Assessment of European biogenic CO_2 balance for SAF production

Final report

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V3.0

The business of sustainability

This study assesses the supply and demand balance of biogenic CO_2 in Europe

Background:

- Stuttgart Airport Consortium (SkyNRG, Stuttgart Airport, SCHWENK Zement) supported by the state of Baden-Württemberg, are conducting a feasibility study of a 50 kt/year sustainable aviation fuel plant using power to liquids (PtL) technology, using CO_2 from the cement industry
- The draft of the Delegated Act on GHG accounting for RFNBOs released in May 2022 indicates that CO_2 from this type of point source will only be allowed until 2036, when only CO_2 from biogenic sources, direct air capture, or some geologic CO_2 would be allowed.
- This raises the question of whether the future demand for CO_2 in Europe for PtL fuel production and other industries could be supplied by biogenic CO_2
- The study will enable the consortium to engage with the European Commission on topics surrounding the eligibility of CO_2 for RFNBOs.

Main question: Could the future demand for CO_2 in Europe for power to liquids (PtL) fuel production and other industries could be supplied by biogenic CO_2?

The main question is broken down into several steps, as shown below

CO_2 supply

Maximum supply: how much biogenic CO_2 is released in the EU today?

Available supply: how much of the maximum supply would be available for use/storage?

CO_2 demand

PtL CO_2 demand: How much CO_2 will be needed to supply EU PtL fuel demand?

EU PtL CO_2 demand: How much of the demand will be supplied by PtL produced in the EU?

Other CO_2 demand: How much biogenic CO_2 might be needed by other EU industries?

Conclusions

Comparing supply and demand:

- Is there enough biogenic CO_2 to meet expected demand?
- Could other CO_2 sources provide sustainable supplies?

Implications for policy: What are the implications for policy in fuels, technology and CO_2 in general?

Contents

An RED Delegated Act proposes to restrict the types of CO_2 that can be used for fuel production, particularly after 2035

- The **delegated act (DA) for greenhouse gas emissions (GHG) accounting** is a proposed supporting document of RED II, which set out the methodology for assessing the GHG savings of renewable fuels of non-biological origin (RFNBOs)

CO_2 used in fuel production must meet one of the following requirements:

- The CO_2 was captured from a (fossil*) **point source**, it has been accounted for in upstream carbon pricing and it has been incorporated into the fuel composition before 2036; or,
- CO_2 is **captured from the air**; or,
- CO_2 stems from production/combustion of bioenergy complying with **Directive 2018/2201's sustainability and GHG savings criteria** and the CO_2 capture did not receive credits for emissions savings from CO_2 capture and replacement; or,
- The captured CO_2 stems from a geological source of CO_2 and the CO_2 was previously released naturally.

- <u>And</u> CO_2 must not be captured from a fuel that is "deliberately combusted for the specific purpose of producing the CO_2" or have received other emissions credits.

This raises several questions, including:

How will this affect planned PtL plants that intend to use other CO_2 sources?

Will this affect the rate of ramp up of the PtL industry?

And the main question for this study:

Could the future demand for CO_2 in Europe for power to liquids (PtL) fuel production and other industries could be supplied by biogenic CO_2?

* Defined as an activity listed in Annex I of Directive 2003/87/EC - i.e. that would be covered by the EUETS if in the EU. Note that this does not include energy from waste plants

This study answers the main question, by breaking it down into several steps

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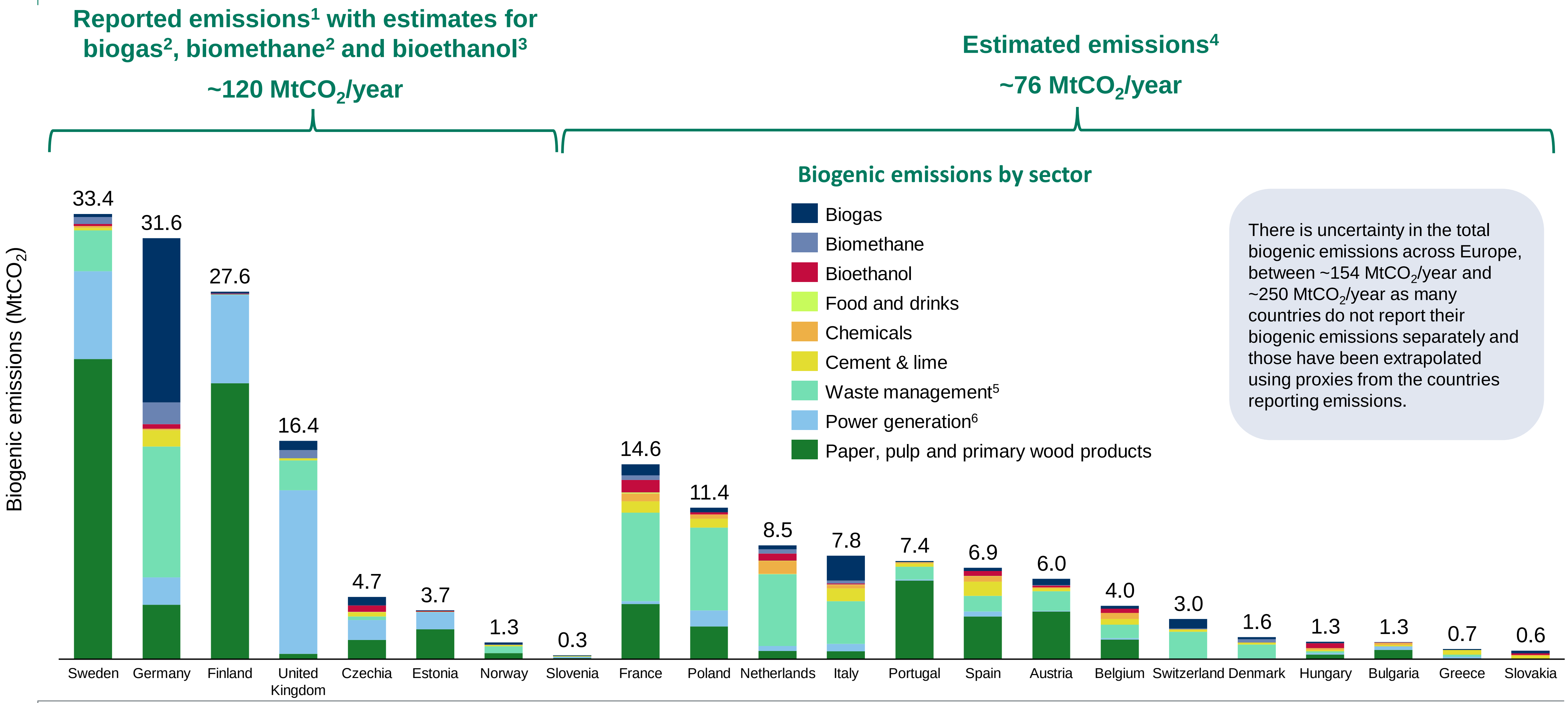
The maximum supply of biogenic CO_2 in Europe today is ~196 $MtCO_2$/year, but not all will be accessible for use



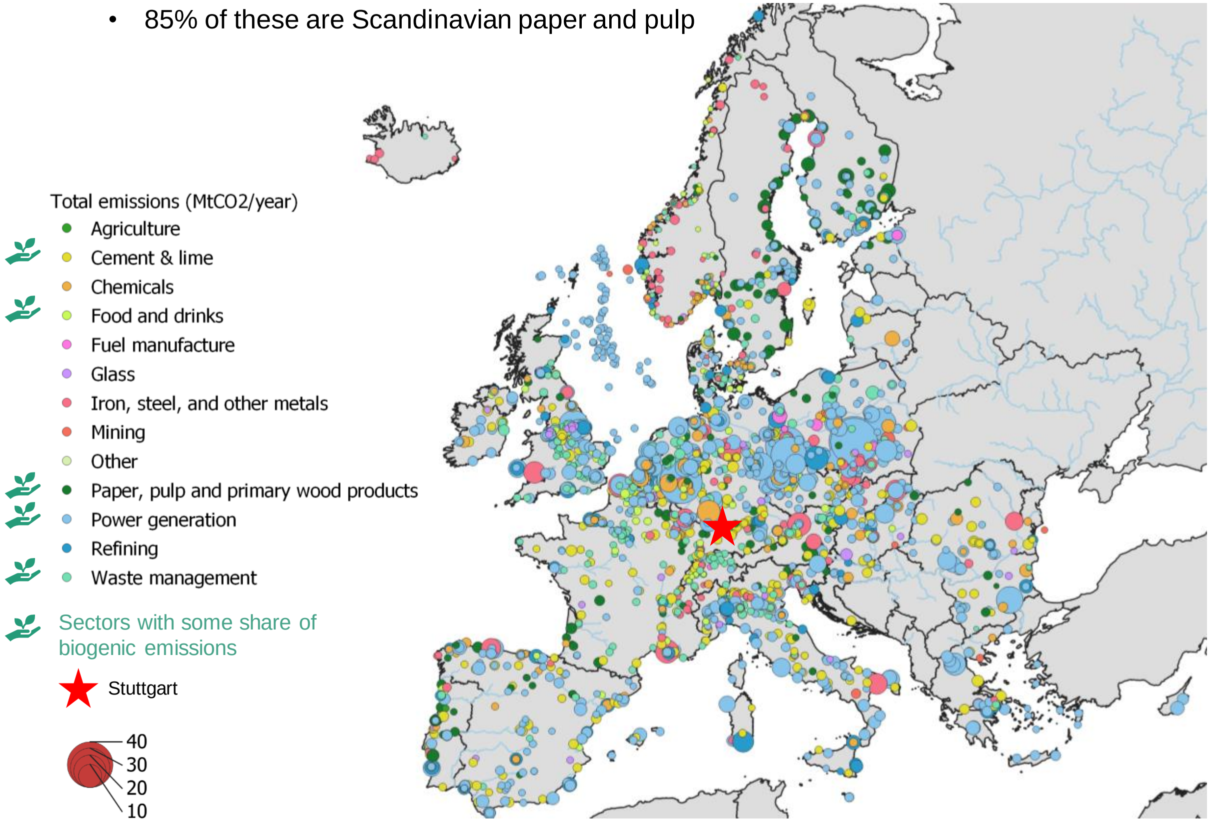
There is uncertainty in the total biogenic emissions across Europe, between ~154 $MtCO_2$/year and ~250 $MtCO_2$/year as many countries do not report their biogenic emissions separately and those have been extrapolated using proxies from the countries reporting emissions.

[1]European Industrial Emissions Portal (europa.eu) [2]European Biogas Association [3]E4tech database [4]Calculated based on average biogenic emissions by sector for reporting countries in the IEP 2019 dataset [5]Average biogenic emissions for waste management is calculated based on country level dataset from: World Bank 2019: What A Waste Global Database [6]Average biogenic emissions from power generation is based average biogenic emissions in Germany.

Biogenic emitters are dispersed across Europe, with location being a key factor reducing the potential for biogenic CO_2 use for SAF production

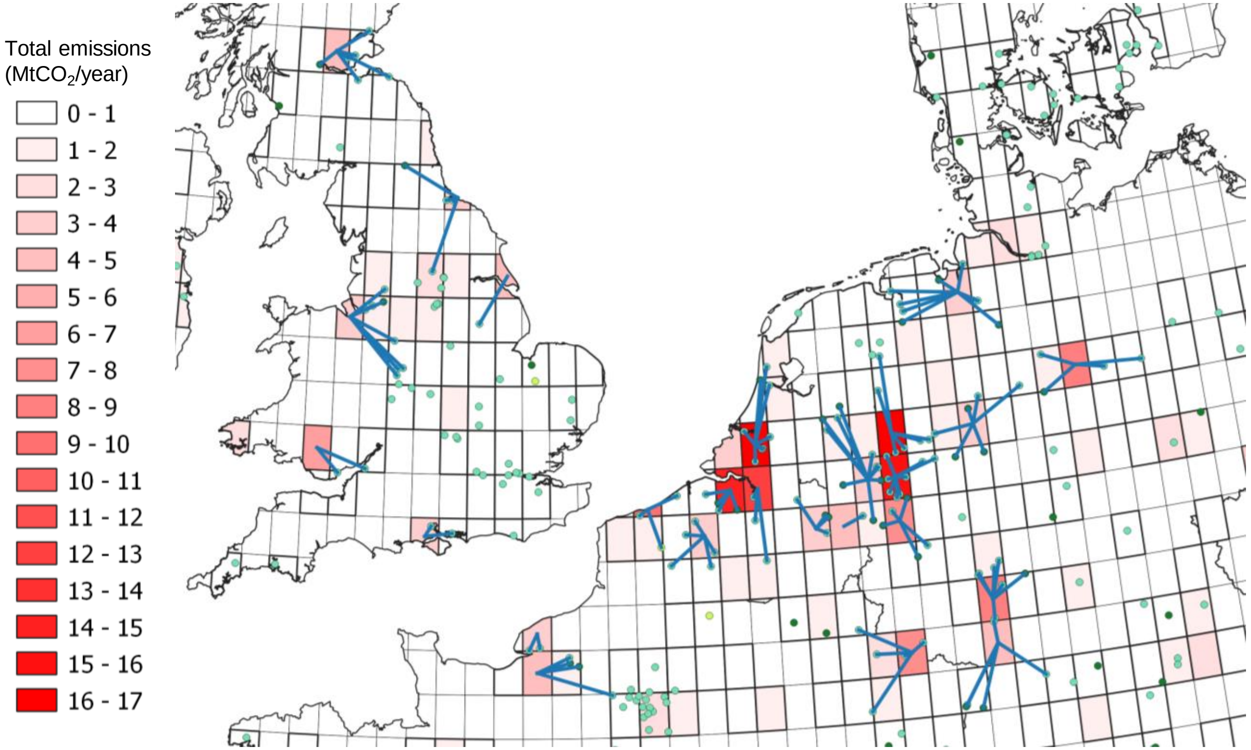
Some biogenic emitters are large enough to host a PtL plant alone

- Using the IEP dataset, it is possible to map the location of both fossil and biogenic emitters across Europe. Key sectors with biogenic emissions include: paper and pulp, waste management and power generation
- From this dataset, there are 52 emitters that are large enough to host a 100kt/yr PtL plant, which emit >409 $ktCO_2$/year biogenic emissions
- 85% of these are Scandinavian paper and pulp



Other biogenic emitters could use CO_2 transport to industrial clusters

- Industrial clusters or hubs (red dots) are expected to be the first areas to develop CO_2 transport infrastructure for collecting fossil and biogenic emissions.
- Many biogenic emitters (green dots) are relatively small in size and often located away from industrial areas, meaning that they many not be able to connect to CO_2 infrastructure.
- To assess any barriers in collecting biogenic CO_2, we have assessed the likelihood of biogenic emitters connecting to industrial clusters, based on their distance from the clusters.



A few other factors have been considered in estimating the accessible biogenic CO_2 potential

Total Biogenic Emissions

- The maximum potential for supply of biogenic CO_2 in Europe today is ~196 $MtCO_2$/year, with an uncertainty range of 154-250 $MtCO_2$/year

Purity of CO_2 stream

- Carbon capture is less economic on low purity CO_2 streams with significant contaminants (e.g. waste management).
- Generally the higher the CO_2 content, the higher the likelihood for sites to deploy carbon capture

Emissions scale

- Small scale emitters are less likely to deploy carbon capture – we filtered out small sites unlikely to deploy carbon capture, with the threshold for this varying by sector.
- In certain sectors, if the CO_2 stream is highly concentrated (e.g. biomethane production) we do consider capture of CO_2 from smaller sites.

Capture rate

- Not all CO_2 will be captured from the emissions stream.
- Typical capture rates vary between 85% and 95% (both considered in our scenarios)

Transport barriers

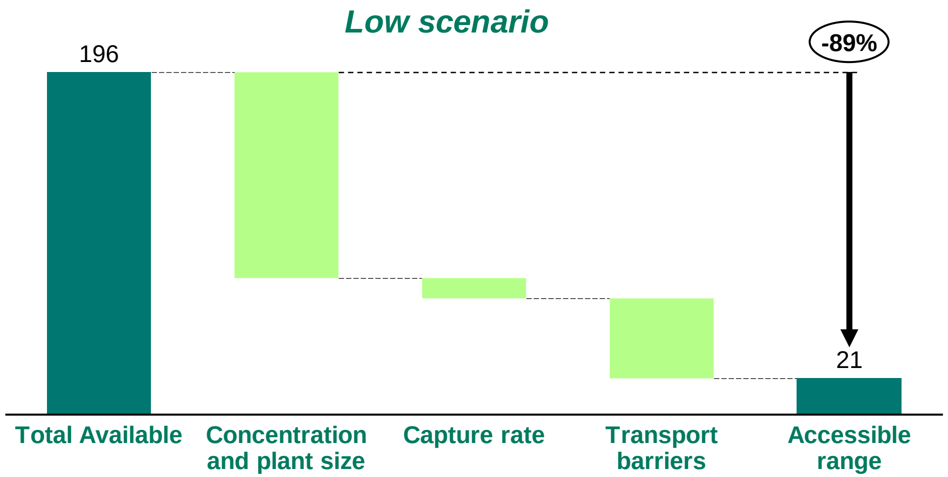
- Dispersed sites are less likely to deploy capture due to the high cost of infrastructure development
- To reflect this uncertainty, we have considered two cases: sites within 50 or 100 km of a hub identified by total current emissions across most sectors. For biomethane and bioethanol plants, where CO_2 is already separated/high purity this constraint is not applied.
- Sites which emit >409 $ktCO_2$/year biogenic emissions are assumed to be able to host their own 100 kt/yr PtL plant and may not face transport barriers.

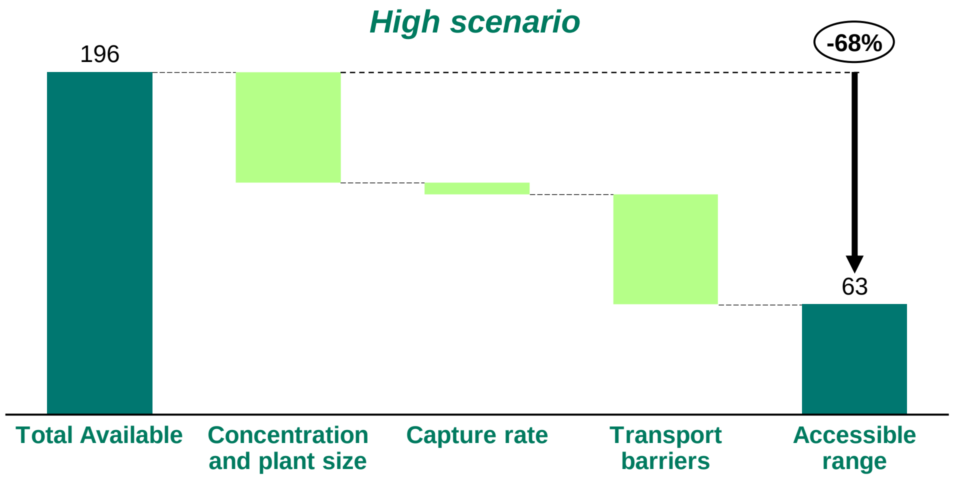
Accessible range

- Two scenarios of accessible biogenic CO_2 ranging between 21-63 $MtCO_2$/year

By considering the accessible potential, biogenic CO_2 emissions available for utilisation are reduced by 68-89%

We developed two scenarios for the accessible biogenic CO_2, considering the filtering criteria on the previous slides. Detailed assumptions behind each step are shown in the full report. There is uncertainty in the total available emissions as some countries do not report their biogenic emissions.





Low and high scenario assumptions

- Carbon capture is unlikely to be economically viable for small scale emitters and is more technically challenging on low-concentration CO_2 streams (<10% CO_2). The low scenario varies from 25-50% deployment of carbon capture and the high from 50-80%, depending on sector.
- Higher capture rates are typically associated with greater energy penalties and therefore operational costs. In the low scenario a minimum capture rate of 85% was assumed whereas in the high scenario the capture rate was assumed to be 95%
- Aggregating emissions in clusters can reduce the cost of infrastructure development. In the low scenario, it was assumed biogenic emitters within 50 km of a proposed industrial hub could make use of the transport infrastructure developed – 29% European biogenic emissions sources fall within 50 km of a cluster. In the high scenario, the range was increased to 100 km (48% biogenic emissions being captured in this range). These constraints are not applied to the biomethane and bioethanol sectors.
- In the long term, to achieve net zero all CO_2 emissions will need to be matched by CO_2 removal and storage. As a result, very strong incentives for negative emissions (including BECCS) may be needed. These incentives could increase the viability of small scale capture, capture from low concentrations and CO_2 transport.

Producing enough e-SAF to meet EU+UK targets would require 117 $MtCO_2$ in 2050, 59% of the max potential for biogenic CO_2

- We have considered what the demand for biogenic CO_2 might be from a range of industries, starting with production of aviation fuels, as shown below

RefuelEU targets include a sub target for e-SAF, at a level which is still to be finalised	Combined with demand projections, this gives e-SAF demand	Assuming a fixed CO_2 input per t SAF gives CO_2 demand	Which can be expressed as a % of total EU+UK biogenic CO_2

	PtL target (% of total jet fuel)			SAF PtL demand (PJ)			CO_2 demand for the SAF product ($MtCO_2$)*			% of today's EU+UK max potential for biogenic CO_2		
	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Commission proposal	0.7%	8%	28%	14	162	582	1.3	15.0	54	0.6%	7.6%	27%
Parliament first reading position	2%	13%	50%	39	263	1038	3.6	24.4	96	1.8%	12%	49%
Parliament first reading + UK (same RFNBO%)	2%	13%	50%	49	326	1265	4.6	30.3	117	2.3%	15%	59%

- However, the demands from other industries are less clear, as there are no defined targets for use of the products that would require biogenic CO_2

* Note that this is only the CO_2 required for the SAF produced, assuming an e-FT plant. CO_2 required to produce the naphtha co-product assumed is accounted for in the road transport sector

Potential total biogenic CO_2 demand could be large, outstripping the accessible and maximum potentials, but is very uncertain

Decreasing level of certainty over drivers and volumes

Biogenic CO_2 removal (BECCS etc) - not quantified
- No policy support in place for negative emissions today

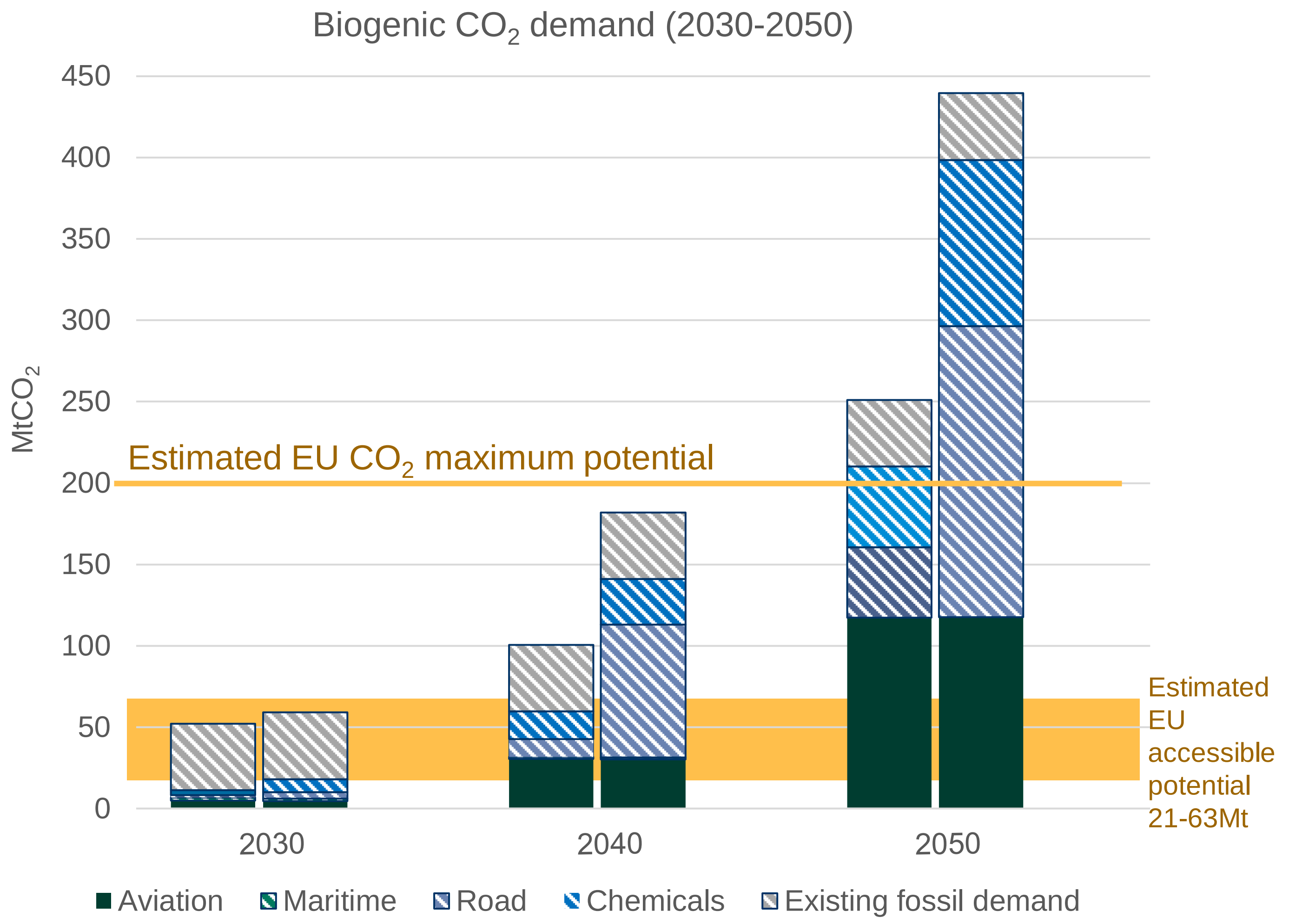
Replacing existing fossil CO_2 demand ESTIMATE
- Existing 41 Mt demand for urea, EOR, food & beverage industries
- No policy drivers yet for biogenic CO_2, but fossil CO_2 production will decline, e.g. from ammonia production, which may move towards H_2.

Chemicals ESTIMATE
- No policy drivers yet for use of biogenic CO_2, but industry interest and so potential future demand

Road ESTIMATE
- No targets for road liquid e-fuels alone, and uncertainty over whether they will be used long term (vs EVs, H_2)
- Low scenario is SAF co-products only. High scenario reaches ~50% of road liquid fuel demand by 2050

Maritime ESTIMATE
- FuelEU Maritime and REDIII policy positions include different RFNBO quotas in maritime, the REDIII target has been considered here
- No consensus on the type of RFNBOs used: Assumed a mix of methanol, e-LNG, NH_3, and H_2, with only NH_3 and H_2 by 2050

Aviation EU TARGET
- Mandate under RefuelEU aviation plus same % target for UK
- One scenario shown here: most recent EP reading position, which would require ~1000PJ of SAF by 2050



However, not all e-fuels used in the EU will be produced in the EU: lower costs and policy support could drive imports

Favouring non-EU production	Favouring EU production
Availability of **low-cost high availability renewable electricity**	Some areas with **high availability of low cost renewable electricity**
Lower **land** costs	Proximity to **location of technology developers**
Wide range of locations with **co-location** of renewable electricity, availability of CO_2 / energy and land available for DAC, proximity to port	**Biogenic CO_2** more likely to meet RED III sustainability requirements
Policy support is currently limited in most regions, except in the US, where the Inflation Reduction Act (IRA) provides strong financial support for domestic clean hydrogen production including if use for e-fuel production.	**Proximity** to EU market
	National or regional **supply side support** for projects

Note that EU rules on additionality, temporal and geographical correlation of renewable electricity supply and electrolyser electricity demand will apply to both EU and imported fuels. This may favour production in some specific countries/regions (e.g. those with high RE shares) but not related to them being EU / non EU

If 40% of EU+UK e-fuels were produced in the EU+UK, 33-61% of the max potential would be needed for fuels alone

Import assumptions

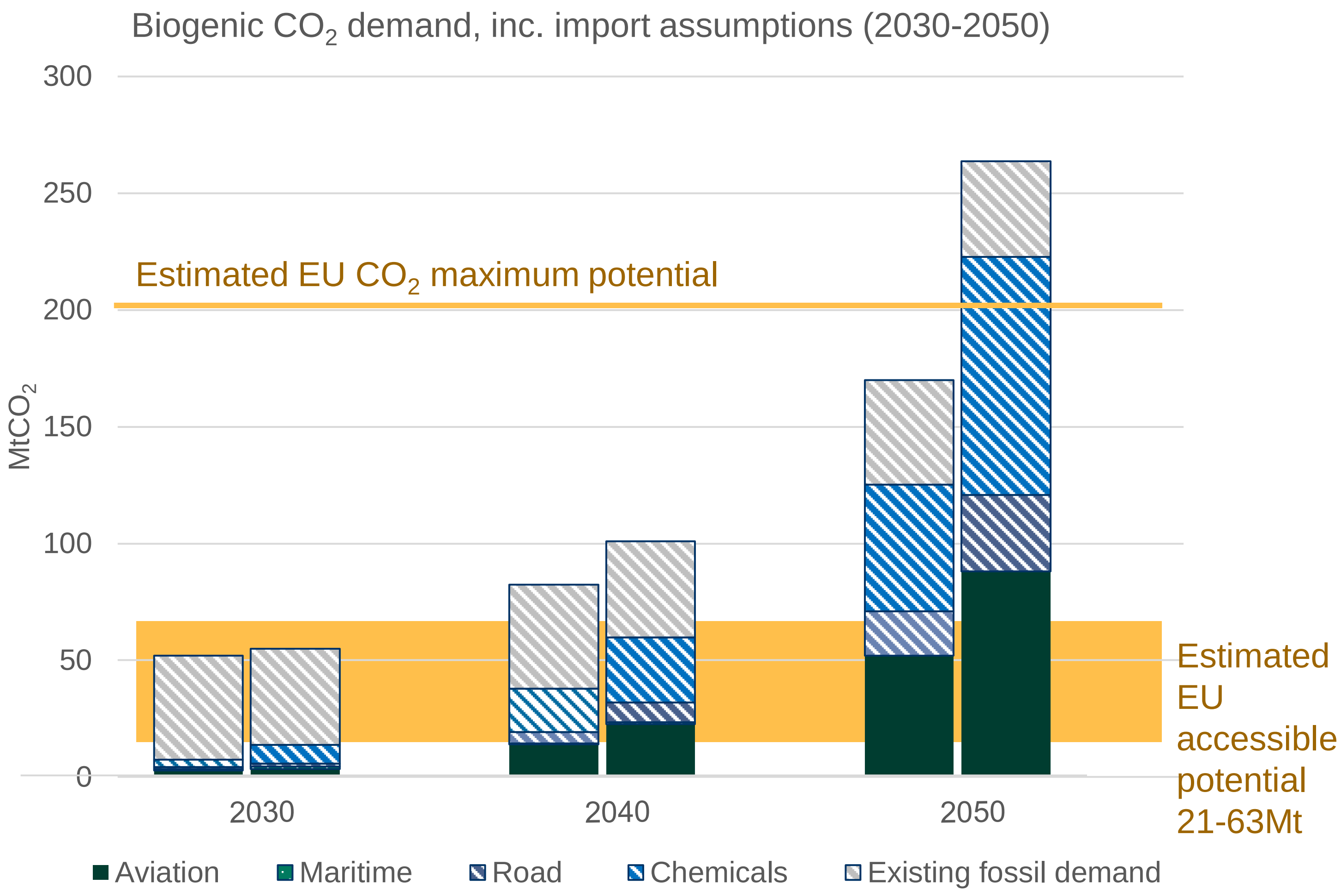
Decreasing level of certainty over drivers and volumes

Biogenic CO_2 removal	**n/a**
Replacing existing fossil CO_2 demand	**All EU**
Chemicals	**All EU**
Road	
Maritime	
Aviation	

E-fuels produced in the EU will compete with imports based on production cost

High EU production scenario: based on currently planned e-fuel production in commercial plants: 75% EU, 25% ROW.

Low EU production scenario: 40% EU, 60% ROW, similar to share of primary energy imported in the EU and projections for hydrogen imports. E4tech's view is that this scenario is more likely as a result of the availability of low-cost renewable electricity globally



Combines the Low demand scenario with Low EU production scenario, and High demand scenario with High EU production scenario

Future biogenic CO_2 emissions are highly uncertain: increased biomass use could be offset by BECCS uptake

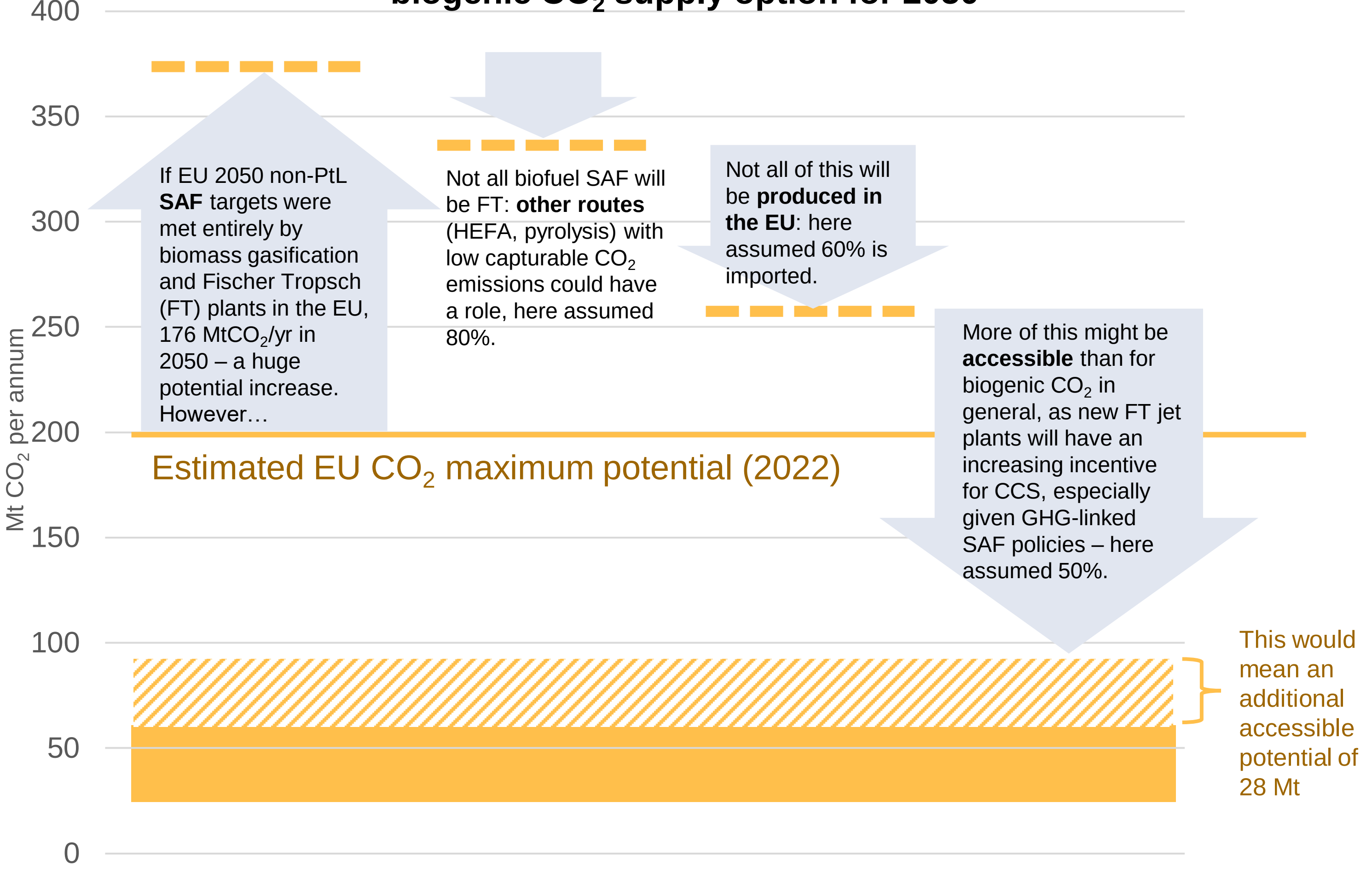
Increased uptake of biomass and biomass derived products in existing industries could increase biogenic emissions.

- Greater use of **solid biomass in industrial fuel switching** and increased use of **biomass in the chemical industry**
- Producing **more ethanol** could increase supply, but the EU outlook is uncertain given gasoline demand reduction and imports.
- Biogenic CO_2 could increase from **gasification-based fuel production** for aviation and road
- Further ramp up of **biogas and biomethane** could increase supply

However, there is the also the potential for **bioenergy with CCS** to ramp up, meaning that these sources of biogenic CO_2 would not be available for CCU.

- Policy to support each of these uses, or to support new industrial plants in general, may include a **requirement or a driver for CCS**. Very little policy is in place today.
- The amount of biogenic CO_2 stored is **highly uncertain** – for example most of the scenarios in the EU 2050 decarbonisation pathways from the 2018 Clean Plant for All report[1] have under 10 Mt/yr BECCS, but one scenario has over 170 Mt/yr.

Illustration of uncertainty over one potential new biogenic CO_2 supply option for 2050



1. EU Commission, 2018

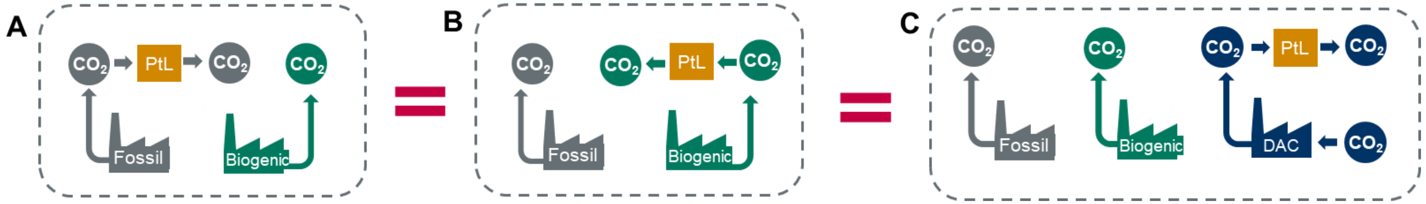
This limit to biogenic CO_2 availability means that other CO_2 sources could be needed to support PtL and other needs

- Availability of accessible biogenic CO_2 is likely to be higher than the projected demand in the near term (2030). However, by 2040, the projected demand for fuels alone is within the projected range of the accessible potential, and surpasses the projected accessible potential by 2050.
  - This is before demand for non fuel uses are taken into account – which are very uncertain.
  - The maximum and accessible potentials are based on current data, with no change projected over time. Future supply is highly uncertain: increased use of biomass in industrial fuel switching and chemicals could increase biogenic CO_2 emissions, whereas new policy drivers for BECCS could decrease them.
- Nevertheless, the scale of demand even from the aviation sector alone, when compared with the accessible potential, shows that the **availability of biogenic CO_2 could become a limiting factor on the growth of PtL** by 2040 in some scenarios and by 2050 in all scenarios
- This means that either supply will be limited, further imports will be needed, or **other sources of CO_2** will be needed.
  - DAC and geological sources – DAC has few inherent constraints on ramp up but few drivers today
  - Imported CO_2 – possible, but less likely than imported fuel, given transport costs
  - Non biogenic point sources: this raises the question of whether other sources could be used sustainably

Using CO_2 from point sources has lower emissions than DAC today, but care is needed on point source use longer term

Direct GHG impacts of CO_2 capture and use

- The source of the CO_2 does not inherently affect the GHG intensity of the PtL product: using the CO_2 from fossil, biogenic or atmospheric sources to produce fuels will not affect total overall emissions, since CO_2 is re-released when PtL fuels are combusted.



- However, capturing CO_2 from different sources uses different amounts of energy and materials. Direct air capture has higher energy use than capture from point sources, as a result of lower CO_2 concentration.

- Using point sources will lead to lower energy use than DAC

Energy system and wider impacts of CO_2 capture and use

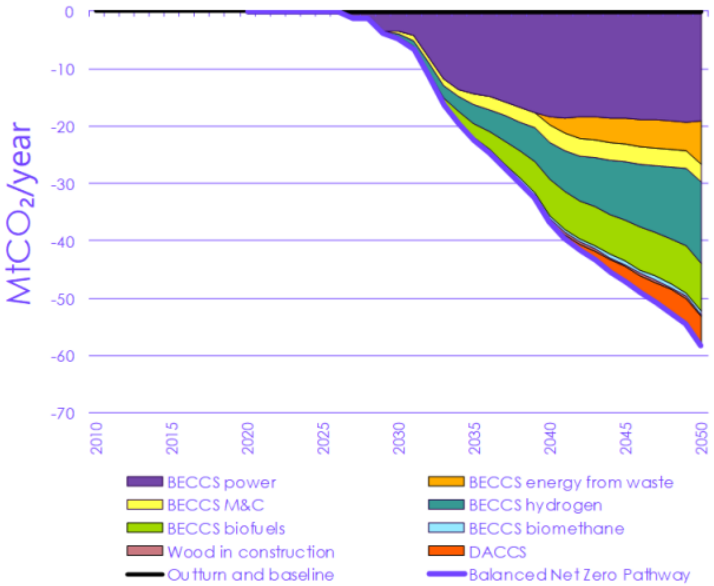
- Payments to point source emitters from sale of their CO_2 to PtL facilities could:
  - Prolong the lifetime of fossil CO_2 emitting plants rather than switching to lower GHG alternatives and/or
  - Divert/delay CCS from point sources, which will be needed to achieve net zero – this applies to both fossil and biogenic sources

- This type of concern led to the DA restrictions on point source use post 2036
- However, as biogenic CO_2 supply is limited, further specific analysis is needed on whether and how other point sources could be used sustainably

To achieve net zero, policy must drive emissions reduction and encourage CO_2 capture from all point sources

- Achieving net zero will be challenging, and require a range of major changes to the energy system, supported by policy
- Fossil point source emissions need to be **reduced as far as possible**, by switching to alternatives, such as electrification using renewables
- A high proportion of **point source emissions of all types will need to be captured**. Any non-biogenic emissions not captured will need to be matched by greenhouse gas removal from the atmosphere. Given that BECCS is one of the major ways to do this, biogenic emissions will need to be captured and stored wherever possible.

Example: GHG removals required for the UK to meet the Climate Change Committee's Balanced Net Zero Pathway, showing BECCS pathways as the major contributor to 2050[1]



Aims

- CO_2 capture and transport from **all point sources** needs to be maximised to support CCS and CCU, including PtL. This includes maximising accessible biogenic CO_2
- In the long term, to achieve net zero, **all remaining CO_2 emissions need to be balanced** by CO_2 removal and storage, e.g. through DACCS and BECCS.

Recommendations

- More support for CO_2 capture and transport infrastructure across all sectors and plant sizes
- Incentives for CO_2 storage, plus additional market-based incentives for negative emissions which would promote capture of biogenic CO_2
- Consideration of the fate of the CO_2 produced for all new plants built, including incentivising new industry in locations likely to have infrastructure in the near term

- Balancing CO_2 emissions with removal and storage will rely on comprehensive CO_2 pricing mechanisms coupled with mechanisms to support negative emission technology deployment

 [1]Sixth Carbon Budget - Climate Change Committee (theccc.org.uk) page 198

Action is also needed to make sure that some of the captured CO_2 is available for CCU, including for PtL

Aims

- **DAC** needs to ramp up quickly and minimise costs and GHG impacts

- Whilst most CO_2 will need to be permanently stored long term, there will be **a need for CO_2 for CCU including PtL**, whether from point sources or from DAC. For point sources meeting the criteria below, CCU rather than CCS may be a more viable option.

  1. The source will **exist long term**, rather than shutting down because it is viable and preferable to move to another location or technology option AND
  2. The source has **no alternative options** that do not release $CO_{2,}$ such as electrification AND
  3. The source has **no economically viable CO_2 transport and storage** options, for example being located far from storage sites, or in regions whether CO_2 infrastructure is unlikely to be developed within the lifetime of a PtL plant

- **PtL imports** will be needed to help meet targets. CO_2 imports are possible, but PtL import is more likely. Barriers to PtL investment globally need to be overcome, including uncertainty over targets and rules.

Recommendations

- Policy mechanisms are needed to encourage **DAC deployment** for all applications (including CCS and PtL)

- In the proposed DA, a range of point sources are allowed but only until 2036 – this will not be enough time for PtL plants to pay back.
- A **project-level approach** to assessing the sustainability of use of point source CO_2 could consider the options available to each site today and in the future, allowing use for PtL post 2036 where other options are not feasible
  - This approach would require the producer of the CO_2 to provide justification of why the criteria given are met, including details of the alternative options available to them, and comparison with the actions taken by other similar emitters
  - This justification could be verified through a voluntary scheme, as for fuel sustainability certification
- Carbon pricing needs to apply to the producer of the CO_2 used in CCU (including PtL) so that the producer has a continued incentive to identify options to remove or reduce them

- Policy decisions on targets and sustainability at EU and MS level need to be **finalised quickly**, to facilitate project investment and deployment.

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European policy context

Overview of policy environment for SAF production and CO_2 utilisation

- The policy landscape in Europe for fuels, sustainability, and CO_2 utilisation is shifting rapidly, with several announcements and proposals in recent years.
- The demand for CO_2 for SAF, and for production of fuels for other sectors, will depend crucially on EU and Member State level policies, given the high production cost of PtL fuels compared with incumbent and competing options.

- The demand for e-fuels in the **aviation sector** in the EU will mainly be driven by **ReFuelEU Aviation,** specifically the PtL subtarget.

- The demand for e-fuels in the EU **maritime sector** is uncertain but it will likely be driven by **FuelEU Maritime**. Currently e-fuels are allowed to claim renewable fuel credits in some European countries but are not obligated.

- The demand for e-fuels in EU **road transport** sector will come from the **RED RFNBO targets, as implemented in each Member State**. The road transport RFNBO demand will depend on:
  - The amount of hydrogen directly used in **fuel-cell vehicles;** hydrogen used as feedstock in conventional fuel **refineries;** RFNBOs used in **aviation and maritime**

Aviation markets for e-fuels in the EU will be driven by ReFuelEU Aviation

- ReFuelEU Aviation is a **legislative instrument** to increase the share of sustainable aviation fuel (SAF) in aviation. This was initially proposed in July 2021. The mandate will **take effect in 2025.**
- The proposed policy sets out targets for both **advanced biofuels** and **green synthetic fuels** (e-fuels), as well as the list of **eligible feedstock and fuel types** within each category.
- Since the proposal, both the Council and Parliament have put forth their positioning amending the initial policy with the Parliament aiming for higher SAF targets (*see table to the right*).
- Currently, an **"informal" trilogue** between the European Commission, Council and Parliament is taking place to reach a compromise between their positions.
  - If the coming trilogue is successful, a final text could be set by the **end of the year**.
  - If the first attempt fails, the draft policy goes back for a "second reading", which means the Council and Parliament have to find new positions respectively, which can take a few months. After that, they will come together for "formal" trilogues, thus delaying the amendment release to **early 2023**.
- CO_2 eligibility will be defined under the Delegated Act, see slide 5.

Proposed & revised ReFuelEU Aviation SAF mandate*

	European Commission, July 2021 Proposal		**European Council, June 2022 Approach**		**European Parliament, July 2022 Amendment position[1]**	
Target	*SAF*	*E-fuel*	*SAF*	*E-fuel*	*SAF*	*E-fuel*
2025	**2%**	-	**2%**	-	**2%**	0.04%
2030	**5%**	0.7%	**6%**	0.7%	**6%**	2%
2035	**20%**	5%	**20%**	5%	**20%**	5%
2040	**32%**	8%	**32%**	8%	**37%**	13%
2045	**38%**	11%	**38%**	11%	**54%**	27%
2050	**63%**	28%	**63%**	28%	**85%**	50%
Eligible e-fuel types	E-fuels: RFNBOs		E-fuels: - drop-in RFNBOs		E-fuels: - RFNBOs, renewable hydrogen, renewable electricity	

*The targets are volume-based

Germany has set minimum blending targets for PtL aviation fuel that deviate from those in ReFuelEU Aviation

- A **PtL obligation** on aviation fuel suppliers was introduced under the national GHG reduction target for transport.
- The Federal Ministry released a **PtL Roadmap**[1] that aims to actively promote the production and uptake of e-fuels in general and particularly PtL-based kerosene. This is reflected in the introduction of a mandatory minimum blending quota for PtL kerosene.
  - This obligation will begin in **2026 at 0.5%** on an energy basis and is set to increase to **2% by 2030.**
- ReFuelEU Aviation would **supersede any national SAF mandates**. However, the EU Commission's proposed policy indicates that Member States (MSs) are entitled to take 'national measures, supportive policies, and initiatives aiming at increasing the level of production and uptake of SAF'[2]. It is uncertain if Germany would be allowed to deviate from the ReFuelEU targets, as such, there could be further negotiations in the future on this topic.
- The CO_2 eligibility is expected to follow the **EU Delegated Act,** see slide 5.

Summary of German biofuels and PtL targets, multipliers and caps to 2030

Implemented targets, multipliers and caps	2022	2023	2024	2025	2026	2027	2028	2029	2030
GHG reduction quota	7.0%	8.0%	9.25%	10.5%	12.0%	14.5%	17.5%	21.0%	25.0%
PtL kerosene in aviation (minimum share, by energy)					**0.5%**		**1%**		**2%**

UK is expected to introduce a SAF mandate in 2025 with a PtL sub-target but details are not yet known

- The greenhouse gas (GHG) based SAF mandate is still under development and is expected to reach the equivalent of at least 10% SAF volume by 2030.
- A PtL sub-target will be implemented which will drive demand for CO_2 based e-fuels, but the target level is currently unknown.
- The CO_2 eligibility is expected to follow the existing rules set out for RFNBO under the RTFO, which is more relaxed than those in the Delegated Act.
  - Eligible CO_2 sources can come from waste fossil sources, biological sources or from atmospheric or naturally-occurring/geothermal sources, provided that this CO_2 is not deliberately produced for the purpose of producing a RFNBO.
- It is expected that the target level set out by the UK SAF Mandate will at least be on par with EU policies. As such, ReFuelEU Aviation targets will be used as a proxy to estimate CO_2 demand in the UK.

This results in the demand for CO_2 for e-SAF as shown in the table below

Scenario	PtL target (% of total jet fuel)			SAF Ptl demand (PJ)			CO_2 demand ($MtCO_2$/year)		
	2030	2040	2050	2030	2040	2050	2030	2040	2050
Commission proposal	0.7%	8%	28%	14	162	582	1.3	15.0	54
Parliament first reading position	2%	13%	50%	39	263	1038	3.6	24.4	96
Parliament first reading + UK (same RFNBO%)	2%	13%	50%	49	326	1265	4.6	30.3	117

Assumptions

- **EU jet fuel demand** – EU reference scenario 2020[1]. This is a high demand case, since there may be reductions in 2030-2050
- **CO_2 required per tonne of SAF** – assumed to be 4.1 $tCO_2/t_{product}$ output, for a RWGS + FT plant with a product slate of 73% jet, 27% naphtha. Note that this is the total CO_2 requirement for the SAF production. Note that the CO_2 associated with the production of the naphtha co-product of the SAF production will be taken into account as part of the RFNBOs in the road transport sector
- **UK jet fuel demand** – Balanced Pathway of CCC 6th Carbon Budget[2]. The RFNBO share of the total jet fuel demand is assumed to be equal to the Parliament's first reading position PtL sub-targets
- **Methanol to Jet route (MTJ) vs. RWGS + FT route** – If all jet fuel consumed in EU was to be produced through the MTJ route instead of RWGS+FT, the total CO_2 demand for the production of e-SAF would be **19% lower;** the MTJ route assumes 3.3 $tCO_2/t_{product}$ output, with a product slate of 75% jet, 15% diesel, and 10% naphtha.

The uptake of RFNBOs in the EU maritime sector is likely to be driven by FuelEU Maritime

- The **FuelEU Maritime** is a proposed legislative instrument within the EU 'Fit for 55' package announced in July 2021 that intends to support the uptake of renewable maritime fuels by setting a limit on the GHG intensity of the energy used by large ships. If the proposal is accepted, it is expected to come into force on Jan 1, **2025**.
- In June 2022, the EU Parliament ITRE and ENVI committees proposed two amendments to the original EU Commission proposal, which raised the greenhouse gas intensity reduction ambition to 100% of the energy used on-board by a ship and introduced the following (energy-based) **RFNBO sub-targets**:

Proposed targets	2030	2035	2040	2045	2050
EU Parliament: ITRE committee[1] (minimum share, by energy)	**2%**	**6%**			
EU Parliament: ENVI committee[2] (minimum share, by energy, inc. renewable hydrogen & electricity)	**6%**	**12%**	**24%**	**48%**	**70%**

- More recently, the European Parliament plenary final position on RED III (September, 2022) included a RFNBO target of 1.2% in maritime starting in 2030, which is lower than the targets in the committees positions. Note that both RED III and FuelEU Maritime are still being finalised, and it is unclear what target will be in the final policy.
- In some countries, e-fuel use in maritime can opt in to policies established for road fuels
  - **In the UK**, Starting from January 2022, the RTFO order has been changed to allow RFNBO fuels including hydrogen, e-methanol and e-ammonia to be used in maritime to **opt in** towards the **RTFO target** (but marine fuel is **not** obligated)
  - **In the Netherlands**, renewable fuel suppliers supplying RFNBOs to the shipping sector can **opt in** and benefit from the HBE trading scheme. Currently, only e-fuels produced with electricity generated in NL are allowed, receiving 2.5 new HBE-O certificates.

It is uncertain how much of this RFNBO demand will be met by fuels requiring CO_2, meaning fuel mix scenarios are needed

- There is yet no consensus on the mix of low carbon fuels in the maritime sector, or the mix within RFNBOs, which could include e-methanol, e-ammonia, e-LNG, and hydrogen
  - In the **long term (2050)** many expect demand to be met by renewable hydrogen, e-ammonia, and renewable electricity, with no resulting CO_2 demand. As such in 2050 we have assumed hydrogen and ammonia only, with no CO_2 demand
  - In the **near term**, most RFNBO interest is in e-methanol (ERM experience) but also in e-LNG (according to DNV[1]). Here we assume a 50/50 split between e-LNG and e-methanol in 2030, and a third each for e-ammonia, e-LNG, and e-methanol for 2040

Scenario	PtL target (% of total marine fuel)			PtL demand (PJ)			CO_2 demand ($MtCO_2$/year)		
	2030	2040	2050	2030	2040	2050	2030	2040	2050
FuelEU ENVI committee	6%	24%	70%	126	554	1650	7.9	23.1	0
FuelEU ITRE committee	2%	6%		23	75		1.4	3.1	0
EU Parliament RED III final plenary position	1.2%			25			1.6		0

Assumptions

- **CO_2 required per PJ of fuel** – assumed to be 0.067 $MtCO_2$/PJ methanol and 0.058 $MtCO_2$/PJ e-LNG
- **EU marine fuel demand** – assumed domestic and international shipping demand from the EU Reference Scenario 2020[1]
  - **FuelEU Maritime** regulates intra-EU plus 50% (original proposal & ITRE committee) or 100% (ENVI committee & assumed for RED III) of international shipping for vessels sailing from and to an EU country.
  - Although it only covers ships > 5000GT (original proposal) 400 GT (ENVI & ITRE committees amendments), in this analysis we assume all ship sizes are regulated by FuelEU Maritime (given that most emissions arise from the fuel consumed by larger ships[2]).

The uptake of e-fuels in the EU road sector will be driven by REDIII's RFNBO sub-targets for transport

- The Renewable Energy Directive (RED) was first proposed in 2009 with the aim of increasing the share of renewables in the EU energy mix. The Commission further proposed more ambitious targets in July 2021 as part of its 'Fit for 55' package. Since then, the Council and the European Parliament have proposed their own revision of the Directive, now labelled 'RED III'.
- RED III introduced a **dedicated target for RFNBOs in transport**, which includes the use of renewable hydrogen and PtL in the transport sectors, as well as renewable hydrogen in refineries for the production of conventional fuels.
- The latest European Parliament position[1] voted on on 14 September 2022 will now be discussed in a trilogue process between the Parliament and Council, at which point it could be adopted, or sent back for further revision.

RED III measures and targets by 2030

Measure	RED II	RED III proposal	Council approach	European Parliament (13 Sept. 2022)
Overall transport target*	14% RES	13% GHG reduction	13% GHG reduction OR 29% RES	16% GHG intensity reduction
RFNBO sub-target* (volume-based)	No sub-target	2.6%, no 2x multiplier	5.2%, with 2x multiplier	5.7%, 1.2 multiplier for aviation & maritime (2.6% by 2028)

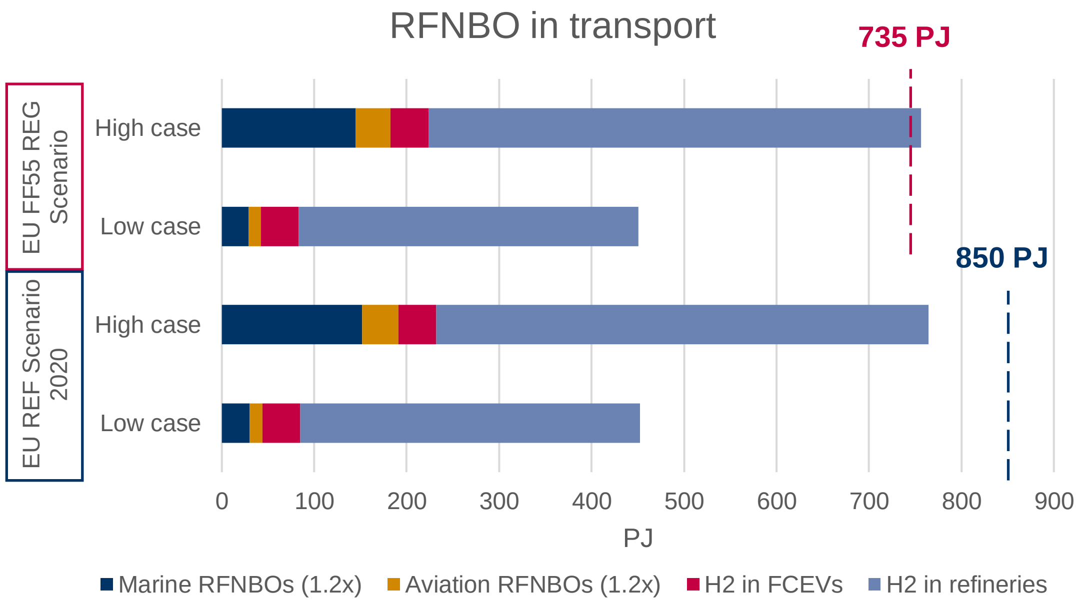
*Including road, rail, maritime, and aviation sectors

Use of hydrogen in refineries could supply a high proportion of the RFNBO in transport sub-target

- The European Parliament latest position on RED III states that in calculating the share of renewable energy in transport, Member States may account for hydrogen when this is used as an **intermediate product for the production of conventional fuels**.
- Hydrogen in conventional refineries is currently obtained as a by-product of specific refinery processes such as catalytic reforming or directly produced by steam methane reforming (SMR) of natural gas
- Replacing grey H_2 with green H_2 for the production of conventional fuels is a technically feasible decarbonisation strategy with low additional costs to refineries; refineries are indeed expected to contribute to the largest demand for renewable or low-carbon hydrogen by 2030 in the EU[1]
- Assuming only the hydrogen produced through SMR is substituted with green $H_{2,}$ **replacing hydrogen in refineries could contribute to 43%** (low case) **to 63%** (high case) of the RFNBO target, given 2030 projections from FCJ JU 2020's H_2 in refineries[1] and the **EU Reference Scenario 2020**[2]; by assuming projections of 2030 fuel consumption in transport from the **EU Fit for 55 REG Scenario**[3]**,** **50%** (low case) and **72%** (high case) of the RFNBO 5.7% target could instead be met by H_2 in refineries by 2030.
- Although it is not clear how the use of hydrogen in refineries will be calculated, some MSs have interpreted this to mean that a MJ of hydrogen input to a refinery should receive the same level of support as a MJ of hydrogen used in a vehicle. The way that this is done is crucial to how the willingness to pay in each country will be calculated.
  - In this analysis the hydrogen used as intermediate product for the production of conventional fuels has been assumed to count once towards the transport target (no multiplier)

Meeting RFNBO targets in transport depends heavily on H_2 in refineries, meaning very different potential demands for road PtL

- Taking a high and low scenario for RFNBO uptake in each of the sectors below, and combining them to give an overall high and low case, shows that the remaining demand for RFNBOs in transport could range from 80 to 400 PJ in the EU REF scenario and 0 to 280 PJ in the EU FF55 REG Scenario in 2030.
- This is based on underlying demand from the 2 scenarios, plus:
  - **Maritime:** REDIII RFNBO sub-target of 1.2% of marine fuel must be met, potentially increasing to 6% (FuelEU Maritime ENVI committee) of marine fuel. 1.2x multiplier towards overall target
  - **Aviation:** ReFuelEU Aviation sub target must be met, ranging from 0.7% (Commission proposal) to 2% (Parliament position) of aviation fuel. 1.2x multiplier towards overall target
  - **Hydrogen in refineries:** 370 PJ (low case) to about 530 PJ (high case) in 2030 according to FCHJU (2020)
  - **Direct use of hydrogen in road transport** (FCEVs) mostly driven by heavy duty vehicle fuel demand[1,2] : about 40PJ as retrieved from the EU FF55 REG Scenario[1]



- This demand could be met with use of PtL in road, including the naphtha produced as a co-product of the SAF production above. For comparison, 1% of road transport demand in 2030 is 92PJ (EU REF Scenario) or 87PJ (EU FF55 REG Scenario)

As a result, we have instead used high level scenarios of liquid e-fuel demand within the road transport sector

- As a result, we have considered a low and high scenario for e-fuel demand in road:
  - **Low case** – assumes that there is little policy driver for liquid e-fuels in road, and so the only liquid e-fuel supplied to road is from the naphtha and diesel co-products of SAF (based on the EP plenary scenario)
  - **High case** – assumes the projected liquid e-fuel demand from a Concawe report[1] , which provides the background data for T&E's analysis on e-fuels in road[3]. The Concawe study is described as supply-limited, but results in e-fuels supplying half of liquid fuel demand in road in 2050, given strongly decreasing road liquid fuel demand. We have compared the Concawe projections with those from E4tech's in house ramp up model and consider that these are high, but not impossible assumptions of the share of global EU fuel production that could come to the EU

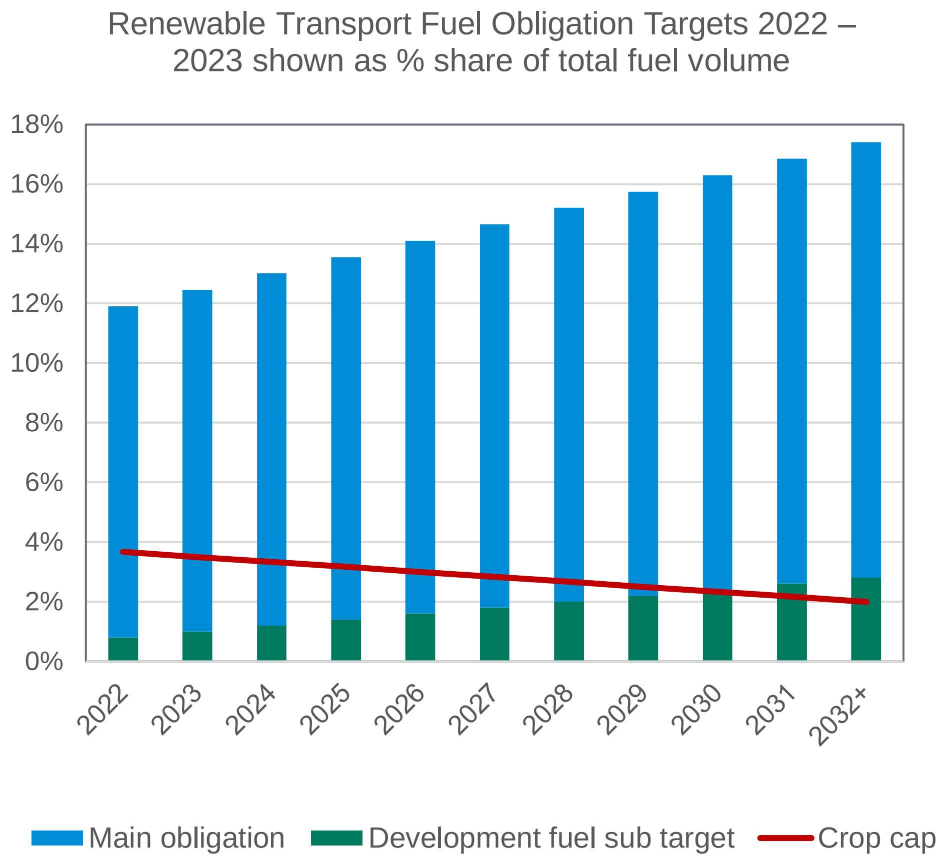
Scenario	PtL demand (PJ/yr)			CO_2 demand ($MtCO_2$/year)		
	2030	2040	2050	2030	2040	2050
Low Case	18	122	472	1.7	11	43
High Case	42	879	1926	3.9	82	179

Assumptions

- **CO_2 required per PJ of fuel** – assuming 44 GJ/t of diesel energy density and 4.1 $tCO_2/t_{product}$ output considered for RWGS + FT plants
- **Naphtha & diesel SAF co-products** – A portion of the above PtL quotas in road transport will be met by naphtha and diesel co-products from SAF production facilities; assuming the ReFuelEU final EP scenario, the SAF co-product portion of the road e-fuels in the high case scenario is 35%, 11%, and 20% in 2030, 2040 and 2050, respectively.

Note that in the UK, road PtL can be counted towards the RTFO but there is no sub-target for it, and we have not included it

- The RTFO sets the target for conventional and development renewable fuel supplied in the road market. These fuels can generate Renewable Transport Fuel Certificates (RTFC) depending on their fuel category.
- Every litre (or equivalent) of CO_2 based e-fuels can claim two conventional RTFC or two development RTFC (dRTFC) if it can be as a drop-in fuel or as an aviation fuel (until SAF mandate begins 2025).
- dRTFCs have a higher value than conventional RTFC. They can also be generated by supplying hydrogen and other types of advanced drop-in biofuels which are expected to make up most of the development fuel market share. In addition, fuel used in both aviation and maritime can be used to generate such certificates, although they are not obligated.
- Currently, the UK is a particularly attractive market for e-fuels because the RTFO is in place today, whilst policy mechanisms in many other MSs are not. However once the supply of other development fuels increases, and policies are established in the EU, this will change. As such, we have not considered UK uptake separately from the EU



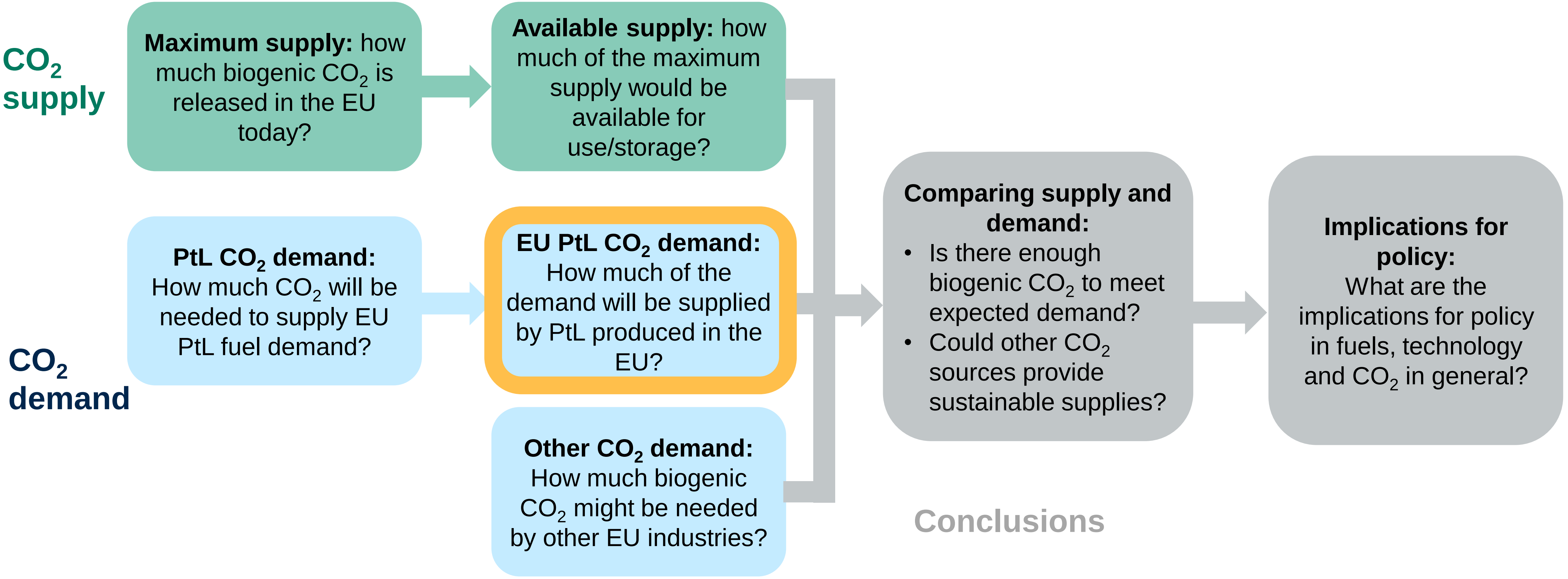
Taken together, this gives the following resulting demand for CO_2 for RFNBO use in all transport sectors

Scenario	PtL demand (PJ)			CO_2 demand ($MtCO_2$/year)		
	2030	2040	2050	2030	2040	2050
Aviation (ReFuelEU final EP) (inc. UK)	49	326	1265	4.6	30	118
Maritime (REDIII final EP)	25	25	25	1.6	1.1	0
Road (Low case)	18	122	472	1.7	11	43
Road (High case)	42	879	1926	3.9	82	179
Total Transport: (Low Case)	**93**	**473**	**1763**	**7.8**	**43**	**161**
Total Transport (High Case)	**116**	**1230**	**3217**	**10**	**113**	**296**

Assumptions

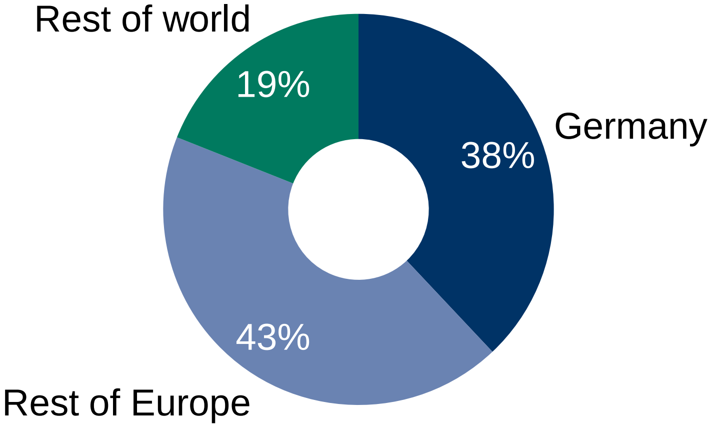
- **Total transport RFNBO demand** – Total RFNBO demand (excluding hydrogen) has been calculated assuming the ReFuelEU Aviation final EP scenario and the REDIII final EP maritime scenario
- **CO_2 required per tonne of fuel** – based on RWGS + FT plants

EU PtL CO_2 demand: How much of demand will be supplied by PtL produced in the EU?

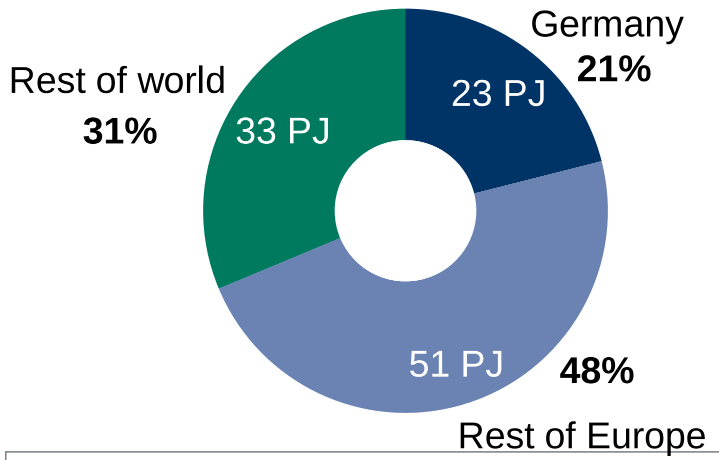


Most PtL plants are located in Europe currently, almost half of which are in Germany

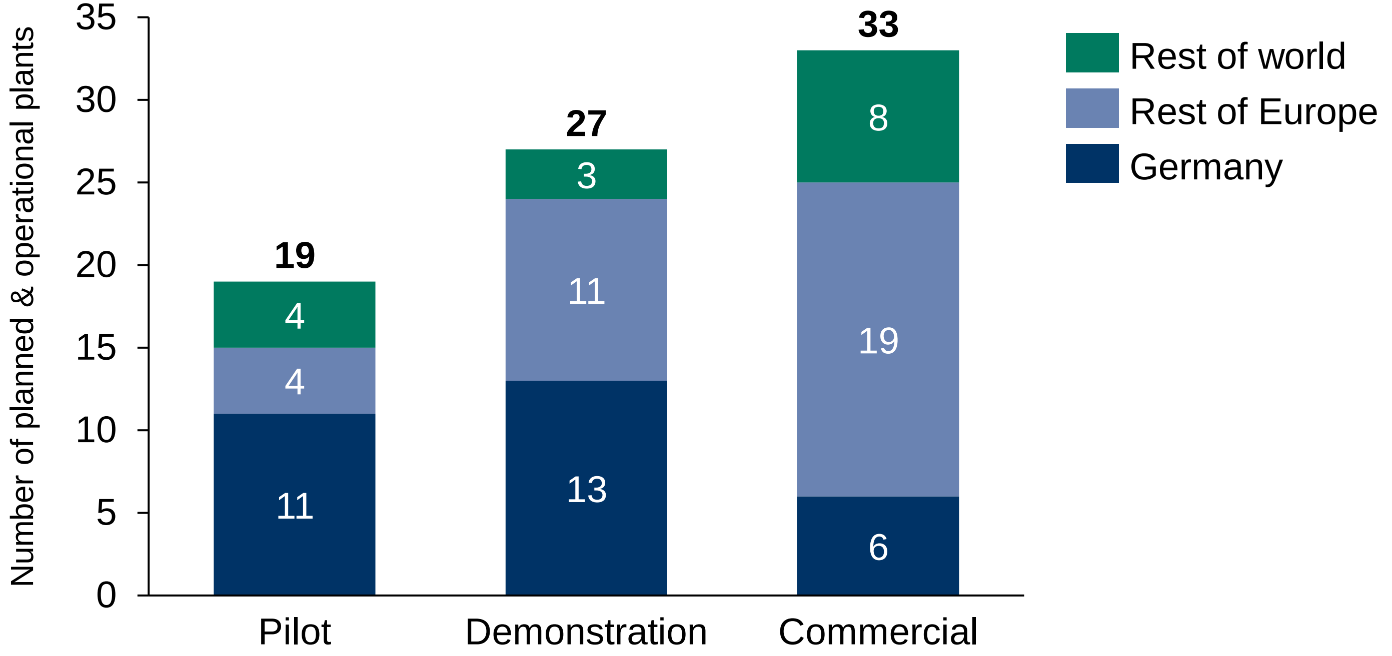
Number of planned/operational plants



Planned/operational capacity (PJ)



- The graphs show total PtL output (all products) from operational and planned plants in E4tech's advanced fuels database
- Currently, 81% of planned and operational plants are located in the EU, 47% of which are in Germany. However, the majority of the plants in Germany are pilot or demonstration scale, representing 62% and 52% of EU and global PtL pilot/demonstration plants respectively. At the commercial scale, this reduces to 24% and 18%.



NB the pilot/demonstration distinction is set in our database by the plant's own description, rather than a fixed capacity cut off

Lower PtL costs and policy support in other regions may drive increased production outside of the EU in the future

Favouring non-EU production	Favouring EU production
Availability of **low-cost high availability renewable electricity**	Some areas with **high availability of low cost renewable electricity**
Lower **land** costs	Proximity to **location of technology developers**
Wide range of locations with **co-location** of renewable electricity, availability of CO_2 / energy and land available for DAC, proximity to port	**Biogenic CO_2** more likely to meet RED III sustainability requirements
Policy support is currently limited in most regions, except in the US, where the Inflation Reduction Act (IRA) provides strong financial support for domestic clean hydrogen production including if use for e-fuel production.	**Proximity** to EU market National or regional **supply side support** for projects

Note that EU rules on additionality, temporal and geographical correlation of renewable electricity supply and electrolyser electricity demand will apply to both EU and imported fuels. This may favour production in some specific countries/regions (e.g. those with high RE shares) but not related to them being EU / non EU

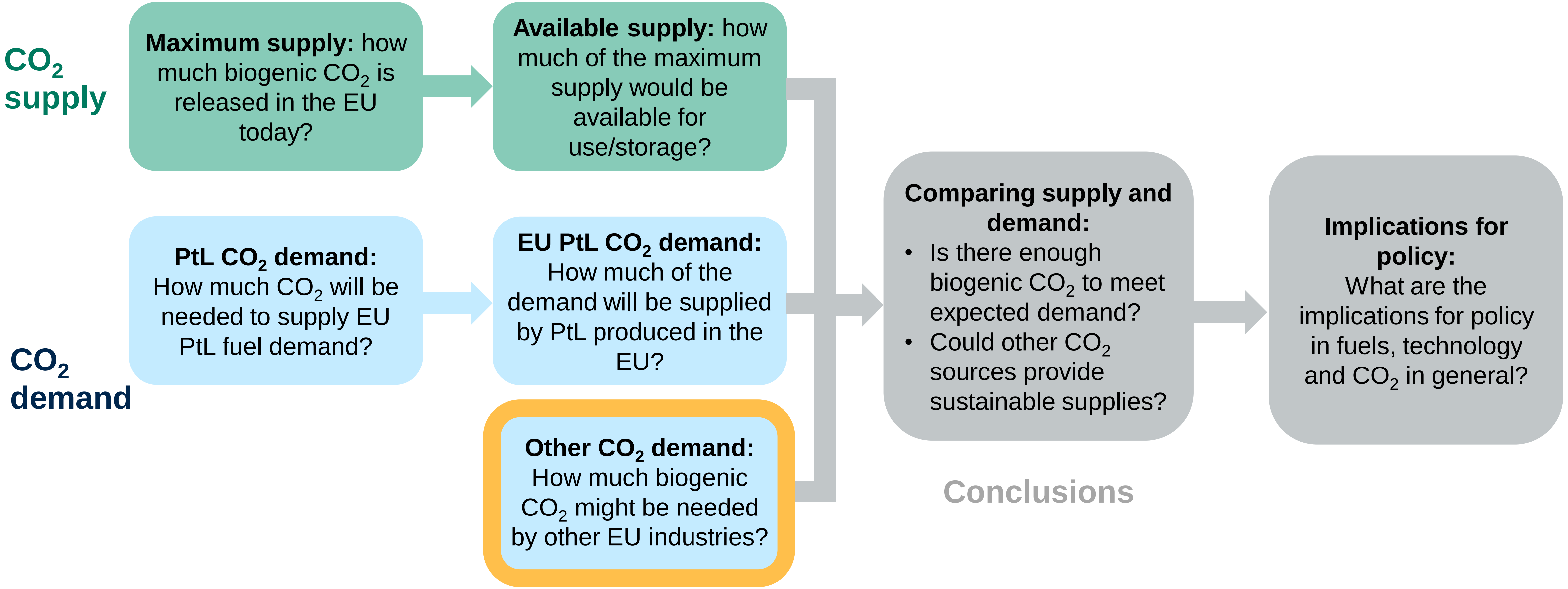
High and low import scenarios were used to reflect the uncertainty in how EU e-fuel demand will be met

E-fuels produced in the EU will compete with imports based on production cost.

- The **high EU production scenario** is based on currently planned e-fuel production in commercial plants. It assumes that of EU e-fuel demand, 75% is met by domestic production and the remaining 25% is met by imports from outside of the EU.
- The **low EU production scenario** is based on the current share of primary energy imported into the EU and projections and targets for hydrogen imports by 2030. In this scenario, 40% of EU e-fuel demand is met by domestic production and 60% is met by imports.

ERM's view is that the low EU production scenario is the most probable as a result of the availability of low-cost renewable electricity globally.

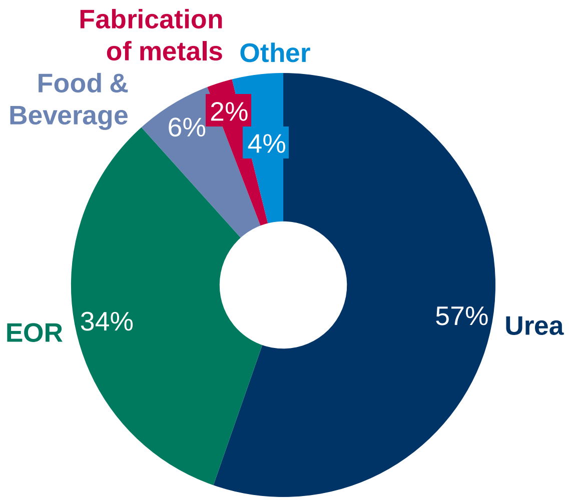
Other CO_2 demand: How much biogenic CO_2 might be needed by other EU industries?



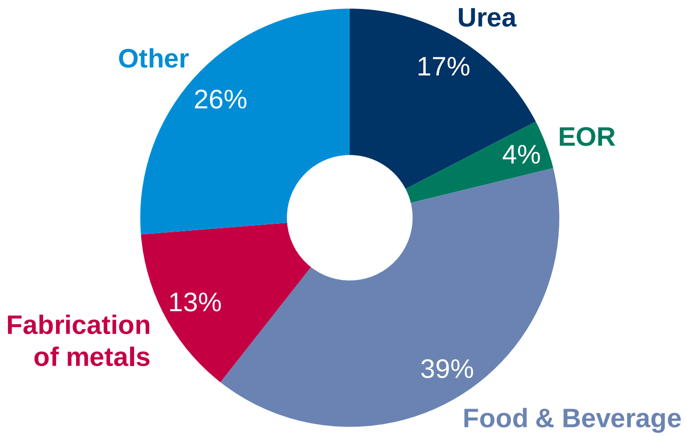
Existing demand is primarily met with by-product CO_2 from fossil fuel reformation

- Currently, the European demand for CO_2 is estimated to be **41 Mt per year** which is 16% of global demand[1]. The following products and sectors are key drivers of demand globally:
  - **Urea:** In industry, urea is conventionally produced by combining ammonia with by-product CO_2 from the reformation of fossil fuels in grey ammonia production. As a result, ammonia and urea production are often co-located. In 2020, approximately 7 Mt of CO_2 was used for the production of urea in Europe.
  - **Food & beverage industries:** In addition to urea production, by-product CO_2 from grey ammonia production can also be used for the carbonation of beverages, packaging, and stunning of animals for slaughter. The European industry has had to cut manufacturing several times over the past few years as spikes in the price of natural gas have resulted in chemicals companies halting ammonia production[3].
  - **Enhanced Oil Recovery (EOR):** Whilst EOR accounts for 34% of global CO_2 demand, this is mostly deployed at North American oil fields. The two sites in Europe are situated in Croatia and Turkey and represent less than 2% of oil produced via EOR worldwide[2]. Therefore, European CO_2 for EOR is likely less than 2 Mt per year.
- As ammonia is decarbonised, it is uncertain whether alternative fossil or biogenic CO_2 sources will be pursued for the urea, food, and beverage industries, particularly as further purification will likely be required regardless of the CO_2 source. Other options for the fertiliser industry include the phase-out of urea in favour of fertilisers.

Global breakdown of CO_2 demand[1]



Estimated European breakdown of CO_2 demand[4]

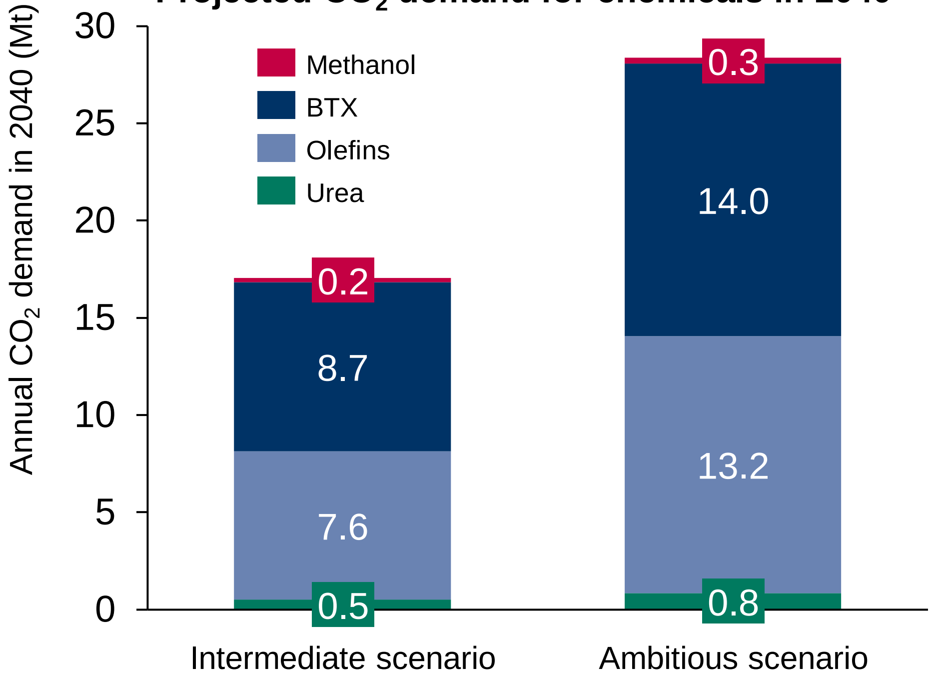


1. Calculations based on IEA, 2019. 2. IEA, 2018 . 3. Reuters, 2022. 4. Calculations based on European CO_2 demand from EOR and urea, with the residual breakdown based on source 1.

CO_2 could also be used as a feedstock for producing chemicals and polymers as industry decarbonises

- As well as fuels, CO_2 and H_2 can be used as feedstocks for Power-to-Chemicals. Alongside efficiency gains, electrification and biomass-based routes, this would support emissions reduction in the chemicals industry.
  - European demand for CO_2 for chemicals in 2040 could reach **17 Mt per year** under DECHEMA's intermediate scenario or **28 Mt** under a more ambitious scenario[1]. In this analysis, chemicals included benzene, toluene, xylenes (BTX), olefins, methanol and urea.
    - Low-carbon production of BTX and olefins is based on methanol produced from CO_2 and H_2. As a result, low-carbon BTX and olefins are at the same TRL as methanol synthesis, TRL 7.
    - Low-carbon urea uses ammonia produced from green hydrogen, currently at TRL 8[2]. As mentioned previously, switching from grey to green ammonia means that alternative CO_2 would need to be sourced.
- Whether the potential CO_2 demand from low-carbon chemical production is met with biogenic or fossil sources remains uncertain.
  - The requirement for 50% of hydrogen used in industry to be met by RFNBOs (using biogenic CO_2) does not directly apply to the conventional production methods for BTX, olefins or methanol. However, manufacturers could choose to meet the RFNBO target by using e-methanol in the production of the chemicals and increasing overall hydrogen consumption.

Projected CO_2 demand for chemicals in 2040



1. Dechema, 2017 . 2. IEA, 2021

Efficiency gains and sequestration potential could see building materials become a key end use of CO_2

- **Concrete curing:** Injecting CO_2 during the curing of concrete can result in a 4-6% reduction in emissions, primarily through reducing the amount of cement required[1]. For a medium sized producer, injecting 24 tonnes of CO_2 over a year would result in 897 tonnes of CO_2 avoided[2].
  - The technology is at TRL 9 with several companies commercialising the process including CarbonCure, Solidia Technologies, and Carbicrete[1].
- **Aggregates from waste:** Alkaline industrial waste residues can be treated and stabilised with CO_2 via the accelerated carbonation process. The CO_2 is permanently sequestered as a result of the process. Once stabilised, the residues can then be reused as aggregate materials.
  - The alkaline waste residues are produced by industries such as steel production, alumina extraction, cement production, and coal-fired power generation[3].
  - It is claimed that more CO_2 is sequestered than is emitted during aggregate manufacture, with a cradle-to-gate CO_2 footprint of -44kg CO_2 per tonne of aggregate reported[4]. Further removal benefits could be realised with the sequestration of biogenic CO_2 instead of fossil. Additional benefits include the potential for a reduction in mining of fresh aggregate material and reduction of wastes.
  - There are three at-scale operations in the UK with one operational since 2012. This puts the process at TRL 9[1].

1. IEAGHG, 2021 . 2. CarbonCure, 2017 . 3. H. Gomes, et al., 2015 . 4. OCO (accessed Oct-22)

Future policy on greenhouse gas removal could also change the availability of biogenic CO_2 for utilisation

- At present, there is no policy support for greenhouse gas removal (GGR) and therefore no clear understanding of how CDR could change the availability of CO_2. However, it is likely to strengthen the case for storage over CO_2 utilisation.
  - The UK is in the process of developing a GGR business model which, in its current proposed form, does not include utilisation[1].

− If bioenergy with carbon capture and storage (BECCS) is incentivised, availability of biogenic CO_2 from sources such as energy from waste is likely to diminish.

+ Future GGR policy may also incentivise direct air carbon capture and storage (DACCS). Whilst this is unlikely to support utilisation, it may bring down the cost of DAC and increase the availability of biogenic CO_2.

− Depending on definitions of "long-term storage", CO_2 use in building materials and possibly even chemicals and other products could benefit as forms of sequestration. Voluntary schemes today such as the Puro Standard, include building materials on the assumption that the lifetime of a building is at least 50 years[2].

1. UK Government, 2022, 2. Puro.Earth, (accessed Oct-22)

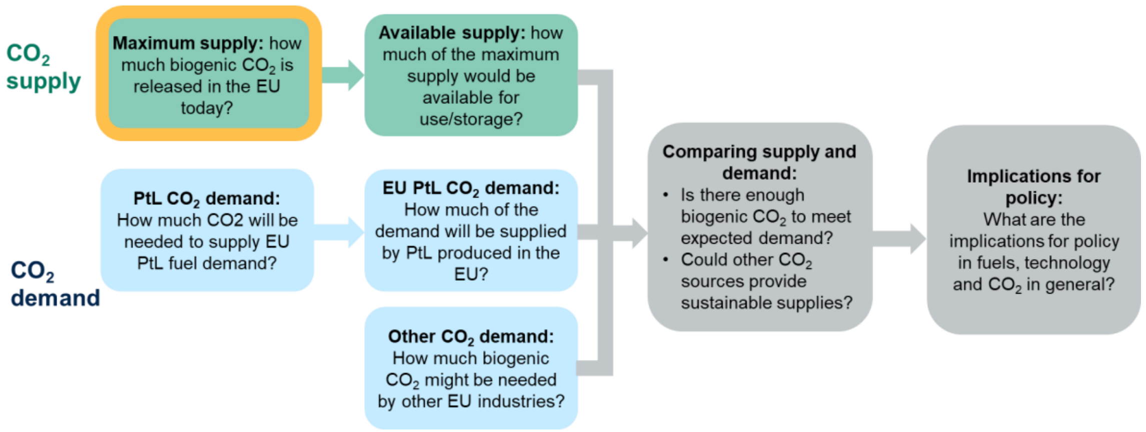
This gives the following resulting demand for CO_2 use in fuels and in other industries

Sector	Scenario	Biogenic or fossil?	CO_2 demand ($MtCO_2$/year)		
			2030	2040	2050
Transport	Low Case (Road transport: Base case)	Biogenic from 2036	8	43	161
	High Case (Road transport: Fast-uptake case)	Biogenic from 2036	10	113	296
Urea	Existing demand replaced	Fossil currently	7	7	7
EOR	Existing demand	Fossil currently	2	2	0
Chemicals (not including urea)	Intermediate	Uncertain	3	17	50
	Ambitious	Uncertain	8	28	102
Food, beverage, fabrication of metals & other	Existing demand replaced	Fossil currently	33	33	33
Total	**Low scenario (intermediate and low road case)**		**53**	**102**	**251**
Total	**High scenario (ambitious with high road case)**		**60**	**183**	**438**

Total RFNBO demand (excluding hydrogen) has been calculated assuming the ReFuelEU Aviation final EP scenario and the REDIII final EP maritime scenario. CO_2 required per tonne of fuel calculated on the basis of RWGS + FT plants

Maximum Supply: How much biogenic CO_2 is released in the EU today ?

Project flow



Maximum CO_2 supply assessment

A. What are the sectors and sources of biogenic CO_2?

B. What is total biogenic CO_2 potential in Europe?

1. Identify best data sources for industrial point sources in Europe.
2. Disaggregate reported biogenic emissions from the database
3. Identify gaps in reported biogenic emissions and close potential data gaps
4. Calculate total available biogenic CO_2 and quantify uncertainties

Approach: we assessed the main sectors expected to have biogenic CO_2 emissions

The aim of this task was to understand:

- What are the main sectors emitting biogenic CO_2 today?
- What is their industrial process, scale and source of biogenic CO_2?
- What is the future trend for the sector (e.g. expanding, declining etc.)?
- What are some of the considerations for the deployment of carbon capture for the sectors?

The insights from this analysis were complemented with the analysis of emissions database (see slides 57-65) and contributed to the estimation of the total and accessible biogenic CO_2 supply at a European level.

Summary of industrial sectors with significant share of biogenic emissions

Sector	Description	Primary biogenic emission sources	Flue gas CO_2 concentration (%)	Future trend of the sector
Paper, pulp and primary wood products	Manufacture of products from wood	Combustion of waste material	14-30	Remain the same
Food and drink	Manufacture of food and drink	Fermentation of alcohol	99	Steady growth
Waste management	Disposing of household and industrial waste	Incineration of food waste	6-12	Growth, particularly of waste to energy plants
Biogas and biofuels	Production of fuels from biomass	Fermentation of bioethanol, upgrading of biogas to biomethane	25-99	Growth
Bio naphtha	Co-product of hydro-processing	Steam cracking	13-15	Growth

Full description of each sector is provided on the following slides

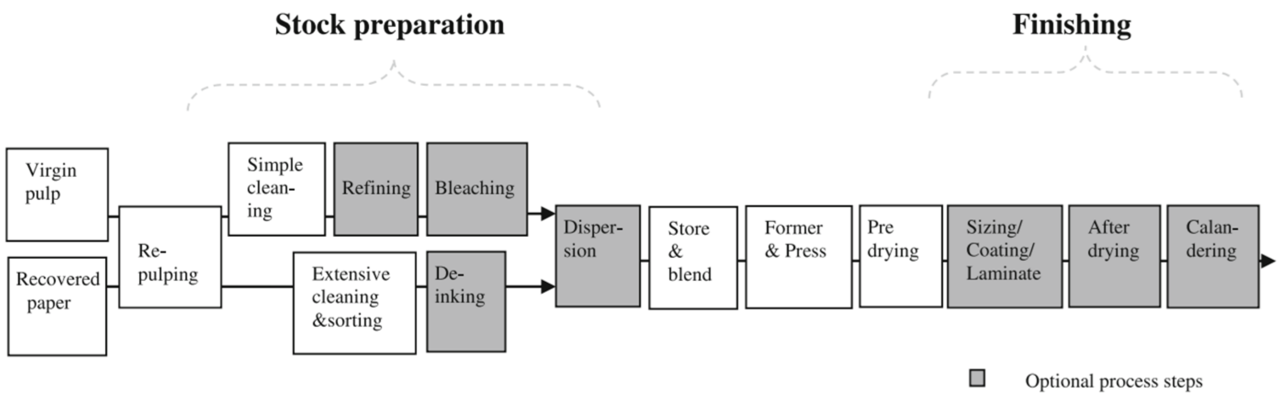
Retrofit of post-combustion CO_2 capture for steam crackers using MEA solvents - Energy.nl

Paper and Pulp

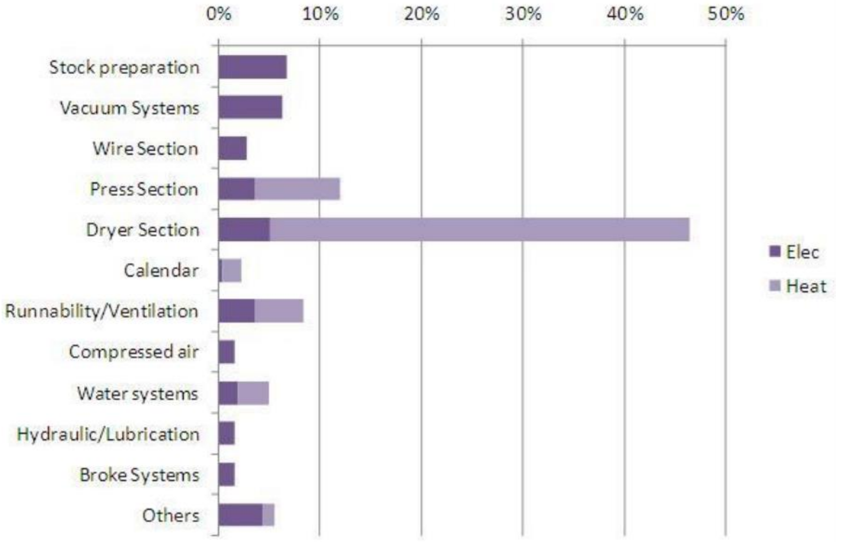
Approximately 60% of all energy used is electricity in the paper and pulp industry

- Paper is made from pulp, which can be produced from wood fibres (via mechanical pulping or chemical pulping), from recovered paper.
- Raw materials included are virgin pulp and recovered paper.
- Pulp from recovered fibres needs to be cleaned in several cleaning steps to remove impurities, e.g. staples, plastics and glue. Sometimes, this type of pulp is also de-inked, depending on product specifications.
- In many paper and board mills, the drying section is divided into a pre-drying and an after-drying section.

Schematic overview of different process steps in paper production



Carbon emissions from a typical paper mill



The paper and pulp industry produces organic process residues that makes fuel switching to bioenergy particularly relevant

- Organic residues can be combusted in their solid form or fed into anaerobic digesters to produce biogas, which can replace natural gas and hence directly reduce fossil CO_2 emissions.
- Combining bioenergy with CCS (BECCS) can result in negative emissions.
- Carbon capture in the pulp and paper sector is mainly applied to steam boilers (some of which are fed by biomass) in the IEA – Sustainable Development Scenario.
- Paper and pulp industry is projected to remain a similar size in the future, declining paper use is offset by increasing cardboard packaging for home deliveries

Deep Decarbonisation Pathways for Scottish Industry Bioenergy with carbon capture and storage (BECCS) Carbon Trust 2011 - Industrial Energy Efficiency Accelerator Prospective scenarios for the pulp and paper industry

Timber industry

Large industry in Scandinavia

- In Sweden, 20 companies account for 80% of production but there are smaller industrial sector in Italy (poplars) and Portugal (oak for cork) producing either softwood (fuel, pulp, paper) or hardwood (furniture, floors)
- ~10% of wood production is used as a feedstock in CHP plants and wood chips feed into the paper and pulp industry
- For every 1 tonne of timber produced, 1.8 tonnes of CO_2 is taken from the atmosphere so there is a net emissions reduction, assuming sustainable forest management is carried out

The majority of energy consumption is from on-site biomass (wood residues) or fossil fuel combustion

- Biomass or fossil fuel is combusted in kilns to provide heat to dry the wood products.
- Approximately 16% of a sawmill's energy demand is electricity based and is used to operate a range of machinery.

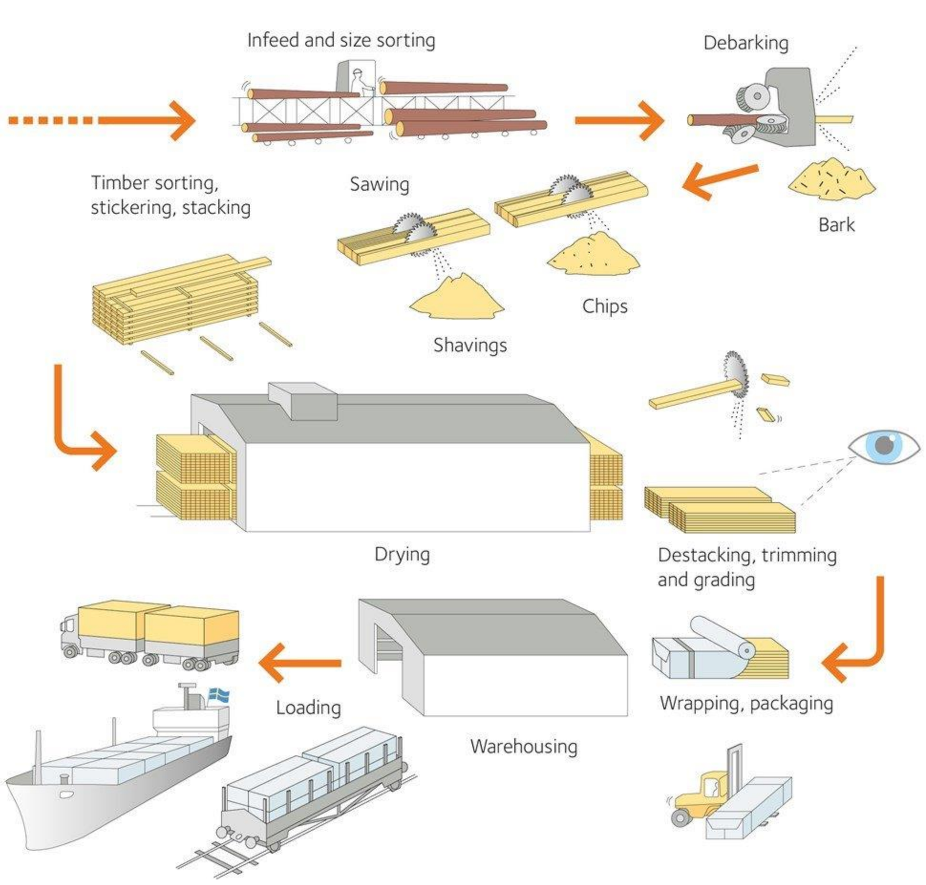
Wood is dried under carefully controlled conditions in special kilns at high temperatures

- The goal is to lower the moisture content of the wood without it cracking, and to achieve optimal moisture content so that it can be stored or transported without damage.
- A kiln chamber is a common way of drying wood with large fans that blow heated air through the timber load but these fans use a lot of electricity, often half as much as an average sawmill.

Carbon capture is unlikely to be deployed in the wood production sector in Europe

- Drying equipment is often small scale and suitable for decarbonisation via alternative pathways such as electrification and hydrogen fuel switching.

The sawmill process from forest to sawn wood product



Carbon Smart – Wood Products   Advantage Environment 2011 – Energy Efficient Timber Drying

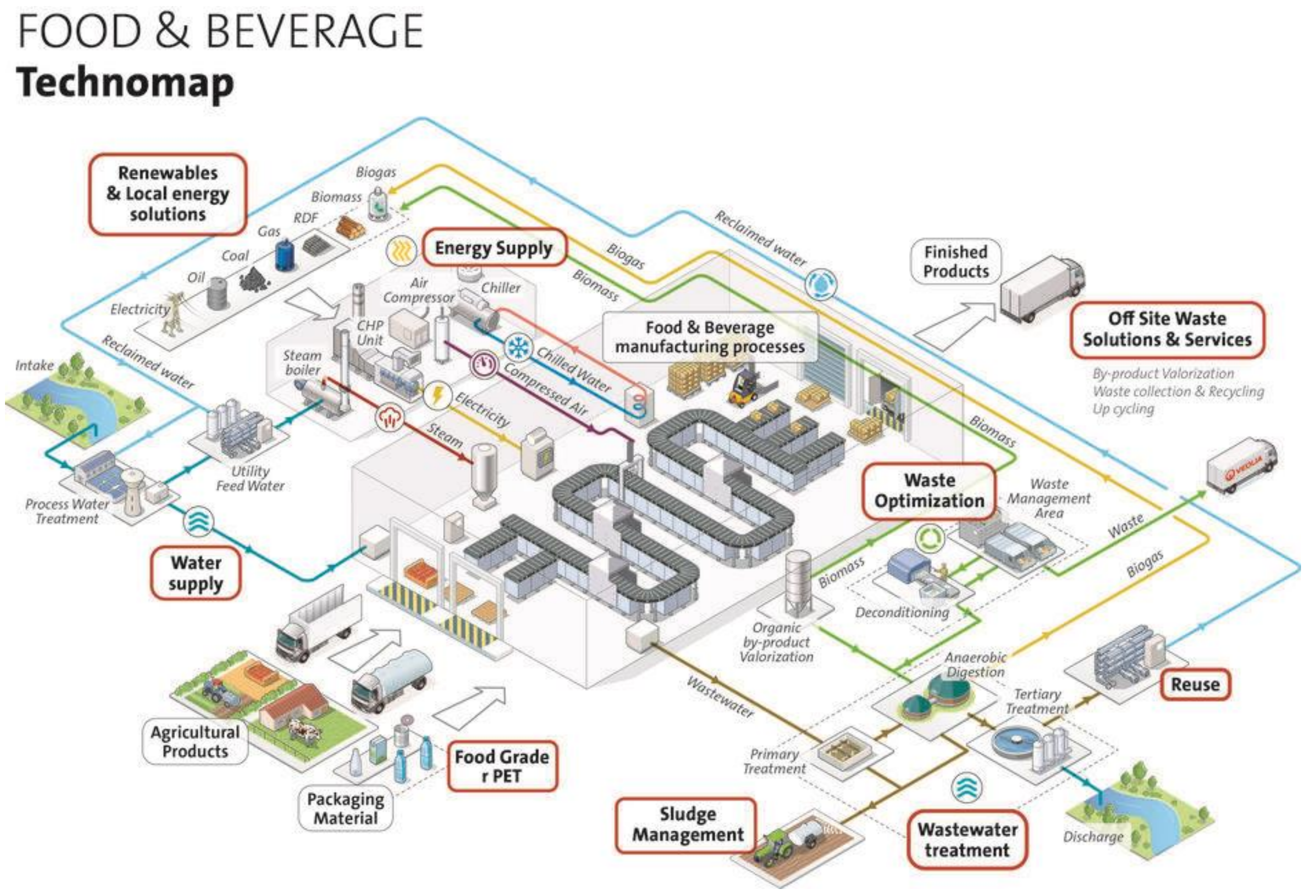
Food and drink

Diverse sector with many subsectors

- 86% companies have fewer than 20 employees
- Dominated by small and medium enterprises who cannot afford high upfront costs
- Product quality cannot be jeopardised – companies are only willing to invest in proven technologies
- Steady growth is projected within the food and drink industry

Electricity and thermal energy used in every step of the process

- Energy consumption dominated by boilers (54%) and direct heating (27%)
- Main processing techniques
  - Material reception/preparation (e.g. peeling, thawing)
  - Size reduction, mixing and forming
  - Separation techniques (e.g. distillation)
  - Product processing technologies (e.g. fermentation, pickling)
  - Heat processing (e.g. baking, pasteurization)
  - Concentration by heat (e.g. freeze-drying)
  - Chilling and freezing
  - Post-processing operations (e.g. packing, gas flushing)
  - Utility processes (cleaning, disinfection)



Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050 - Food and Drink Ricardo Veolia Water Technologies State of industry report Q2 2022 | The Food & Drink Federation (fdf.org.uk)

Case study: Fermentation in Scotland

Fermentation sector is responsible for large scale biogenic CO_2 emissions

- 13% of Scotland's biogenic CO_2 is derived from fermentation to produce alcohol (beer, grain spirits, malt whisky)
- Most sites are small (<5 ktCO_2/year) but one beer producer and 15 spirit producers are larger than this.

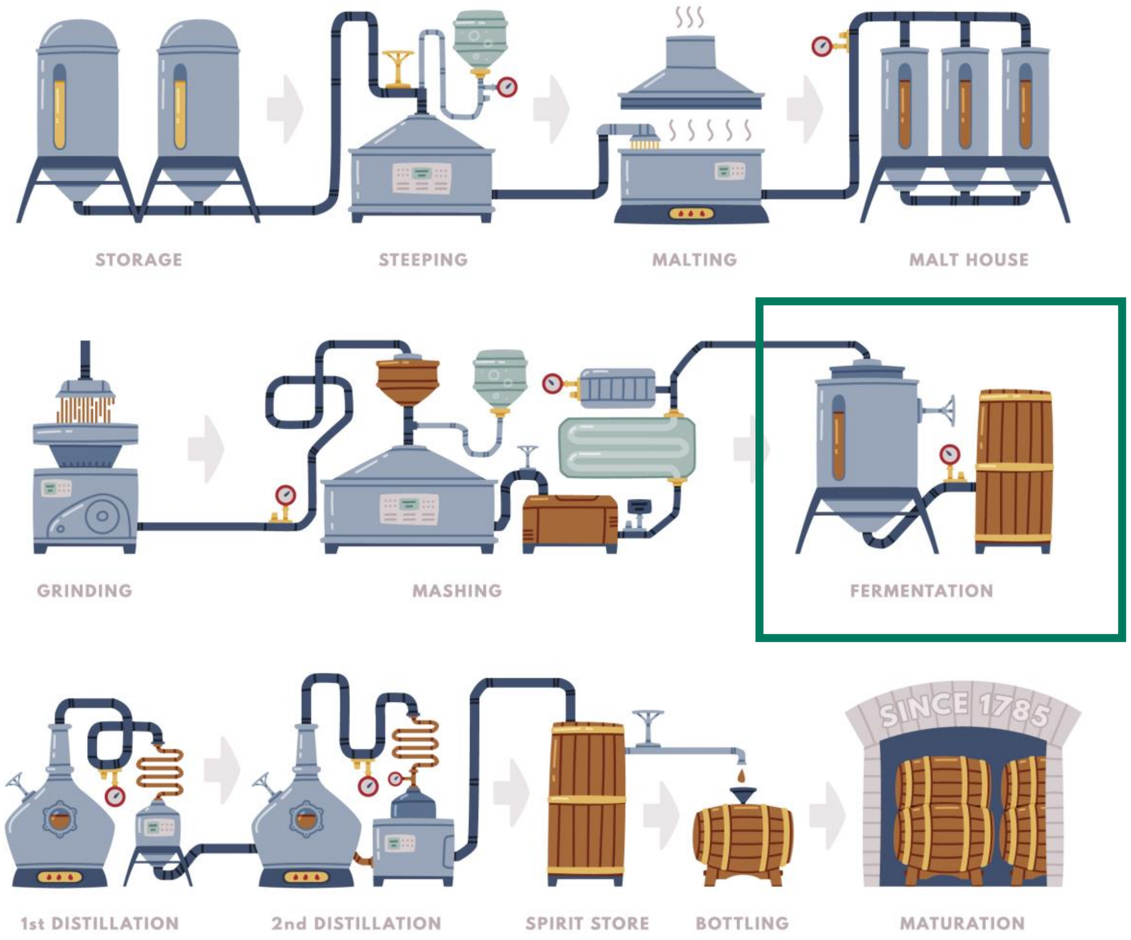
Carbon capture has been practiced extensively in the past

- Gas from fermentation is very pure in CO_2
- CO_2 can be re-used within the drinks industry for carbonation
- Today, typically CO_2 supplies are outsourced, mostly derived from hydrogen manufacture using natural gas or a by-product of fertilizer production
- North British Distillery (Edinburgh) still captures up to 20 ktCO_2/year

The German Beer Purity Law (Reinheitsgebot)

- In Germany, the carbonation of beer can only occur from CO_2 released during fermentation of the same beer
- All carbon dioxide released during fermentation is captured in order to carbonate the same beer in later stages of production

Whisky Production Process



Negative Emission Technology in Scotland New fermention strategy of whisky with Yellow Label Angel Yeast - Distilled spirits and Biofuels - AngelYeast

Waste management

Energy from waste combines waste incineration with carbon capture

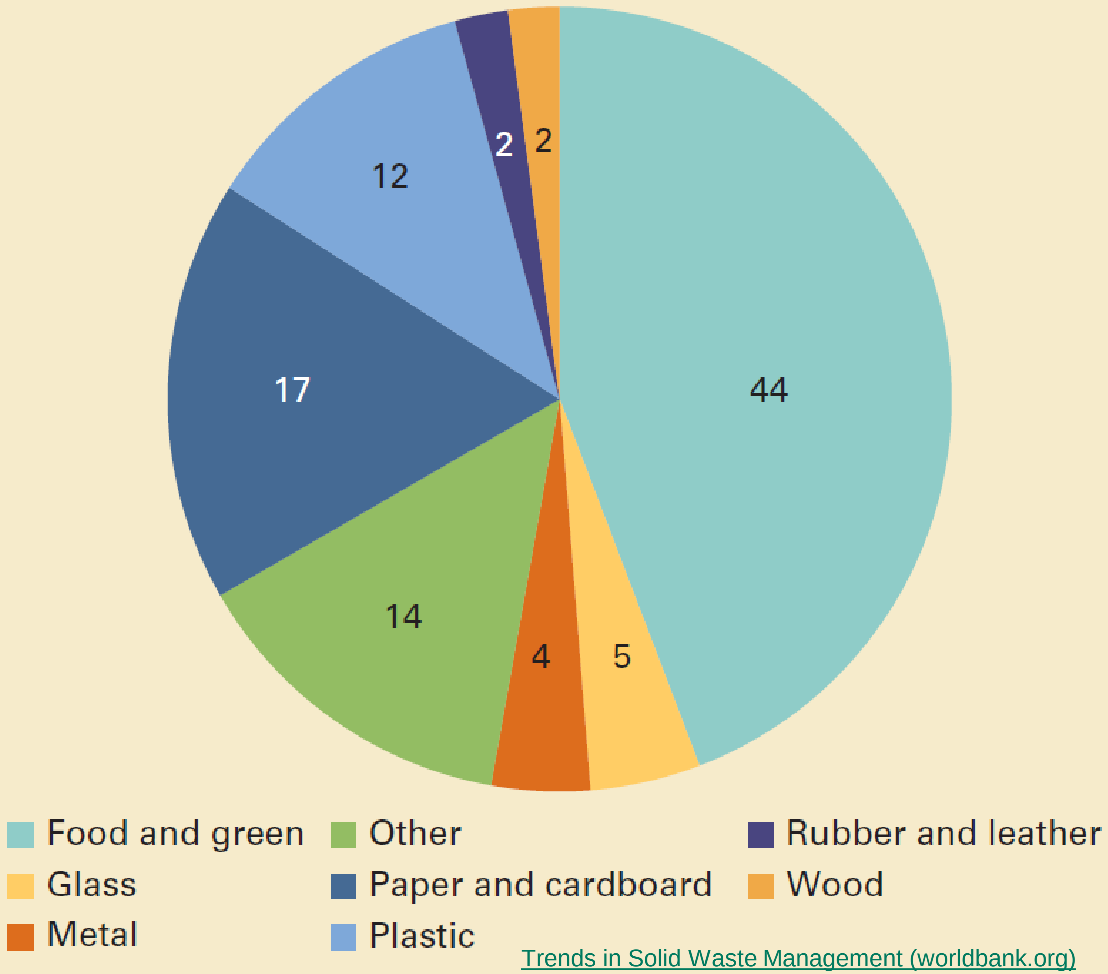
- High content of biomass (~50%)
- Few other uses
- Hard to abate industry

Waste incineration is typically small scale but close to cities

- More than 500 waste-to-energy plants across the EU, most of which are relatively modern so CCUS retrofit is viable
- Biogenic CO_2 emissions result primarily from the combustion of landfill gas, municipal solid waste and other biogenic fuels in reciprocating internal engines, municipal waste combustors and other combustion units
- Significant waste feedstock available in the UK with 100 million tonnes of carbon containing waste and 14 million tonnes of bio-base residue from crops/forestry
- Public acceptability of incineration is a challenge - recycling is obviously the preferred option for waste
- Waste facilities tend to be built close to cities so building infrastructure for CO_2 transport may be logistically challenging

Energy from Waste sector is projected to grow rapidly

- Dependent on the uptake of the circular economy
- Conditional on new plants applying carbon capture



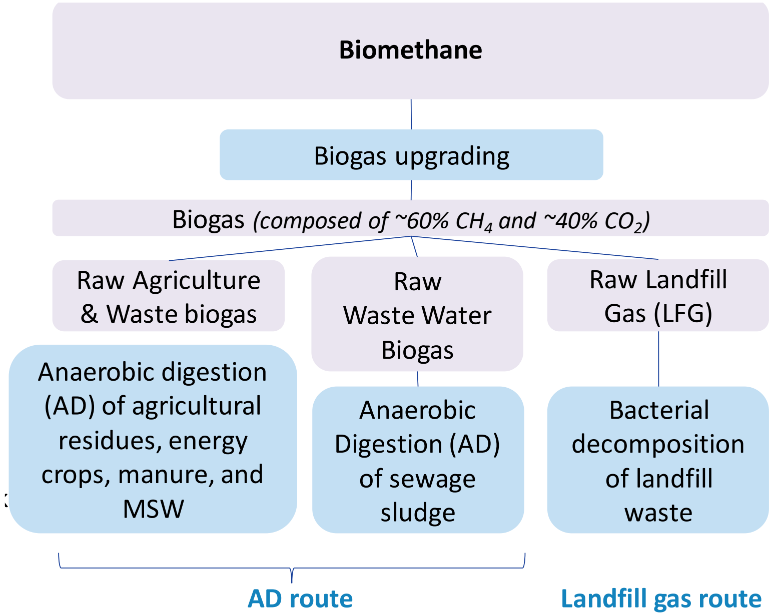
Trends in Solid Waste Management (worldbank.org)

Waste statistics - Statistics Explained Report (publishing.service.gov.uk) EPA waste profile A full-scale carbon capture and storage (CCS) project initiated in Norway Confederation of European Waste-to-Energy Plants ES Catapult

Biogas and biofuel production

Biomass conversion to biogas and biofuels produces biogenic $CO_{2,}$ for example through

- Bioethanol – fermentation of sugar or starch crops, or hydrolysis and fermentation of lignocellulosic materials. This produces a very high purity stream of CO_2 suitable for carbon capture and subsequent utilisation
- Biogas – produced through anaerobic digestion of wet wastes such as food waste, wastewater sludge, manure. Anaerobic digestion technology is a well developed and mature technology worldwide (TRL9). Biogas production emits significant quantities of biogenic CO_2 but the concentration of these in the flue gases is lower than .
- Biomethane - biogas can then be upgraded to biomethane, for gas grid injection or use in vehicles. During this process, CO_2 is removed, which has high purity



Cement

The cement and lime industry emitted ~150 $MtCO_2$ in Europe in 2019.

- The majority of CO_2 emissions from cement production are from clinker production.
- High temperatures drive 'calcination', creating calcium carbonate (CaO) and CO_2.
- Extra CO_2 is produced also, through the combustion of fuels – usually coal or natural gas – to provide the heat needed to drive the reaction.

Carbon capture is key in the cement sector as there are no other ways to reduce the process emissions significantly.

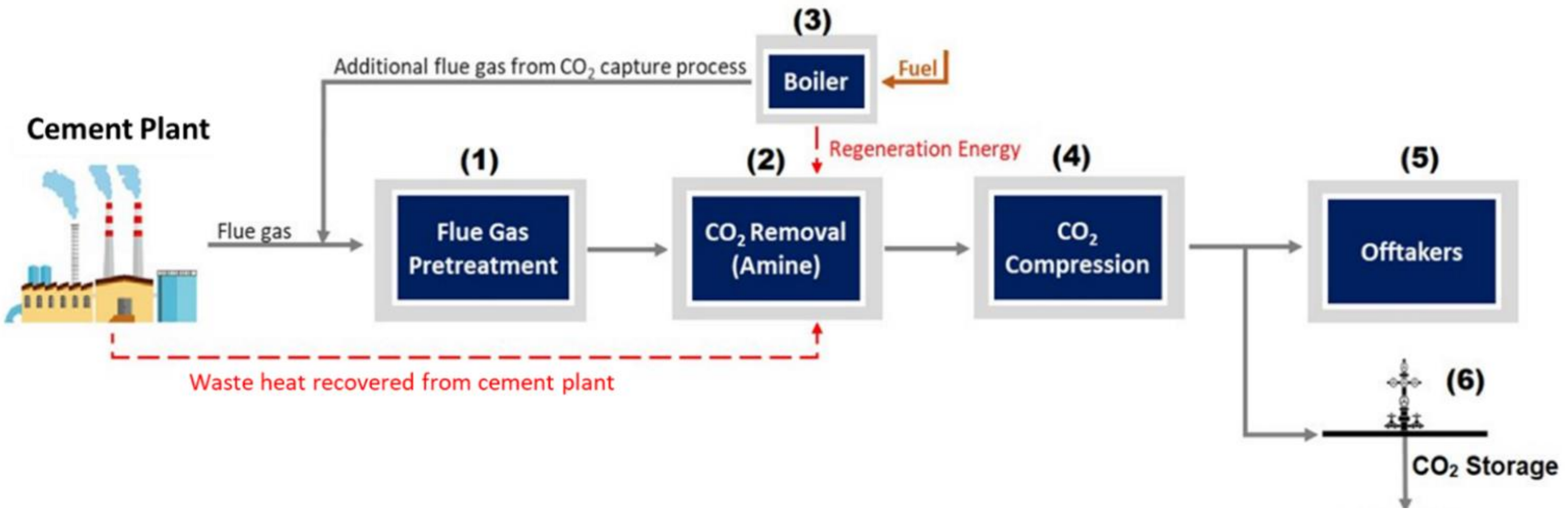
- Process emissions (heating of limestone and release of CO_2) represents 60 to 65% of cement manufacturing emissions.
- Post-combustion carbon capture is a relatively straightforward solution to implement, as on a cement factory there is just one source of CO_2.
- Incorporate CO_2 utilization during the curing stage to permanently sequester CO_2 (instead of water)

Cement production facilities are geographically distributed as cement is mostly locally produced and consumed.

- On average, each facility has emissions of 0.6 $MtCO_2$/year.
- Carbon capture uptake may be limited in dispersed sites where the opportunities for developing shared CO_2 T&S infrastructure are limited.

Norcem cement entered an agreement with Aker Solutions to capture CO_2 from the Brevik cement plant in Norway.

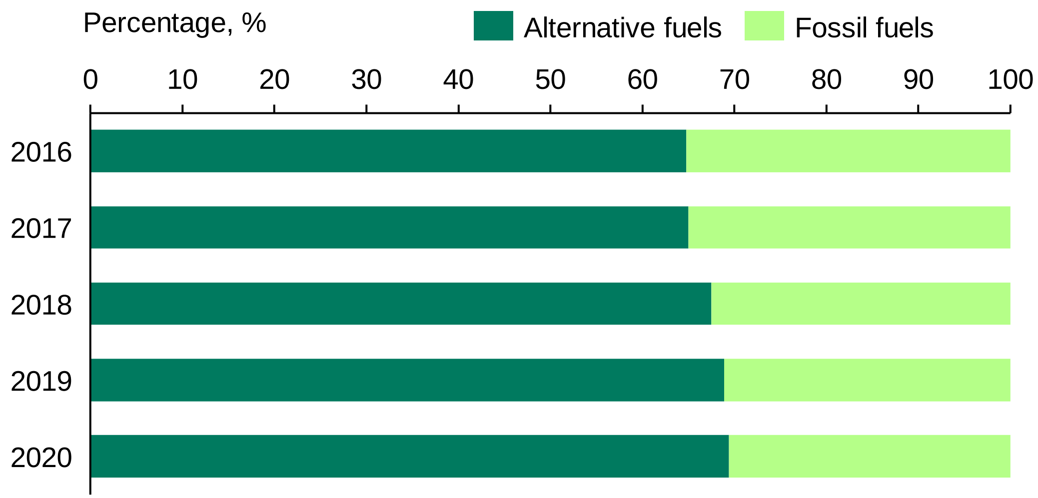
- A proprietary solvent-based carbon capture plant will be installed to capture flue gas from the cement kiln.

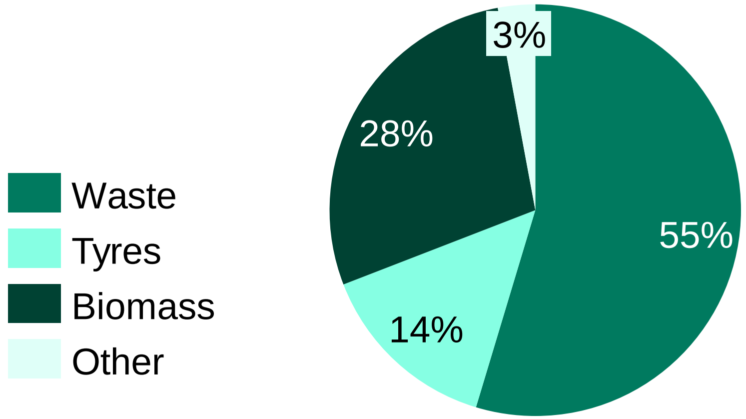


Carbon Limits – The Role of Carbon Capture and Storage in a Carbon Neutral Europe Global CCS Institute – Status Report 2020 International CCS Knowledge Centre

Cement

Percentage of different alternative fuel types used in the cement industry[2]





A wide range of alternative fuel sources can be used to meet the heating demands in cement production

- Materials like waste oils, plastics, waste tyres and sewage sludge are often offered as alternative fuels for the cement industry**.** Agricultural biomass and industrial waste can also be utilised.
- CO_2 emissions from combusting biogenic content is considered to be carbon neutral from a GHG accounting perspective.
- The countries leading the usage percentage of alternative fuels are mostly European countries.

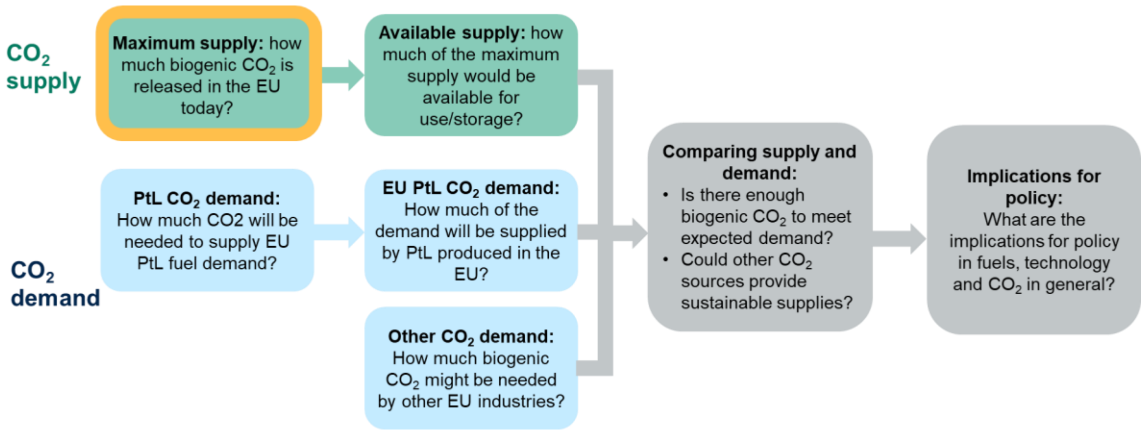
The use of alternative fuels is well established in the cement industry

- The challenges currently faced in the cement sector relate to incorporating higher substitution rates, and **utilising fuels with higher biogenic content.**
- Industrial and household waste, tyres and biomass are the most common alternative fuels currently used by cement companies.
- Aside from fuel cost and availability, it is necessary to understand the composition, including the fixed carbon, moisture, and volatiles content of AFs. These will determine the flue gas emission characteristics from the kiln stack, changing the concentrations of other pollutants besides CO_2.

[1] Rahman et. al, 2015. [2] Rahman et. al, 2011.

Maximum Supply: How much biogenic CO_2 is released in the EU today ?

Project flow



Maximum CO_2 supply assessment

A. What are the sectors and sources of biogenic CO_2?

B. What is total biogenic CO_2 potential in Europe?

1. Identify best data sources for industrial point sources in Europe.
2. Disaggregate reported biogenic emissions from the database
3. Identify gaps in reported biogenic emissions and close potential data gaps
4. Calculate total available biogenic CO_2 and quantify uncertainties

We estimated the total biogenic CO_2 potential using database screening and targeted research to close any data gaps

Our approach to quantify and map out current level of biogenic CO_2 emissions from large point-sources

- We assessed **CO_2 emissions** from sites included in the European Industrial Emissions Portal, providing a **sector-** and **country-level breakdown**
- Using report data, we **differentiated between biogenic and fossil CO_2**.
- An estimate of the **portion of biogenic CO_2** emissions for each sector, based on reported data.
  - For countries where data was not reported and sectors where data was missing, additional research was conducted and numerical extrapolation was conducted.
  - The proportion of biogenic CO_2 was sense-checked against sector specific insights gathered in earlier tasks (see slides 44-53)
- **The emissions data was also mapped using GIS software** to provide insightful visuals and enable easier identification of the hotspots for potential future CO_2 supply.
- The steps undertaken are detailed in the following slides, each step being marked with in the upper right corner
- This analysis fed into the assessment of the accessible biogenic CO_2 potential – this is shown on slides 72-79.

1 **Identify best data sources for industrial point sources in Europe**

2 **Disaggregate reported biogenic emissions from the database**

3 **Identify gaps in reported biogenic emissions and close potential data gaps**

3a Extrapolation of the emissions to countries not reporting using EU averages

3b Bioethanol facilities

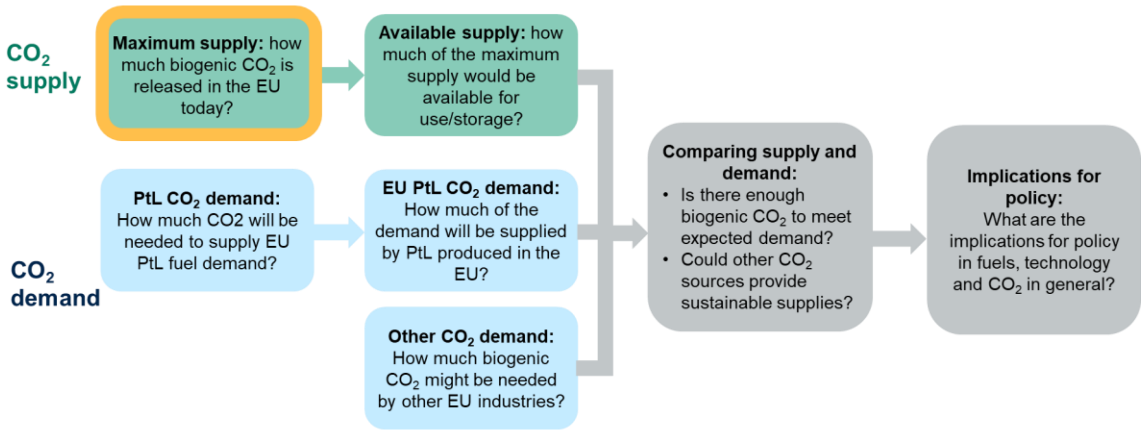
3c Biofuels facilities

3d Bio-naphtha facilities

4 **Calculate total available biogenic CO_2 and quantify uncertainties**

Maximum Supply Section: How much biogenic CO_2 is released in the EU today ?

Project flow



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Both fossil and biogenic CO_2 emissions are reported by the Industrial Emissions Portal

1

Germany and central Europe dominate total emissions reported by the Industrial Emissions Portal

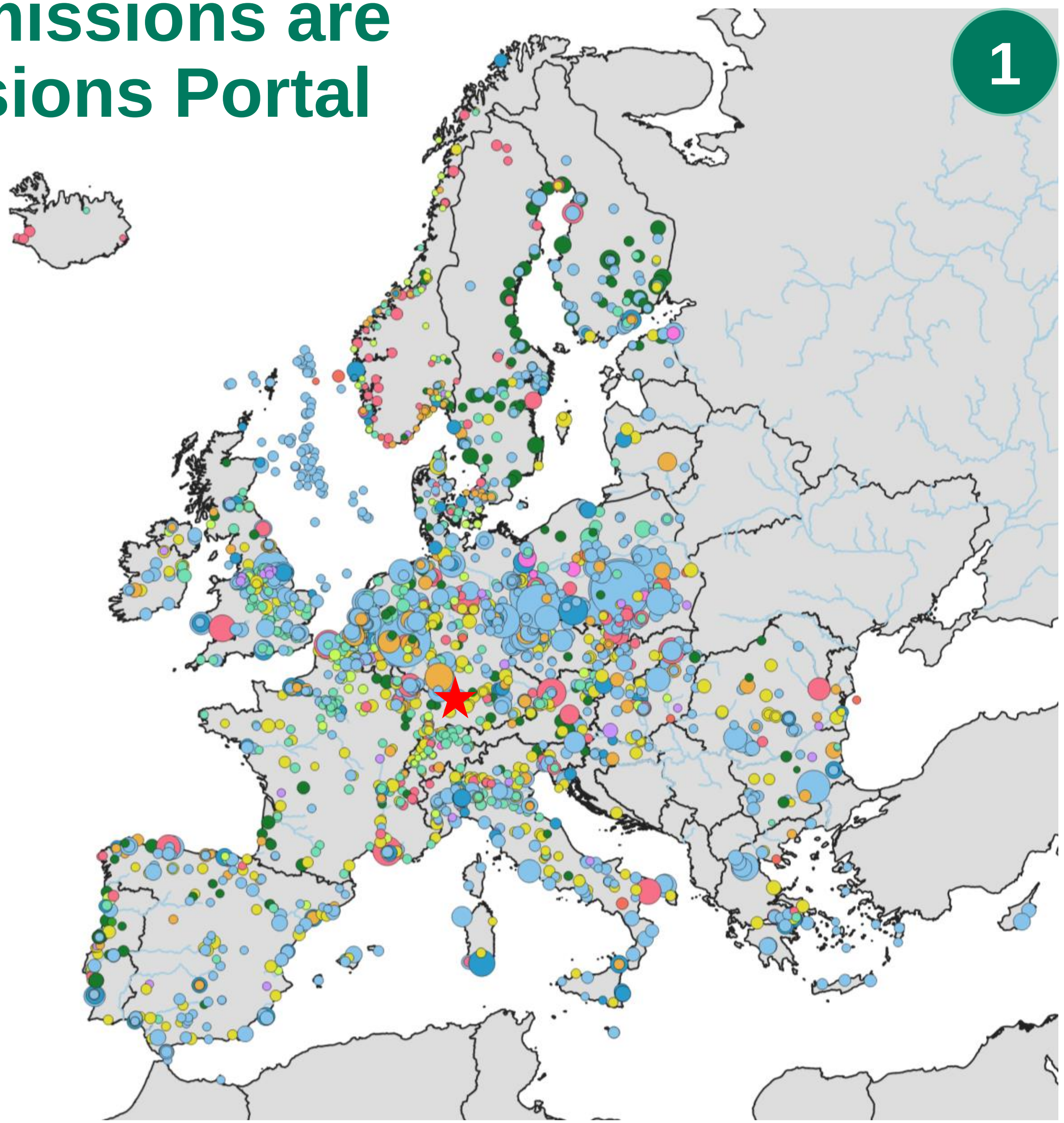
- The first step of the analysis consisted of identifying the latest data on industrial emissions in Europe. The European Industrial Emissions Portal (IEP) data for 2019 was chosen as the most complete dataset. For Germany, Lithuania and Liechtenstein, 2017 is the most complete dataset so is used instead for these countries
- Total fossil and biogenic emissions reported by the IEP across Europe are ~780MtCO$_2$/year
- Currently the **largest point source** emissions are from the **power generation** sector and emit up to ~40 MtCO$_2$/year.
- **Cement** industry accounts for **~19%** of total emissions across Europe.
- Sectors with a significant biogenic component like the **paper and pulp** and **waste management** industries do not tend to be large scale emitters and account for **~12%** and **~13%** of total emissions, respectively.

Total emissions (MtCO2/year)

- Agriculture
- Cement & lime
- Chemicals
- Food and drinks
- Fuel manufacture
- Glass
- Iron, steel, and other metals
- Mining
- Other
- Paper, pulp and primary wood products
- Power generation
- Refining
- Waste management

40
30
20
10

★ Stuttgart

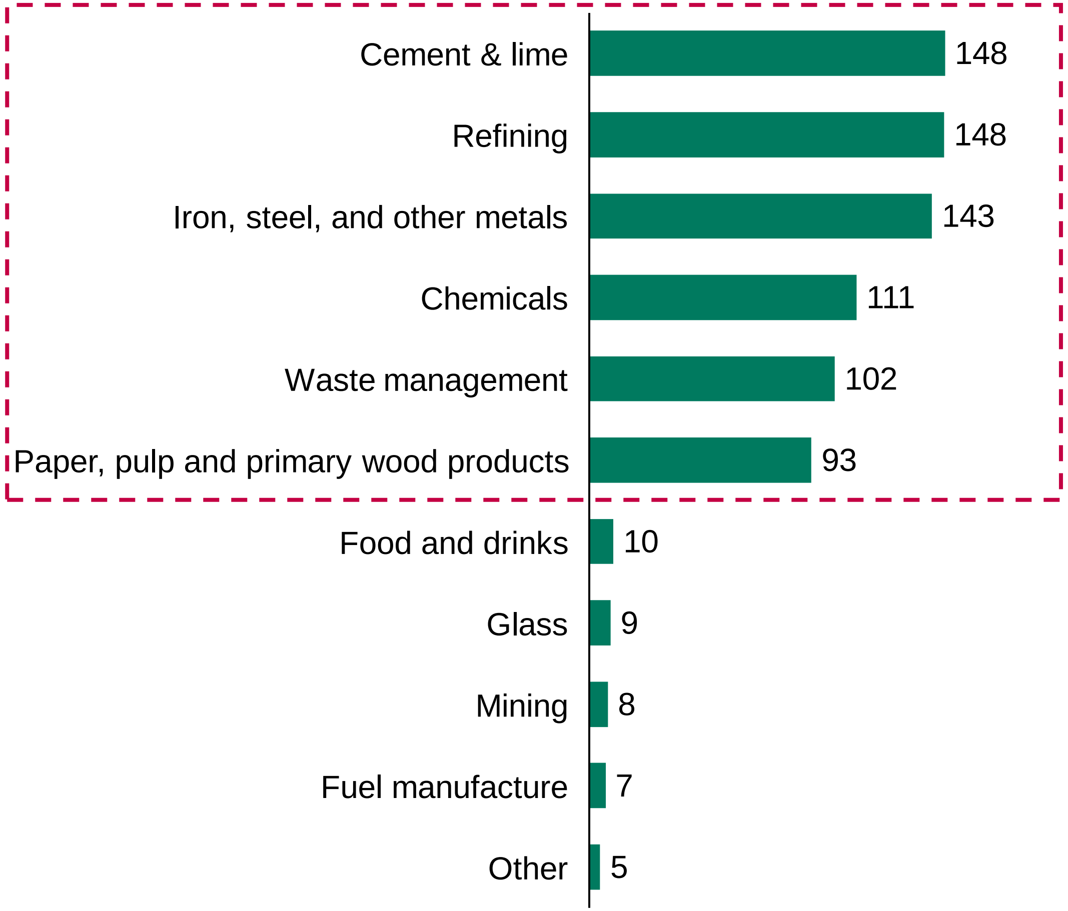


[European Industrial Emissions Portal (europa.eu)]

Emissions from the IEP can be disaggregated by sector and country

1

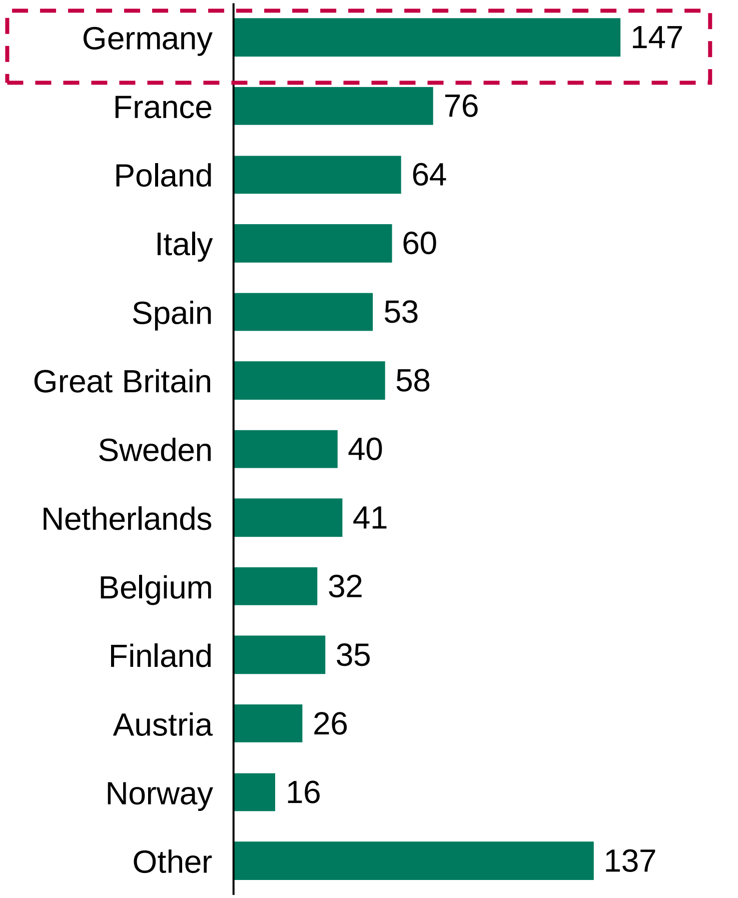
Emissions from industrial sectors ($MtCO_2$)



Both fossil and biogenic emissions are used to cross-check the IEP with other data sources

- Germany has the largest industrial emissions of all countries studied (147 $MtCO_2$)
- Sectors which have a significant biogenic component, for example waste management and paper, pulp and primary wood products do not generate as many emissions as fossil sectors such as cement and lime and refining.

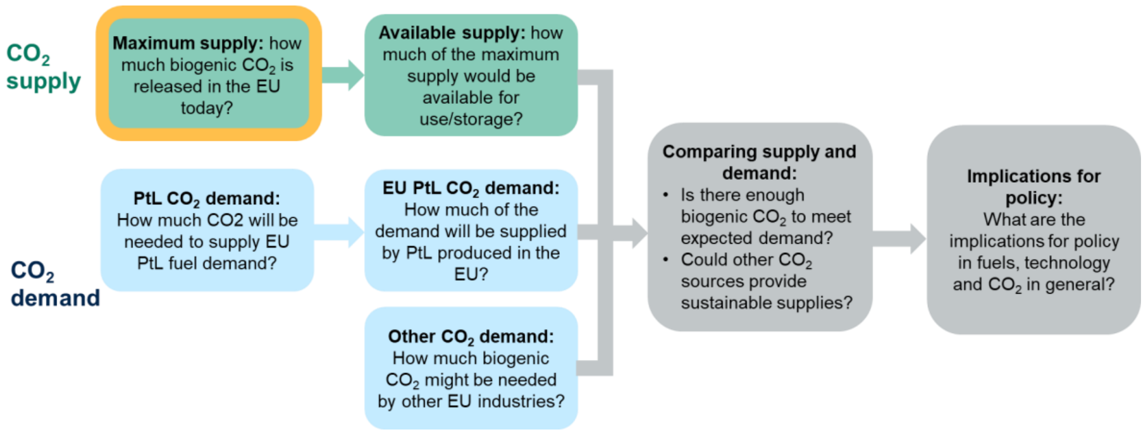
Industrial emissions by country ($MtCO_2$)



Data shown includes both fossil and biogenic emissions

Maximum Supply Section: How much biogenic CO_2 is released in the EU today ?

Project flow



Maximum CO_2 supply assessment

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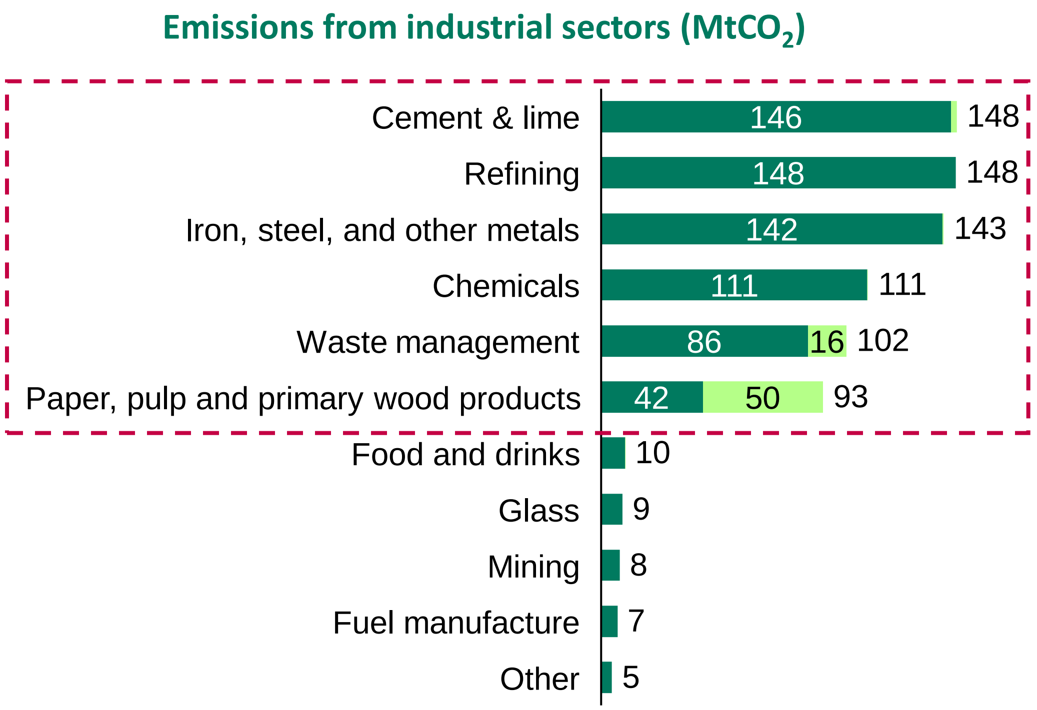
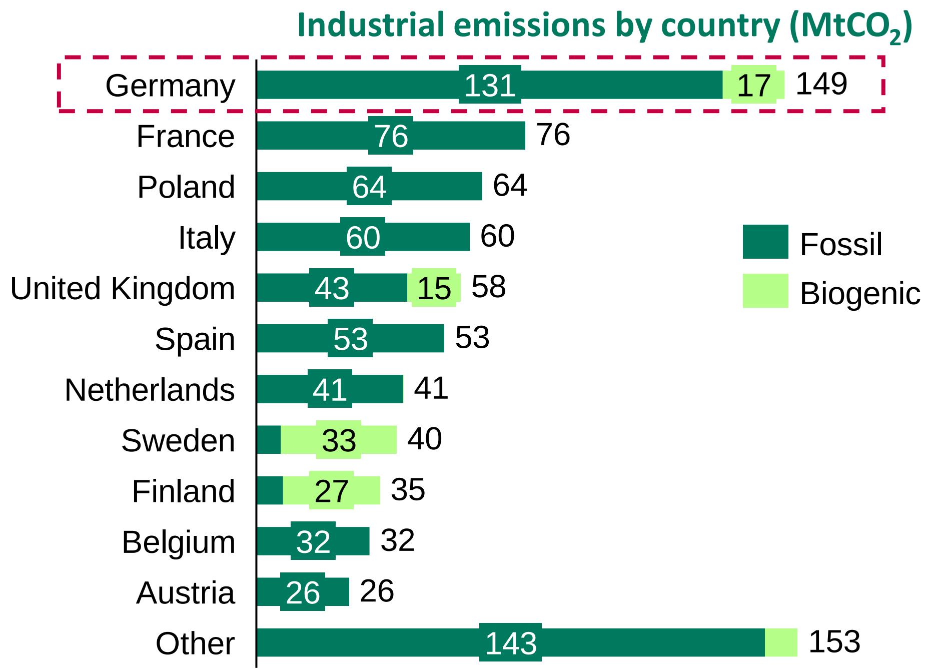
Only some countries report their biogenic emissions separately in the IEP

2





For most countries and sectors, biogenic emissions are much smaller than both fossil and biogenic emissions combined

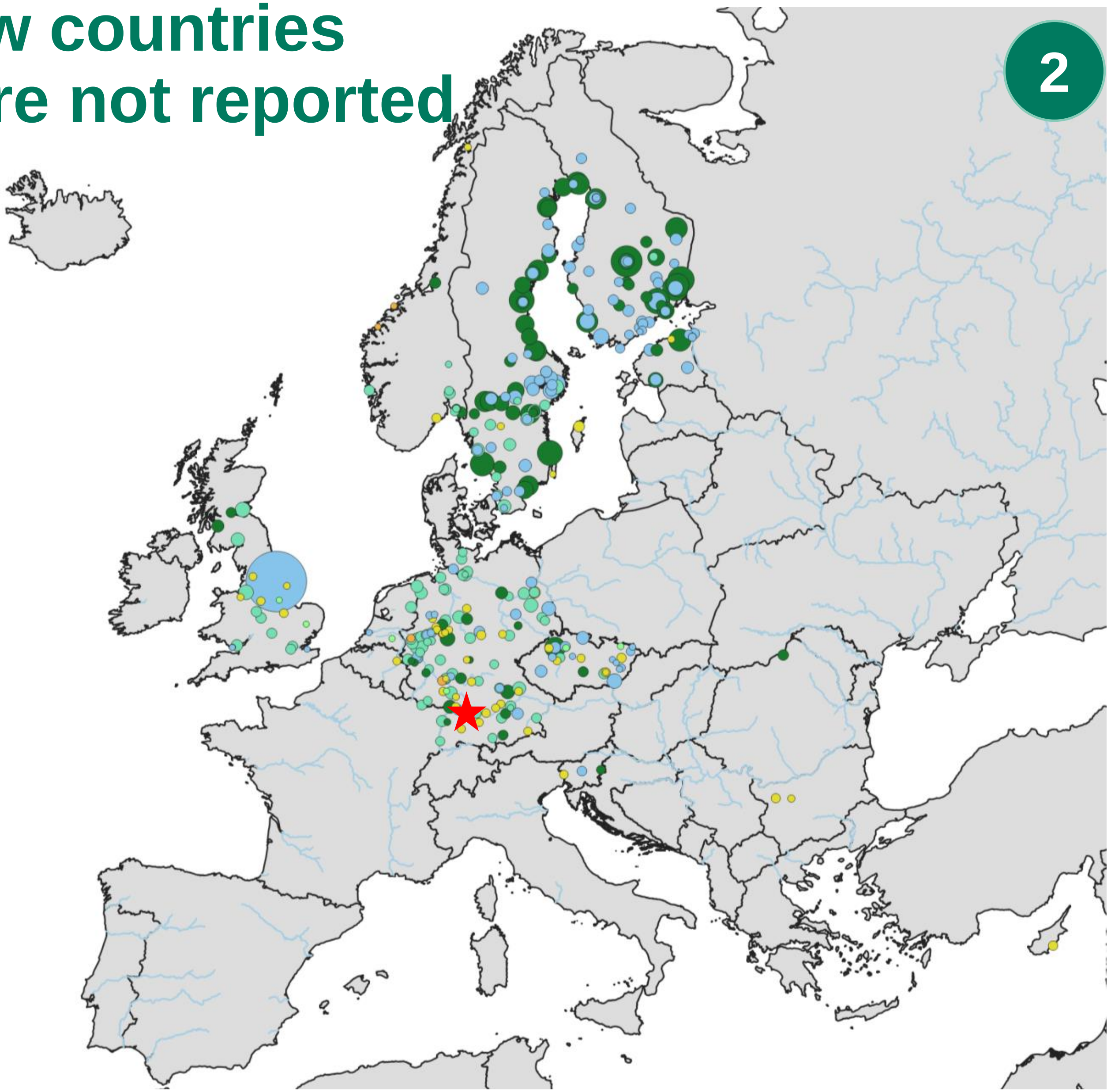
- The paper and pulp industry has the highest proportion of biogenic CO_2 emissions (54%), followed by the waste management industry
- Sweden and Finland are the countries with the highest proportion of biogenic emissions
- 15 countries (e.g. France, Poland, Italy, Spain, Netherlands, Belgium, Austria) do not report their biogenic emissions separately
- An estimate for the biogenic emissions of these counties was undertaken and is shown on this slide.

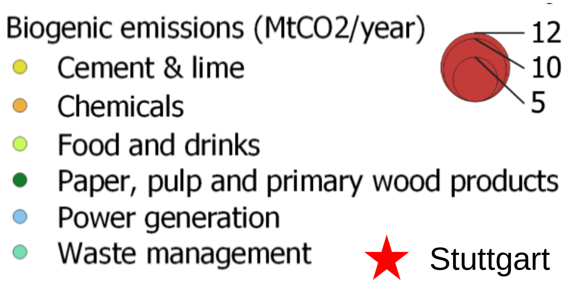
Emitters are mapped to show countries where biogenic emissions are not reported

2

Biogenic emissions (>0.1 $MtCO_2$) have been mapped across Europe from the Industrial Emissions Portal database

- The **paper and pulp** industry in **Scandinavia** accounts for **~43%** of Europe's total reported biogenic emissions (43 $MtCO_2$).
- **Drax** power station is a significant biogenic emitter in the UK **(~12 $MtCO_2$).**
- Large biogenic emitters in **Germany** account for **~17.5 $MtCO_2$**, particularly in the paper and pulp industry and energy from waste sector.
- The **cement** industry account for **~2%** of Europe's reported **biogenic emissions**.
- 15 countries (including France, Spain) do not report the biogenic component of emissions, an estimate of these **unreported emissions** must be made.

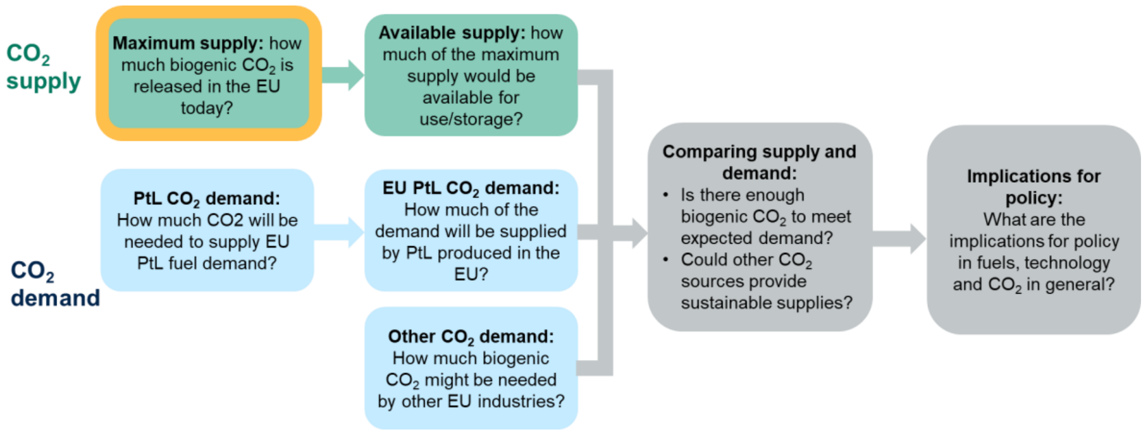




European Industrial Emissions Portal (europa.eu)

Maximum Supply Section: How much biogenic CO_2 is released in the EU today?

Project flow



Maximum CO_2 supply assessment

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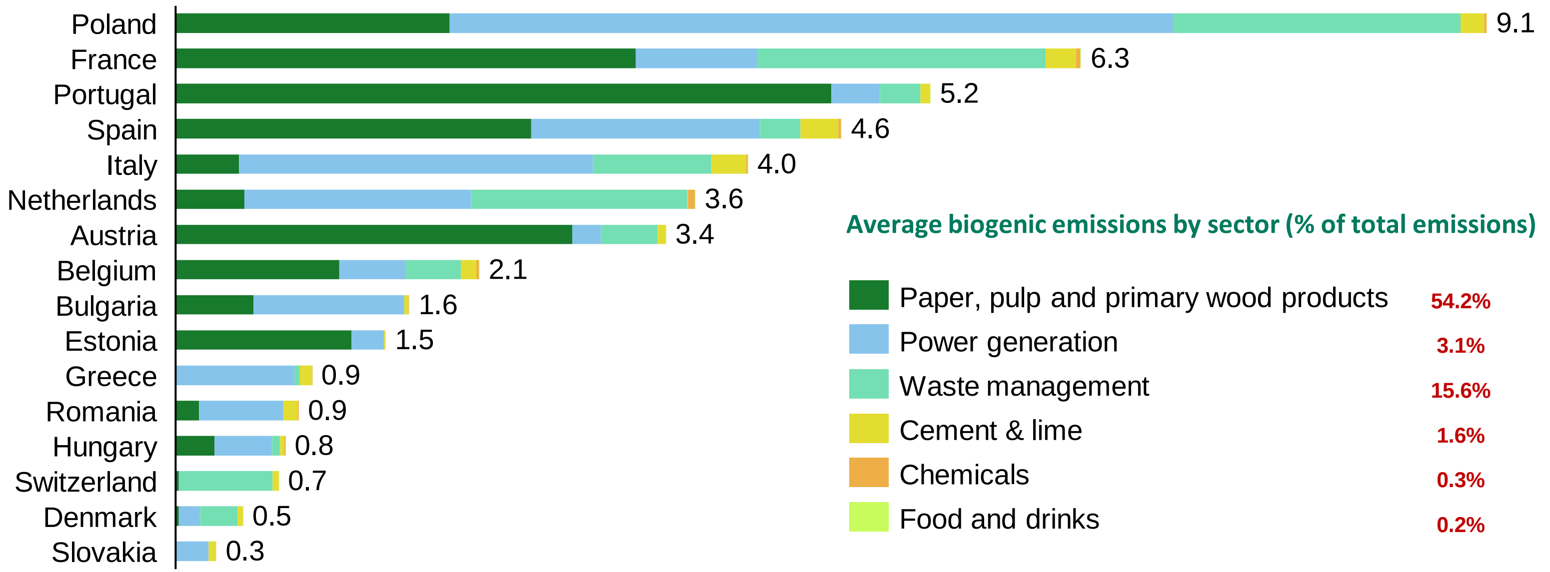
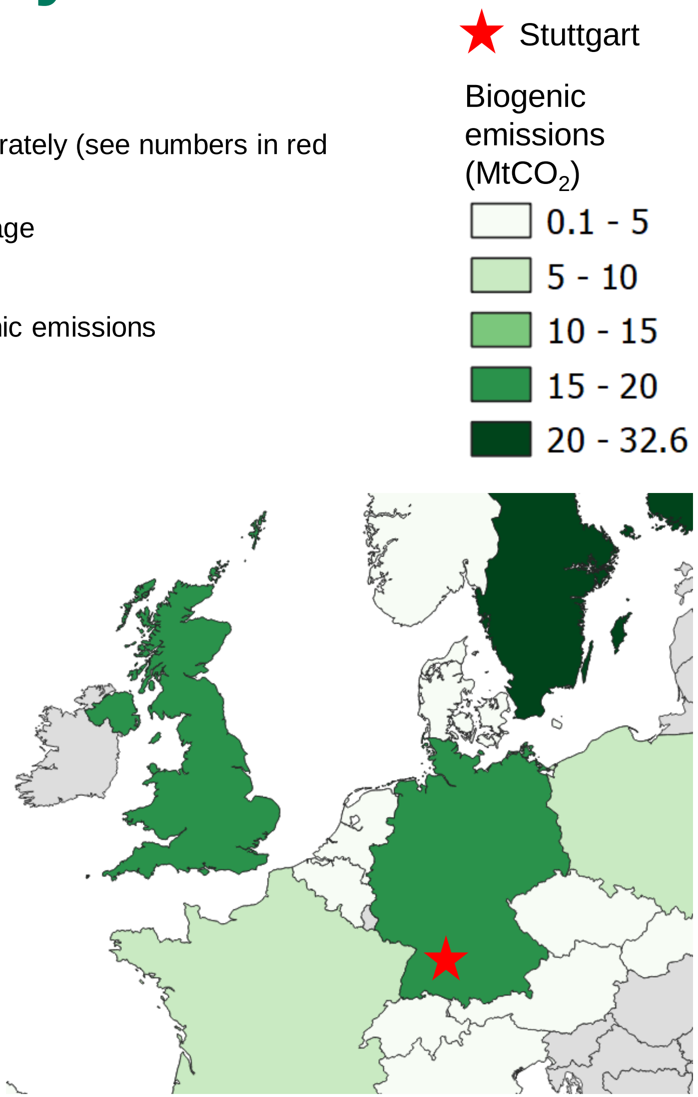
An estimate of biogenic emissions must be made for countries which do not report them separately

3a

Methodology for estimating unreported biogenic emissions

1. For each sector, average biogenic emissions are calculated for countries which do report their biogenic emissions separately (see numbers in red below)
   a) Anomalies in biogenic emissions are identified (e.g. Drax Power Station in the UK) and are not included in the average
   b) For the power sector, the fraction of biogenic emissions is based on the average for Germany
2. The average biogenic emissions by sector is multiplied by the size of the sector in each country that do not report biogenic emissions
3. The results are cross-checked with countries which do report their biogenic emissions to ensure consistency
4. Uncertainties between sectors are highlighted on this slide





Bioethanol production contributes additional biogenic emissions

Bioethanol production is projected to peak in the near future

- Bioethanol is a renewable fuel that can be used to meet renewable energy in transport targets through gasoline blending
- The bioethanol may potentially grow but this is uncertain given gasoline demand reduction and further ethanol import potential, and the potential for ethanol to jet plants
- Around 0.56 tCO_2 biogenic emissions are produced per tonne bio-ethanol produced

Bioethanol database

- The European Commission, Joint Research Centre (JRC), has complied an extensive map (on the right) of EU facilities producing bioethanol
- To provide the latest market insights, in this study we use our internal database of biorefineries for estimating the scale of opportunity for biogenic CO_2 from bioethanol plants
- This database comprises 90 facilities which produce 5.1 $MtCO_2$/year, with the average facility size being 57.1 $ktCO_2$/year
- Since fermentation from ethanol production generates a very high purity stream of CO_2 (99%), a large fraction of these emissions should be accessible for carbon capture

[1]European Commission, Joint Research Centre (2020) - Bio-based industry and biorefineries [3]The future of the British Bioethanol industry (parliament.uk).

Biogas and biomethane also contribute significant biogenic emissions across Europe

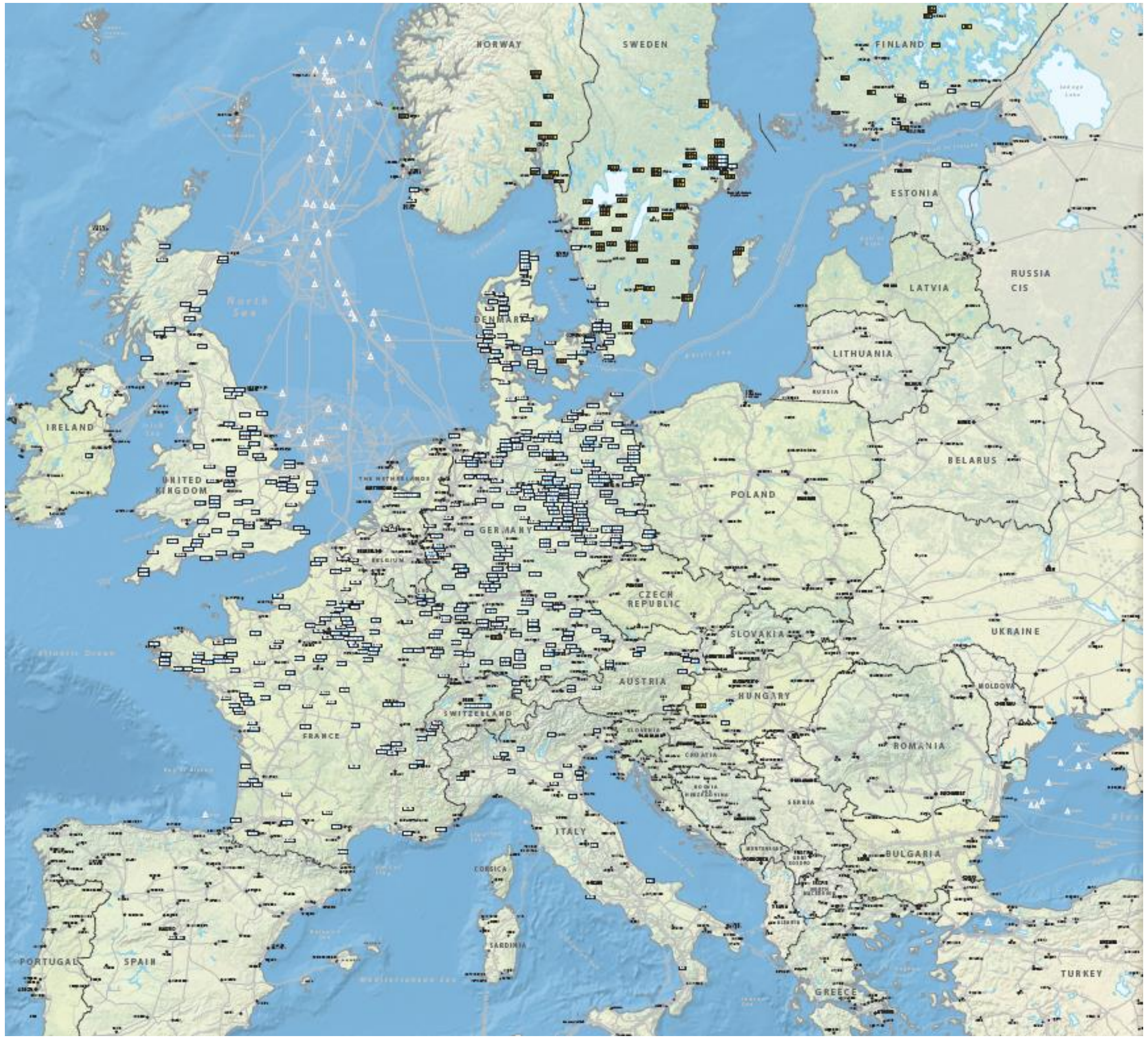
3b

Biogas and biomethane reported biogenic emissions come from the European Biogas Association[1]

- Total biomethane production capacity in Europe is ~330,000 m^3/hour, with additional biogas production capacity which is not upgraded to biomethane.
- To estimate the biogenic CO_2 from biomethane upgrading, we deployed the following approach:
  - We extracted biomethane production capacity data from the Biomethane Map (2021)[1], reported as m^3/hour
  - To convert from methane in m^3 to tonnes we assumed the density to be 0.72 kg/m^3 and the energy content of biomethane to be 34 MJ/m^3
  - It is also known that the production of one tonne of biomethane produces two tonnes of biogenic CO_2[1]
- Using the approach above, we estimate 4.0 $MtCO_2$/year from biomethane production
- An additional of 20 $MtCO_2$/year biogenic emissions are also expected to arise from biogas production across Europe in total[1]

Key uncertainties

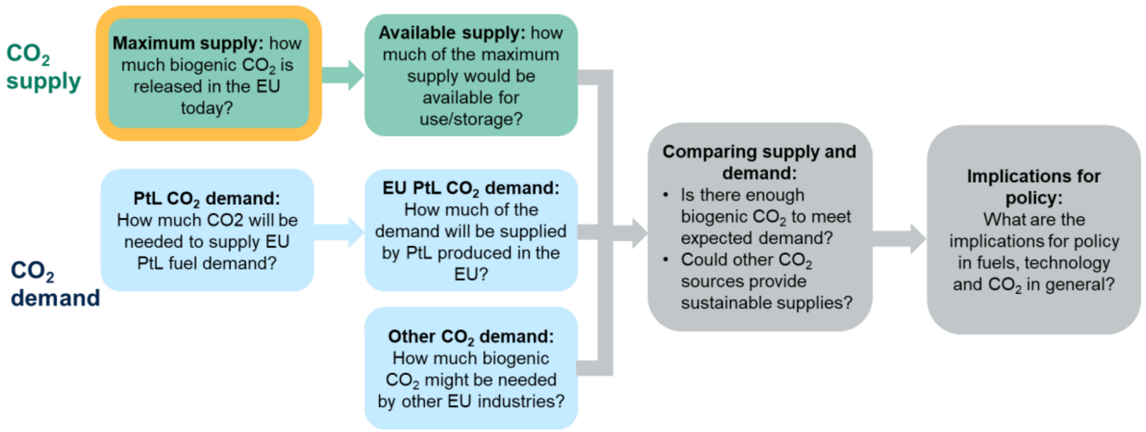
- Reporting accuracy of individual plants can introduce uncertainty into our reported emissions for biomethane
- As we do not have the locations of biogas plants, the location of biogenic emissions across Europe from biogas is uncertain
- Both the biogas and biomethane sectors are rapidly expanding industries and their production is likely to ramp-up



[1]Biomethane Map 2021 | European Biogas Association

Maximum Supply Section: How much biogenic CO_2 is released in the EU today ?

Project flow



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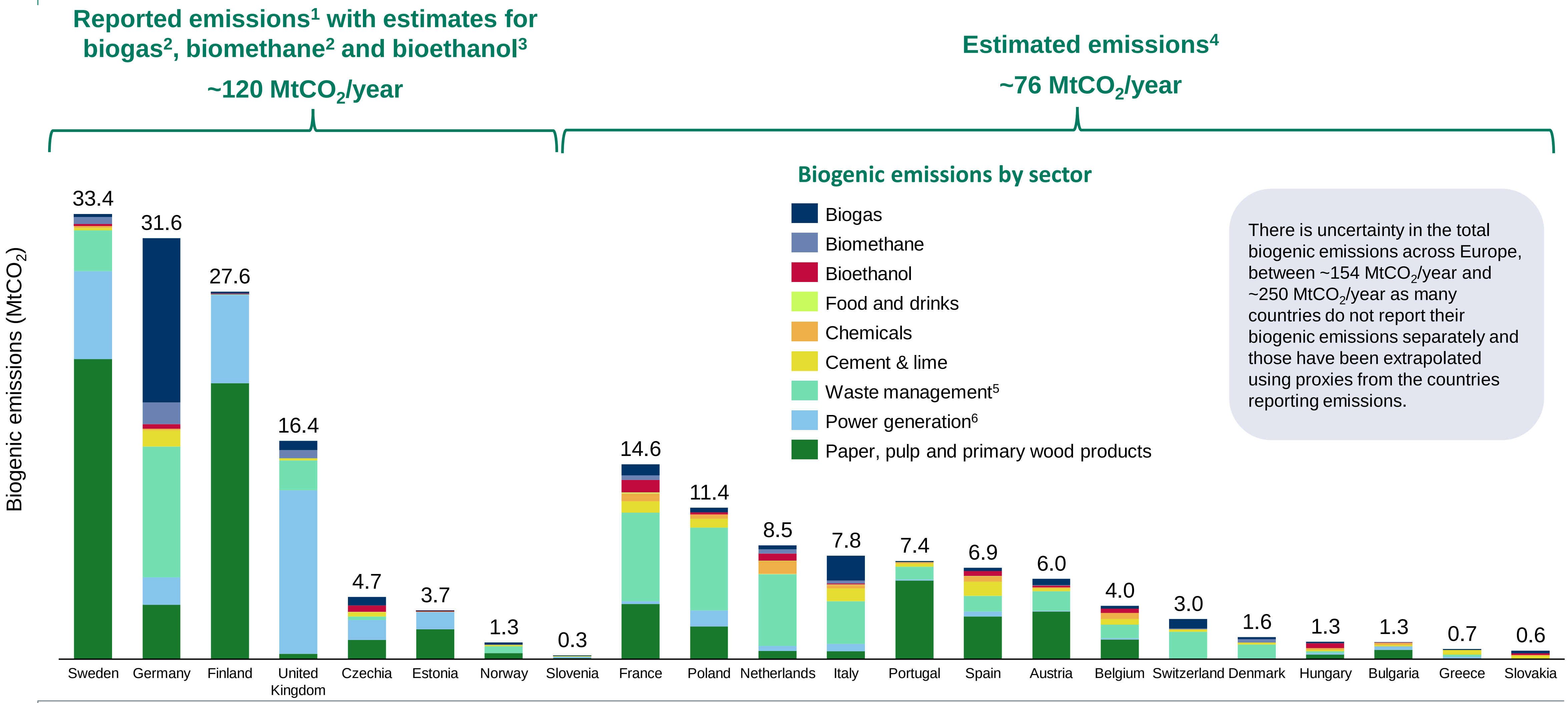
4. **Calculate total available biogenic CO_2 and quantify uncertainties**

Considering the sectors and sources discussed previously, the maximum potential for supply of biogenic CO_2 in Europe today is ~196 $MtCO_2$/year

4



There is uncertainty in the total biogenic emissions across Europe, between ~154 $MtCO_2$/year and ~250 $MtCO_2$/year as many countries do not report their biogenic emissions separately and those have been extrapolated using proxies from the countries reporting emissions.

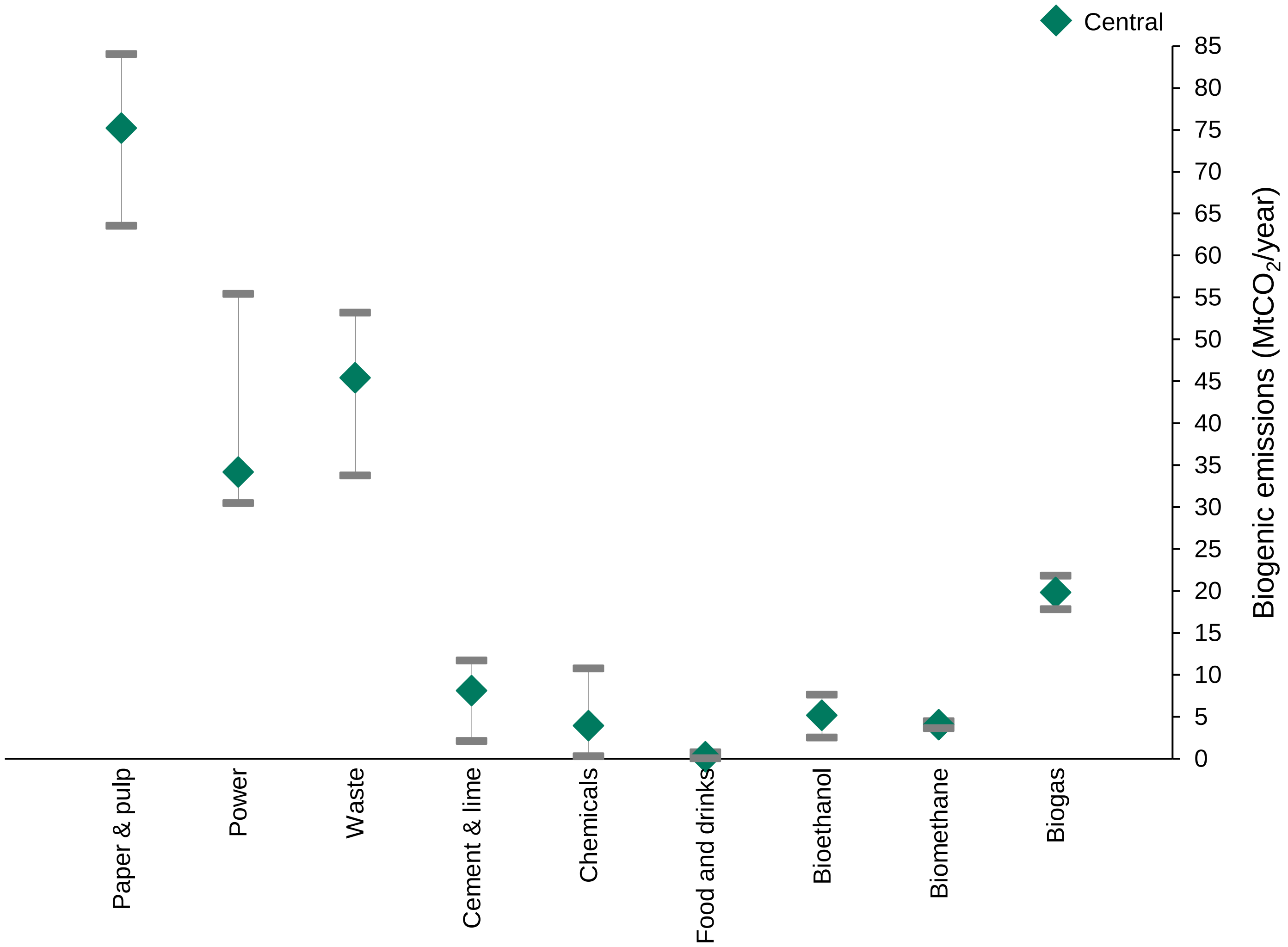
[1]European Industrial Emissions Portal (europa.eu) [2]European Biogas Association [3]E4tech database [4]Calculated based on average biogenic emissions by sector for reporting countries in the IEP 2019 dataset [5]Average biogenic emissions for waste management is calculated based on country level dataset from: World Bank 2019: What A Waste Global Database [6]Average biogenic emissions from power generation is based average biogenic emissions in Germany.

However, this maximum potential could be as high as ~250 $MtCO_2$/year or as low as ~154 $MtCO_2$/year

4

For each sector considered there is uncertainty in the current biogenic emissions across Europe

- The most significant uncertainty arises from countries which do not report their biogenic emissions separately.
- The high uncertainty is based on the reporting country with the highest fraction of biogenic emissions for that sector, and the low uncertainty is based on the reporting country with the lowest fraction of biogenic emissions for that sector. An exception is made for the power generation sector where the UK is excluded from the reporting countries due to Drax.
- For Germany, Lithuania and Liechtenstein the reporting year is 2017 but for all other countries, the 2019 data was used (most recent save 2020 which will have been affected by the COVID-19 pandemic)
- The database only includes emitters which emit more than 0.1 $MtCO_2$/year so smaller emitters are not included in the total
- For bioethanol, biomethane and biogas, uncertainties are based on uncertainties in the biogenic emissions factor (i.e. the quantity of biogenic CO_2 produced from the manufacture of one tonne of bioethanol, biomethane or biogas). There is wider uncertainty in the data reported by individual plants but this cannot be quantified.



Future biogenic emissions are highly uncertain, depending on increased biomass use, and BECCS

Alongside decline or growth of the industrial sectors discussed, **increased uptake of biomass and biomass derived products** in existing industries could also affect biogenic emissions.

- Greater use of **solid biomass in industrial fuel switching** could increase the biogenic proportion of CO_2 from point-source capture.
- Increased use of **biomass in the chemical industry** could also allow for biogenic CO_2 capture.
  - Using bio-naphtha, a co-product from HVO (hydrogenated vegetable oil) and FT diesel production, in place of fossil naphtha in steam crackers would create another source of biogenic emissions. If all HVO bio-naphtha produced in the EU currently went to chemicals, this would amount to 0.34 $MtCO_2$/year[1]. Imports of bio-naphtha could increase this value further. However, it is not clear whether bio-naphtha is more likely to be used in chemicals or road transport. At present, there is less driver for use in chemicals and so would require significant consumer, business or policy pull.
  - Bio-based chemical production via fermentation could also yield additional biogenic emissions in the future. Currently, the total capacity of biorefineries for these fermentation pathways is 0.33 Mt/year but this is could increase to up to 1.49 Mt by 2030. Therefore, biogenic emissions from fermentation could increase from 0.02 $MtCO_2$/year in 2022 to up to 0.83 $MtCO_2$/year in 2030[2].
- Producing **more ethanol** could also add to biogenic emissions, but is uncertain given gasoline demand reduction and ethanol imports.
- Biogenic CO_2 could also be captured from **gasification-based fuel production** processes. Currently, there is approximately 210 kt of gasification and FT/catalytic synthesis capacity and almost 1900 kt planned in the EU before 2030[3]. However, the use of MSW in many of the planned plants will reduce the biogenic proportion of any captured CO_2.

However, there is the also the potential for **bioenergy with CCS** to ramp up, if supported by policy, meaning that these sources of biogenic CO_2 would not materialise. Policy to support each of these uses, or to support new industrial plants in general, may include a requirement or a driver for CCS.

1. USDA FAS, 2022, 2. EU/E4tech, 2021, 3. E4tech Advanced Fuels Database

Available supply section: How much of the maximum supply would be available for use/ storage?

CO_2 supply

Maximum supply: how much biogenic CO_2 is released in the EU today?

Available supply: how much of the maximum supply would be available for use/storage?

CO_2 demand

PtL CO_2 demand: How much CO_2 will be needed to supply EU PtL fuel demand?

EU PtL CO_2 demand: How much of the demand will be supplied by PtL produced in the EU?

Other CO_2 demand: How much biogenic CO_2 might be needed by other EU industries?

Comparing supply and demand:

- Is there enough biogenic CO_2 to meet expected demand?
- Could other CO_2 sources provide sustainable supplies?

Implications for policy: What are the implications for policy in fuels, technology and CO_2 in general?

Conclusions

Recap: Over 20,000 biogenic European emitters were identified during the previous tasks

Summary of biogenic emitters based on previous tasks

Sector	Number of facilities in Europe	Average CO_2 emissions per plant ($MtCO_2$/year)	Average biogenic CO_2 emissions per plant ($MtCO_2$/year)	Current share of European biogenic CO_2 (%)	Fraction of CO_2 in flue gases (%)	Likelihood for deploying CO_2 capture based on technical aspects	Future sector trend – will CO_2 emissions increase or decrease
Paper, pulp and primary wood products	614	0.74	0.68	39.0%	14-30	High potential for large plants located in suitable locations	Remain same
Power generation	Few pure biomass plants	0.36	Almost full emissions for those burning biomass	17.4%	10 – 12 (biomass fired)	Medium – depends on location and asset lifetime	Very uncertain, likely an overall reduction in emissions and also growth in BECCS
Waste management	925	0.30	0.18	23.1%	6-12	Medium – depends on location and asset lifetime	Growth particularly of waste to energy plants
Food and drink	212	0.13	0.00042	0.1%	99	Sites relatively small and dispersed	Steady growth
Cement	829	0.74	0.05	4.1%	18 (kiln flue gas) 20-30 (pre-calciner)	High potential for CO_2 capture to remove process emissions	Similar size
Biomethane production	729	0.006	0.006	2.0%	96	CO_2 already separated but unlikely to be used for CCU due to scale	Rapid growth
Biogas production	17,779	0.001	0.001	10.1%	25-50	Low – many small scale plants	Growth
Bioethanol	146	0.12	0.06	2.2%	99	High – already captured for other uses	Potential growth but uncertain given gasoline demand reduction and further ethanol import potential

Our approach to estimating total accessible biogenic CO_2 across the 20,000 Europe emitters

- Not all of the maximum biogenic emissions will be available for capture and utilisation/ storage.
- To estimate the total accessible biogenic CO_2 amount (i.e. biogenic CO_2 that could be used for SAF production), we conducted a screening and shortlisting of the key sectors identified previously.
- The screening process is shown on the right of the slide, with various filtering steps being applied in sequence. Key factored covered both:
  - **Internal considerations**, such as the scale of the emitter, CO_2 concentration within flue gases, and potential capture rate
  - **External factors**, such as location of the emitters and proximity to pipeline infrastructure for the collection of CO_2
- Due to uncertainty around the impact of each screening factors, **we developed two scenarios for the accessible biogenic CO_2.**
- The assumptions behind each screening step are shown on the following slides.

Total Biogenic Emissions

- The maximum potential for supply of biogenic CO_2 in Europe today is ~196 $MtCO_2$/year, with an uncertainty range of 154-250 $MtCO_2$/year

Purity of CO_2 stream

- Carbon capture is less economic on low purity CO_2 streams with significant contaminants (e.g. waste management).
- Generally the higher the CO_2 content, the higher the likelihood for sites to deploy carbon capture

Emissions scale

- Small scale emitters are less likely to deploy carbon capture – we filtered out small sites unlikely to deploy carbon capture and this threshold varies by sector.
- In certain sectors, if the CO_2 stream is highly concentrated (e.g. biomethane production) we do consider capture of CO_2 from smaller sites.

Capture rate

- Not all CO_2 will be captured from the emissions stream.
- Typical capture rates vary between 85% and 95% (both considered in our scenarios)

Transport barriers

- Dispersed sites are less likely to deploy capture due to the high cost of infrastructure development
- To reflect this uncertainty, we have considered two cases: sites within 50 or 100 km of a hub identified by total current emissions across all sectors. . For biomethane and bioethanol plants, where CO_2 is already separated/high purity this barrier to capture is not applied.
- Sites which emit >409 $ktCO_2$/year biogenic emissions are assumed to be able to host their own 100 kt/yr PtL plant and may not face transport barriers.

Accessible range

- Two scenarios of accessible biogenic CO_2 ranging between 21-63 $MtCO_2$/year

Carbon capture is less economic on low purity CO_2 streams with significant contaminants

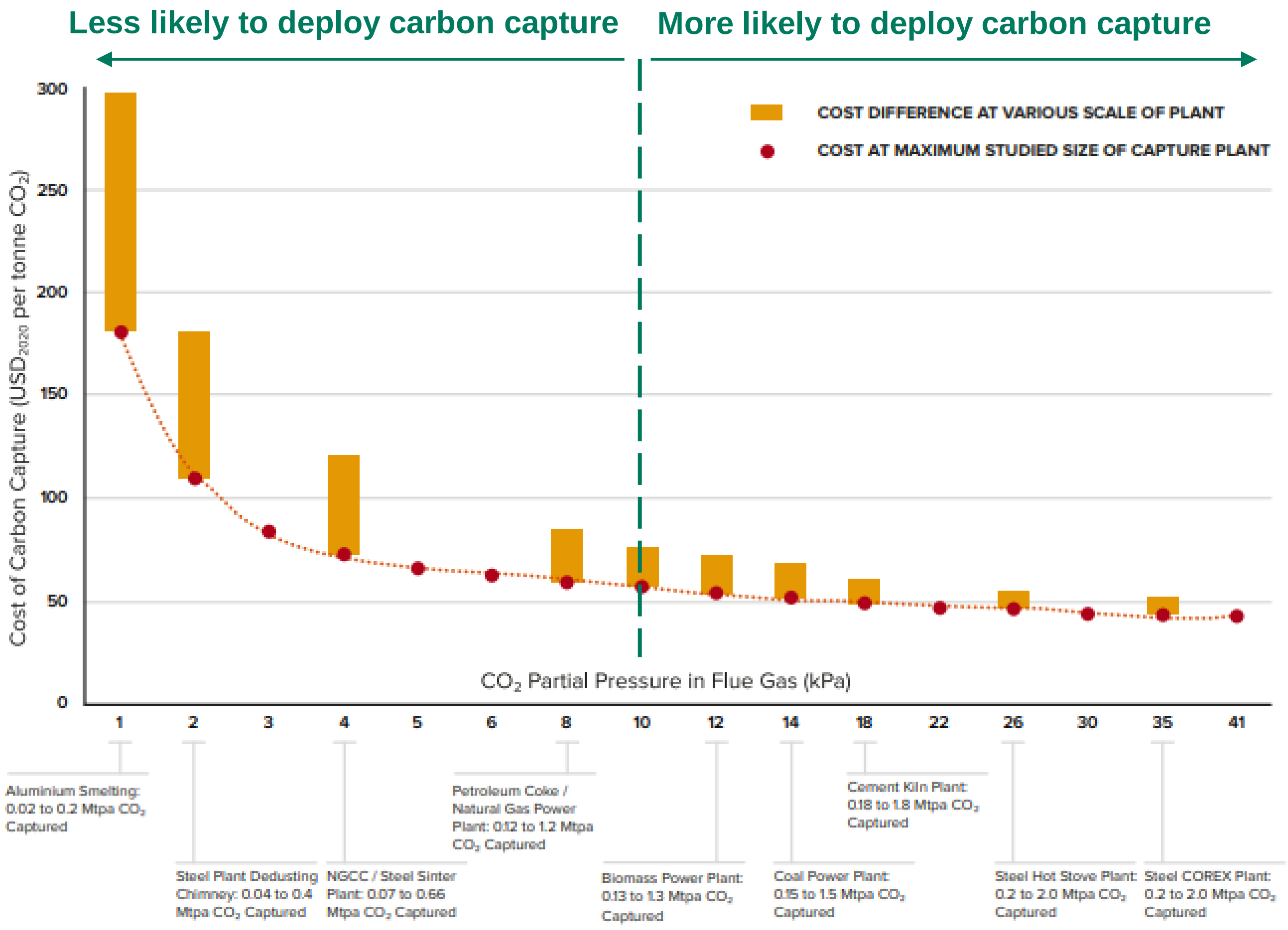
Purity of CO_2 stream

Increasing partial pressure reduces the cost of capture

- Amine-based chemical absorption is the preferred capture technology
- The cost and therefore the incentive to deploy carbon capture depends on the partial pressure (i.e. concentration x pressure) of the flue gas stream, higher CO_2 partial pressures mean that the CO_2 will transfer more rapidly from the source gas to the solvent[1]
- Flue gas from biogas upgrading is CO_2 at a high pressure and concentration so capture will reach cost parity sooner
- For other sectors, the pressure of the flue gas will be close to atmospheric with a lower concentration, therefore the partial pressure will be lower

Impurities make carbon capture less economic

- Capture plants can be degraded if there is a high fraction of NO_x and SO_x present in the flue gas
- Pre-treatment of the flue gases is needed if there are significant impurities – this will increase the cost of carbon capture
- Sectors such as Energy from Waste will contain multiple impurities in their flue gases including NO_x, SO_x and chloride, making carbon capture more expensive in this sector
- EU has stringent limits on NO_x emissions so should not need to do as much pre-cleaning (compared to other countries)



[1]Technology-Readiness-and-Costs-for-CCS-2021-1.pdf (globalccsinstitute.com)

Small scale emitters are less likely to deploy carbon capture

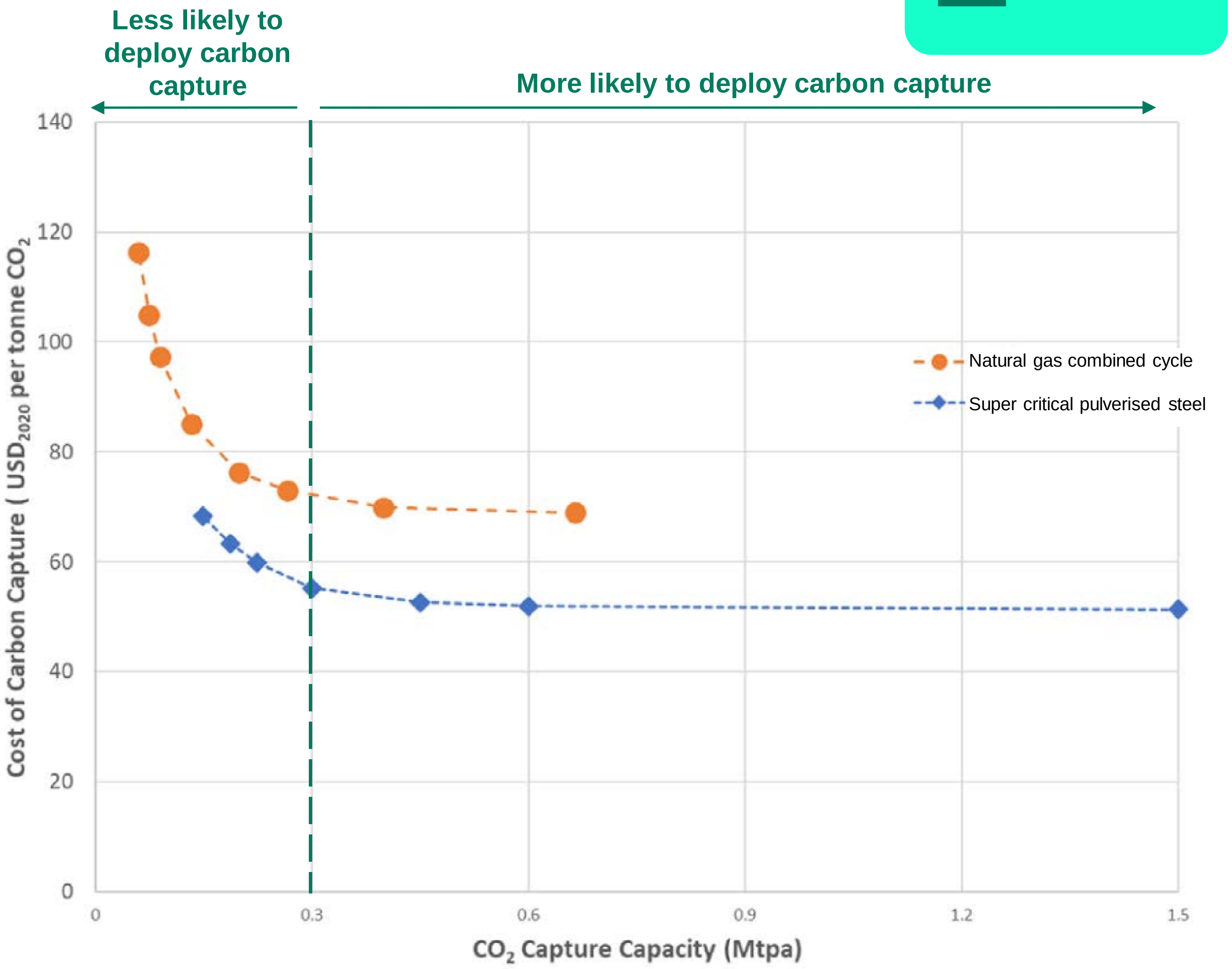
Emissions scale

The smallest technical threshold for carbon capture is between 15 and 30 ktCO_2/year

- Modular units such as developed by Aker carbon capture (Just catch) and Carbon Clean can capture 30 and 40 ktCO_2/year respectively
- This threshold will vary depending on the purity of the flue gases, for example because the stream is so pure from biogas upgrading, the technical feasibility of deploying carbon capture will be lower

The economic threshold will depend on the sector

- Cost reductions for carbon capture diminish above around 0.3 MtCO_2/year and level off around 0.5-0.6 MtCO_2/year[1]
- To minimise capture costs the capacity should be at least 0.4-0.45 MtCO_2/year[1]
- Costs are likely to fall in the next decade or so
- Deployment of carbon capture is assumed to be economical >0.3 MtCO_2/year[2] for industries without a high purity CO_2 stream
- The threshold is lower for industries (e.g. biomethane production) which has a very pure CO_2 stream
- These thresholds are likely to change in the future with differing policy and/or economic incentives



[1]Technology-Readiness-and-Costs-for-CCS-2021-1.pdf (globalccsinstitute.com) [2]Thresholds_CCC-backgrounder_.pdf (carboncapturecoalition.org)

Access to biogenic CO_2 for CCS or CCU will depend on both the purity of the flue gases and the size of the plant

Purity and scale

Considering the scale and purity of the CO_2 streams, we assessed the sector's suitability for carbon capture as follows:

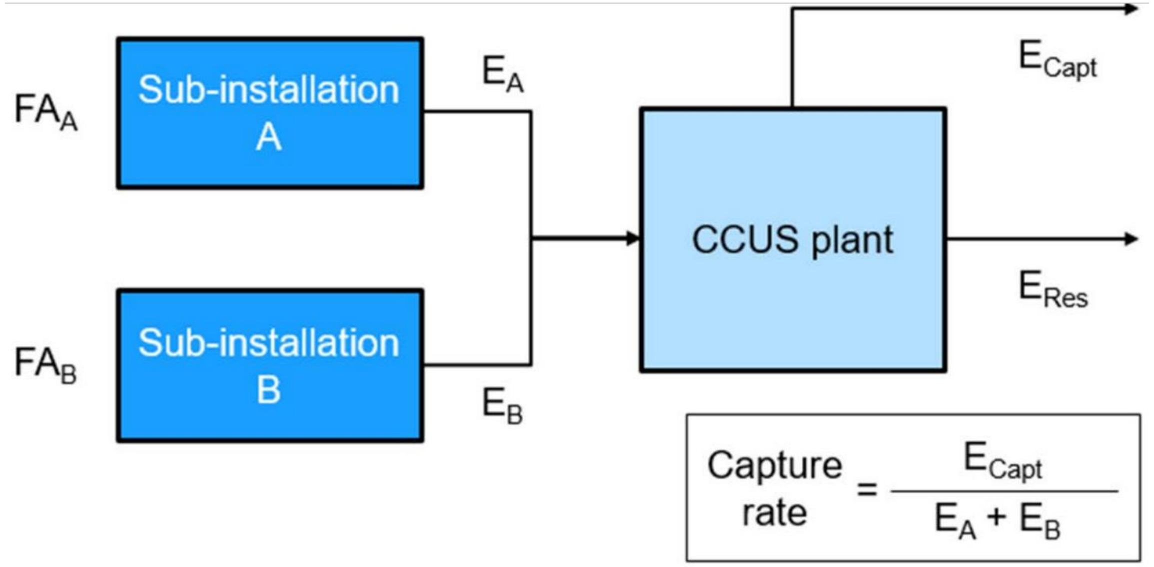
- If average plant size for the sector is >0.3 $MtCO_2$/year, then the sector is more likely to deploy carbon capture (green) whereas if the average plant size is <0.3 $MtCO_2$/year, the sector is less likely to deploy carbon capture (red)
- If the fraction of CO_2 in the flue gas is >10% the sector is more likely to deploy carbon capture (green) or if purity is <10%, the sector is less likely to deploy carbon capture (red) due to increased impurities
- The high and low carbon capture deployment uptakes for each sector are illustrative and consider both the average CO_2 emissions per plant and the fraction of CO_2 in the flue gases (i.e. the purity of the stream). For example:
  - Small site (<0.3$MtCO_2$/y) and high purity (>10% CO_2), e.g. bioethanol – low scenario = 33% and high scenario = 66% capture
  - Large site (>0.3$MtCO_2$/y) and low purity (<10% CO_2) e.g. waste management – low scenario = 25% capture and high scenario = 50% capture
  - Large site (>0.3$MtCO_2$/y) and high purity (>10% CO_2) e.g. paper and pulp - low scenario = 50% capture and high scenario = 80% capture

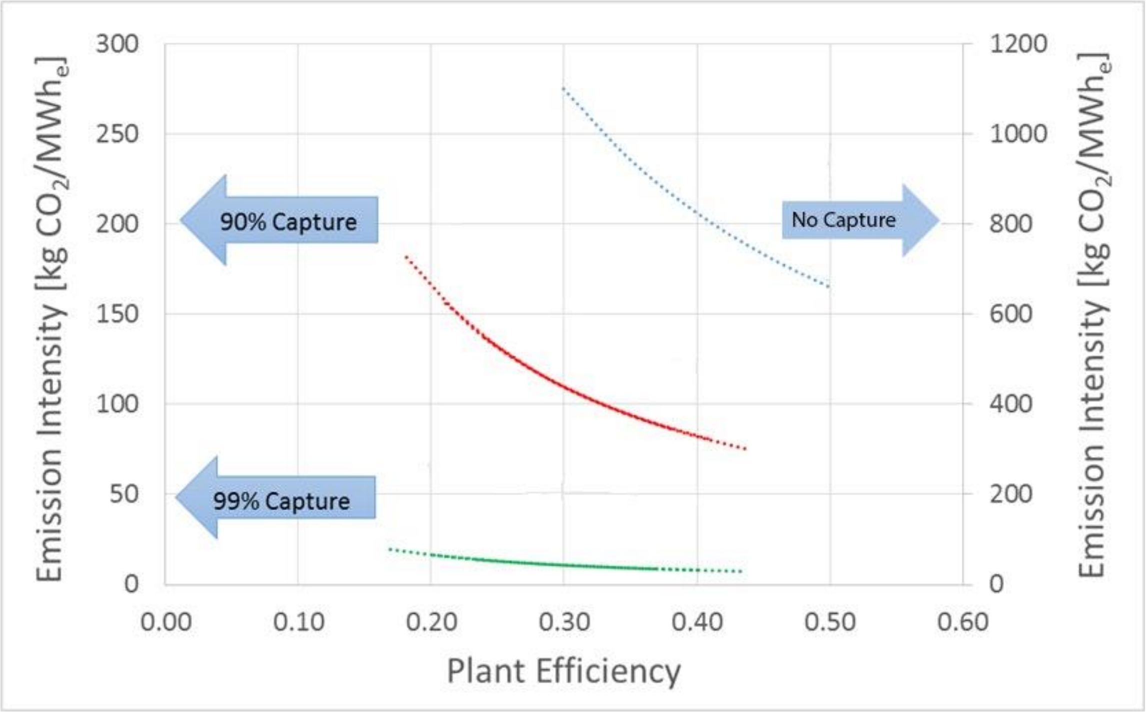
Sector	Number of facilities in Europe	Average CO_2 emissions per plant ($MtCO_2$/year)	Fraction of CO_2 in flue gases (%)	Low carbon capture deployment uptake (%)	High carbon capture deployment uptake (%)
Paper, pulp and primary wood products	614	0.74	14-30	50%	80%
Power generation	Few pure biomass plants	0.36	10 – 12 (biomass fired)	50%	80%
Waste management	925	0.30	6-12	25%	50%
Food and drink	212	0.13	99	33%	66%
Cement	829	0.74	18 (kiln flue gas) 20-30 (pre-calciner)	50%	80%
Biomethane production	729	0.006	96	33%	66%
Biogas production	17,779	0.001	25-50	25%	50%
Bioethanol	146	0.12	99	33%	66%

Not all CO_2 will be captured from the emissions stream to which capture is applied

% Capture rate

- Capture rate is the **percentage of CO_2 emissions captured from the emissions stream**. It does not refer to the percentage of captured emissions from the whole site
- Higher capture rates are typically associated with greater energy penalties and therefore operational costs.
- Capture rate is generally thought to be **around 90%[1], but minimum capture rate is around 85%[2]** for both new build and retrofit facilities
- Differences in capture rate will occur due to differences between different sectors, varying levels of technological readiness and dilute CO_2 concentrations in the stream directed to the capture plant[2]
- There are no technical barriers to increasing capture rates over 99% so this could improve in future, especially with increasing plant efficiency[1]





[1]Zero-emission carbon capture and storage in power plants using higher capture rates – Analysis – IEA [2]Carbon Capture, Usage and Storage: an update on the business model for Industrial Carbon Capture (publishing.service.gov.uk)

We deployed a statistical approach to determine the barriers of biogenic emitters to CO_2 transport infrastructure

Transport barriers

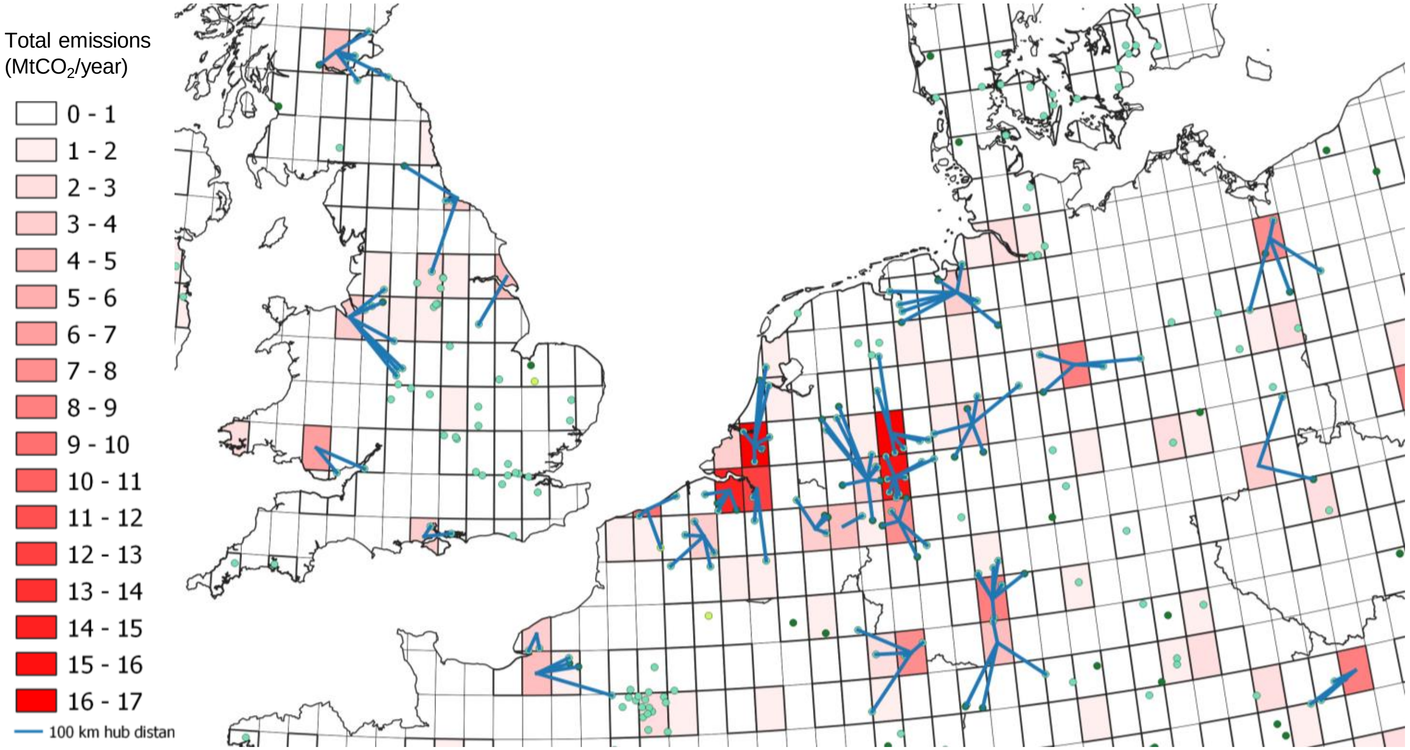
Proximity of biogenic emitters to clusters will increase their likelihood of participating in CO_2 utilisation and/or storage projects

- Industrial clusters or hubs are expected to be the first areas to develop CO_2 transport infrastructure for collecting fossil and biogenic emissions.
- Many biogenic emitters are relatively small in size and often located away from industrial areas, meaning that they many not be able to connect to CO_2 transport infrastructure .
- To assess any barriers in collecting the biogenic CO_2, we have assessed the likelihood of biogenic emitters connecting to industrial clusters, based on their distance from the clusters.

Methodology

1. Hubs of industrial emitters (both fossil and biogenic emissions) are identified
   - A hub is defined by having current total emissions >3 $MtCO_2$/year (excluding power generation) within a grid square (0.5° x 0.5°)
2. Mapped biogenic emitters close to these hubs that can make use of nearby CO_2 transport infrastructure
   - Only biogenic emitters with total emissions >0.1 $MtCO_2$/year have been considered
   - 52 emitters which have >409 $ktCO_2$/year biogenic emissions were removed from this analysis as they could be co-located with their own 100 kt/yr PtL plant
   - Two scenarios were considered: 50 km and 100 km between hubs and biogenic emitters
3. The fraction of biogenic emitters connected to a hub relative to total biogenic emitter was estimated for each scenario.
4. The ration was then used to calculate the proportion of biogenic emissions which are likely to have access to CO_2 transport infrastructure. This fed into the screening assessment and is shown in the waterfall diagrams on this slide.

Mapping of biogenic emitters (green dots) to industrial clusters (red hotspots)



Note: this approach does not take into consideration barriers to transport (e.g. topology) which will decrease accessibility to captured biogenic CO_2 emissions

Between 28%-44% of European biogenic emitters fall within 50-100km of industrial clusters

Transport barriers

To consider a large number of CO_2 transport operational scenarios, we have explored the potential of emitters within 50km and 100km from industrial clusters.

Almost one quarter of biogenic emitters are within 50km of an industrial cluster

- **23% of emitters** from the biogenic sectors are **within 50 km** of these hubs
- These connected emitters account for **29% of total emissions** from biogenic sectors

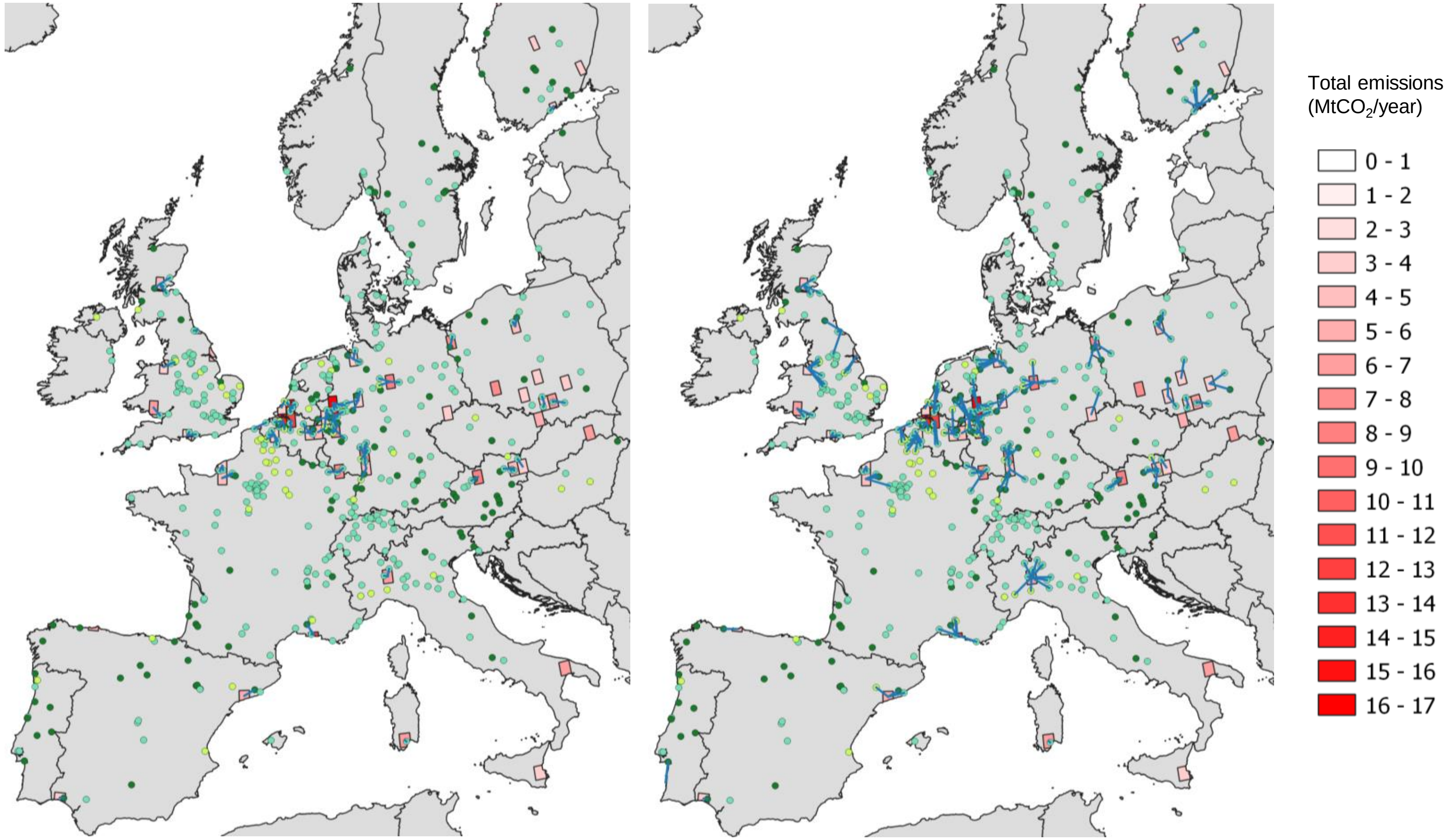
Just under half of biogenic emissions fall within 100km of a cluster

- **41% of emitters** from biogenic sectors are **within 100 km** of these hubs, significantly more than in the 50 km case.
- These connected emitters account for **48% of total emissions** from biogenic sectors

Transport barriers

- For both the 50 km and 100 km case, the fraction of total emissions which are not connected to a hub are used to generate a high and low scenario for the reduction in accessible potential due to transport barriers
- This approach does not take into consideration barriers to transport (e.g. topology) which will decrease accessibility to captured biogenic CO_2 emissions
- There are 52 biogenic emitters >409 ktCO_2/year across Europe who could be co-located with their own PtL plant and do not need to rely on a cluster for transport infrastructure.
- It is assumed that the biomethane and bioethanol plants do not have any barriers to transport since the CO_2 is already separated.

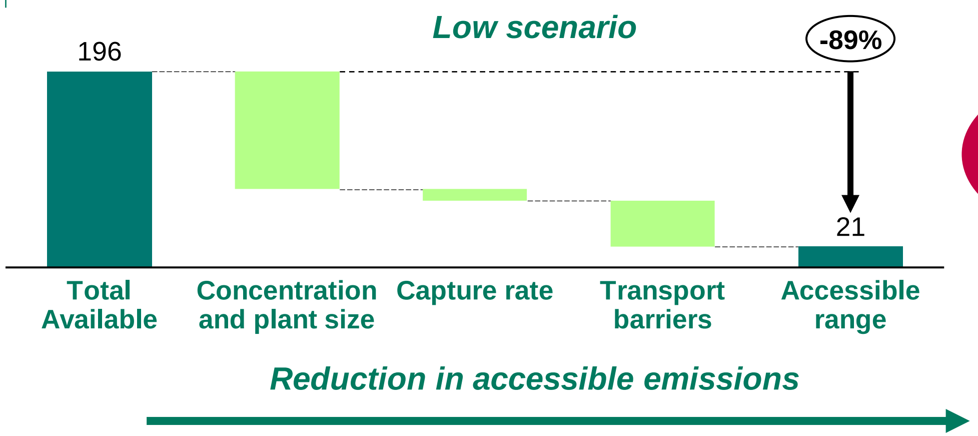
Mapping of biogenic emitters (green dots) to within 50km (left) and 100km (right) of industrial clusters (red hotspots)



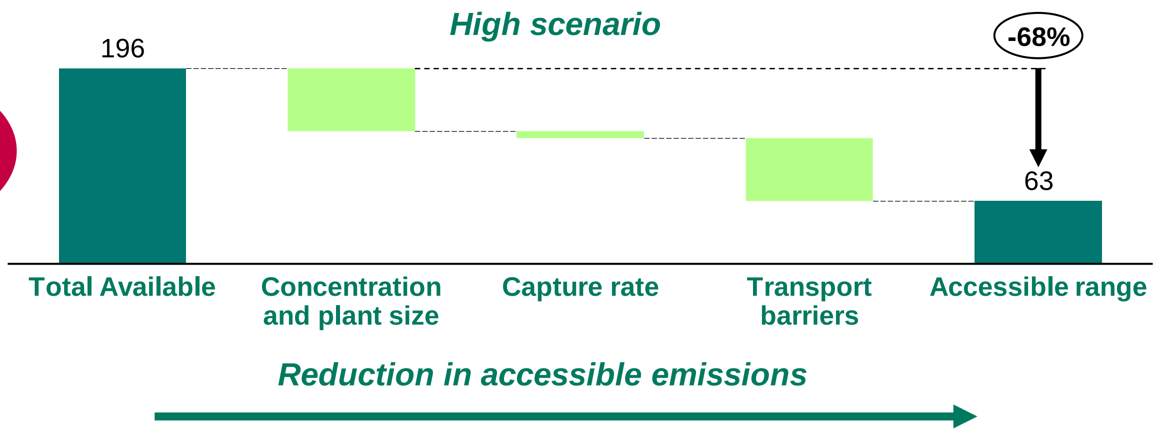
Green dots show biogenic industrial sites (paper and pulp, waste management and food & drink) with current total emissions >0.1 MtCO_2/year

This could reduce the accessible potential by **68-89%** compared with the maximum available

Accessible range

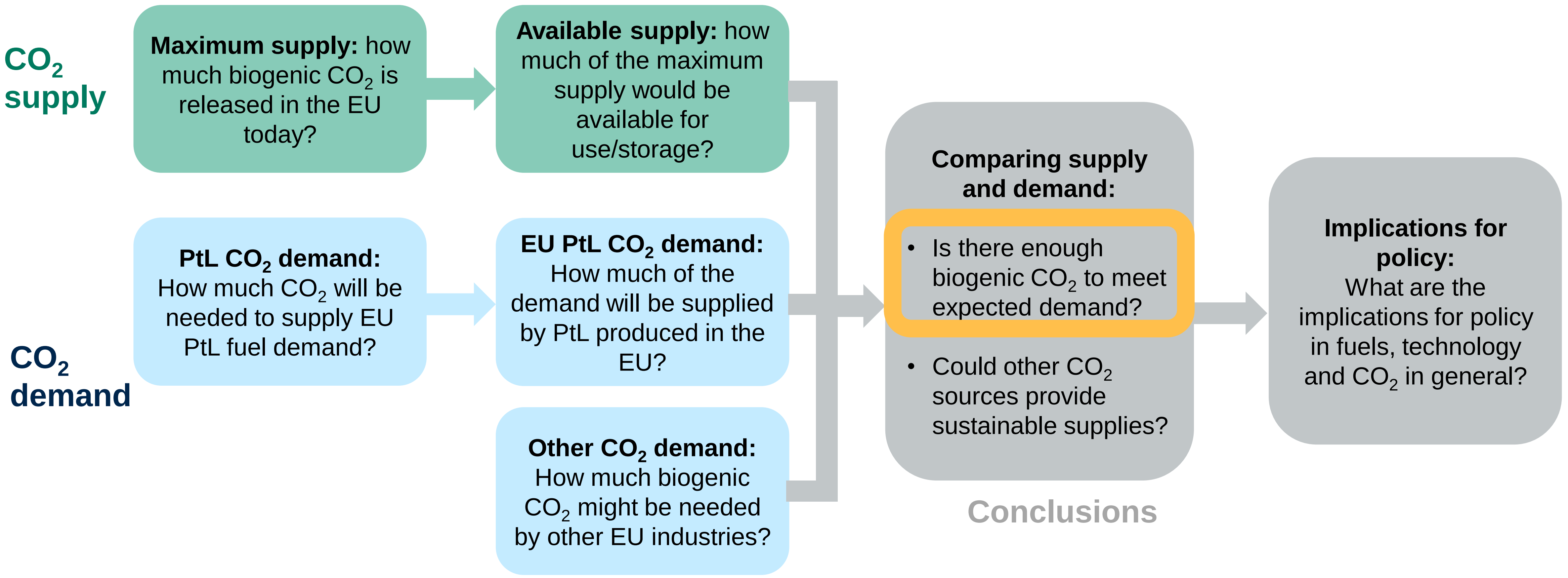


Graphs changed



Total Available	Purity of CO_2 and size of emitter	Capture rate	Transport barriers	Accessible range
This is the total biogenic emissions produced by the sector. It is unlikely that 100% of available emissions will be accessible due to technical and economic factors.	Carbon capture is unlikely to be economic for small scale emitters and is more technically challenging on low-concentration CO_2 streams. It is assumed that a portion of biogenic emissions is not viable to capture due to technical and economic factors, depending on sector. **Low: 25-50% deployment depending on sector** **High: 50-80% deployment depending on sector**	Higher capture rates are typically associated with greater energy penalties and therefore operational costs. The following capture rates are assumed: **Low = 85% (minimum capture rate)** **High = 95% (no technical barriers to high capture rates)**	Dispersed sites are less likely to deploy capture due to the high CAPEX costs associated with infrastructure development. **Low = Biogenic sectors within 50 km of a hub (29% of emissions can be captured)** **High = Biogenic sectors within 100 km of a hub (48% of emissions can be captured)** It is assumed that the biomethane and bioethanol sectors do not have barriers to CO_2 transport	The accessible range of biogenic emissions is calculated as: **Low = 20.7 $MtCO_2$/year** **High = 63.0 $MtCO_2$/year**

Comparing supply and demand section: Is there enough biogenic CO_2 to meet expected demand?



Is there enough biogenic CO_2 supply to meet expected demand ?

- On the following slide, we compare the sum of the biogenic CO_2 demand figures presented above, projected from 2030 to 2050, with the maximum and accessible potential figures for biogenic CO_2
- Whilst the estimates of demand and supply have inherent uncertainties, as discussed previously, this enables us to review whether the availability of biogenic CO_2 could present a barrier to ramp up of PtL production in the EU

Potential total biogenic CO_2 demand could be large, outstripping the accessible and maximum potentials, but is very uncertain

Decreasing level of certainty over drivers and volumes

Biogenic CO_2 removal (BECCS etc) - not quantified
- No policy support in place for negative emissions today

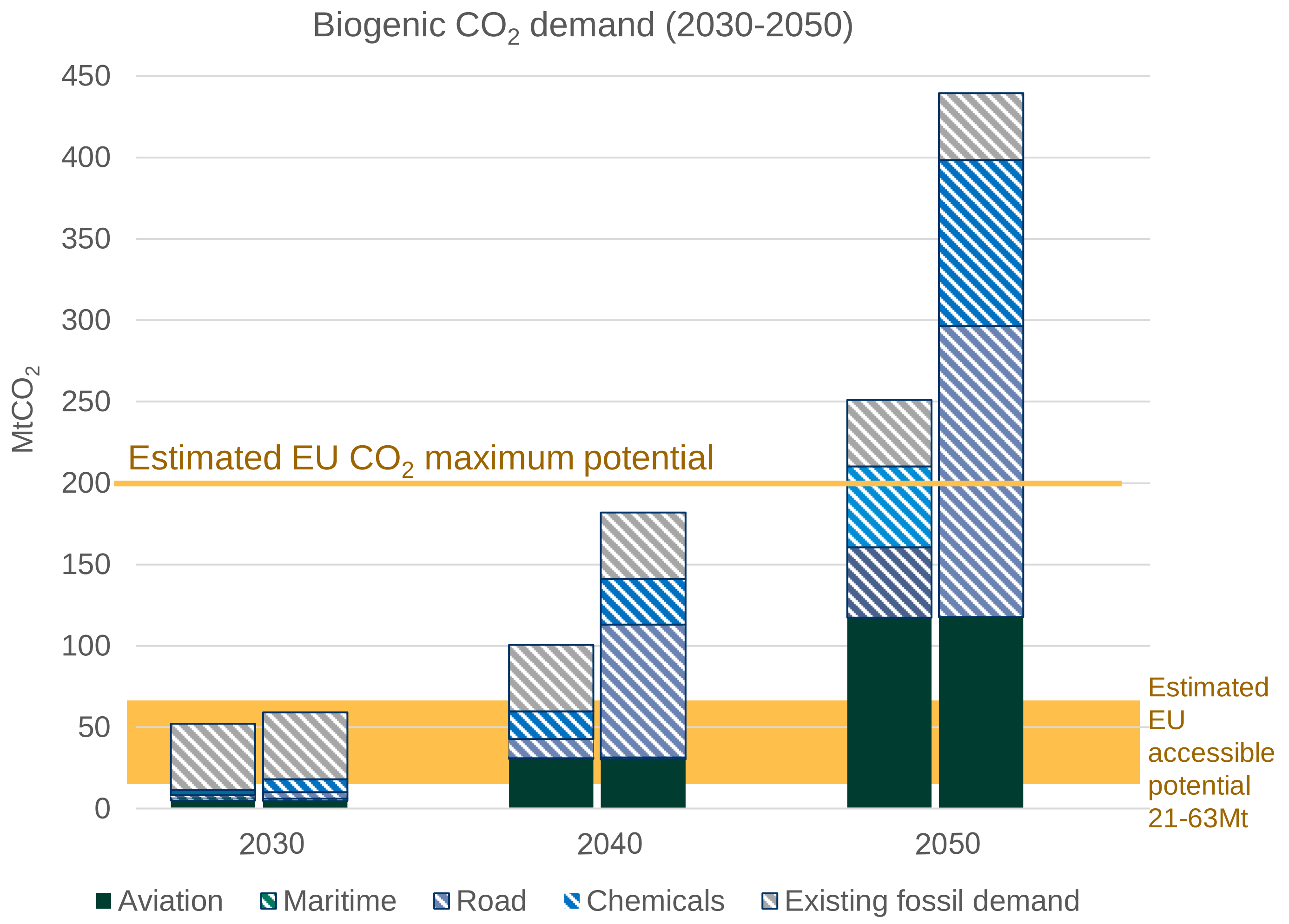
Replacing existing fossil CO_2 demand ESTIMATE
- Existing 41 Mt demand for urea, EOR, food & beverage industries
- No policy drivers yet for biogenic CO_2, but fossil CO_2 production will decline, e.g. from ammonia production, which may move towards H_2.

Chemicals ESTIMATE
- No policy drivers yet for use of biogenic CO_2, but industry interest and so potential future demand

Road ESTIMATE
- No targets for road liquid e-fuels alone, and uncertainty over whether they will be used long term (vs EVs, H_2)
- Low scenario is SAF co-products only. High scenario reaches ~50% of road liquid fuel demand by 2050

Maritime ESTIMATE
- FuelEU Maritime and REDIII policy positions include different RFNBO quotas in maritime, the REDIII target has been considered here
- No consensus on the type of RFNBOs used: Assumed a mix of methanol, e-LNG, NH_3, and H_2, with only NH_3 and H_2 by 2050

Aviation EU TARGET
- Mandate under RefuelEU aviation plus same % target for UK
- One scenario shown here: most recent EP reading position, which would require ~1000PJ of SAF by 2050



If 40% of EU+UK e-fuels were produced in the EU+UK, 33-61% of the max potential would be needed for fuels alone

Import assumptions

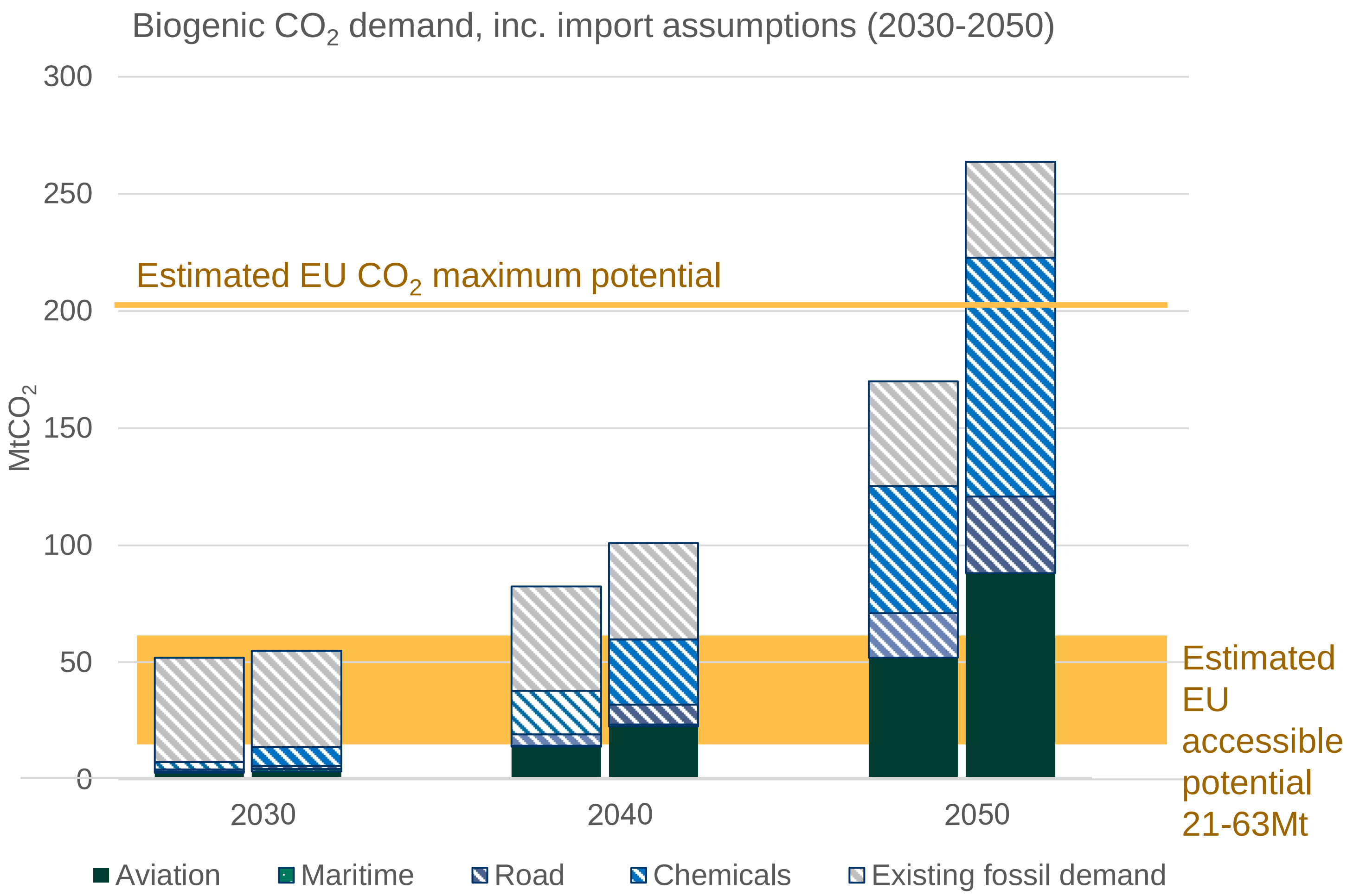
Decreasing level of certainty over drivers and volumes

Biogenic CO_2 removal	n/a
Replacing existing fossil CO_2 demand	All EU
Chemicals	All EU
Road	
Maritime	
Aviation	

E-fuels produced in the EU will compete with imports based on production cost

High EU production scenario: based on currently planned e-fuel production in commercial plants: 75% EU, 25% ROW.

Low EU production scenario: 40% EU, 60% ROW, similar to share of primary energy imported in the EU and projections for hydrogen imports. E4tech's view is that this scenario is more likely as a result of the availability of low-cost renewable electricity globally



Combines the Low demand scenario with Low EU production scenario, and High demand scenario with High EU production scenario

Future biogenic CO_2 emissions are highly uncertain: increased biomass use could be offset by BECCS uptake

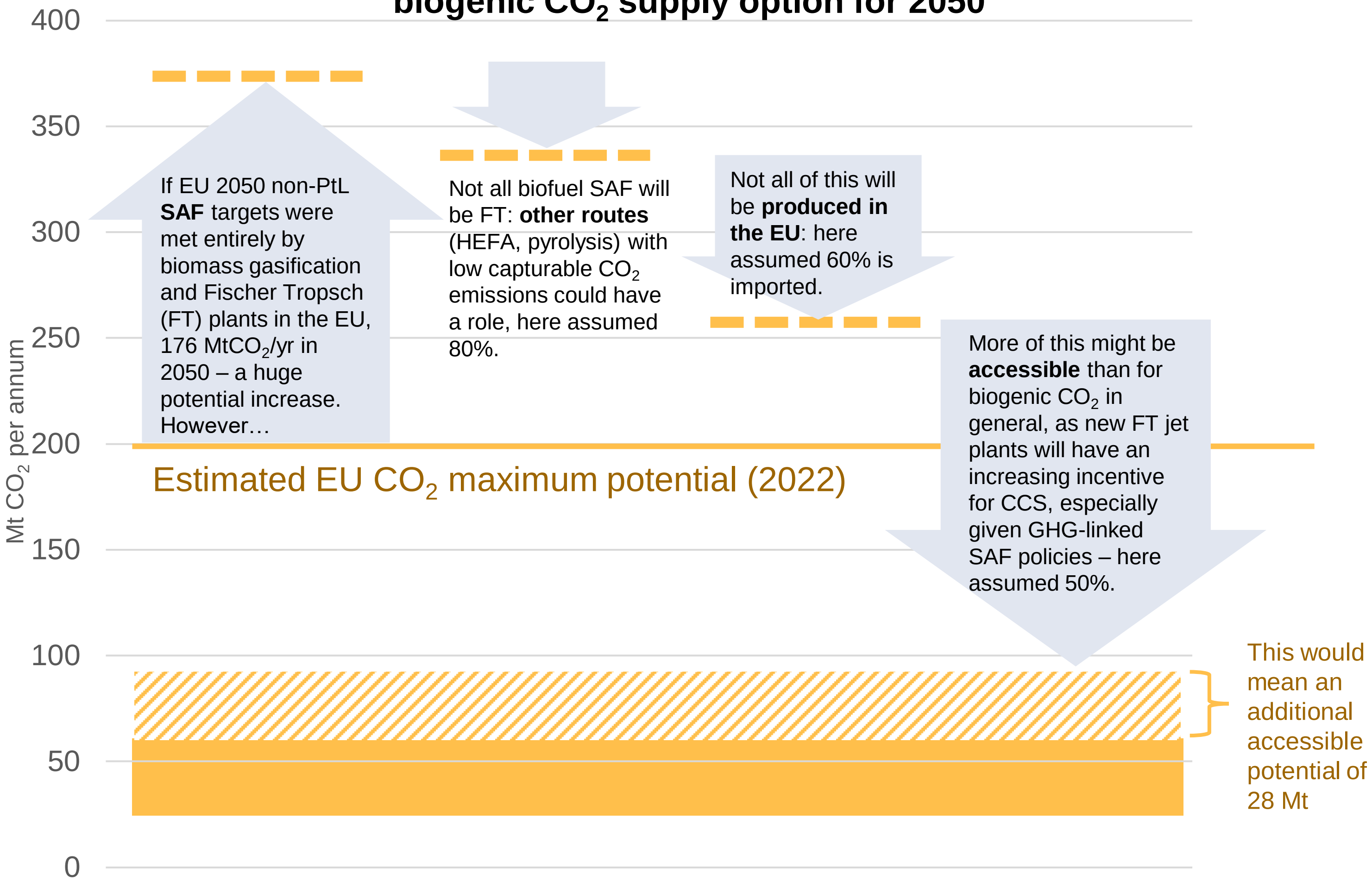
Increased uptake of biomass and biomass derived products in existing industries could increase biogenic emissions.

- Greater use of **solid biomass in industrial fuel switching** and increased use of **biomass in the chemical industry**
- Producing **more ethanol** could increase supply, but the EU outlook is uncertain given gasoline demand reduction and imports.
- Biogenic CO_2 could increase from **gasification-based fuel production** for aviation and road
- Further ramp up of **biogas and biomethane** could increase supply

However, there is the also the potential for **bioenergy with CCS** to ramp up, meaning that these sources of biogenic CO_2 would not be available for CCU.

- Policy to support each of these uses, or to support new industrial plants in general, may include a **requirement or a driver for CCS**. Very little policy is in place today.
- The amount of biogenic CO_2 stored is **highly uncertain** – for example most of the scenarios in the EU 2050 decarbonisation pathways from the 2018 Clean Plant for All report[1] have under 10 Mt/yr BECCS, but one scenario has over 170 Mt/yr.

Illustration of uncertainty over one potential new biogenic CO_2 supply option for 2050

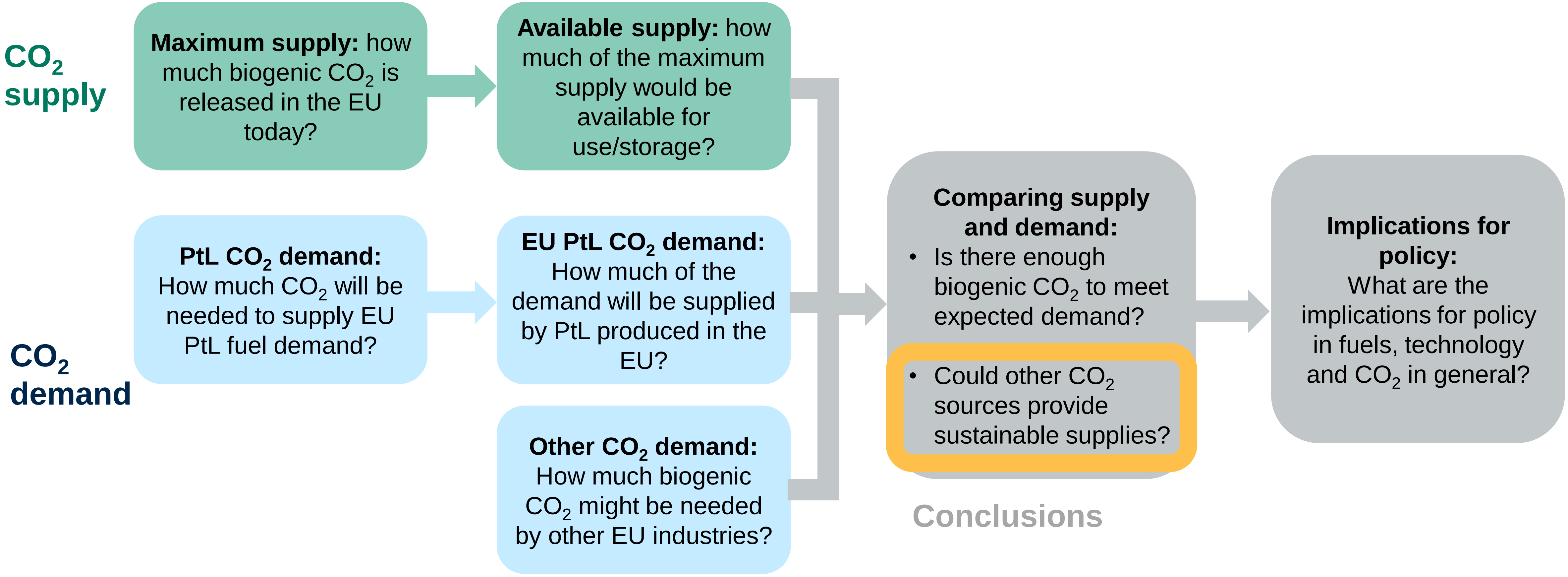


1. EU Commission, 2018

Availability of biogenic CO_2 could become a limiting factor by 2040 in some scenarios and by 2050 in all scenarios

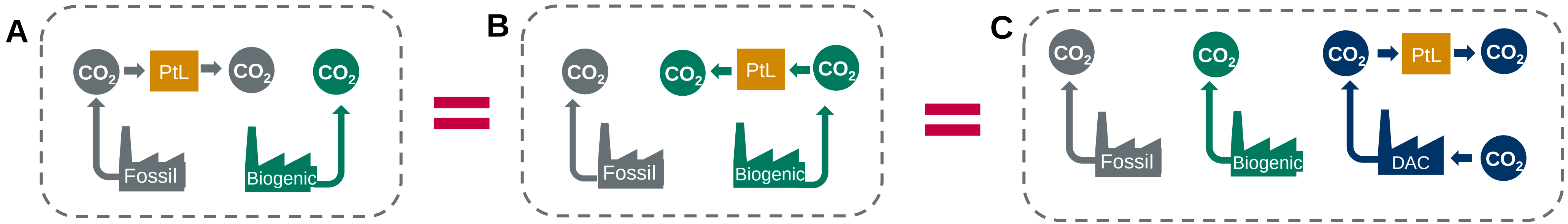
- The graphs show that the availability of accessible biogenic CO_2 is likely to be higher than the projected demand in the near term (2030). However, by 2040, the projected demand for fuels is within the projected range of the accessible potential, and surpasses the projected accessible potential by 2050.
  - The maximum and accessible potentials are based on current data, with no change projected over time: this is as a result of the wide range of uncertainties about future supply levels depending on policy priorities and industry responses. For example, increased use of bioenergy in industrial fuel switching and chemicals could increase biogenic CO_2 emissions, whereas new policy drivers for BECCS could decrease them.
- Nevertheless, we consider that the scale of demand even from the aviation sector alone, when compared with the accessible potential, shows that the availability of biogenic CO_2 could become a limiting factor on the growth of PtL by 2040 in some scenarios and by 2050 in all scenarios
- This means that other sources of CO_2 will be needed. The DA allows only for DAC and geological sources: this raises the question of whether other sources could be used sustainably

Comparing supply and demand section: Could other CO_2 sources provide sustainable supplies?



The source of CO_2 used for PtL does not inherently affect the GHG intensity of the PtL product

- It is important to consider whether different sources of **CO_2 (fossil-based, biogenic, atmospheric, etc.) for PtL production have different sustainability impacts**. These impacts can then be considered alongside other factors such as their costs, availability and speed of ramp up to assess which are acceptable for PtL production.
- From a direct lifecycle greenhouse gas perspective, the **source of the CO_2 does not inherently affect the GHG intensity of the PtL product**, as explained below. However, capturing CO_2 from different sources may use different amounts of resources (energy and material), as explained on the following slide.
- The simplified illustration below illustrates the equivalence of using three different sources of CO_2 to produce renewable fuels in today's mostly non-decarbonised economy.
  - This shows a plant emitting fossil-based CO_2, a plant emitting biogenic CO_2 and a DAC plant, all with a potential to capture the same amount of CO_2.
  - If the fossil and biogenic plants are freely emitting to the atmosphere, capturing and **using the CO_2 from any of the three sources to produce fuels will not affect total overall emissions, since CO_2 is re-released when PtL fuels are combusted**.



Direct air capture has higher energy use than capture from point sources, as a result of lower CO_2 concentration

The table below lists different sources of CO_2 and summarises the energy demand for carbon capture based on the literature. As energy demand is a function of flue gas CO_2 composition, there is a relationship between these parameters; DAC has the highest energy penalty, since air is very dilute in CO_2.

CO_2 Source	Examples	Flue gas CO_2 Composition	Energy Demand (MWh/tCO_2)
Atmosphere	Direct air capture	0.04% (~410 ppm)	Elec: 0.64 – 1.1 and Heat: 1.9 – 3.0 [1]
Biogenic – high purity	Ethanol, breweries, pulp and paper	99% (bioethanol) 96% (biomethane) 14–30% (pulp & paper)	0.64 – 1.0 [2]
Biogenic – low purity	Biomass power	10-12%	0.56 – 1.0 [3]
“Unavoidable” fossil point source	Cement kiln, waste incineration	18% (kiln flue gas) 20–30% (pre-calciner)	0.33 – 1.23 [4]
Other fossil point source	Fossil power plants	12–15%	0.25 – 0.30 [5]

Depending on the choice of technology and plant setup different amounts of electricity or heat (as steam) may be used. It is also possible to use heat pumps to provide heat through electricity.

GHG emissions will depend on the energy source used; in any of the cases presented renewable electricity can be used, significantly reducing the carbon footprint of the process.

[1] Global Assessment of DAC Costs (2021), report by Element Energy for IEAGHG [Link]. The values represent ranges for first-of-a-kind solid and liquid DAC technologies. Total demand is sum of heat and electricity demand.
[2] Techno-Economic Assessment of Bio-Energy with Carbon Capture and Storage Systems in a Typical Sugarcane Mill in Brazil, Restrepo-Valencia, S., Walter A., (2019), *MDPI* [Link]. Range based on modelling of a typical sugarcane mill in Brazil. The fermentation process produces pure CO_2 with no energy demand for separation, however, the co-generation plant requires separation and produces the majority of the plant emissions. Values reported are average energy demand for both streams.
[3] Bio-Energy with CCS (BECCS) performance evaluation: Efficiency enhancement and emissions reduction, Bui M., Fajardy M., Mac Dowell N. (2017), *Applied Energy* [Link].
[4] CO_2 Capture, Use, and Storage in the Cement Industry: State of the Art and Expectations, Plaza, M., Martinez, S., Rubiera, F. (2020), *MDPI* [Link]. Range representing publicly available data for various cement CCS technology types and projects.
[5] “Efficiency Parameters of CCS” on Climate Policy Watcher website (last updated 04.07.2022) [Link].

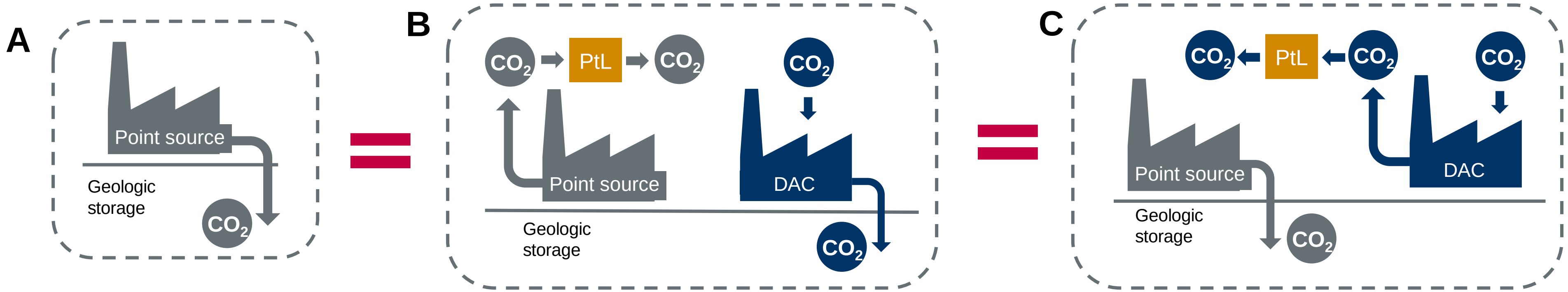
However, in the long term, point source CO_2 emissions will need to be reduced and/or stored permanently, and DAC ramped up

Near to mid term (e.g., < 2040)

- In general, greater climate benefits may be achieved by using point source capture rather than DAC for PtL, as a result of lower energy use. Near term DAC deployment will be needed, however, to ensure that this technology ramps up and reduces in cost and energy demand for future use.
- However, payments from sale of CO_2 to PtL facilities could prolong the life of fossil CO_2 emitting plants that would not be compatible with a decarbonised future, or divert/delay CCS from fossil and biogenic point sources. To avoid this, it would be best to focus support for CO_2 utilisation such as PtL on:
  - plants with very limited alternative decarbonisation options (e.g., cement and waste incineration) AND without feasible CO_2 storage availability OR
  - plants without CCS options today, but willing to shift to permanent storage in the future

Longer term, after wide decarbonisation (e.g., > 2040)

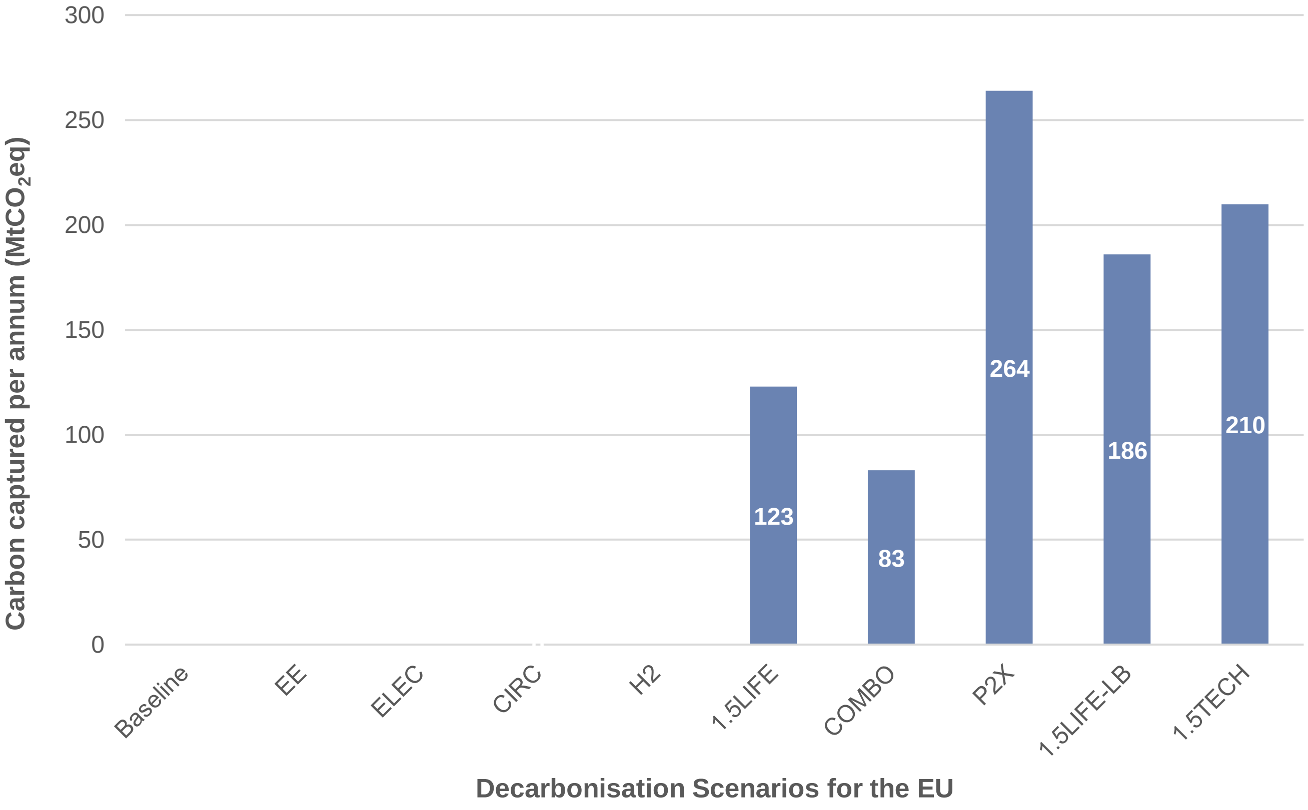
- In order to fully decarbonise the economy, sites with carbon capture installed must store their CO_2 or offset emissions through DAC, as illustrated below.
  - Panel A depicts a decarbonised future where all emitting plants have CCS installed. If PtL were be added to the system whilst keeping total emissions constant, new DAC capacity must also be deployed, either to provide CO_2 for PtL (panel C) or to neutralise emissions from point sources that are now not stored (panel B).
  - At this point the decision to use point source CO_2 for PtL will likely depend on relative economic benefits and other practicalities. For example, there may still be plants without alternative decarbonisation options AND without feasible CO_2 storage, which may be good candidates for PtL applications.



Without policy drivers, the scale of DAC in the EU remains uncertain

- Currently, there are **no policy drivers for DAC in the EU**.
- Estimates for the deployment of DAC vary between 0 and 264 MtCO_2eq per year by 2050[1]. A 2021 Commission press release suggests that 5 MtCO_2eq should be removed annually by 2030 but this has not been integrated into legislation[2].
- The EU Commission's *Clean Planet for All* report analysed DAC deployment in 2050 for ten decarbonisation scenarios, the result of which can be seen on the graph. Across the scenarios, the average carbon capture capacity via DAC is 87 MtCO_2eq[1]. However, half of the scenarios involve no DAC deployment at all.
- At the member state level, only Denmark, Germany, Greece and Italy mention DAC in their carbon removal frameworks. Of these, only Denmark quantifies the removal potential, with 0.5 MtCO_2eq estimated by 2030[3].

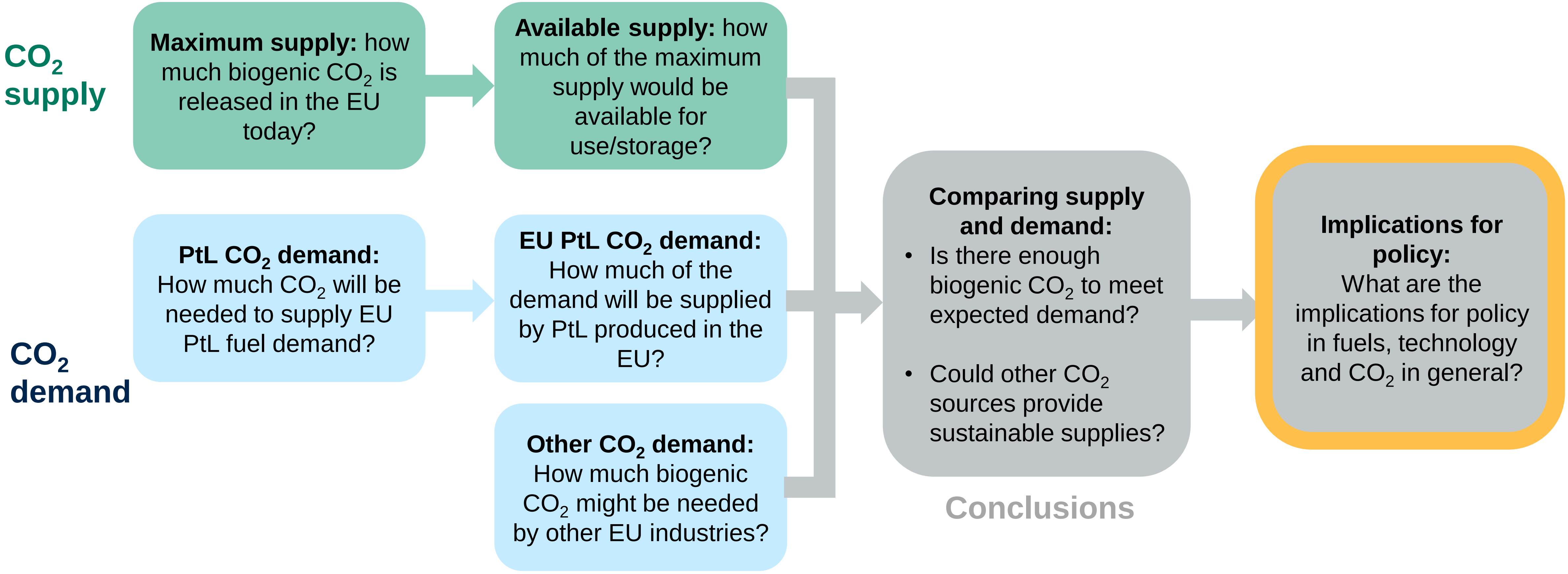
Carbon captured through DAC in the EU in 2050[1]



- From a global perspective, DAC deployment is expected to accelerate rapidly between after 2030. In the IEA's 2021 report on *Net Zero by 2050,* DAC capacity increases more than ten fold from 90 to 985 MtCO_2eq per year between 2030 and 2050[4].

1. EU Commission, 2018, 2. EU Commission, 2021, 3. Ecologic, 2022, 4. IEA, 2021

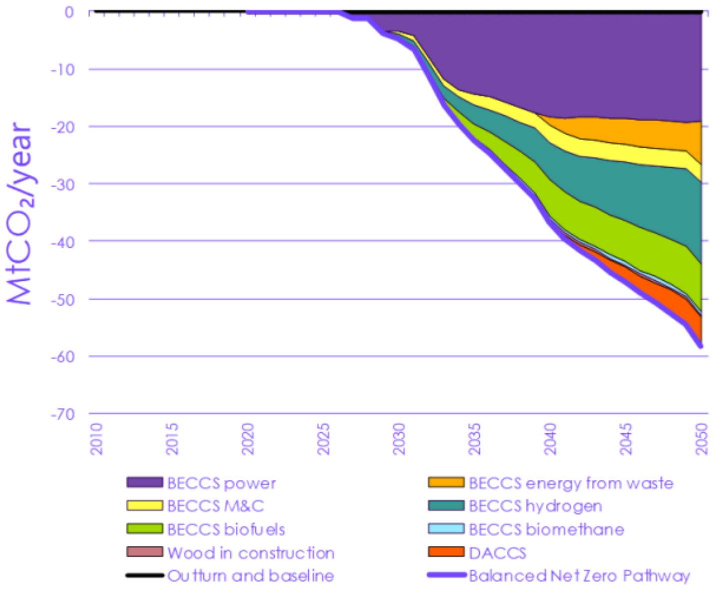
Implications for policy: What are the implications for policy in fuels, technology and CO_2 in general?



To achieve net zero, policy must drive emissions reduction and encourage CO_2 capture from all point sources

- Achieving net zero will be challenging, and require a range of major changes to the energy system, supported by policy
- Fossil point source emissions need to be **reduced as far as possible**, by switching to alternatives, such as electrification using renewables
- A high proportion of **point source emissions of all types will need to be captured**. Any non-biogenic emissions not captured will need to be matched by greenhouse gas removal from the atmosphere. Given that BECCS is one of the major ways to do this, biogenic emissions will need to be captured and stored wherever possible.

Example: GHG removals required for the UK to meet the Climate Change Committee's Balanced Net Zero Pathway, showing BECCS pathways as the major contributor to 2050



Aims

- CO_2 capture and transport from **all point sources** needs to be maximised to support CCS and CCU, including PtL. This includes maximising accessible biogenic CO_2
- In the long term, to achieve net zero, **all remaining CO_2 emissions need to be balanced** by CO_2 removal and storage, e.g. through DACCS and BECCS.

Recommendations

- More support for CO_2 capture and transport infrastructure across all sectors and plant sizes
- Incentives for CO_2 storage, plus additional market-based incentives for negative emissions which would promote capture of biogenic CO_2
- Consideration of the fate of the CO_2 produced for all new plants built, including incentivising new industry in locations likely to have infrastructure in the near term

- Balancing CO_2 emissions with removal and storage will rely on comprehensive CO_2 pricing mechanisms coupled with mechanisms to support negative emission technology deployment

Sixth Carbon Budget - Climate Change Committee (theccc.org.uk) page 198

Action is also needed to make sure that some of the captured CO_2 is available for CCU, including for PtL

Aims

- **DAC** needs to ramp up quickly and minimise costs and GHG impacts

- Whilst most CO_2 will need to be permanently stored long term, there will be **a need for CO_2 for CCU including PtL**, whether from point sources or from DAC. For point sources meeting the criteria below, CCU rather than CCS may be a more viable option.

    1. The source will **exist long term**, rather than shutting down because it is viable and preferable to move to another location or technology option AND
    2. The source has **no alternative options** that do not release $CO_{2,}$ such as electrification AND
    3. The source has **no economically viable CO_2 transport and storage** options, for example being located far from storage sites, or in regions whether CO_2 infrastructure is unlikely to be developed within the lifetime of a PtL plant

- **PtL imports** will be needed to help meet targets. CO_2 imports are possible, but PtL import is more likely. Barriers to PtL investment globally need to be overcome, including uncertainty over targets and rules.

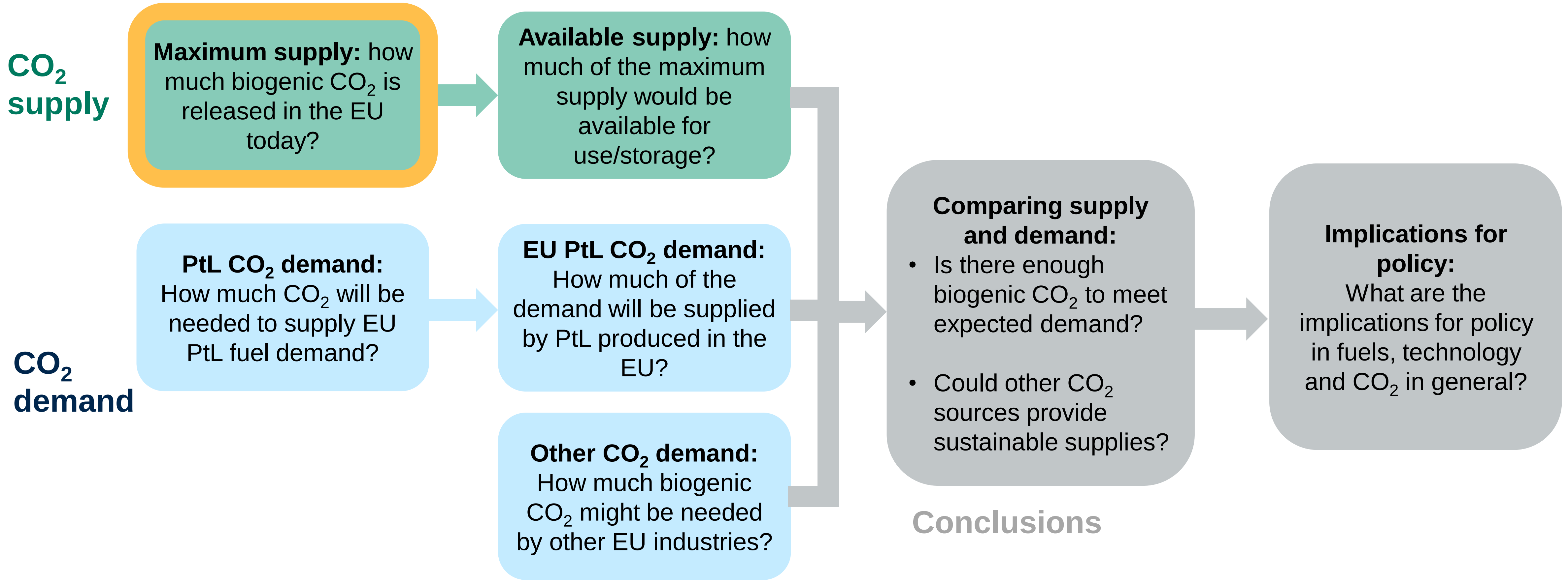
Recommendations

- Policy mechanisms are needed to encourage **DAC deployment** for all applications (including CCS and PtL)

- In the proposed DA, a range of point sources are allowed but only until 2036 – this will not be enough time for PtL plants to pay back.
- A **project-level approach** to assessing the sustainability of use of point source CO_2 could consider the options available to each site today and in the future, allowing use for PtL post 2036 where other options are not feasible
    - This approach would require the producer of the CO_2 to provide justification of why the criteria given are met, including details of the alternative options available to them, and comparison with the actions taken by other similar emitters
    - This justification could be verified through a voluntary scheme, as for fuel sustainability certification
- Carbon pricing needs to apply to the producer of the CO_2 used in CCU (including PtL) so that the producer has a continued incentive to identify options to remove or reduce them

- Policy decisions on targets and sustainability at EU and MS level need to be **finalised quickly**, to facilitate project investment and deployment.

Appendix: Maximum supply: How much biogenic CO_2 is released in the EU today ?



References for carbon capture in biogenic industries

Sector	Number of facilities	Average CO_2 emissions per plant ($MtCO_2$/year)	Average biogenic CO_2 emissions per plant ($MtCO_2$/year)	Current fraction of biogenic CO_2	Fraction of CO_2 in flue gases	Likelihood for deploying CO_2 capture based on technical aspects	Uncertainties in sector growth
Paper, pulp and primary wood products	European Industrial Emissions Portal (europa.eu)	European Industrial Emissions Portal (europa.eu)	European Industrial Emissions Portal (europa.eu)	European Industrial Emissions Portal (europa.eu)	IEAGHG Document Manager	ERM analysis	JRC Publications Repository - Energy efficiency and GHG emissions: Prospective scenarios for the pulp and paper industry (europa.eu)
Power generation	European Industrial Emissions Portal (europa.eu)	European Industrial Emissions Portal (europa.eu)	European Industrial Emissions Portal (europa.eu)	European Industrial Emissions Portal (europa.eu)	CCE-CCS-Technology-Readiness-and-Costs-22-1.pdf (globalccsinstitute.com)	ERM analysis	The future of the global power sector | Deloitte | challenges, power companies, transform, cost reductions
Waste management	European Industrial Emissions Portal (europa.eu)	European Industrial Emissions Portal (europa.eu)	European Industrial Emissions Portal (europa.eu)	European Industrial Emissions Portal (europa.eu)	Microsoft Word - WTE perspective v1.0.docx (globalccsinstitute.com)	ERM analysis	ISWA-2021f-Rev2-FK-1.pdf (iswa-germany.de)
Food and drink	European Industrial Emissions Portal (europa.eu)	European Industrial Emissions Portal (europa.eu)	European Industrial Emissions Portal (europa.eu)	European Industrial Emissions Portal (europa.eu)	https://growthenergy.org/wp-content/uploads/2022/06/GROW-22019-Issue-Brief-Carbon-Capture-2022-06-22-R8.pdf	ERM analysis	State of industry report Q2 2022 | The Food & Drink Federation (fdf.org.uk)
Cement	European Industrial Emissions Portal (europa.eu)	European Industrial Emissions Portal (europa.eu)	European Industrial Emissions Portal (europa.eu)	European Industrial Emissions Portal (europa.eu)	CCE-CCS-Technology-Readiness-and-Costs-22-1.pdf	ERM analysis	https://materialeconomics.com/publications/industrial-transformation-2050
Biogas and biomethane	Biomethane Map 2021 | European Biogas Association	Biomethane Map 2021 | European Biogas Association	Biomethane Map 2021 | European Biogas Association	Biomethane Map 2021 | European Biogas Association	Implications of Integrating Biogas Upgrading (globalccsinstitute.com)	ERM analysis	Biomethane Map 2021 | European Biogas Association
Bioethanol	E4tech database	E4tech database	E4tech database	E4tech database	https://growthenergy.org/wp-content/uploads/2022/06/GROW-22019-Issue-Brief-Carbon-Capture-2022-06-22-R8.pdf	ERM analysis	The future of the British Bioethanol industry (parliament.uk)

Various CO_2 transport options exist, although scale and transportation distance influence overall economics

Method	CO_2 transport volume	TRLs	Pros	Cons
Pipeline	<30 $MtCO_2$/year	9	• Only option transporting CO_2 at significant scale • Excellent safety record • Can be repurposed, leading to cost savings • Subject to large economies of scale	• May be difficult to plan new builds due to safety, planning and consenting. • Lack of widespread quantitative risk assessments industry-wide acceptance of HSE systems
Road	<30 tCO_2	9	• Best suited for small quantities and for short distances, where demand is geographically dispersed. • Large flexibility when it comes to final CO_2 destination.	• Route choice constraints because CO_2 is considered to be a dangerous substance • Most carbon intensive form of transport • Required additional storage capacity may affect feasibility at space constrained sites
Rail	<60 tCO_2	7-9	• Can carry larger CO_2 volumes than road alternatives • Cost savings possible if rail infrastructure is already in place	• Large scale transport for CCS has not yet been achieved • Limited to deliveries where rail infrastructure exists
Shipping	<60 $ktCO_2$	3-9	• Technical feasibility and the cost of CO_2 shipping are well understood • Ships and port infrastructure are similar to those for LNG and LPG	• Large scale transport for CCS has not yet been achieved • Use is largely conditioned by port infrastructure limitations.

Plans for CO_2 pipeline infrastructure are currently in development at a number of industrial clusters in Europe

Pipelines

- Pipelines are currently the most common method of transporting very large quantities of CO_2 and are predicted to remain the preferred method of transporting CO_2 in the future.
- Huge networks of CO_2 pipelines already exist in the United States where they have primarily been utilised to transport CO_2 for enhanced oil recovery.
- Backbone pipelines provide the advantage of being able to connect multiple CO_2 emitting sources in a hub. Captured CO_2 can then be redistributed to a single storage or utilisation location.
- It is possible to repurpose existing natural gas (or other hydrocarbon transporting) pipelines for CO_2 transport. This can significantly reduce transport costs via pipeline which are dominated by CAPEX.

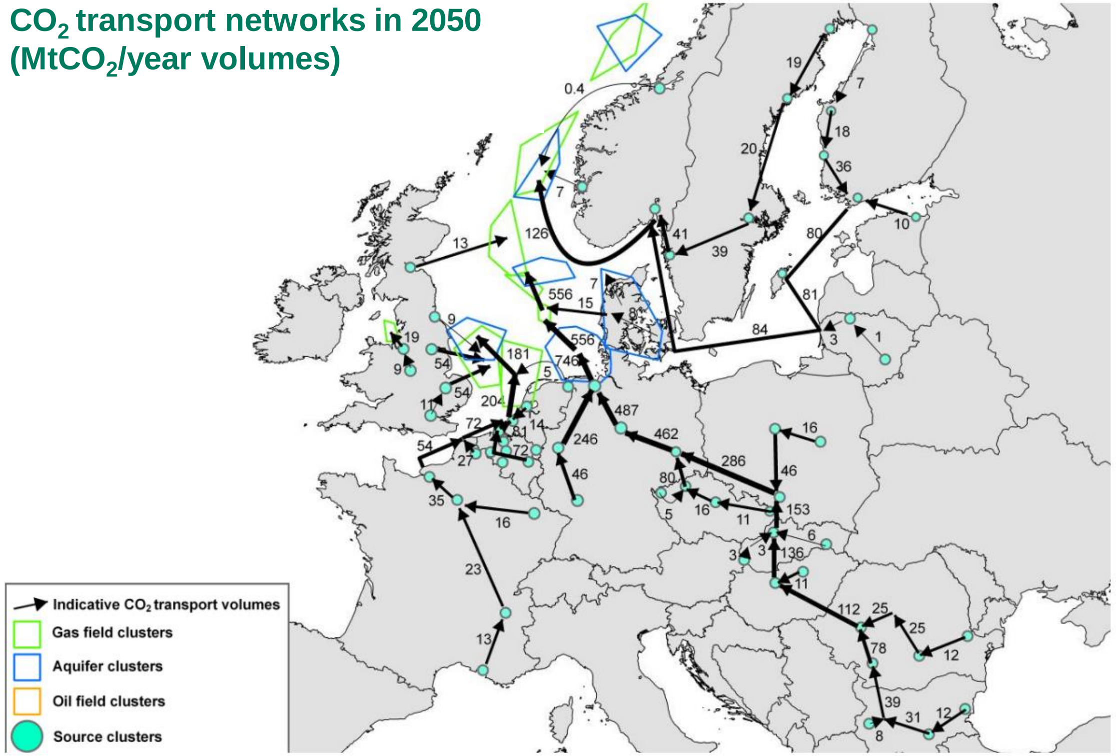
Shipping

- Shipping of CO_2 has been operational at small scale for the past 30 years. Demand has primarily come from the food and beverage industry but larger ship capacities are required for commercial transportation of CO_2 for CCS.
- CO_2 is first liquified when transporting via ship to increase cost effectiveness. Temporary storage (1-1.5 times ship size) is required to enable fast loading of the ship. From the temporary storage tanks, CO_2 is loaded onto the ship via a cargo handling system.
- CO_2 transport pressure has a significant impact on all parts of the shipping chain. Transporting CO_2 at low pressure and temperature (5.2 bar & -56.6°C) when CO_2 coexists in all three phases is most cost effective.

Road and rail

- Transportation via road and rail is most economic for small-scale transport applications.
- CO_2 is liquefied and stored in cryogenic vessels.
- Road and rail transport could be suitable for transporting biogenic emissions from small-scale emitters.

CO_2 transport networks in 2050 ($MtCO_2$/year volumes)



 Global CCS Institute Athos Consortium IEAGHG Northern Lights - seaborne CCS solution BEIS Shipping CO2 IEAGHG - CO2_Transport_Overview Ascoco2 - co2 tanks Railwayage - bulk-transport-of-lng-by-rail Trans-European-CO2-Transportation-Infrastructure-for-CCUS

Transporting CO_2 via ship is more economic than pipelines over long distances and small CO_2 capacities

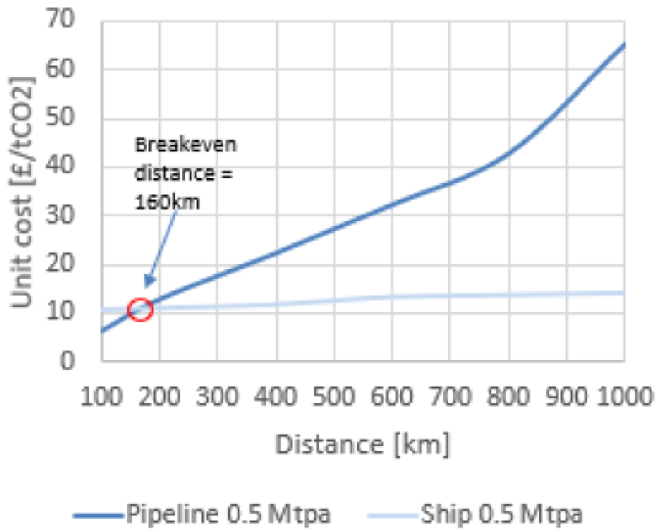
- Liquification of CO_2 is energy intensive and represents one of largest contributors to the cost of CO_2 shipping.
- CO_2 shipping costs are dominated by operational and fuel costs (OPEX). CAPEX only constitutes approximately 14% of the total transportation cost.
- Transporting CO_2 large distances overseas can be more cost effective than constructing a new pipeline. Transporting CO_2 via pipeline is more expensive than shipping over very large distances and short project durations due to the high CAPEX requirements of the pipeline infrastructure.
- Pipeline costs are dominated by CAPEX. Reusing existing pipelines can significantly reduce transport costs.

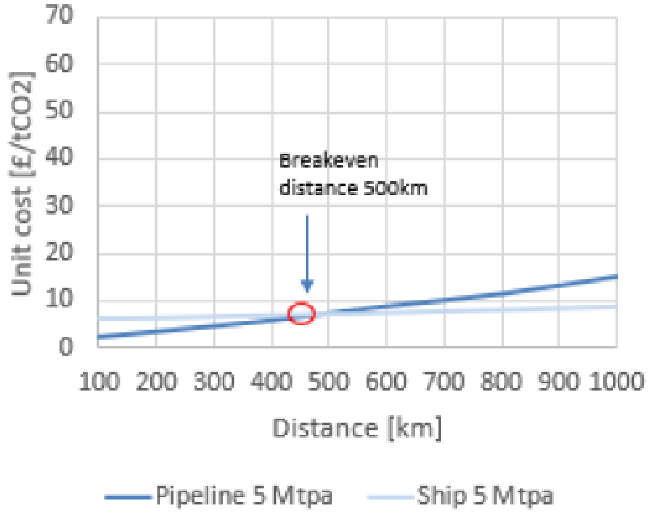
Three key parameters can have significant impacts on CO_2 transportation costs

1. CO_2 flow rate – high pipeline flow rates can reduce the cost per tonne of CO_2 stored or utilised.
2. Project duration – longer project lifetimes favour transport via pipeline. Shipping and road transport are less Capex intensive and provide increased flexibility for shorter projects.
3. Transport distance and terrain – pipelines are the most cost effective method of transporting CO_2 onshore (unless terrain or routing is significantly challenging). Shipping is a more cost effective method of transporting CO_2 over very large distances overseas.

Transport of biogenic emissions

- Biogenic emitters located in close proximity to industrial clusters could be aggregated with other nearby emitters into share pipeline infrastructure. This could be connected directly to a SAF production facility.
- Dispersed emitters may be suitable road or shipping transportation methods – especially if small quantities of emissions are being transported





Shipping CO_2 – UK Cost Estimation Study - https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/761762/BEIS_Shipping_CO2.pdf