane is 82 times more potent than carbon dioxide at trapping heat.

Over 100 years, methane is 28 times more potent than carbon dioxide.

Sources: Kayrros; Kearney Energy Transition Institute analysis

Section 1 detailed in Appendix

2. Measuring and tracking global carbon emissions



Methods to monitor and track carbon emissions are evolving, and an integrated system using in-situ and remote sensing tracking will provide the most accurate emission estimates

2.0 Executive summary

Measuring and tracking global carbon emissions
(pages 21–65)

Data monitoring, estimation, and sourcing infrastructure play key roles

Global emission assessment models are based on analyzing changes in the atmospheric carbon emissions and carbon sinks, but their effectiveness is dependent on sourcing accurate datasets.

Measurement and quantification estimation of emissions is dependent on various factors, such as sensor type, sensor placement, and calculation methodology

- **Sensors** are used to measure GHG concentrations which are then exploited to estimate GHG emissions through the use of calculation models (for example, atmospheric inversion models).
- **Sensor placement** options determine from where a GHG concentration is measured (for example, in-situ or remote sensing), and each option has its own set of advantages and disadvantages.
- **Satellite technology** has matured over the years and brings unique benefits in terms of coverage and resolution. The new generation of satellites based on active sensors to overcome the limitations of passive sensors (used in earlier generation of satellites) and targeting the detection threshold of 100 kg per hour, greatly increasing the range of hotspots visible from space, are being planned. Satellites play an important role in tracking methane emissions (basin, super-emitters, flaring, and so on), which are challenging to monitor and are often underreported but can be abated at low costs relatively easily compared to carbon dioxide.
- **Integrated systems** allow for remote sensing monitoring to be complemented with in-situ sensors that can detect smaller leaks and pinpoint the exact source. This system should be optimized for cost to be deployed at scale. However, even with well-designed measurement campaigns, using precise instruments under ideal conditions, there is an uncertainty range in the quantification estimates.

Global climate monitoring systems have matured with time but still face key challenges:

- **Coverage and compliance.** Large variance exists between regions in terms of reporting of measurement data and quality of reporting with Africa and some parts of Asia having limited reporting due to sparse distribution of in-situ stations and low quality of data.
- **Accuracy.** Ground-based monitoring systems suffer from limited accuracy in regions with no or less coverage, and for non-CO_2 GHG gases (such as methane), emissions can be difficult to map to specific source/sectors.
- **Standardization.** Many datasets are derived from different sources (satellite, ground, air, and model-based), and despite the efforts to keep the data consistent, inconsistencies do occur. Further, variance exists in emission estimates derived from measured concentrations depending on the assumptions of the inverse models.
- **Regulation.** There is no widely agreed-upon methodology for measuring, reporting, and certifying corporate emissions, especially across borders, and in many jurisdictions, the existing GHG standards and protocols are not binding on companies.

Role of international collaboration

- The trend toward standardizing emission reporting has accelerated but remains fragmented across geographies and sectors. Efforts to standardize reporting and certifying of corporate emissions globally are under way with establishment of the **International Sustainability Standards Board (ISSB) in COP 26.**
- The **World Meteorological Organization (WMO)**, in collaboration with a wide range of UN partners and international organizations, supports the UNFCCC. It coordinates a global network of national observation stations (across air, land, and sea) to provide regular updates on various parameters under essential climate variables (ECV) including on annual GHG emission bulletins using data and information from multiple scientific sources on the latest trends of concentrations and emissions.

This chapter aims at illustrating key technologies and organizations involved in global GHG emissions assessment and reporting but does not provide the exhaustive picture.

Source: Kearney Energy Transition Institute analysis

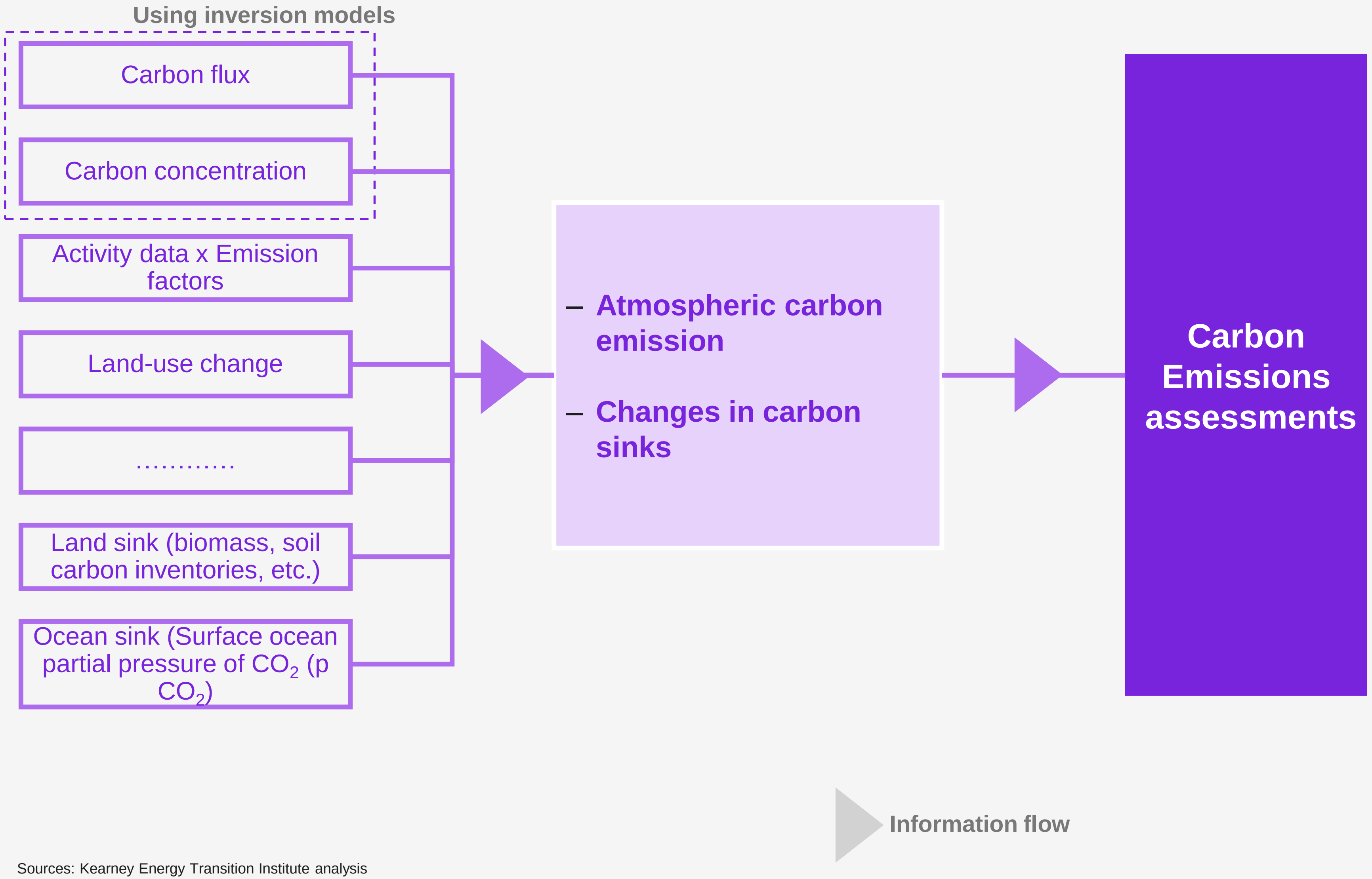
Carbon Emissions assessments entail measuring and monitoring various variables associated with emissions

Accurate data monitoring and reliable sourcing infrastructure play key roles in providing inputs to the global carbon or methane emission models/exercises

2.1 Overview of global GHG assessment

Carbon emissions assessments
(based on different types of inputs)

Indicative



Sources: Kearney Energy Transition Institute analysis

Global carbon budget exercises, such as Global Carbon Project's global carbon cycle, utilize variety of data types as inputs

Not exhaustive

Datasets are used to quantify the five major components of the carbon cycle

2.1 Overview of global GHG assessment

Global Carbon Cycle

Emissions (fossil fuels)	+	Emissions (land use change)	=	Growth in atmospheric concentration	+	CO_2 uptake by the land	+	CO_2 uptake by the ocean	+	Budget imbalances
1A		1B		2		3A		3B		4

	Key components and data sources
1A	**Fossil fuel emissions and Industry**: United Nations Framework Convention on Climate Change (UNFCCC), national emissions sources, UN Statistics Division, Carbon Dioxide Information and Analysis Center (CDIAC), British Petroleum annual energy review and US Geological Survey
1B	**Land use change emissions:** Three book-keeping models and Global Dynamic Vegetation Models
2	**Global growth rate in atmospheric CO_2 concentration:** US National Oceanic and Atmospheric Administration Earth System Research Laboratory (NOAA/ESRL) and data from Mauna Loa and South Pole stations per CO_2 Program at Scripps Institution of Oceanography (1959–79)
3A	**Ocean CO_2 sink:** Multiple global ocean biogeochemistry models (GOBMs) that meet observational constraints over the 1990s
3B	**Terrestrial CO_2 sink:** Multiple Global Dynamic Vegetation Models
4	**Budget imbalances:** The difference between the estimated total emissions and the estimated changes in the atmosphere, ocean, and terrestrial biosphere, is a measure of imperfect data and understanding of the contemporary carbon cycle

Sources: Global carbon project, Kearney Energy Transition Institute analysis

Sensor types, sensor placement and calculation technique are the key factors influencing measurement

1 Sensor types

The sensor type and design determines what can be measured and under which condition:.

- **In-situ,** some types of in-situ sensor-based solutions can only be used in a plume as gas molecules must be in contact with the sensor for chemical or physical interactions
- **Remote sensing,** other sensor technologies are based on detection of an electromagnetic signal, typically infrared light from the sun or a dedicated laser, it can be ground based or spaceborne

2 Sensor placement

The placement determines where in or around the plume measurements take place (which may vary over time and space) and how many data points are captured, in addition to capture of relevant meteorological data:

- The distance determines the spatial and temporal resolution of what the sensor is able to detect (e.g. a small leak from a pipeline close to the sensor)
- The situation is different for a geostationary satellite (more than 35,000 km away from the source) that takes images at high temporal resolution independent of its distance to a source but will only see a huge leak

3 Calculation technique

The technique determines the emission flow rate and the uncertainty based on different types of models (atmospheric inversion models)

- However, the estimation methods can only give estimates, and multiple factors can contribute to uncertainty.
- Uncertainties in the calculations can arise from multiple factors, including sensor precision, the quantity and spatial extent of measurement data, simulation of atmospheric transport, and a priori information and other settings of atmospheric inversion models

Sources: “Overview of methane detection and measurement technologies for offshore applications” Carbon Limits, June 2020; Kearney Energy Transition Institute analysis

There are a variety of sensors to detect a concentration of GHG, each with its own application

Not exhaustive

Within indirect measurements, **passive sensors** measure changes in background energy, such as reflected sunlight caused by the presence of GHG in contrast to **active sensors,** which transmit bursts of energy in the direction of interest, e.g., a laser beam, and record the origin and strength of the backscatter (LIDAR - Light Detection and Ranging)

2.2 Key global GHG assessment technologies: sensors

Different types of sensors

Type	Description	Deployment	Location
Metal-oxide semiconductors	– Electric circuits are doped with oxide materials to react with the target gas, where tin dioxide used for methane and VOC detection. Gas particles react with the oxide material and result in change in measured electrical resistance.	Handheld, fixed	In-situ only
Printed nanotube sensors	– The gas molecules change the electrical response of the carbon nanotube sensors, which can be detected and converted to a methane concentration.	Fixed	In-situ only
Gas chromatography	– A gas passes through a separator column, and the molecular weight of the gases determines the time it takes to pass. The timing and magnitude of the peaks indicates the type of gas, and gas sensors in combination with the technique can therefore determine their presence.	Fixed	In-situ only
Mass spectrometry	– Mass spectrometers are used to identify molecules by ionization of the sample and measuring the mass to charge ratios. Mass spectrometer systems may be able to determine isotopes and therefore be used to distinguish between thermogenic and biogenic methane.	Fixed	In-situ only
Absorption spectroscopy	– It utilizes the wavelength-dependent absorption of light/laser to quantify the concentration of any gas in a mixture. Furthermore, the amount of light depends on the specific gas, gas concentration, wavelength, and total path length over which this light goes through air.	Vehicle mounted and fixed	Both, in-situ and remote sensing
Optical gas imaging	– Optical gas imagers (OGI) are specialized infrared cameras use a narrow range of the infrared spectrum, which GHG absorb. The cameras are not able to distinguish between specific gases (depending on their spectral resolution and domain)	Vehicle mounted, handheld and fixed	Both, in-situ and remote sensing
Multispectral and hyperspectral imaging	– Spectral imaging sensors consists of many different techniques to image multiple bands across the electromagnetic spectrum that go beyond the RGB-bands of visible light. Spectral imaging sensors may have the capability to distinguish between gases based on their specific wavelength absorption properties.	Vehicle mounted, handheld and fixed	Both, in-situ and remote sensing

In-situ or air samples | Remote sensing

Sources: "Overview of methane detection and measurement technologies for offshore applications" Carbon Limits, June 2020; Kearney Energy Transition Institute analysis

Direct measurements are based on chemical and physical properties of the gas, and the emission rate or flux is deduced from the temporal change in gas concentration with an atmospheric inversion model

Not exhaustive

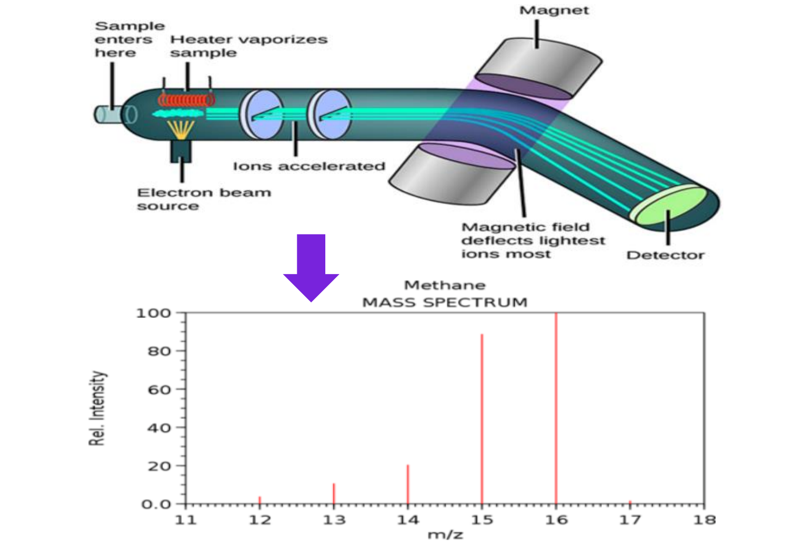
Metal oxide semiconductor

Metal oxide semiconductor (MOS) sensors are circuits specifically doped with oxide materials that will react to the intended target gas. Tin dioxide is commonly used for methane and VOC detection.

When gas particles react with the oxide material, a change in sensor resistance occurs. The change in resistance amount is proportional to the gas concentration. The sensor often includes a heating element to raise the sensor temperature to minimize the effect of water vapor and maximize the reaction to the target gas.

Sources: Kearney Energy Transition Institute analysis

Mass spectrometer



All mass spectrometers measure the mass-to-charge ratio (m/z) of an analyte. There are a variety of approaches used to determine mass-to-charge ratio including quadrupole mass analyzer, ion traps, and time-of-flight mass analyzers. These systems use a multitude of ionization sources, such as electron impact (EI), chemical ionization (CI), and electrospray ionization (ESI), to produce ions that are detected by the instrument.

A solid, liquid, or gas sample is ionized (i.e., by bombarding with electrons), then mass analyzed and detected. The m/z ratio is plotted versus its relative abundance producing mass spectrum.

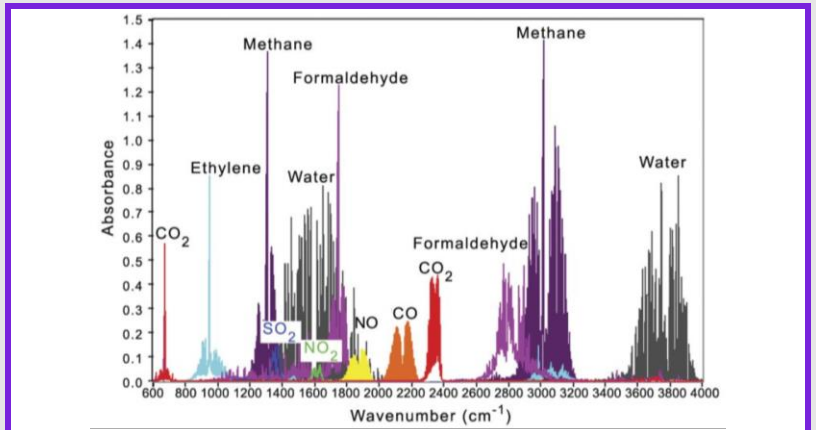
Atmospheric concentrations (dry-air column-averaged mixing ratios) of CO_2 and CH_4 are measured for inverse modeling of natural and anthropogenic CO_2 and CH_4 surface fluxes

Not exhaustive

Some sensors using narrow-band absorption only respond to methane, while passive IR OGI respond to multiple hydrocarbons and cannot distinguish methane from other gases such as ethane.

2.2 Key global GHG assessment technologies: Indirect

Absorption spectroscopy



The position of the absorption peaks in an Infrared spectrum are characteristic of the sample's chemical composition or purity

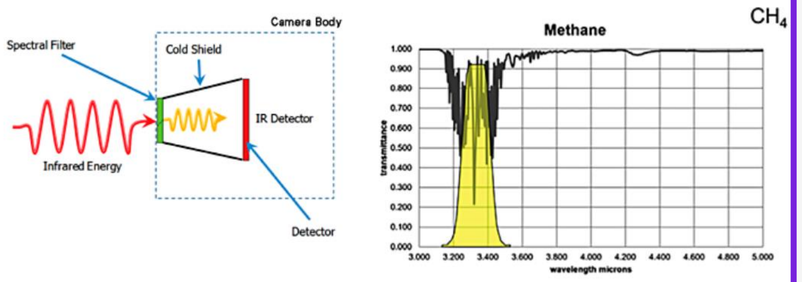
The intensity of an absorption peak is proportional to the concentration of the species for which that peak is a characteristic

Spectrometers collect and break down the incoming light (from transmitter/reflected by the surface) by wavelength. Molecules in the light's path will absorb a certain pattern of wavelengths, leaving dark bands in the spectrum. The greater the concentration of those molecules, the darker the bands.

The typical scientific quantity retrieved using spectroscope measurements is the dry air column averaged methane mixing ratio (e.g., in the units of parts per billion or ppb, denoted as XCH_4 in case of Methane) i.e., raw atmospheric gas concentrations, which are not actual gas emissions.

The emission rates or flux can be computed using gas concentrations data using inversion models adapted to the scale at which flux is desirable to be calculated.

Optical gas imaging



Optical gas imaging technology is a specialized infrared (IR) ie thermal imaging camera to visualize gas leaks and can have various configurations that include handheld cameras, portable cameras using a mobile stand, and fixed installed cameras within a facility.

Optical gas imagers detect methane and other hydrocarbons due to the molecules of these gases and how they absorb IR radiation.

Passive IR imaging cameras use available ambient IR radiation to detect intensity differences between the ambient background IR radiation and the gas plume radiation. Active IR imaging uses an IR light source (i.e., an infrared laser) that is projected toward the area of interest, reflected off a background and is absorbed or attenuated as it encounters a gas species along the optical path. The reflected attenuated infrared light signal is then captured by an infrared detector.

The sensor placement determines where a GHG concentration is measured from and therefore what data can be used to calculate emission flow rates

Not exhaustive

Depending on the placement, the method can be **bottom-up** (directly measure or estimate emissions at the source/ activity level) or **top-down** (measure ambient air concentrations of GHG, calculate flux based on atmospheric conditions, and attribute emissions to a source).

2.2 Key global GHG assessment technologies: Sensor placement

Sensor placement options

Type	Distance	Method	Advantages +	Disadvantages –
Handheld instruments	10 cm–10 m	Bottom-up	– Very close proximity to individual components and sources	– Full-site emissions are difficult to survey, and per-component resolution is only for short periods of time. Low accuracy, the flux rate needs to be known
Fixed sensors	1–100 m	Bottom-up	– Close proximity to individual components and sources	– Full-site emissions are difficult to survey unless full array of sensors are deployed around emission area and susceptible to changes in wind direction. Low accuracy, the flux rate needs to be known
Surface mobile	500 m–2 km	Top-down	– More frequent readings	– Resolution depends on sensor measurement frequency and travel path and can only measure concentrations from the surface, not in the vertical column of the plume.
Drones	10 m–1 km	Top-down	– Possible to measure full-site emissions in all three dimensions, effective on offshore fields and platforms	– Resolution depends on sensor type/measurement frequency and flight path.
Planes	500 m–2 km	Top-down	– Possible to measure full-site emissions in all three dimensions	– Resolution depends on sensor type/measurement frequency and flight path and can miss intermittent emissions.
Satellites	500 km–2,000 km, 35,786 km (geostationary)	Top-down	– Possible to measure full-site emissions with relative high frequency and spatial resolution	– Temporal issues, attribution of emissions events, and geographical constraints can be some of the challenges (though not always)

Sources: "Overview of methane detection and measurement technologies for offshore applications" Carbon Limits, June 2020; Kearney Energy Transition Institute analysis

The key aim of a calculation technique is to determine the flow rate

Not exhaustive

Even with well-designed measurement campaigns using precise instruments under ideal conditions, there is an uncertainty range in the quantification estimates.

2.2 Key global GHG assessment technologies: Calculation

Different calculation methods

Type	Description
Mass balance	– This approach is based on the law of conservation, and by accounting for GHG entering and leaving a system, emission flows from the system can be measured. By measuring the concentration and wind speed and direction at many altitudes and positions around an emission source, a mass – Balance can account for net GHG emitted by a source.
Inverse dispersion Modeling	– Inverse dispersion modeling is based on upwind and downwind GHG concentrations measurements using an array of sensors. By using meteorological fields and models to calculate how a plume would disperse downwind to result in a concentration as measured, the emission rate is estimated. – The meteorological parameters are either based on measured or modeled wind fluxes in the different layers of atmosphere and turbulence/stability.
Downwind tracer flux	– Tracer measurements involve access to a site for controlled releases of known amounts of tracer gases, near emission sources, and measurements downwind to measure the enhancements and ratios of tracer gas to GHG. Since the emission rate of the tracer is known, GHG (especially methane) emissions are calculated by multiplying the integrated methane concentration enhancement by the tracer ratio. – The tracer flux correlation approach is a highly accurate method for quantifying site emissions and has been used to assess other methodologies and unlike dispersion methods, tracer flux methods do not require knowledge of micrometeorological conditions such as turbulence and exact wind conditions. – However, the requirement for onsite tracer release is a disadvantage.
Quantitative imaging	– For technologies using hyper-, multispectral, or optical gas imaging, quantification can be done by using the image data and to derive a leak rate from the images by using a method to measure and control all the variables and derive quantitative results. – Background concentration, temperature of gas and background, wind speed, and measuring distance are important variables.

Sources: "Overview of methane detection and measurement technologies for offshore applications" Carbon Limits, June 2020; Kearney Energy Transition Institute analysis

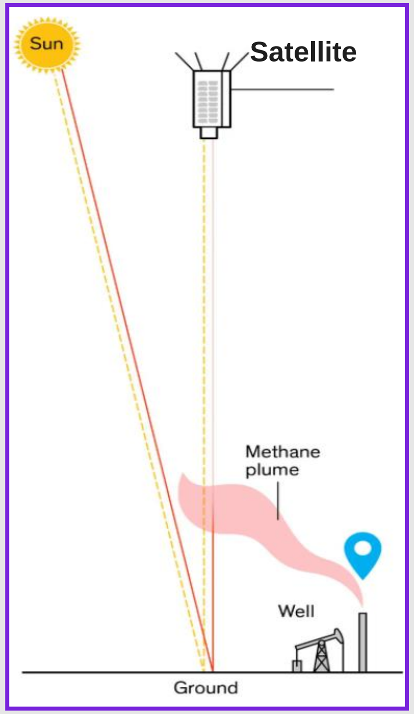
Measurement of greenhouse gas concentrations by satellites

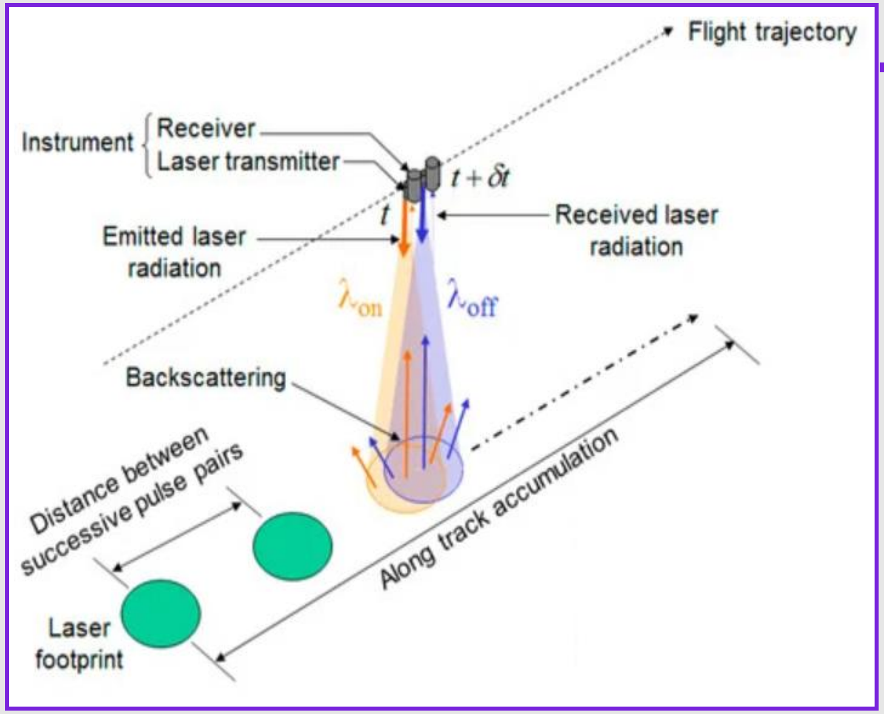
In spaceborne spectral imaging systems, one dimension of the imager (sensor) is used for spectral dispersion, and the other is used for spatial imaging

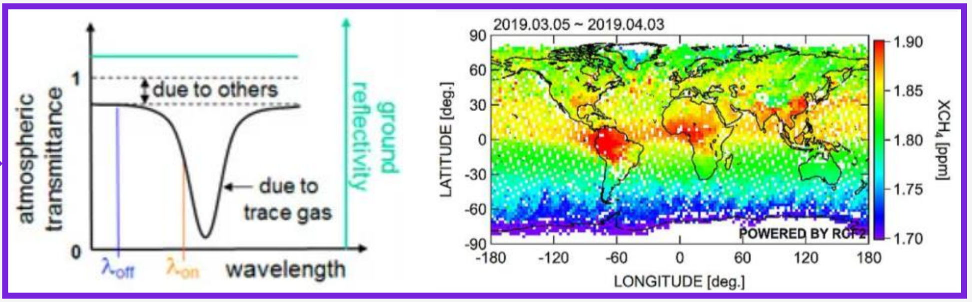
Indicative

Backscattering

Sunlight (passive sensor)	Laser (active sensor)







2.3 Satellites technologies: Basic principle

- Measuring GHG emissions from space offers a drastic improvement in observational capacity to potentially provide either global coverage of GHG concentrations on a regular temporal basis (solar synchronous orbits), or regional coverage with continuous observations during daytime (geostationary orbits). However, satellites do suffer from certain limitations (i.e. no clouds bias, etc.) which are detailed later in this section.
- Since 2000s, various satellites based on reflected sunlight have provided column-averaged dry air mole fractions using shortwave infrared absorption spectrometry (SWIR) and thermal infrared (TIR) spectroscopy but suffer from drawbacks, such as limited coverage in cloud-covered regions, offshore regions and high latitudes, and high sensitivity to mid-troposphere concentrations.
- Satellites based on active sensors would not rely on sunlight for measurements as they would emit their own radiation (such as laser). Active sensors enable measurements to be made in all seasons at all latitudes, during daylight and at night, and may also overcome the weak reflectivity of water. MERLIN is an upcoming satellite mission with active sensors for methane emissions
- Since active sensors based satellites do not take images, they are limited in their ability to estimate emissions from small scale sources/points

Sources: Kearney Energy Transition Institute analysis

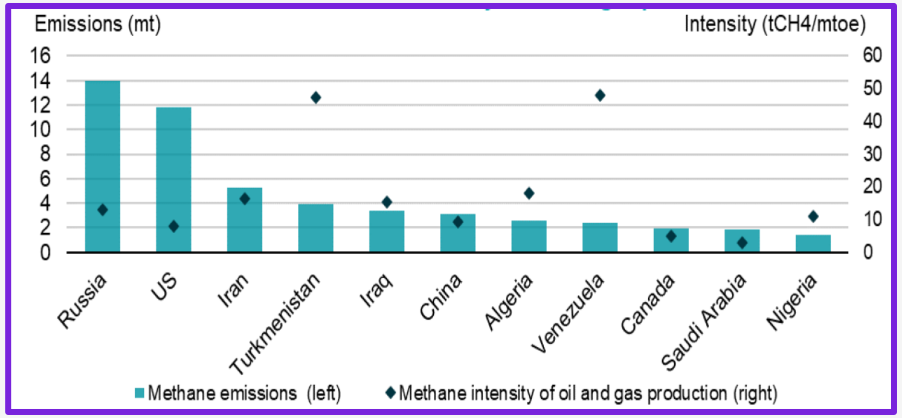
Methane emissions are challenging to monitor using traditional methods and can be understated by a factor of ten

Bottom-up emission estimates using emission factors for energy asset components alone consistently underestimate the amount of methane leaked into the atmosphere.

Fossil fuel methane emissions estimated from atmospheric observations are 60–110% greater than current estimates.[1]

2.3 Satellites technologies: global methane assessment

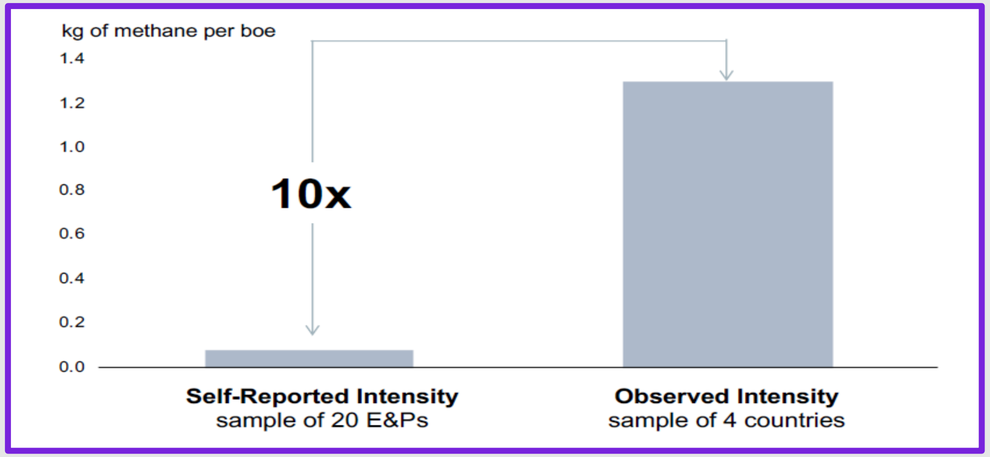
Selected national methane emissions and methane intensity of oil and gas production (2020)



Network quality and flaring intensity unevenly impact real methane emissions intensity of oil and gas production. Data from countries and production basins show that **methane emissions are not directly proportional to the amount of energy being produced.**

The emissions intensity of oil and gas production can be **more than 10 times** higher among the lower-performing countries compared with higher performing ones. For example, some top producers, including Saudi Arabia, are among the lowest emitters in intensity and absolute terms.

Methane intensity of oil and gas production[2, 3]



1. Schwietzke et al, 2016
2. E&P = Exploration and production
3. Basis company reports and Kayross's analysis of Sentinel-5P, IEA and EIA data

Sources: Kayrros; Kearney Energy Transition Institute analysis

Company reporting may understate emissions by a factor of 10 as operators follow legacy methodologies based on emission factors.

Self-reported intensity is based on a weighted average from company reports downloaded in November 2020 for a sample of oil and gas producers that accounts for approximately 27% of global hydrocarbon production.

The observed intensity is a weighted average of seven oil and gas basins in four countries using inversion models developed by Kayrros.

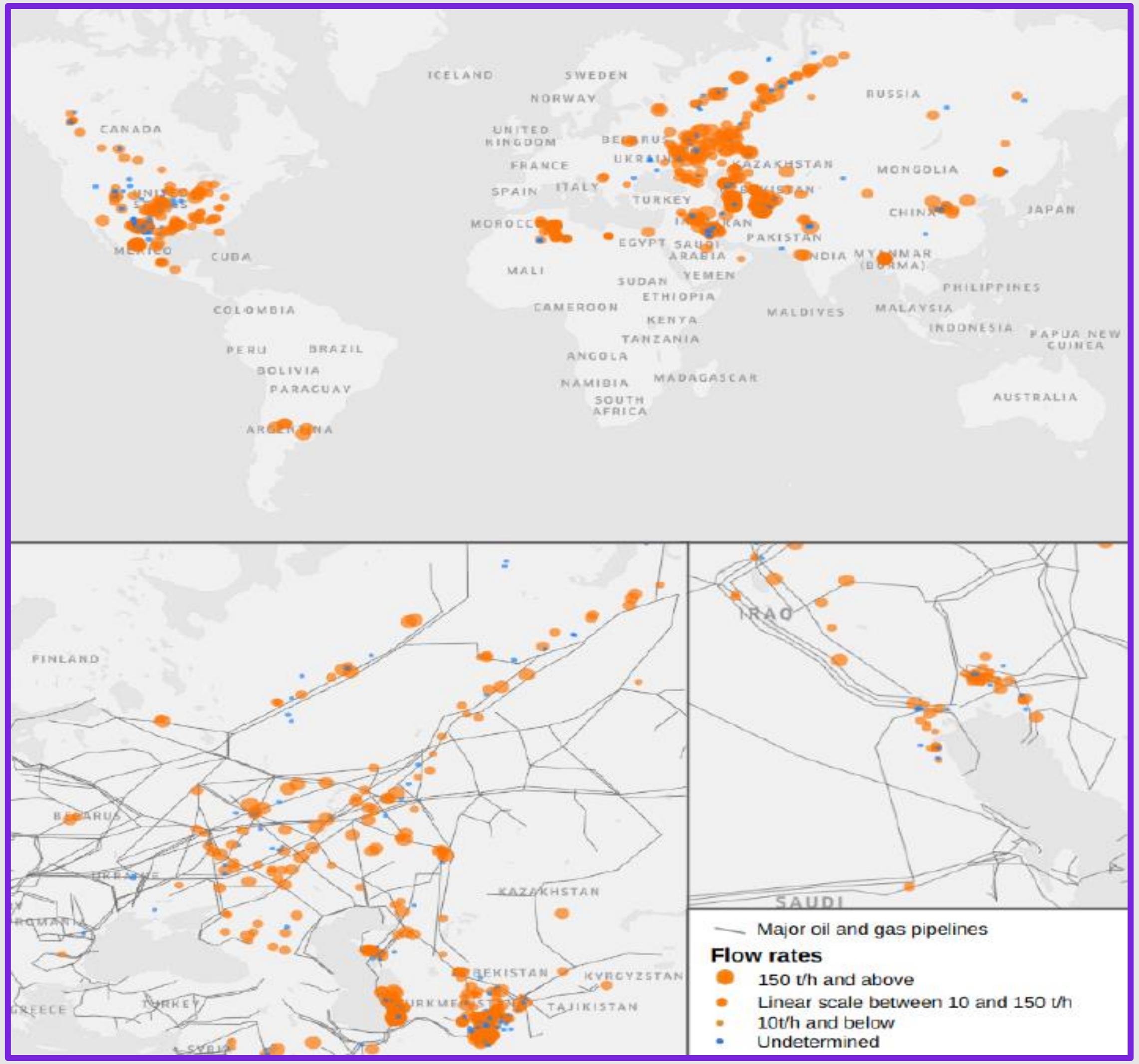
Observed from space, methane hotspots are more frequent than expected and primarily occur in the energy infrastructure spread across the globe

Oil and gas emissions from national inventories **have been widely underestimated by conventional reporting**, as massive loss events called ultra leaks, which represent a variable fraction of national emissions of a country, are captured by the **ESA Sentinel 5-P satellite mission carrying the TROPOspheric Monitoring Instrument (TROPOMI, launched 2018**

However, smaller leaks are not visible through TROPOMI

2.3 Satellites technologies: global methane assessment

Global map of about 1,200 oil and gas detections with a focus on Russia, Central Asia (lower left), and Middle East (lower right)
2019–2020



1. Ultra-emitters are classified as having methane flow rate ranging from 5 tons per hour to several hundred tons per hour
Sources: Kayrros analysis of TROPOspheric Monitoring Instrument (TROPOMI) data, Lauvaux et al. 2021; Kearney Energy Transition Institute analysis

Detections vary in magnitude (refer to the flow rates range in the map) and number between **50 to 150 per month.**

Oil and gas production facilities constitute about two-thirds of the detections (or about 1,200 out of the total 1,800 captured detections), while ultra-emitters from **coal, agriculture, and waste management only represent a relatively small fraction** (33%) of the total detections.

Ultra-emitters[1] are attributed to oil and gas infrastructure (major pipelines and most of the largest oil and gas basins) which represent **more than 50% of the total onshore natural gas production across the globe.**

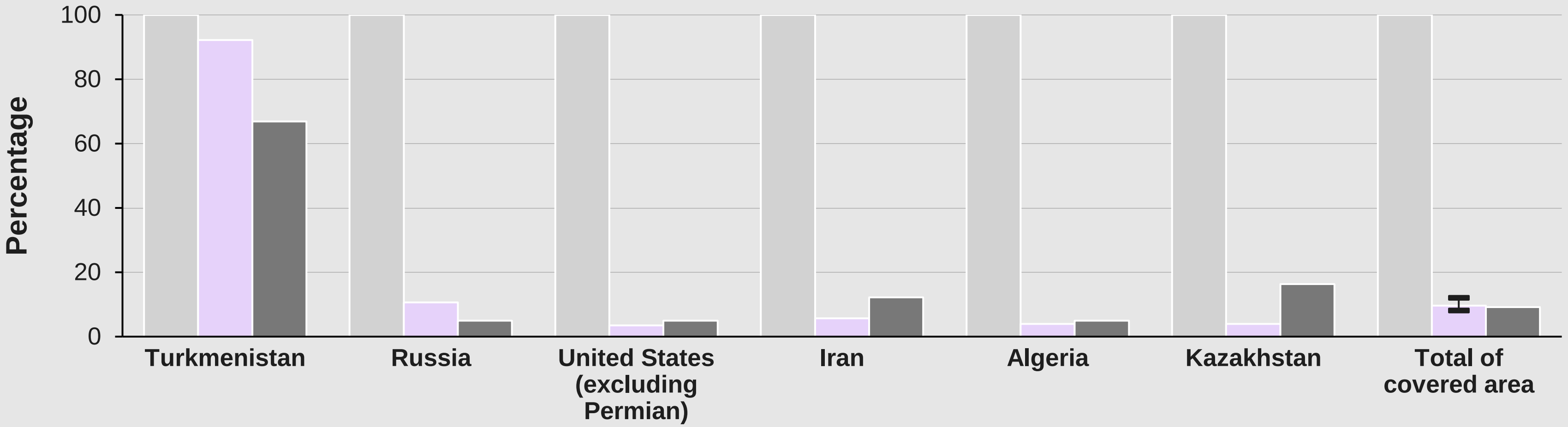
Offshore emissions remain invisible to satellites and are excluded from this analysis.

Ultra-emitters[1] from oil and gas production are unreported and amount to 8 to 12% of the global oil and gas methane emissions

2.3 Satellites technologies: global methane assessment

Ultra-emitters[1] unreported contribution compared with nation-scale methane inventories in major oil and gas basins

Ratio of the unreported emissions from ultra-emitters now detected with satellite technology to national-scale methane emissions inventories (EDGAR, EPA)



Oil and gas unreported emissions from ultra-emitter estimates represent 8–12% of oil and gas CH_4 emissions from national inventories, a contribution not included in current inventories (Alvarez et al., 2018).

As one of the largest natural gas reserves of the world (~20 trillion cubic meters, ranking fourth in the world based on IEA), Turkmenistan's ultra-emitters event represent between 70 and 95% of its O&G CH_4 emissions from current inventories, which means its reported emissions could be double counting ultra-emitters contribution.

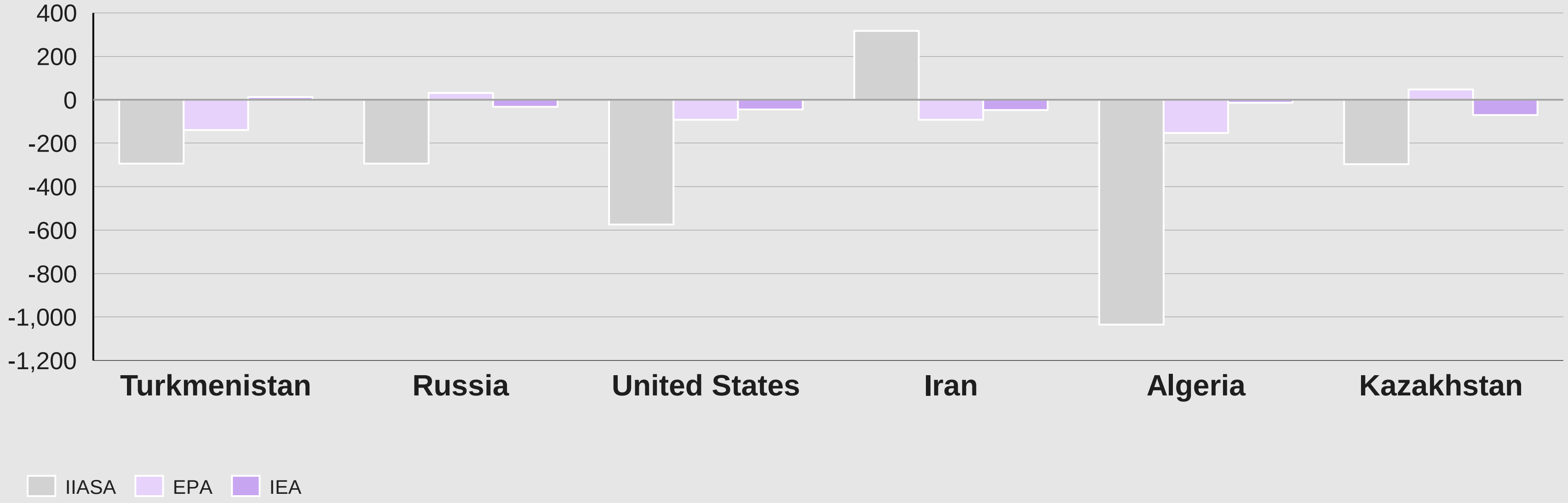
Ultra-emitters are also relatively large (as %) in Russia, Iran, Kazakhstan, and Iran, representing between 10 to 20% of annual reported emissions. The United States revealed fewer ultra-emitters (5% of the annual inventory emissions).

1. Ultra-emitters are classified as having methane flow rate ranging from 5 tons per hour to several hundred tons per hour
Sources: Global Assessment of Oil and Gas Methane Ultra-Emitters, Lauvaux et al. 2021; Kearney Energy Transition Institute analysis

Mitigation of ultra-emitters[2] is achievable at low costs and would lead to net benefits for the six major oil and gas producing countries

Mitigation cost per ton of methane for high emissions[1] across countries

Estimated mitigation costs in USD per ton of methane for high emissions in the oil and gas sector



Averaged across these mitigation analyses, spending would be net positive in Iran (~$60 per ton), whereas it is net negative in all other high-emitting countries with net savings of around $100-150 per ton in Russia, Kazakhstan and Turkmenistan, about $250 per ton in the US, and $400 per ton in Algeria, though values vary greatly across the available analyses.

1. Lavaux et al. computed different analyses of mitigation costs recently produced by several groups: the International Energy Agency (IEA, 2021), the US Environmental Protection Agency (US EPA, 2019), and the International Institute for Applied Systems Analysis (IIASA; Höglund-Isaksson et al., 2020). Author kept high emissions because large emissions are expected to be related to upstream operations or long-distance transport of fuels and thus more cost-effective to mitigate than average sources
2. Ultra-emitters are classified as having methane flow rate ranging from 5 tons per hour to several hundred tons per hour

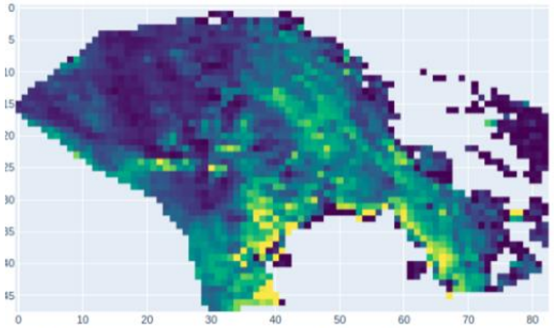
Source: Kearney, Global Assessment of Oil and Gas Methane Ultra-Emitters, Lauvaux et al. 2021

Satellite-based measurements can play an important role in improving the accuracy of emissions data and reporting, especially for methane

Multiple methods for estimating methane emissions with satellite analytics exist through which regional basin-wide anomalies and individual cases of very large methane emission events can be tracked

2.3 Satellites technologies: global methane assessment

Basin inversion



Methane concentrations in Iran-Iraq-Kuwait
2019-20 average

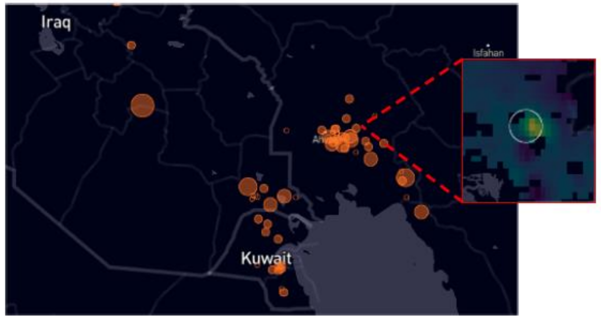
Basin inversion methods based on satellite technologies can detect more than 90% of total basin methane emissions and enable covering regional emissions.

These technologies can quantify total emissions across an entire oil and gas basin.

Satellite measurements of methane concentrations are analyzed to determine the volume and sources of emissions.

Every basin requires a dedicated model and a database of energy infrastructure.

Methane hotspots



Methane hotspots in Iran-Iraq-Kuwait
January 2019 to date

Methane hotspots account for **~10% of total methane emissions from the oil and gas sector sector.**

Algorithms detect methane plumes and provide the flow rate and location of the source within a c.10 km radius.

High-resolution images can be analyzed to pinpoint the exact source.

Tropical regions and offshore areas are out of scope

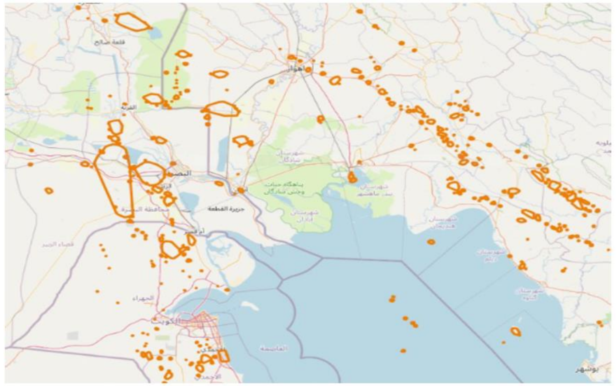
Sources: Kayrros; Kearney Energy Transition Institute analysis

Flaring data from satellites provides additional context on the sources of methane emissions

The Oil and Gas Climate Initiative (CEO-led consortium of 12 companies) has methane-intensity reduction and routine flaring elimination as one of its stated goals.

2.3 Satellites technologies: global methane assessment

Flaring activity in the Persian Gulf

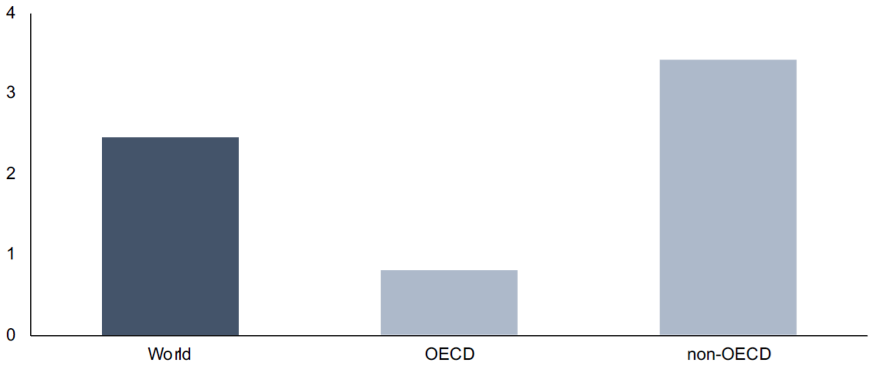


Flaring gas should combust methane and release only carbon dioxide into the atmosphere, but flares are often inefficient and combust incompletely, releasing methane instead of carbon dioxide into the atmosphere. Studies show that **flaring is generally underreported.**

Satellite imagery is best positioned to monitor flaring intensities to assess the efficiency of the flare and whether excess methane is released.

Flaring intensity can be **measured by assessing the radiant heat of the flare in the infrared**, for instance, from the VIIRS sensor onboard the Suomi–NPP satellite. This radiant heat is proportionate to the amount of gas burnt.

Flaring intensity of hydrocarbon production in 2020, by region - m3 per boe



Sources: Kayrros analysis of VIIRS and IEA data; Kearney Energy Transition Institute analysis

Flaring intensity varies regionally with **non-OECD region' estimated flaring intensity to be than double the flaring intensity of OECD region.**

Satellite capabilities have matured over the past few years and are constantly improving

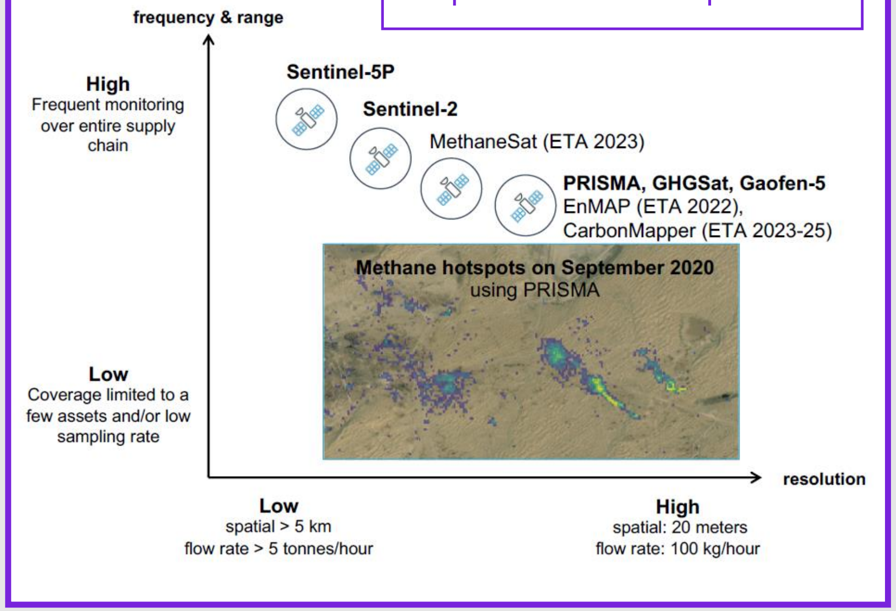
Satellites measurements cover three core metrics

Satellite monitoring can be used to identify, monitor, and assess:

- **Methane intensities** of hydrocarbon production across the supply chain (ratio of methane leaked and/or vented to hydrocarbon output)
- **Super-emitter events** (major leak events)
- **Flaring intensities** (to detect underreported or inefficient flaring)

These **three metrics** are core to the proposed methodology to **estimate methane emissions** and can be used by countries to define emission baselines and credible mitigation targets.

The detection threshold is falling from < 2000kg/hour to 100kg/hour, greatly increasing the range of hotspots visible from space.



Satellites bring unique benefits in terms of coverage and data transparency and offer a low-cost methodology when prioritizing public satellite data.

These metrics were designed to accomplish the following:

A **first assessment** can be run with satellite measurements, helping build a (partial) baseline without requiring higher-cost surveillance tools.

Realistic actions can be put in place for mitigation, and the effectiveness of these actions can be measured.

These metrics can be refined by **running an integrated model** and by ground-truthing.

2.3 Satellites technologies: Benefits

Sources: Kayrros, Kearney Energy Transition Institute analysis

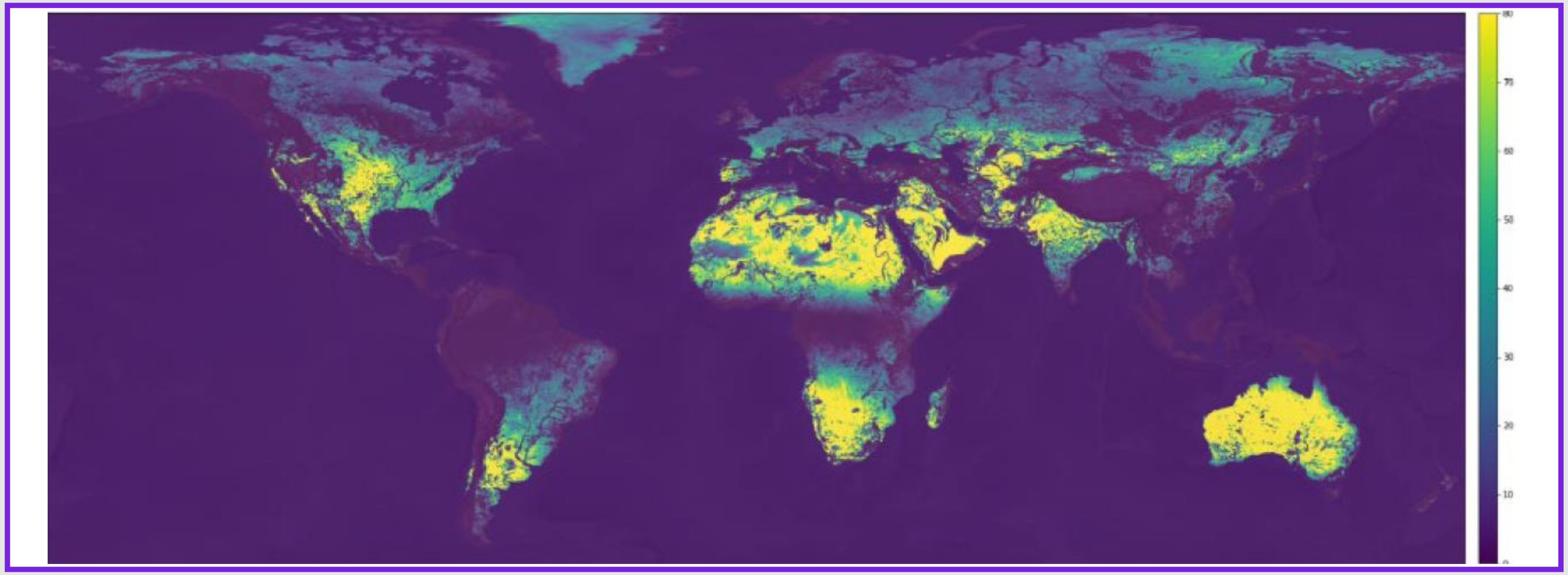
Satellite technology limitations include temporal issues, attribution of emissions events, and geographical constraints

Significant oil and gas assets are out of scope i.e. southern Mexico (offshore production and high humidity) and Nigeria (proximity to equator)

Data quality issues prevent data to be used in global inversions for methane budget so far

2.3 Satellites technologies: Limitations

Sentinel-5P TROPOMI coverage: usable pixels in a year (2020–2021)
Yellow indicates the highest number of pixels, and dark purple indicates no available data.



Temporal issues

Measurements limited to cloudless days with limited wind, leading to a "blue sky bias"

Attributional issues

Inability to discern the exact source of a given event when there may be overlap of multiple potential sources, e.g., agriculture and energy infrastructure

Geographic constraints

Inability to accurately measure over wetlands, snow, and offshore installations, high latitudes or along the equator

However, several planned satellites will use sun-glint technology to provide some measurements over water.

Sources: Kayrros; Kearney Energy Transition Institute analysis

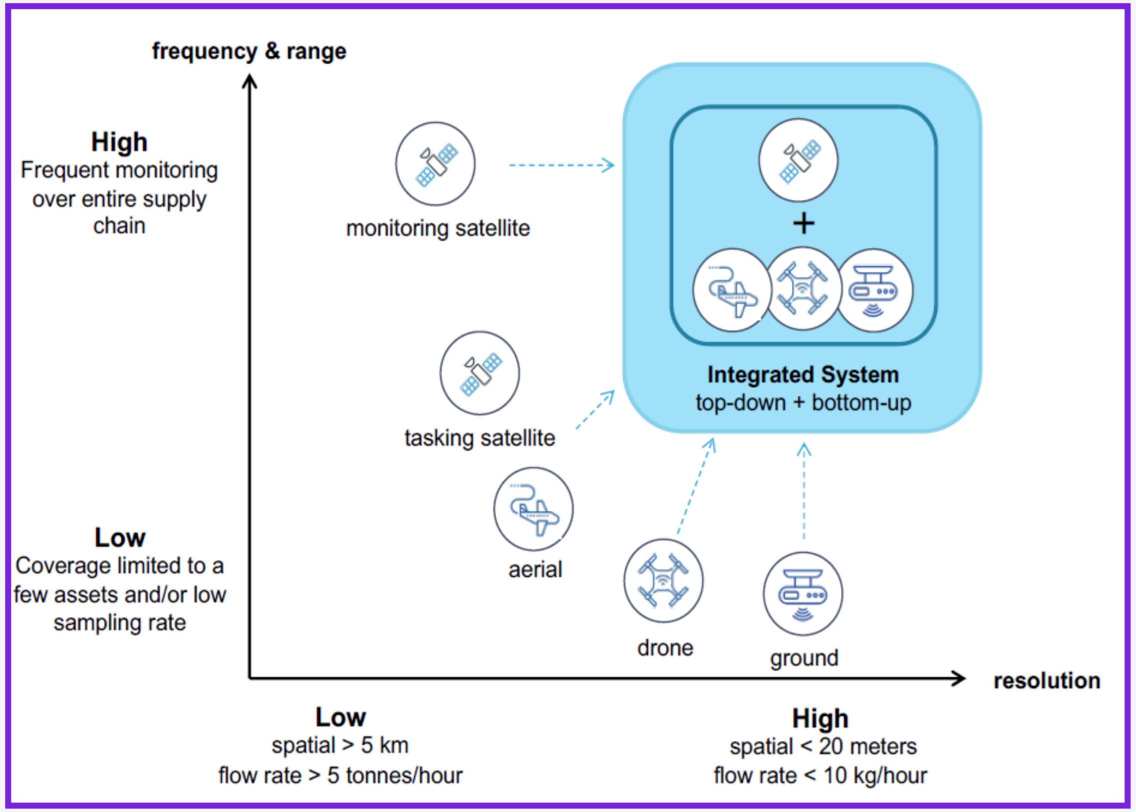
Top-down monitoring from space can be complemented by aerial devices, drones, and bottom-up sensors

However, such an integrated system should be optimized for cost as ground sensors can cost **$1,000 per facility per year**, while the cost of aerial and commercial satellite analytics can range **from $5,000 to $150,000** depending on the type of asset, resolution and number of revisits required.

2.4 Integrated system

Integrated measurement and monitoring system

A monitoring system must combine frequent measurements, wide geographical coverage, and high sensitivity.



An effective monitoring system must meet the following criteria:

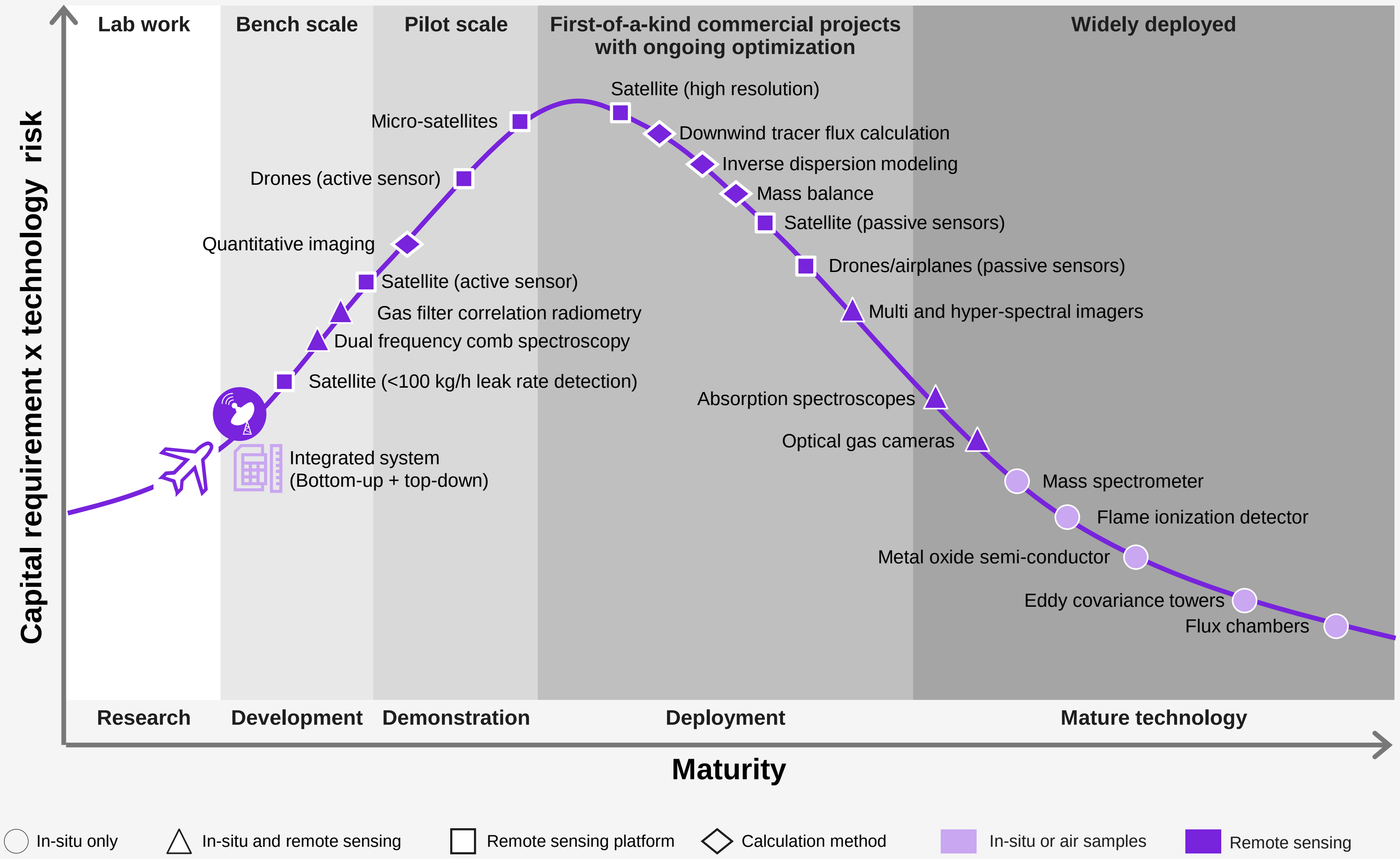
- **Frequency:** taking frequent measurements is crucial to accurately define inventories and account for large emission events that cannot easily be detected or measured with other means.
- **Coverage:** comprehensive geographical coverage is necessary to benchmark and define context.
- **Resolution:** high resolution is needed to detect smaller sources and attribute to the right asset.

Sources: Kayrros, IEF; Kearney Energy Transition Institute analysis

Many new technologies are being developed and deployed to solve for increased coverage resolution, accuracy, and frequency

Not exhaustive

Maturity curve of emission monitoring and estimation technologies



Sources: Kearney Energy Transition Institute analysis

Global GHG monitoring systems have matured but still face constraints and challenges

Satellites have been launched to provide a more uniform set of data (ex: Greenhouse Gases Data Pathfinder)

“Vulcan” joint-project from NASA and US DOE (to quantify CO_2 emissions due to fossil fuel burning in North America, etc.) as a bottom-up inventory exercise

2.6 Challenges of global GHG emissions assessment

1 Coverage and compliance

Tracking emissions from certain geographies is a challenge, i.e., the global terrestrial observing network monitors CO_2, water vapor, and cover a broad spatial area, but Asia/Africa have limited reporting due to sparse distribution of such stations in these regions. Further, many stations didn’t report data meeting minimum requirements.

2 Accuracy

In many cases, GHG inventories are largely limited to self-reported data, and further, GHG emissions are rarely measured directly and instead primarily estimated using activity data (i.e., the amount of fuel consumed, vehicle miles traveled, etc.). Particularly for non-CO2 gases, such as methane, emissions are often under-reported.

Space based monitoring systems can have temporal issues and ground-based monitoring network can suffer due to patchy distribution of observing stations.

3 Standardization

Many datasets are derived from different sources (satellite, ground, air, and model based) and processing systems. Even though most of the research systems are inter-calibrated, inconsistencies creep in, including the use of different auxiliary datasets, simplifications in corrections and retrieval algorithms, calibration uncertainties, and differences in sampling and gridding.

4 Regulations

In many cases, GHG standards and protocols are not binding on companies, and hence, they are under no legal obligation to measure and report their emissions.

There is no widely agreed-upon methodology for measuring, reporting, and certifying emissions, especially across borders (lack of a robust international co-ordination).

Concerns about the proprietary and confidential nature of data further prevents free and open exchange of climate-related data relevant for tracking progress.

Sources: Kearney Energy Transition Institute analysis

Huge regional differences exist in quality of reporting and reported data

GUAN – The GCOS Upper-Air Network (GUAN) is a program of the World Meteorological Organization (WMO)'s Global Climate Observing System (GCOS)

GSN - The GCOS Surface Network (GSN) is a baseline network of stations chosen mainly to give a fairly uniform spatial coverage

Note: These stations are weather stations (not GHG specific stations) covering weather and climate related parameters

2.6 Challenges of global GHG emissions assessment

GSN NCEI CLIMAT availability monitoring statistics

2011–2019

How to read the graph:

According to the GCOS requirements, a fully compliant GSN/RBCN (Regional Basic Climatological Networks) shall have 12 CLIMAT (monthly climatological summary) reports annually. The above color-coded graph depicts the % of stations (out of the total stations) as per their reporting status, i.e., 12 CLIMAT reports - GREEN, 6-12 CLIMAT reports – YELLOW, 1-6 CLIMAT reports – ORANGE and 0 CLIMAT reports – RED.

1. According to GCOS requirements, a fully compliant GSN/RBCN (Regional Basic Climatological Networks) shall have 12 CLIMAT (monthly climatological summary) reports

Sources: GCOS Status Report 2021; Kearney Energy Transition Institute analysis

Regional grouping

All WMO members are classified per regional associations.

Presently, there are six regional associations in addition to Antarctica.

Regional disparities

Africa was the poorest-performing region in 2019, with only 26% of stations meeting the minimum requirement and 35% not providing any CLIMAT messages[1] and only 22% of the GUAN stations meeting the minimum requirement

Recent improvement efforts have not yielded results.

Data sources used for emission reporting are standardized but, in many cases, rely on calculations and estimations, which can lead to inconsistencies

Not exhaustive

2.7 International organizations monitoring GHG emissions

Variation in data reporting

Data producers	Data description
United Nations Framework Convention on Climate Change (UNFCCC)	GHG data is reported from official submissions of GHG emissions and removals data by countries that are parties to the Climate Change Convention.
International Energy Agency (IEA)	The data are originally collected by official bodies (often national statistical offices) in OECD member countries and then GHG emissions from energy sector are estimated. Similar to UNFCCC.
Global carbon project (GCP)	Produces annual emission data from different sources and estimates
EDGAR - Emissions Database for Global Atmospheric Research	Produces annual emission data from different sources and estimates

Data aggregators	Data description
United Nations Statistics Division and United Nations Environment Program (UNEP) Global Environment Outlook (GEO)	Emission data are provided by UNFCCC, OECD/IEA, CDIAC, and RIVM.
The World Bank World Development Indicators (WDI) Online Database	Environmental data and most socioeconomic data are taken from other sources, such as CDIAC, IEA (for data on CO_2), and UNEP.
Statistical Office of the European Communities (EUROSTAT) and European Environment Agency	Data is collected by member states.

Source: Kearney Energy Transition Institute analysis

The WMO is a key global institution which coordinates the in-situ networks across land, ocean and air

Not exhaustive

WMO co-ordinates the global efforts on GHG atmospheric observations (mainly in-situ) and produces annual GHG bulletins basis data which is consistent with UNFCCC, GCP, etc.

2.7 International organizations monitoring GHG emissions

GHG emissions monitoring and analysis

Organization	Brief description	Comments
The World Meteorological Organization (WMO)	It provides a wide range of scientific and technical inputs on the state of the global climate such as analysis and publication of greenhouse gas data around the globe from the High Arctic to the South Pole. The greenhouse gases monitored include: • Carbon Dioxide (CO_2) (incl. Δ14C, δ13C and δ18O in CO_2, and O_2/N_2 Ratios) • Methane (CH_4) • Nitrous Oxide (N_2O) • Halocarbons and SF_6 • Molecular Hydrogen (H_2)	Global network of observation stations across land, ocean and air. Co-ordination of in-situ networks

Expanded in the next slides

*“The **World Meteorological Organization - WMO** is a specialized agency of the United Nations. The WMO is dedicated to international cooperation and coordination on the state and behaviour of the Earth’s atmosphere, its interaction with the land and oceans, the weather and climate it produces, and the resulting distribution of water resources.*

The WMO provides the framework for international cooperation at a global scale, which is essential to implement an Earth system approach for the development of meteorology, climatology, operational hydrology and related environmental services as well as to reap the benefits from their application.

Through its Technical Commissions, Programmes, Projects and Regional Offices, as well as its synergistic and public-private partnerships, WMO facilitates and coordinates an Earth system approach to the gathering and free exchange of observations, promotion and integration of research and the development and delivery of services in the areas of weather, climate and water.”

Sources: Kearney Energy Transition Institute analysis

WMO acts as an umbrella source for scientific information on weather, climate, and water

Not exhaustive

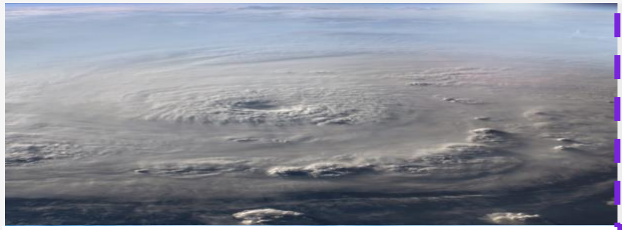
Atmosphere ✓

Land ✓

Ocean ✓

2.7 International organizations monitoring GHG emissions

Listing of WMO's programs



Co-sponsored

Global Climate Observing System (GCOS) is a co-sponsored program that regularly assesses the status of global climate observations and promotes accuracy of the data.

WMO

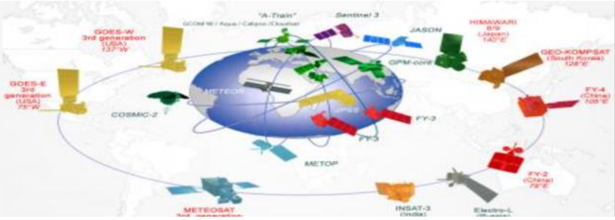
Global Atmosphere Watch (GAW) studies the variability and trends in atmospheric composition and related physical parameters and assesses the consequences.

Co-sponsored

Global Ocean Observing System (GOOS) provides observations, modeling, and analysis of marine and ocean variables to support research, assessments, and operational ocean services worldwide.

WMO

Instruments and Methods of Observation Program (IMOP) is a commission for technical standards, quality control procedures, and guidance for meteorological instruments and observation methods.



WMO

WMO Space Program (WSP) coordinates the activities related to the space-based observing system to ensure sustained and interoperable satellite observations and applications.

In focus

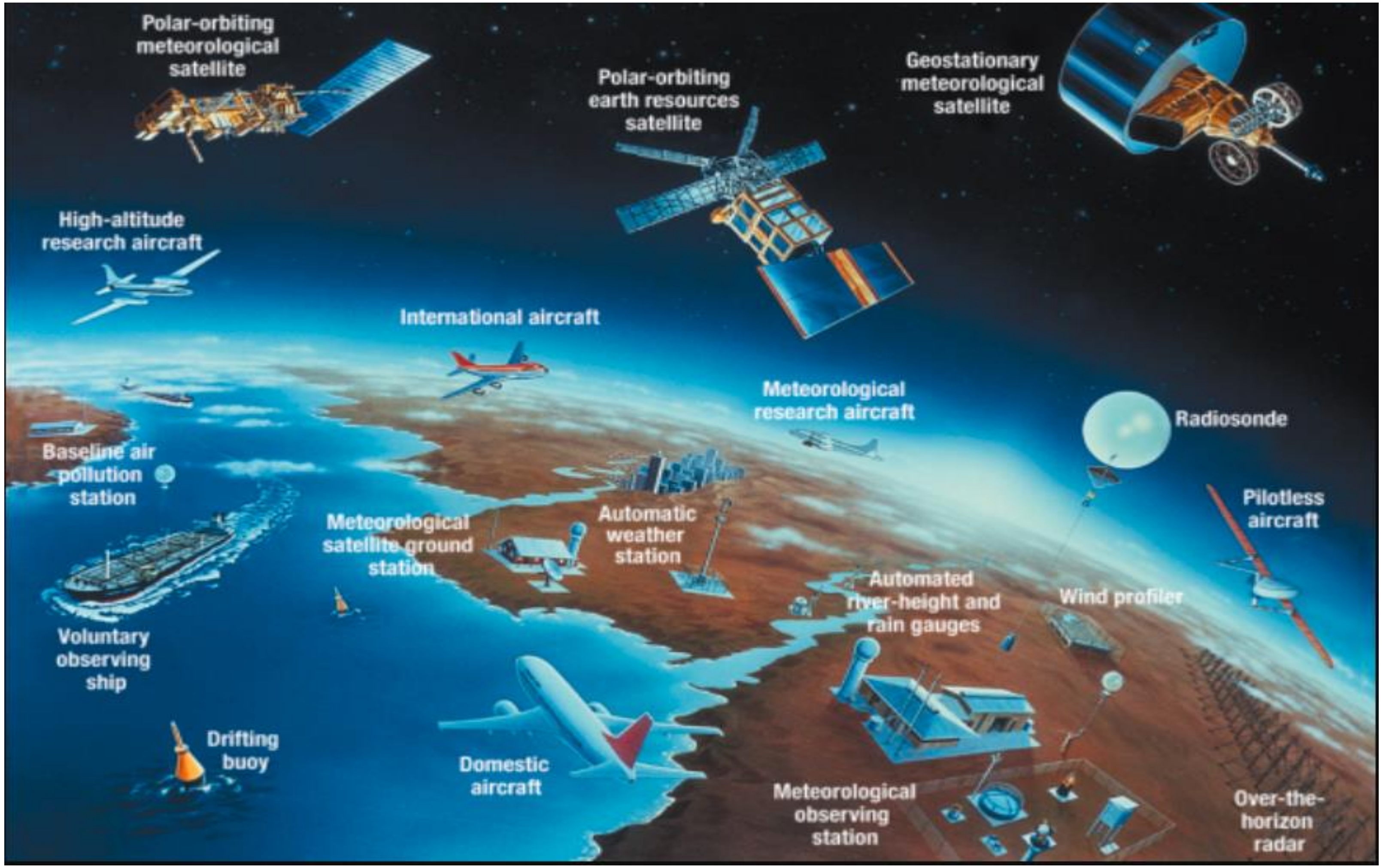
Sources: Kearney Energy Transition Institute analysis

The components of the observation system belong to the National Meteorological and Hydrological Services of WMO members and to other national and international agencies, such as space agencies, or to private entities

Interoperability and compatibility is achieved through the application of internationally accepted standards and best practices. Data compatibility is supported using standardized data representation and formats.

2.7 International organizations monitoring GHG emissions

WMO's Integrated Global Observing System (WIGOS)



The World Meteorological Organization (WMO) Integrated Global Observing System provides a framework for the integration and sharing of observational data.

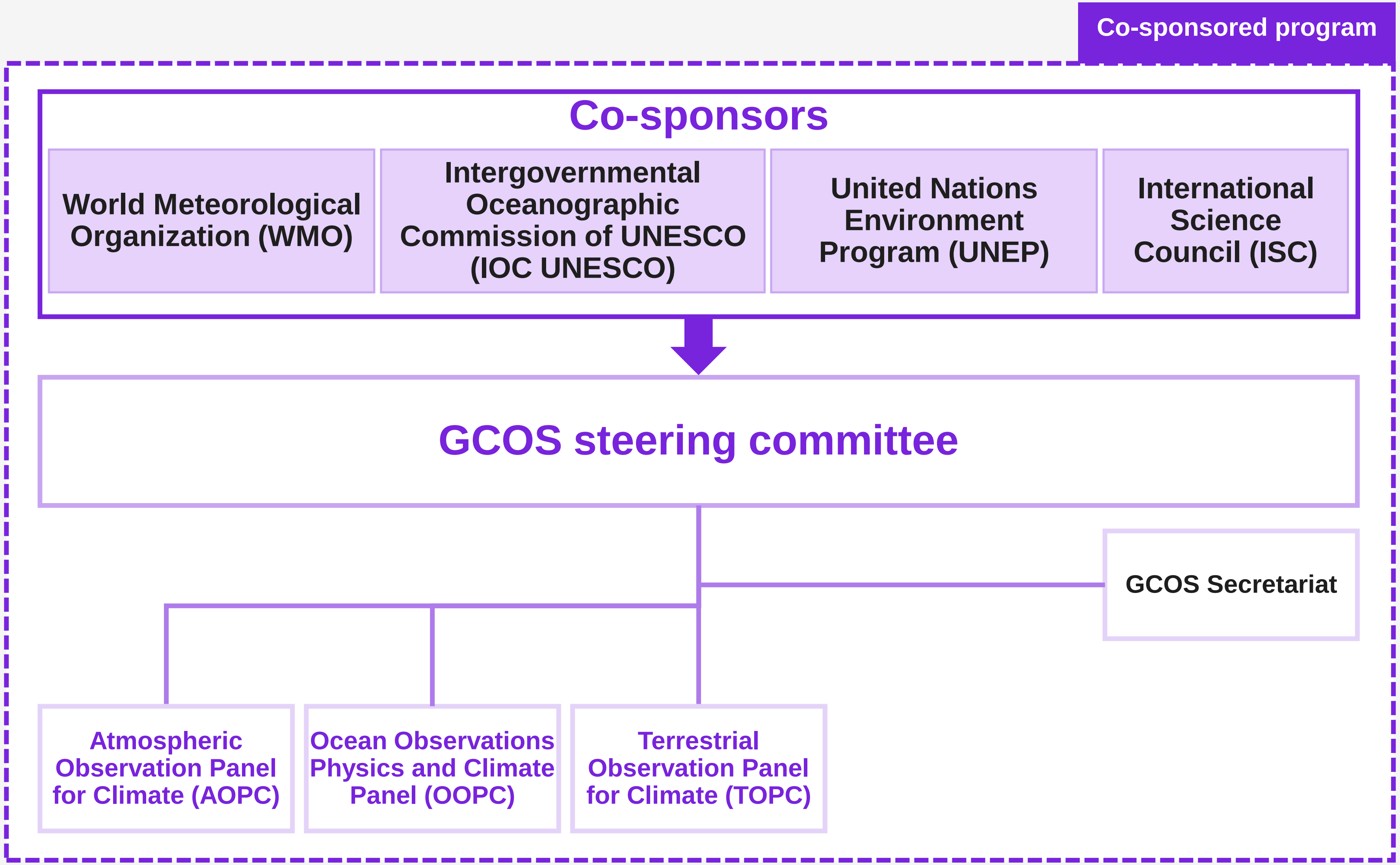
Sources: GCOS Status Report 2021; Kearney Energy Transition Institute analysis

The Global Climate Observing System (GCOS) is a co-sponsored program that regularly assesses the status of global climate observations and produces guidance for its improvement

GCOS expert panels maintain definitions of essential climate variables (ECVs) and identify gaps by comparing the existing climate observation system with these ECVs.[1]

2.7 International organizations monitoring GHG emissions (GCOS) - WMO

Global Climate Observing System (GCOS)



GCOS is reporting under UNFCCC Workstream "Systematic Observations."

1. ECVs are the observations required to systematically observe Earth`s changing climate.
2. These programs and organization have no funding for allowing any observation.Their role is mainly to encourage governments, notably space agencies and in situ agencies to measure ECVs

Source: Kearney Energy Transition Institute analysis

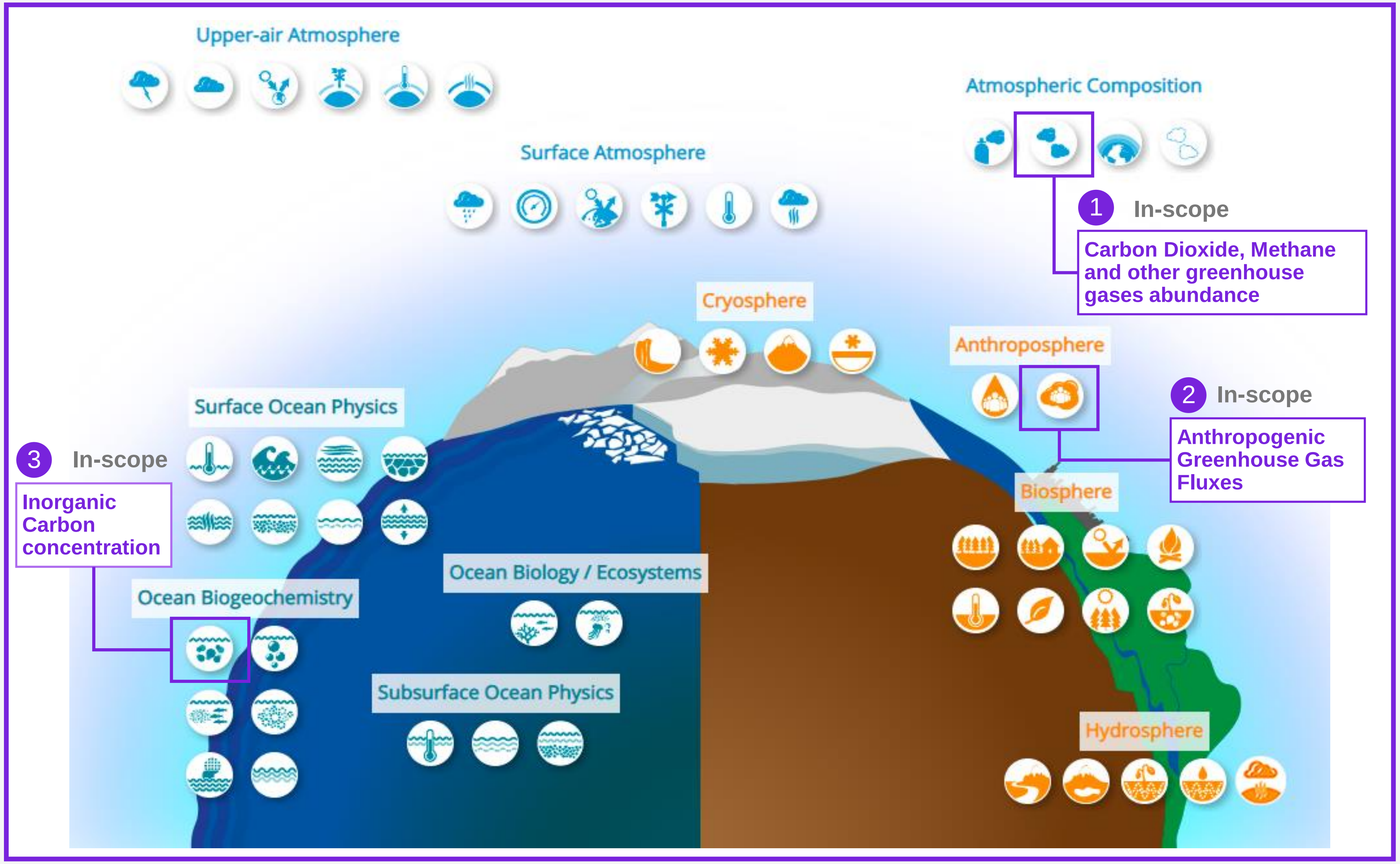
Essential climate variables are physical, chemical, or biological variables or a group of linked variables that critically contribute to the characterization of Earth's climate

Carbon dioxide, methane and other greenhouse gases abundance (under Atmospheric Composition category), **Anthropogenic Greenhouse Gas Fluxes** (under Anthroposphere category) and **Inorganic Carbon** (under Ocean Biogeochemistry category) are key ECVs tracking GHG emissions

2.7 International organizations monitoring GHG emissions – ECV (WMO)

Essential climate variables (ECV)

Currently, 54 ECVs are specified across various categories.



Sources: GCOS Status Report 2021; Kearney Energy Transition Institute analysis

The global coverage of total column observations of both CO_2 and CH_4 has improved over the past decade with the addition of several satellite instruments dedicated to GHGs

Flux measurements from ground-based stations are coupled with the near-global coverage of satellite measurements, resulting in a more complete picture of atmospheric composition.

2.7 International organizations monitoring GHG emissions – Global observation infrastructures

1 Carbon dioxide, methane, and other greenhouse gases

Products covered	– Tropospheric CO_2 column; tropospheric CO_2 profile; tropospheric CH_4 column; tropospheric CH_4 profile; stratospheric CH_4 profile
Adequacy of observational system assessment	– Average – Column values of CO_2 and CH_4 are not temporally and spatially adequately sampled despite the global coverage achieved with satellites. Vertically resolved measurements are very sparse.
Availability and stewardship assessment	– Average – Satellite and some ground-, aircraft- and balloon-based datasets are well-curated and accessible, while ground-, balloon-, and aircraft-based datasets are in various formats and spread among several data repositories
Networks	– TCCON/NDACC: total column CO_2 and CH_4 and some in situ balloon-based measurements – ICOS, GAW: surface in situ CO_2 and CH_4 – NOAA GGGRN: global flask network CO_2 and CH_4 with sparse in situ ground-, aircraft and balloon-based measurements of CO_2 and CH_4 – IAGOS/CARIBIC: CO_2 and CH_4 measurements from commercial aircraft – Regional and national in situ and flask networks: surface values
Satellites	– MetOp IASI, Aqua AIRS, Suomi-NPP CrIS, JPSS-1 CrIS, Sentinel-5P TROPOMI, GOSAT and GOSAT-2 TANSO, OCO-2, ISS OCO-3, OCO-2, SCISAT ACE-FTS, TANSAT
Models, reanalysis, etc.	– CAMS (forecast, (re)analysis, inverse modelling), C3S (reanalysis), MERRA-2 (reanalysis), NOAA carbon tracker (data assimilation/model), carbon cycle and Earth system models, NASA DAO, etc.

Expanded in the next slides

Sources: GCOS Status Report 2021, Kearney Energy Transition Institute analysis

Climate and climate change research and applications require regular observational data from sources distributed across the globe

The most essential subset of these observing stations is operating under the regime coordinated by the World Meteorological Organization (WMO), involving clear commitments regarding the site, the exposure of instruments, error handling, units of measurement, coding, and exchange of reports.

Established in 1995 as Global Climate Observing System (GCOS) Baseline Networks, both GSN and GUAN are part of GCOS Atmospheric Network.

2.7 International organizations monitoring GHG emissions – Global observation infrastructures

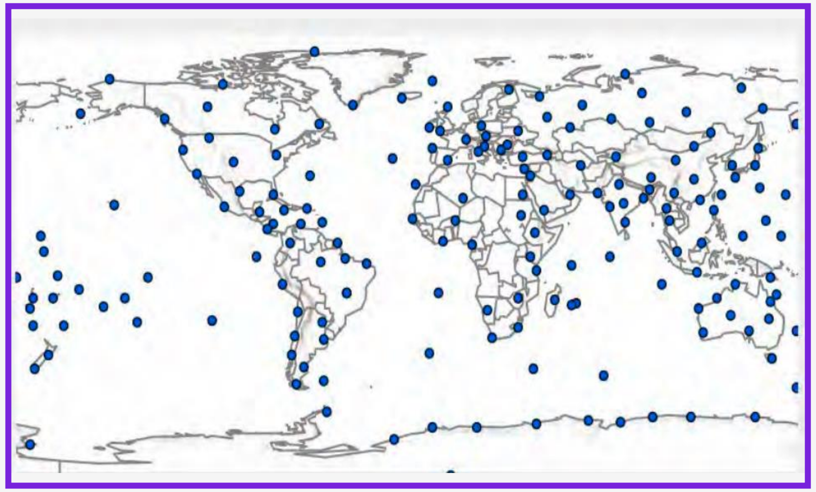
GCOS Surface Network (GSN)[1]

1,022 stations in 2020

GSN is a global network of more than 1,000 stations selected from a network of many thousands of meteorological stations. The GSN is intended to comprise the best possible set of land stations with a spacing of 2.5 to 5 degrees of latitude, thereby allowing coarse-mesh horizontal analyses for some basic parameters.

GCOS Upper-Air Network (GUAN)[2]

177 stations in 2020



GUAN specifically serves the needs of global climate applications and has been established mainly based on existing GOS networks. It forms a minimum configuration required for global applications for upper-air.

Note: 1 & 2: GSN and GUAN stations highlighted here are to indicate the networks' reach. These are not specific stations for GHG measurement.
Sources: GCOS Status Report 2021; Kearney Energy Transition Institute analysis

A network of measurement stations forms the backbone of WMO's Global Atmosphere Watch program

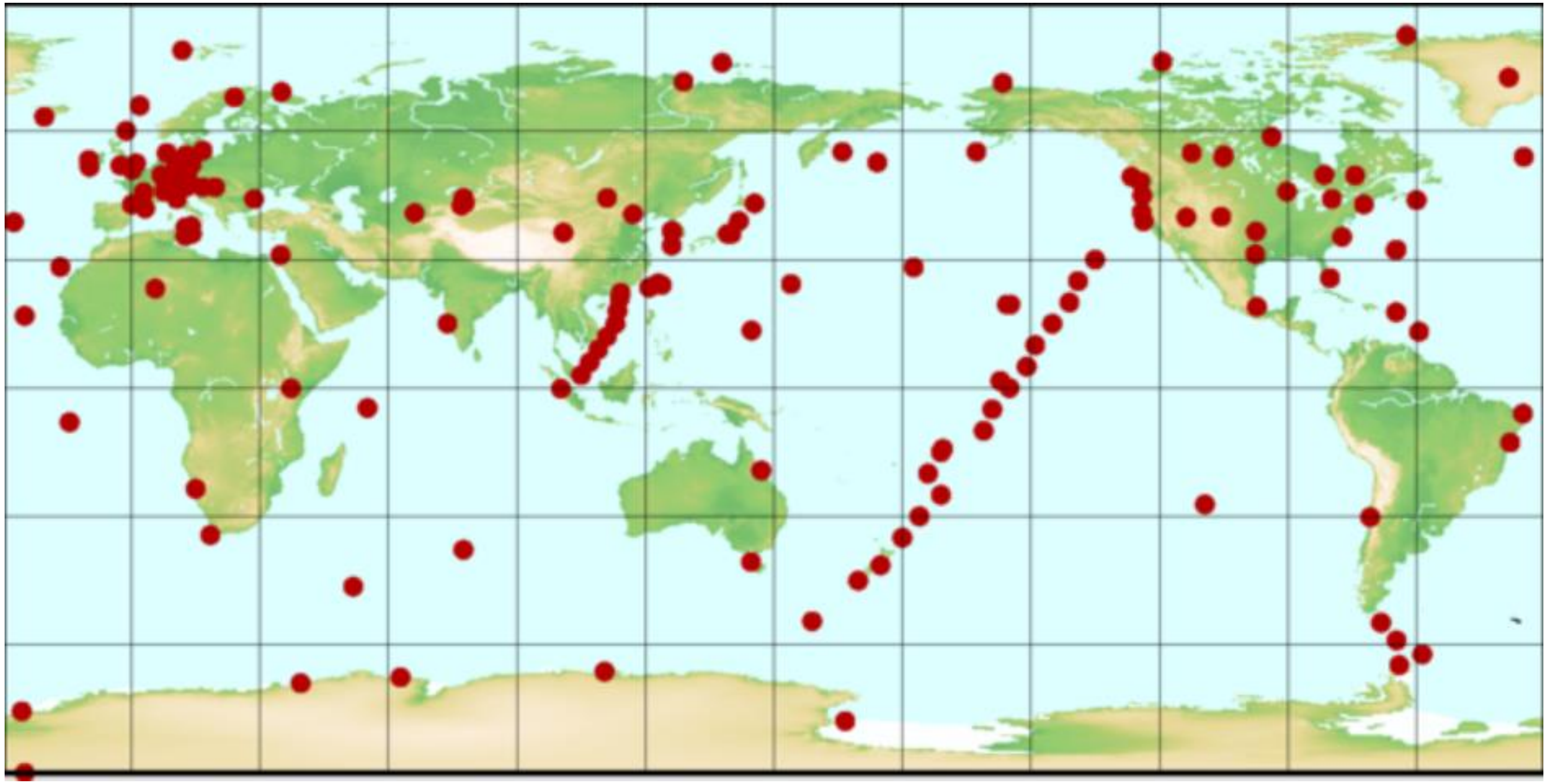
Example network- Global

Data from the Global Atmosphere Watch (GAW) feed several bulletins, including greenhouse gas bulletins, WMO Arctic and Antarctic ozone bulletins, and aerosol bulletins.

Currently, GAW coordinates activities and data from 30 global stations, more than 400 regional stations, and around 100 contributing stations operated by contributing networks.

2.7 International organizations monitoring GHG emissions – Global observation infrastructures

Global Atmosphere Watch (GAW) global stations for greenhouse gas[1]



The World Data Centre for Greenhouse Gases (WDCGG) was established at the Japan Meteorological Agency (JMA) in October 1990 and collects and distributes data on the mixing ratios of greenhouse (CO_2, CH_4, CFCs, N_2O, etc.) and related reactive (O_3, CO, NOx, SO_2, VOC, etc.) gases in the atmosphere and the ocean. Station distribution map for the WDCGG global analysis is produced above.

1. Detailed list of contributing stations can be accessed at https://gaw.kishou.go.jp/publications/bulletin/station_list/2020

Sources: GCOS Status Report 2021; World data centre for greenhouse gases, Kearney Energy Transition Institute analysis

More than 80 countries host GAW stations that are operated either by their national meteorological services or by other national scientific organizations

Not exhaustive

A contributing network is one that has signed a letter of agreement (LoA) with WMO and meets a list of standards set out in advance.

2.7 International organizations monitoring GHG emissions – Global observation infrastructures

Networks contributing to the GAW program
(not all networks address GHG emissions)

Contributing network	Coverage scope	Description
The Total Carbon Column Observing Network (TCCON)	Global	– The Total Carbon Column Observing Network is a ground-based network of high-resolution Fourier transform spectrometers (FTSs) that record the near-infrared solar absorption spectrum and retrieve column-average mixing ratios of multiple gases.
Integrated Carbon Observation System Research Infrastructure (ICOS RI)	Europe (13 countries)	– The Integrated Carbon Observation System Research Infrastructure (ICOS RI) integrates atmosphere, ecosystem, and ocean greenhouse gas observations to provide timely and reliable data for research, policymaking, and the general public.
NOAA (National Oceanic and Atmospheric Administration)	US based but global network	– Among many mandates, NOAA conducts research greenhouse gas and carbon cycle feedbacks, changes in clouds, aerosols, and surface radiation, and recovery of stratospheric ozone (through its Global Monitoring Laboratory - GML)
In-service Aircraft for Global Observing System (IAGOS)	Global	– The European Research Infrastructure IAGOS operates a global-scale monitoring system for atmospheric trace gases, aerosols and clouds utilizing the existing global civil aircraft. IAGOS is unique in collecting regular in-situ observations of reactive gases and greenhouse gases concentrations and aerosol properties in the upper troposphere and lowermost stratosphere (UTLS) at high spatial resolution.
NASA Micro-Pulse Lidar Network (MPLNET)	Global	– The NASA Micro-Pulse Lidar Network (MPLNET) is a federated network of micro-pulse lidar (MPL) systems designed to measure aerosol and cloud vertical structure continuously, day and night, over long periods of time.
National Atmospheric Deposition Program (NADP)	North America	– The US-based National Atmospheric Deposition Program (NADP) is a long-term, measurement cooperative composed of representatives from federal, state, tribal, and national agencies, universities, private companies, and non-governmental organizations. Most NADP stations are in the United States, but several are in Canada and in other nations. Each monitoring network follows well-defined protocols to measure acidic compounds, nutrients, base cations, and mercury in precipitation and ambient concentrations of ammonia and mercury for estimates of dry deposition.

Expanded in the next slides

Note: Many countries have national GHG networks and not all these sites are on GAW list
Sources: Kearney Energy Transition Institute analysis

The Total Carbon Column Observing Network is a network of ground-based Fourier transform spectrometers that record spectra of the sun in the near-infrared

Example network: global

Support for the network is provided in part by NASA through grants made to the California Institute of Technology.

Data is mainly used for validating satellite measurements

2.7 International organizations monitoring GHG emissions – Global observation infrastructures

Total Carbon Column Observing Network (TCCON) sites

TCCON participants agree to adhere to a common set of standards for instrumentation, data acquisition, calibration, and analysis as determined by the TCCON Steering Committee. From the recorded spectra, accurate and precise column-averaged abundances of atmospheric constituents including CO_2, CH_4, N_2O, HF, CO, H_2O, O_2 and HDO, are retrieved

Sources: GCOS Status Report 2021; Kearney Energy Transition Institute analysis

More than 40 devices are operated around the globe by working groups in Germany, the United States, the United Kingdom, India, Namibia, Japan, China, and Mexico under the COCCON network

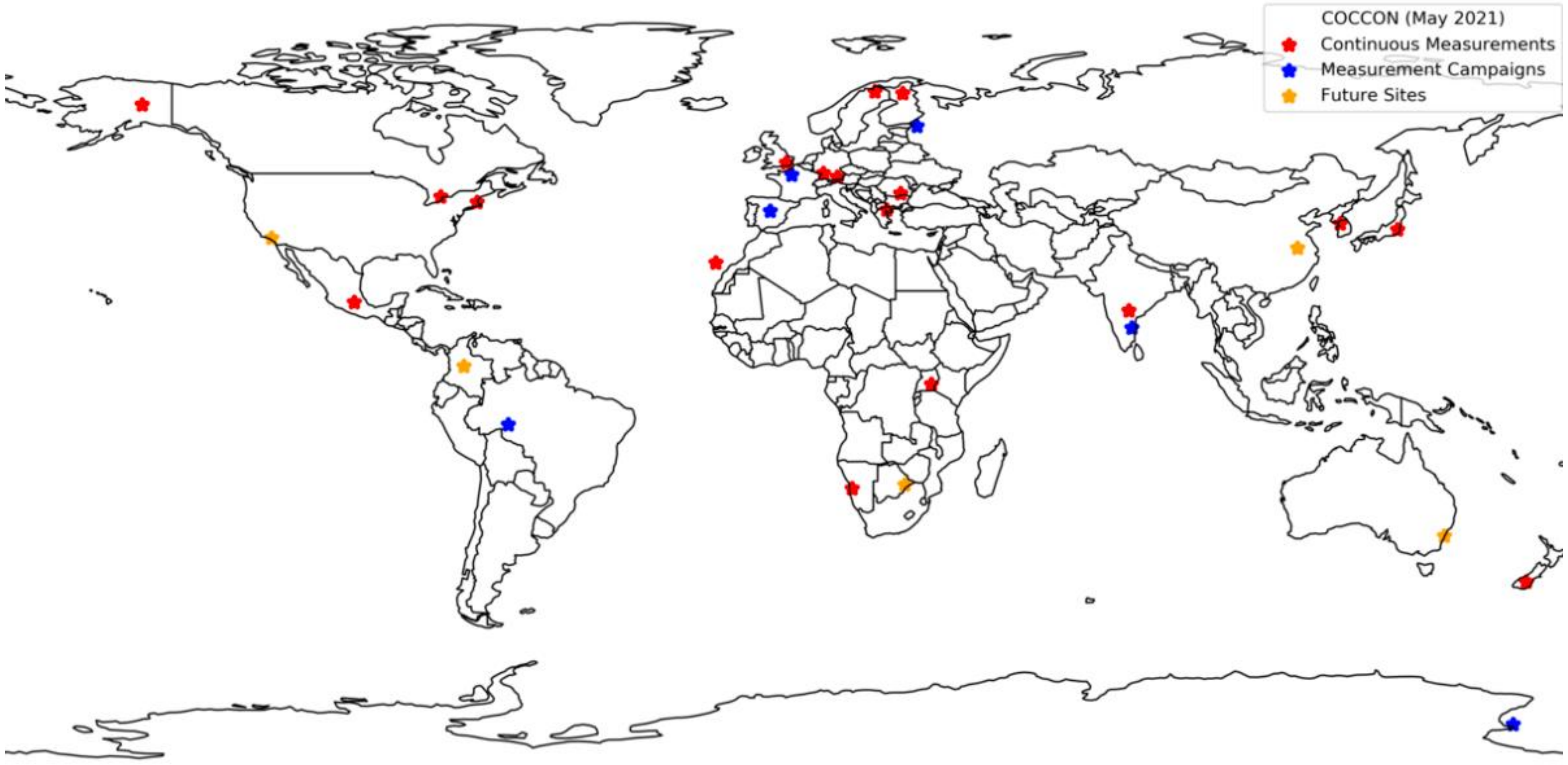
Example network: global

Column-averaged abundances of carbon dioxide, methane, water vapor, and carbon monoxide can be deduced from the recorded solar absorption spectra.

Design and performance of the devices have opened the possibility of supporting the Total Carbon Column Observing Network (TCCON).

2.7 International organizations monitoring GHG emissions – Global observation infrastructures

Collaborative Carbon Column Observing Network (COCCON)



In 2011, a new type of portable FTIR spectrometer for the measurement of the main greenhouse gases was developed by the KIT in cooperation with Bruker Optics (Ettlingen, Germany). Since 2014, these spectrometers are commercially available under the model designation EM27/SUN.

Sources: GCOS Status Report 2021; Kearney Energy Transition Institute analysis

ICOS, the European Integrated Carbon Observation System, is a distributed European research infrastructure

Example network: Europe

The key aim is to measure, analyze, and understand GHG fluxes in the **atmosphere, over the ocean, and at the ecosystem level by capturing data from a network of stations and observation centers.**

The ICOS Station Network consists of more than 140 measurement stations in three domains in 13 European countries.

2.7 International organizations monitoring GHG emissions – Global observation infrastructures

Atmosphere observations

Step 1: Observe
The ICOS atmosphere station network, 38 stations in 13 countries, observes GHG in atmosphere.

Step 2: Coordinate
The atmosphere observations are coordinated by the Atmosphere Thematic Centre (ATC).

Step 3: Analyze
The Central Analytical Laboratories provides services for additional quality control and an extended set of parameters.

Ecosystem observations

Step 1: Observe
The ICOS ecosystem station network consists of 86 stations in 13 countries and observes components and drivers responsible for the exchange of GHG, water, and energy between ecosystems and the atmosphere.

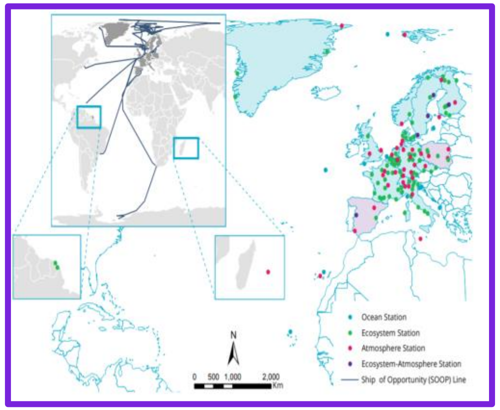
Step 2: Coordinate
The ecosystem observations are coordinated by the Ecosystem Thematic Centre (ETC).

Ocean observations

Step 1: Observe
The network of ICOS ocean stations includes 23 stations in eight countries to observe surface ocean carbon levels to deliver the data needed to quantify the ocean's role in planetary carbon cycling.

Step 2: Coordinate
The ocean observations are coordinated by the Ocean Thematic Centre (OTC).

ICOS observing stations



Sources: ICOS; Kearney Energy Transition Institute analysis

NOAA's Annual Greenhouse Gas Index, known as the AGGI, tracks increases in the warming influence of most heat-trapping gases

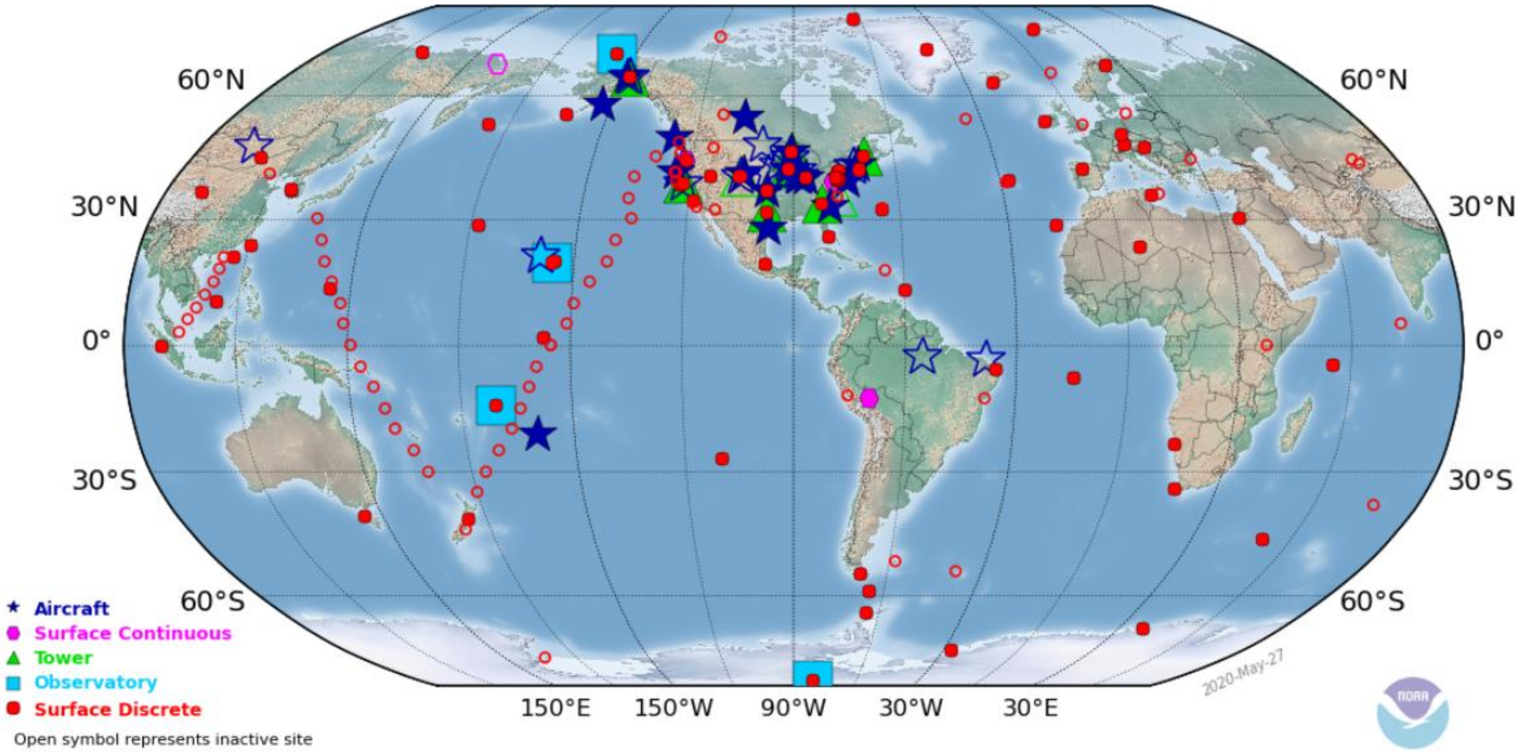
Example network: global

NOAA's Global Greenhouse Gas Reference Network (GGGRN) maintains the WMO international calibration scales for CO_2, CH_4, CO, N_2O, and SF_6 in air.

2.7 International organizations monitoring GHG emissions – Global observation infrastructures

Cooperative measurement programs

NOAA GML Carbon Cycle



The Global Greenhouse Gas Reference Network measures the atmospheric distribution and trends of the three main long-term drivers of climate change, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) as well as carbon monoxide (CO) which is an important indicator of air pollution

Sources: Global monitoring laboratory; Kearney Energy Transition Institute analysis

Anthropogenic greenhouse gases continue to be globally emitted at an annual rate that is not yet significantly decreasing

Satellite observations (e.g., GOSAT2 or OCO-2) provide useful and reliable information and spotted emission sources, which were neglected or missing earlier (e.g., fugitive CH_4 emissions from coal mines).

2.7 International organizations monitoring GHG emissions – Global observation infrastructures

2 Anthropogenic greenhouse gas fluxes

Products covered	– National annual CO_2, CH_4 and N_2O emission inventory time series and their uncertainty per sector and covariance matrix; also disaggregated spatially (e.g., to 0.1degx0.1deg) and temporally (monthly, daily, hourly) and their grid map uncertainties
Adequacy of observational system assessment	– Poor – Considerable differences between bottom-up (inventory based) and top-down (atmospheric inversion based) results
Availability and stewardship assessment	– Average – Emissions estimates are available but without a data center or data stewardship.
Networks	– For CO_2 and CH_4: TCCON, COCCON – For CO_2 and CH_4 and N_2O: ICOS
Satellites	– For CO_2: GOSAT2, OCO-2, OCO-3 and in the future GOSAT3, and CO2M Sentinel – For CH_4: GOSAT2, Sentinel 5P, Methanesat, GHGsat, and in the future GOSAT3, CO2M Sentinel
Models, reanalysis, etc.	– Multiple ex: ensemble models of the Copernicus Atmospheric Monitoring Service (including IFS model of ECMWF)

Regions that are poorly equipped with in situ stations or that are subject to less well-managed land-use changes or less well-confined (less well-characterized or less well-regulated) human activities (e.g., exploratory drilling, shale gas fracking, waste Incineration, or disposal) could benefit from additional in situ measurements.

Sources: GCOS Status Report 2021; Kearney Energy Transition Institute analysis

Collections of surface ocean pCO2 data have been made largely by ship-based underway measurements and augmented with fixed-point measurements by moorings

Coverage of data in space and time is good in the open oceans of the northern hemisphere but is low in many regions of the vast oceans in the southern hemisphere and in coastal zones in light of the resolutions required.

2.7 International organizations monitoring GHG emissions – Global observation infrastructures

3 Inorganic carbon in ocean

Products covered	– Surface ocean partial pressure of CO2 (pCO2), subsurface ocean carbon storage (DIC/TA, pH), ocean acidity (pH)
Adequacy of observational system assessment	– Poor – There is a large range in the adequacy of the data. The coverage and accuracy of inorganic carbon in surface layers in the open ocean of the northern hemisphere is good but is low in others.
Availability and stewardship assessment	– Good – Availability and stewardship of data collected as part of global observing systems is good, but their QC rely largely on voluntary services.
Networks	– Ship-based Repeat Hydrography: GO-SHIP – Ship-based Underway Observations: SOOP-CO2 – Ship-based Fixed-point Observations – Moored Fixed-point Observatories: OceanSITES – Profiling floats: Biogeochemical Argo – Autonomous Underwater Vehicles: OceanGliders – Autonomous Surface Vehicles: no coordinated network
Satellites	– None
Models, reanalysis, etc.	– Global Ocean Data Analysis Project (GLODAPv2), Surface Ocean CO2 Atlas (SOCAT), Lamont-Doherty Earth Observatory (LDEO) Climatology

Detailed in the appendix

Sources: GCOS Status Report 2021; Kearney Energy Transition Institute analysis

Initiatives targeting methane emissions use a variety of tools and serve different goals

Not exhaustive

80% of countries have included methane in their GHG targets of their NDC, **but only 5% have set specific targets for methane reduction.**

2.7 International organizations monitoring GHG emissions – Global methane initiatives

List of key initiatives to track methane

Initiative	Public/private, for/non-profit	Launch	Data availability	Methodology
IMEO (UNEP)	IGO led, non-profit, 193 member countries	Launched in November 2021	– Public dataset of empirically verified methane emissions, with an initial focus on fossil fuel sources	– Aggregating company reporting, satellite data, and data from scientific studies
IEF Methane Initiative	IGO led, non-profit, 71 member countries	June 2021	– Methodology provided; confidential data was provided to select countries during the Initiative	– Consultative, iterative, top-down supported by global satellite data/advanced analytics, and bottom-up company reporting and country contextual data
Global Methane Initiative	Government-led, public–private initiative, nonprofit, 45 member Countries	2004	– Historical US EPA emission data provided	– Technical support to deploy methane-to-energy projects
MethaneSAT (EDF)	NGO led, non-profit	Planned Q4 2022	– Raw data publicly Available	– Top-down, targeted area mapping (not global) by satellite
OGCI	Industry driven, CEO led, for-profit, 12 companies as members	2014	– Aggregate statistics of member companies available	– Members provide bottom-up data; verified by third-party
OGMP 2.0	Public–private initiative, led by UNEP, EDF, and EC, and has 67 companies as members	2014	– Company data remains confidential	– Member companies provide bottom-up emission data of assets but not disclosed
Methane Guiding Principles	Industry led, 24 companies as members	2017	– Companies publicly report	– Companies report how they are – meeting the intent of reducing – emissions and improving data

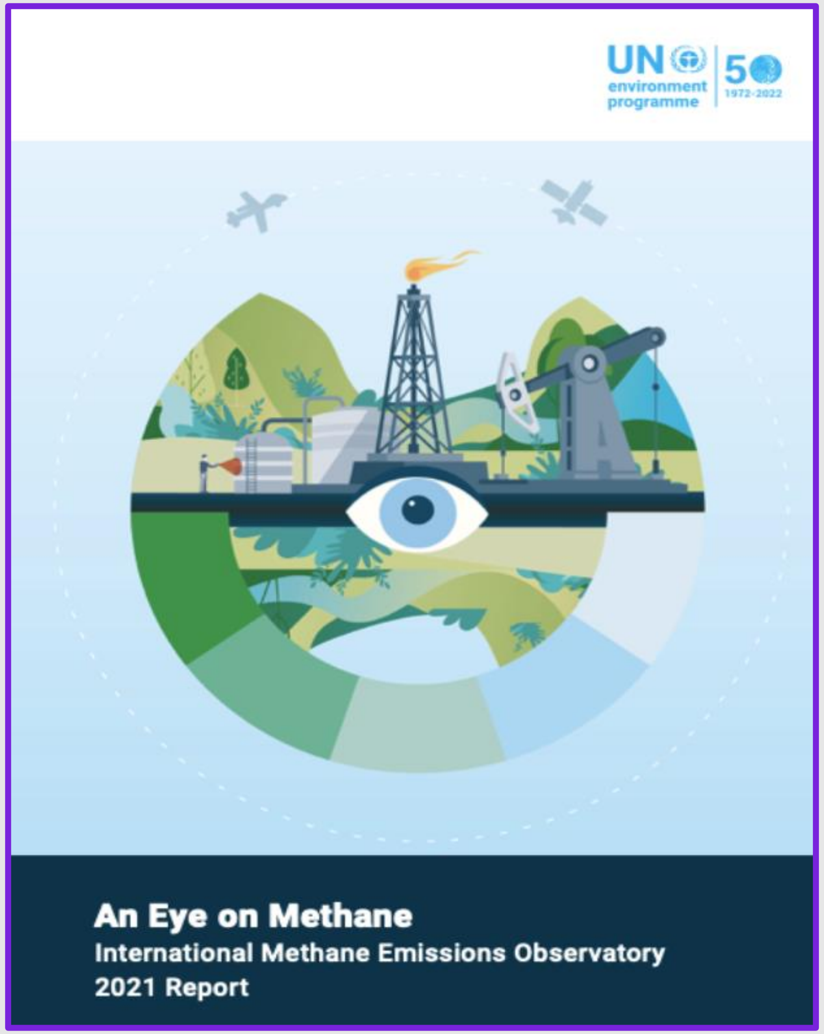
Expanded in the next slide

Sources: Kayrros; Kearney Energy Transition Institute analysis

The International Methane Emissions Observatory (IMEO) is set to revolutionize the approach to methane reduction by connecting data with action on research, reporting, and regulation

2.7 International organizations monitoring GHG emissions – Global methane initiatives

UNEP 2021 annual report
released on October 31, 2021



Sources: Kearney Energy Transition Institute analysis

The IMEO is an initiative by the UN Environment Program (UNEP) with support from the European Commission to catalyze dramatic reduction of methane emissions, starting with the energy sector.

Key aims:

- The IMEO along with public data will set the basis for standardization and transparency in methane emissions measurements.
- The IMEO will collect and integrate diverse methane emissions data streams to establish a global public record of empirically verified methane emissions at an unprecedented level of accuracy and granularity.
- Provide near-real time, reliable, and granular data on the locations and quantity of methane emissions that targets strategic mitigation action, to catalyze strategic mitigation actions that are urgently needed to achieve the Paris agreement goals.

The IMEO's annual report seeks to provide decision-makers with a framework of action to track and monitor methane emissions to plan targeted and ambitious action for their mitigation.

The release of its first annual report coincides with the G20 Summit in Rome and took place just a few days ahead of the beginning of the 2021 UN Climate Change Conference (COP26) in Glasgow.

Regulation is crucial for standardizing measuring, reporting, verifying, and certifying the emissions content of internationally traded products

"The lack of international cooperation and agreement surrounding GHG emissions impedes energy transition pathways."

Policy brief by Task Force 2 for G-20, September 2021

2.8 Measurement, reporting and certification standards

Framework to foster international collaboration

(per G-20 policy brief)

International standards but implemented locally

1 Measure

It is imperative to measure carbon content over a product's life cycle from inception to final processing.

2 Report

Emissions should be reported and verified in a consistent, uniform, and transparent manner.

3 Certify

Products, especially those traded internationally, should be certified on emissions basis a standard methodology.

Mixed membership (public-private) body

Enable countries to agree on and implement global standards.

Incentivize corporations both to comply with global standards and to invest in emissions-reducing technologies.

Facilitate the international trade of goods with certified emissions.

Source: "International cooperation to accalarate the development and deployment of circular carbon economy" (G-20 policy brief, September 2021)

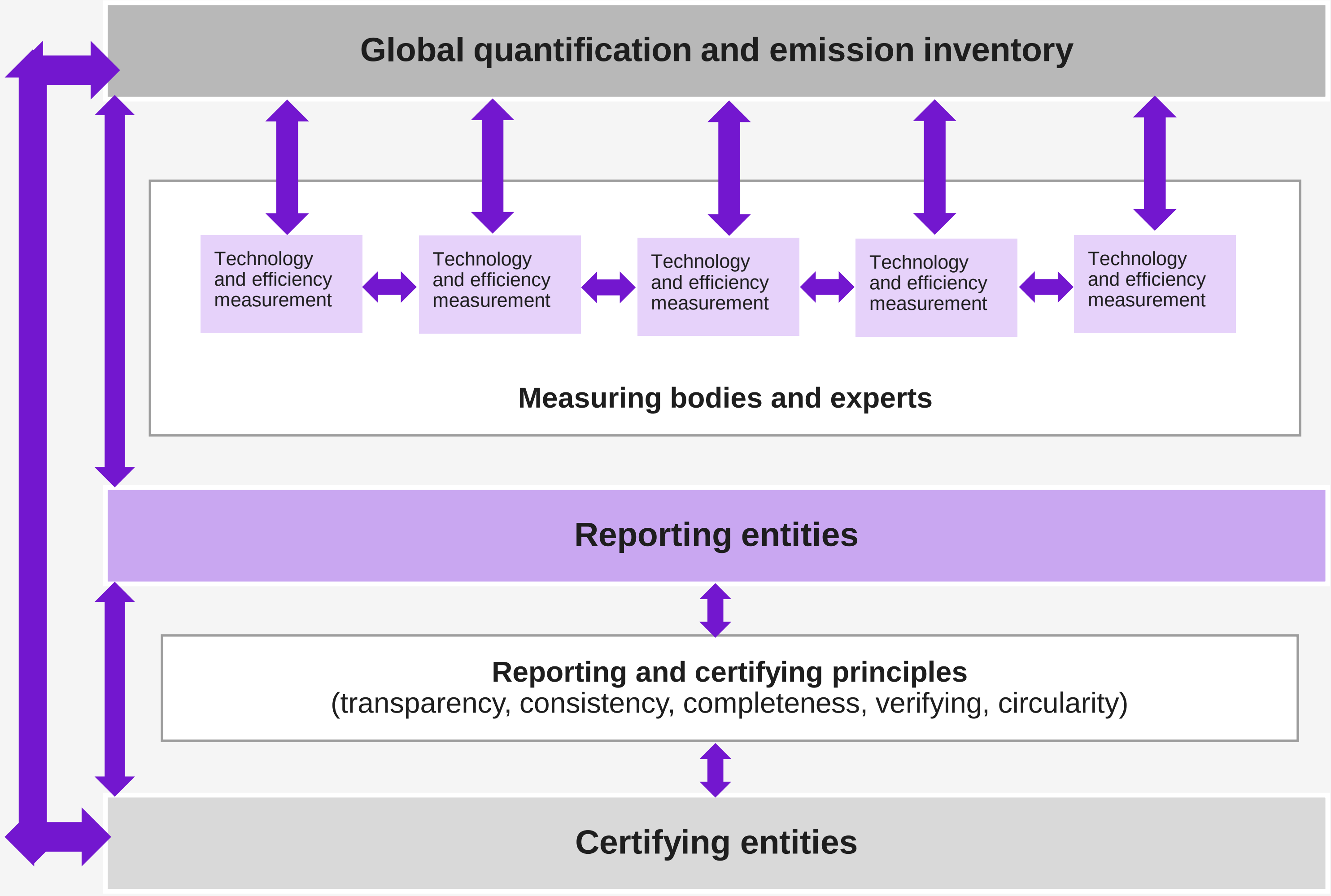
Independent international bodies should be created to promote GAAP-E and its adoption by local actors

National bodies should be formed to implement the mandates locally.

2.8 Measurement, reporting and certification standards

Proposed process flow for implementing an international cooperation framework

(per G-20 policy brief)



Note: GAAP-E is Generally Accepted Accounting Principles for Emissions.
Source: "International cooperation to accelarate the development and deployment of circular carbon economy" (G-20 policy brief, September 2021)

The trend toward standardizing emission reporting has accelerated but remains fragmented across geographies and sectors

Not exhaustive

History of measuring, reporting, and certifying efforts

Global Reporting Initiative (GRI)

Carbon Disclosure Project (CDP)

UN-backed Principles for Responsible Investment

Sustainable Accounting Standards Board (SASB)

United Nations Sustainable Development Goals (SDGs)

Paris Agreement – Non-State Actor Platform (NAZCA)

Climate Action 100+

Taskforce on Climate-Related Financial Disclosure (TCFD)

NFRD Guidelines Supplement

EU Reg. 2088/2019 on Sustainable Finance entry into force

SEC Announces Enforcement Task Force on Climate and ESG Issues

ISSB[3] announced at COP26

1st deadline for annual product-level ESG disclosure (EU Reg. 2088/2019)

1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022

Current examples of regulations, standards, and guidelines on GHG emissions

GHG emissions are a sub-set of wider ESG[1] metrics that are being studied with increasing details

Not exhaustive

Global	Local	Sectoral
– IPCC guidelines for GHG – The Greenhouse Gas Protocol – UN Forum on Sustainability Standards – ISO 14064 – PAS 2060 (BSI & Carbon Trust)	– Life Cycle Assessment (European Environment Agency, 1998) – France (Bilan Carbone) – China Corporate Energy Conservation and GHG Management Programme	– The Cement CO_2 and Energy Protocol (WBCSD[2]) – World Steel Association CO_2 emissions data collection guidelines – Canadian Association of Petroleum Producers, GHG Emissions, 2003

[1] ESG is environmental, social, and governance.
[2] WBCSD is World Business Council for Sustainable Development.
[3] ISSB is International Sustainability Standards Board.
Source: Kearney Energy Transition Institute analysis

IPCC guidelines (2019 update to 2006 guidelines) are the most comprehensive emission accounting guidelines even though they don't recommend atmospheric GHG measurements to corroborate emission estimates

Faced with a patchwork of climate disclosure norms for companies, G20 leaders at the COP26 backed the creation of a new International Sustainability Standards Board (ISSB)

The ISSB is part of the **IFRS Foundation**, whose International Accounting Standards Board writes accounting rules used in about 140 countries.

IFRS®

The key aim is to weed out companies' unjustified climate claims (greenwashing)

1 Structure and organization

Consolidations of existing standards

- The IFRS, CDP, and the Climate Disclosure Standards Board (CDSB) have completed the consolidation of the CDSB into the IFRS Foundation to support ISSB (February 2022).
- The **Value Reporting Foundation** is expected to consolidate by June 2022. VRF was formed earlier in 2022 in a merger of the International Integrated Reporting Council (IIRC) and the Sustainability Accounting Standards Board (SASB).

Composition of ISSB

The ISSB will be headquartered in Frankfurt and will have 14 members:

- **Geographical spread:** three members from the Asia–Oceania region, three members from Europe, three members from the Americas, one member from Africa, and four members appointed from any area
- **Emmanuel Faber** (former CEO of Danone) has been appointed as ISSB chair with **Sue Lloyd** (former vice chair of IASB) as vice chair.

Sources: press research; Kearney Energy Transition Institute analysis

2 Execution and endorsement

Current plans

The ISSB plans to launch its first global baseline company climate disclosure standards, IFRS Sustainability Disclosure Standards, in the **second half of 2022.** However, it will be up to each country to decide if and how the standards are applied.

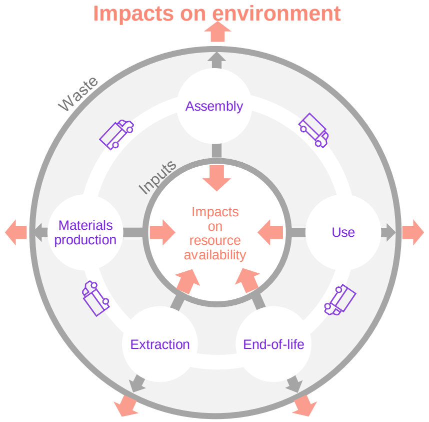
Outlook

The success of the ISSB will hinge on backing from major countries and organizations:

- More than 40 jurisdictions, including the United States, Japan, China, and Britain, have welcomed the ISSB.
- The **International Organization of Securities Commissions (IOSCO),** the global umbrella body for securities regulators, is considering a possible assurance framework to ensure rigorous checks on whether the ISSB standards are properly applied by companies. If formally endorsed, its members, accounting for 95% of the world's securities markets, would then be obliged to implement and enforce the new standards.

3. Estimating direct and indirect carbon emissions: the concept of life-cycle assessment

Life-cycle assessment is an ideal but demanding method for an environmental impact assessment



3.0 Executive summary

Measuring real carbon emissions: the concept of life-cycle analysis
(pages 66–77)

The international journey toward life-cycle assessment started in the 1970s in Europe, began to be harmonized in the 1990s, and is not yet complete. Among the major steps in that journey, a first code of practice for life-cycle assessment (LCA) was introduced in 1993, and the ISO 14040 series were released in 1997. The Integrated Product Policy (IPP) highlighted the need for LCA in European policies.

LCA is a standardized method to evaluate the potential environmental impacts of a product or service following the principles of the broad concept called life-cycle thinking, which aims to offer a comprehensive approach. LCA is a decision-making tool for policies and mitigation strategies. All activities included in a system or a product's life cycle are linked together by physical exchanges and related to the environment through elementary flows.

LCA can be used at different levels. Its original scope is product-based, but top-down studies of national economies now rely on LCA to point out crucial drivers of environmental impacts of the country. At the European level, the slow increase of mentions of LCA in environmental policies, which are only mentioned as potential improvements of policies, is due to the complexity, the amount of time and comprehensive information needed for high-quality life-cycle assessments, and its variable knowledge among industrial actors.

Despite being in theory an ideal method for environmental assessment, adapting databases and models to the scope and capabilities of the study is complex in practice. LCA is composed of four main steps, which contribute to making it universal, replicable, and science-based: definition of goal and scope, life-cycle inventory, life-cycle assessment, and interpretation. The first two phases are the most time-consuming and often suffer from limitations in terms of expertise, data, and resources.

Main best practices and axes for further research stem from quantifying the ease of implementation and accuracy of current databases and models. For instance, using bottom-up engineering-based models with global sensitivity analyses back and forth between the inventory phase and assessment/interpretation phases would benefit from improving methods relying on statistical proxy. Also, best practices for LCA include involving industrial stakeholders when defining the goal and scope of the study.

There is no appropriate method for all applications. The trade-off between ease of implementation and accuracy of outputs depends on the goal of the study. As opposed to absolute assessments, indicators relative to the definition of the system boundaries and the characterization methods can be used when the goal is to compare several systems within the same category or the same system over time.

Source: Kearney Energy Transition Institute analysis

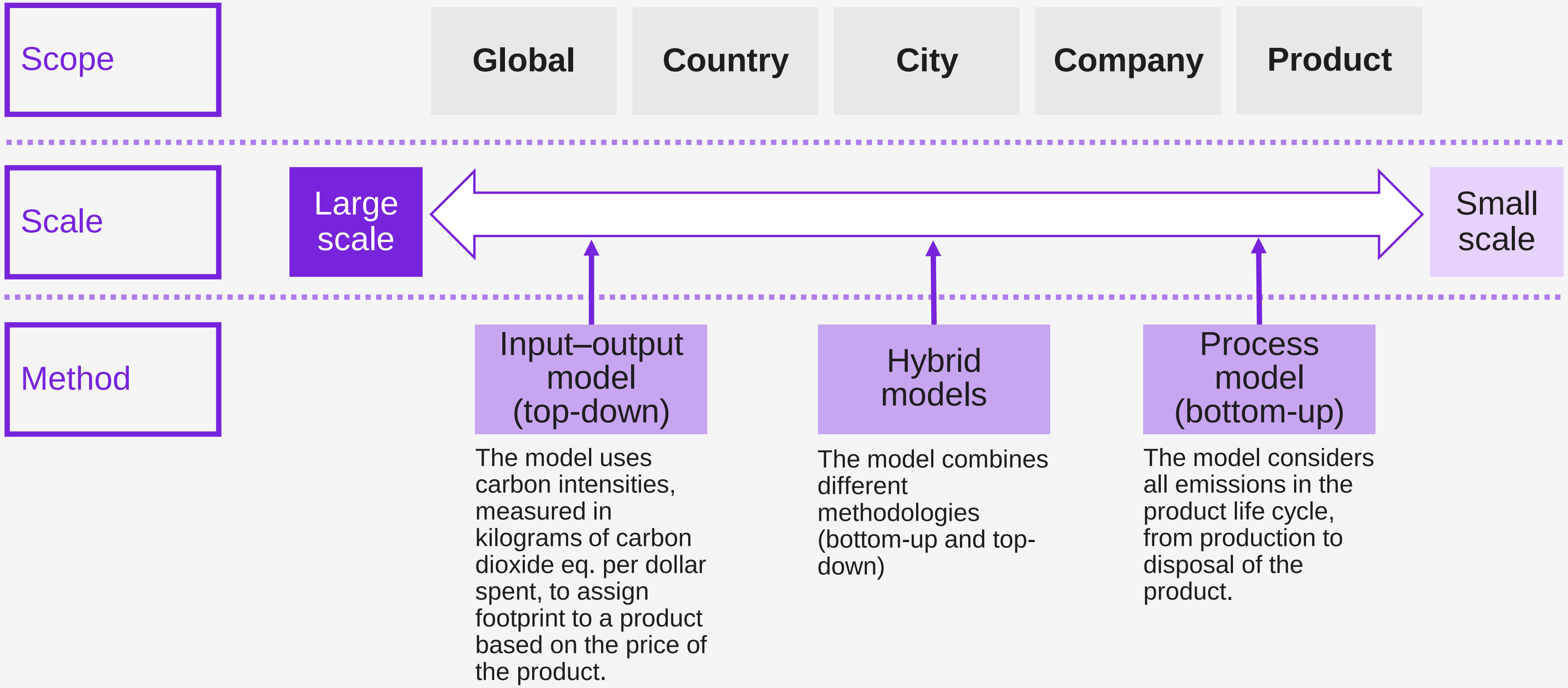
There are three main approaches to assess carbon emissions

The Kyoto protocol defines the six main greenhouse gases, and by weighting each of the gases according to the damage it causes to the environment, the protocol allows the impact to be quantified in terms of a single measure: kilograms of carbon dioxide equivalent.

Carbon footprint: the greenhouse gas emissions of a process or the life cycle of a product measured in kilograms of carbon dioxide equivalent

3.0 The concept of life-cycle analysis

Approaches for life-cycle assessment
measured in carbon dioxide equivalent



Multiple standards have been formulated globally (GHG protocol by World Resources Institute and World Business Council for Sustainable Development, International Standards Organisation (ISO) 14000 series, International Society for Environmental Toxicology and Chemistry standards) **and locally** (PAS 2050 in the UK, Bilan Carbone™ in France, etc.)

Sources: GHG protocol Life Cycle Database, “A comparative study of carbon footprint and assessment standards” (Gao, Liu and Wang 2013); Kearney Energy Transition Institute analysis

The international journey toward coherent life-cycle environmental policies started in the 1970s and is not yet complete

Before 1990, policies were focused on certain polluting substances and did not have a comprehensive view of the environmental impacts of products. During the 1990s and increasingly since 2000, new types of environmental policies have been developed throughout the world.

There is a need for more accurate and comprehensive databases to build more representative LCA models but also for homogenization of the scope and system boundaries definition to consider all the potential direct and indirect environmental impacts of a product or an activity to design environmental policies accordingly.

1970 1975 1980 1985 — Environmental policies with a very specific focus

1990 1995 — Consideration of a broader set of pressures

2000 2005 2010 2015 2020 — Integration of the principle of LCT to an increasing number of policy instruments

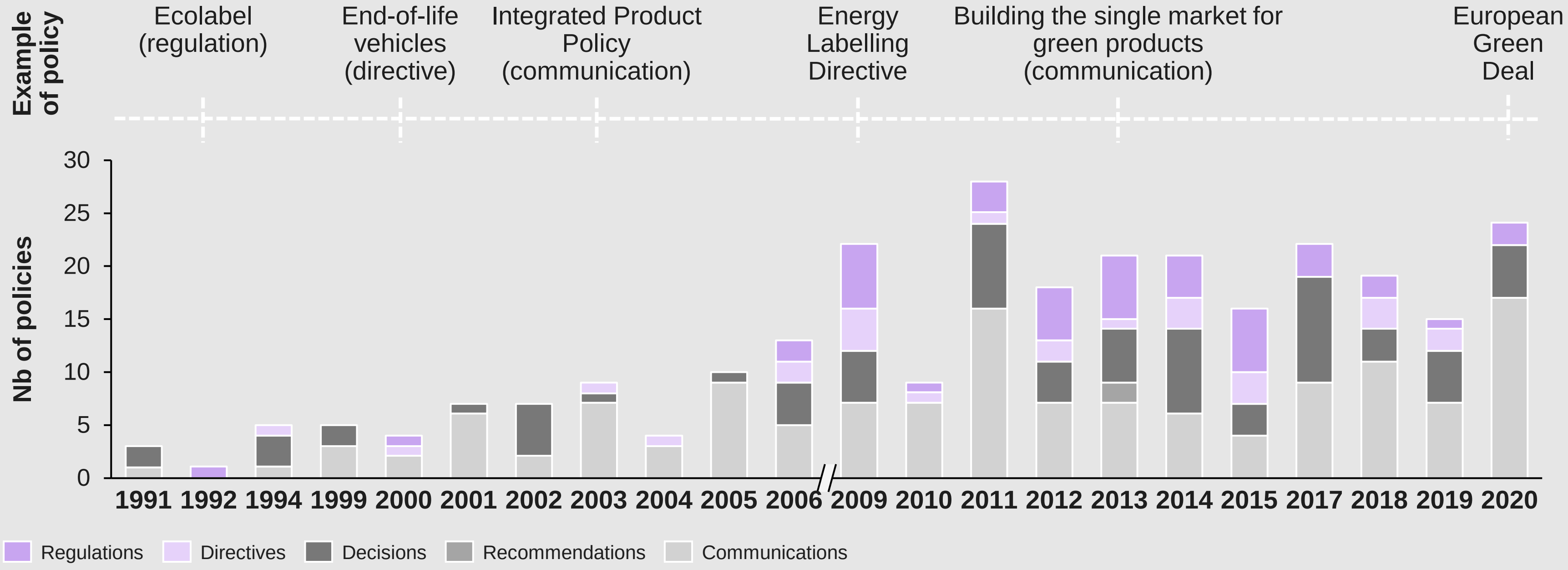
- Clean Water Act
- Clean Air Pact
- Nuclear Waste Policy Act
- Montreal Protocol on Substances that Deplete the Ozone Layer
- European EcoLabel
- First code of practice in LCA (SETAC[1])
- ISO 14040 series
- First version of eco-invent database
- UNEP/SETAC Life Cycle Initiative (LCI)
- Japan EcoLeaf
- Integrated Product Policy (IPP)
- European platform on LCA
- European thematic strategy on the prevention and recycling and waste
- SCP/SIP[2]
- JRC's ILCD[3]
- FAO partnership on bioenergy
- FAO partnership on livestock
- Mexican life-cycle inventory
- A resource-efficient Europe–flagship initiative
- International Resource Panel
- Latest revision of ISO 14040
- French Grenelle II law
- China Life Cycle Database
- Brazilian LCA Program
- Thailand National Green Growth Strategies
- EU Environmental Footprint pilots
- US LCA Digital Commons Project
- Development of National LCA Database Roadmaps projects in South Africa

3.1 International policy evolution

1. Society of Environmental Toxicology and Chemistry; 2. European Sustainable Consumption and Production (SCP) and Sustainable Industrial Policy (SIP); 3. ILCD: International Life Cycle Data system
Source: Kearney Energy Transition Institute analysis

At the European level, adoption of life-cycle thinking in policy design is increasing slowly because of the complexity and lack of familiarity within the industry

The integration of life-cycle thinking in key EU environmental policies is slowly increasing



In the European Union, the Ecolabel regulation (CEC 1992) was the first policy promoting life-cycle thinking (LCT). Strengthened by the Integrated Product Policy (CEC 2003), the concept of LCT has been integrated in an increasing number of environmental policies since then.

Life-cycle assessment can be used to support each step of the policy cycle. It allows to identify emerging issues and prioritize intervention during the first step consisting in policy anticipation and problem definition. During the last phase of policy evaluation, LCA is useful for analyzing the effectiveness of the policy in terms of environmental impact.

In 2015, LCA was included as one of the methods for better environmental regulation. In the communication “Better rules for better results – An EU Agenda” (CEC 2015) new “Integrated Guidelines on Better Regulation” are provided by the Commission in order to ensure that environmental, social and economic aspects are properly considered at each stage. A Better Regulation toolbox is provided, and LCA is included as tool number 583. Some policies include an explicit mention of LCA to implement (e.g., in the Building Sector Communication (2014)).

However, the number of environmental policies has been stagnating since 2009, and many policies only mention LCA as future improvement. For example, this is the case in the Energy Labelling Directive or EU taxonomy to improve the classification of sustainable economic activities, and mentions LCA as a tool. Policymakers still tend to consider the LCT concept—and more specifically, the LCA approach—as an inconclusive method because of the great variability in results of comparable systems.

Sources: Life cycle assessment for the impact assessment of policies, Sala, S., Reale, F., Cristobal-Garcia J., Marelli, L., Pant R. (2016); Sala, S., Amadei, A.M., Beylot, A. et al. The evolution of life cycle assessment in European policies over three decades. Int J Life Cycle Assess (2021); Kearney Energy Transition Institute analysis

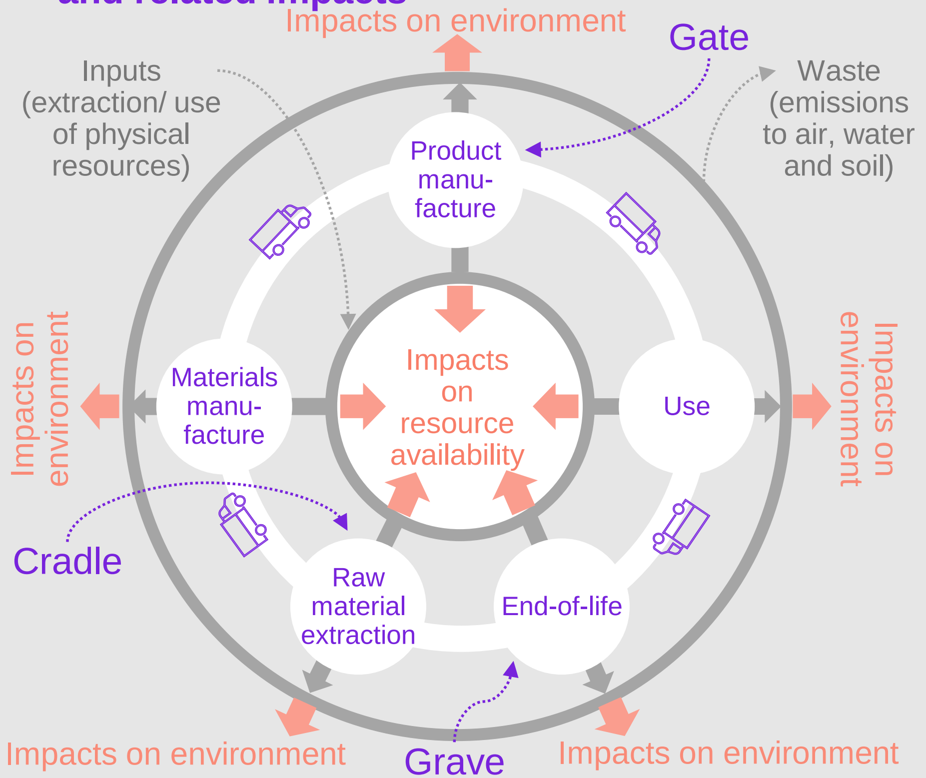
Life-cycle thinking offers a comprehensive approach to evaluating various environmental impacts of a system

Life-cycle thinking (LCT) is a concept promoting the adoption of a comprehensive perspective, from raw materials extraction to end of life. LCT can be applied to economic, social, and environmental pillars.

Life-cycle assessment (LCA) is an internationally standardized method (ISO 14040, ISO 2006a) supporting the environmental pillar.

- LCA is used as a **decision-making tool** for performance-oriented policies, for **analysis of environmental footprints** and **mitigation strategies** from industrial operations, and carbon **risk assessment** of future investments in the fossil fuels industry.
- All activities (unit process) occurring in a product's life cycle are described. They are **linked** by physical exchanges (flow, materials, energy, components) and **related to the environment** through elementary flows (materials, emissions).
- In addition to greenhouse gas emissions, LCA also allows to evaluate potential environmental impacts related to other groups of pollutants thanks to its multi-criteria nature.

Schematic vision of a product's life cycle and related impacts



Different approaches of LCA depending on the system boundaries definition:

- **Cradle-to-grave:** full LCA from resource extraction to end-of-life phase
- **Cradle-to-gate:** assessment of a partial product's life cycle from resource extraction to the factory gate
- **Cradle-to-cradle**: specific type where the EOL step is a recycling process
- **Gate-to-gate:** only for one value-added process
- **Well-to-wheel:** specific LCA used for transport fuels and vehicles (broken down into well to station, well to tank, station to wheel, tank to wheel)

3.2 Basic principles of LCA

Sources: IFP Life Cycle Assessment; The International Reference Life Cycle Data System (ILCD) Handbook, M-A. Wolf, R. Pant, K. Chomkhamsri, S. Sala, D. Pennington (2012); Life cycle assessment for the impact assessment of policies, Sala, S., Reale, F., Cristobal-Garcia J., Marelli, L., Pant R. (2016); Kearney Energy Transition Institute analysis

LCA is a standardized tool with four complementary steps

Goal and scope

Definition of the goal

- Intended application
- Reasons for carrying out the study
- Audience
- Whether the results will be used in a comparative assertion released publicly

Definition of the scope

- Product system functional unit (precise definition of the system: What? How much? How? How long?)) and reference flow (amount of product or energy)
- System boundary definition underlying assumptions and limitations
- Data quality requirements
- Allocation procedure if needed (used to partition the inputs and outputs)
- Impact assessment (outline of central impact categories)
- Documentation of data

Life-cycle inventory (LCI)

Production of a compiled inventory of elementary flows from each stage of the product's life cycle (energy, raw material, products, co-products, waste, emissions to air/water/soil, …). The procedure includes:

- Preparation of data collection based on goal and scope
- Data collection
- Data validation
- Data allocation
- Relating data to the unit process
- Relating data to the functional unit
- Data aggregation

LCI, as each step of LCA, is an iterative process: new data requirements or limitations may be identified that require a change in the data collection procedures.

Life cycle impact assessment (LCIA)

Classification of LCIA results into environmental categories & impact characterization
Selection of categories, indicators & characterization models

- Classification of elementary flows quantified in the LCI phase
- Characterization to convert elementary flows into common units of environmental impacts for comparison

Common categories are:

- **Climate change**
- Eutrophication
- Land use
- Resource depletion
- Acidification
- Ozone depletion
- Ecotoxicity
- Ionizing radiation
- Photochemical ozone formation
- Water depletion
- Human toxicity

Interpretation

Identification quantification, checking and evaluation results from LCI and LCIA

- Identification of significant issues based on the results of the LCI and LCIA phases of an LCA
- Evaluation of the study considering completeness, sensitivity and consistency checks
- Conclusions, limitations and recommendations

Five methodological aspects are key issues:

- Functional Unit
- System Boundary (differences exist among the norms)
- Multi-functionality (when a process fulfils more than one function)
- LCIA method (several methods exist based on different environmental models)
- Type (primary and/or secondary data) and quality of data

3.2 Basic principles of LCA

Sources: "Life cycle assessment for the impact assessment of policies," Sala, S., Reale, F., Cristobal-Garcia J., Marelli, L., Pant R. (2016); ISO 14040:2006; SO 14040:2006/AMD 1:2020; Kearney Energy Transition Institute analysis

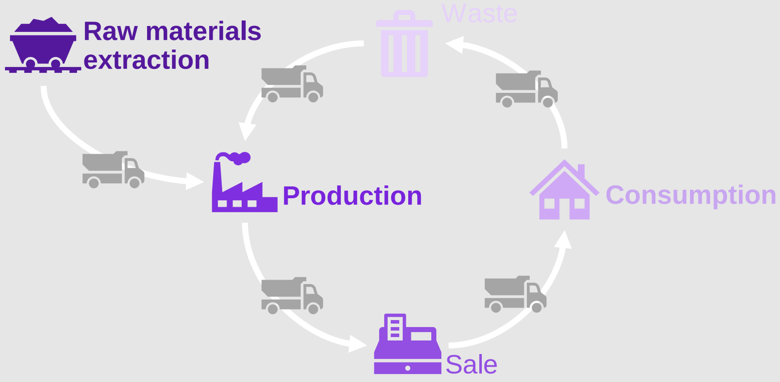
Life-cycle assessment has emerging applications at different levels

The main goals in all application levels is to identify environmental hotspots to guide decisions on product improvement, corporate sustainability strategy, consumer lifestyle, or national sustainable consumption and production policy-setting.

3.2 Basic principles of LCA

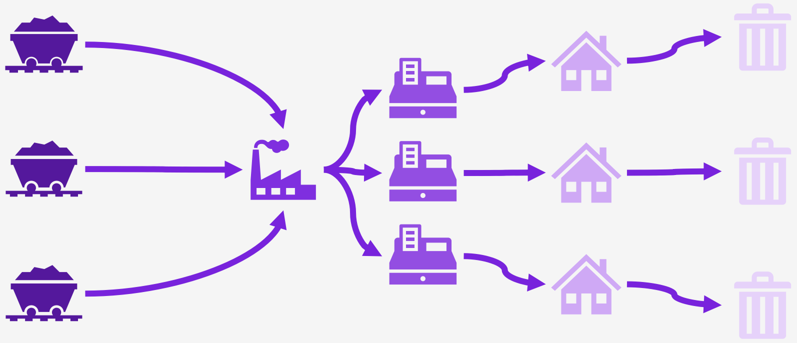
Original product-based scope

The traditional use of LCA has been to assess and improve specific product systems (e.g., eco-design, process optimizations, supply-chain management, marketing, and strategic decisions).



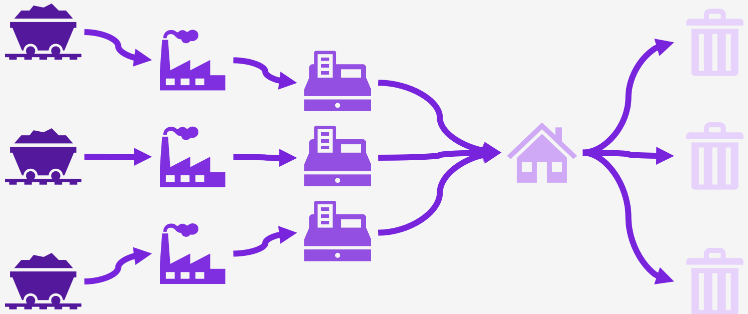
Organizational company LCA

Today, the application is much broader: companies use it to determine the key drivers of the environmental impact of their product portfolios.



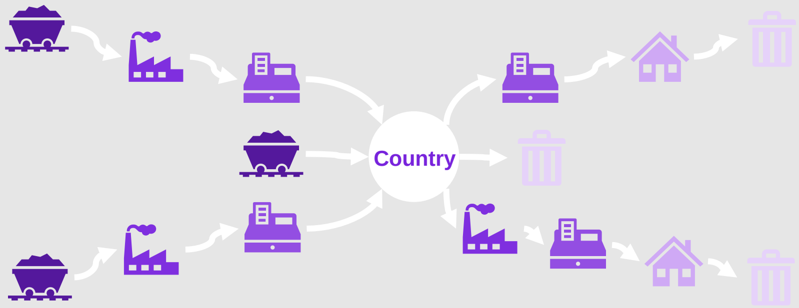
Consumer LCA (analyzing consumption patterns and lifestyles)

Environmental scorecards analyze current and future consumer-specific purchases.



National-level assessments

Top-down studies of national economies aim to highlight crucial drivers of environmental impacts (e.g., housing, mobility, and food).

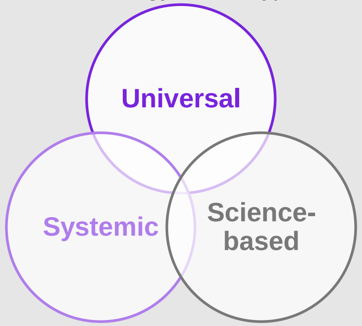


Sources: Stefanie Hellweg and Llorenç Milà I Canals, Science (2014); Kearney Energy Transition Institute analysis

LCA methods require improvements to become more coherent and accurate

In theory, LCA is an ideal method for environmental impact assessment

It integrates a wide range of environmental issues and is applicable to any defined system (goods, service, company, technology strategy, country)



It avoids burden shifting, resolving one problem (e.g., during production) while creating others (e.g., during use or end-of-life treatment)

It relies on a scientific and quantitative approach that minimizes subjective elements and make them transparent

In practice, the conditions necessary for the method to be effective are difficult to meet

Many constraints are necessary to reach a satisfactory level of accuracy:
- **Quality** of the system's model:
  - High level of detail
  - Consideration of variation in system's characteristics, processes, and operating conditions
- **Availability** and **representativeness** of data
- Good definition of the **goal** and **scope**

Constraints are even more important for LCA of new sectors and products in development (use of biomass, eco-design of products in their R&D phase).

Existing methods have important weaknesses

Studies present a high variability in impacts results for comparable systems (e.g., for beverage cups[1]).
- Many LCA practitioners use top-down approaches, which rely on black box models based on macroeconomic or industry-average data. Errors arise due to omission of underlying physical drivers, uncertainty due to omission of variation of processes.
- Bottom-up approaches are increasingly used, with engineering-based models. But there can be a lack of detail due to unavailability of required input parameters, high data and computational demands.

The improvement of LCA is the subject of advanced research

Existing databases are constantly improved or updated, new computational tools are developed (e.g., OPGEE), hybrid and new approaches (ex ante LCA for emerging process) are increasingly used.
Robustness of characterization methods and methods for uncharacterized impacts to date are improved.
Stakeholders (from the industrial and scientific fields) are increasingly involved to reduce uncertainties.
Guides of best practices are created to help LCA practitioners, especially when defining the system boundaries and functional unit.

Sources: Eugenie van der Harst, José Potting,Variation in LCA results for disposable polystyrene beverage cups due to multiple data sets and modelling choices, Environmental Modelling & Software (2014); The International Reference Life Cycle Data System (ILCD) Handbook, M-A. Wolf, R. Pant, K. Chomkhamsri, S. Sala, D. Pennington (2012); Life cycle assessment for the impact assessment of policies, Sala, S., Reale, F., Cristobal-Garcia J., Marelli, L., Pant R. (2016); Kearney Energy Transition Institute analysis

3.3 LCA improvement areas

Various ways of dealing with uncertainties can be used to improve the accuracy of LCA outputs

3.3 LCA improvement areas

Methods for dealing with uncertainties must be chosen according to the specificities of the context of the study

Aspect	Purpose	Most appropriate context for use
Stakeholder engagement	Incorporating expert knowledge into the goal and scope definition of the study by directly bringing stakeholders into conversations. Integrating them to the data collection process.	Studies on big industries (e.g., oil and gas): involving stakeholders is very helpful to define relevant system boundaries. Indeed, in comparison to local measurements made by industries, advanced carbon impacts models prove to be very reliable in their calculations, but the main differences made are due to different system boundaries.
Characterization of uncertainties	Assessing the lack of information around inputs in the database (spatial and temporal resolution, missing data, stochastic uncertainties …) for both foreground (direct processes on which the stakeholder asking for an LCA has control of) and background system (processes that are "out of our control"), that are modeled in databases and that also present uncertainty.	All contexts, no matter the dimension of the study (products/systems/sectors/regions) and the approach chosen. However, quantifying uncertainties can be harder in the case of ex-ante LCAs, while it may be the context in which uncertainties are the highest.
Propagation of uncertainties	Assessing that extent uncertainties in input values produce uncertainties in model outputs by using advanced statistical methods	
Local sensitivity analysis (LSA)	Determining how sensitive model outputs are to each input. It helps to understand a system and avoids omitting treatment of some input parameters.	Bottom-up approaches for simple systems, and top-down approaches
Global sensitivity analysis (GSA)	Identify key influencing input parameters to deduce a simplified model that allows fast and relatively accurate estimates of impact results without need for a very exhaustive data collection process. It is especially efficient in the case of high magnitude of uncertainties.	Engineering-based models for complex systems
Inventory regionalization	Assessing for variation among systems and practices by differentiating data and treatment of data depending on the region. GSA can help prioritizing the needs for regionalization and therefore reduce the effort needed.	Global studies on systems that are highly dependent on local conditions (e.g., food systems)

Source: Kearney Energy Transition Institute analysis

Research is under way to help LCA practitioners find the best methods within their scope and capabilities (1/2)

Choosing databases, models, and methods for dealing with uncertainties is a trade-off between ease of implementation and result precision

Justifying the choice of methods on which a LCA is based (database, modeling of the system, uncertainties assessment) and their ease of implementation is necessary as some methods can be out of reach of practitioners.

There are four levels of accuracy of outputs: indeterminacy, ignorance, uncertainty, and risk.[1]

There are two large groups of uncertainties: epistemic uncertainties, which are those related to lack or scarcity of data and/or limits of the models to represent the reality and/or methodological choices, **and stochastic uncertainty,** also called variability, related to geographical, temporal or technological variability.

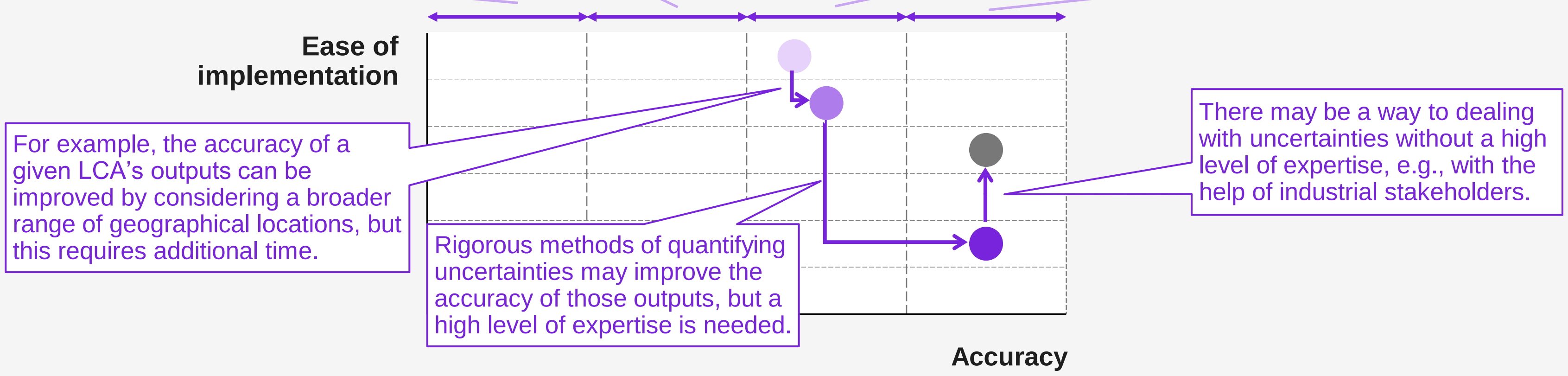
The ease of implementation decreases with three factors: financial cost, level of expertise required, and general effort (e.g., time). We consider an indicator where each factor is rated on three levels (0, 1, or 2), which leads to six levels in total.

Indeterminacy: the system under study is inherently undetermined (e.g., if decisions have not been taken in a R&D phase of a product).

Ignorance: sources of uncertainty are identified, but system parameters are not defined (e.g., if experts do not agree on how to model the system).

Uncertainty: System parameters are defined, and sources of uncertainties are identified, but not quantified.

Risk: system parameters are defined, and uncertainties are quantified.



1. Wynne (1992)
Sources: "Treatment of uncertainties in life cycle assessment," Jack W. Balker & Michael D. Lepech (2009); Kearney Energy Transition Institute analysis

3.3 LCA improvement areas

Research is under way to help LCA practitioners find the best methods within their scope and capabilities (2/2)

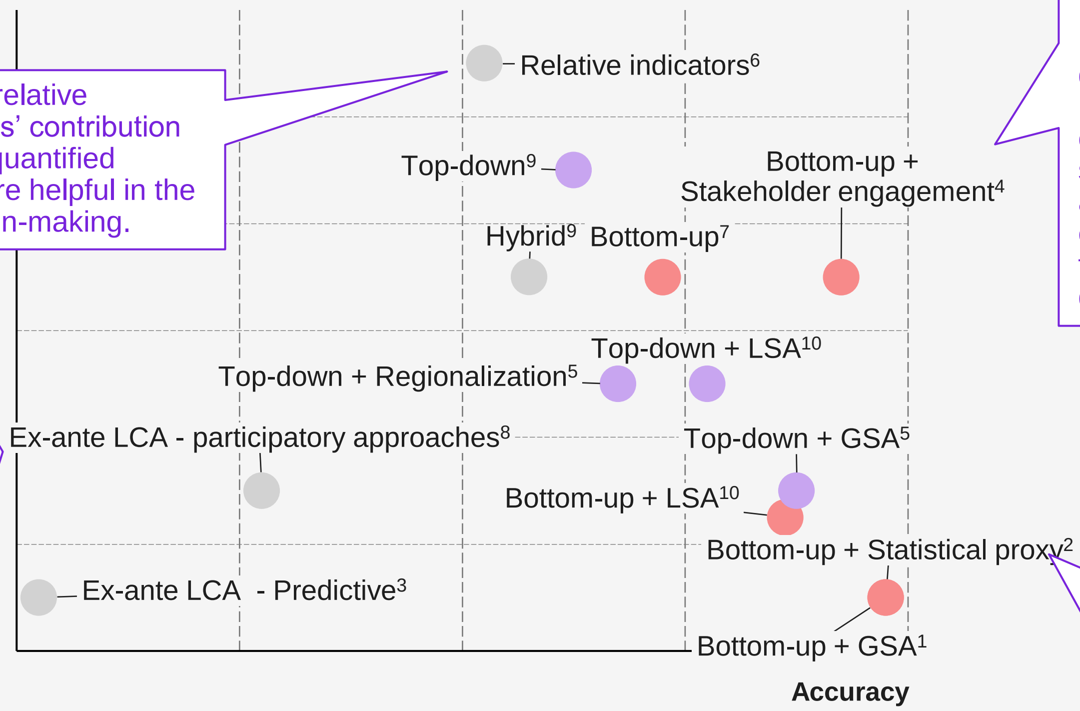
Current best practice and priority axes for further research

Current best practices include engaging stakeholders when studying site-levels approaches, regionalizing the analysis for top-down approaches, and at least always conducting local sensitivity analysis (LSA).

Priority research axes include allocation in multi-functional systems, prospective LCAs at macro-scenario levels, end-of-life modeling, further development of impact characterization methods (e.g. biodiversity, plastics in the sea, toxicity indicators that already exist but are still not robust enough…), making global sensitivity analysis (GSA), and statistical proxy more affordable, as they allow for very high accuracy but require high expertise for now.

Eunomia and Civancik[1] relative indicators for carrier bags' contribution to littering have high unquantified uncertainties, but they are helpful in the context of urgent decision-making.

For products in development, participatory approaches can be useful when it is not about being accurate but about designing sustainable technologies in the best possible way.



In the case of LCA of big industries (e.g., oil and gas), stakeholders can be directly brought into conversations about selection of assumptions and data, incorporating expert knowledge into the goal and scope definition of the study.

Statistical reduced-order models (proxy) from engineering simulations show high performance, but still require high expertise and computational capacities.

1. Understanding LCA results variability: developing global sensitivity analysis with Sobol indices. A first application to photovoltaic systems, Padey, Beloin-Saint-Pierre, Girard, Le Boulch, Blanc; 2. Statistical proxy modeling for life cycle assessment and energetic analysis, Masnadi, Perrier, Wang, Rutherford, Brandt, Energy (2020); 3. A critical view on the current application of LCA for new technologies and recommendations for improved practice, van der Giesen, Cucurachi, Guinée, Gert Jan Kramer, Arnold Tukker, Journal of Cleaner Production, Volume 259, (2020); 4. S. Sleep, Z. Dadashi, Y. Chen, A. R. Brandt, H. L. MacLean, J. A. Bergerson, Improving robustness of LCA results through stakeholder engagement: A case study of emerging oil sands technologies, Journal of Cleaner Production (2021); 5. Patouillard, L., Collet, P., Lesage, P. et al. Prioritizing regionalization efforts in life cycle assessment through global sensitivity analysis: a sector meta-analysis based on ecoinvent v3. Int J Life Cycle Assess (2019); 6. Plastics: Can Life Cycle Assessment Rise to the Challenge, Eunomia Research & Consulting (2020); Civancik-Uslu D, Puig R, Hauschild M, Fullana-I-Palmer P. Life cycle assessment of carrier bags and development of a littering indicator. Sci Total Environ. (2019); 7. Ferrando, Causone, Hong, Chen, Urban building energy modeling (UBEM) tools: A state-of-the-art review of bottom-up physics-based approaches, Sustainable Cities and Society (2020); 8. Sevigné-Itoiz E, Mwabonje O, Panoutsou C, Woods J. 2021 Life cycle assessment (LCA): informing the development of a sustainable circular bioeconomy? (2021); 9. Feng, Chapagain, Suh, Pfister, Klaus. Comparison of bottom-up and top-down approaches to calculating the water footprint of nations. Economic Systems Research (2011) ;10. Wei W, Larrey-Lassalle P, Faure T, Dumoulin N, Roux P, Mathias JD. How to conduct a proper sensitivity analysis in life cycle assessment: taking into account correlations within LCI data and interactions within the LCA calculation model. Environ Sci Technol. (2015); Kearney Energy Transition Institute analysis

3.3 LCA improvement areas

LCA to assess carbon footprint methods are characterized by certain inherent flaws

Use of carbon footprint is largely dependent on the number of products being footprinted and the amount of available data as well as the time available to perform the analysis.

3.3 LCA improvement areas

	Description
1 Data availability	– Lack of data, especially in manufacturing processes, in a niche industry/emerging countries presents a key issue for using carbon footprinting models. Also, after a point, getting accurate real-time data is cost-prohibitive. An input–output analysis requires less data, so the risk of missing data is low compared with a process analysis, which requires more data.
2 Boundary conditions	– In carbon footprint analysis, boundaries need to be defined to determine the level of detail to be included. Faulty boundary definitions can lead to double counting of emissions both in a consumer's carbon footprint and in a supplier's carbon footprint.
3 Uncertainty analysis	– In many instances, carbon footprint analysis is presented without an uncertainty analysis, which implies that it's not possible to compare it to a different carbon footprint analysis.
4 Lack of harmonization among studies	– Even if many carbon footprint standards seem to use a similar approach overall, there are subtle differences in the way each of them allows methodological choices, e.g., for selecting the functional unit, system boundaries, background processes, or environmental impact assessment methods. For example, some emissions can be reported on a voluntary basis in the GHG protocol, whereas it is mandatory in other methodologies. These differences explain why there are issues when comparing or aggregating impact assessments from different organizations. These impacts can be minimized if all the information, methodological and modeling choices are transparently reported.

Sources: "A history of product carbon footprinting" (Barnett et all, 2013), Teads Engineering; Kearney Energy Transition Institute analysis

Section 3 detailed in Appendix

4. Defining effective decarbonization boundaries: LCA of key activities

Carbon emissions can be broken down into an equation where each part is impacted by different parameters

Isolated key parameters impacting carbon footprint and defined boundary conditions to minimize the carbon footprint decisions

4.1 General assessment framework

General definition of LCA computation

Emissions are produced at each phase of the product life cycle.

To each life-cycle phase corresponds a specific service requirement.

To provide a given service, variable amounts of energy are required, and different energy sources can be used to produce that energy.

In addition, different carbon-consuming reactions can be required for goals other than energy production.

Different amounts of emissions can intentionally or unintentionally leak.

$$\text{Carbon emissions} = \text{Service requirement} \times \left[\underbrace{\frac{\text{Energy need}}{\text{Service requirement}} \times \frac{\text{Combustion emissions}}{\text{Energy need}}}_{\text{Energy consumption emissions}} + \frac{\text{Process emissions}}{\text{Service requirement}} + \frac{\text{Fugitive emissions}}{\text{Service requirement}} \right]$$

Life-cycle phase: production, use, end of life …

Parameters affecting the required service:
- Volume of production
- Intensity of use distance of transportation
- Composition of materials
- …

Parameters affecting the amount of energy consumed to meet the need:
- Type of process
- Efficiency of process
- …

Parameters affecting the carbon content of energy:
- Type and mix of energy source (fossil fuel, electricity, biomass …)

Parameters affecting carbon content per source:
- Mix of sources used to produce electricity, emission factors of fuels, upstream emissions …

Parameters affecting amounts of emissions produced during physical or chemical reactions:
- Type of reactions
- Efficiency of reactions
- …

Parameters affecting amounts of emissions intentionally or unintentionally released during the process:
- Type of process
- Type of equipment
- Location
- …

Note: Dashed lines indicate that process and fugitive emissions are more rare than mobile and stationary combustion emissions.
Source: Kearney Energy Transition Institute analysis

The chapter illustrates selected carbon emission building blocks and highlights the importance of defining boundary conditions to optimize carbon emissions reduction[1]

Primary energy production > **Raw material extraction** > **Secondary energy production** > **Application and energy use**

Example: Fossil fuels

Carbon emissions from fossil fuels

- Fossil fuels are used in almost all value chains, where they can represent a significant fraction of the overall carbon footprint.
- Fossil fuels-related emissions can be difficult to measure accurately across operations, especially in upstream, and hence are often underreported.

Example: Metal mining

Carbon emissions from metals

- Global mining and refining operations are responsible for about 10% of global annual GHG emissions.
- Metals are used in many value chains, including in key energy transition technologies and applications
- Variability in mining conditions and extractive processes used for mining and refining results in a wide range of carbon footprints across metals.

Examples: Solar PV, Offshore Wind

Carbon emissions from renewable technologies

- Solar photovoltaic and offshore wind are the fastest growing renewable energy sources which are now cost-competitive to fossil fuels in some regions
- Manufacturing accounts for about 75% of global wind turbines life-cycle emissions, and it is mostly driven by the materials' carbon-intensity.

Example: Battery Electric Vehicle

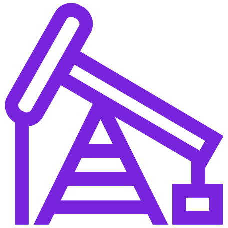
Carbon emissions from Battery Electric Vehicles

- Millions of battery electric vehicles (BEVs) are already on the road with a robust growth forecast as governments incentivize their purchase:
- In many countries, a BEV is less carbon efficient than a similar-size ICE because of the high carbon footprint of batteries, which necessitates a low carbon electricity mix and higher mileage.

The examples provided in that section are illustrative and does not give an exhaustive overview of technologies in each building block.

1. However, since the analysis involve complexities and many assumptions, the results should be taken as indicative rather than definitive
Source: Kearney Energy Transition Institute analysis

Emissions from fossil fuels consumption depend on fuel characteristics, the value chain, and uses



Life-cycle approaches enable integrating various parameters that impact the carbon footprint of fossil fuels or any energy generation system. This avoids, for example, errors of not considering the upstream stage of activities.

Carbon emissions at each stage can be broken down into two elements: emissions from operations to produce fossil fuel (including fugitive emissions) and emissions from their combustion (related to fuel chemical content and combustion efficiency). Combustion emissions depend on energy efficiency of process and carbon contents of fossil and non-fossil energy sources (biomass-based) and include mainly carbon dioxide emissions.

Regarding operations, methane leaks from natural gas production systems are very much underestimated. Intentional and unintentional methane emissions occur along the oil and gas supply chain. National inventories currently underreport leaks by a factor of about 1.5. Of this error, 80 percent is due to lack of accuracy in measurements in the gas production stage. Methane leaks are heterogeneously distributed across gas production sites. About 5 percent of US wells account for roughly 50 percent of total methane emissions. Sites with low production rates emit a lot more in proportion than high-production sites. The contribution of super-emitters would be much higher if methane leaks were proportional to gas production level.

Using the approach used by national inventories highlights the need for hybrid estimation approaches to improve them. There are two types of approaches for estimating leaks: bottom-up and top-down. The US national inventory relies on a component-level bottom-up approach. Equipment leaks and storage tanks are the main underestimated sources of methane within the gas production segment. Validating component-level direct measurement campaigns with downwind truck, airplane-based, or satellite-based measurements would help national inventories correct their database over time.

Emission factors of fossil fuels used to directly convert the need for primary energy into carbon emissions are uncertain. Their variability concerning CO_2 emissions can reach up to 40 percent of the average for coal products and less than 20 percent for petroleum products. There are three main sources of variability: variation in the chemical composition of fuels, differences between calculation methods, and imprecision of the measurements on which calculation is based.

Standardized default emission factors as reported by the IPCC rely on two characteristics of fuels: net calorific value and carbon content, which vary over time and across geographies. For crude oil, gravity and sulfur content are responsible for around half of the roughly 5 tCO_2/TJ total variability across emission factors. Occasionally, emission factors include emissions from upstream phases of fuels extraction. Confusions between default and generic emission factors lead to underestimating emissions by a factor of up to six.

4.2 Emission from fossil fuels consumption: executive summary

Source: Kearney Energy Transition Institute analysis

The CO_2 emissions from a fossil fuel is commonly estimated using an emission factor

Emission factors are used for converting energy need into carbon emissions

Emission factors are numerical features of fossil fuels, expressed in tCO_2/GJ. They allow to directly convert primary energy into carbon emissions. We focus here on activities consisting of the combustion of fuels, which must be separated from the use of fuels in chemical reactions in industrial processes or as industrial products.

The notion of "primary energy" must be distinguished from "final energy." In the case of the combustion fossil fuels, primary energy is equal to the energy contained in the fuel burnt to make the product or to deliver the service, while final energy is the energy that can be really used at the end of the production chain: final energy = primary energy × system efficiency.

Emission factors allow to estimate CO_2 emissions yielded by using the product or system, without actually measuring CO_2 emissions, knowing the amount of final energy needed to meet the service requirement (e.g., number of square meters heated to a certain temperature), the efficiency of the system (including the efficiency of the system used to burn fuel) and the type of fuel burned.

$$\text{CO}_2 \text{ emissions } (tCO_2) = \text{Final energy (GJ)} \times \text{System efficiency} \times \text{Emission factor of primary energy } (tCO_2/GJ)$$

The method for their calculation is well-defined

A unique emission factor must be assigned to each type of fuel. Default values are given by national and international institutions. In particular, the IPCC releases inventories gathering values given by each country for each type of fuel. This values have initially been calculated by measuring the amount of CO_2 emitted, knowing the mass of fuel burnt and the calorific value of the fuel.

In some cases, the 'fuels' databases also include 'upstream' emission factors, corresponding to CO_2 emitted during the production and transport phase of the fuels. Using these 'upstream' emission factors is less precise than adopting a complete life cycle approach, which would by definition consider those production and transport phases.

$$\text{Emission factor } (tCO_2/J) = \frac{\text{Measured CO}_2 \text{ emissions } (tCO_2)}{\text{Mass of fuel (t)} \times \text{Calorific value of the fuel (GJ/t)}}$$

4.2 Emission from fossil fuels consumptions - Assessment

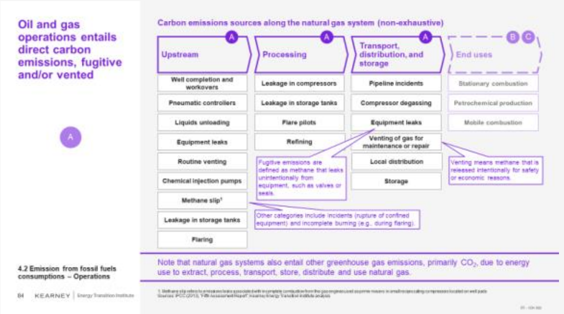
Sources: 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Ch1 Introduction; Typologie des facteurs d'émission, Fiche Ressource N°3, ADEME (2011); Kearney Energy Transition Institute analysis

In addition to emission factors, which are fuel-specific, emissions from operations and combustion efficiency impact GHG emissions

GHG emissions of fossil fuels consist of three main components

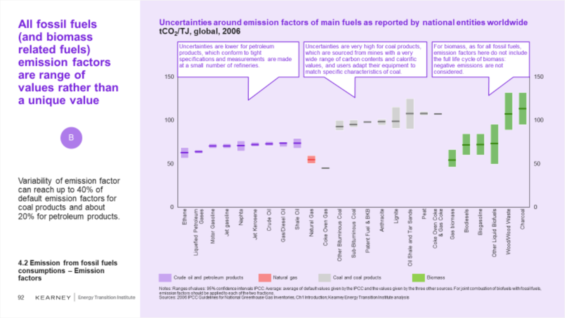
A Emissions across the operations

- Oil and gas operations (exploration and production, transport, and distribution) can produce various types of GHG emissions, from own use of internal combustion engine to various possible types of leaks across its value chain.
- Based on the LCA principle, the GHG emissions generated during the exploration, production, refining, and distribution of fossil fuel products should be considered in the assessment of their carbon footprint.



B Fossil-fuel chemical composition

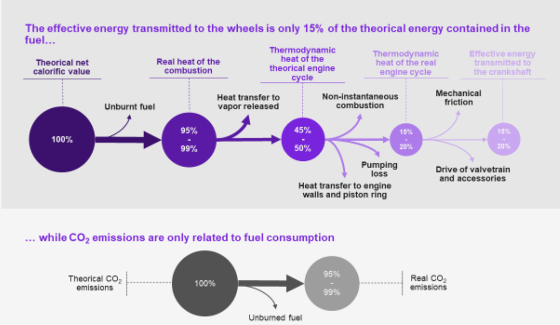
- The chemical composition of fossil fuels varies widely across geographies, depending on geological conditions.
- Fossil fuels are generally composed of a complex mix of carbon molecules with different properties (alkane, alkene, aromatics…).
- The composition of the fossil fuels affects the amount of CO_2 emitted during the burning and thus affects the values of emission factors.
- Fuels also contain impurities, which varies in quantity and type.
- Natural crude oil contains dirt, CO, moisture, gas vapor, and H_2S mineral salts in different quantities, depending on the variety and quality of oil plant, oil processing technology and methods.



Considered by emission factors

C End-use combustion efficiency of fossil fuel

- Emission factors are calculated assuming a complete combustion, but real reactions are never complete.
- Calculated emission factor is therefore underestimated, and the error depends on the efficiency of the combustion.
- Plus, "generic" emission factors are sometimes used, taking as inputs final energy data, and the result therefore depends on the efficiency of the system, which varies across technologies and operational practices. Since the calculation of emission factors is based on carbon emission measurements and knowledge of the amount of fuel burned, there are uncertainties due to possible measurement inaccuracies or poor knowledge of fuel supply.



Sources: 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Ch. 1 Introduction; Typologie des facteurs d'émission, Fiche Ressource N°3, ADEME (2011); Kearney Energy Transition Institute analysis

4.2 Emission from fossil fuels consumptions: drivers

Oil and gas operations entails direct carbon emissions, fugitive and/or vented

A

Carbon emissions sources along the natural gas system (non-exhaustive)

Upstream (A)	Processing (A)	Transport, distribution, and storage (A)	End uses (B, C)
Well completion and workovers	Leakage in compressors	Pipeline incidents	Stationary combustion
Pneumatic controllers	Leakage in storage tanks	Compressor degassing	Petrochemical production
Liquids unloading	Flare pilots	Equipment leaks	Mobile combustion
Equipment leaks	Refining	Venting of gas for maintenance or repair	
Routine venting		Local distribution	
Chemical injection pumps		Storage	
Methane slip[1]			
Leakage in storage tanks			
Flaring			

Fugitive emissions are defined as methane that leaks unintentionally from equipment, such as valves or seals.

Venting means methane that is released intentionally for safety or economic reasons.

Other categories include incidents (rupture of confined equipment) and incomplete burning (e.g., during flaring).

Note that natural gas systems also entail other greenhouse gas emissions, primarily CO_2, due to energy use to extract, process, transport, store, distribute and use natural gas.

1. Methane slip refers to emissions leaks associated with incomplete combustion from the gas engines used as prime movers in small reciprocating compressors located on well pads
Sources: IPCC (2013), “Fifth Assessment Report”; Kearney Energy Transition Institute analysis

The US national inventory greatly underestimates methane emissions from the Oil&Gas supply chain, mostly from the Natural Gas production portion

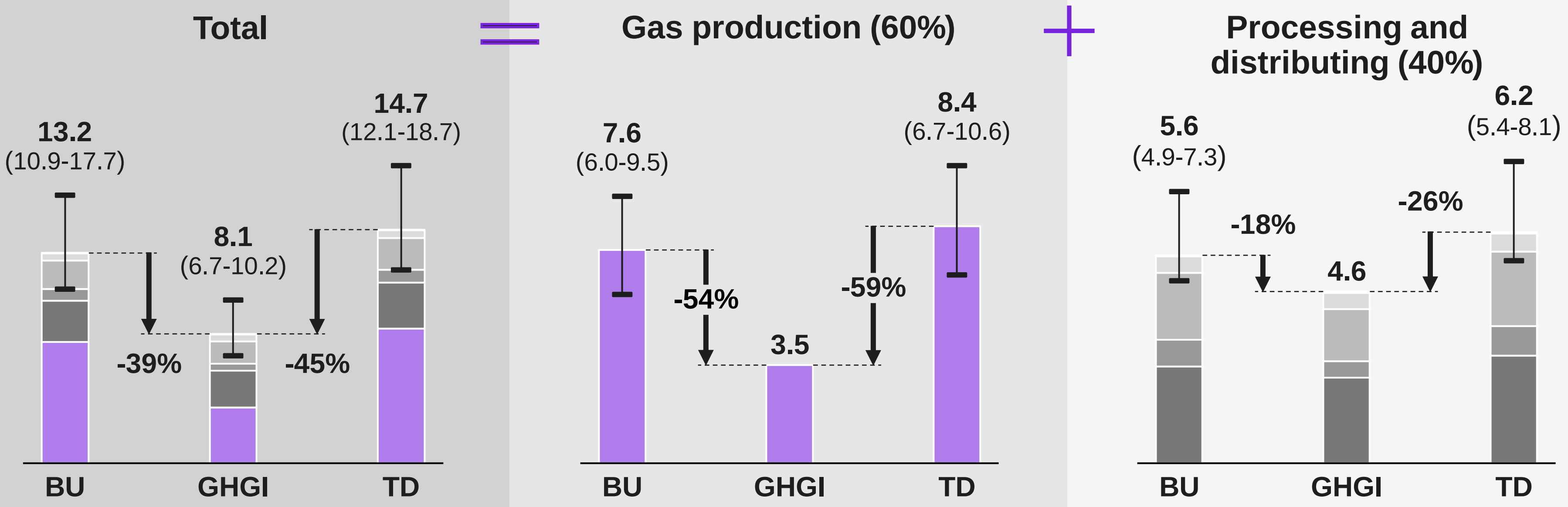
A

The underestimation of methane leakages has a magnitude of 40–45%, of which up to 80% is due to estimates errors in the gas production phase.

4.2 Emission from fossil fuels consumptions – Operations

Comparison of most recent bottom-up (BU) and top-down (TD) studies to greenhouse gas inventory (GHGI) estimates of CH_4 emissions from the US oil and natural gas supply chain

$TgCH_4$/year, 2015



GHGI underestimates total annual methane leakages by ~5.1Tg compared to most recent BU studies and by ~6.6Tg compared to most recent TD studies.

- Production
- Gathering
- Processing
- Transmission and storage
- Local distribution
- Oil refining & transportation

Gas production accounts for around 60% of methane emissions of the value chain but **is responsible for a highest share of total underestimation by GHGI**: ~74% (=(8.4-3.5)/6.6 with TD) to **~80%** (=(7.6-3.5)/5.1 with BU)

This is likely related to the technical difficulty and safety and liability risks associated with measuring large emissions, e.g., from venting tanks.

The rest of the O&NG supply chain accounts for ~40% total emissions but is only responsible for ~20% to 26% of the total underestimation.

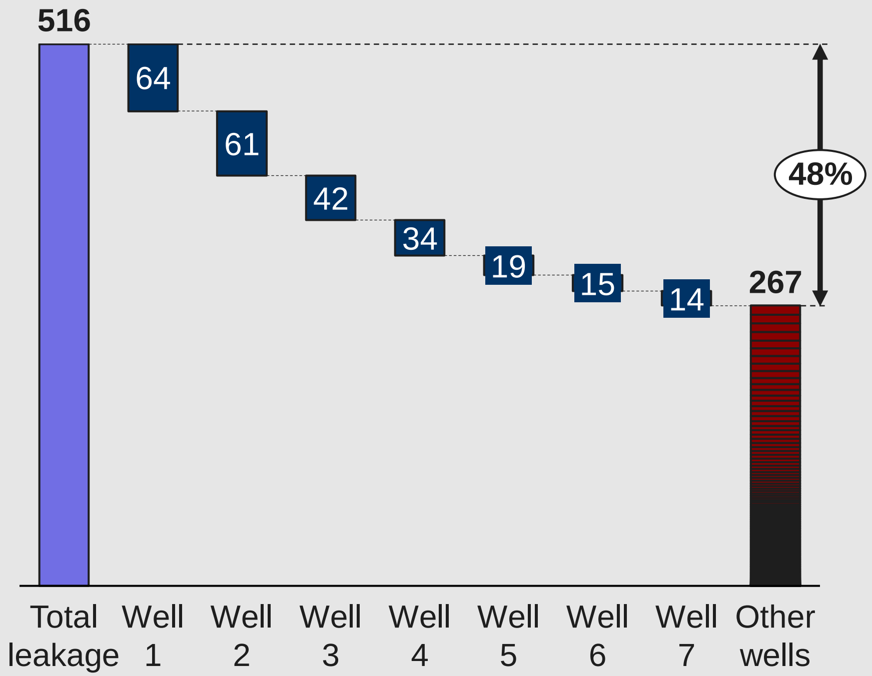
- Gathering
- Processing
- Transmission and storage
- Local distribution
- Oil refining and transportation

Notes: For local distribution and transportation and oil refining and transportation, the estimates are taken directly from the GHGI. The GHGI only reports industry-wide uncertainties.
Sources: Alvarez et al., Assessment of methane emissions from the U.S. oil and gas supply chain, Science (2018); Kearney Energy Transition Institute analysis

A small number of emitters are thought to be responsible for a large share of leakage

A

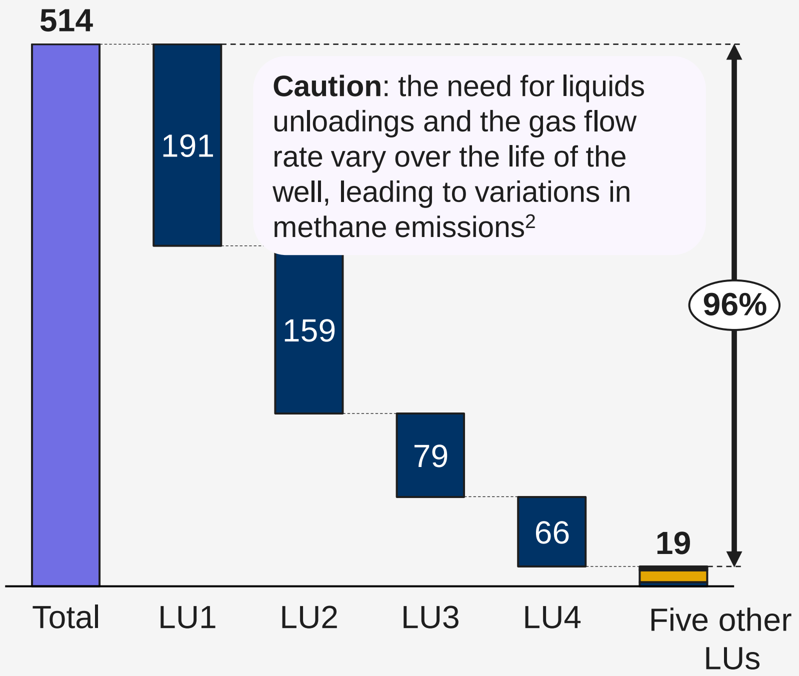
Distribution of leakage rates across 203 wells in the Fort Worth region



Seven wells out of 203 (those with a leakage rate above 10 mcf/d) account for 48% of total emissions.

Methane emissions measured during nine liquid unloading on different wells

mcf of methane emitted[1]



Four wells out of nine account for 96% of methane emitted.

The heavy-tailed distribution of emissions is both a challenge regarding sampling representativeness and generalizability, and, in science speak, an opportunity “for large mitigation benefits if scientists and engineers can develop reliable (possibly remote) methods to rapidly identify and fix the small fraction of high-emitting sources.”[3]

1. U for liquids unloading: in some cases, water and other hydrocarbon liquids accumulate and need to be unloaded periodically to restore or improve gas flow; 2. Unlike workovers, plunger lift, which can be used for liquids unloading, does not result in direct venting of gas to the atmosphere.
Sources: Alvarez et al. (2013), “Greater focus needed on methane leakage from natural gas infrastructure” data set derived from Easter Research Group (2011), “City of Fort Worth Natural gas Air Quality Study”; Allen et al. (2013), “Measurements of methane emissions at natural gas production sites in the United States”; [3]Brandt et al. (2013), “Methane leaks from North American natural gas systems”; Kearney Energy Transition Institute analysis

Methane leaks from natural gas production occur more in low-production sites than in high-production sites

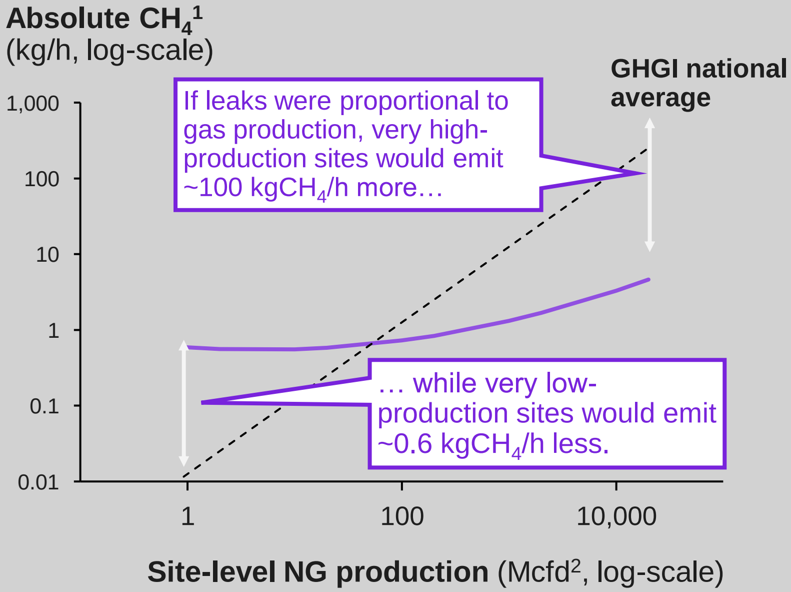
A

In the United States, if site-level emissions leakages were proportional to gas production, high-production sites would account for almost twice their current share of total leakage.

4.2 Emission from fossil fuels consumptions – Operations

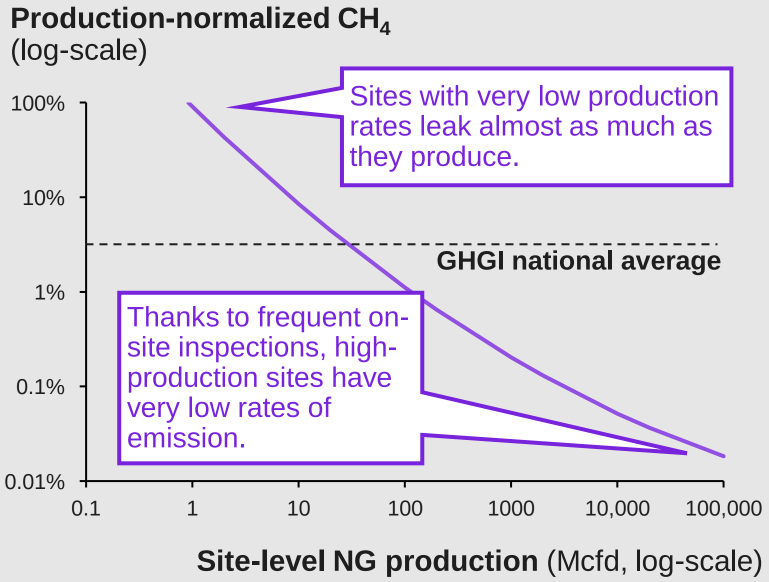
Absolute CH_4 emissions modestly increase with site-level natural gas production

1,000 US sites, 2015



Production-normalized CH_4 emissions strongly decrease when site-level production increases

1,000 US sites, 2015



The strong decrease in production-normalized emissions is explained by the fact that high-production sites have **optimally performing** equipment and components and are **more frequently inspected** on-site than old, low producing sites. High methane emissions at these sites would be **audible** and/or **visible**, thus **more easily detected** and **repaired.**

Considering the current distribution of sites across production rates, **if methane leaks were proportional** to gas production (~1.15% leaks rate), **very-high production sites** (>1,000Mcfd) **would be responsible for 97% of total methane leaks**.

– Almost all leaks would come from sites that produce more than 100Mcfd (which represents ~15% of US sites).

– Today, sites with production levels >1,000 Mcfd represent ~3% of all US sites and are responsible **50%** of total methane leaks. Very-low production sites (<10Mcfd) represent 45% of all sites and leak **~25%** of the total.

1. he trends come from statistical fitting of 1,000 on-site measurements, showing that 74% of the variability in methane leaks is explained by natural gas production rates; 2. Million cubic feet a day
Sources: Methane Emissions from Natural Gas Production Sites in the United States: Data Synthesis and National Estimate, M. Omara, N. Zimmerma, M. R. Sullivan, X. Li, A. Ellis, R. Cesa, R. Subramanian, A. A. Presto & A. L. Robinson, Environ. Sci. Technol. (2018); Kearney Energy Transition Institute analysis

Real fossil fuels are mixtures of chemical species with a composition that is variable

B

Gas (natural gas)

Natural gas is composed of mainly methane (CH_4). It is gaseous at any temperature over -107.2°C. Its quality and composition varies greatly depending on the reservoir and field or formation from which it is extracted. Typical composition[1]:

Methane	CH_4	70–90%
Ethane	C_2H_6	0–20%
Propane	C_3H_8	
Butane	C_4H_{10}	
Carbon Dioxide	CO_2	0-8%
Oxygen	O_2	0-0.2%
Nitrogen	N_2	0-5%
Hydrogen sulfide	H_2S	0-5%
Rare gases	A, He, Ne, Xe	trace

Liquid (crude oil and petroleum products)

Petroleum is a mixture of different hydrocarbons such as:

- Alkanes: saturated hydrocarbons with straight or branched chains, formula C_nH_{2n+2}, refined into:
  - Gasoline if $5 \leq n \leq 8$
  - Diesel fuel, kerosene and jet fuel if $9 \leq n \leq 16$
  - Fuel oil and lubricating oil refined if $n \geq 17$
  - Paraffin wax if $n \approx 25$
  - Asphalt if $n \geq 35$
- Cycloalkanes: saturated hydrocarbons which have one or more carbon rings, formula C_nH_{2n}
- Aromatic hydrocarbons: unsaturated hydrocarbons with benzene, formula C_nH_{2n-6}.
- Asphaltene
- Other chemicals.

Solid (coal and coal products)

Coal is mostly carbon with variable amounts of hydrogen, sulfur, oxygen, and nitrogen. The generic formula for anthracite is $CH_{0.4}O_{0.02}$. Natural coal is made of coal and non-coal matter.

Non-coal matter	Coal matter
Moisture (amount of water present in the coal)	Fixed carbon
Ash (residue remaining after complete combustion of all organic coal matter and decomposition of the mineral matter)	Volatile matter (proportion of the air-dried coal sample released in the form of gas during a standardized heating test)

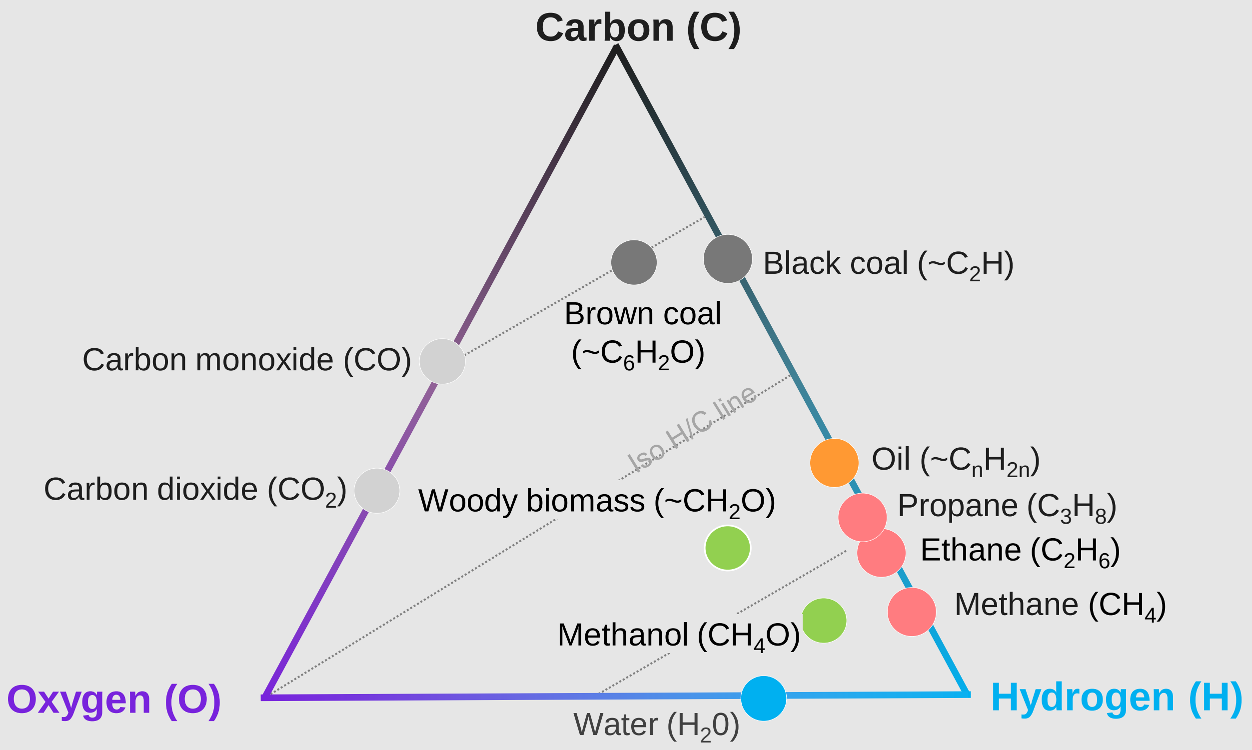
Note that some fields have much higher CO_2 content e.g. Natuna field
Sources: IEA Energy Statistics Manual, 2005; V. Vassilev, et al, An overview of the chemical composition of biomass, Fuel, 2010; Kearney Energy Transition Institute analysis

Natural gas is often considered environmentally friendly because of its low-carbon content compared with other fossil fuels

B

Carbon-to-hydrogen ratio

Composition of key chemical fuels



Compared with most alternative chemical fuels, the main components of natural gas (methane, ethane, propane …) have relatively low carbon-to-hydrogen ratios.[1]

- This means that, when burned, natural gas releases less carbon dioxide (CO_2) per unit of energy than other fuels, such as oil, diesel and coal.[2]
- All other things being equal (e.g., engine or turbine efficiency), this results in lower greenhouse gas emissions at the point of use.

1. ot considering non-hydrocarbon fractions (e.g., H_2S). Other components, such as butane or pentane, also have low H/C ratio (10/4 and 12/5 respectively). When combined with heating value, the heat of combustion per mole of CO_2 produced is around 20% higher for methane than for gasoline; 2. The chemical equations of the combustion of methane [$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(l)$], octane [$C_8H_{18}(l) + 25/2\ O_2(g) \rightarrow 8CO_2(g) + 9H_2O(l)$] and carbon [$C(s) + O_2(g) \rightarrow CO_2(g)$] correspond to heat release (kJ) per mole of CO_2 of 890 kJ, 683.8 kJ and 393.5 kJ, respectively (under standard condition of 24.8 C° and 1 bar). Methane, octane and carbon (c) are used as proxy for natural gas, gasoline and coal, respectively.
Source: Kearney Energy Transition Institute analysis

Emission factors are calculated using net calorific values of fossil fuels

B

4.2 Emission from fossil fuels consumptions – Emission factors

Burning fossil fuels release heat through the combustion of hydrocarbons

Combustion is a redox reaction—in this case, the oxidization of hydrocarbon molecules by oxygen.

The products of this reaction are carbon dioxide and water. The general formula is:

$$C_xH_y + zO_2 \rightarrow xCO_2 + \frac{y}{2}H_2O$$

The weight of carbon emitted from the combustion of a specific fuel can be directly derived from the quantity of carbon introduced to produce heat.

Emission factors are usually expressed as the weight of carbon divided by the heat released by the complete combustion of fuel (net calorific value).

It can also be expressed as the weight of carbon divided by the weight, volume, distance, or duration of the activity that emits carbon.

Source: Kearney

The calorific value is defined as the heat of complete combustion per unit mass of fossil fuel

A complete reaction is a reaction that yields stable products that cannot react with oxygen. The energy released is the thermodynamic heat of combustion (ΔH), calculated thanks to the standard heat of formation of the products and reactants: The standard heat of formation is: $\Delta_r H^0 = \sum_i \nu_i . \Delta_f H_i^0$ ($\nu_i > 0$ if i is a product and $\nu_i > 0$ if i is a reactant).

Examples of standard heats of formation of various chemicals

Chemical compound	$\Delta_f H^0$	Chemical compound	$\Delta_f H^0$
CO_2 (g)	-393.52	C_4H_{10} (g)	-124.78
CO (g)	-110.58	C_5H_{12} (g)	-146.5
CH_4 (g)	-74.9	C_6H_{14} (g)	-167.25
C_2H_4 (g)	-84.7	C_7H_{16} (g)	-187.89
C_3H_8 (g)	-103.88	C_8H_{18} (g)	-208.52

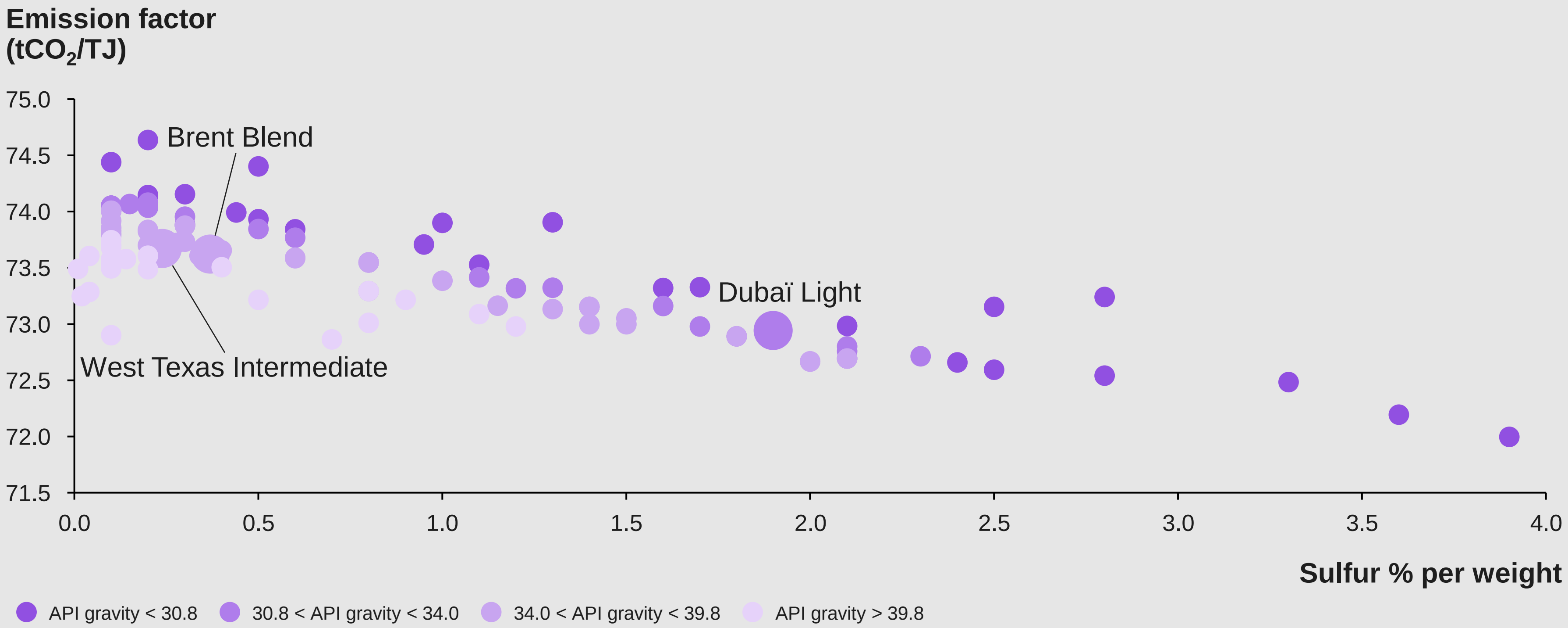
- The **gross calorific value (GCV)** or “higher heating value” is the calorific value under laboratory conditions or if the device has a built-in condensation system. It assumes all the water component is in liquid state at the end of combustion.
- The **net calorific value (NCV)** or “lower heating value” is the useful calorific value in boiler plant.
- The difference is essentially the latent heat of the water vapor produced, that is the latent heat of vaporization of water (L_v) multiplied by the mass of water produced (m): **GCV = NCV + m.L_v**
- The difference is typically about 5% to 6% of the gross value for solid and liquid fuels, and about 10% for natural gas.
- Emission factors are calculated using the net calorific value (NCV).

There is a broad range of crude oils with different emission factors

B

4.2 Emission from fossil fuels consumptions - Fossil Fuel composition

The emission factor of crude oil is highly dependent on its gravity and sulfur content



There are about 161 internationally traded crude oils, with different characteristics, quality, and market penetration.

Almost all crude oils have 82 to 87% carbon by weigh and 12 to 15% hydrogen by weight. They are characterized by the type of hydrocarbon compounds: paraffins, naphtenes, and aromatics.

Their most important physical property is their American Petroleum Institute (API) gravity, which is an index of their weight relatively to water. The lower the API gravity, the heavier the oil. Another characteristic is their level of sulfur. If that level is inferior to 0.5% per weight, the oil is considered as sweet; if it is higher than 1%, it is sour.

From the analysis of 182 crude oil samples, the US Department of Energy (Energy Information Administration) proposed a formula useful to estimate the carbon content and the calorific value of different crude oil types depending on their API gravity and level of sulfur.

Note: The graph was obtained using data from the IPCC on 99 crude oil streams (gravity and sulfur %) and from the EIA.
Sources: The International Crude Oil Market Handbook, Energy Intelligence Group, 2004; IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories; Kearney Energy Transition Institute analysis

All fossil fuels (and biomass related fuels) emission factors are range of values rather than a unique value

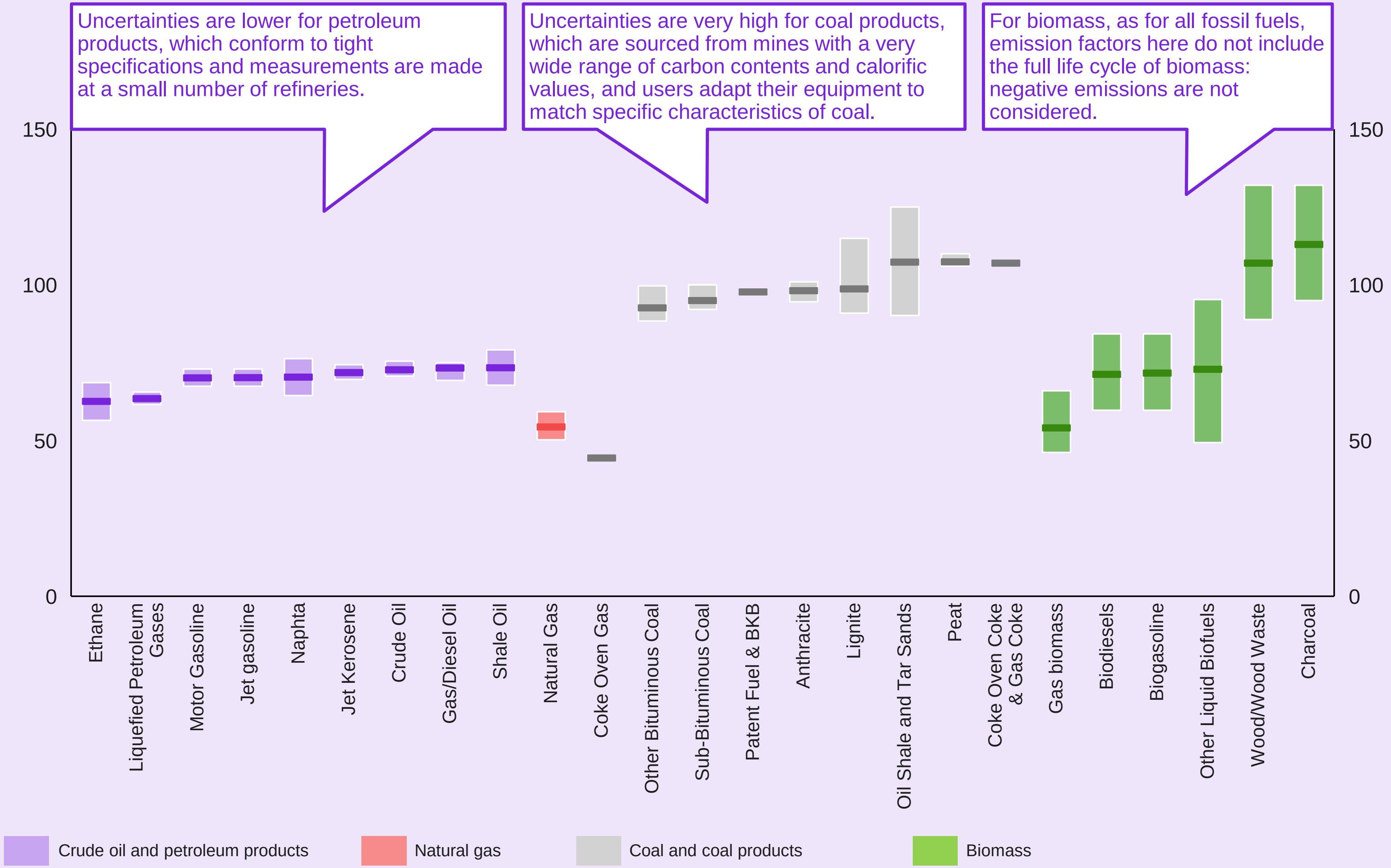
B

Variability of emission factor can reach up to 40% of default emission factors for coal products and about 20% for petroleum products.

4.2 Emission from fossil fuels consumptions – Emission factors

Uncertainties around emission factors of main fuels as reported by national entities worldwide

tCO_2/TJ, global, 2006



Notes: Ranges of values: 95% confidence intervals IPCC. Average: average of default values given by the IPCC and the values given by the three other sources. For joint combustion of biofuels with fossil fuels, emission factors should be applied to each of the two fractions.
Sources: 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Ch1 Introduction; Kearney Energy Transition Institute analysis

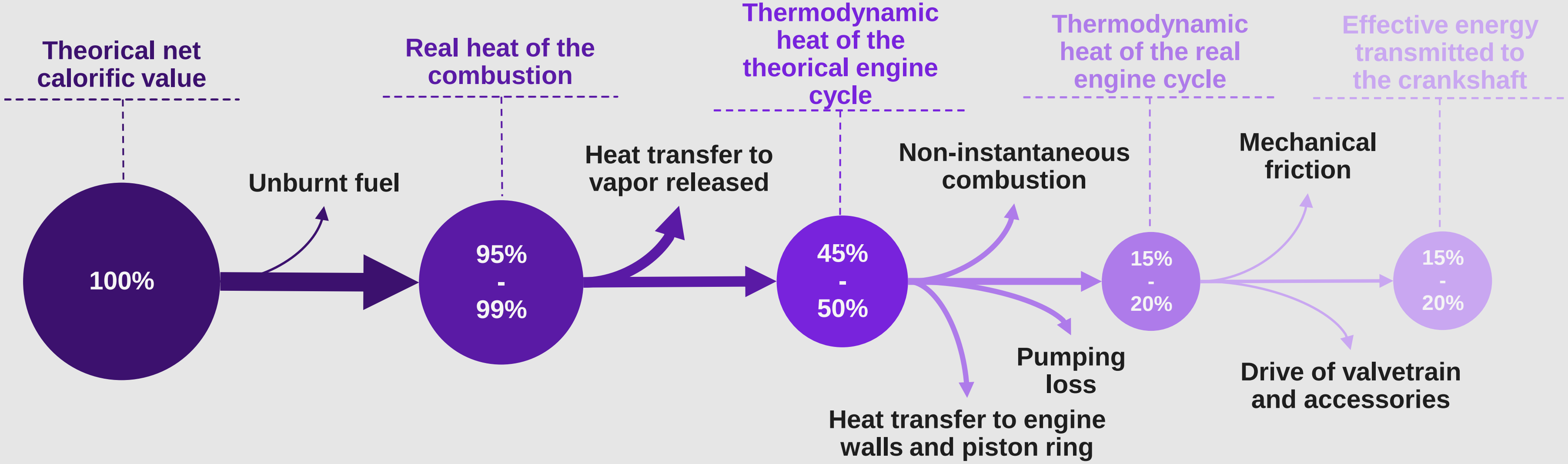
In a car engine, CO_2 emissions are highly underestimated if they do not consider the successive energy losses

C

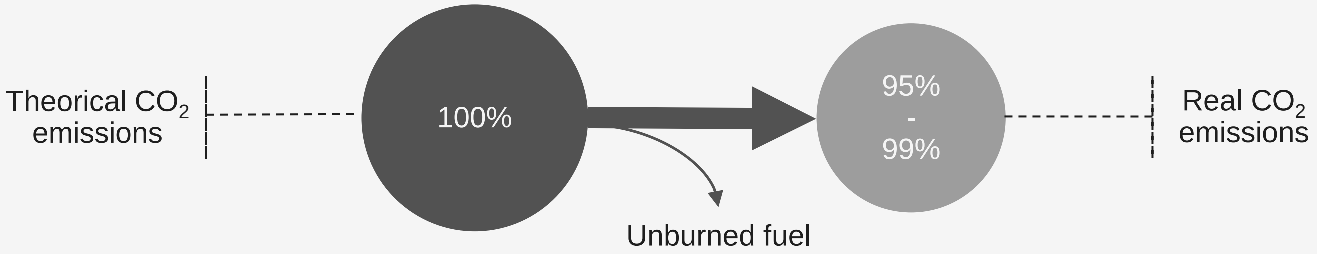
Using a fuel default emission factor to assess the CO_2 emissions from a car engine results in underestimating emissions by a factor of six.

4.2 Emission from fossil fuels consumptions - Fossil fuel use (Combustion efficiency)

The effective energy transmitted to the wheels is only 15% of the theorical energy contained in the fuel…



… while CO_2 emissions are only related to fuel consumption



Fuel generic emission factor without considering energy losses in the engine:	Fuel generic emission factor with considering energy losses:	Ratio between the two:
$\frac{\text{Real } CO_2 \text{ emissions}}{\text{Final energy}}$	$\frac{\text{Theorical } CO_2 \text{ emissions}}{\text{Primary energy}}$	$\frac{\text{Real } CO_2 \text{ emissions} \times \text{primary energy}}{\text{Theorical } CO_2 \times \text{final energy}} = 0.95/0.15 \approx 6$

Source: Kearney Energy Transition Institute analysis

Section 4.2 detailed in Appendix

The carbon footprint of metals varies depending on the mining conditions and the industrial processes used

Many metals used for energy transition technologies have very high carbon footprints. Nickel used in almost all technologies is about seven times more carbon-intensive than iron, and gallium used in solar PV is about 150 times more carbon-intensive than iron. Metals demand from energy technologies in 2050 is expected to reach more than 20 Mt. Critical metals are those used in a large number of low-carbon technologies (and usually in higher quantities than the current conventional technologies which are more carbon-intensive), including those for which today's scenarios project a large increase in use by 2050 but with potential supply constraints. Global mining and refining operations are responsible for about 10 percent of global annual GHG emissions.

Primary metals production is a four-step process starting with mine exploration followed by mining, transportation, and ending with final products refining. The main emissions come from energy consumption. The first three phases account for around 35 percent of total GHG emissions, and the last one for 65 percent, but the precise breakdown of energy use is highly dependent on the metal under study. Diesel is the main energy source for mining phases, while refining is usually mostly electricity consuming.

Carbon emissions from primary metal production are particularly variable. A major parameter is the geographic location. Although mining is mainly condensed in a couple of countries per metal, smaller mines are spread around the world. In particular, geographic variations in ore type, production methods (technology and energy sources), and transportation characteristics affect the carbon footprint of copper by almost one order of magnitude.

Decreasing ore grade greatly increases the energy requirements. Mines with high ore grades were exploited first, and the energy need grows exponentially as ore grade decreases. In Chile, it has been responsible for about 70 percent of the total direct and indirect GHG emissions increase of copper production in 10 years.

The carbon footprint of secondary production is most sensitive to the concentration of source. Secondary can be up to 60 percent more carbon intensive than primary production for copper. Depending on the primary and secondary copper production methods, projections of increased metal recycling rates can result in impacts ranging from 10 percent more GHG emissions to 65 percent less.

Energy losses in metal production currently account for more than 40 percent of total energy used. For the mining stage, energy efficiency processes can still be increased by up to 80 percent. Global initiatives are emerging, such as the World Bank Climate-Smart Mining Initiative. In 2019, new renewable projects associated with mining companies provided around 2,500 MWe at the global scales, and many projects are under development, especially in Australia.

4.3 Metal mining: executive summary

Source: Kearney Energy Transition Institute analysis

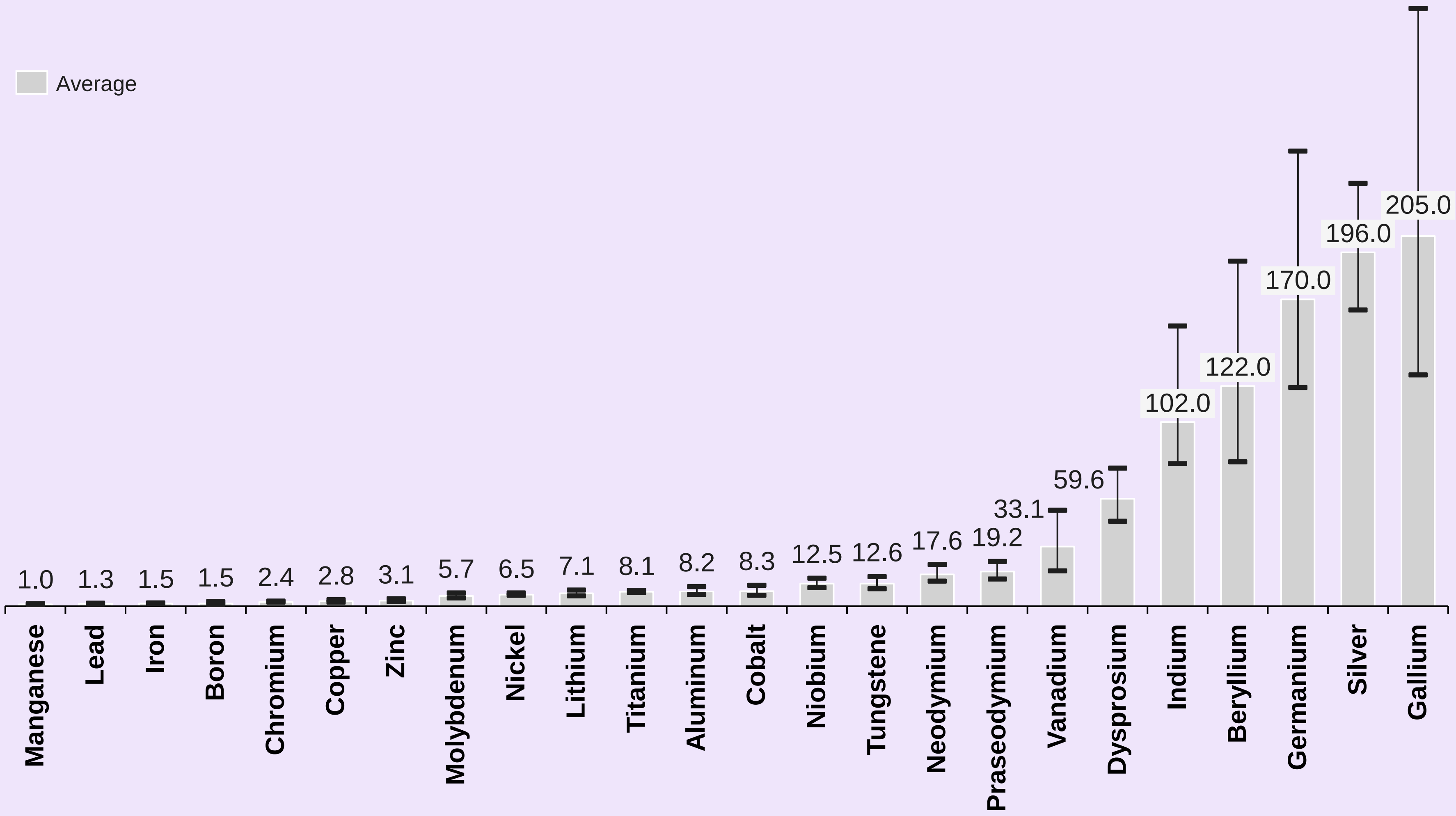
Many primary metals used for low-carbon energy technologies have very large carbon footprints

Gallium used in solar PV is 150 times more carbon-intensive than iron.

4.3 Metal mining – carbon footprint

Carbon footprints of mining and refining of primary metals[1,2]

tCO$_2$e/ton of metal



1. Carbon footprints depicted above are metal specific not impact/usage specific i.e. Gallium is used in CIGS solar cells, but CIGS solar cells are a very small part of the market, which is dominated by silicon-based systems (>90% according to recent Fraunhofer reports on PV sector)
2. Variability exist in the above carbon footprints estimates due to differences in the local mining conditions, primary production or use of scrap/recycling, chemical composition and purity of the ore, etc.

Sources: Philip Nuss and Matthew J. Eckelman, “Life Cycle Assessment of Metals: A Scientific Synthesis” (2014); Kearney Energy Transition Institute analysis

A low-carbon energy transition is metal-intensive

For each metal:	2018 total world production (kt, 2018)	× 2050 demand from energy technologies as % of 2018 production (%, 2050 under 2DS)	= 2050 demand from energy technologies (kt, 2050 under 2DS)
Iron	1,200,000	1%	7,584
Aluminum	60,000	10%	5,583
Nickel	2,300	100%	2,268
Copper	21,000	10%	1,378
Zinc	13,000	10%	1,300
Lead	4,400	20%	781
Manganese	18,000	5%	694
Cobalt	140	465%	644
Lithium	85	490%	415
Chromium	36,000	5%	366
Vanadium	73	190%	138
Molybdenum	300	10%	33
Silver	27	55%	15
Neodymium	23	40%	8
Titanium	6,199	5%	3
Indium	1	235%	2

~13 Mt (Iron, Aluminum)

~8 Mt (Nickel to Indium)

Total 2050: ~21 Mt

Cobalt and Lithium are mostly used for energy storage, whose use is predicted to increase a lot.

An additional parameter to consider when analyzing the predicted demand of metals is the dependance on **transition scenarios**. While some metals rely on one or two technologies (e.g., Co and Li), others are cross-cutting and will exist no matter which technologies are included in the scenario. For example, Fe and Al are used across almost all energy technologies. Even if their demand from energy technologies in 2050 represents less than 10% of their respective 2018 production level, they account for ~13Mt in absolute, which represents ~60% of 2050 total metal demand.

[1] 2DS: IEA scenario with at least a 50% chance of limiting the average global temperature increase to 2°C by 2100

Sources: “Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition,” World Bank Group, Kirsten Hund, Daniele La Porta, Thao P. Fabregas, Tim Laing, John Drexhage (2020); Kearney Energy Transition Institute analysis

Some metals are used in almost all low-carbon transition energy technologies

Technology \ Metal	Copper	Nickel	Aluminum	Chromium	Iron	Manganese	Molyb-denum	Titanium	Niobium	Boron	Cobalt	Neody-mium	Praseo-dymium	Indium	Gallium	Germanium	Dyspro-sium	Zinc	Silver	Lithium	Lead	Beryllium	Tungestene	Vanadium
LIBs	X	X	X			X		X	X		X									X				
Wind turbines	X	X	X	X		X	X		X	X		X	X				X	X			X			
Solar PV technologies	X	X	X		X		X			X				X	X	X		X	X		X			
Fuel cells (FCs)	X	X		X				X			X													
Nuclear power	X	X		X	X	X	X				X	X		X				X	X		X			
Traction motors	X		X	X	X		X			X		X	X				X							
Digital technologies	X	X		X		X				X	X			X	X	X			X	X			X	
Robotics	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X					X		
Drones	X	X	X		X			X	X			X	X	X	X	X						X		
3D printing	X	X	X	X	X	X	X	X	X		X												X	X

4.3 Metal mining: context

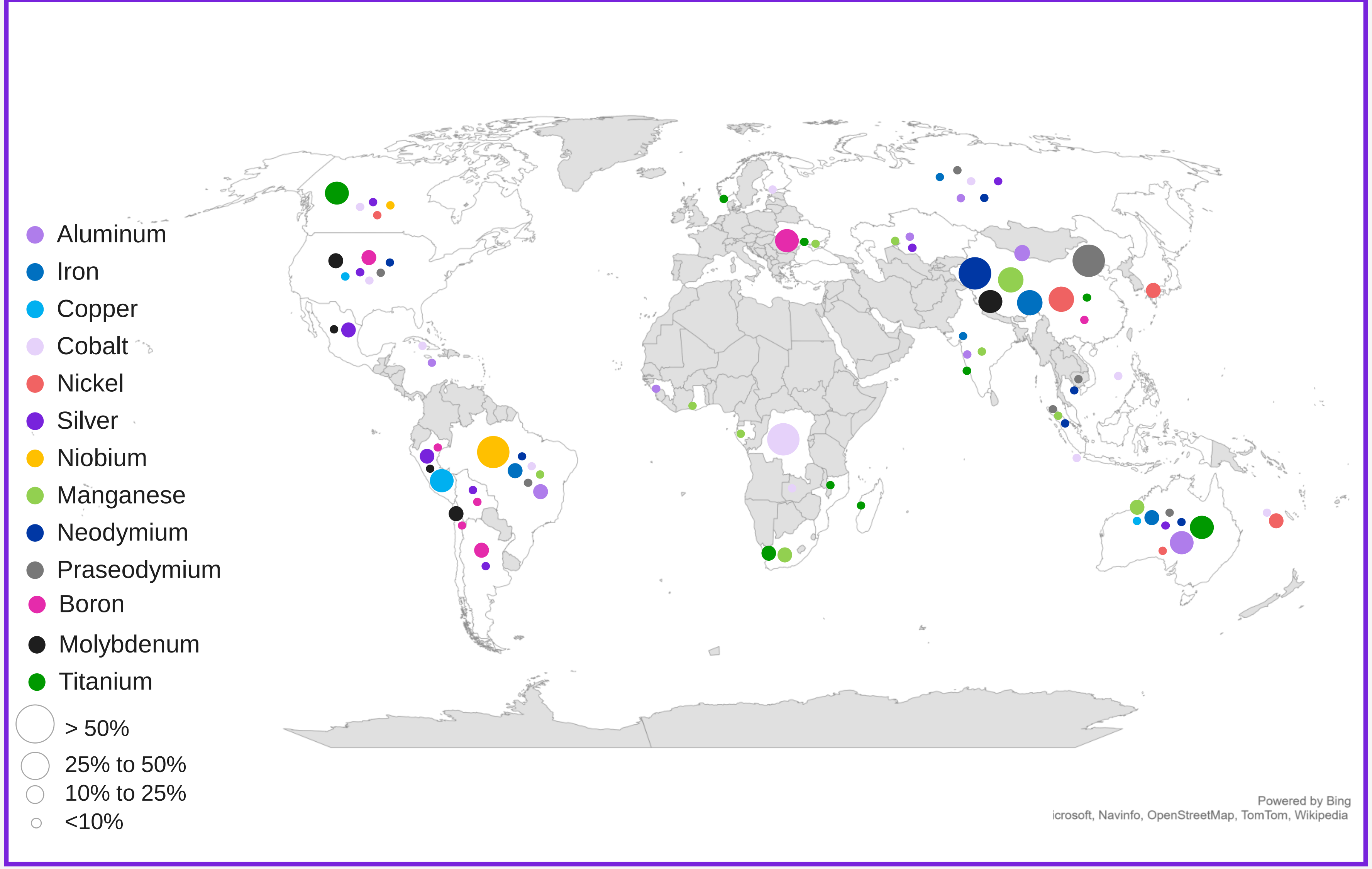
Sources: Study on the review of the list of Critical Raw Materials, Critical Raw Materials Factsheets & Non-critical Raw Materials Factsheets, European Commission, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs Raw Materials (2017); Kearney Energy Transition Institute analysis

Metal mine production takes place in a variety of countries

4.3 Metal mining - context

Geographical distribution of global metal mining production

% of global mine production per metal, 2017



Notes: Metals represented are those most used in new technologies (solar PV for example, but also robotics or drones) for which the demand is strongly increasing.
Sources: Study on the review of the list of Critical Raw Materials, Critical Raw Materials Factsheets & Non-critical Raw Materials Factsheets, European Commission, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs Raw Materials (2017); Kearney Energy Transition Institute analysis

The metals mining and refining process consists of four main phases

Exploration and mine construction

The first phase starts with a long process of metal and mineral exploration to determine where there is sufficient mineral deposit to warrant mining. The submission of a social and environmental assessment for approval of mine production takes one to three years. The final stage consists in a one- to three-year feasibility study on all aspects of mine's future (costs, mining method, waste treatment, …).

Extraction

There are two types of mining:

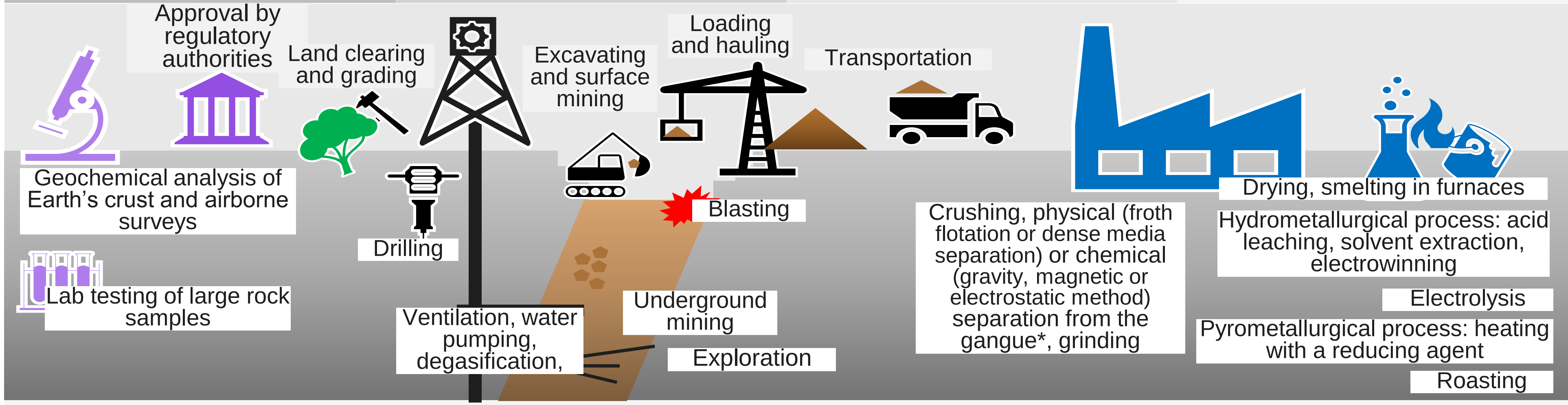
– **Surface mining** includes stripping of vegetation, soil, and layers of bedrocks to reach buried ore deposits. Open-pit and quarrying or strip-mining methods can be used.
– **Subsurface mining** requires mining a vertical shaft into the ground, from which lateral tunnels are excavated at different depths. Conveyors carry the ore to the shaft and the ore is lifted to the surface. Sometimes, in-situ leaching is used: solutions are injected into fissures and cracks in the ground to dissolve the materials.

Processing and concentration

Metal processing consists of separating metal resource from the ore. It depends on the grade of the metal. Pieces are crushed or ground into a fine powder. Then resource is extracted using various processes (gravity, heavy oils, mechanically, chemically…).

Purification and refining

Metal purification depends on the state of the metal (solid, liquid or slurry, dissolved). Slurry forms metals are filtered and dried before smelted (high-temperature process that extracts the molten from the slag) or roasted (high-temperature process that produces metal oxide particles). The metals are further chemically refined to increase their purity to the standard set for world metal markets (99.9% in most cases).



* Non-ore mineral
Source: Kearney Energy Transition Institute analysis

4.3 Metal mining – value chain overview

Different parameters affect carbon emissions at each phase of the primary metals' life cycle

Parameters are rarely fully considered in the assessment of metals' carbon emissions assessment. Carbon intensity of production of metals used in clean energy technologies is often underestimated

4.3 Metal mining – Emissions drivers

$$\text{Carbon emissions} = \text{Parameters} \times \frac{\text{Energy}}{\text{Need}} \times \frac{\text{Carbon emissions}}{\text{Energy}}$$

	Parameters	Energy / Need	Carbon emissions / Energy
2 **Exploration & production**	– Size of the mine – Depths and type of mine – Metal ore grade – Production method	– Efficiency of testing process – Efficiency of drilling – Type of extraction: e.g., underground or open-pit – Efficiency of extraction process (e.g., equipment fleet)	1 – Type and quantity of energy used for exploration and production operations, mineral processing, transportation and refining (fossil fuels and carbon intensity of electricity mix)
Mineral processing	– Metal grain size expected at the end of the process	– Efficiency of equipment at the concentration plant	
Transportation[1]	– Distance from mine to processing plant – Country of production / country of exportation	– Efficiency of means of transportation (loading, fleet size, etc.)	
3 **Purification, refining, and possibly recycling**	– Expected degree of purity – Characteristics which depend on the future uses of the metal – Recycling rate and methods	– Efficiency of purification and refining technology (e.g., for nickel pyrometallurgy is more efficient in the case of low ore grade while high pressure acid leaching is more efficient in the case of high ore grade)	

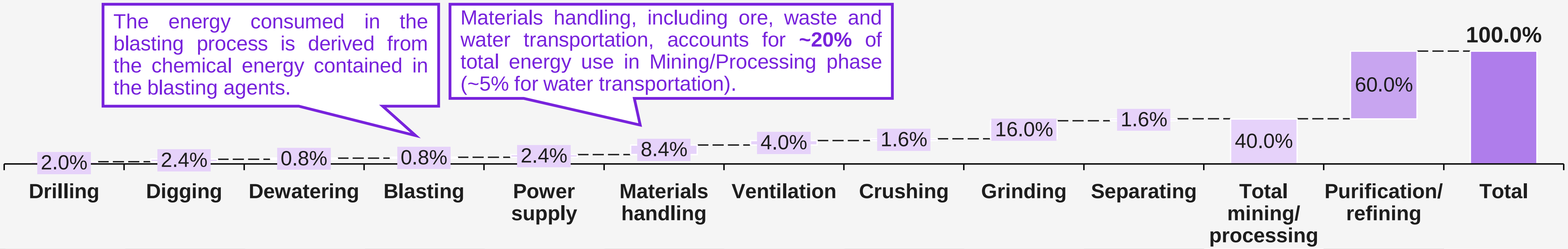
1. Transport is not considered in the analysis due to large variations involved depending on the region, etc.
Source: Kearney Energy Transition Institute analysis

Various fuel sources are used depending on the phase of metal production process

1

Typical repartition of energy use in each phase of primary metal production

% of total energy use



	Drilling	Digging	Dewatering	Blasting	Power supply	Materials handling	Ventilation	Crushing	Grinding	Separating	Total mining/ processing	Purification/ refining	Total
Fuel source	Electricity, diesel, compressed air	Electricity and diesel	Electricity	NA	Fossil fuels	Electricity (20%) and diesel (80%)	Electricity and natural gas	Electricity	Electricity	Electricity and fossil fuels		Electricity and fossil fuels	
Activities and equipment	Loader trucks, diamond or rotary drills, jumbos	Hydraulic or cable shovels, continuous miners, front-end loaders	Pumps	Blasting agents	Generators	Discrete (trucks, bulldozers)/ Continuous (conveyor belts, pipelines)	HVAC (heating, ventilating, air conditioning)	Crushers	Mills	Physical (centrifuge)/ chemical (electro-winning)		Drying, firing, smelting in oven or furnace, and electrolytic refining …	

For mining/processing, the different ore particularities—from ore mineralogy and grade, mining type and technologies to resources for the mining and processing-affect energy requirements. In iron ore mining, most energy is required for hauling and loading (50%). In copper production, crushing and grinding are the most energy-intensive parts.

For purification/refining, energy requirements and sources depend on the type of process affects the energy requirements and carbon emissions: 60% of energy requirements in a hydrometallurgical process is met with electricity while 60% of the energy requirement in a pyrometallurgical process is met with metallurgical coke and anthracite.

4.3 Metal mining – Energy used

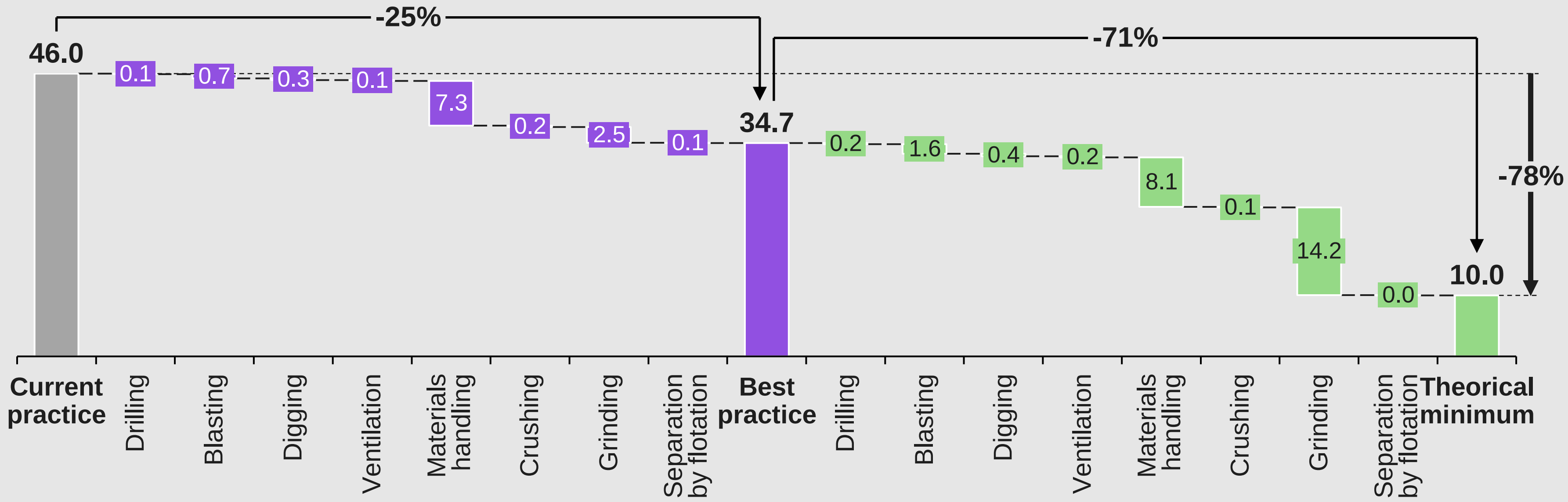
Sources: “Energy Consumption in Mining Comminution,” Jack Jeswiet, Alex Szekeres (2016); “Mining Industry Energy Bandwith Study,” US DOE, June 2007; Kearney Energy Transition Institute

Energy efficiency measures can be deployed across the value chain

1

The energy efficiency of mining processes can increase by 78% before reaching minimum energy requirement.

Theorical possible energy efficiency increase per phase of mining and processing
2007, US, kWh/t ore



The theoretical minimum energy requirement is based on the current efficiency of equipment and current equipment energy consumption. Efficiencies estimates an sources include calculations from the SHERPA modeling software[1] and published equipment efficiency values. Because starting raw materials and conditions for production vary a lot in energy intensity (sometimes by more than an order of magnitude), average theorical values are used.

Best practice energy consumption was determined from a variety of sources describing mining operations that use significantly less energy compared to typical operations. It is important to point limitations of the study:

- Best practice was benchmarked at a specific point in time (2007) and may be surpassed,
- The sample used has a small size (eight commodities selected by the US DOE and the National Mining Association)
- Energy estimates for each commodity are limited by the number of mining methods analyzed for that commodity
- However, the eight commodities analyzed account for ~80% of energy consumption in US mining, and many commodities can be representative of other commodities (e.g., copper of molybdenum and gold of platinum).

1. Software used by the mining industry to model mining operations and estimate capital, labor, and other costs of production
Sources: Mining Industry Energy Bandwidth Study, US DOE, June 2007; Kearney Energy Transition Institute analysis

A growing number of private renewable energy projects have been undertaken in recent years

1

Most of the systems in 2018 and 2019 are hybrids—i.e., a combination of wind, solar, energy storage, and other technologies—generally backed by fossil fuels to smooth the variability of the renewable energy generation

Annual new renewable projects associated with mining companies worldwide

2019, MWe

Examples of achieved and ongoing projects since 2020

Mine emplacement	Energy provider	Date	Facilities
Rio Tinto Ilmenite Mine Southeast Madagascar	CrossBoundary Energy (CBE)	Signed in July 2021, planned for 2022	– Three wind and solar facilities (18,000 panels capable of producing 8 MWp), combined capacity of 20 MW
Gruyere Gold Mine Western Australia	APA Grounds	Signed in end of 2020, planned for end of 2021	– Hybrid microgrid (first phase: gas fired engine, second phase: 13.6 MW solar farm backed up with 4.4 MW battery energy storage)
Gold Fields Granny Smith Gold Mine Western Australia	Aggreko	Completed in October 2020	– Hybrid microgrid (20,000 solar panels capable of producing 7.7 MWp supported by a 2 MW battery system)
Gold Fields Agnew Gold Mine Western Australia	EDL Energy	Completed in May 2020	– 18 MW wind power, 4 MW farm, 14 MW battery storage system and off-grid 21 MW gas/diesel engine power plant, all controlled by an advanced microgrid system

Sources: Integrating Clean Energy in Mining Operations: Opportunities, Challenges, and Enabling Approaches Tsisilile Igogo, Travis Lowder, Jill Engel-Cox, Alexandra Newman, Kwame Awuah-Offei Missouri (July 2020); APA Group Builds Hybrid Microgrid for Australian Mine; Gold Fields powers Agnew mine with hybrid renewable energy; Aggreko completes renewable microgrid at gold mine; Rio Tinto signs groundbreaking renewable energy agreement in Madagascar; Kearney Energy Transition Institute analysis

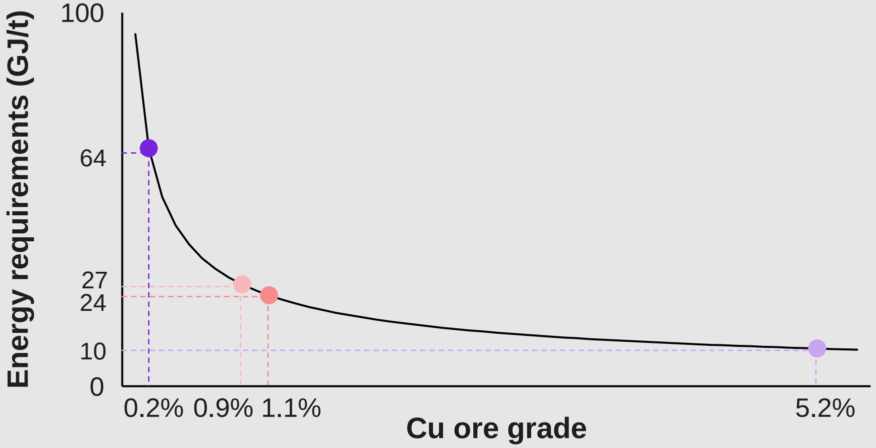
An ore grade decrease leads to higher energy requirements

2

In Chile, an ore grade decrease is responsible for 70% of the total energy increase for copper production.

4.3 Metal mining – ore grade

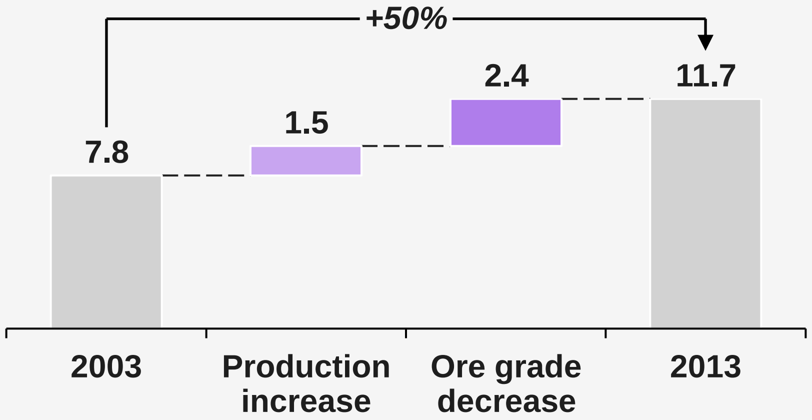
Energy requirements for copper as a function of the ore grade
GJ/t, 2003–2013, global



When the ore grade decreases in a mine, the energy required for metal extraction increases. Mines with higher ore grades are exploited first. Even if technology improves, because the energy needed if exponentially high when the ore grade approaches crustal abundance, the minimum energy required cannot be reduced.

- Today, Cu ore grade ranges from **0.3%** (e.g., in Telfer, Australia) to **5.2%** (e.g., in Sepon, Viêt Nam), with an average of **0.9%.** The corresponding energy consumption ranges from **10 to 64 GJ/t**, with an average of **27 GJ/t**.
- On average, **Cu ore grade decreased** by 20% from 2003 to 2013, and the energy requirement therefore increased by **3 GJ/t**.

Energy increase in Chilean copper mines
107 GJ, 2003 to 2013, Chile



Total energy consumed in the copper mining projects ($\boldsymbol{E}$) depends on mass of copper extracted ($\boldsymbol{M}$) and on energy requirement per mass of Cu ($\boldsymbol{e}$):

$$\boldsymbol{E} = \boldsymbol{M} \times \boldsymbol{e}$$

The increase in energy consumption can then be broken down into two parts: the additional energy due to copper production increase, and the additional energy due to a decrease in ore concentration:

$$\Delta \boldsymbol{E} = \underbrace{\Delta \boldsymbol{M} \times \boldsymbol{e}}_{\text{Production increase}} + \underbrace{\boldsymbol{M} \times \Delta \boldsymbol{e}}_{\text{Ore grade decrease}}$$

From 2003 to 2013, total energy consumed increased by **~50%.**

- **30%** of that increase is due to copper production increase, which overall increased by 30% during that period (**4 Mt** to **5 Mt**).
- The remaining **70%** of total energy increase is due to ore grade decrease, which decreased from **1.1%** to **0.9%** on average.

Sources: Calvo, G.; Mudd, G.; Valero, A.; Valero, A., "Decreasing Ore Grades in Global Metallic Mining: A Theoretical Issue or a Global Reality?" Resources 2016; Kearney Energy Transition Institute analysis

In Chile, decreasing ore grade has led to high emissions increase

2

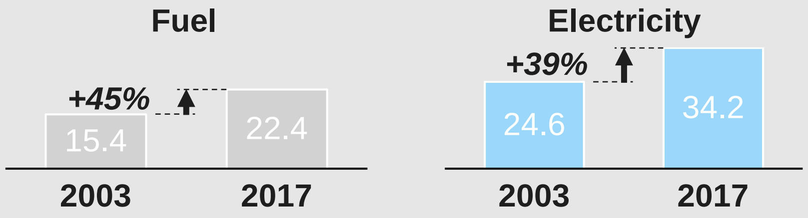
From 2003 to 2017, carbon emissions from copper production in Chile increased by more than 50%.

4.3 Metal mining – ore grade

Different energy sources are used to face increase of energy need of Cu production

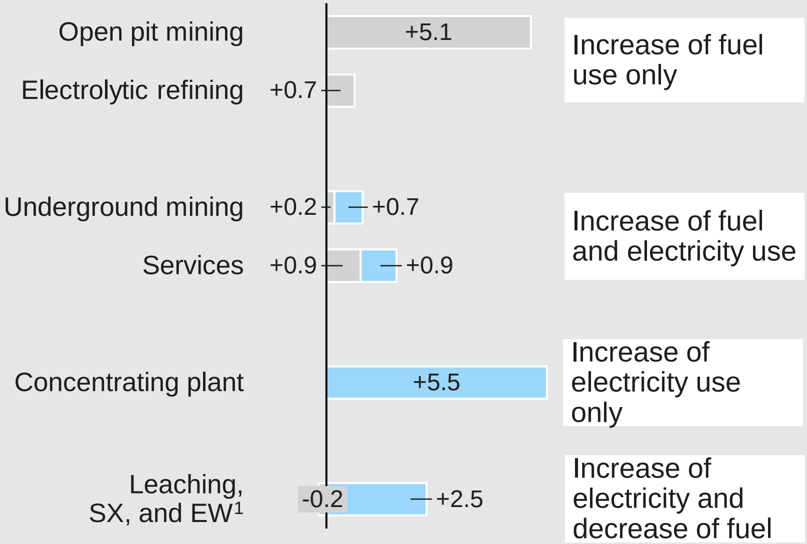
Energy requirements increase per source

Chile, 2003 to 2017, GJ/t Cu



Breakdown of energy use increase per process stage2

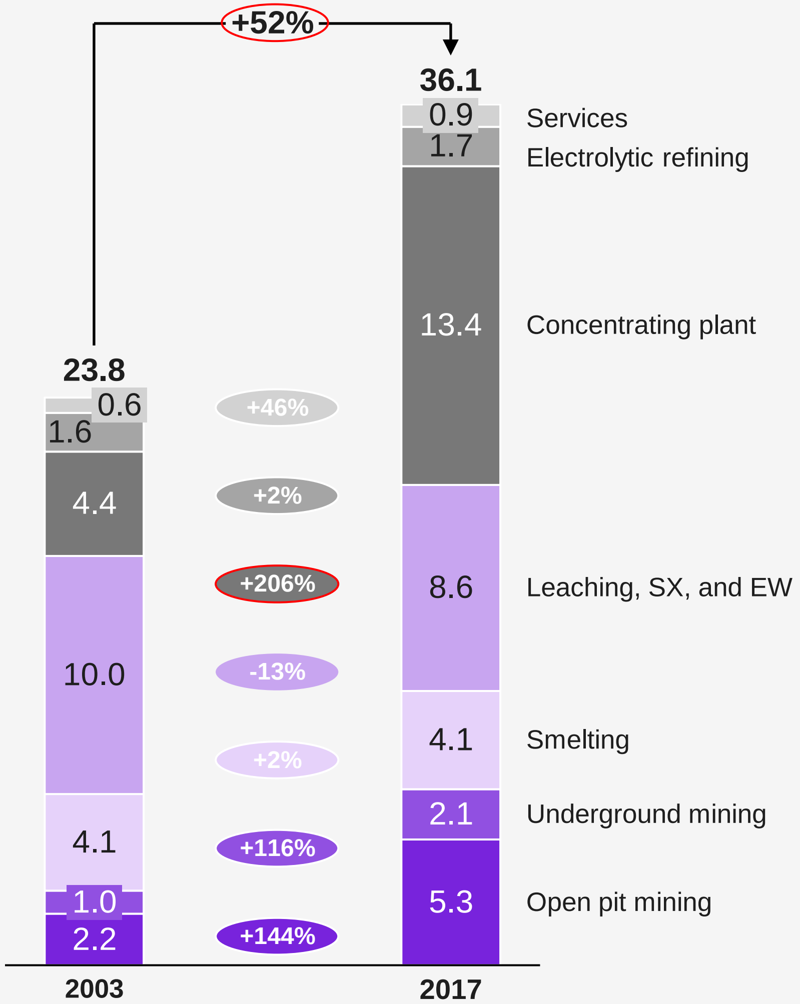
Chile, 2003 to 2017, GJ/t Cu



A carbon emissions increase depends on the mining and refining process phase

Direct and indirect carbon emissions increase

Chile, 2003 to 2017, MtCO2e



1. X is solvent extraction; EW is electrowinning: 2.Fuel consumption for smelting was divided by two from 1995 to 2003, with an increase of 20% of electricity use, but then stabilized.
Sources: Azadi, M., Northey, S.A., Ali, S.H. et al. "Transparency on greenhouse gas emissions from mining to enable climate change mitigation" (2020); GlobalData Mining Intelligence center; Kearney Energy Transition Institute analysis

Secondary production carbon-intensity depends on material and recovery pathway

2

Several parameters affect the carbon footprint of Cu produced from secondary sources

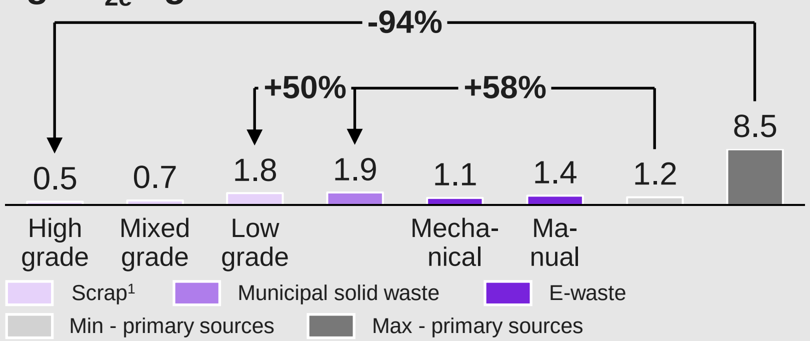
Cu can be recovered from most of its end-products and returned to the production process without loss of quality during recycling.
– The main differences compared with production from primary source are the first steps: mining and beneficiation, disassembly, sorting, and transportation.

The values of carbon footprint (CF) vary from 0.9 to 1.9 kgCO_2e/kg. It is lower than from primary sources.
– In particular, CF of production from high grade scrap is 94% lower than the maximum value from primary sources.

However, depending on the type of source and the methodology for recovery, production from secondary materials can be more carbon-intensive.
– In particular, production from municipal solid waste incineration (in which pieces of Co are dispersed) or from low grade scrap can be 50% to 58% more carbon-intensive than from primary sources.

Comparison of carbon footprint of Cu from primary and secondary sources

kgCO_{2e}/kg



Several parameters affect the carbon footprint of Zn produced from secondary sources

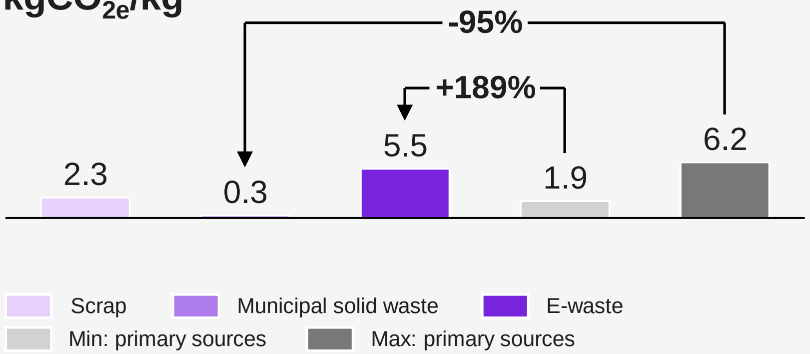
Zn can be recovered from different secondary resources with different levels of impurities, including ash, zinc dross, flue dust of the electric arc furnace and brass smelting, automobile shredder scrap, rayon industry sludge, and cathodic tubes from e-waste.

The CF of Zn produced from secondary sources ranges from 0.2 to 5.5 kgCO_2e/kg. It is a magnitude lower than from primary sources.
– In particular, CF of production from municipal solid waste is 95% lower than the maximum value from primary sources.

However, depending on the type of source and the methodology for recovery, production from secondary materials can be more carbon intensive.
– In particular, production from e-waste incineration or from low grade scrap can be 189% more carbon intensive than from primary sources.

Comparison of carbon footprint of Zn from primary and secondary sources

kgCO_{2e}/kg



1. Waste resulting from either metals discarded in semis fabrication or generated during the initial manufacturing process

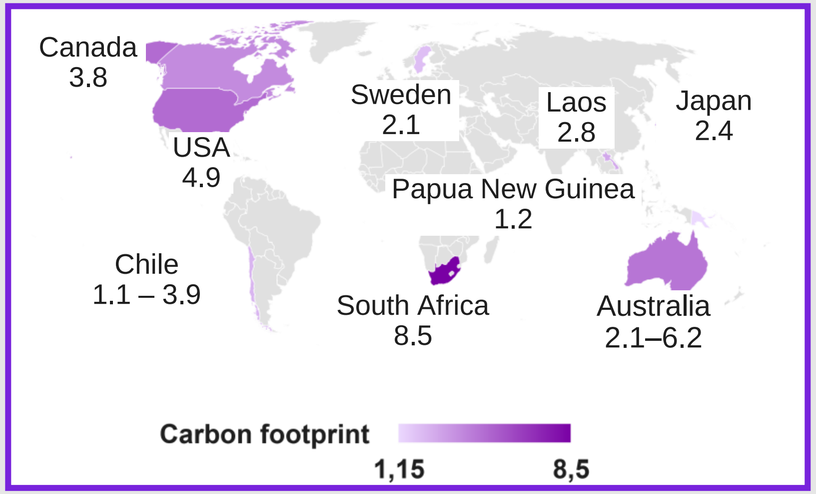
Sources: Ekman Nilsson, A.; Macias Aragonés, M.; Arroyo Torralvo, F.; Dunon, V.; Angel, H.; Komnitsas, K.; Willquist, K., “A Review of the Carbon Footprint of Cu and Zn Production from Primary and Secondary Sources.” Minerals 2017; “Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition,” World Bank Group, Kirsten Hund, Daniele La Porta, Thao P. Fabregas, Tim Laing, John Drexhage (2020); Kearney Energy Transition Institute analysis

The estimated carbon footprints of primary metals vary geographies

2

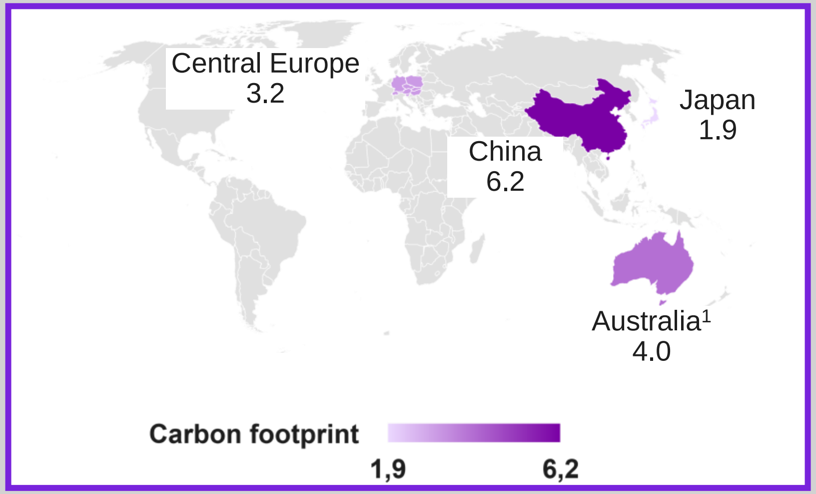
Carbon footprint of copper is estimated to vary by a factor of seven across the world

kgCO_2e/kg Cu



The carbon footprint of zinc is estimated to vary by a factor of three across the world

tCO_2e/t Cu



Geographical variations are mainly explained by ore characteristics and mining and refining methods

	Copper	Zinc
Ore grade	0.4% to >12%	3% to 10%
Ore types[2]	Porphyry copper (upper portions: oxides, lower levels: sulfides), massive deposits (higher metal content), mixed ores (with nickel, zing or lead), native copper (unadulterated metal)	Zinc sulfide (or blende, ZnS), ferrous form of zinc blende (marmatite (ZnFe)S), or zinc carbonate (calamine or smithsonite ($ZnCO_3$))
Mining	Open-pit (more for oxides) or underground	Open-pit (for oxidized ore bodies) or underground
Metal processing	Froth flotation, further concentration, water removal, moisture content reducing, flash and anode furnace charging, electrochemical refining	For ZnS: froth flotation and roasting to convert the sulfide to oxide, leaching, electrowinning. For Zn-Pb: pyrometallurgical process: sintering, smelting, refining, casting

1. In Australia, 100% coal-based electricity was assumed for Zn production. 2. Listed from the most to the least common
Note: A part of the variation is also explained by differences in estimation methods.
Sources: Ekman Nilsson, A.; Macias Aragonés, M.; Arroyo Torralvo, F.; Dunon, V.; Angel, H.; Komnitsas, K.; Willquist, K. A Review of the Carbon Footprint of Cu and Zn Production from Primary and Secondary Sources. Minerals 2017; Kearney Energy Transition Institute analysis

In a metal production process, the refining phase is generally more carbon-intensive than mining

3

Global mining and refining operations are responsible for ~10% of global annual GHG emissions.

4.3 Metal mining

Global production of primary metals is divided into mining and refining phases

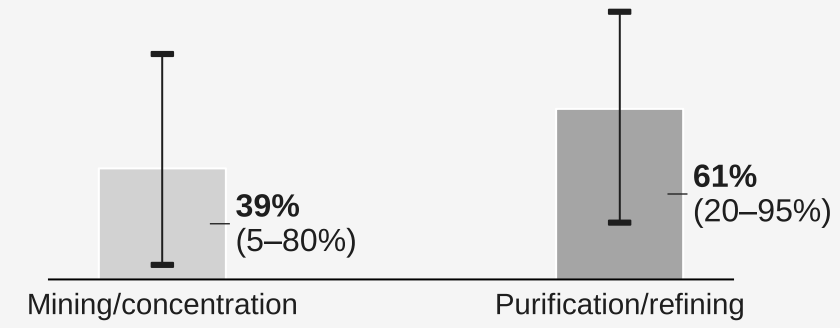
Ore mining and concentrating account for about **40%** of the total metal production process energy use.

Purifying and refining ores to the end-product requires energy-intensive processes (precise melting, hydrometallurgy) and accounts for **60%** of the total energy use.

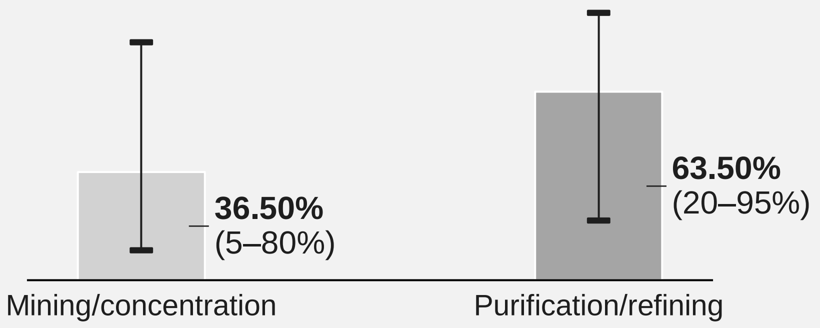
The **GHG emissions** of the process are distributed similarly between **mining (~35%) and refining (~65%)** as emissions are strongly linked to energy consumption in the production process.

The energy intensity of the overall metal production process is likely to increase (but higher share of low-carbon energy sources in power mix can blunt the increase to an extent) as we shift exploitation to lower-grade metal ores and more complex deposits.

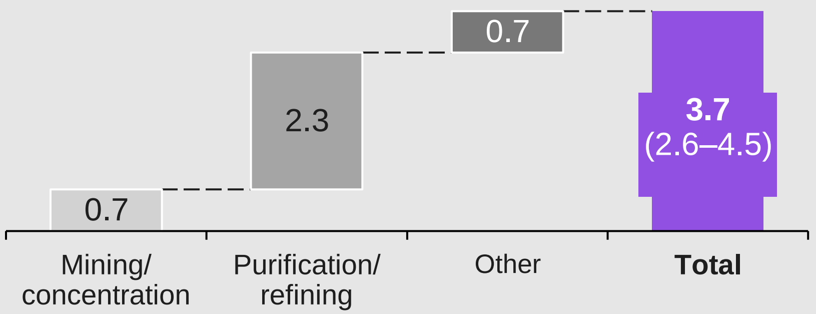
Global distribution of energy use per phase of metal primary production
World, 2014



Global distribution of GHG emissions per phase of metal production
World, 2014



Global GHG emissions of primary material production
World, 2018,$GtCO_2e$



Sources: Philip Nuss and Matthew J. Eckelman, “Life Cycle Assessment of Metals: A Scientific Synthesis” (2014); Azadi, M., Northey, S.A., Ali, S.H. et al., “Transparency on greenhouse gas emissions from mining to enable climate change mitigation (2020)”; Kearney Energy Transition Institute analysis

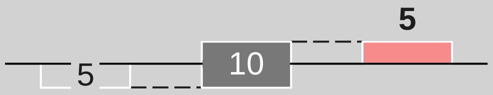
The carbon benefit of increased metal recycling depends on the methods used for recycling

3

Increasing recycling rates can either result in additional or avoided emissions from Copper production

$MtCO_2e$, global, 2018–2050

First case

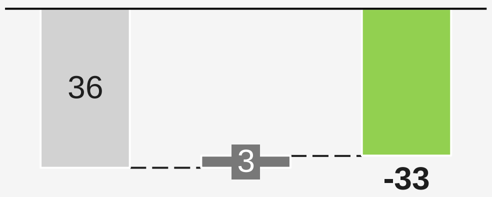


First case, assuming:
– Primary Cu produced with **best practice hydrometallurgical** method
– Secondary Cu recovered **from low grade scrap**

Second case

Second case, assuming:
– Primary Cu produced with **average hydrometallurgical** method
– Secondary Cu recovered from **waste electrical and electronic equipment**

Third case



Third case, assuming :
– Primary Cu produced with **worst practice hydrometallurgical** method
– Secondary Cu recovered from **high grade scrap**

For copper, the current recycled content rate (RC, % of a new product that is made using secondary [recycled] material) is equal to 28.5%.

If the ratio of scrap availability to overall Cu demand changes, a 100% end-of-life rate can be reached (EOL, % of material that is recovered at the end of a products life and recycled into new material). An increase to 100% EOL by 2050 increases RC rates to 59%, which reduces the overall cumulative demand for primary copper from energy technologies by 26%.

This can be achieved by changing the design of products to enable better metal recovery or because of large falls in demand for Cu from other sectors outside the energy industry.

Emissions avoided by reduction of demand for primary Cu | Additional emissions due to increase of demand for secondary Cu | Net impact on cumulative emissions

Sources: Ekman Nilsson, A.; Macias Aragonés, M.; Arroyo Torralvo, F.; Dunon, V.; Angel, H.; Komnitsas, K.; Willquist, K., “A Review of the Carbon Footprint of Cu and Zn Production from Primary and Secondary Sources,” Minerals 2017; Kearney Energy Transition Institute analysis

Section 4.3 detailed in Appendix

The carbon benefit of BEVs is constrained by boundary conditions, with predominant importance of carbon intensity of the power mix used

Batteries used in battery electric vehicles (BEVs) have a cradle-to-gate carbon footprint that is driven by their size and the energy source of their production. Lithium–ion batteries (LIBs) are the most common batteries. Metal components used in both cathode and anode parts account for around two-thirds of their weight. Nickel–manganese–cobalt (NMC) is the most used variety of cathode. Eighty percent of a NMC battery's cradle-to-gate carbon footprint is due to material production, and the remaining 20 percent to cell production and pack assembly. Cradle-to-gate carbon footprint varies by a factor of four from small-capacity batteries produced with renewable-energy electricity to large batteries produced with coal-fired electricity.

Two main parameters affect the comparison between BEV and internal combustion engines (ICEs) in terms of their carbon footprint: the carbon intensity of electricity used to power the vehicle and its lifetime mileage. Other parameters of interest exist (for example, vehicle size) but these two parameters enable definition of boundary conditions for carbon efficiency of BEV compared with ICE. If a BEV is driven for less than 8,000 km and powered with an electricity mix more carbon intensive than 500 gCO_2e/kWh, it is less carbon-efficient than an ICE no matter the size and energy source used to produce the vehicles. Any ICE is more carbon intensive than a BEV driven for more than 40,000 km and powered by an electricity mix of less than 120 gCO_2/kWh.

In many countries worldwide, driving a BEV is for the moment less carbon efficient than driving a similar size ICE. LIBs have a high carbon footprint, requiring a BEV to be powered by a low-carbon electricity mix to offset that footprint. Above 500 gCO_2e/kWh, which is lower than the world average, BEVs do not always outperform ICEs in terms of emissions. More precisely, if powered by such electric mixes, BEVs with the worst possible cradle-to-gate carbon footprint are environmentally worse than combustion vehicles, except for the most fuel-intensive combustion engines, which are on their way out. In some countries (for example, in Northern Europe), however, driving a BEV is always less carbon-intensive than using an ICE.

There is a minimum lifetime mileage after which driving a BEV starts being more carbon efficient than using an ICE, and that mileage depends on various parameters. After a certain number of km on the road, CO_2 emissions avoided consuming electricity instead of fossil fuel start compensating for the high carbon footprint of battery production as long as the electricity mix is not too carbon-intensive. Small BEVs produced with a low-carbon energy mix need to be driven for 8,000 km to 17,000 km depending on the electricity mix and the consumption rate of the thermal vehicle to which it is compared. Large BEVs produced with a carbon-intensive energy mix need at least 40,000 km on the road.

Several battery recycling processes are commercially available, but none are cost-effective and innovation labs are working to improve them. There exist three approaches for materials recovery: pyrometallurgical, hydrometallurgical, and direct recycling. The impact of recycling of battery carbon footprint depends on the battery composition and process used. It ranges from -10 percent for NMC batteries recycled with the hydrometallurgical method to +18 percent for LFP batteries. Improvements can be found at each stage of recycling process, from improving process flexibility to relying on innovative methods from robotics, chemistry, or the electronics field. Hybrid processes are assumed to allow for a reduction of 30 percent to more than 50 percent of cradle-to-gate carbon footprint, which enables electric vehicles to be powered with electricity mixes 3 percent to 10 percent more carbon-intensive than in the case of virgin production.

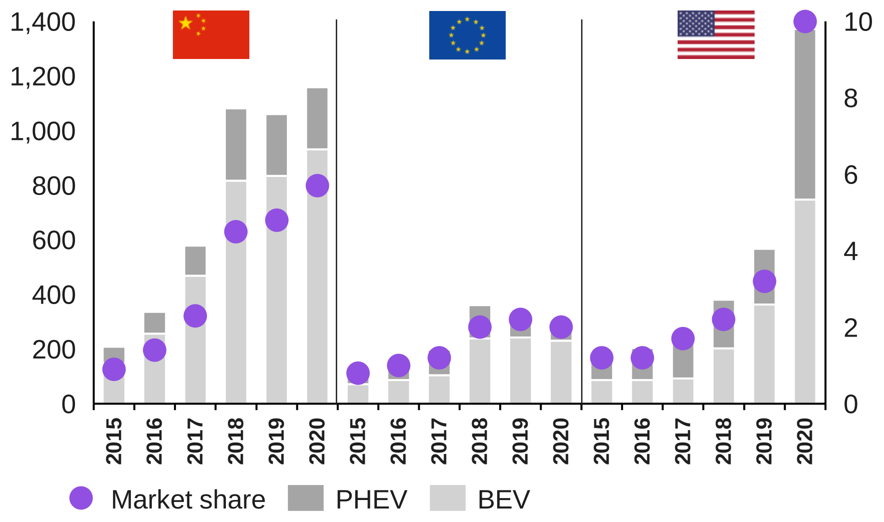
Source: Kearney Energy Transition Institute analysis

4.4 Electric mobility: executive summary

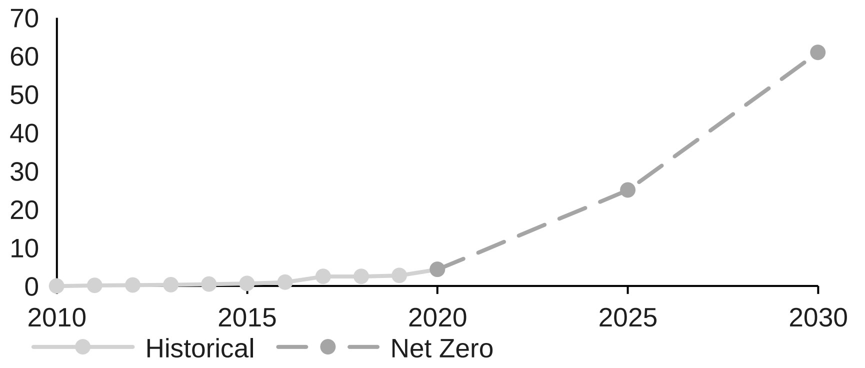
The market share for electric vehicles is growing rapidly, but the emissions reduction benefits depend on the geography and carbon intensity of the electricity mix

Battery electric vehicles' market share increases especially in Europe and China

Global electric car registrations and market share (thousands)

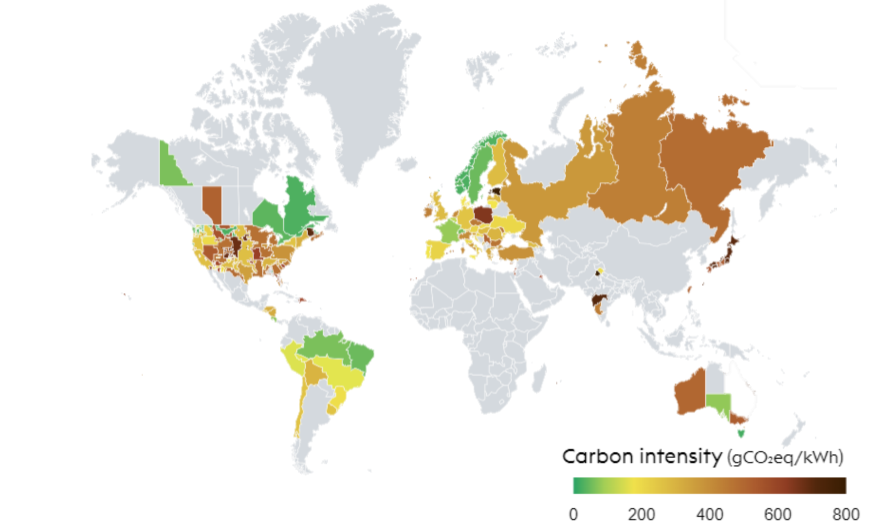


Electric car sales share in the net-zero scenario (%)

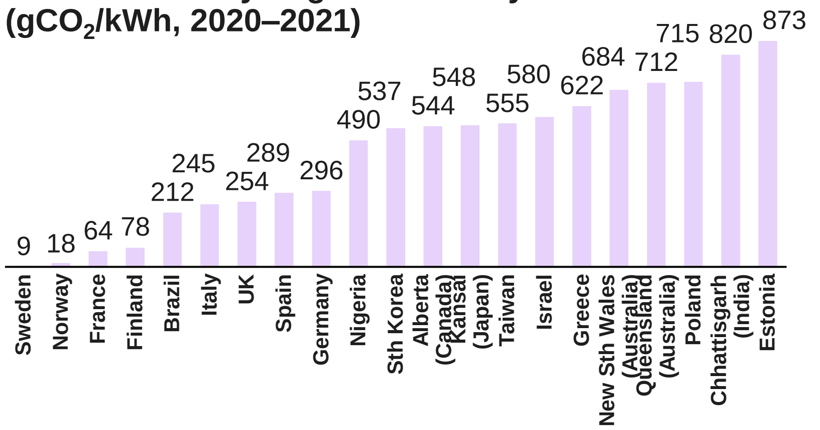


But the carbon intensity of the electricity mix is highly country-dependent[1]

Carbon intensity of electricity generation in selected countries and regions, 2020



Carbon intensity of grid electricity mix (gCO_2/kWh, 2020–2021)



4.4 Electric mobility: context

1. However, electricity mix in general are evolving towards lower carbon
Sources: IEA Global EV Outlook 2021, Electricity Map; Kearney Energy Transition Institute analysis

Several factors influence the benefits of switching to electric mobility

LCA result highlights variable boundary conditions to benefits from

4.4 Electric mobility

Key factors impacting the carbon footprint of mobility solutions

- **The carbon emissions related to vehicle manufacturing** (including batteries, or fuel cells)
- **The carbon emissions related to the fuel consumption**: diesel or gasoline for ICEs, carbon-intensity of electricity for BEVs, or the carbon-intensity of hydrogen for FCEVs
- **The mileage and use of vehicles**
- The emissions associated to **the management of the vehicle at its end of life (recycling)**

Manu-facturing → Use → Recycling

Source: Kearney Energy Transition Institute analysis

Key specificities of vehicle types impacting their carbon footprint

Vehicle type	Material specificities	Fuel used
ICE *Internal Combustion Engine*	– Thermal engine	– Diesel, Gasoline, LPG…
BEV *Battery Electric Vehicle*	– Electric engine – Batteries	– Electricity
FCEV *Fuel Cell Electric Vehicle*	– Electric engine – Fuel cell – Hydrogen storage unit	– Hydrogen

The carbon footprint of a traditional Internal Combustion Engine (ICE) vehicle essentially comes from the manufacturing of the vehicle and use

Three scenarios pertaining to vehicle size (i.e. min-small, median-medium, max-large) are studied with the assumptions for the key parameters, both variable and constant.

CO_2 emissions = Service requirement × Energy need / Service requirement × Carbon emissions / Energy need

	Service requirement	Min	Median	Max	Energy need / Service requirement	Min	Median	Max	Carbon emissions / Energy need	Min	Median	Max
Vehicle and engine production phase	**Vehicle mass** (t)	1.15	1.40	1.96	**Vehicle and engine production energy requirement** (MWh/t)	10.1	10.1	10.1	**Carbon footprint of energy mix used for vehicle production[1]** (gCO_2e/kWh)	475	475	475
Use phase	**Lifetime mileage (same as BEV)** (thousands km)	270	320	411	**Fuel consumption** (l/100km)	4.0	7.5	9.5	**Type of fuel**	Diesel	Gasoil	Gasoil
									Well-to-tank emissions ($kgCO_2e/l$)	0.6	0.7	0.7
									Tank-to-wheel emissions ($kgCO_2e/l$)	2.7	2.4	2.4
									Well-to-wheel emissions ($kgCO_2e/l$)	3.3	3.1	3.1

1. Share of electricity in energy mix used for vehicle and engine production is 100% for all three scenarios, used 2019 World average as carbon footprint of electricity
Source: Kearney Energy Transition Institute analysis

The carbon footprint of Battery Electric Vehicles (BEVs) essentially comes from the battery manufacturing and the carbon content of the power mix used for charging

Three scenarios pertaining to vehicle size (i.e. min-small, median-medium, max-large) are studied with the assumptions for the key parameters, both variable and constant.

CO_2 emissions = Service requirement × $\frac{\text{Energy need}}{\text{Service requirement}}$ × $\frac{\text{Carbon emissions}}{\text{Energy need}}$

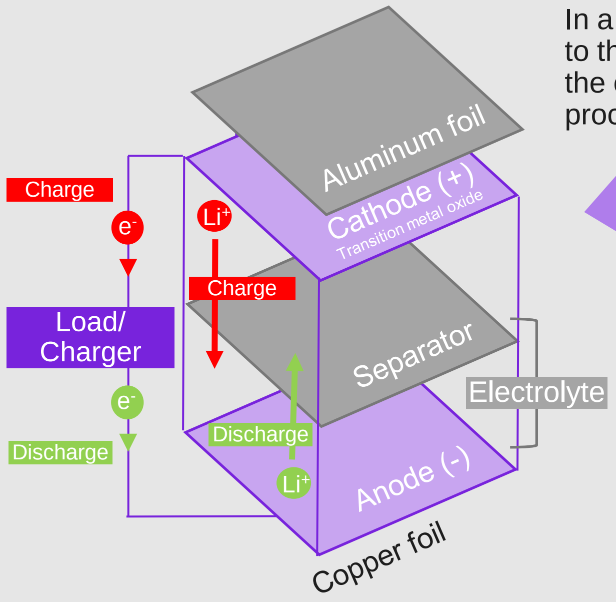
Phase	Service requirement	Min	Median	Max	Energy need / Service requirement	Min	Median	Max	Carbon emissions / Energy need	Min	Median	Max
Vehicle production phase	**Mass** (t)	1.15	1.40	1.96	**Glider and powertrain production energy requirement** (MWh/t)	10.1	10.1	10.1	**Carbon footprint of energy mix used for vehicle production**[1] (gCO_2e/kWh)	475	475	475
Battery production phase	**Battery capacity** (kWh cap)	45	60	90	**Material, cell and pack production**[2] (kWh/ kWh cap)	306	306	306	**Carbon footprint energy mix used for battery production**[3] (gCO_2e/ kWh)	213	348	445
Use phase	**Initial battery autonomy** (km)	281	342	429	**Average electricity consumption** (kWh/km)	16.0	17.5	21.0	**Carbon footprint of electricity mix** (gCO_2e/kWh generated)	25[4]	475[5]	800[6]
	Battery autonomy degradation (% per lifetime)	64%	64%	64%					**Grid losses and upstream emissions** (gCO_2e/kWh generated)	4	84	142
	Number of cycles (thousands)	1.5	1.5	1.5					**Total carbon footprint of electricity used to power the car** (gCO_2e/kWh consumed)	29	550	952
	Lifetime distance[7] (thousand km)	270	320	411								

1. Share of electricity energy mix used for vehicle production is 100% for all three scenarios, used 2019 World average as carbon footprint of electricity
2. Detailed split: material production represent 250 kWh / kWh cap and cell and pack production represent 56 kWh / kWh cap
3. Share of electricity in battery production energy mix is 30% for all three scenarios, scenario Min, Med and Max used respectively 100% RES, 2019 World average and 15% oil, 85% coal as carbon footprint of electricity used for battery production ; 70% of energy mix from fossil heat generation (25% NG, 50% Coal, 25% Oil) at $293gCO_{2e}$/kWh
4. 100% RES; 5. 2019 World average; 6. 15% oil, 85% coal; 7. Lifetime distance based on initial battery autonomy, degradation and number of cycles, results comparable to T&E's analysis of electric car lifecycle CO_2 emissions 2020 Source: Kearney Energy Transition Institute analysis

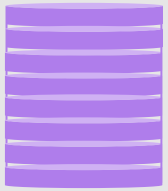
The life cycle of a battery is divided into four main stages

A battery life cycle is complex and variable due to the variety of materials and production methods.

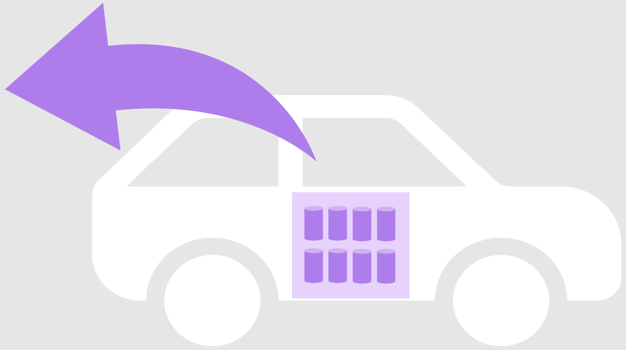
Lithium–ion batteries (LIB) are the most used type of battery



In a LIB cell , lithium ions flow to the anode (cathode) during the charging (discharging) process.



Multiple stacked layers of single LIB cells constitute a module.



An on-board LIB in an electric vehicle contains hundreds of cells packed together.

There are four main elements to be considered in a typical NMC battery life cycle

Materials

Mining and refining

- Mineral mining and metal refining

Specific material production

- Cathode material production
  - For example, NMC111 powder:
    - Co-precipitation: reaction of $NiSO_4$, $MnSO_4$, $CoSO_4$ with NaOH and NH_4OH
    - Calcination of $Ni_{1/3}Mn_{1/3}Co_{1/3}(OH)_2$ and Li_2CO_3 to produce the cathode powder

Cell production and pack assembly

- Slurry preparation
- Electrode production:
- Dry room assembly
- Cell formation
- Battery pack assembly

Battery use

Recycling

4.4 Electric mobility

Sources: "Lithium–Ion Vehicle Battery Production," Erik Emilsson, Lisbeth Dahllöf (2019); Dai et al. (2019); Yuan et al. (2017); "T&E's analysis of electric car life cycle CO_2 emissions" (2020); Kearney Energy Transition Institute analysis

Several factors impact the carbon footprint of the batteries of electric vehicles (BEV)

CO_2 emissions =	Service requirement ×	Energy need / Service requirement ×	CO_2 emissions / Energy need
Mining and refining 1	Battery composition Battery capacity	Efficiency of extraction and refining processes (technologies, machines)	Proportion and type of fossil fuels (e.g., oil or coal for refining) The carbon-intensity of the electricity mix depends on energy sources used to generate electricity (fossil fuels/renewables), grid losses and upstream emissions
Materials production	Battery composition Battery capacity	Efficiency of chemical process	Proportion of fossil fuels and carbon-intensity of electricity mix
Cell and pack production	Battery capacity	Efficiency of cell production and pack assembly process	Proportion and type of fossil fuels (natural gas, oil, gasoline, diesel) Carbon-intensity of electricity mix
Battery use 2	Number of km on the road (depends on battery capacity, the number of cycles the battery can be used until reaching 70% of initial capacity: it depends on battery intensity of degradation)	Battery capacity Battery efficiency	Carbon-intensity of electricity mix used to power the car
Recycling 3	Amount of recycled materials (cathode/other parts)	Efficiency of process: sorting, diagnosticating, disassembly, recycling process (hydrometallurgical, pyrometallurgical, direct)	Proportion and type of fossil fuels Carbon-intensity of electricity mix used in recycling process

Source: Kearney Energy Transition Institute analysis

4.4 Electric mobility

Batteries have various material compositions

1

65% of total battery mass is made of metal materials

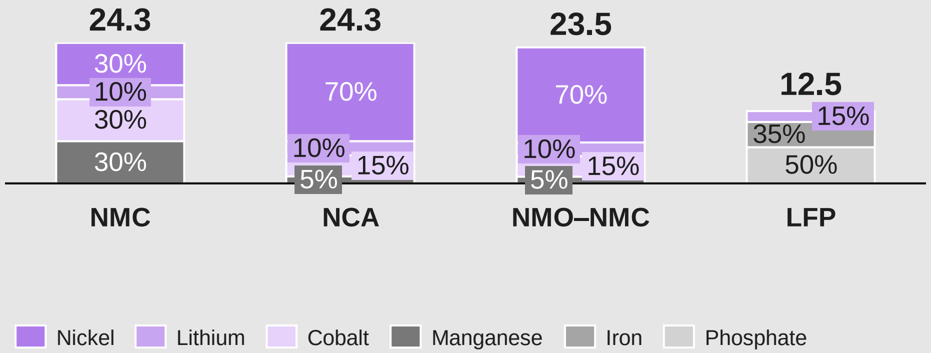
Composition and mass of battery cells vary depending on the type of battery and manufacturers.
- About 25–30% of the total mass of the battery corresponds to the cathode, and the anode represents ~15–30% of the total mass.
- In total, metal components account for 65% of total battery mass. Among them, cells collector foils (aluminum and copper) account for 20% of total battery mass.

The anode is supported on a copper foil that act as current collector. There are three types of anodic material:
- Graphite, the most used one
- Lithium titanate (LTO), for specific applications
- Metallic Li, expected to expand in the next decade

The cathode is supported on an aluminum foil and is composed of ~85% metal oxides, ~10% polyvinylidene fluoride and ~5% carbon. There are a few types of metal oxides used for electric vehicles:
- Lithium–nickel-manganese cobalt (NMC), which represent the largest percentage of the worldwide LIB market; used for example in Bolt Chevrolet
- Lithium–manganese oxide (LMO); used for example in Nissan Leaf
- Lithium–nickel-aluminum-oxide (NCA); used for example in Tesla
- Lithium–iron phosphate (LFP); used for example in BYD 86.

Composition of cathodes for different types of cells

kg



The remaining 35% is made of other chemicals and minerals

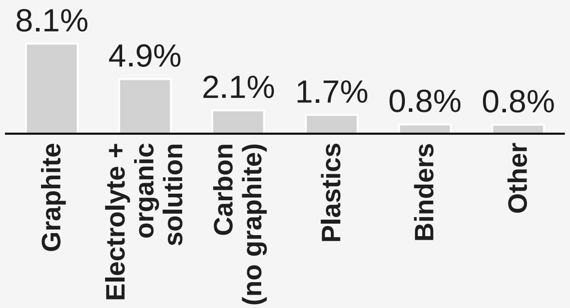
The separator is usually made of polypropylene or microporous polyethene (plastic).

The cells also contain as electrolyte a lithium salt ($LiPF_6$, $LiBF_4$ or $LiClO_4$) in a non-aqueous solvent.

Some non-metal components require a lot of energy to be produced.

Non-metal components contribution to typical NMC battery mass

wt %



Sources: Villen-Guzman, Maria & Arhoun, Brahim & Vereda, Carlos & Gomez-Lahoz, Cesar & Rodríguez-Maroto, José & Paz-García, Juan. (2019). “Electrodialytic processes in solid matrices.” “New insights into batteries recycling. A review: New insights into Lithium-Ion batteries recycling.” Journal of Chemical Technology & Biotechnology; Nickel: The Secret Driver of the Battery Revolution; Kearney Energy Transition Institute analysis

The cradle-to-gate carbon footprint of a battery is the result of two production steps

1

Materials are responsible for 80% of battery cradle-to-gate carbon footprint.

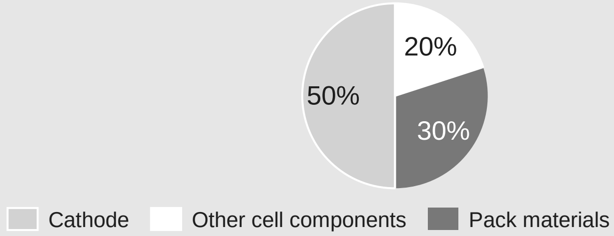
First step: materials production

We focus on NMC batteries. Battery carbon footprint before use (cradle-to-gate) ranges from 60 to 120 kgCO_2e/kWh cap.

About 80% of it corresponds to carbon-intensity of materials.

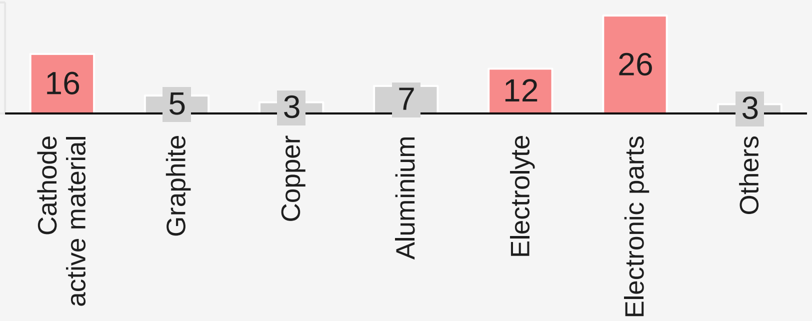
Materials production includes all steps from mining to specific materials production: cathode material, anode material, electrolyte, and other components of the pack (copper, aluminum, electronic parts, …)

Repartition of carbon-intensities of materials



Zoom: carbon-intensity of materials per mass unit in typical NMC battery

kgCO_2e/kg material

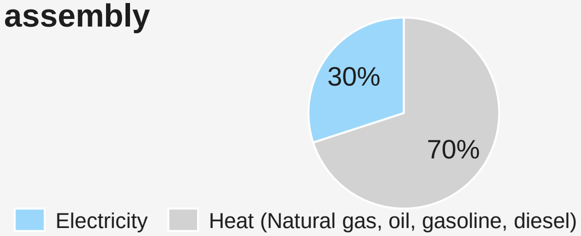


Per kg basis, electronics parts, cathode material and $LiPF_6$ (electrolyte) are the three main contributors to carbon emissions. This is due to high energy intensive production process.

Second step: Cell production and pack assembly

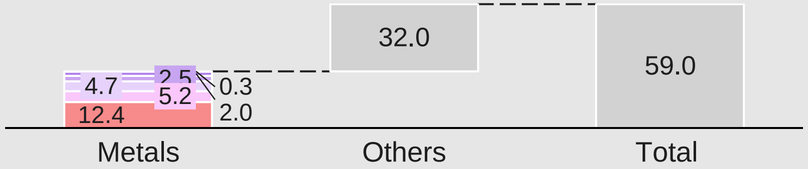
The remaining **~20%** of battery cradle-to-gate carbon footprint results from energy consumption in cell production and pack assembly.

Energy sources in cell production and pack assembly



Zoom: carbon-intensity for metal use in typical NMC battery

kgCO_2e/kWh



Mining and refining Al is highly carbon-intensive. Al is thus first contributor to materials carbon footprint, even if its weight % per battery is low.[1]

Lithium Nickel Copper Manganese Cobalt Aluminum

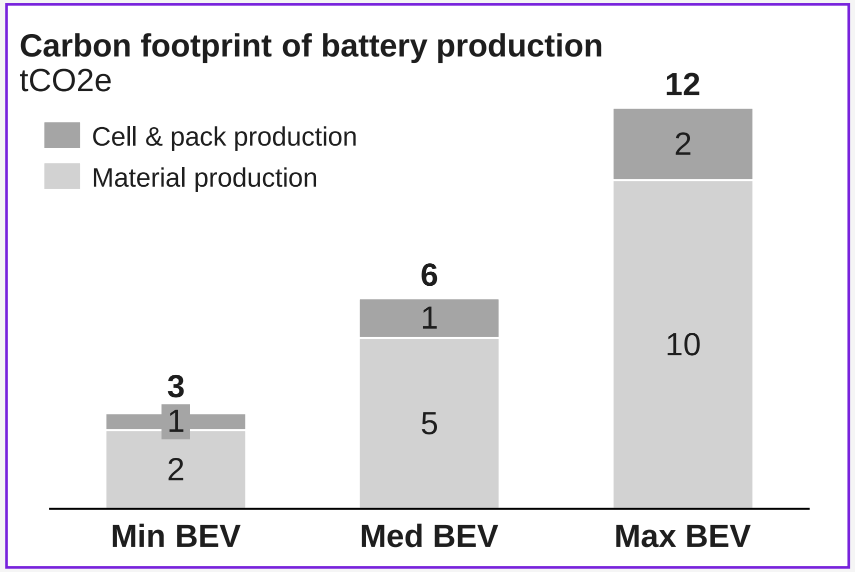
1. See previous slide. We consider here a typical NMC111 battery with a total 59 kgCO_2e/kWh cap carbon intensity for material. Depending on the composition of the battery, metal respective carbon impacts can vary.
Note: kWh cap = unit of battery capacity
Sources: "Lithium–Ion Vehicle Battery Production," Erik Emilsson, Lisbeth Dahllöf (2019); Dai et al. (2019); Yuan et al. (2017); "T&E's analysis of electric car life cycle CO_2 emissions" (2020); Kearney Energy Transition Institute analysis

BEV has higher carbon footprint from production step than ICE because of the battery carbon footprint

1

Battery production involves additional carbon footprint for BEV compared to ICE

We consider that the difference between BEV and ICE in the manufacturing carbon footprint only comes from the battery pack (either small, medium or large for BEV versus no battery pack in ICE). Difference between thermal and electric powertrain manufacturing carbon footprint is not addressed in this study.



	Min BEV	Med BEV	Max BEV
Vehicle example	Renault Zoe	Nissan Leaf	Tesla Model S or X
Battery capacity (kWh)	45	60	90

To compensate for the initial carbon footprint of the battery, BEV must abate carbon emissions during usage compared with ICE.

Depending on the battery size (here three different capacities of 45, 60 and 90kWh), the battery production step has a carbon footprint varying between 3 and 12 tons of CO_{2eq} mostly coming from the energy-intensive processes required for its material production (e.g., mining, purification, transformation).

Several parameters impact the amount of emissions reduction during BEV’s lifetime, mostly:
- Mileage
- Carbon footprint of electricity used to charge the BEV

Source: Kearney Energy Transition Institute analysis

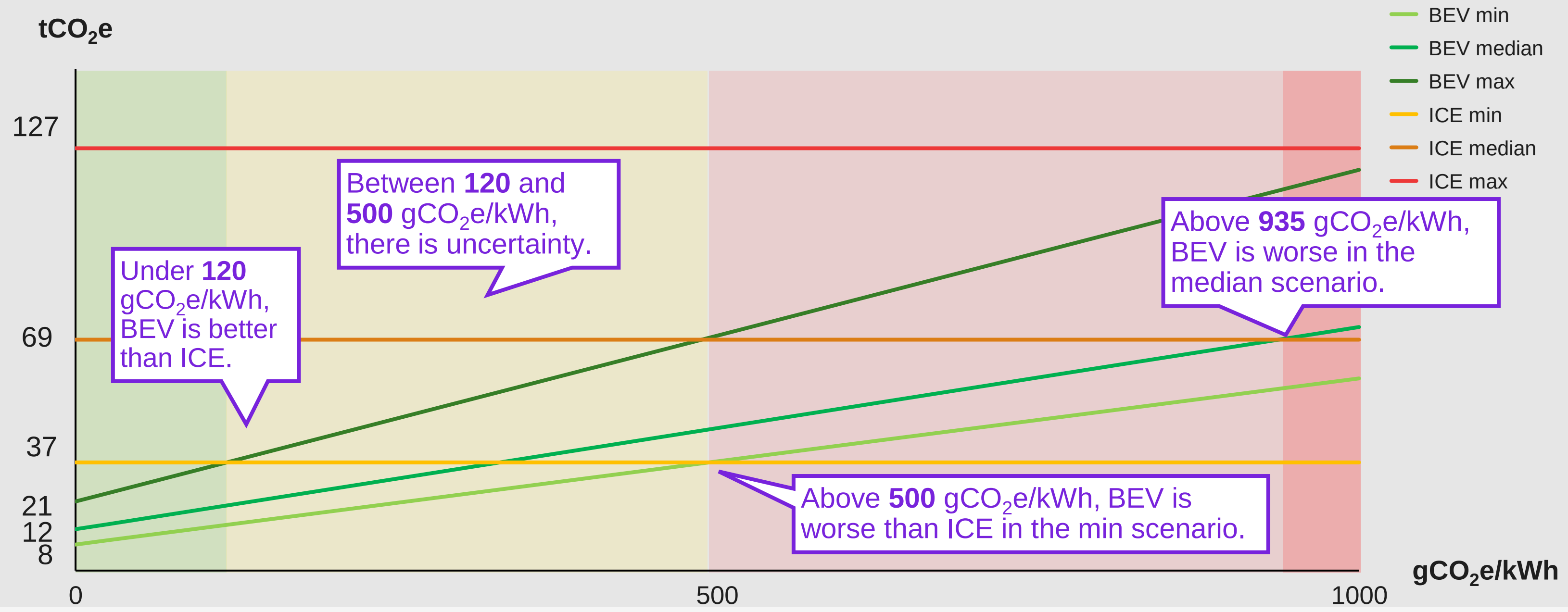
4.4 Electric mobility

Above a certain carbon footprint of electricity mix, BEV is more carbon-intensive than ICE

2

Above ~500 gCO_2e/kWh of electricity carbon-intensity, BEV does not surpass ICE.

Carbon footprint of production and use phases of BEV and ICE depending on electricity mix used to power the vehicle



BEV is less carbon-intensive than ICE only if the electricity mix used to power the vehicle is low enough.
We consider three scenarios for BEV and ICE, defined by three values of the following parameters[3]:
- For BEV: battery capacity, vehicle size, energy mix for production, electricity consumption per km, lifetime distance
- For ICE: vehicle size, energy mix for production type of fuel, fuel consumption per km, lifetime distance

If the electricity mix has a carbon footprint lower than 120 gCO_2e/kWh, BEV is better. Above 500 gCO_2e/kWh, min ICE is better than min BEV. Above 935 gCO_2e/kWh, median ICE is better than median BEV.
We give the following examples of vehicles for each scenario:
- Min: Renault Zoe for BEV, Ford Fiesta for ICE
- Median: Nissan Leaf or Volkswagen I.D. 3. for BEV and Volkswagen Golf or Nissan Qhashqai for ICE
- Max: Tesla Model S or X for BEV and Audi A6 or A7 for ICE

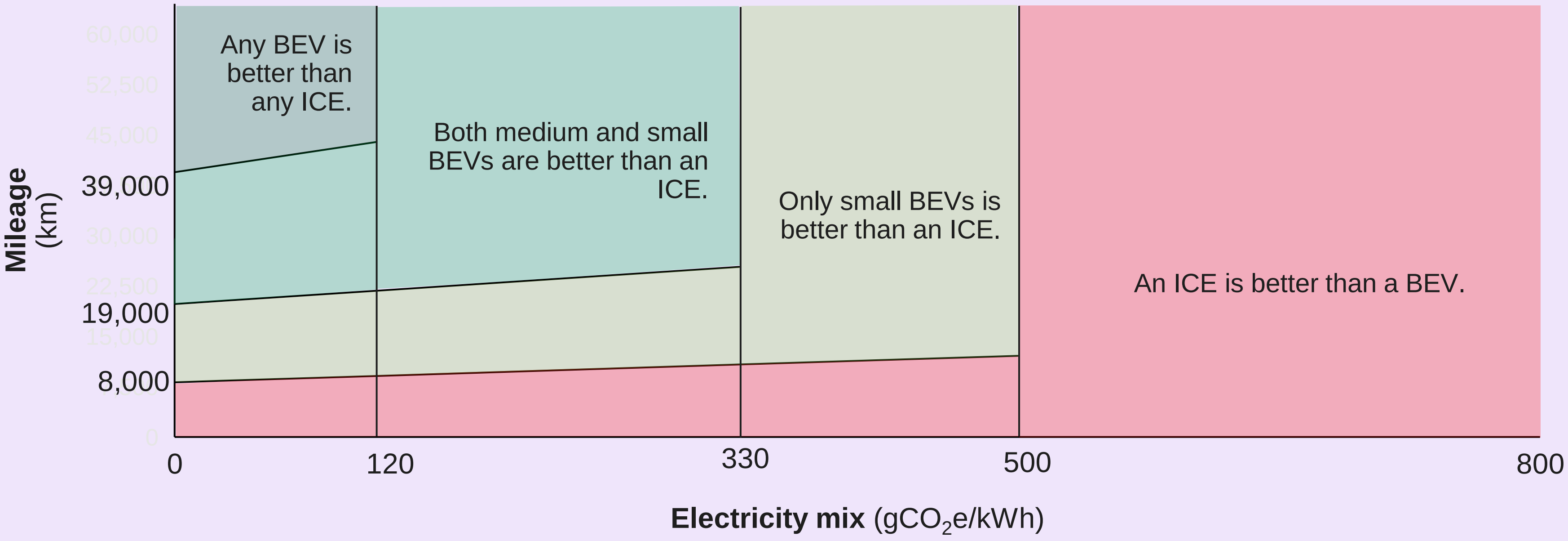
Some ICE manufacturers (e.g., Peugeot 208) claim to achieve a fuel consumption of 2l/100km, in which case, considering the same batteries, an electricity mix above 300 gCO_2e/kWh would be enough for ICE to be better than BEV.

1. Recycling is not considered here. Batteries are NMC cells; 2. Carbon footprint of electricity generation (without considering grid losses and upstream emissions); 3. Each scenario (Min, Median, Max) is defined by the corresponding values of the parameters (Min, Median, Max): see slides with the parameters.
Sources: "Lithium–Ion Vehicle Battery Production," Erik Emilsson, Lisbeth Dahllöf (2019); Dai et al. (2019); Yuan et al. (2017); "T&E's analysis of electric car life cycle CO_2 emissions (2020)"; Electricity Map; bp Statistical Review of World Energy 2020; Methodology for GHG Efficiency of Transport Modes–Fraunhofer-Institute for Systems and Innovation Research ISI (2020); Kearney Energy Transition Institute analysis

Two parameters determine the carbon benefit of a BEV compared with an ICE

2

Above a certain mileage and under a specific carbon footprint of electricity mix used to power the car, a BEV is less carbon-intensive than an ICE



We consider three types of BEV (min-small, median-medium, max-large) with different sizes and battery capacity, and we compare their carbon footprint with the carbon footprint of ICE, depending on two parameters:

- Minimum mileage above which the emissions avoided by using electricity instead of fuel compensates for the high carbon footprint of battery production: we compare BEV to large ICE to have the highest value.
- Maximum carbon footprint under which producing and using a BEV is less carbon-intensive than ICE: we compare BEV to small ICE to have the lowest value.

The results depend on a set of parameters that can vary. Carbon footprint is decomposed into two phases:

- **Production:** Carbon footprint of production depends on vehicle size and energy used for production.
- **Use:** Carbon footprint of use depends on electricity mix used to power BEV and fuel consumption of ICE.[1]

1 See slide with all parameters.
Sources: "Lithium–Ion Vehicle Battery Production," Erik Emilsson, Lisbeth Dahllöf (2019); Dai et al. (2019); Yuan et al. (2017); "T&E's analysis of electric car life cycle CO_2 emissions" (2020); Kearney Energy Transition Institute analysis

There are many different types of battery recycling processes

3

Various processes allowing for the recovery of battery materials are in development

Spent LIBs represent various risks (safety, environmental impact, pressure on natural resources).
Batteries have second-life applications:
- Applications where less than 70% capacity is acceptable
- Grid storage
- Uninterruptable power supply
- Home energy storage coupled with solar panels

In the waste management hierarchy, re-use is considered preferable to recycling, which is not yet profitable. Recycling is currently a closed loop system, where raw materials are re-used indefinitely for battery production.

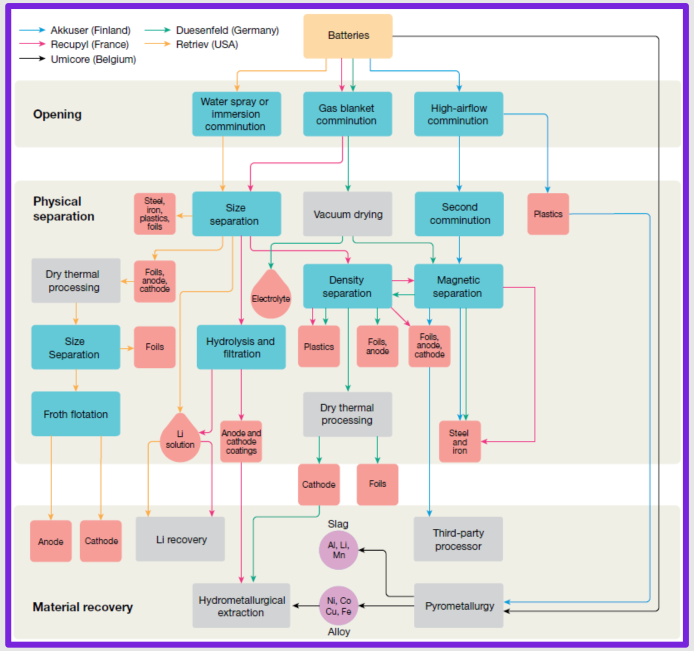
There are three approaches for physical separation of batteries and recovery of materials

Pyrometallurgical method uses a high-temperature furnace to reduce the component metal oxides to an alloy of Co, Cu, Fe and Ni. The products are metallic alloy fraction, slag and gases. Despite the production of toxic gases, high energy costs, and the limited number of materials reclaimed, it is frequently used process.

Hydrometallurgical treatments include the use of aqueous solutions to leach the desired metals from cathode materials. Once leached, the metals are recovered through precipitations reactions. This method has a better material efficiency but produces chemical reagents and release a high quantity of wastewater.

Direct recycling is the removal of cathode or anode material from the electrode for reconditioning and re-use in a remanufactured LIB. So far, only laptop and mobile phone batteries are directly recycled (especially because a large amount of those are already available).

Five entities worldwide are commercializing different recycling processes



Sources: “Simulation-based LCA for recycling,” Aalto University (2021); Umicore; Sustainable Materials & Technologies, Commission for Environmental Co-operation (US, Canada, Mexico); “Recycling lithium–ion batteries from electric Vehicles,” Harper et al., Nature (2019); Kearney Energy Transition Institute analysis

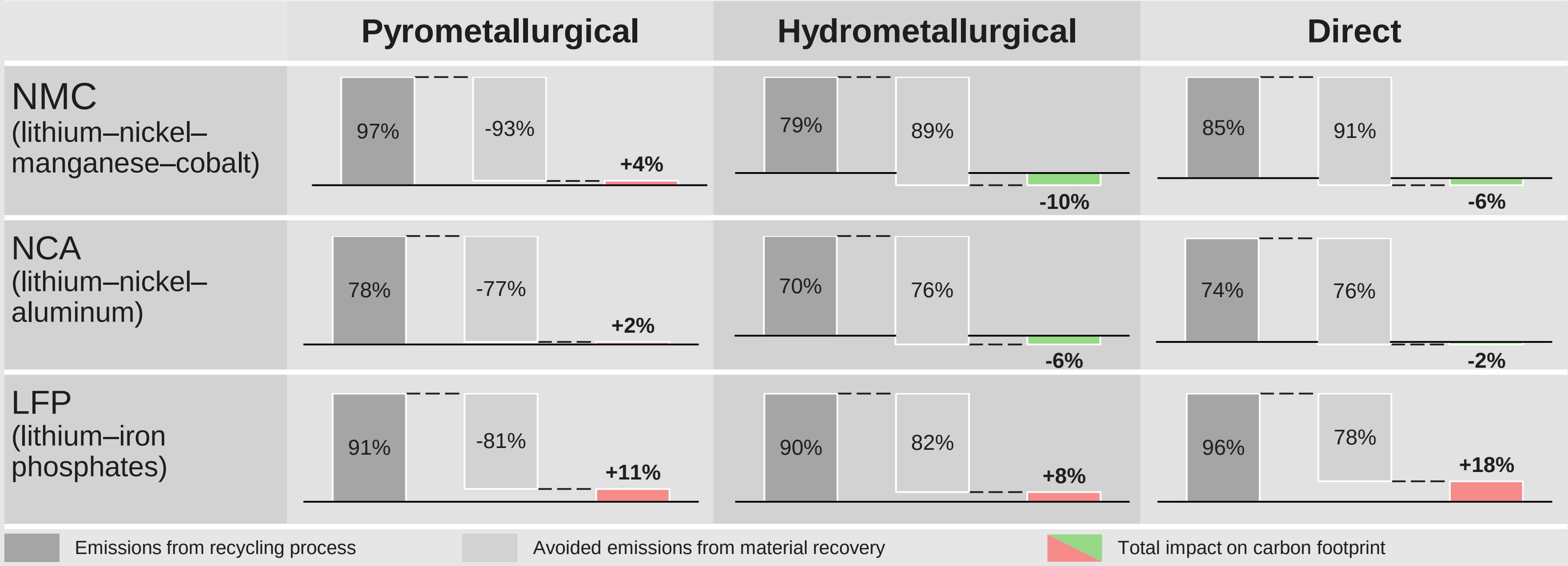
4.4 Electric mobility

Carbon reduction thanks to the main recycling processes depends on the emissions related to the extraction of the metals contained in the battery

3

The net impact of recycling on the battery carbon footprint depends on the recycling process and cell type

% of battery cradle-to-gate carbon footprint, US, 2019



Assuming the use of the US electricity grid as an energy source for the recycling process, 100% of cathode recovery, and assuming that any materials not recovered through the process are incinerated, **the emissions avoided by recovering materials do not always offset the emissions from recycling processes:**

– Pyrometallurgical methods are the most emissive: for all types of batteries, this method increases total battery carbon footprint.
– Recycling LFP batteries is highly emissive because extracting Iron produces very few emissions.
– Recycling NMC and NCA cells results in a reduction of up to 18% of battery carbon footprint because nickel, cobalt, and manganese extraction processes are high-emissive.

In addition, the portion of cathode material recovered affects recycling benefits: **between 59% and 88%** of cathode material must be recovered to result in a net CO_2e emissions reduction, depending on the type of cell.

Sources: Ciez, R.E., Whitacre, J.F. “Examining different recycling processes for lithium-ion batteries.” Nat Sustain 2, 148–156 (2019); “Commission staff working document on the evaluation of the Directive 2006/66/EC on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC”; Kearney Energy Transition Institute analysis

Several forms of innovation are sought throughout the battery recycling value chain

3

Innovations can be found at each stage of the process

Research is under way into the **Faraday Institution ReLiB** project in the United Kingdom, the **ReCell** Project in the United States, **CSIRO** in Australia, and at many European Union projects, including **ReLieVe**, **Lithorec** and **Amplifill**. Several solutions are considered.

Using electrochemical impedance spectroscopy to diagnosticate batteries
The diagnostic of battery pack, module, and cells includes their state of health (the degree to which a battery meets its initial design specifications) and the state of charge (the degree to which a battery is charged or discharged).

Optimizing battery discharge
Immersing LIBs in liquid nitrogen or in sodium chloride solution

Optimizing acid leaching
The use of inorganic acids leads to higher leaching efficiency than organic acids. However, organic acids allow for separating other important metals, such as Al. An optimal combination of both types is thus required. A lower initial pH value increases the leaching speeds of Li and Co. Removing reductants can allow better selective recover of Li.

- Standardizing batteries
- Better characterizing and sorting different battery types
- Better diagnosticating battery
- Optimizing the design of pack, modules, and cells for disassembly
- Sophisticating the approach for disassembly
- Optimizing material recovery process
- Improving process flexibility

Using advanced robotics to automate battery disassembly
The Optisort system uses computer vision algorithms to recognize the labels on batteries and pneumatic actuators to segregate batteries into different bins according to their type of chemistry. It can recognize about 2,000 types of batteries and is used to sort one third of those recycled in the UK. Up to 10 batteries can be processed per second.

Using electrodialytic remediation (EDR) to remove contaminants from soils and solid waste products
EDR combines electrokinetic remediation1 with electrodialysis2. Parameters to optimize include pH value, selection of enhancing agent, current density, type of membrane …

Each battery is photographed by the camera.

Batteries are fed on a conveyor belt.

Each image is compared to a database with different types of batteries until a match is made.

A jet of compressed bin based on air directs batteries into a designated bin based on the battery's chemical content.

1 Application of an electric current between a pair of electrodes to mobilize toxic metals or organic compounds (species are transported through electromigration, electroosmosis and electrophoresis); 2. Membrane process using anion- and cation-selective membranes
Sources: Ciez, R.E., Whitacre, J.F., "Examining different recycling processes for lithium–ion batteries." Nat Sustain 2, 148–156 (2019); Villen-Guzman, Maria & Arhoun, Brahim & Vereda, Carlos & Gomez-Lahoz, Cesar & Rodríguez-Maroto, José & Paz-García, Juan. (2019). "Electrodialytic processes in solid matrices. New insights into batteries recycling. A review: New insights into Lithium-Ion batteries recycling." Journal of Chemical Technology & Biotechnology; Kearney Energy Transition Institute analysis

Battery life-cycle emissions depend on a variety of parameters

On average, a mileage higher than ~16,000 km and an electricity mix less carbon-intensive than ~354 gCO_2e/kWh are needed for BEV to be less carbon-intensive than ICE.

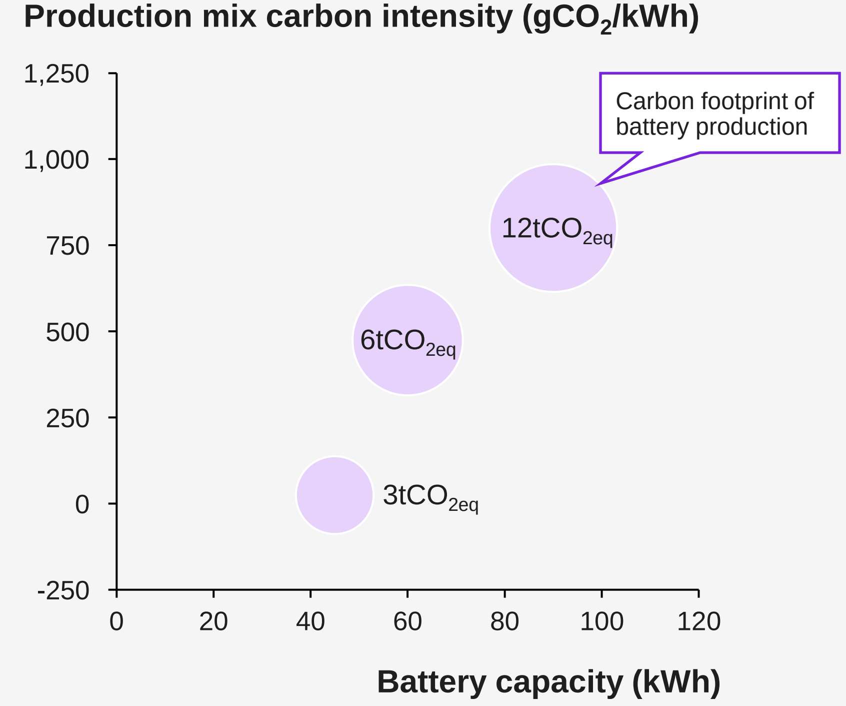
4.4 Electric mobility

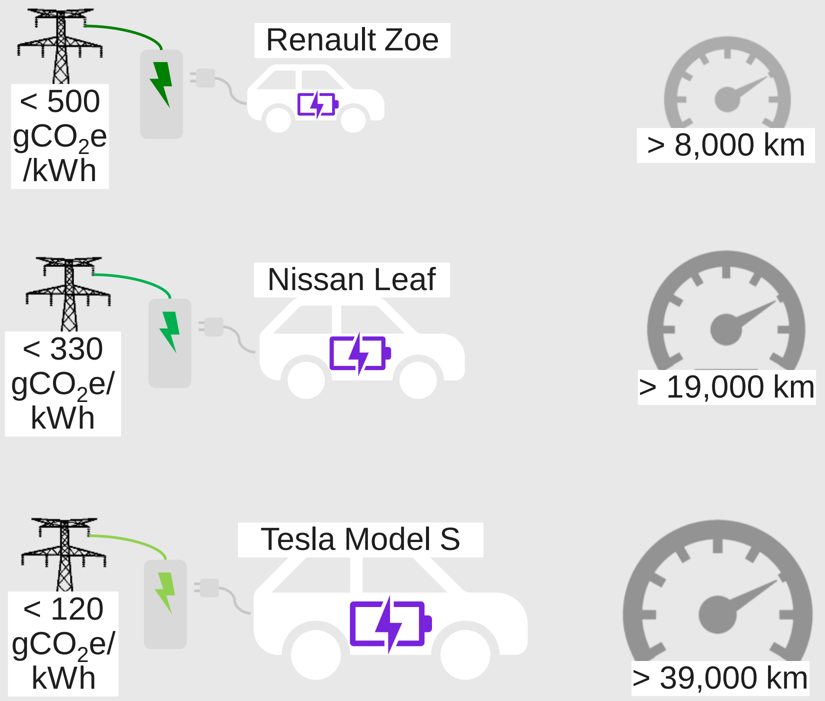
Battery life cycle is composed of three main phases: production, use, and end-of-life

The **first phase** of a battery life cycle is **production**: materials production, cell manufacturing, and pack assembly. Depending on battery capacity and energy used for production, batteries have a cradle-to-gate carbon footprint of **~3 to ~11 tCO_2e**, which represents ~50% of total carbon emissions due to vehicle production.

The **second phase** is **use**. BEV need to be powered with an electricity mix lower than **~130 to ~500 gCO_2e/kWh** for their life-cycle carbon footprint to be lower than one of ICE. They need to be used for at least **~7,000 km to ~34,000 km** before the emissions avoided by using electricity instead of gasoline/diesel compensate for the high carbon footprint of battery production.

Carbon footprint of battery production (tCO_{2eq})





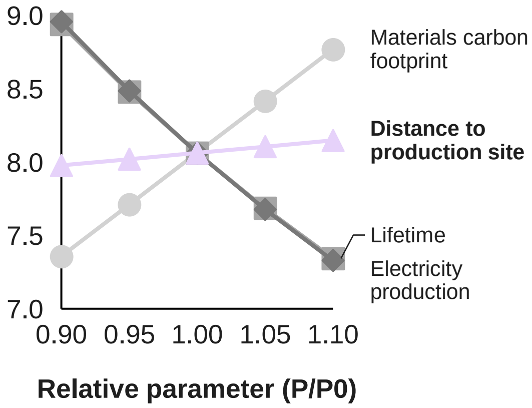
The **last phase** is **end-of-life** (EOL). Recycling methods are in development. Today, using recovered materials from EOL batteries only allows a **small reduction** of cradle-to-gate carbon footprint (up to -10%). It can even result in an **increase** (up to +6%).

Source: Kearney Energy Transition Institute analysis

Section 4.4 detailed in Appendix

The carbon footprint of wind power depends on many parameters, especially materials carbon footprint, load factor, and lifetime

Carbon footprint of offshore wind electricity (gCO_2eq/kWh)



4.5 Offshore wind: executive summary

Different parameters affect carbon emissions at each phase of the offshore wind turbine life cycle, which can be divided into four main steps: raw material extraction and manufacturing, transport and installation, operation and maintenance, and end of life (dismantling, recycling, and disposal).

Manufacturing represents about 75 percent of global wind turbine life-cycle emissions and is mostly linked with the materials carbon footprint and the large quantity of materials required.[1] Except for aluminum, which has a very high carbon intensity (22 $kgCO_{2eq}/kg$) compared with the other materials used (0.22-4.7 $kgCO_{2eq}/kg$), the important carbon footprint of the materials used to manufacture offshore wind turbines is due to the massive amount of materials required, for example, 2,000 tons of concrete for foundations.

Thus, according to the sensitivity analysis, the carbon footprint of an offshore wind turbine is sensitive to several parameters, such as the lifetime of the turbine, its electricity production (linked to its load factor based on location and weather conditions), and the materials used for manufacturing carbon footprint and quantity.

Wind power is a low-carbon electricity source, but its carbon footprint also depends on its load factor. The load factor is the ratio between the observed electricity production and the installed capacity. Depending on weather conditions and turbine installation location, load factor for offshore wind varies between 25 and 65 percent, which can induce a variation in produced electricity carbon footprint up to 70 percent.

Even when considering the sensitivity range of offshore wind carbon footprint, it is a low-carbon electricity source, competitive with other renewables and nuclear in terms of carbon abatement. The results, according to the conditions considered in the LCA conducted in this report, gives a carbon footprint for offshore wind power of 8.1 gCO_{2eq}/kWh, and according to reviews of different LCA, offshore wind electricity carbon footprint is in the range 5.2 to 32.0 gCO_{2eq}/kWh with a mean at 18.4 g CO_{2eq}/kWh. Offshore wind power carbon footprint is among the lowest and comparable to other renewables (PV, hydro) and nuclear power. Offshore wind electricity carbon footprint is about 100 times less than coal-based electricity and 50 times less than gas-based electricity.

Recycling offshore wind turbine materials decreases the manufacturing carbon footprint by about 30 percent. Metals represent about 85 percent in mass of the materials, excluding foundations concrete, and about 40 percent of materials GHG emissions, including foundations concrete, and offshore wind turbines metallic parts can easily be recycled. Recycling the metal parts of the turbine decreases its manufacturing carbon footprint by 27.6 percent. The rest of the materials (composite for the blades, concrete for foundations) are landfilled (often left in the ground on site) or incinerated respectively because of lack of recycling process and because of their important weight.

[1] Carbon-intensity comes from the indirect emissions related to the extraction and transformation of such raw materials, that can come from the energy consumption for extraction and transformation, materials needed for these processes, and so on. Transport of these raw materials from mine to transformation sites and components' manufacturing facilities is not included here.
Source: Kearney Energy Transition Institute analysis

Offshore wind electricity case overview

LCA results highlights variable operation conditions to benefit from more or less GHG emissions abatement using offshore wind electricity.

4.5 Offshore wind

Context and key questions

Wind energy can in general be considered as a low-carbon electricity source, and it is expected to represent 21% of the world electricity mix in 2030.[1]

Several factors are to be monitored to estimate the environmental impacts of offshore wind electricity, notably:

- The carbon emissions related to material manufacturing (mostly metals and concrete)
- The carbon emissions related to the material transport from wind turbine production site to wind farm location
- The location influences the load factor and thus the electricity production
- Recycling the materials

This section seeks to identify and quantify the key parameters that influence the carbon emissions of wind power on LCA basis.

Material extraction & manufacture → Transport and installation → Operation and maintenance → Dismantling and disposal

[1] Future of wind, IRENA, October 2019
Source: Kearney Energy Transition Institute analysis

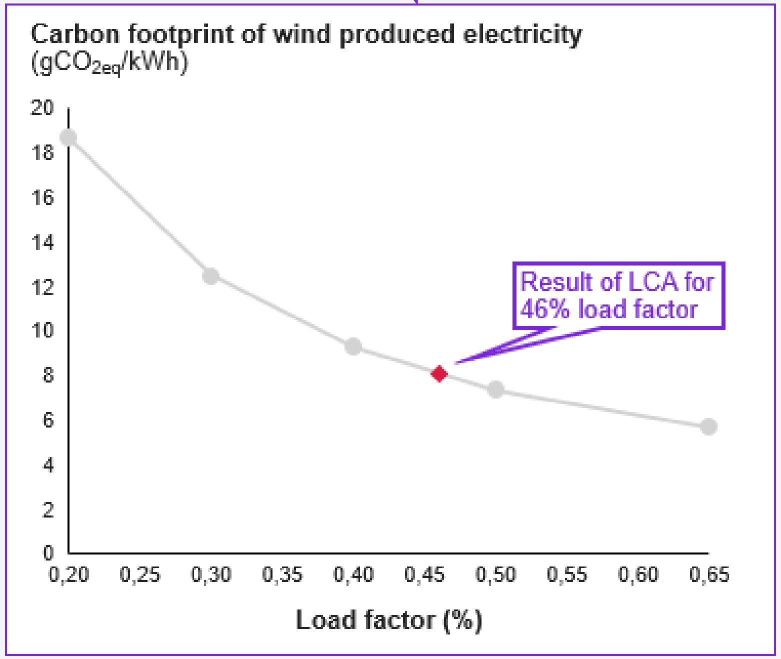
Key findings

Operating conditions unlocking the maximum decarbonization impact for offshore wind electricity

Manufacturing represents 75% of emissions; thus, carbon footprint is sensitive to materials carbon content

Turbine location/ load factor impacts the yearly production thus the carbon footprint of each produced kWh.

Recycling metals reduces the carbon footprint by about 30%.

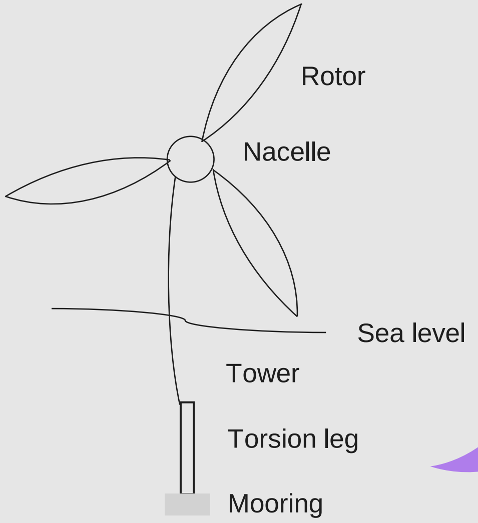


Manufacturing represents about 75% of global wind turbines life-cycle emissions

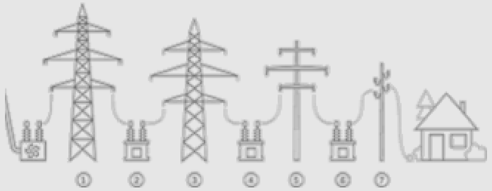
For a 2MW offshore wind turbine, producing 8,088 MWh (46% load factor – e.g. France's Atlantic coast average load factor) within a 20-year lifetime.

Life-cycle analysis of 2MW offshore wind turbine

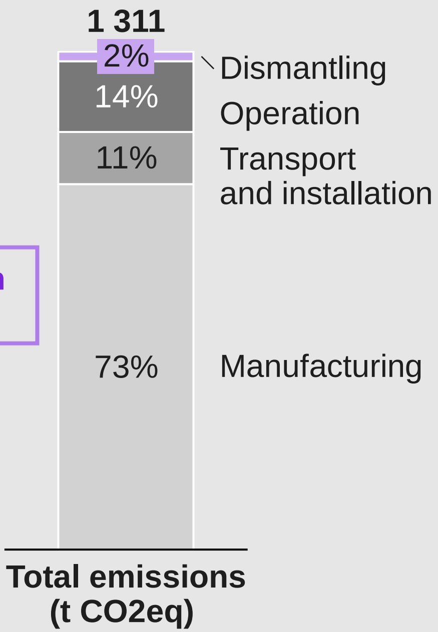
Offshore wind turbines are deployed in shallow water or deep sea with a relatively strong wind profile and thus high energy output.



Wind turbines transmit electricity to the local grid, which is then distributed.



8,1 gCO_{2eq}/kWh electricity



There are four main elements to be considered in a typical offshore wind turbine life cycle

Manufacturing[1]

- Foundation
- Rotor
- Tower
- Transmission grid
- Nacelle

Transport and installation[2]

- Transportation assumed by boat, negligible road transport
- Marine transport and road transport emission intensity: 140 g/ton-km
- Average transport distance from factory to installation: 400km

Operation and maintenance

- Oil and lubricant are changed at each check-up (three times a year).
- Rotor blade, gearbox, and generator are replaced once in the turbine lifetime.

Dismantling and disposal

- Metals are recycled (except buried copper in transmission cables) with 10% losses.
- Concrete is left on site; other materials are landfilled.

1 All the components of wind turbine are assumed to be produced in the wind turbine factory ; 2. Material transportation including concrete ;
Sources: "Life-cycle green-house gas emissions of onshore and offshore wind turbines," Wang et al. 2019; "Specific CO_2 emissions per ton-km and per mode of transport in Europe", European Environment Agency, 2017, ADEME LCA Wind in France 2015; Kearney Energy Transition Institute analysis

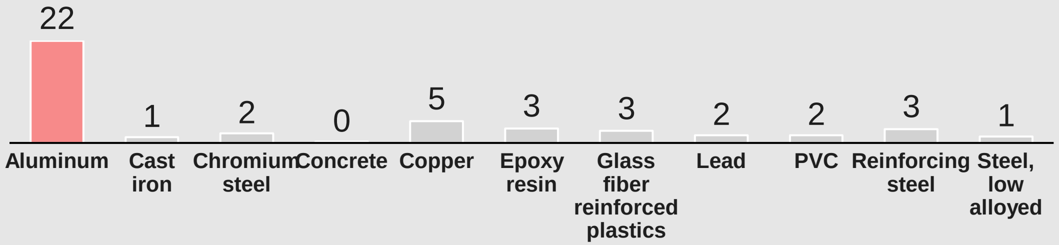
Manufacturing represents about 75% of life-cycle emissions for offshore wind turbines, mostly due to the large amount of material required

Manufacturing carbon footprint of a 2MW offshore wind turbine

Manufacturing represent about **75% of life-cycle emissions** for offshore wind turbines.

Emissions calculation is based on the carbon footprint of **materials**, form mining to specific materials production, assuming all the components of wind turbine are produced in the wind turbine factory.

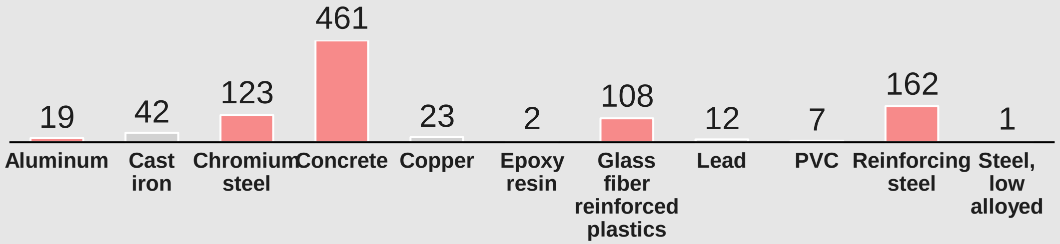
kg CO_{2eq}/kg materials



The material composition of a wind turbine globally have carbon footprint on a per-kg-basis except for aluminum.

It is the required quantity of materials that is responsible for the high emissions, e.g., 2,000 t of concrete for foundations

t CO_{2eq}/material for 2MW wind turbine



Zoom: materials emission intensity sensitivity

Materials	Carbon footprint kgCO_{2eq}/kg material	Variation
Concrete	0.22; 0.16[1]	- 27%
Aluminum	22; 7–24[2]	+ 8%
Steel	2.9; 1.1–2.2[3]	- 24 %

We consider in the analysis that concrete's carbon footprint is 0.22 kg CO_{2eq}/kg of concrete which leads to 961tCO_{2eq} emitted for the manufacturing of the offshore wind turbine.

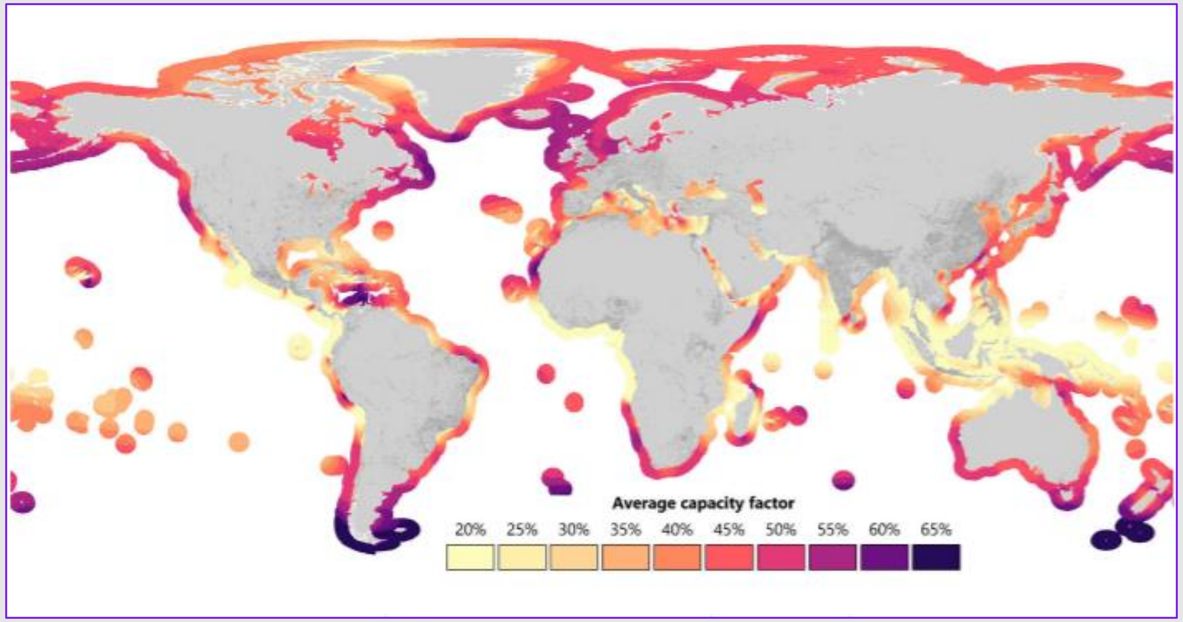
When considering a carbon footprint of 0,16 kgCO_{2eq}/ kg of concrete, manufacturing emits 835 tCO_{2eq} e.g. **a 13% decrease compared to base scenario**.

The life-cycle analysis is highly sensitive to materials carbon footprint, which depends on process, location, fuel type used for their extraction and transformation …

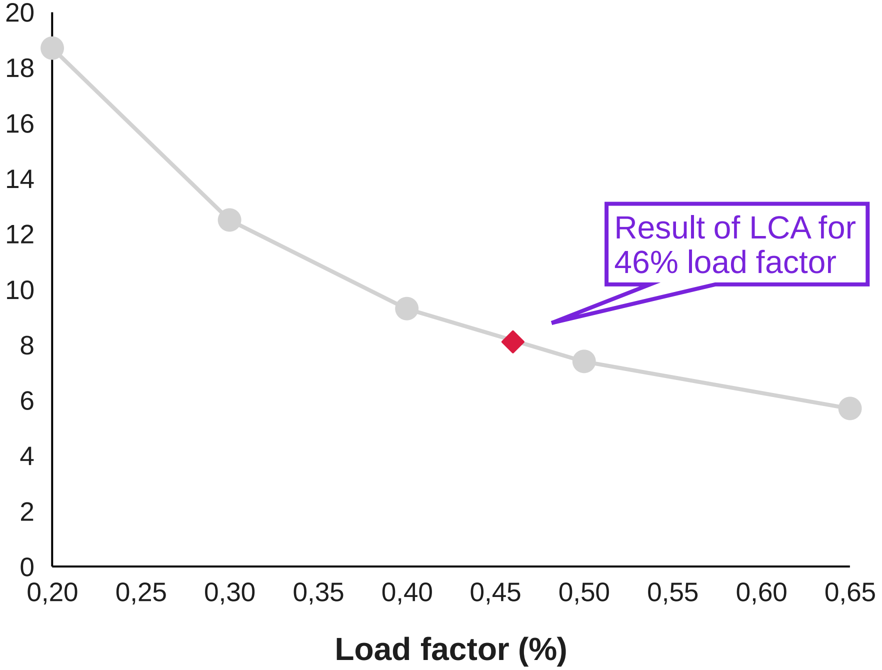
1. ADEME 2019; 2. Paraskevas et al. 2016; 3. Hasanbeigi et al. 2016
Sources: "Life-cycle green-house gas emissions of onshore and offshore wind turbines," Wang et al. 2019; Kearney Energy Transition Institute analysis

The electricity production level of an offshore wind turbine highly depends on its location, load factors range from 20 to 65% and impact carbon footprint of produced electricity

Offshore wind average capacity factor[1] in % by geography



Carbon footprint of wind produced electricity
(gCO_{2eq}/kWh)



4.5 Offshore wind

1. Ratio between yearly produced electricity and maximum yearly production capacity

Sources: IEA Offshore Wind Outlook 2019, "Life-cycle green-house gas emissions of onshore and offshore wind turbines," Wang et al. 2019; Kearney Energy Transition Institute analysis

Recycling offshore wind turbine materials decreases the manufacturing carbon footprint by about 30%

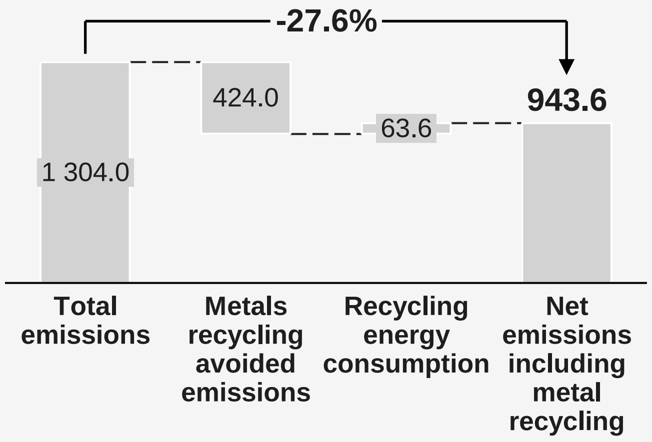
Recycling leads to a large reduction of wind turbines raw materials carbon footprint

Metals represent **~85% in mass** of the materials (excluding foundations concrete) and **~40% of materials GHG emissions** (incl. foundations concrete).

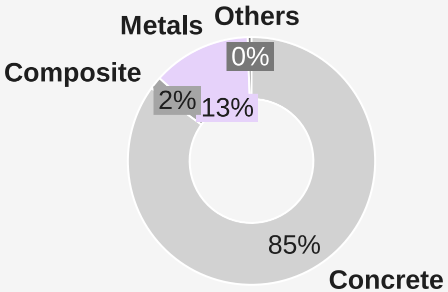
Offshore wind turbines metallic parts can easily be recycled:
- Metals from the components of the wind turbine (tower, nacelle, transmission) are recycled with varying recovery rates: copper (95% recovery) and recycling requires up to 85% less energy than primary copper production; iron, steel, and aluminum recycled aluminum requiring 95% less energy than primary production and steel (90% recovery).

Recycling metals with the above assumptions decrease the overall carbon footprint of the offshore wind turbine by about 30%.
The rest of the materials are landfilled or incinerated:
- Composite materials: blades are made from composite material and difficult to recycle. In the past decade, the vast majority of the European Union have voted in favor of legislation forbidding landfill disposal of such materials. As far as incineration is concerned, the main problematic point is a potential release of toxic byproducts.
- Concrete represent 85% of the offshore wind turbine in mass and 48% of the GHG emissions, it is assumed to be left in the ground on site and is therefore classified as landfilled.

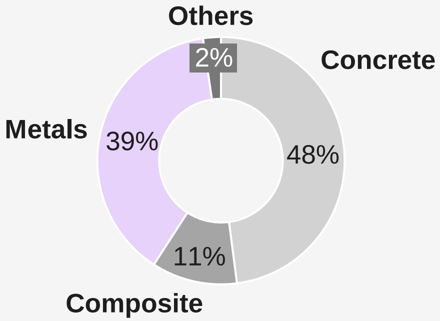
Impact of metal recycling on offshore wind turbine carbon footprint
$kgCO_{2eq}$



Materials repartition in mass
% of offshore wind turbine in mass



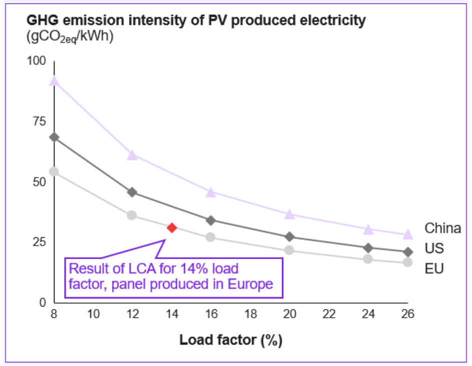
Materials repartition in GHG emissions
% of offshore wind turbine in emissions



Sources: Psomopoulos et al. 2019, Tota-Maharaj et al. 2020; Kearney Energy Transition Institute analysis

4.5 Offshore wind

The carbon benefit of solar power depends on many parameters, especially the country of production electricity mix and the load factor



4.6 Solar PV: executive summary

Different parameters affect carbon emissions at each phase of the solar panel life cycle, which can be divided into four main steps (cradle-to-grave): raw material extraction and manufacturing, transport and installation, operation and maintenance, and end of life (dismantling, recycling, and disposal).

Manufacturing represents about 90 percent of global solar panel life-cycle emissions and is mostly linked with the materials' carbon footprint and the energy mix used for purification and transformation of theses materials. Transforming sand into solar grade silicon and glass is energy intensive, thus the electricity mix carbon content of the country where the panel is produced highly impacts the overall carbon footprint of manufacturing. Production in a region with a carbon footprint of electricity around 354 gCO_2/kWh (for example, the EU) instead of in a region with electricity mix of around 673 gCO_2/kWh (for example, mainland China) can decrease the carbon footprint of the PV-produced electricity by about 35 percent.

Solar PV is a low-carbon electricity source, but its carbon footprint heavily depends on its load factor. The load factor is the ratio between the observed electricity production and the installed capacity. Depending on weather conditions and solar panel installation location, load factor for solar PV varies between 8 and 26 percent, which for a fixed-production country induces a variation in produced electricity carbon footprint up to 70 percent.

Thus, according to the sensitivity analysis, the carbon footprint of a solar panel is very sensitive to several parameters, including the energy emissions intensity used for manufacturing and the lifetime of the panel or its electricity production (linked to its load factor based on location and weather conditions).

Solar is a low-carbon electricity source, competitive with other renewables and nuclear in terms of carbon abatement. The result of the LCA conducted in this report gives a carbon footprint for solar power of 36.0 gCO_{2eq}/kWh, and according to reviews of different LCA results, solar electricity carbon footprint is in the range 12 to 125 gCO_{2eq}/kWh with a mean at 51 g CO_{2eq}/kWh. Solar power carbon footprint is among the lowest and comparable to other renewables (biomass, hydro) and nuclear power. Solar power carbon footprint is about 20 times less than coal-based electricity and 10 times less than gas-based electricity.

Recycling solar panel materials decreases the manufacturing carbon footprint by about 20 percent. Materials represent about 30 percent of the embedded carbon footprint and depending on the recycling process, 75 to 90 percent of the materials can be recovered. Three end-of-life scenarios are possible for solar panels: landfilling, laminated glass recycling, and full recycling. The full-recycling process can decrease the carbon footprint of produced electricity by 20 percent when considering the material recovery positive impact on panel's carbon footprint.

Source: Kearney Energy Transition Institute analysis

Solar PV electricity case overview

LCA results highlights variable operation conditions to benefit from more or less GHG emissions abatement using solar PV electricity.

4.6 Solar PV

Context and key questions

Solar PV energy can in general be considered as a low-carbon electricity source, and it is expected to represent 13% of the world electricity mix in 2030.[1]

Several factors are to be monitored to estimate the environmental impacts of photovoltaic electricity, notably:

- The carbon emissions related to material manufacturing (silicon refining is energy intensive)
- The design of the panel to maximize its yield, lifetime and reduce its maintenance requirements
- The location which influences the irradiance thus the load factor and electricity production
- Recycling the materials

This section seeks to identify and quantify the key parameters that influence the carbon emissions of solar PV on LCA basis.

Material extraction & manufacture → Installation → Operation and maintenance → Dismantling and disposal

[1] Future of solar PV, IRENA, November 2019
Source: Kearney Energy Transition Institute analysis

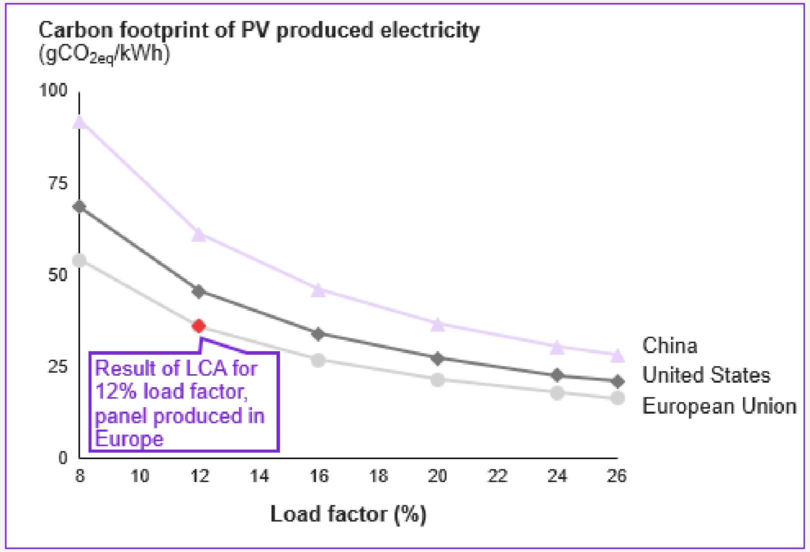
Key findings

Operating conditions unlocking the maximum decarbonization impact for solar electricity

Manufacturing represents 89% of emissions; thus, the electricity carbon footprint is sensitive to materials' carbon footprint (e.g. energy used for transformation)

The panels' country of production impacts the final carbon footprint of produced electricity.

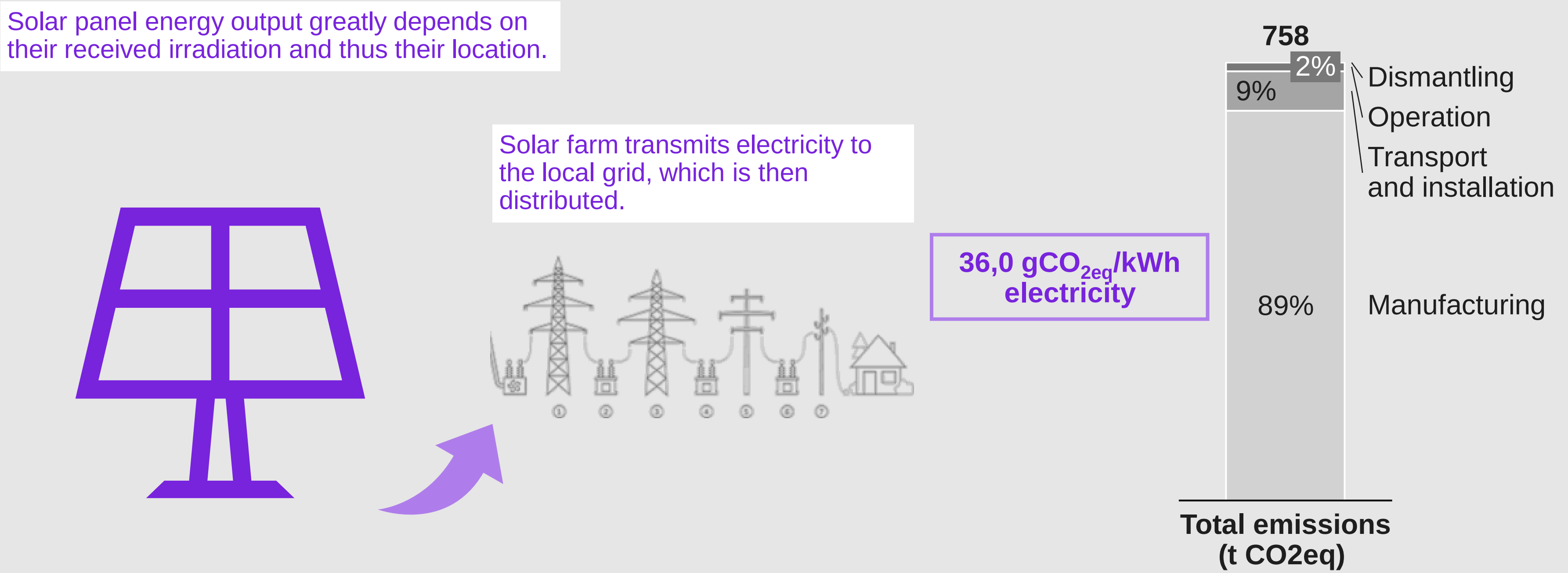
Panel location and load factor impact the yearly production and thus the carbon footprint of each produced kWh.



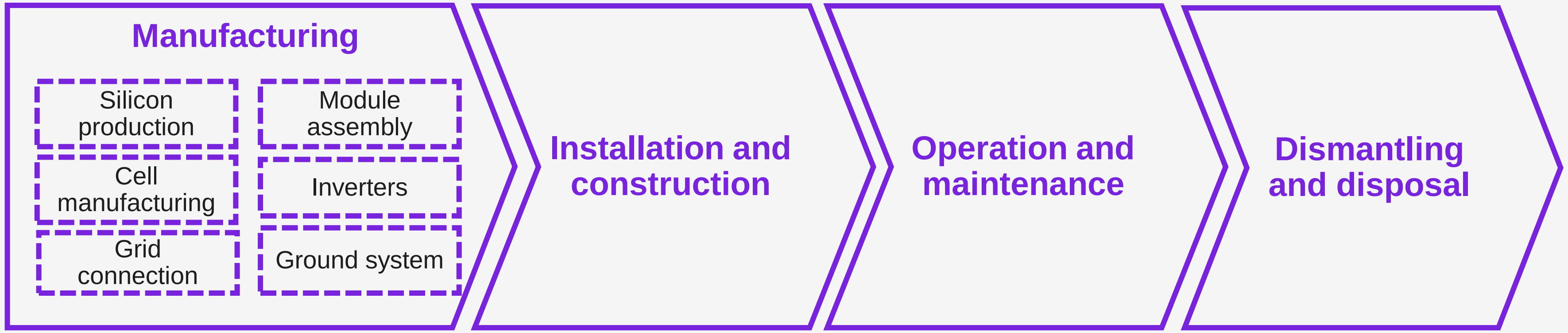
Manufacturing represents about 90% of global solar panel life-cycle emissions

For 1MW of multi-silicon, ground-mounted, photovoltaic power production in Europe (Germany) with a 20-year lifetime and 12% load factor

Life-cycle analysis of 1MW ground-mounted silicon solar panel installation in Europe



There are four main elements to be considered in a typical solar PV farm life cycle:



Sources: Life Cycle Assessment of Electricity Generation Options, United Nations Economic Commission for Europe; Kearney Energy Transition Institute analysis

4.6 Solar PV

The country of production impacts the overall carbon footprint of the PV panel

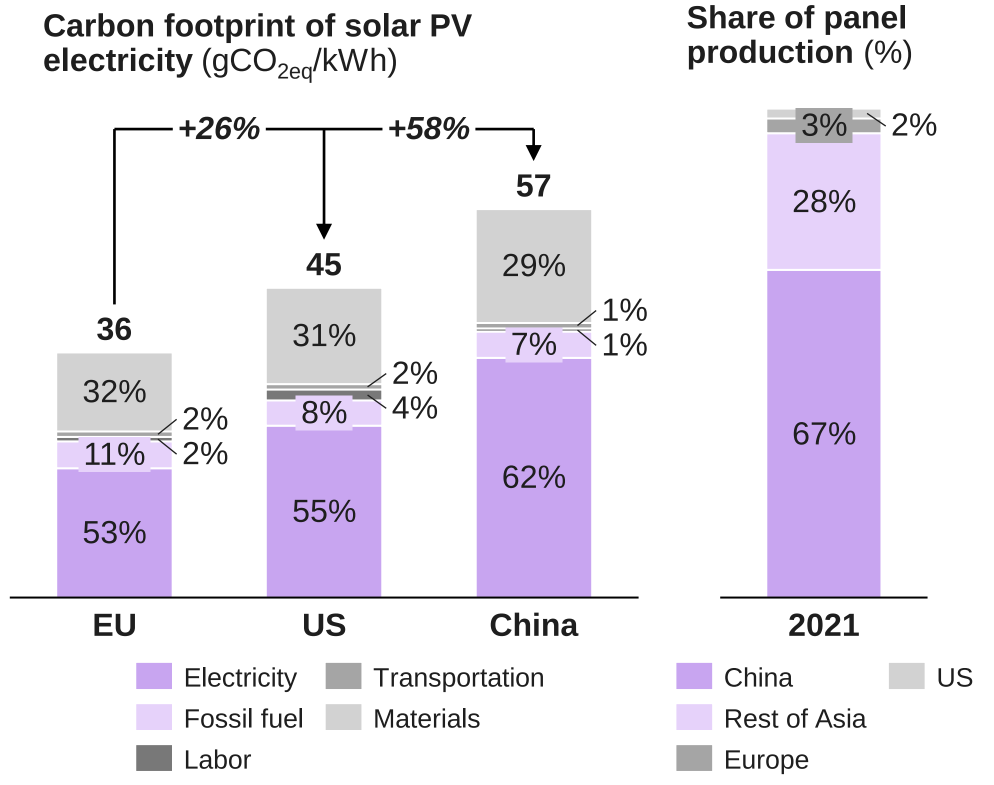
67% of the crystalline solar panels are produced in China, even though it results in a higher carbon intensity embodied in the panel than in Europe or in the United States.

4.6 Solar PV

Carbon footprint of 1MW of solar PV

Manufacturing of the panel (module, frame) and of the balance of system (BOS) (cables, inverters, grid connection) represent **89% of life-cycle emissions** for solar PV panels.

The energy requirements to purify and transform sand to solar grade silicon are high, thus depending on the energy/electricity mix of the country of production, the manufacturing strongly impacts the final carbon intensity of the electricity produced by the panels.



In this figure, electricity and fossil fuels represent the direct energy input in the life cycle, excluding the energy used in the transportation process as it is separately shown. Labor and material are indirect energy inputs.

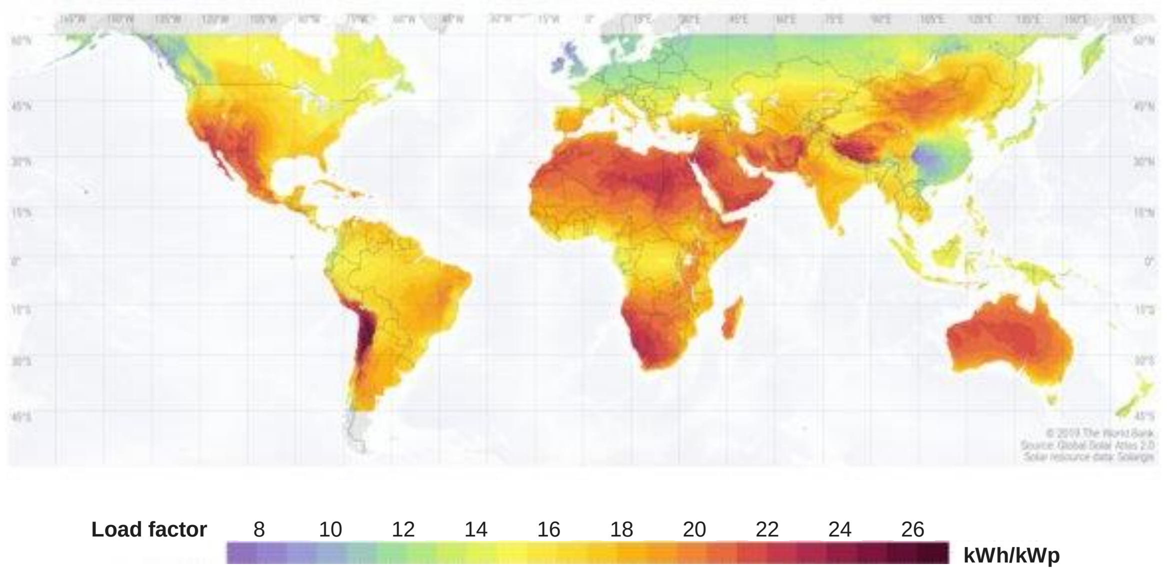
Carbon dioxide emissions embodied in solar power are determined by the carbon footprint of energy and non-energy inputs to the life cycle.
The EU has the lowest carbon footprint of power generation among the three regions (354gCO_2/kWh), due to the high share of renewable power in its electricity mix as well as advanced generation technologies. The USA follow with a carbon footprint of power generation of 478 gCO_2/kWh, whereas China high share of coal power leads to a higher carbon footprint of electricity (673 gCO_2/kWh).

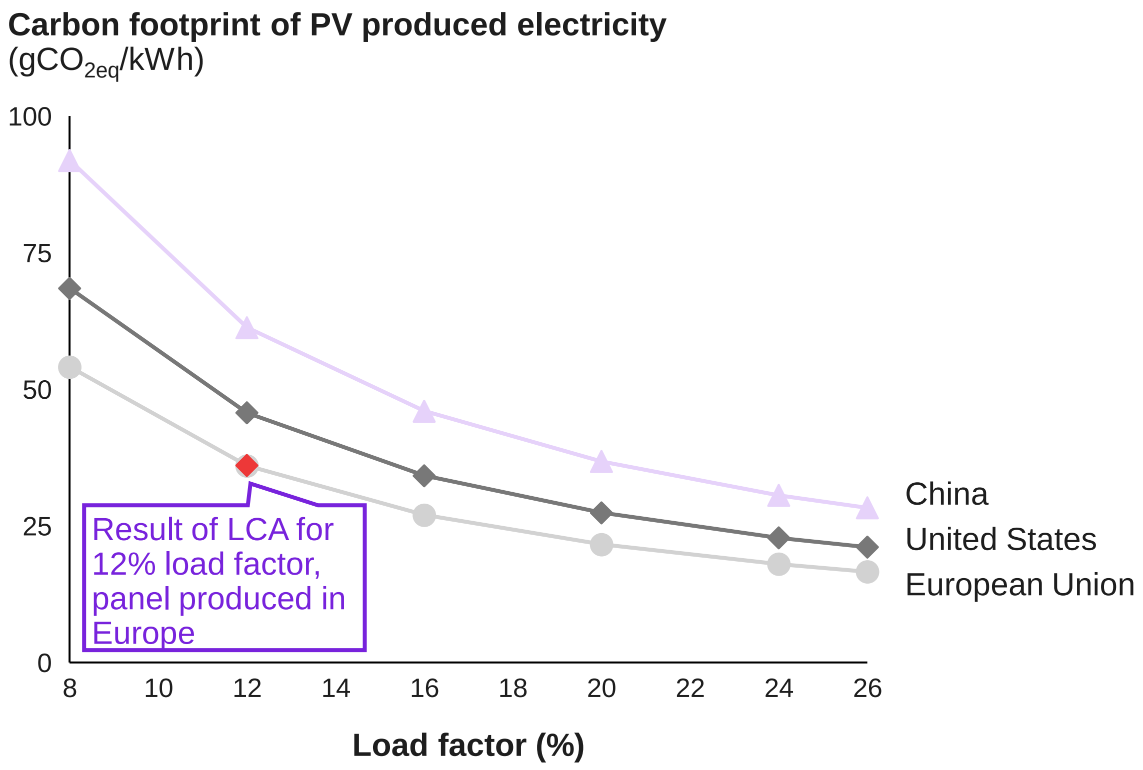
More CO_2 is emitted in the life cycle of solar panel produced in China followed by the United States and then the EU.

Sources: Liu & al., Differences in CO_2 emissions of solar PV production among technologies and regions: application to China, EU and USA, Fraunhofer ISE July 2021; Kearney Energy Transition Institute analysis

The electricity production level of a solar power plant greatly depends on its location; load factors range from 8 to 26%

Solar PV average capacity factor in % by geography





4.6 Solar PV

[1] Carbon intensity of electricity mix: EU (354gCO_2/kWh), US (478 gCO_2/kWh), China (673 gCO_2/kWh)
Sources: World Bank, Global Solar Atlas 2.0, Solar resource data: Solargis; Kearney Energy Transition Institute analysis

Recycling solar PV panel materials decreases the manufacturing carbon footprint by about 20%

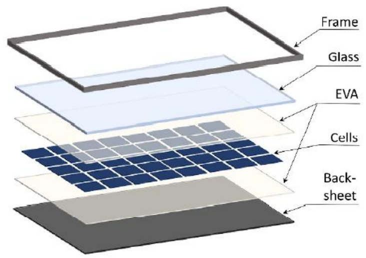
Recycling leads to a large reduction of solar panels' carbon footprint

At end-of-life (EoL), a solar panel can be landfilled, laminated for glass recycling, or fully recycled.

Laminated glass recycling. Only the recovery of the glass, copper from the cables, and the aluminum frame can occur. The silicon, silver, and other metals in the PV panel cannot be recovered and are put into a landfill. This reduces the material recovery and increases the risks associated with leaching toxic substances in landfill into soil and possibly water basins.

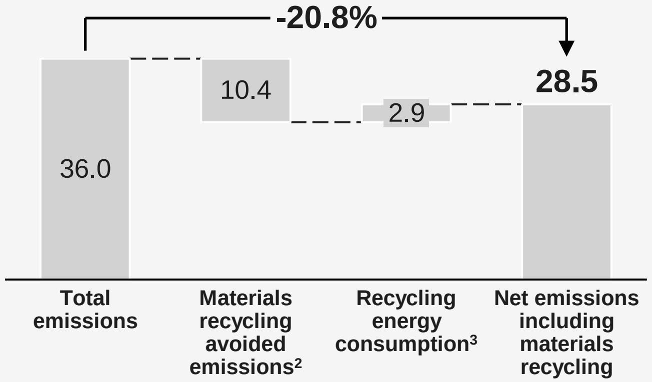
Full recycling. The process was developed from an EU initiative as a result of the WEEE Directive (extended-producer-responsibility principle setting the producers legally liable for the costs of collection, transport, treatment, management, and monitoring). The WEEE Directive sets out specific targets regarding collection, recovery, and recycling 85% of materials should be recovered, while 80% should be reused or recycled. This process combines chemical and mechanical processes to separate each material and recover most of the panel.

Multi-crystalline solar PV panel structure, Fraunhofer Institute



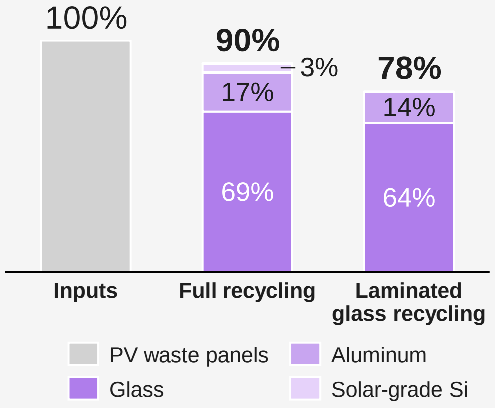
Impact of full recycling process on solar electricity carbon footprint[1]

gCO_{2eq}/kWh of produced electricity



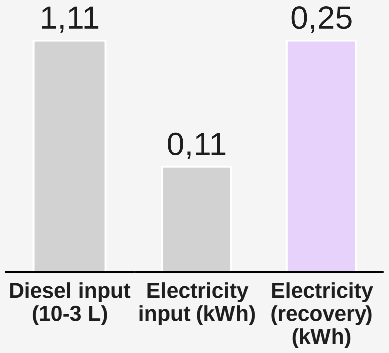
Recovered materials from laminated glass and full recycling processes

% of solar panel in mass



Energy inputs and outputs for full recycling process

L, kWh

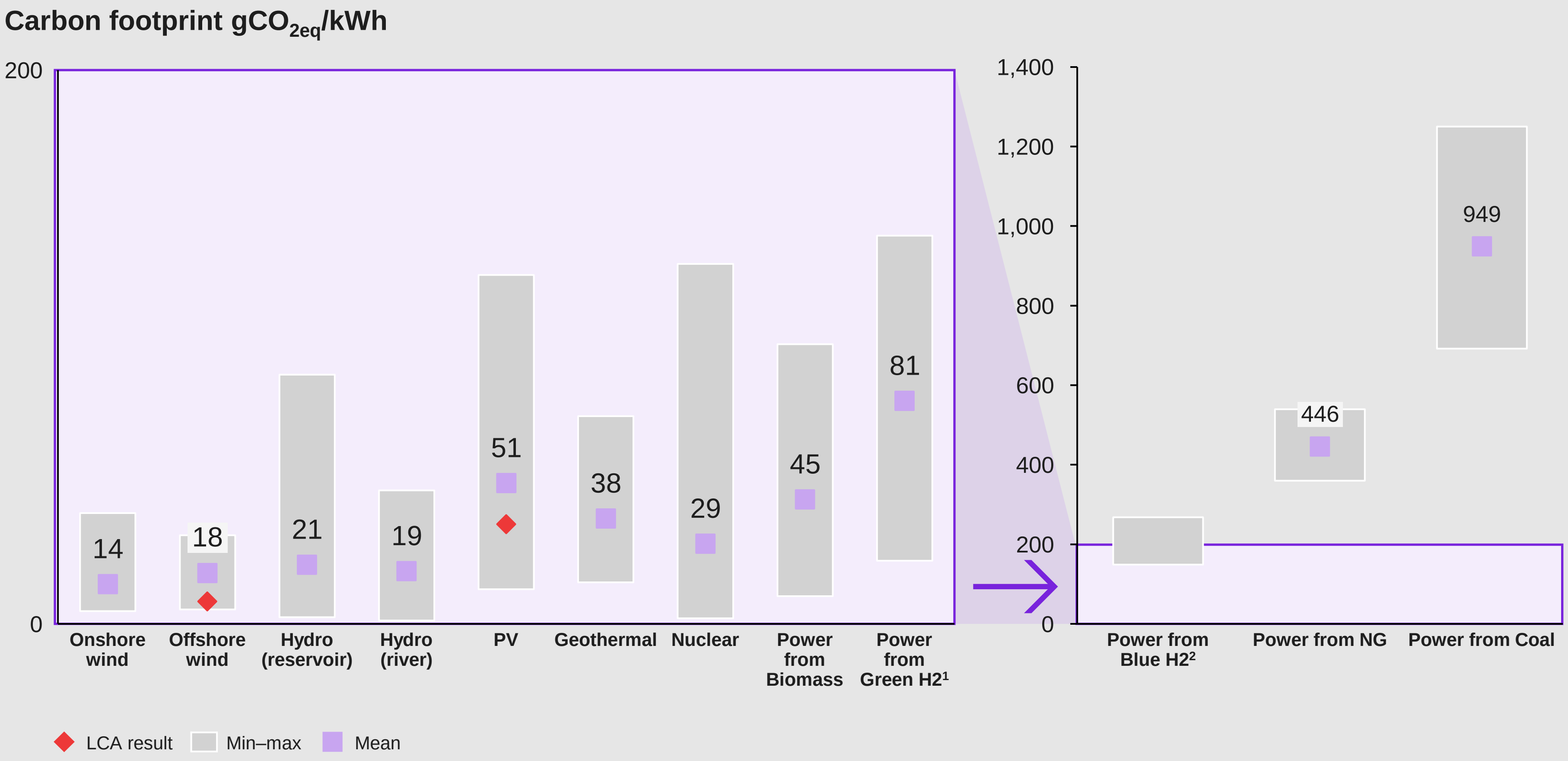


4.6 Solar PV

[1] For the generation of 1kWh of electricity, 3.34.10-6 tons of PV panels are needed, according to Ecoinvent v3.6.
[2] Materials avoided emissions calculated based on the approximation that 90% of recycled material was equivalent to a 90% decrease of materials related emissions without considering type of material recovered
[3] Recycling energy consumption considered 1.11 10-3 L of diesel with emission factor of 2,639kgCO_2/L, electricity consumption of recycling process is balanced with electricity recovery, we don't include the additional recovered electricity benefits in recycling impact.
Sources: Singh et al, Life Cycle Assessment of Disposed and Recycled End-of-Life Photovoltaic Panels in Australia, 2021; Kearney Energy Transition Institute analysis

Considering LCA results, nuclear, renewables, and green H_2 have very low carbon footprints compared with fossil sources

Electricity sources' carbon footprint review



LCA results for various electricity sources show high variability in terms of related carbon footprint which should be considered when assessing other value chains embodying energy inputs.

[1] Green hydrogen values based on electrolysis from wind electricity with an overall yield of the power to hydrogen to power value chain of 22,8%

[2] Blue hydrogen values based on methane steam reforming with 93% carbon capture (with 0,2% fugitive methane emissions) with an overall yield of hydrogen to power value chain of 40,2%

Sources: Ostfold, "Life cycle GHG emissions of renewable and nonrenewable electricity generation technologies," 2019; WNA Comparison of Life Cycle Greenhouse Gas Emissions of Various Electricity Generation Sources, 2011; Rendement de la chaine hydrogène Cas du « power-to-h2-to-power », Janvier 2020, ADEME, CertifHy Definition of Green Hydrogen, Blue Hydrogen GCCSI, Avril 2021; Kearney Energy Transition Institute analysis

Appendix and bibliography

Liquid (crude oil and petroleum products)

Emission factors of main fuels used for energy purpose

Fuel type and name			Definition	Emission factors (gCO_2/MJ) IPCC	EPA	ADEME
Primary	Crude oil		Mineral oil of natural origin consisting of a mixture of hydrocarbons and associated impurities. Includes field or lease condensate recovered from associated and non-associated gas. Highly variable physical characteristics (density, viscosity, …)	73.30	70.65	73.00
	Natural gas liquids		Liquid or liquefied hydrocarbons produced in the manufacture, purification and stabilization of natural gas. Include but not limited to ethane, propane, butane, pentane, natural gasoline and condensate.	64.20		
Secondary/ products	Gasoline	Motor gasoline	Light hydrocarbon oil for use in internal combustion engines such as motor vehicles (cars and light trucks), excluding aircraft.	69.30	70.22	73.00
	Gasoline	Aviation and jet gasoline	Includes aviation gasoline (motor spirit with a specific freezing point and an octane number suited to aviation piston engines), and jet gasoline (all light hydrocarbon oils for use in aviation turbine power units, obtained by blending kerosenes and gasoline or naphthas and sometimes additives)	70.00	70.22	73.00
	Kerosene	Jet kerosene	Medium distillate used for aviation turbine power units, with a much higher flash point than gasoline-based fuel. High-quality fuel with particular specifications required by the International Air Transport Association (IATA)	71.50	72.22	71.60
	Kerosene	Other kerosene	Refined petroleum distillate intermediate in volatility between gasoline and gas/diesel oil. Used as a cooking and lighting fuel		75.20	
	Shale oil		Mineral oil extracted from oil shale used in power generation.	73.30		73.00
	Residual oil		Oils that make up the distillation residue. Comprises all residual fuel oils, including those obtained by blending.	77.40	74.02	70.16
	Gas/diesel oil		Includes gas oils (lowest fraction from distillation of crude oil) and heavy gas oils (obtained from vacuum redistillation of the residual from distillation). Gasoil includes transport diesel, heating oil and other gasoil. Transport diesel oil is used to power diesel engines in buses, trucks, trains, cars and other industrial machinery. Heating oil is used in domestic/residential and commercial buildings, and industrial boilers. Gasoil is also used for power generation. Difference between diesel and heating oil: sulfur content of the fuel. Heavy oil is used by the power generation to produce electricity and heat, by industrial users for process heat and by the commercial sector to provide heating fuel for their buildings. It is also the most important fuel for international marine bunkers to fuel their ships.	74.10	74.01	75.00
	Liquefied petroleum gases		Light hydrocarbons fraction of the paraffin series, derived from refinery processes, crude oil stabilization plants and natural gas processing plants comprising propane and butane or a combination of the two. Used in domestic/residential heating and cooking, for agricultural purposes and increasingly in the road transport sector for use in internal combustion engines.	63.10		

Sources: 2006 IPCC Guidelines for National Greenhouse Gas Inventorie; OCDE Glossary of Statistics Terms; WEO2020; EIA Glossary IEA Energy Statistics Manual, 2005; Kearney Energy Transition Institute analysis

Gas (natural gas) and solid (coal and coal products)

Emission factors of main fuels used for energy purpose

Fuel type and name			Definition	Emission Factors (gCO_2/MJ) IPCC	EPA	ADEME
Primary	Natural Gas		Gases occurring in deposts, consisting mainly of methane. Includes both "non-associated" gas from fields producing hydrocarbons only in gaseous form, and "associated" gas produced in association with crude oil as well as methane recovered from coal mines. Includes blended natural gas (high calorific value gas obtained as a blend of natural gas with other gases).	56.10	53.06	56.10
Primary	Anthracite		High rank coak used for industrial and residential applications, with less than 10% volatile matter and a high carbon content.	98.30	103.69	98.30
	Coking Coal & Other Bituminous Coal		Coal used for steam raising purposes. Includes coking coal, which has the quality necessary to produce coke for blast furnace charge.	94.60	93.28	95.00
	Sub-Bituminous Coal		Non-agglomerating coals containing more than 31 percent volatile matter. Used for steam-electric power generation	96.10	97.72	96.00
	Lignite		Non-agglomerating coal with more than 31 percent volatile matter, used in the power sector mostly in regions near lignite mines	101.00	97.72	100.00
	Oil Shale & Tar Sands		Oil Shale: Inorganic, non-porous rock yielding hydrocarbons and other solid products, when subjected to pyrolysis. Tar sands: sand mixed with a viscous form of heavy crude oil.	107.00		107.00
	Peat		Combustible soft, porous or compressed, sedimentary deposit of plant origin including woody material with high water content. Can be used as a fuel in power stations.	106.00	111.84	110.00
Secondary /Products	Patent Fuel & Brown Coal Briquettes (BKB)		Composition fuel manufactured from hard coal fines with the addition of a binding agent for patent fuel, and from lignite/brown coal for BKB	97.50		98.00
	Coke Oven Coke & Gas Coke		Solid product obtained from the carbonization of coal. Low in moisture content and volatile matter. Important industrial product, used mainly in iron ore smelting, but also as a fuel in stoves and forges when air pollution is a concern.	107.00		107.00
	Derived Gases	Coke Oven Gas	By-product of the manufacture of coke oven coke, used for the production of iron and steel.	44.40		47.00
		Blast Furnace Gas	By-product of the combustion of coke in blast furnaces in the iron and steel industry. Recovered and used as a fuel within the plant and in other steel industry processes/power stations.	260.00	274.32	268.00

Sources: 2006 IPCC Guidelines for National Greenhouse Gas Inventorie; OCDE Glossary of Statistics Terms; WEO2020; EIA Glossary IEA Energy Statistics Manual, 2005; Kearney Energy Transition Institute analysis

Biomass

Emission factors of main fuels used for energy purpose

Fuel type and name			Definition	Emission factors (gCO_2/MJ) IPCC	Emission factors (gCO_2/MJ) EPA
Primary	Solid biofuels	Wood/wood waste	Wood and wood waste combusted directly for energy	112.00	83.80
Secondary/ Products	Liquid biofuels	Biogasoline	Includes bioethanol (ethanol produced from biomass and/or the biodegradable fraction of waste), biomethanol (methanol produced from biomass and/or the biodegradable fraction of waste), bioETBE (ethyl-tertio-butyl-ether produced on the basis of bioethanol (47% by volume))and bioMTBE (methyl-tertio-butyl-ether produced on the basis of biomethanol (36% of volume)	112.00	
		Biodiesels	Includes biodiesel (a methyl-ester of diesel quality made from the transesterification of vegetable oil or animal fat)), biodimethylether (dimethylether produced from biomass), fischer tropsh (fischer tropsh produced from biomass), cold pressed bio oil (oil produced from oil seed through mechanical processing only) and all other liquid biofuels which are added to, blended with or used straight as transport diesel	70.80	73.84
		Other Liquid Biofuels	Other liquid fuel derived from biomass or waste feedstocks; can be classified as conventional and advanced biofuels according to the technologies used to produce them and their respective maturity	70.80	52.07
	Gas biomass	Gas biomass (landfill gas, sludge gas, other biogas)	Mixture of methane, CO_2 and small quantities of other gases derived from the anaerobic fermentation of biomass and solid wastes from sewage and animal slurries and combusted to produce heat and/or power	79.60	52.07
	Solid biofuels	Charcoal	Solid residue of the destructive distillation and pyrolysis of wood and other vegetal material	54.60	

Sources: 2006 IPCC Guidelines for National Greenhouse Gas Inventorie; OCDE Glossary of Statistics Terms; WEO2020; EIA Glossary IEA Energy Statistics Manual, 2005; Kearney Energy Transition Institute analysis

Table of conversions

Units of energy

Convert to:	TJ	Gcal	Mtoe	Mbtu	Gwh
From:	multiply by:				
Terajoule (TJ)	1	238.8	2.388×10^{-5}	947.8	0.278
Gigacalorie	4.1868×10^{-3}	1	10^{-7}	3.968	1.163×10^{-3}
Mtoe*	4.1868×10^{-4}	10^{7}	1	3.968×10^{7}	11630
Mbtu	1.0551×10^{-3}	0.252	2.52×10^{8}	1	2.931×10^{-4}
GWh	3.6	860	8.6×10^{-5}	3412	1

*Million tons of oil equivalent

Units of volume

Convert to:	gal US	gal UK	bbl	ft³	l	m³
From:	multiply by:					
US gallon (gal)	1	0.8327	0.02381	0.1337	3.785	0.0038
UK gallon (gal)	1.201	1	0.02859	0.1605	4.546	0.0045
Barrel (bbl)	42.0	34.97	1	5.615	159.0	0.159
Cubic foot (ft³)	7.48	6.229	0.1781	1	28.3	0.0283
Liter (l)	0.2642	0.220	0.0063	0.0353	1	0.0001
Cubic meter (m³)	264.2	220.0	6.28	35.3147	1000.0	1

Units of mass

Convert to:	kg	t	lt	st	lb
From:	multiply by:				
Kilogramme (kg)	1	239	2390	948	0.278
Tonne (t)	1000	1	0.984	1.1023	2204.6
Long ton (lt)	1016	1.016	1	1.120	2240.0
Short ton (st)	907.2	0.9072	0.893	1	2000.0
Pound (lb)	0.454	4.54×10^{-4}	4.46×10^{-4}	5.0×10^{-4}	1

*Million tons of oil equivalent
Source: Kearney

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Acronyms

Ag	Silver
AGTP	Absolute GTP
AGWP	Absolute GWP
bbl	Barrel
BTU	British thermal unit (Btu)
BEV	Battery electric vehicle
CCS	Carbon capture & storage
CCUS	Carbon capture use & storage
CGTP	Combined CGTP
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
COP	Conference of Parties (UNFCCC)
CH_4	Methane
Co	Cobalt
Cu	Copper
DAC	Direct air capture
EPA	Environmental Protection Agency (United States)
EU	European Union
FC	Fuel cell
FCEV	Fuel cell electric vehicle
GHG	Greenhouse gas
$GtCO_{2eq}$	Giga tons of CO_2 equivalent
GWP	Global warming potential
ICE	Internal combustion engine
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
K	Kelvin (unit of measurement for temperature)
kWh	Kilowatt hour
LCA	Life cycle analysis
LCOE	Levelized cost of electricity
LDV	Light duty vehicle
NCV	Net calorific value
Li	Lithium
LNG	Liquified Natural Gas
LPG	Liquefied petroleum gas
LULUCF	Land use, land-use change and forestry
Mtoe	Million tons of oil equivalent
NG	Natural gas
NGLs	Natural gas liquids
Ni	Nickel
NMC	Lithium Nickel Manganese Cobalt Battery
N_2O	Nitrous oxide
NPV	Net present value
O&G	Oil and gas
Pb	Lead
PV	Photovoltaics
R&D	Research and development
RF	Radiative forcing
SDG	Sustainable Development Goals (United Nations)
UNFCCC	United Nations Framework Convention on Climate Change
WEO	World Energy Outlook
Zn	Zinc

Appendix
bibliography and acronyms

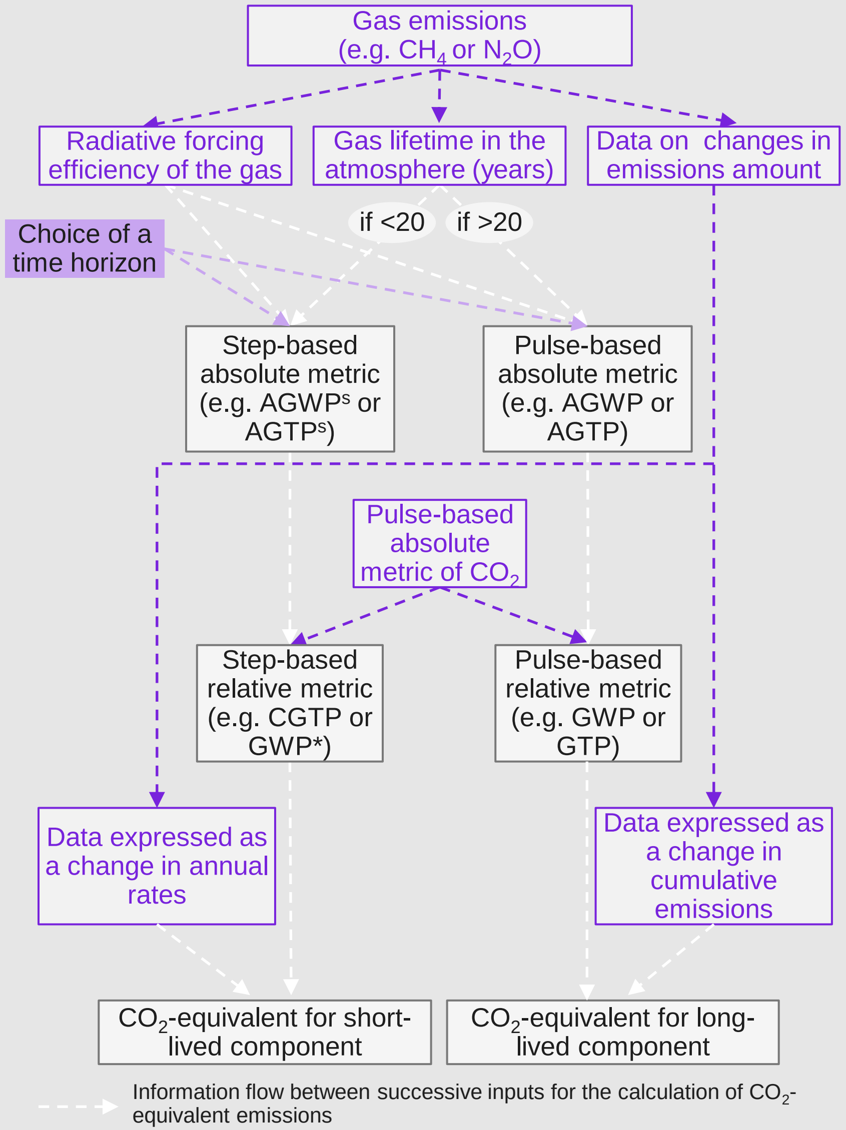
APPENDIX of Section 1

Using a rigorous common scale for GHG emissions enables mitigation policies to be adapted to the diverse characteristics of gas

CO_2-equivalent relying on emission metrics is useful to compare the impact of different GHG, but there is no single metric or time horizon appropriate for all applications and all gases.

1.4 GHG and climate change: key concepts and uncertainties

Successive steps in putting GHG emissions on a common scale[1]



1. Purple boxes: gas characteristic directly measured or known about the gas; white boxes: calculated values
Sources: Methane emissions: choosing the right climate metric and time horizon, P. Balcombe, J. F. Speirs, N. P. Brandon & A. D. Hawkes (2018); Kearney Energy Transition Institute analysis

Key points for the determination of a common scale

The purpose of a common scale based on emission metrics is to compare the impact of all gases to that of CO_2 without using complex climate models. Two choices must be made, which are not independent:
- Choice of a **type** of metric (pulse-based or step-based), on which the value of CO_2-equivalent relies.
- Choice of a **time horizon** for impact assessment.

There is no single metric or time horizon appropriate for all applications and all gases. Several recommendations can be made regarding these choices:
- Always specifying the **assumptions** regarding the time horizon and the type of metric
- **Tempering** the use of short time horizon with longer ones
- Reporting emissions **separately** for short- and long-lived components

More precisely:
- For **short-term assessments** (e.g. annual estimates of processes, facilities or regions): **2 options**
  - Using a unique time horizon but separating contributions from short-lived and long-lived gases
  - Using two time horizons (1 short, 1 long)
- For **multi-year technology assessments**, or life cycle assessments: using two or more time horizons and separating emissions reports
- For **long-term modelling** of multiple energy systems and decarbonization pathways: climate models are more suitable than using CO_2-equivalent.

AGWP is a time-dependent measure of energy accumulation due to a pulse emission of gas

Looking at a 20-year time frame, a pulse emission of CH_4 is responsible for a radiative forcing greater by about 2 orders of magnitude than that of CO_2

1.4 GHG and climate change: key concepts and uncertainties

AGWP is the time-integrated radiative forcing induced by a pulse emission

The presence of GHG in the atmosphere induces a positive radiative forcing (RF). Over time, RF decreases at a certain rate, which is determined by the average elimination speed of the GHG particle. The average lifetime of methane in the atmosphere for example is 12 years.

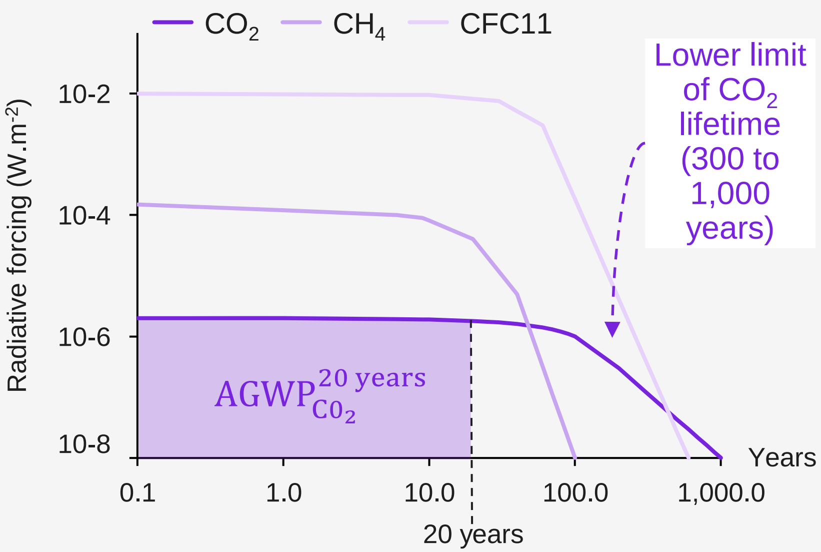
CO_2 has a longer atmospheric lifetime than most components but causes a lower radiative forcing than of the two other gases (~10^{-6} W.m ^{2} vs ~10^{-4} for CH_4 and ~10^{-2} for CFC11).

AGWP is a metric aiming at quantifying the RF over a certain time frame (e.g. 20, 100 or 500 years). It is calculated by integrating RF over the chosen time frame. So the value of AGWP is highly dependent on the chosen time frame.

AGWP is approximative by definition since the lifetime of a gas is very uncertain. In particular, lifetime depends on the presence of other components in the atmosphere.

On a graph that represents radiative forcing as a function of time after a pulse emission of a given component, the AGWP of that component for a given time frame is equal to the surface area under the RF curve, for the time frame considered.

Graph of radiative forcing due to pulse emissions of CO_2, CH_4, and CFC11 show their respective lifetimes and AGWP



We see on the graph that CO_2 has a lifetime of 300 to 1,000 years, while that of CFC-11 is around 52 years (±10.4), and CH_4 is a short-lived gas with a lifetime of ~11.8 years (±1.8).

With a 20-year time frame, the surface area under the curve for radiative forcing of CO_2 can be assimilated to a rectangular shape (width ~2.10^{-6}, length 20 years). So AGWP of CO_2 has an order of magnitude of ~$20 \times 2.10^{-6} = 4.10^{-5}$ yrs.W.m^{-2}.

In comparison, AGWP20 of CH_4 is approximatively equal to 4.10^{-3} yrs.W.m^{-2} (2 orders of magnitude higher than that of CO_2), and AGWP20 of CFC11 is approximatively 2.10^{-2} yrs.W.m^{-2}.

Note: AGWP is absolute global warming potential.
Sources: Intergovernmental Panel on Climate Change AR5 (2014) and AR6 (2021), William J Collins et al 2020 Environ. Res. Lett; Kearney Energy Transition Institute analysis

GWP is the traditionally used time-dependent metric for comparing the impact of pulse emissions

The Global Warming Potential of a gas reflects its integrated impact on radiative forcing, relative to that of CO_2 over a certain time frame. The GWP of a gas quickly falls when the time frame chosen exceeds the gas lifetime.

1.4 GHG and climate change: key concepts and uncertainties

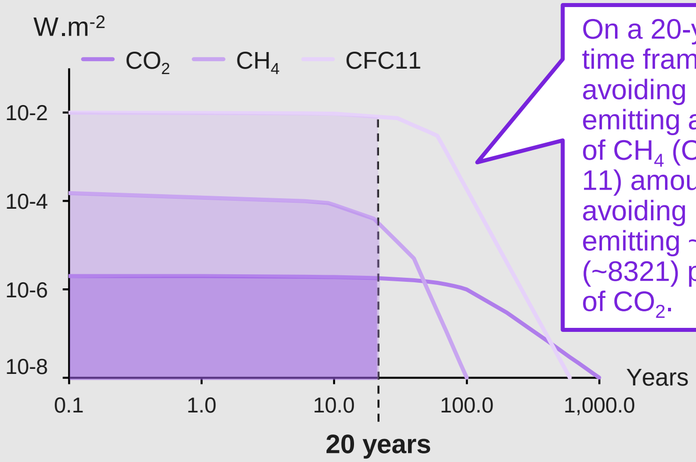
The GWP of a given gas relies on the comparison of AGWP of that gas with AGWP of CO_2

- GWP of a gas is equal to the ratio of its AGWP over the one of CO_2.
- On the graph below, the three surface areas under the three radiative forcing curves represent the AGWPs of the 3 gas. They can be assimilated to rectangular shapes for time horizons much shorter than their atmospheric lifetime.
- Thus, we can estimate the order of magnitude of GWP with a 20-year time frame: e.g., for CH_4:

$$\mathrm{GWP}_{\mathrm{CH_4}}^{20} = \frac{\mathrm{AGWP}_{\mathrm{CH_4}}^{20}}{\mathrm{AGWP}_{\mathrm{CO_2}}^{20}} \approx \frac{20 \times 2.10^{-4}}{20 \times 2.10^{-6}} = 100$$

- In reality, $\mathrm{GWP}_{\mathrm{CH_4}}^{20} \approx 81$ and $\mathrm{GWP}_{\mathrm{CFC11}}^{20} \approx 8321$.

Graph of radiative forcing with graphical representation of GWP of CH_4 and CFC-11 (20-year time frame)

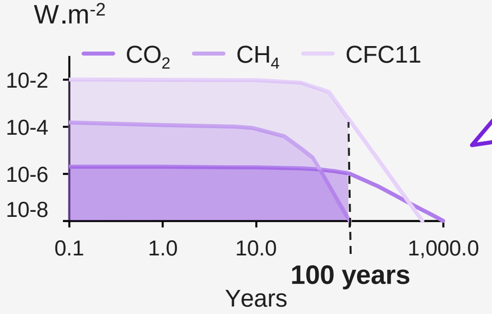


On a 20-year time frame, avoiding emitting a pulse of CH_4 (CFC-11) amounts to avoiding emitting ~81 (~8321) pulses of CO_2.

The GWP of short-lived components rapidly decreases with the chosen time-horizon

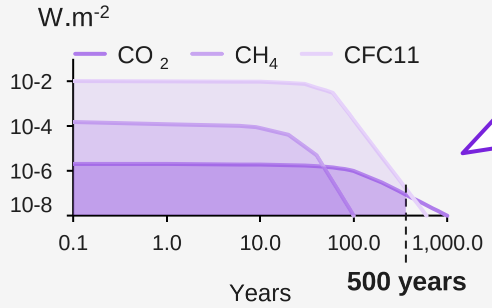
- Because the lifetime of CO_2 is more than 2 orders of magnitude higher than one of CH_4, the ratio between the areas under CH_4 curves and the one under CO_2 curve decreases when the time horizon increases. Therefore, GWP of CH_4 decreases with the time horizon.
- GWP of CFC11 also decreases as its lifetime is shorter than that of CO_2, but more slowly than for CH_4.

GWP of CH_4 and CFC11 (100-year time frame)



On a 100 years timescale, avoiding emitting a pulse of CH_4 (CFC11) amounts to avoiding emitting ~ 27 (~ 6226) pulses of CO_2

GWP of CH_4 and CFC-11 (500-year time frame)



On a 500-year time frame, avoiding emitting a pulse of CH_4 (CFC11) amounts to avoiding emitting ~7 (~ 2093) pulses of CO_2.

Sources: Intergovernmental Panel on Climate Change AR5 (2014) and AR6 (2021), William J Collins et al 2020 Environ. Res. Lett; Kearney Energy Transition Institute analysis

Using GWP100 may undervalue the true efficiency of methane emissions reduction policies

While zero CO_2 emissions are needed to achieve a zero-temperature increase, steadily decreasing CH_4 emissions are sufficient and would even induce cooling relative to the current temperature.

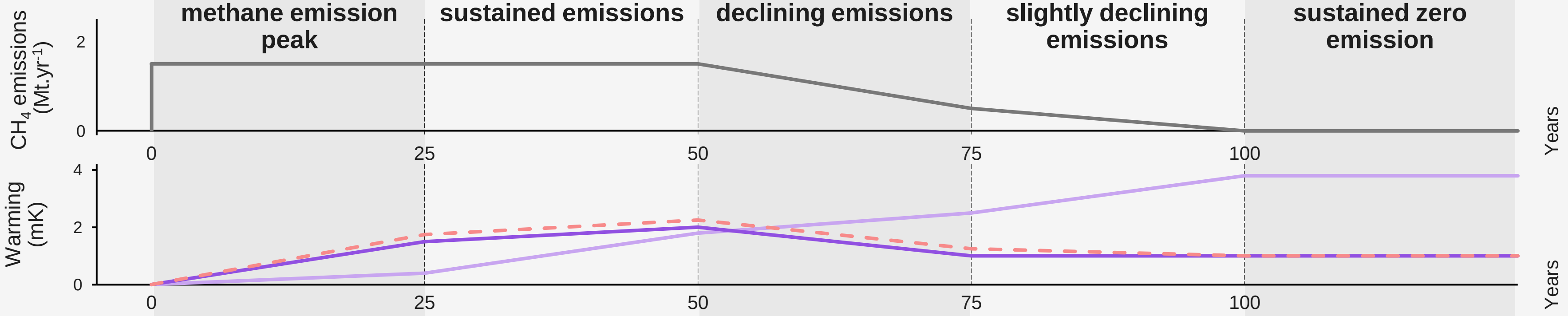
1.4 GHG and climate change: key concepts and uncertainties

Comparison of global warming resulting from a methane emission pathway, using a climate-carbon-cycle model and two emission metrics: GWP100 and GWP*

GWP is a recent metric designed to describe dynamic climate responses of short-lived gas emissions over any time frame.

We consider a CH_4 emission trajectory over five periods and compare three ways of calculating the global warming induced:
- Using the climate-carbon cycle model Finite-Amplitude Impulse Response (FaIR) v1.3: this is the closest approximation of climate response. We consider it as the reference.
- Multiplying CO_2-eq emissions based on GWP100 by the TCRE function (Transient Climate Response to cumulative carbon Emissions)
- Multiplying CO_2-eq emissions based on GWP* by the TCRE function

The results show that using GWP100 to design climate change mitigation policies leads to inefficient and dangerous choices:
- It underestimates the impacts of increasing methane emissions (see 1st period).
- It overestimates the level of action needed to offset sustained methane emissions (see 2nd period).
- It underestimates short-term benefits of reducing methane emissions (see 3rd and 4th periods).



1st period: methane emission peak	2nd period: sustained emissions	3rd period: declining emissions	4th period: slightly declining emissions	5th period: sustained zero emission
Following an emission peak, warming predicted by GWP100 increases much slower than with GWP, which approximatively fits temperature increase modeled with FaIR.	As emissions stagnate, GWP100 predicts a much higher increase in warming than GWP, which fits the modeled temperature change.	As emissions decline, GWP100-based warming keeps increasing while with GWP it decreases, as predicted by FaIR. Indeed, declining CH_4 emissions correspond to negative GWP CO_2eq emissions, while GWP-100 CO_2eq emissions are still positive.	With a very low (~0.3%/yr) declining rate, GWP100-based warming increases a lot, while with GWP it stagnates, as predicted by FaIR. Indeed, such a rate is equivalent to 0 GWP* CO_2eq emissions but corresponds to positive GWP100 CO_2eq emissions.	A constant zero emission rate results in zero additional warming with both GWP and GWP100 and as modeled by FaIR. Only with 0 methane emissions does the temperature stagnate using GWP100 metric, while GWP shows that slightly decreasing emissions are enough.

Sources: John Lynch et al 2020, Environ. Res. Lett.; Kearney Energy Transition Institute analysis

APPENDIX of Section 2

Two main categories of satellites can estimate methane emissions: monitoring satellites and tasking satellites

Monitoring satellites scan the entire atmosphere and generate large volumes of data, which in the case of public satellites (such as Sentinel-5P) is freely available in raw, unprocessed form.

Tasking satellites only scan specifically requested areas, and in the case of commercial satellites, the data is provided only to clients.

2.3 Satellites: List of key satellites

Listing of prominent satellites
Past, present, and future

Instrument	Agency or company	Public data?	Launch	Smallest leak rate detectible (kg/h)	Pixel size (km x km)	Coverage
SCIAMACHY	ESA	Yes	2003	70,000	30 x 60	– Global (every 6 days)
GOSAT	JAXA	Yes	2009	7,100	10 x 10	– Global (every 3 days)
GHGSat	GHGSat, Inc	No	2016	1,000	0.05 x 0.05	– Targeted (revisit every 14 days)
Sentinel-5P	ESA, NSO	Yes	2017	4,000	7 x 7	– Global (daily)
GOSAT-2	JAXA	Yes	2018	4,000	10 x 10	– Global (every 6 days)
PRISMA	ASI	Yes	2019	1,000	30 x 30	– Global (every 7 days)
GHGSat-C1	GHGSat, Inc	No	2020	70–250	0.05 x 0.05	– Targeted (revisit every 14 days)
MethaneSAT	EDF	Yes	2022	100	1 x 1	– Targeted (revisit every 10 days for most sites)
GeoCARB	NASA	Yes	2022	4,000	4 x 5	– Limited to Americas (revisit every 2–8 hours)
GHGSat-C2	GHGSat, Inc	No	2022	100	0.025 x 0.025	– Targeted (revisit every 14 days)
Sentinel-5	ESA, NSO	Yes	2022	4,000	7 x 7	– Global (daily)
Bluefield	Bluefield Technologies	No	2023	70	0.02 x 0.02	– Targeted
TANGO	ESA	Yes	2024	500–1,000	0.3 x 0.3	– Targeted
CO2M	ESA	Yes	2026	1,000	2 x 2	– Global (every 7 days)

Sources: Kayrros, Kearney Energy Transition Institute analysis

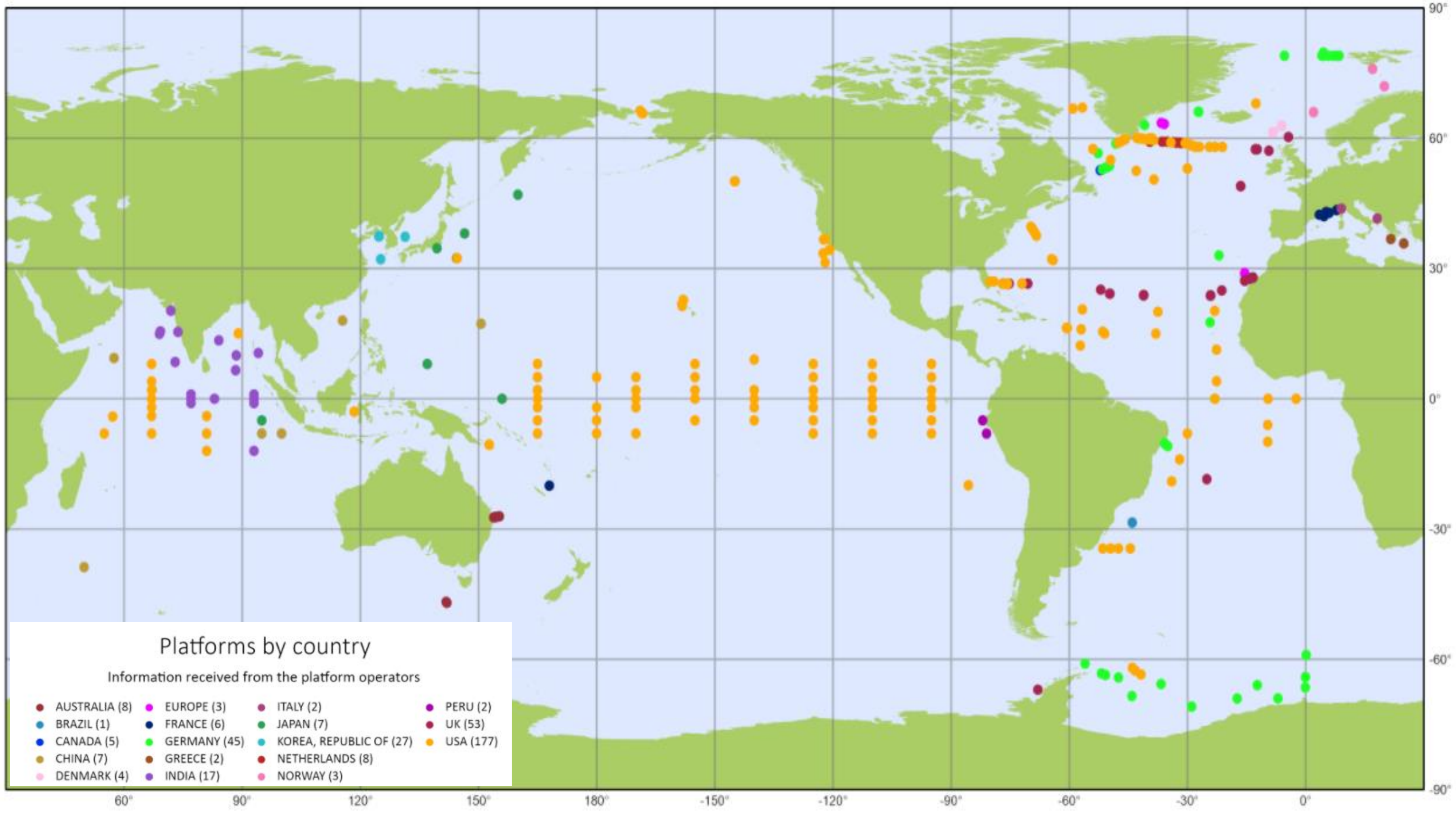
OceanSITES is a worldwide system of long-term, deepwater reference stations measuring dozens of variables and monitoring the full depth of the ocean, from air-sea interactions down to 5,000 meters

Example network: global

The network is made up of three types of sites: transport moored arrays, air/sea flux reference sites, and multidisciplinary Global Ocean Watch sites, which are operated in key regions of the global ocean.

2.7 International organizations monitoring GHG emissions – Global observation infrastructures

OceanSITES global map (August 2021)



Monitoring and process observations are provided with a temporal resolution from minutes to decades to detect, understand, and predict global physical, biogeochemical and ecosystem state and changes, including ocean warming, **ocean carbon uptake/storage and acidification**, ocean deoxygenation, but considering also the role of and impact on ecosystem.

Sources: GCOS Status Report 2021; Kearney Energy Transition Institute analysis

APPENDIX of Section 3

Life-cycle assessment practitioners have some leeway regarding three main aspects

Choices regarding defining the goal and scope as well as data inputs and modeling must be made according to the context of the study

Matter	Options	Example
Definition of the goal and scope	– Choice of an approach: relative/absolute – Definition of the functional unit – Choice of system boundaries	– Eunomia and Civancik indicators calculate relative impacts of comparative carrier bags concerning their contribution to littering. – Environmental impact assessment can be made for products in their R&D phase (ex-ante approach) – For big industries (e.g., oil and gas), stakeholders can be directly brought into conversations about selection of assumptions and data, incorporating expert knowledge into the goal and scope definition of the study.
Choice of database	– Definition of spatial resolution – Definition of temporal resolution – Choice of range of data	– For biomass-based systems, the temporal dimension is important: a lot of time can separate carbon uptake and release, accounting for biogenic carbon storage depends on the product's durability and land management practices.
Modeling decisions	– Choice between top-down, bottom-up, and hybrid approaches – Choice of the number of components modeled – Definition of the interactions between components – Depth of analysis for each component	– To avoid using computationally intensive modeling, statistical reduced-order models (proxy) from engineering simulations can be used.

Source: Kearney Energy Transition Institute analysis

APPENDIX of Section 4.2

Two methodologies can be used to assess methane emissions: top-down and bottom-up

Comparison of top-down and bottom-up methodologies for methane measurement

	Top-down approach	Bottom-up approach
Target	– Aggregate emissions across large geographies	– Emissions from individual pieces of equipment, operations or facilities
Method	– Atmospheric or high elevation air-quality measurements by aircraft, satellites or tower networks	– Direct onsite measures at the emission point or downwind in the case of facilities
Challenge	– Attribute methane emissions to specific contributors	– Aggregate and extrapolate measurements to build representative samples
Application	– Science-oriented	– Action-oriented

In both approaches, obtaining sufficient good-quality data is costly. There is a consensus better data and measurement are required. Both approaches are necessary and complementary. They need to be completed by reconciliation efforts to improve methane emissions estimates.

– In the top-down approach, methane-emissions estimates are based on measurements of air samples that may coincide with specific/unusual venting events. In addition, separating emissions from natural (e.g., geological sources) and legacy emissions sources (e.g., abandoned wells) from current natural gas operations is highly challenging.

– For the bottom-up approach, it is difficult to include all sources. Random re-sampling methods and simulations can help fill the data gaps. In addition, estimates suffer from considerable variations in operational practices between different natural gas plays and results are highly sensitive to extreme values.

Sources: Brandt et al. (2014), "Methane Leaks from North American Natural Gas Systems"; Allen (2014), "Methane emissions from natural gas production and use: reconciling bottom-up and top-down measurements"; Kearney Energy Transition Institute analysis

Research is under way to improve the reporting of methane leaks during gas production

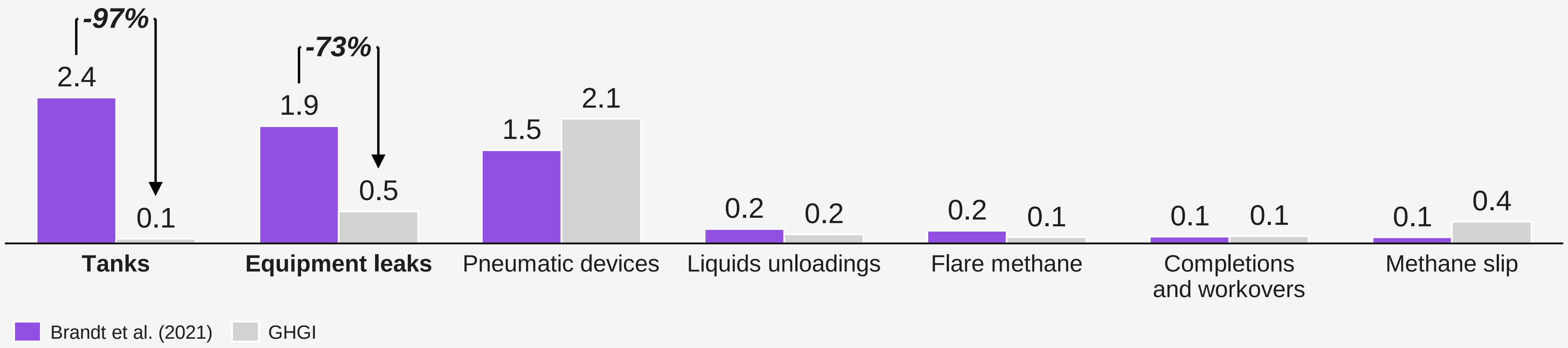
A recent study identified the two main sources of underestimation of methane leaks by US GHGI.

A recent study presented a method for improving GHGI by applying a resampling statistical analysis within a component-level bottom-up approach. Their total estimate is ~1.8 times that of the GHGI. Super-emitters are better assessed.

4.2 Methane leaks

Source-specific emissions comparison between the recent study and the US GHGI

$TgCH_4$.yr-1, 2015



Differences in emissions from storage tanks are decomposed into two factors.

High-emissions events are frequently observed at storage tanks, and the frequency of unintentional emissions events is much higher than the rate suggested by the EPA (2%).

Emissions from tanks = **unintentional** + intentional

Emissions per event × frequency of events per tank

1 order of magnitude higher than GHGI

1 order of magnitude higher than GHGI

GHGI underestimates unintentional equipment-level emissions from tanks by two orders of magnitude.[1]

Differences in equipment leaks are decomposed into three factors.

GHGI underlying equipment measurements lack accuracy, regarding the fraction of leaking equipments, their emissions per unit time and the equipments count per site.

Equipment leakages =

fraction of leaking eq. × eq. count × emission factors[2]

×1 to ×0.06 compared to GHGI

×0.05 to ×20 compared to GHGI

×5 to ×46 compared to GHGI

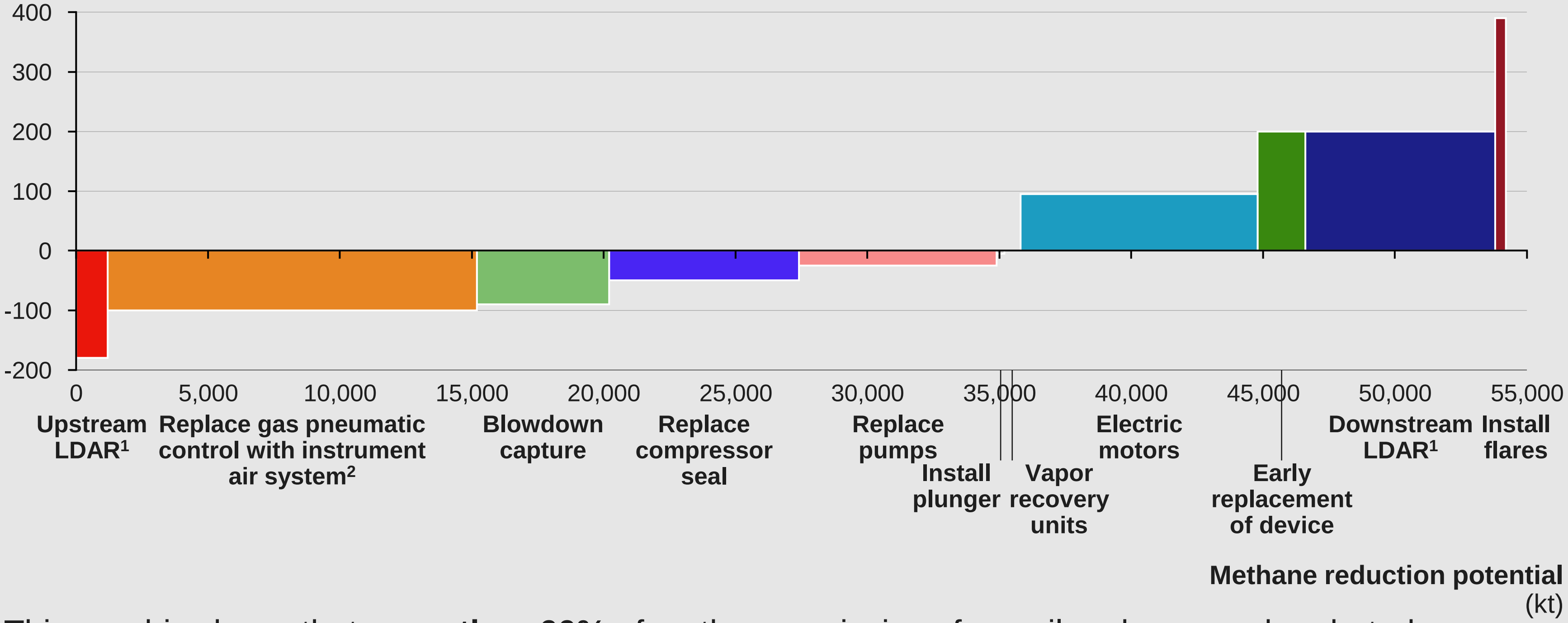
At the equipment level, equipment leaks are underestimated by a factor of five to seven.[1]

1. Equipment-level emissions are then multiplied by activity factors and extrapolated to the national level, which explains that the differences on the graph above are not equal to those described here; 2. The term "emission factor" refers to the emissions per component or equipment per unit time.

Sources: J.S. Rutherford, E.D. Sherwin, A.P. Ravikumar, G.A. Heath, J. Englander, D. Cooley, D. Lyon, M. Omara, Q. Langfitt, A.R. Brandt, "Closing the methane gap in US oil and natural gas production emissions inventories," Nature Communications (2021); Kearney Energy Transition Institute analysis

According to multiple estimates, about 50% of methane emissions from oil and gas can be abated at a negative cost by deploying various abatement measures

Cost of targeted methane abatement measures in the oil and gas sector
Direct cost, 2018, $/t



This graphic shows that **more than 60%** of methane emissions from oil and gas can be abated at a net negative cost.

Unlike carbon dioxide emissions, which are easier to estimate but harder to address, methane emissions have been elusive to identify but, once detected, are easily and cost-effectively addressable.

Reducing methane leaks would be decisive to mitigate climate change and buy time to tackle carbon dioxide emissions. The United Nations Environment Program (UNEP) reports that the energy sector can reduce methane emissions from oil, gas and coal by **50%** at a low cost.

4.2 Methane leaks

[1] LDAR is leak detection and repair.
[2] Blowdown: emptying or depressurizing natural gas from the equipment designed to contain it for the purpose of maintenance, testing or other activities such as installing new pipeline
Sources: IEF, UNEP Global Methane Assessment, CCAC; Kearney Energy Transition Institute analysis

Fuel emission factors are much lower than the real ratio between emissions and the amount of recovered energy after burning that fuel

C

4.2 Emission from fossil fuels consumptions - Fossil fuel use (Combustion efficiency)

The perfect combustion of isooctane produces an amount of energy equal to the net calorific value of the fuel

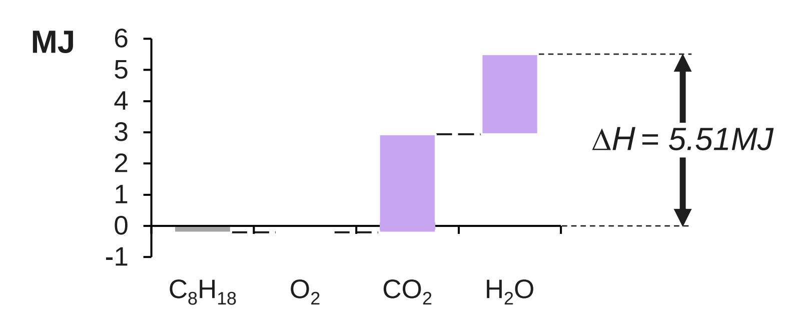
Isooctane is a hydrocarbon widely used in gasoline.

Its combustion reaction is:

$$C_8H_{18\,(g)} + 12.5O_{2\,(g)} \rightarrow 8CO_{2\,(g)} + 9H_2O_{\,(g)}$$

We consider here the stoichiometric combustion reaction of 1 mol of isooctane.

The heat of combustion is calculated by adding the heats of formation of CO_2 and H_2O and subtracting those of the reactant species (isooctane and oxygen).



The net calorific value is then calculated by subtracting the latent of vaporization and dividing by the mass of 1 mol of isooctane.

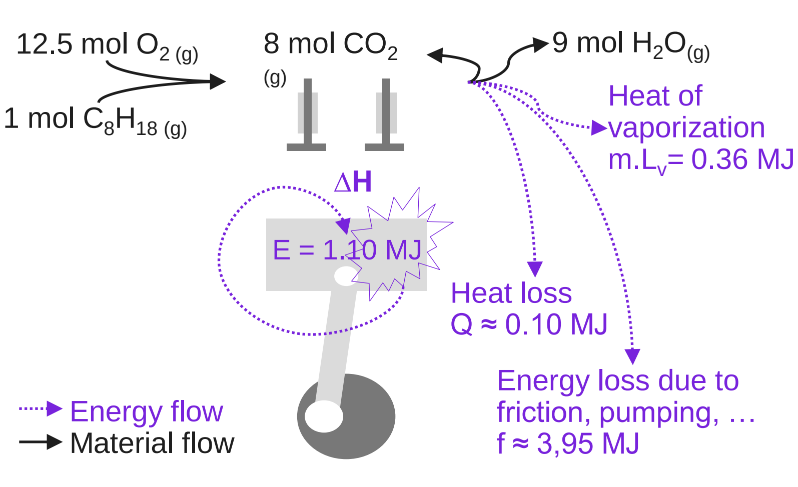
The emission factor is then obtained by calculating the amount of emitted CO_2.

Fuel feature	Formula	Result
Net calorific value (NCV)	$\frac{\Delta H - m.Lv}{\text{Mass of } C_8H_{18}}$	45.3 GJ/t
Emission factor	$\frac{\text{Mass of } CO_2}{\text{Mass of } C_8H_{18} \times NCV}$	68.4 tCO_2/TJ

Source: Kearney Energy Transition Institute analysis

In practice, the real energy produced by to the combustion is much lower

The real amount of usable energy produced by burning 1 mol of isooctane in an engine is about five times lower than the ideal heat of the combustion.



The ratio between CO_2 emissions and the amount of usable energy is around ~4.7 times higher than the theorical emission factor. This highlights the importance of considering the assumptions underlying the definition of emission factors when using them in carbon footprint calculations.

Fuel feature	Formula	Result
Usable energy per mass unit	$\frac{E}{\text{Mass of } C_8H_{18}}$	9.6 GJ/t
Emissions per usable energy unit	$\frac{\text{Mass of } CO_2}{E}$	320.6 tCO_2/TJ

APPENDIX of Section 4.3

Several factors impact the carbon footprint of primary metal

LCA analysis highlights variable boundary conditions to benefits from…

Context and key questions

- Carbon intensity of production of metals used in clean energy technologies is underestimated.

Several factors impact the carbon footprint of primary metals:

- Metal ore grade
- Country of production (from ore mining to metal purification) and energy mix
- Expected degree of metal purity
- Methods used (type of extraction, concentration methods, etc.)
- Recycling rate and methods

This section seeks to identify and estimate the impact of the key parameters that influence the carbon footprint of different metals production at each stage of production.

Mining → Transport → Refining → Recycling

Source: Kearney Energy Transition Institute analysis

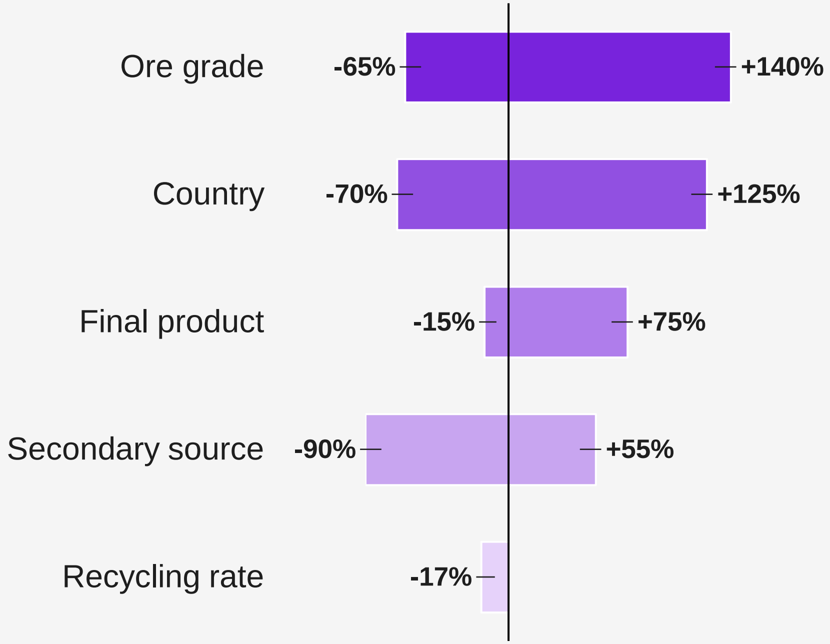
Key findings

Emissions from metal production are particularly variable and a context-based approach is required.

For typical metals such as copper, zinc, nickel, or cobalt, orders of magnitude at the global scale of sensitivity analysis can be found.

Overall, ore grade and country of production are the most sensitive parameters.

Impact of main parameters on carbon emissions from metal production



4.3 Metal mining

Global initiatives are beginning to emerge to coordinate the decarbonization of the mining sector

World Bank Climate-Smart Mining (CSM) initiative supports sustainable mining

In **May 2019**, the World Bank launched the Climate-Smart Mining Facility, a fund dedicated to making mining for minerals climate-smart and sustainable.

It supports the **sustainable extraction and processing of minerals and metals used in clean energy technologies** (wind, solar power, and batteries for energy storage and electric vehicles).

It evolved out of a World Bank report “The Growing Role of Minerals and Metals for a Low-Carbon Future”, which found that the production of minerals such as lithium and cobalt could increase by nearly 500% by 2050 to meet the growing demand for clean energy technologies.

CSM is built on **four main blocks**, two of which directly aim at decarbonating mining sector, and which complement **five UN Sustainable Development Goals** in particular, among which four are directly related to decarbonation.

Climate mitigation	Climate adaptation	Reducing material impacts	Creating marketing opportunities
Integration of renewable energy in the mining sector	Forest-smart mining with landscape management	Adoption of a circular economy for low-carbon minerals	De-risking investments for low-carbon minerals
Innovation in extractive practices	Resource efficiency in mineral value chain	Reuse/Recycling of low-carbon minerals	Leverage carbon finance instruments
Energy efficiency in mineral value chain	Innovation waste solutions	Low-carbon mineral supply chain management	Robust geological data management

The CSM initiative also provides tools and knowledge for sustainable mining:

- The Growing Role of Minerals and Metals for a Low Carbon Future (2017)
- Minerals for Climate Action: infographic and video (2019)
- Making Mining Forest-Smart (2019)
- Building Resilience: A Green Growth Framework for Mobilizing Mining Investments (2019)
- Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition (2020)
- Reuse and Recycling: Environmental Sustainability of Lithium–Ion Battery Energy Storage System (2020)

4.3 Metal mining - context

Sources: “Climate-Smart Mining: Minerals for Climate Action,” World Bank; Kearney Energy Transition Institute analysis

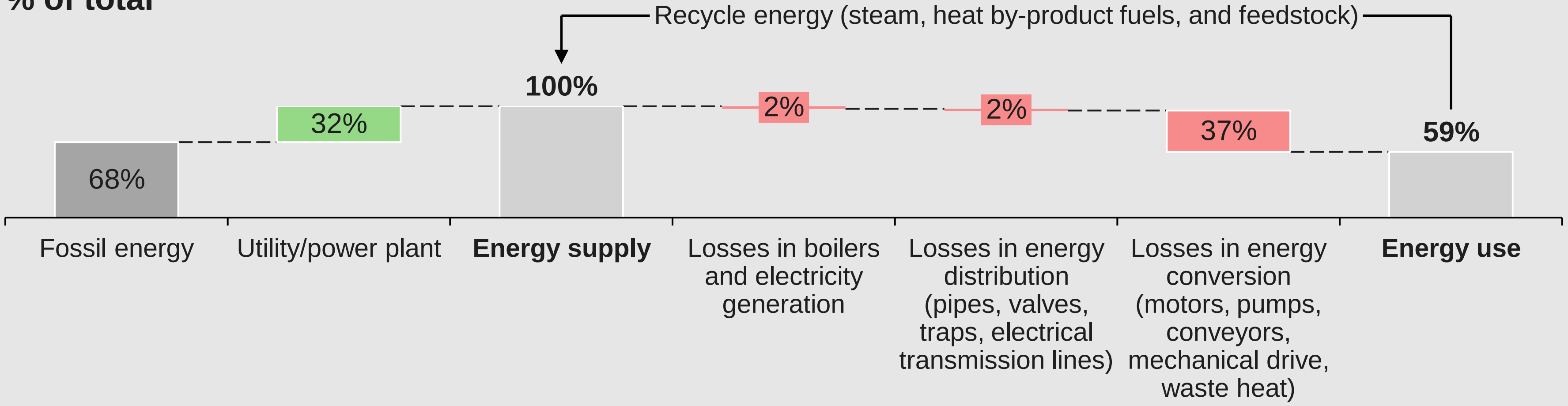
Opportunities for energy efficiency improvements can be derived from mining and refining energy loss patterns

More than 40% of total energy supply is lost during mining and refining.

4.3 Metal mining

Breakdown of the mining's industry onsite losses and general energy flow

% of total

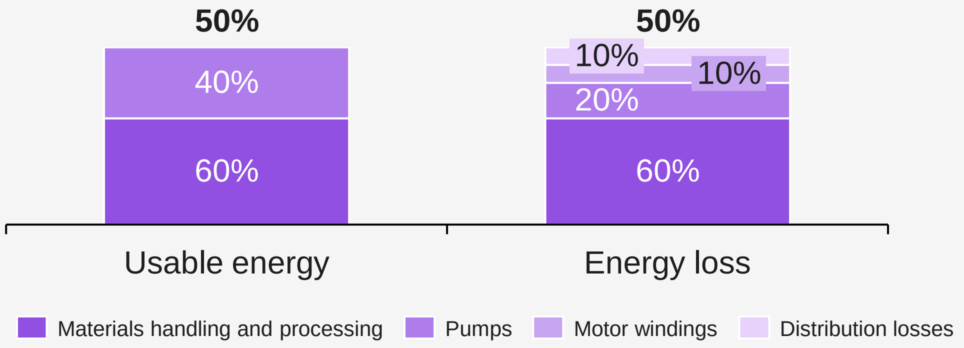


As much as **41%** of the energy supplied is lost prior to use in process units. These losses occur in equipment and distribution systems that convert energy into work or supplying energy to process operations.

Energy conversion accounts for most of total onsite losses (~90%[1]).

Zoom: motor system energy use and loss profile

% of total energy inputs in motors systems, US, 2004



Motor system inefficiencies represent ~31% of total onsite losses.

50% of energy input to motor system is lost through subcomponent inefficiencies.

The greatest losses are exhibited by materials processing systems, with inefficiencies as high as 90%: they are responsible for 60% of total losses.

1. 0%=37/(2+2+37)

Sources: "Energy Use, Loss and Opportunities Analysis: U.S. Manufacturing & Mining," Prepared by Energetics, Incorporated and E3M, Incorporated for the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Industrial Technologies Program (December 2004); Kearney Energy Transition Institute analysis

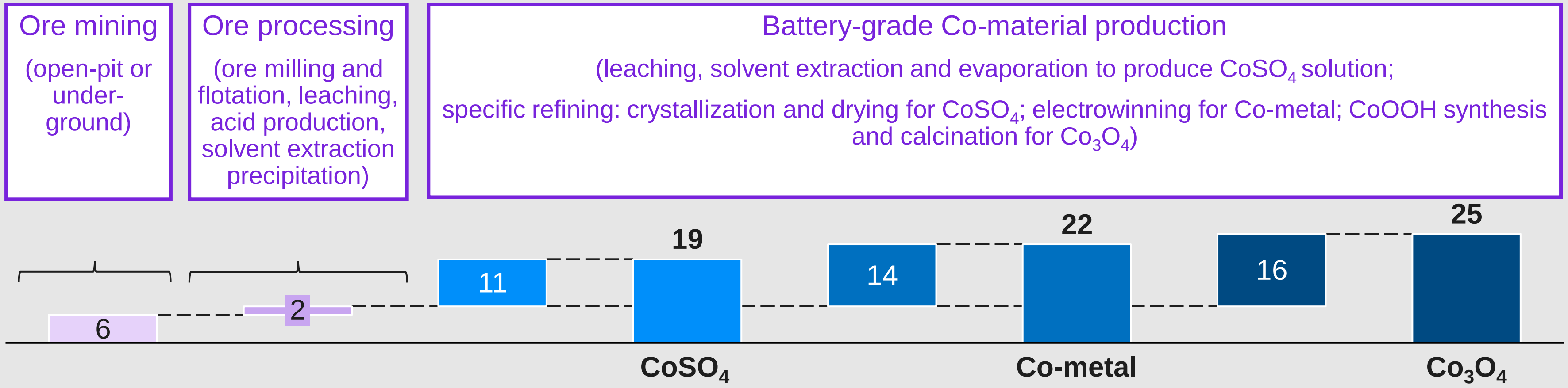
The cobalt carbon footprint depends on the type of final refined product and the energy source

The carbon footprints of Co-materials reach up to ~4 $kgCO_2e/t$ product.

4.3 Metal mining - refining

Energy intensity of the successive mining & refining stages

DRC, 2018, kWh/t Co eq.

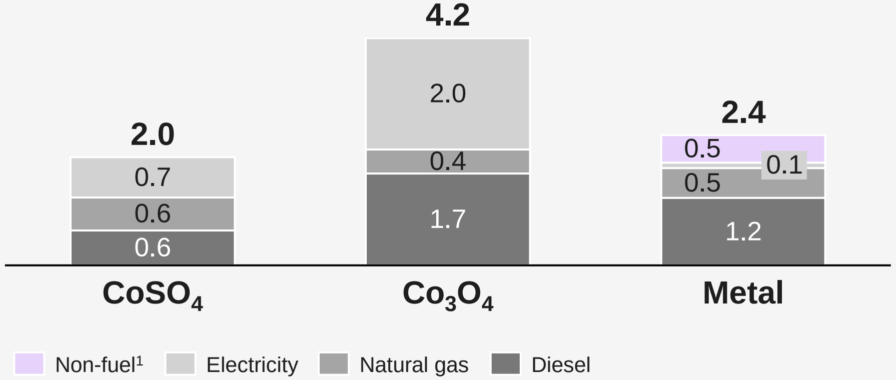


Cobalt (Co) is mostly used in rechargeable batteries as a precursor for cathode materials of LIBs, additives for NiMH batteries. It is also used in electronics, healthcare, alloys, and cobalt as catalyst for fuels (cobalt chemicals).

The energy consumption per ton of Co is calculated assuming 80% yield during the ore processing phase (and 100% for the other steps).

Carbon footprint of Co-products

DRC, 2018, $kgCO_{2e}/t$ product



Ore processing is assumed to consume electricity with a carbon footprint of 24 gCO_2e/kWh (DRC: 100% hydro).

Electricity used for further refining is assumed to have a carbon footprint of 624 gCO_2e/kWh (China: 70% coal, % hydro, nuclear, natural gas).

Emissions per ton of Co-product equal emissions per ton of Co multiplied by carbon mass percentage in the products (38% in $CoSO_4$, 73% in Co_3O_4, 100% in Co metal).

1. Thermal decomposition of CoCO3 during the calcination step for $CoCO_3$

Sources: "Cobalt Life Cycle Analysis Update for the GREET Model," Dai et al. (2018); Kearney Energy Transition Institute analysis

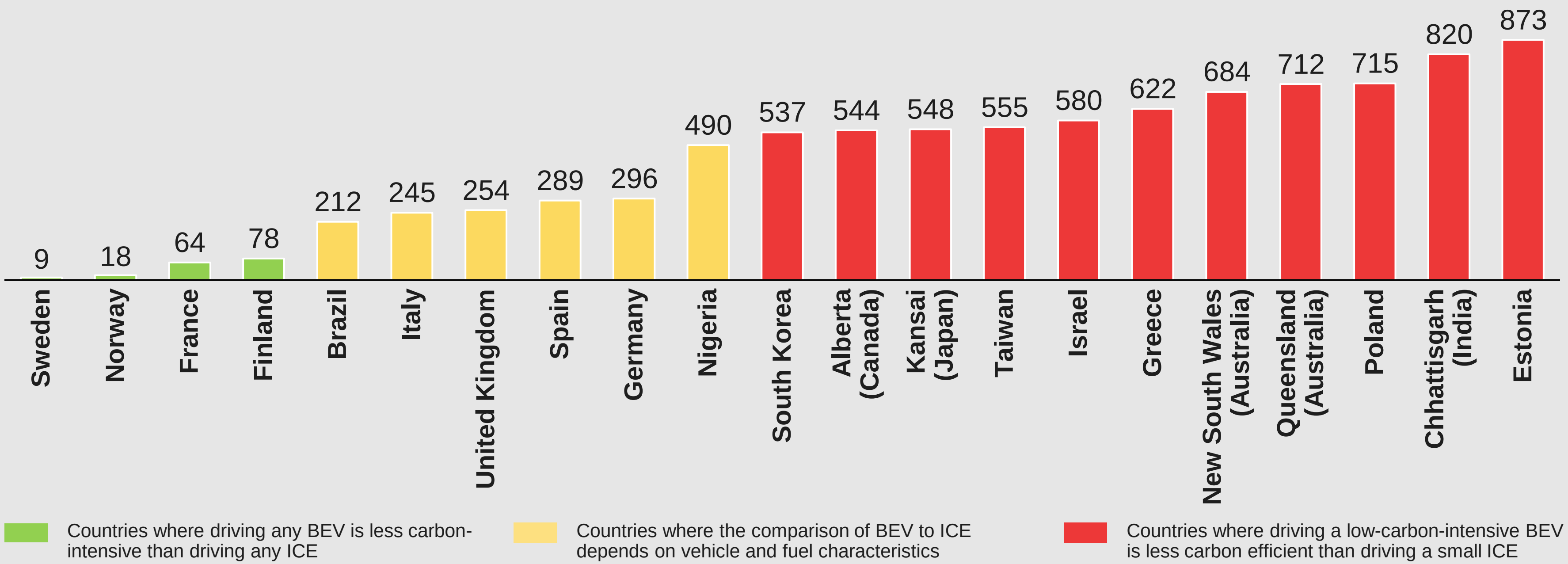
APPENDIX of Section 4.4

Electricity carbon footprint of generation is highly variable across countries

Some regions of India produce electricity about 100 times more carbon-intensive than Sweden.

In some countries, BEV with a very low cradle-to-gate carbon footprint have a bigger well-to-wheel carbon footprint than similar size thermal vehicles

gCO_2e/kWh, 2020-2021



BEV and ICE in each scenario have various values of carbon footprint of vehicle production (which depends on vehicle size, battery capacity, energy use for production), and of energy consumption per km.

- In **Estonia**, it is better to drive a thermal vehicle than to drive an electric vehicle, even considering the most optimistic scenario for BEV cradle-to-gate carbon footprint. For example, it is better to drive a Peugeot 208 than a Renault Zoe.
- However, in **Sweden** it is better to use a BEV than a thermal one, even if we consider the most pessimistic scenario for battery production (which could correspond to a Tesla Model X compared to an Audi A6).

1. Without considering transportation: the comparison is made assuming both vehicles are produced in the same place

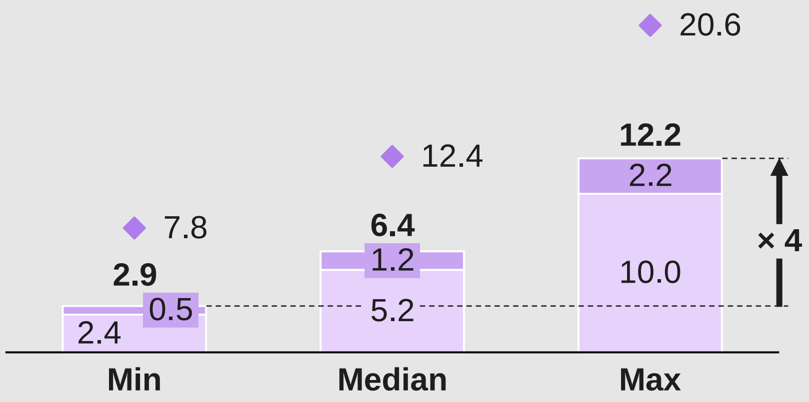
Sources: For non-European countries: Electricity Map, June 2021. For European countries: Methodology for GHG Efficiency of Transport Modes–Fraunhofer-Institute for Systems and Innovation Research ISI (2020); Electricity Map; Kearney Energy Transition Institute analysis

The carbon footprint of battery production depends on vehicle and energy for production

Battery carbon footprints vary by a factor of four depending on the battery characteristics and energy used for production.

4.4 Electric mobility

Battery cradle-to-gate carbon footprint
tCO_2e



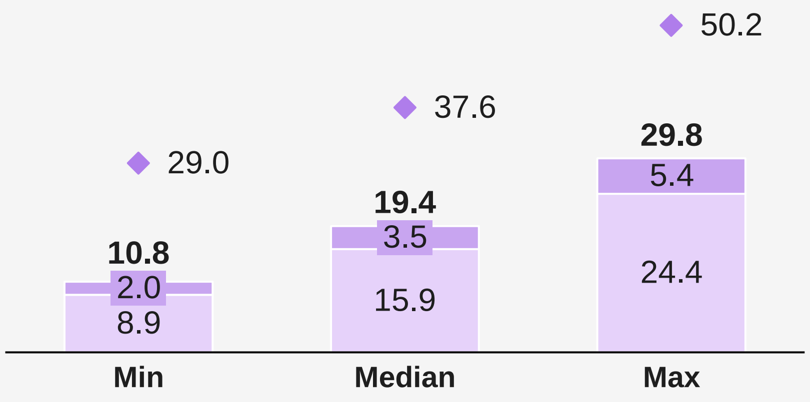
We consider three scenarios of BEV, depending on vehicle, battery and energy parameters.

- Min: small vehicle with battery capacity of 45 kWh cap produced with an electricity mix carbon footprint of 25 gCO_2e/kWh.
- Median: medium vehicle with battery capacity of 60 kWh cap produced with an electricity mix carbon footprint of 475 gCO_2e/kWh.
- Max: large vehicle with battery capacity of 90 kWh cap produced with an electricity mix carbon footprint of 800 gCO_2e/kWh.

Battery accounts for ~35% to ~55% of total vehicle cradle-to-gate carbon footprint.

Depending on battery characteristics and energy used for production, battery cradle-to-gate carbon footprint varies by a factor of about four.

Battery cradle-to-gate carbon footprint per km driven in a lifetime
gCO_2e/km



Considering the lifetime distance of vehicles, which depends the number of charge/discharge cycles in battery life (1,500) and on intensity of degradation (64% in lifetime), we determine the cradle-to-gate carbon footprint per kilometer on the road.

Experts expect the number of cycles per battery lifetime to increase to between 5,000 and more than 10,000 in 2030, which corresponds to a battery carbon footprint of 1.5 to 4.5 gCO_2e/km.

Lifetime distance also depends on type of cell: some modern NMC cells should be able to power an electric car for more than 1.6 million km.

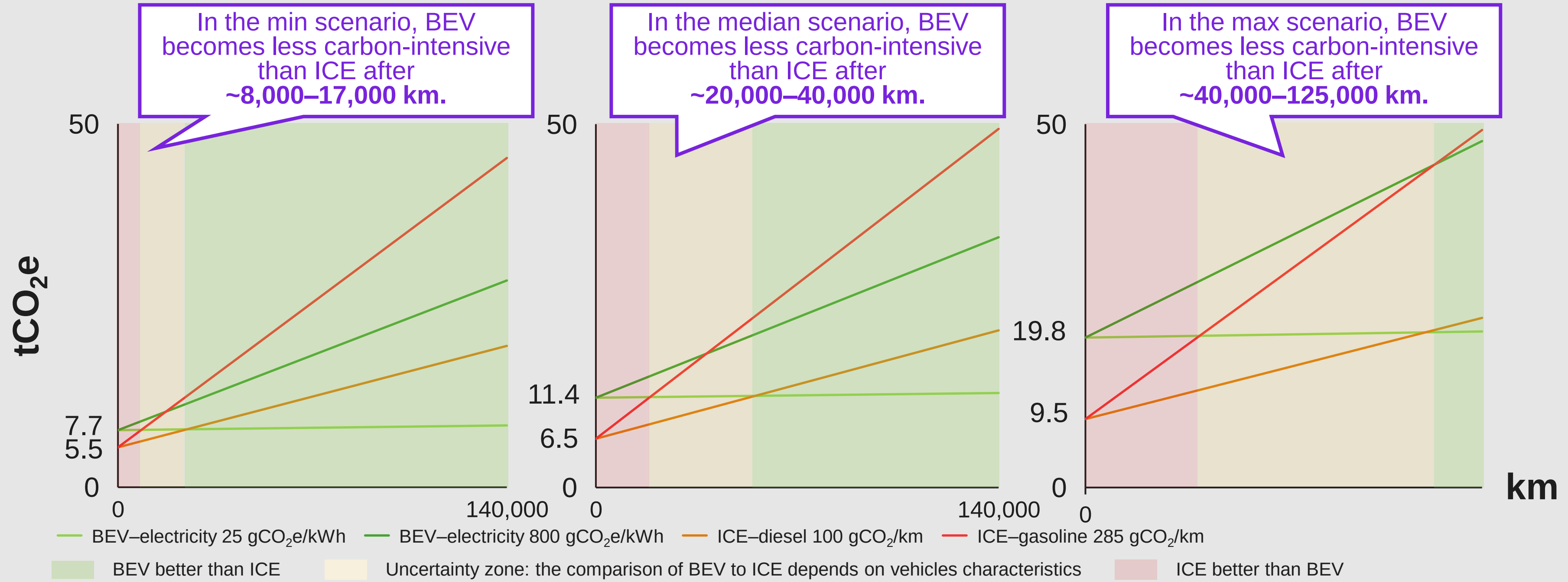
1. The electricity carbon footprint is calculated using the electricity carbon footprint of generation without considering grid losses and upstream emissions because of the high variability; 2. They correspond to battery lifetime assuming 1,500 cycles per lifetime and taking into account battery capacity degradation.
Notes: The range of battery capacities has been deduced from a literature review: Chevrolet Volt, Chevrolet Bolt EV, Mitsubishi iMiEV, Smart Fortwo ED, BMW i3, Nissan Leaf, Tesla S, Tesla 3 and from T&E's analysis.
Sources: "Methodology for GHG Efficiency of Transport Modes, Fraunhofer-Institute for Systems and Innovation Research ISI, 2020"; "Lithium–Ion Vehicle Battery Production," Erik Emilsson, Lisbeth Dahllöf (2019); Dai et al. (2019); Yuan et al. (2017); "T&E's analysis of electric car life cycle CO_2 emissions" (2020); Kearney Energy Transition Institute analysis

A BEV starts being less carbon-intensive than an ICE after high mileage

Sometimes, a BEV must drive up to 100,000 km to have a lower carbon footprint than an ICE.

Different parameters affect the minimum mileage at which cumulative carbon footprint of BEV becomes lower than of ICE

tCO_2e per vehicle mileage in km



Battery production is highly carbon-intensive, but driving a BEV is generally less emissive than driving an ICE because electricity is used instead of fuel. Therefore, after a certain mileage, CO_2 emissions avoided by driving a BEV compensate for the high carbon footprint of battery production. That mileage depends on electricity mix used to power BEV and fuel consumption of ICE.

We consider here three values of cradle-to-gate carbon footprint of BEV and ICE (min, median, and max). It corresponds to the three scenarios of size of vehicle, battery capacity, and energy use for battery production.[1]

1 See slide with all parameters.
Sources: IEA Global Energy & CO_2 Status Report 2019; “Lithium-Ion Vehicle Battery Production,” Erik Emilsson, Lisbeth Dahllöf (2019); Dai et al. (2019); Yuan et al. (2017); “T&E’s analysis of electric car life cycle CO_2 emissions” (2020); Kearney Energy Transition Institute analysis

Batteries recycled with the specific Umicore process have a much lower carbon footprint

Recycling can allow for the use of vehicles with electricity mixes up to 10% more carbon-intensive than without recycling.

4.4 Electric mobility

Umicore leads to a large reduction of carbon footprint of battery materials production

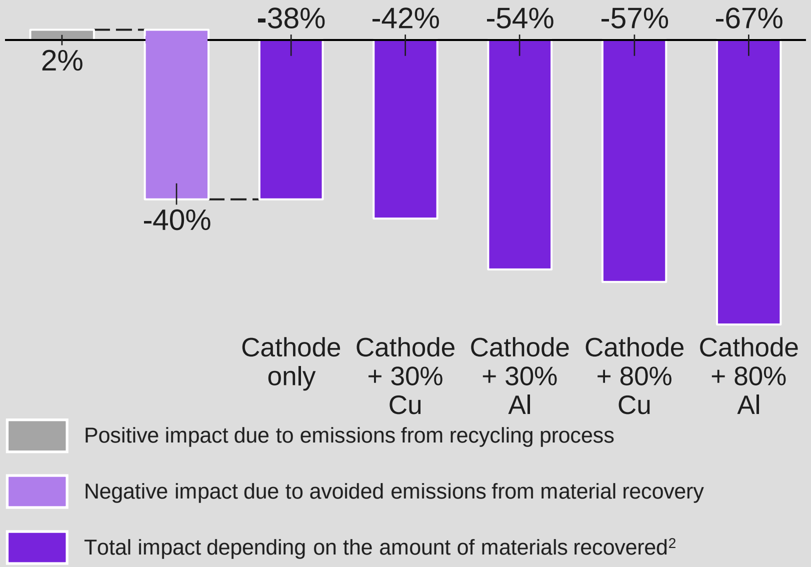
The Umicore process allows for the recovery of **~95%** nickel (Ni), cobalt (Co), copper (Cu) from two types of cells: nickel metal hybrid (NiMH) and LIB cells without needing further mechanical pretreatment.

Umicore has a recycling capacity of **7,000 Mt** in Hoboken, Belgium, of which **35,000** BEV batteries, and are used by e.g., Tesla. A pyro-metallurgical phase divides into an alloy, slag, and gases. Alloy (Co, Ni, Cu) is treated in hydro-metallurgical process for further refinement. Li-ion slag can be further recovered, and NiMH slag is processed to a REEs concentrate.

A major issue with the Umicore process is the long-term availability of waste NiMH batteries: by 2030s, the mass of EOL LIBs will be more than six times that of EOL NiMH batteries, and the difference will be increasing fast.

The impact of recycling on carbon-intensity of battery materials production depends on the recovered portion of collector foils

% Europe, 20211



Recycling increases benefits of driving a BEV instead of an ICE

The reduction of carbon-intensity of materials production leads to a **decrease of battery total cradle-to-gate carbon footprint of 30%[3] to 54%**, depending on the quantity of recovered materials from collector foils.

This allows electric vehicles to run with an electric mix that is 3% to 10% more carbon-intensive than in the case of virgin production.

Thanks to recycling, driving a small BEV in South Korea becomes better than an ICE in terms of carbon footprint.

- In South Korea, the electricity mix has a carbon impact of 537 gCO_2e/kWh.
- In the case of virgin production, a BEV with a small battery (45kWh cap) produced with a low carbon-intensive electricity mix (25 gCO_2e/kWh) is more carbon-intensive than an ICE.
- Considering the same battery with recycled materials, BEV becomes better than ICE.

1 This is the upper boundary of impact of recycling. The scope here is Europe only (low carbon footprint of energy). Authors pointed limitations: lack of proper data for battery pretreatment, lack of presentiveness of data used for raw materials, lack of applicability of process parameters determined in lab experiments; 2. Assuming Cu and Al occupy approximately 12% and 20% of LIB cells; 3. 30%≈80%×38%
Sources: "Simulation based LCA for recycling," Aalto University (2021); Kearney Energy Transition Institute analysis

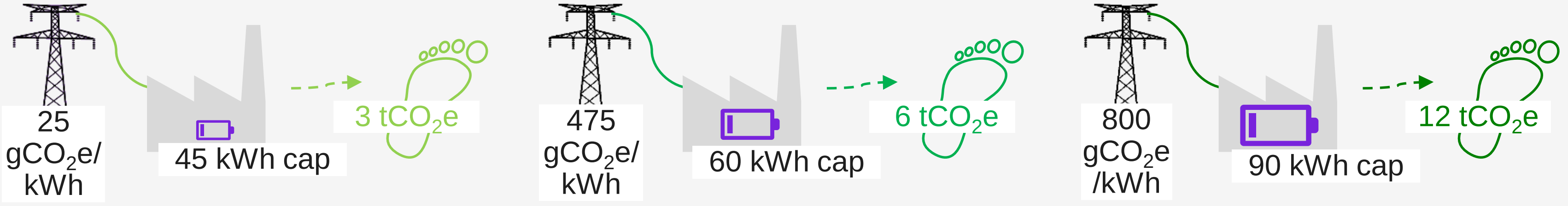
Battery life-cycle emissions depend on a variety of parameters

On average, a mileage higher than ~16,000 km and an electricity mix less carbon-intensive than ~354 gCO_2e/kWh are needed for BEV to be less carbon-intensive than ICE.

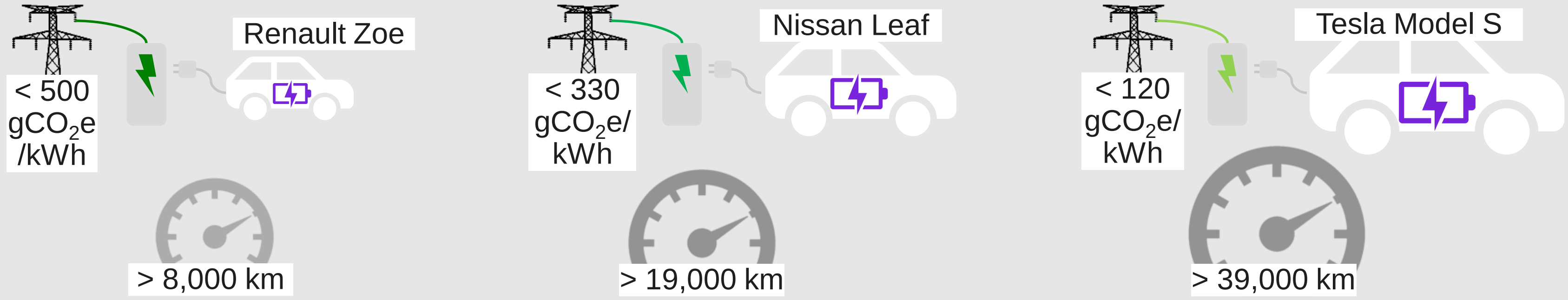
4.4 Electric mobility

Battery life cycle is composed of three main phases: production, use, and end-of-life

The **first phase** of a battery life cycle is **production**: materials production, cell manufacturing, and pack assembly. Depending on battery capacity and energy used for production, batteries have a cradle-to-gate carbon footprint of **~3 to ~11 tCO_2e**, which represents ~50% of total carbon emissions due to vehicle production.



The **second phase** is **use**. BEV need to be powered with an electricity mix lower than **~130 to ~500 gCO_2e/kWh** for their life-cycle carbon footprint to be lower than one of ICE. They need to be used for at least **~7,000 km to ~34,000 km** before the emissions avoided by using electricity instead of gasoline/diesel compensate for the high carbon footprint of battery production.



The **last phase** is **end-of-life** (EOL). Recycling methods are in development. Today, using recovered materials from EOL batteries only allows a **small reduction** of cradle-to-gate carbon footprint (up to -10%). It can even result in an **increase** (up to +6%).

Source: Kearney Energy Transition Institute analysis

AFOLU and voluntary markets

Vol.2 – Carbon Emissions Management Series

KEARNEY | Energy Transition Institute

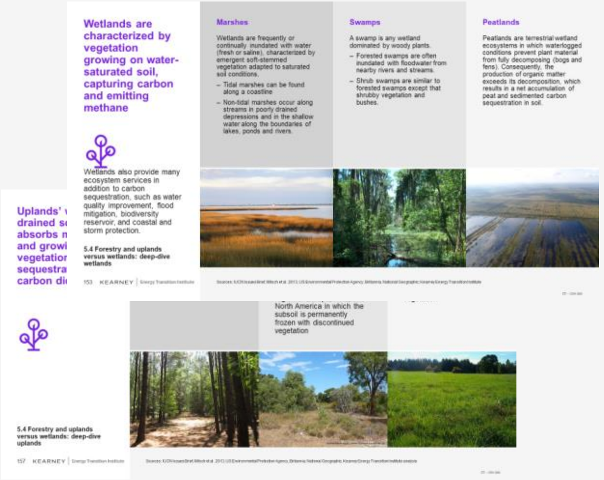
Next FactBook will address carbon management through AFOLU and voluntary markets

Next Factbook topics

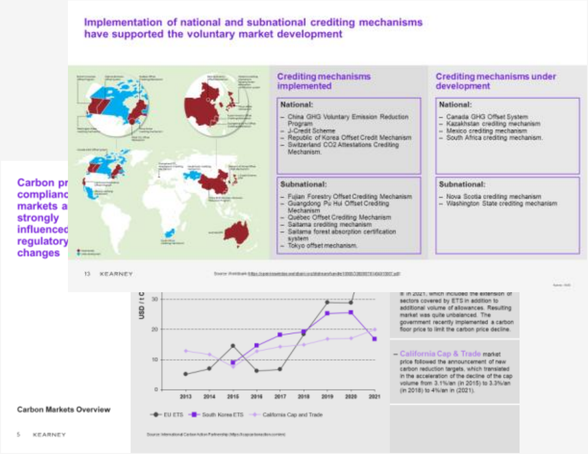
- **AFOLU in global carbon cycle:** Agriculture and land use change
- **Carbon cycle of natural ecosystems:** Forest carbon storage, afforestation, deforestation
- **LCA of agricultural activities:** Rice, agriculture, cattle
- **Voluntary markets:** Compensation mechanisms and markets

Content sample

Carbon cycle of natural ecosystems



Voluntary markets



The ETI has a collection of FactBooks providing an overview of solutions to reduce GHG emissions

H2 applications and business models

Provides an overview of hydrogen-related technologies, emerging applications, and new business models. Covers the entire value chain and analyzes the environmental benefits and economics of this space

Carbon Capture & Storage (CCUS)

Provide an overview of the latest changes in the CCUS landscape. It summarizes the main R&D priorities, analyzes the economics of the technology, and presents the status and future of large-scale integrated projects.

Gas Hydrates

Assesses the potential of this resource, by presenting key concepts; E&P technologies; R&D; and HSE challenges of potential exploitation of gas-hydrate resources

Biomass to energy

Provides an overview of biomass related technologies, applications and business models, covering the entire value chain, analyzing the environmental benefits and economics of this space along with key insights.

Solar Photovoltaic

Summarizes the status of the PV industry and its prospects, technology challenges, R&D focus areas, and the economics of PV technology

Introduction to the Water and Energy Challenge

Summarizes water resources globally, economic forecast, and links to energy by showing water shortage risks today and recommendations

Introduction to Smart Grid

Examines the innovations of Smart Grid technologies, gives an assessment of the transition to a modern, digital, and optimised electric grid

Climate Change

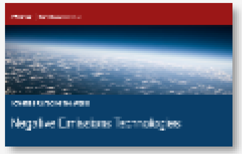
Summarizes scientific studies, concepts, projections, human-induced changes and consequences, key uncertainties and issues of debate

Introduction to Natural Gas

Assesses the reasons behind the growing importance of natural gas within the global energy mix and associated challenges, and technology developments

Electricity Storage

Summarizes status and future development, technology hurdles and economics, R&D focus areas. Outlines its pertinent role in the Energy Transition as an enabler



Negative Emissions Technologies

Summarizes the status of the negative emissions technologies and their prospects, lists the main technological hurdles and principal areas for research and development, and analyzes the economics of this space.

Wind Power

Summarizes the status of the wind industry and its prospects, the main technology hurdles, R&D focus areas, and analyses the economics of this technology

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