Background material for the roadmap to climate neutral chemical industry by 2045

VTT-CR-00519-24, VTT (2024)

Contents

Executive summary

The Chemical Industry Federation of Finland has a goal to become climate neutral and biodiversity positive by 2045. The aim of this work was to update earlier studies and to provide the necessary background information for an updated roadmap towards Climate neutral chemical industry by 2045.

In 2022, the direct and indirect fossil greenhouse gas (GHG) emissions from the Finnish chemical industry were 4.5 Mt CO_2e. Since 2018, a reduction of 0.6 Mt CO_2e (~11%) has been achieved. Chemical industry companies have set climate targets and announced several investments which enable significant reduction in sector's GHG emissions.

Three scenarios were created for describing potential future development of both direct and indirect fossil GHG emissions originating from the chemical industry in Finland. Two baseline scenarios highlight how changes in the operational environment may either hinder or promote implementation of existing climate neutrality plans and planned investments. In the baseline scenarios, assumed emission reductions range between 1.7-3.3 Mt CO_2e by 2045.

A climate neutrality scenario presents a possible future development path in which the operational environment supports companies' climate targets, and several different investments are made to reach the climate neutrality goal by 2045. In the climate neutrality scenario, a reduction of 4.2 Mt CO_2e in annual, direct and indirect GHG emissions is achieved, compared to emissions in year 2022.

Executive summary continues

The biggest future challenge in the chemical sector relates to the raw material transition that is required for reaching climate neutrality. Moving towards renewable, recycled, and synthetic raw materials potentially increases production costs and requires major investments.

Reaching climate neutrality by 2045 would require over 3 billion euros of investments during the next ten years. Important means for achieving GHG emission reductions include switching to clean energy, moving away from crude oil refining, electrification and fuel switching in industrial processes, improving energy and raw material efficiency and switching to less GHG intensive raw materials.

Despite the transition, some hard-to-abate virgin-fossil raw materials and fossil GHG emissions will remain. To reduce direct emissions close to zero by 2045, investments in carbon capture and/or removal are most likely needed. Technological means must be combined with education, training and value chain cooperation activities.

Achieving planned reductions and raw material switches requires strong demand for new, climate neutral products, incentives for the new alternative feedstocks, and a clear and harmonised regulatory framework with strong carbon leakage protection. Necessary enablers for the transition include carbon neutrality of the energy system and availability of clean electricity, R&D funding and clear permitting procedures.

When successful, the combined climate and raw material transition in the chemical sector creates significant handprint potential in other sectors, promoting green transition in Finland.

Aim of the work

Aim of the work

- The Chemical Industry Federation of Finland has a goal to become climate neutral and biodiversity positive by 2045. The climate neutrality goal covers direct (Scope 1) greenhouse gas (GHG) emissions and indirect (Scope 2) GHG emissions from purchased energy. In addition, the aim is to reduce value chain GHG emissions (Scope 3), and to increase the carbon handprint of the sector.
- The aim of this work was to review and to update earlier studies and to provide the necessary background information for preparing an updated roadmap towards Climate neutral chemical industry by 2045.
- The project was conducted by VTT in cooperation with the Chemical Industry Federation of Finland.

Methods and data

Methods

- Potential future scenarios towards climate neutral chemical industry by 2045 were considered for the five clusters of the chemical sector
  - The focus of the analysis was on the assumed impacts and plans of the biggest and the most energy intensive companies with the highest total GHG emissions.
  - Data from the whole sector was collected and reviewed, highlighting potential development and means for cutting GHG emissions.
- Estimation covered direct (Scope 1) GHG emissions and indirect (Scope 2) emissions from purchased energy.
- Additionally, potential changes in future raw materials and related Scope 3 emissions were estimated based on existing data and assumed future production volumes, following the development paths identified in the studied scenarios.
- Diversity in the composition of the cluster, variety in the used raw materials and production technologies together with the global value chains cause significant uncertainty to the results.

Data

- Fossil GHG emissions were evaluated in five clusters. The clusters differ in the number of companies included, the amount of production, the energy and raw materials used, and the amount of GHG emissions created.
- After the previous roadmap, new companies producing battery materials have been added to the inorganic chemistry cluster.
- Due to changes in annual reporting and different background data, results in this roadmap are not comparable with the figures presented in the previous roadmap (AFRY, 2019).
- Applied data was a combination of
  - Measured data from years 2018-2022, originating from companies participating in the Responsible Care program (available at cluster level)
  - Data available from public sources, like company sustainability reports, statistics, existing studies and technical reports.
  - Expert opinions and views collected from discussions with industry representatives and researchers

Clusters of the chemical industry

Studied industry clusters

- In the following section, the studied chemical industry clusters are briefly described, considering their main characteristics, status, main raw materials, GHG emissions and potential means for achieving emission reductions.
- Throughout the study, it is important to remember that each cluster contains a group of versatile companies that vary in size, applied technologies, raw materials and end-products. This study considers the required change on a general level, providing selected examples and ideas.
- Consequently, also the challenges that companies face as part of their climate and energy transition vary. What is in common for most companies, is that changes in current production systems and raw materials are required, to reach the climate neutrality targets.
- Currently, companies in the sector are in different positions and levels of maturity in their sustainability transition. Many companies have set climate and energy related targets, but their timing and level of ambition varies, and so does the availability of alternative raw materials and technologies.

Studied industry clusters

- Energy intensive chemical industry < 10 companies
- Inorganic chemistry, including battery materials < 20 companies
- Reactive chemistry ~ 30 companies
- Formulating ~ 20 companies
- Converters ~ 30 companies

Energy intensive chemical industry

- Large chemical industry facilities that have a significant role in the future development of the sector’s GHG emissions. Main products include transport fuels, petrochemicals, plastics and water purification chemicals.
- Examples of companies: Neste, Borealis and Kemira.
- **Current status**
  - Responsible for the highest production volumes (>60%) and the majority of direct GHG emissions in the sector
  - Companies have already announced ambitious plans related to climate neutrality. The timing of these investments is still uncertain.
- **Main raw materials**
  - Crude oil, naphtha, natural gas, minerals
- **Assumed development**
  - Shifting away from fossil feedstocks
  - Green hydrogen solutions

Energy intensive chemical industry

- **Means of GHG reduction**
  - Power Purchase Agreements (PPAs) for large scale renewable energy production
  - Changes and investments in existing production capacity to increase the share of recycled & renewable feedstock
  - Electrification
  - Carbon Capture & Utilization (CCU) in the context of plastic recycling, providing an additional source for recycled plastics
- **Main challenges**
  - Consumption of energy from fossil sources
  - Production volumes, cost and availability of alternative feedstocks - Switching fully from fossil to renewable and recycled feedstocks leads to decreasing levels of production.
  - Technological, economic and regulatory bottlenecks related to new synthetic feedstocks.

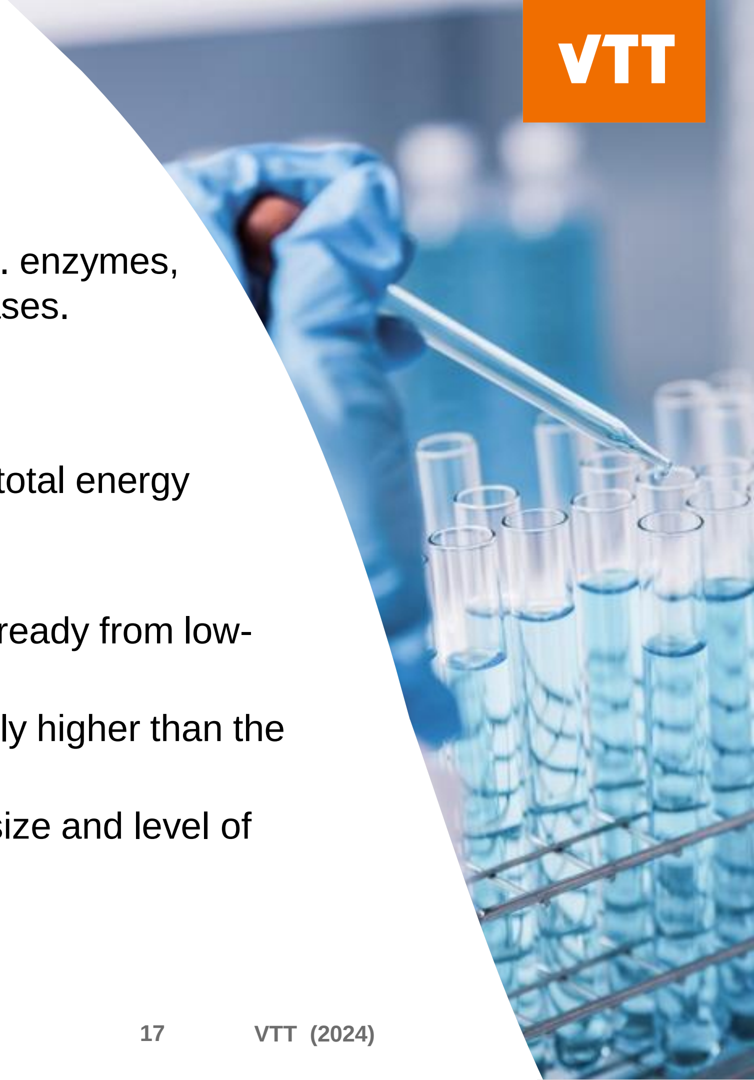
Inorganic chemistry, including battery materials

- Energy intensive processes include e.g. crushing, grinding and electrolysis. Typical products include minerals, metals and salts that are used in various industry sectors and agriculture.
- Examples of companies: Yara, Tetra Chemicals, and Terrafame.
- **Current status**
  - Third largest direct CO_2 emissions among the clusters
    - >90% of energy used in the cluster is non-renewable
  - Around 70% of cluster’s emissions are direct emissions
- **Main raw materials in the cluster**
  - Nickel, ammonia, cobalt, gas, naphtha, benzene

Inorganic chemistry, including battery materials

- **Assumed development**
  - Investments in raw materials and clean energy sources as well as new technologies for better utilisation of renewable and clean energy sources
  - Investments in emission-free transportation
  - Investments in CCU technologies
  - Increased recycling of metals
- **Means of GHG reduction**
  - Shifting to clean energy sources, electrification
  - Shifting to renewable feedstock, improving and increasing recycling
- **Main challenges**
  - In scopes 1&2, energy is currently mostly non-renewable
  - Achieving net zero battery chemical production, due to nickel and cobalt
  - Source of cobalt (around 70% originates from the Democratic Republic of Congo, and is processed in China)

Reactive chemistry



- Characterised by complex processes. Products include e.g. enzymes, dispersion polymers, resins, biochemicals and industrial gases.
- Examples of companies: St1, LindeGas and CH-Polymers.
- **Current status**
  - Third largest cluster in terms of production volumes and total energy consumption
  - ~ 60% of emissions are direct emissions
  - Majority of used energy is electricity, of which ~50% is already from low-carbon sources.
  - Share of recycled & renewable raw materials considerably higher than the share of fossil raw materials
  - Cluster includes a large group of companies, varying in size and level of climate ambition
- **Main raw materials**
  - Petroleum-based plastics

Reactive chemistry

- **Assumed development**
  - Further increase in the share of clean electricity and heat requires additional investments
  - Cluster is already providing waste/side streams to other sectors as raw materials
- **Means of GHG reduction**
  - Shifting to clean energy & electricity
  - Bio-based plastics
  - Green hydrogen production
- **Main challenges**
  - Availability of alternative raw materials

Converters

- Processes include moulding and compounding. Typical products are plastic and rubber products.
- Examples of companies: Excel Composites, Nokian Renkaat, Visko Teepak and Orthex.
- **Current status**
  - The smallest production volumes of all clusters
  - The second lowest CO_2e emissions within the clusters
  - The majority of the energy usage is already clean
- **Main raw materials**
  - Rubber and plastics

Converters

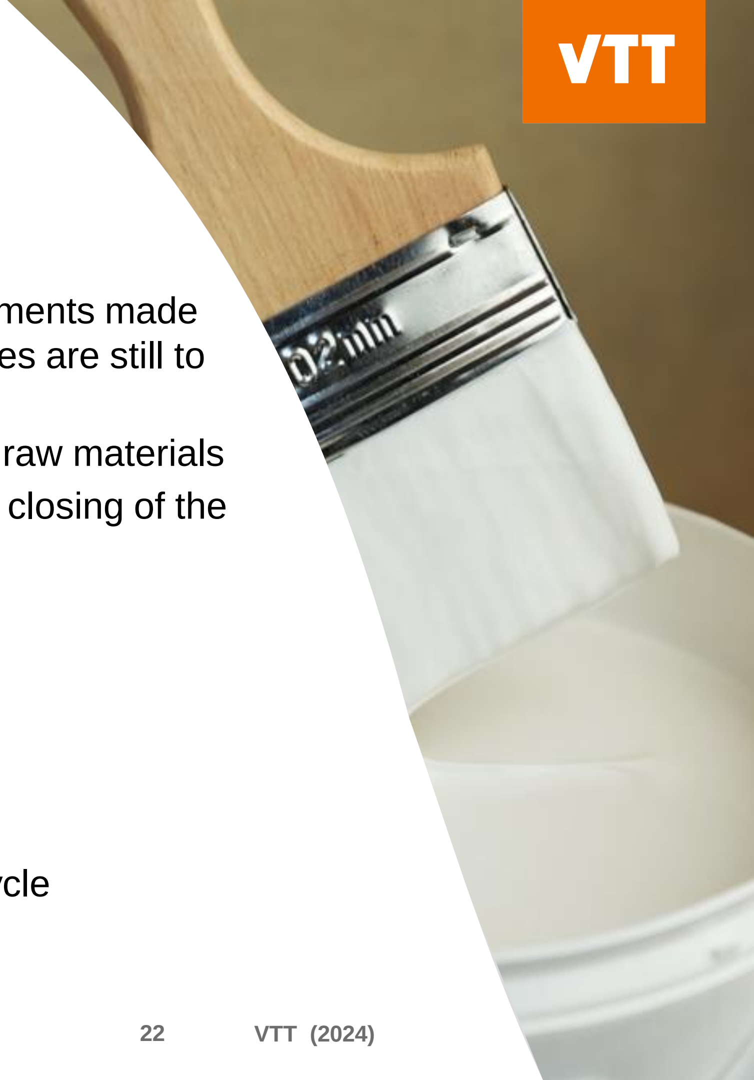
- **Assumed development**
  - Purchased non-renewable electricity replaced with clean electricity sources
- **Means of GHG reduction**
  - Replacing purchased electricity with clean electricity
  - Shifting towards renewable feedstocks
- **Main challenges**
  - A versatile cluster including companies of different sizes and various levels of ambition and abilities in climate related actions and plans
  - Availability of renewable heat and fuels
  - Reducing the amount of waste used for power generation

Formulating

- Typical products are paints, coatings, pharmaceuticals and detergents.
- Examples of companies: Kiilto, Orion and Tikkurila.
- **Current status**
  - The smallest total contributor to the sector's GHG emissions, direct emissions ~1% of the sector's total emissions.
  - Total energy consumption the lowest among the five clusters
  - Very high share of renewable energy (both electricity and heat/fuels)
  - Several companies with ambitious climate plans and targets
  - Share of renewable & recycled feedstock ~13%
- **Main raw materials**
  - Pigments, titanium dioxide

Formulating

- **Assumed development**
  - Share of clean energy steadily increasing due to commitments made by several of the companies, but the most difficult switches are still to be made
  - Difficult to increase the share of renewable and recycled raw materials
  - Small increase in alternative feedstocks expected due to closing of the raw material loops, some potential in CCU application
  - Improvements in energy efficiency
- **Means of GHG reduction**
  - Shifting to clean energy & electricity
- **Main challenges**
  - Availability and cost of alternative raw materials
  - Some of the raw materials (such as sand) difficult to recycle
  - Availability of biogas to abate for remaining emissions
  - Scope 3 emissions create high share of emissions



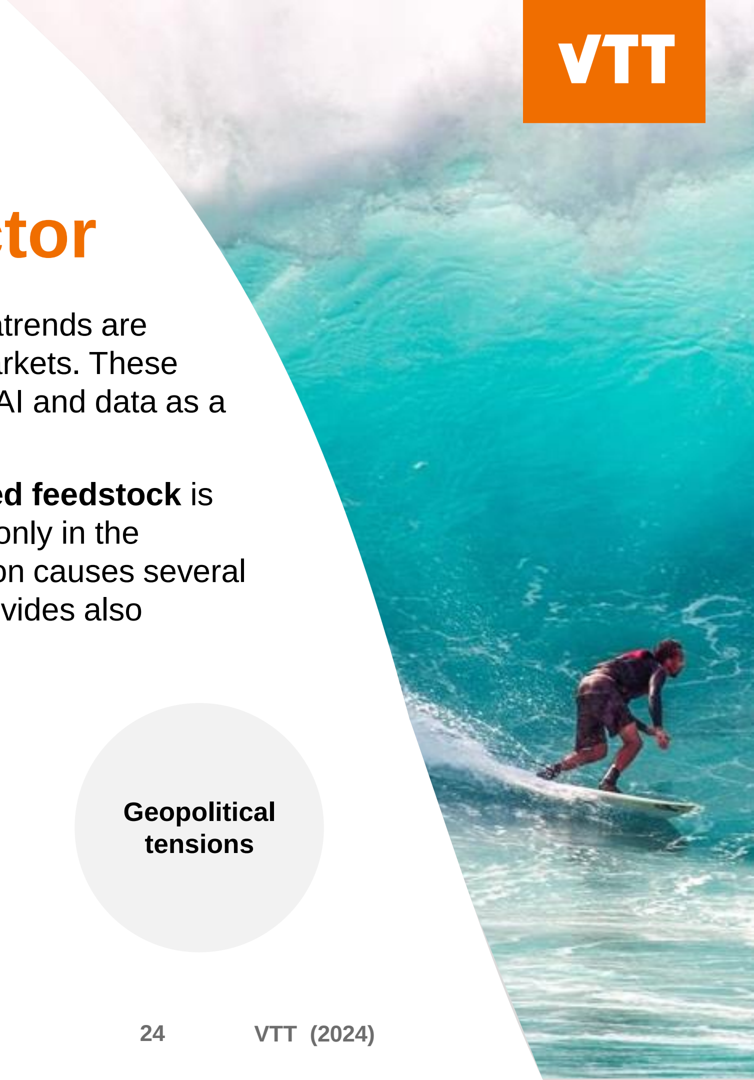
Climate and Raw Material transition

Megatrends challenging companies in the chemical sector

From the Finnish chemical industry's viewpoint, several significant megatrends are challenging current business processes, value chains, products, and markets. These trends include shifting to renewable and recycled feedstock, embracing AI and data as a transition accelerators, talent availability, and geopolitical tensions.

While all megatrends are important, **shifting to renewable and recycled feedstock** is crucial for mitigating climate change and reducing GHG emissions. Not only in the chemical sector, but in other sectors too. Required sustainability transition causes several technological and business-related challenges. On the other hand, it provides also significant opportunities.

- **Shifting to renewable and recycled feedstock**
- **AI and data as transition accelerators**
- **Talent availability crisis**
- **Geopolitical tensions**

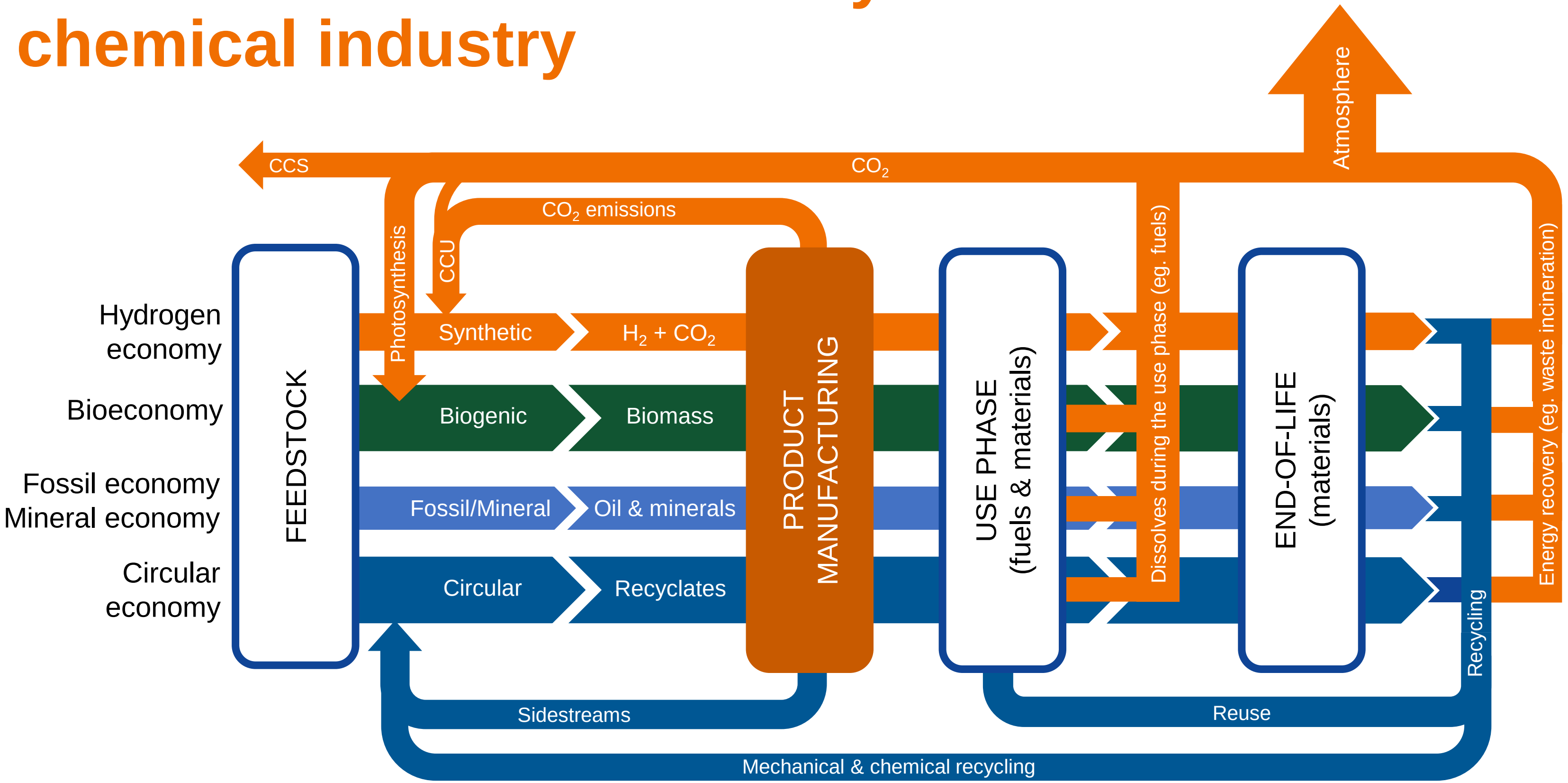


Source: Future Radar of the Finnish Chemical Industry (VTT, 2024)

Estimated climate impacts of the raw material transition

- In this study, potential climate impacts of the required raw material transition are considered together with other actions required for reducing fossil GHG emissions in the chemical industry.
- To some extent, applied raw materials affect direct (Scope 1) GHG emissions from different chemical industry processes.
- The most significant GHG impacts related to applied feedstocks take place in companies' value chains (Scope 3 emissions related to raw material acquisition and end-products).
- Due to the global nature, complexity and interlinked nature of the value chains, estimating these impacts is challenging and includes a lot of uncertainty. In this study, potential Scope 3 GHG emissions were estimated on a general level.
- Replacing virgin fossil feedstocks with new feedstocks from renewable, recycled and synthetic sources is a major challenge for the chemical sector. The potential for this transition and the required support mechanisms are discussed within the scenarios included in this study.

Raw material and carbon cycles in the chemical industry



Studied scenarios

Studied scenarios

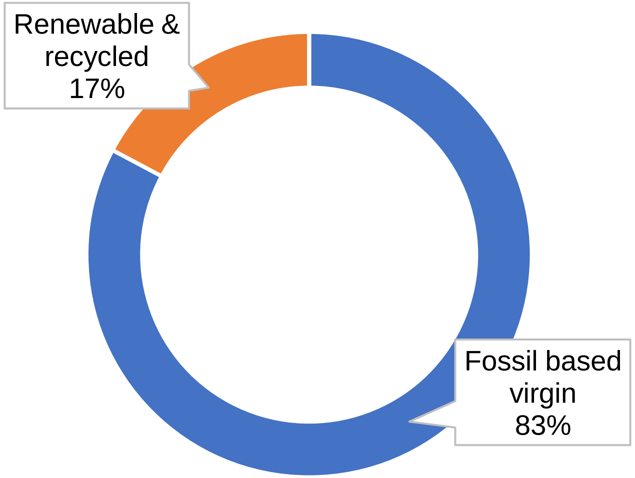
- Altogether **three scenarios were created** for describing potential future development of the direct and indirect fossil GHG emissions originating from the chemical industry in Finland.
- The starting point for all the scenarios was year 2022, which was selected as a reference year.
- Firstly, **two baseline scenarios** highlight how changes in the operational environment may either hinder or promote implementation of existing climate neutrality plans and investments already announced by the sector.
- Secondly, **a climate neutrality scenario** presents a possible future development path in which the operational environment supports companies' climate targets, and several different investments are made to reach the climate neutrality goal of the chemical industry by 2045.
- Thirdly, additional estimates for evaluating the CCU (Carbon Capture and Utilisation) potential, development of value chain (Scope 3) emissions and feedstocks were prepared, building upon other available studies and estimates.

Reference year 2022

- Total production 21.7Mt
- Total energy consumption 20.3 TWh
  - Total amount of energy from renewable sources 3.9 TWh (19% of total energy consumption)
- Total electricity consumption 5.3 TWh
  - Amount of renewable electricity 2.7 TWh (~51% of total electricity consumption)
- Hydrogen consumption 0.12 Mt
- Total GHG emissions 4.6 Mt CO_2e
  - Direct emissions (Scope 1): 3.5 Mt CO_2e
  - Indirect emissions from purchased energy (Scope 2): 1.1 Mt CO_2e

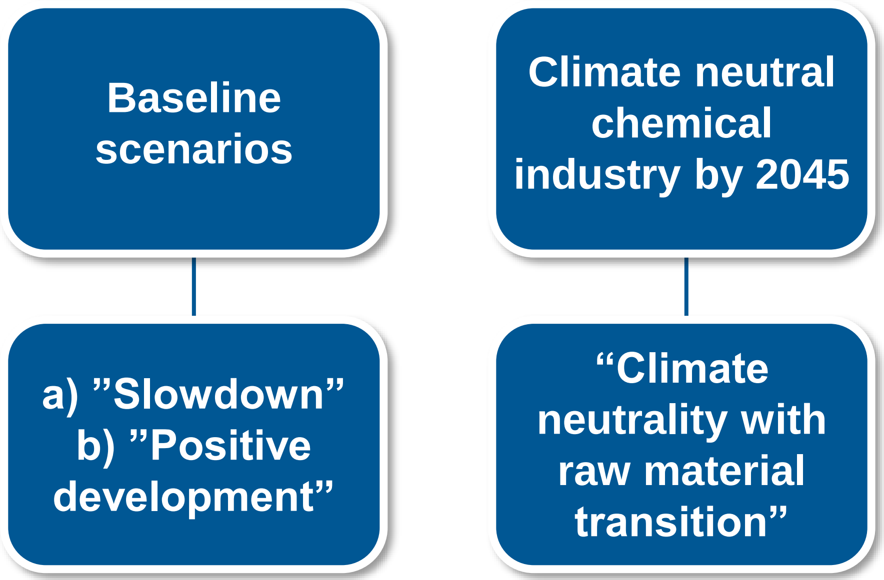
  + Indirect emissions from the value chain (Scope 3): ~ 60 Mt CO_2e (estimate)
- Annual investments ca. 1 billion euros

Feedstock composition in 2022



Note: *Fossil based virgin* includes raw materials from fossil & mineral sources. *Renewable & recycled* includes all renewable and recycled raw materials (organic & inorganic)

Studied scenarios in short



Baseline scenarios until 2045 - Two alternative pathways

Two baseline scenarios until 2045

- More than half (65%) of the chemical industry companies have set climate related targets. These companies represent 97% of chemical industry’s production and 96% of total energy consumption.
- However, timing and realisation of these targets is still uncertain.
- Lack of resources (funding, knowhow, suitable technologies, alternative feedstocks, energy sources and customer demand) can postpone already announced plans.
- Reducing Scope 1 GHG emissions and switching to alternative feedstocks from renewable, recycled and synthetic sources requires new investments (e.g. electrification), clear regulatory environment and steady demand for new green products.
- In all the scenarios, it is estimated that Finnish energy system becomes carbon neutral after 2030 reducing Scope 2 GHG emissions from purchased energy.

Two baseline scenarios until 2045

- Two alternative scenarios were created:
  - **’Slowdown scenario’,** in which already announced climate-related targets are not realised, and planned investments are postponed.
  - **’Positive development’,** in which already announced climate-related plans are implemented in time.
- Both scenarios lead to reductions in fossil GHG emissions compared to current levels, but their level of ambition varies.
- Estimated fossil GHG emission reductions depend on the developments taking place in the operational environment.
- Currently planned activities included in the two baseline scenarios are not yet enough for reaching chemical industry’s climate neutrality target.

Main assumptions for the baseline scenario: Slowing down current development

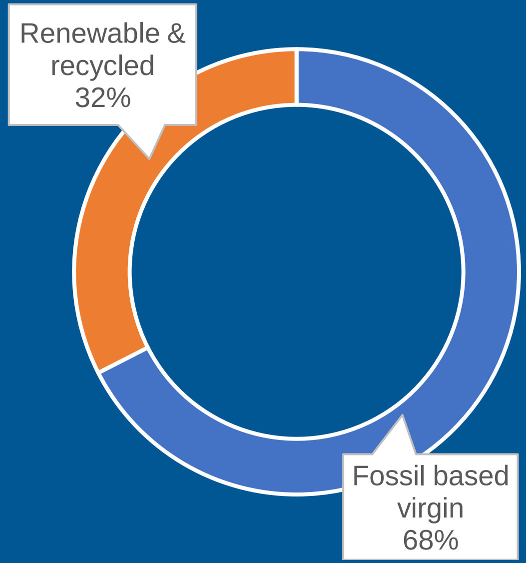
- Policy measures required for the green transition are not fully implemented.
- Economic development is slower than expected.
- Due to uncertainty in the operating environment, companies can't implement their climate actions as planned.
  - Energy system becomes carbon neutral after 2030, reducing scope 2 emissions.
  - Demand for fossil fuels continues, as the distribution obligation remains on a lower level.
  - Assumed ETS price is ~ 80 €/ton by 2030 and above ~140 €/ton by 2045.

Key figures

- Scope 1: ~ 2.8 Mt CO_2e
- Scope 2: ~ 0 Mt CO_2e
- Scope 3: ~ 50 Mt CO_2e (estimate)
- Share of renewable & recycled feedstock: ~ 32%
- Assumed GHG emission reduction compared to 2022: 1.8 Mt CO_2e
- Assumed annual investments: ~1 billion EUR baseline investments (no significant additional investments)
- Hydrogen consumption: 0.2 Mt (6.7 TWh)
- Green hydrogen: 0
- Clean electricity: 5.7 TWh
- Total energy consumption: 20.2 TWh (5.7 TWh electricity, 14.5 TWh other)

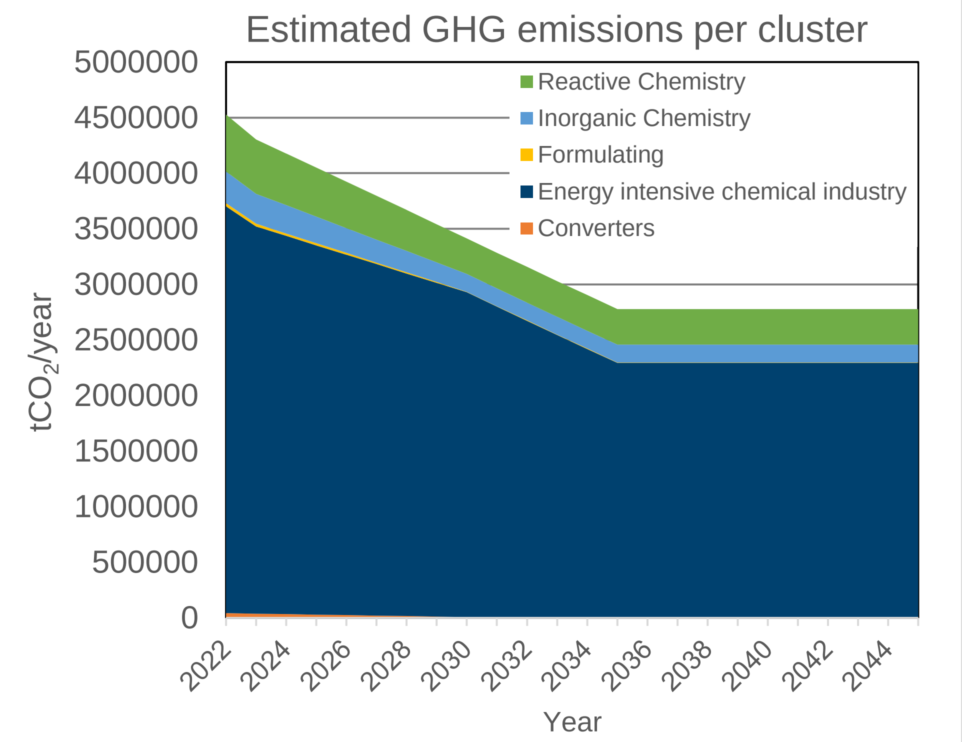
Main assumptions for the baseline scenario: Slowing down current development

- Crude oil refining decreases by 30% and is substituted by renewable (virgin) feedstock.
- Use of renewable raw materials increases, but majority of the raw materials are still fossil-based.
- Some reductions in value chain (Scope 3) GHG emissions take place due to increasing share of renewable feedstock and products.
- Share of recycled feedstock is not growing as expected due to higher costs of raw material processing, and lack of incentives. Virgin materials are more cost-efficient.
- Regulatory status of chemical plastics recycling remains unclear, slowing down expected investments in plastics recycling and use of recycled raw materials.
- Planned actions and investments related to green hydrogen and for reducing Scope 1 GHG emissions are not realised.



Assumed feedstock 2045

Baseline scenario: Slowing down current development



Main reasons for assumed GHG reductions

Before 2030

- Large companies switching fully or partly to clean electricity
- Fuel switches (e.g. crude oil to LNG)
- Power Purchase Agreements (PPAs)

2030-2035

- Carbon neutral energy system after 2030
- 30% reduction in crude oil refining
- Replacing part of the virgin fossil feedstock with renewable virgin feedstock

Main assumptions: Political framework & operational environment Slowing down current development

General	Infrastructure & investments	Raw materials	Markets
Policy measures required for the transition not fully implemented	Grid development challenges	Legislation doesn’t recognize alternative feedstocks clearly	Difficulties and uncertainties with the definitions - Green, clean, low-carbon, sustainable, permanent…
Clear and ambitious climate targets are lacking	Almost all relevant infrastructure investments lacking behind	Conflicts between different legislative fields: Climate, waste, product	Lack of incentives – Not enough demand nor markets for new products with low-carbon footprint
Adequate carbon leakage protection for the industry missing	Challenges with hydrogen and carbon capture development and related infrastructure	Virgin fossil remains the most cost-efficient raw material option	
Energy taxation not supporting electrification	Availability of emission-free electricity slowing down investments		
Permitting procedures are not efficient	Not enough funding available for investments		

Sensitivity assessment

- All results presented here are sensitive for the assumptions made. These are related to both assumed emission reductions and potential development of the operational environment.
- If assumed carbon neutrality of the Finnish energy system is not achieved and/or if availability of affordable clean electricity is not realised, estimated GHG emissions in this scenario could be ca. 1 Mt CO_2e higher.
- Without assumed reduction in crude oil refining and assumed change in feedstock from fossil to biobased sources, estimated Scope 3 emissions would not reduce compared to levels of year 2022 (estimated impact could be ca. 10 Mt CO_2e).
- In this scenario, it was assumed that total production levels don't increase from the levels of year 2022. New products from renewable feedstocks would create additional value. If growth in production of fossil feedstocks would take place instead, fossil GHG emissions could start increasing.
- On the other hand, if a steady, 1% annual improvement in emission and energy intensity could be achieved in the whole sector, an additional reduction ca. 0.5 Mt CO_2 emissions could be achieved annually, in addition to reductions already presented.

Main assumptions for the baseline scenario: Positive development

- Necessary policy measures required for the green transition are in place, but Finland competes with other countries for green investments.
- Companies proceed with planned investments required for reaching company-level climate neutrality targets.
  - Energy system becomes carbon neutral after 2030 reducing Scope 2 GHG emissions.
  - Distribution obligation creates steady demand for renewable fuels
  - CBAM* together with ETS*1 & 2 and good carbon leakage protection measures create strong incentives for switching to low-carbon feedstocks reducing Scope 3 emissions.
  - Assumed ETS price is ~ 90 €/ton by 2030 and above ~150 €/ton by 2045.

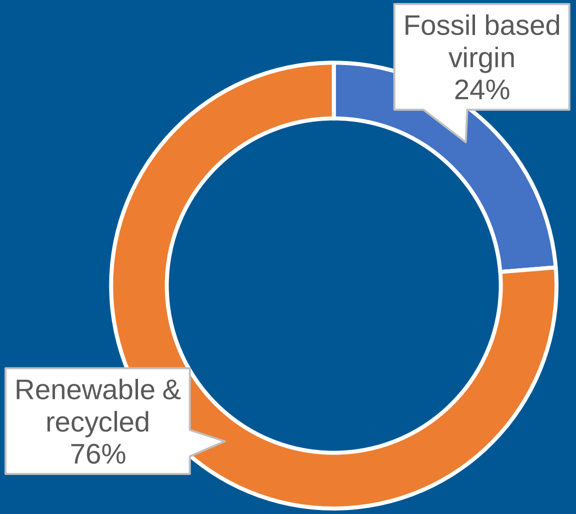
Key figures

- Scope 1: ~ 1.2 Mt CO_2e
- Scope 2: ~ 0
- Scope 3: ~ 11.2 Mt CO_2e
- Share of renewable & recycled feedstock: ~ 76%
- Assumed scope 1 & 2 reduction compared to 2022: 3.4 Mt CO_2e
- Assumed annual investments:
  0.3 billion EUR on top of 1 billion EUR baseline investments
- Required investments to achieve CO_2 emission reductions: 3.5 billion EUR before 2035
- Green hydrogen consumption: 0.2 Mt (6.7 TWh)
- Clean electricity: 14.7 TWh
- Total energy consumption: 22.2 TWh (14.7 TWh electricity, 7.9 TWh other)

CBAM = Carbon border adjustment mechanism, ETS = Emission trading scheme

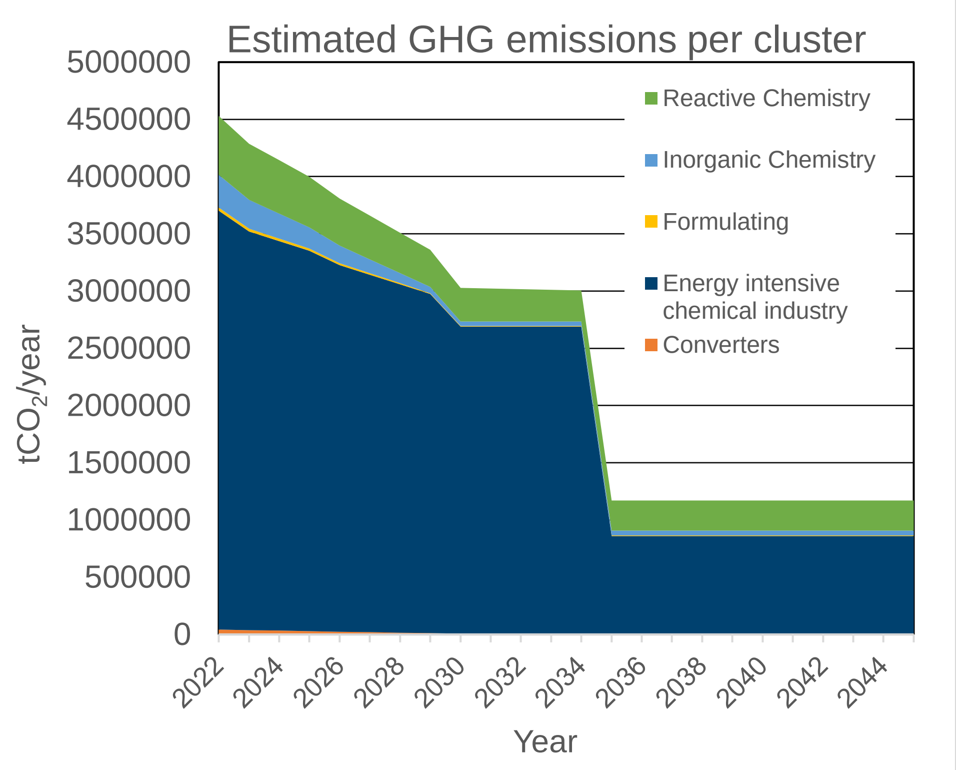
Main assumptions for the baseline scenario: Positive development

- Crude oil refining ends after 2035.
- The share of renewable and recycled feedstock increases significantly but move away from virgin fossil raw materials leads to decline in total production volumes.
- Fossil based hydrogen is replaced with green hydrogen, but hydrogen consumption doesn't increase, due to declining production volumes.
- Increased share of renewable raw materials (including imported green ammonia) decreases Scope 3 GHG emissions from the value chain.
- Company plans towards climate-neutrality are mostly implemented, but difficult to abate Scope 1 emissions require additional investments that are not yet feasible for all companies.



Assumed feedstock 2045

Baseline scenario with positive development



Main reasons for assumed GHG reductions

- Increasing share of clean electricity
- First investments in green hydrogen
- Natural gas replaced with biogas.
- Large companies in the inorganic cluster manage to reduce Scope 1 emissions.
- Carbon neutral energy system after 2030
- Crude oil refining ends 2035, leading to declining production volumes.
- First CCU implementation in plastic recycling.

Main assumptions: Political framework & operational environment Positive development

General	Infrastructure & investments	Raw materials	Markets
Policy measures required for the transition are supporting the first steps towards climate neutrality.	Successful electricity grid development	Regulation partially supporting new alternative raw materials	Some uncertainties with the definitions remain - Green, clean, low-carbon, sustainable, permanent…
Clear and stable climate targets and incentives	Some relevant infrastructure investments lacking behind	Some conflicts between different legislative fields remain: Climate, waste, product	Incentives for products with low carbon footprint
Good carbon leakage protection for the industry	Availability of emission free electricity and H2 enough for the first steps towards climate neutrality	Availability and cost of recycled raw materials remains as a challenge	Growing markets for alternative raw materials (non-virgin-fossil products)
Energy taxation supporting electrification and new products	Challenges with hydrogen and carbon capture development and related infrastructure not yet solved	Share of biobased raw materials increases, but total production volumes decrease	Not yet enough demand for H2 based synthetic products
Permitting procedures are smooth	Enough funding for ”the first steps”		

Sensitivity assessment

- All results presented here are sensitive for the assumptions made. These are related to both assumed GHG emission reductions and potential development of the operational environment.
- If assumed carbon neutrality of the Finnish energy system is not achieved and/or if availability of affordable clean electricity is not realised, estimated GHG emissions in this scenario could be ca. 1 Mt CO_2e higher.
- For achieving estimated reductions in direct GHG emissions (Scope 1) and within the companies' value chains (Scope 3), switch from fossil to renewable and recycled feedstock is necessary.
- If use of fossil feedstocks continues or only a modest change is achieved, fossil GHG emissions would likely remain on a level similar to the slowdown scenario.
- If growth in production based on fossil feedstocks would take place, GHG emissions could start increasing.
- If a steady, 1% annual improvement in emission and energy intensity could be achieved in the sector, direct (Scope 1) emissions in this scenario could go below 1 Mt CO_2e.

Climate neutrality with raw material transition by 2045

Climate neutrality scenario

- This scenario assumes an almost complete transition away from fossil energy sources and fossil-based virgin raw materials.
- Combined Scope 1 & 2 GHG emissions are getting close to zero by 2045.
- New investments in carbon removal (or compensation) are made for reaching zero emissions.
- Clean investments in Finland are profitable and there is strong demand for new climate neutral products and recycled raw materials.
- Decrease in total production volumes is partly compensated by a switch to new, more valuable products and additional policy measures.
- Versatile feedstock includes a combination of renewable, recycled and synthetic raw materials, many of which are imported from other countries if domestic options are not available.
- New products from the chemical industry create handprint potential in various sectors, enabling raw material transition and reducing fossil GHG emissions in value chains (Scope 3).

Main assumptions for the climate neutrality scenario

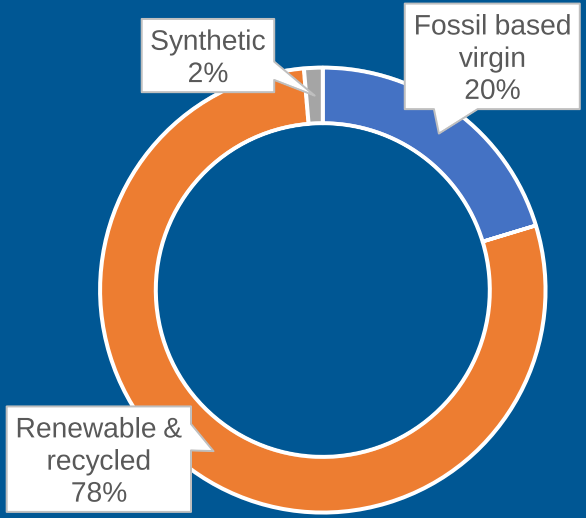
- Policy measures for the green transition are fully in place.
- Green investments in Finland are attractive options for multinational companies.
- There is strong demand for new carbon neutral products.
  - Energy system becomes carbon neutral after 2030.
  - Regulations related to carbon removal and carbon capture and utilisation (CCU) are effective.
  - Status of plastic products derived from chemical recycling is clear, and incentives for using recycled raw materials are in place.
  - Biogas is available and investments in energy infrastructure support companies' climate investments.
  - Assumed ETS price is ~ 90 €/ton by 2030 and above 200 €/ton by 2045

Key figures

- Scope 1: ~ 0.3 Mt CO_2e
- Scope 2: ~ 0 Mt CO_2e
- Scope 3: ~ 4 Mt CO_2e
- Share of renewable, recycled & synthetic feedstock: ~ 80%
- Assumed Scope 1 & 2 reduction compared to 2022: 4 Mt CO_2e
- Assumed annual investments: 0.4 billion EUR on top of 1 billion EUR baseline investments
- Required investments to achieve CO_2 emission reductions: 4 billon EUR before 2035
- Green hydrogen: 0.2 Mt (6.7 TWh)
- Clean electricity: 19.2 TWh
- Total energy consumption: 22.2 TWh (19.2 TWh electricity, 3.0 TWh other)

Main assumptions for the climate neutrality scenario

- Crude oil refining ends after 2035.
- Plans towards climate-neutrality are fully implemented by 2045, some companies achieving their targets earlier than anticipated.
- Fossil scope 1 GHG emissions are reduced close to zero by means of electrification and switching to renewable and recycled feedstocks.
- Together with chemical recycling of plastics, metals recycling in battery manufacturing increases the share of recycled raw materials.
- CCU from chemical industry processes creates new synthetic feedstock.
- Carbon removal is applied to compensate for remaining fossil emissions.

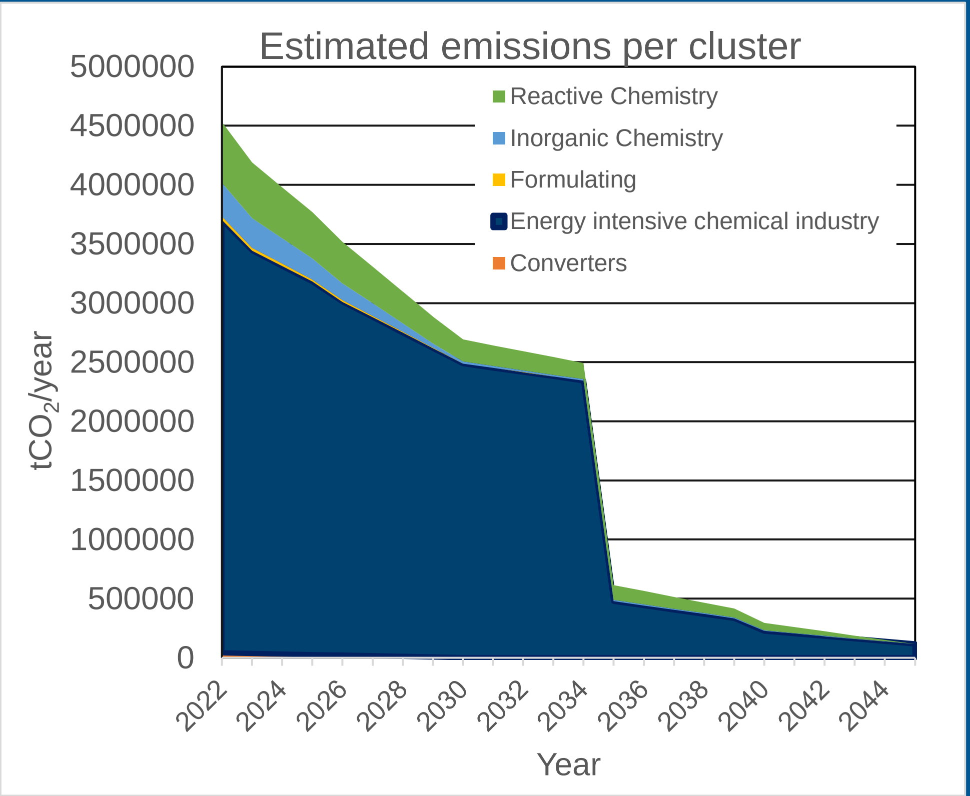


Assumed feedstock 2045

Main assumptions: Political framework & operational environment Climate neutrality

General	Infrastructure & investments	Raw materials	Markets
Policy measures required for the transition are supporting climate neutrality.	Successful electricity grid development	Regulation recognizes new feedstocks and products.	Certification schemes are available and definitions for new sustainable products and raw materials are mostly clear
Clear and stable climate targets and incentives	Support for hydrogen, hydrogen derivatives and CCU economy including infrastructure development	Chemical, environmental, product and waste policies and legislation are aligned.	Incentives for products with low carbon footprint and recycled content
Strong carbon leakage protection for the industry	Enough emission-free electricity and H2 available for climate neutrality.	Circular economy development supports feedstock revolution	Growing markets for alternative raw materials (non-virgin-fossil products)
Energy taxation supporting electrification	Strong support for energy efficiency improvements	Share of recycled and synthetic raw materials slowly increasing	Demand for H2 based synthetic products
Permitting procedures are smooth	National and European funding is available	CCU regulation for products and raw materials is established.	Voluntary carbon markets are active

Climate neutrality scenario



Main reasons for assumed GHG reductions

- Fossil fuels almost totally replaced in processes.
- Electrification
- Increasing use of recycled and renewable feedstocks in all clusters reduce Scope 1 emissions
- Carbon neutral energy system after 2030
- Crude oil refining ends 2035, leading to declining production.
- Green hydrogen production and utilisation.
- Carbon capture from selected chemical industry processes.

Sensitivity assessment

- All results presented here are sensitive for the assumptions made.
- If assumed carbon neutrality of the Finnish energy system is not achieved or not enough affordable clean electricity becomes available, estimated GHG emissions in this scenario could be ca. 1 Mt CO_2e higher.
- For achieving estimated reductions in direct GHG emissions (Scope 1) and within the companies' value chains (Scope 3), a switch from fossil to renewable and recycled feedstock is crucial.
- Important investments assumed to take place in this scenario are related to electrification, fuel and raw material switches, CCU and green hydrogen production.
- Biogenic CO_2 for potential new, synthetic feedstock would mostly need to be sourced from other sectors. This new synthetic feedstock could be needed, as it was assumed that with available renewable and recycled feedstocks alone, it is not possible to reach production levels comparable to those of year 2022 in a sustainable manner.
- It is assumed that despite all efforts, some hard-to-abate fossil emissions remain. These need to be either compensated or treated via selected carbon removal mechanisms.
- In case transition to renewable and recycled feedstocks is not successful, the amount of fossil GHG emissions to be abated could be significantly higher than what is currently assumed in this scenario (ca. 0.3 Mt CO_2e).

Carbon capture and utilisation potential

Carbon removal, capture and utilisation

- **Carbon removals** (i.e. technologies and practices for removing carbon dioxide (CO_2) directly from the atmosphere) have been recognized among key enablers for achieving EU's intermediate climate target for 2040.
- The provisional agreement on the 'Regulation establishing an EU-wide voluntary framework for certifying permanent carbon removals, carbon farming and carbon storage in product' (CRCF Regulation) includes the following definitions for permanent carbon removals:
- **Permanent carbon removals:** Industrial technologies that capture carbon from the atmosphere and securely store it for several centuries, preventing any release back into the air (including geological formations, reactive minerals and permanently chemically bound carbon in products). This includes technologies like **direct air carbon capture with storage (DACCS)** and **biomass with carbon capture and storage (BECCS).**
- **Carbon stored in products:** Atmospheric or biogenic carbon can be captured and stored in long-lasting products, such as wood-based construction elements or bio-based insulation materials. The storage of carbon in products needs to be guaranteed over the long term, which excludes short-lived products such as paper or furniture.
  - Activities in this category do not include fossil Carbon Capture and Storage (CCS) or Utilisation (CCU). While these technologies do help storing or recycling fossil CO_2 emissions, they don't remove carbon from the atmosphere.

Source: Q&A on the provisional agreement on the Regulation establishing an EU-wide voluntary framework for certifying permanent carbon removals, carbon farming and carbon storage in products (CRCF Regulation) (V.10, 05.04.2024)

Carbon capture potential (CCU & CCS)

- In the climate neutrality scenario, it is assumed that ca. 0.5 Mt CO_2 is captured annually, including ca. 0.2 Mt biogenic CO_2 from processes taking place in the chemical industry.
- Fossil CO_2 emissions are captured in the context of recycled feedstock production, and biogenic emissions in the context of renewable fuel production.
- To reach climate neutrality, some negative emissions (or compensations) are most likely needed. In these scenarios, required amount would be below 0.5 Mt CO_2e.
- This figure is highly sensitive for the assumptions made, and would require fast, positive development and investments in GHG emission reductions in the sector.
- In Finland, biggest future potential for carbon capture is in forest and energy sectors.
- Carbon Capture, Utilisation and Storage (CCUS) will have an impact on the industrial use and production of energy. Sector integration might be needed to make efficient use of heat generated in hydrogen production.

Carbon capture key figures

- In the climate neutrality scenario, carbon capture is mainly assumed in the context of chemical plastics recycling and situations where inherent biogenic CO_2 capture is possible.
- The green growth potential in utilization of biogenic CO_2 is much higher if CO_2 is captured from industrial facilities in forest industry and energy sectors.
- Produced from CO_2 and hydrogen, CCU products are replacing fossil materials in both raw material and product portfolios within the chemical industry.

Key figures

- In total, 0.5 Mt CO_2 captured annually after 2030.
- Annually 130 kt of chemical industry products created from CO_2.
- Required hydrogen: 1.7 TWh & 70 kt
- Required investments 1 billion EUR, excluding investments to clean electricity.

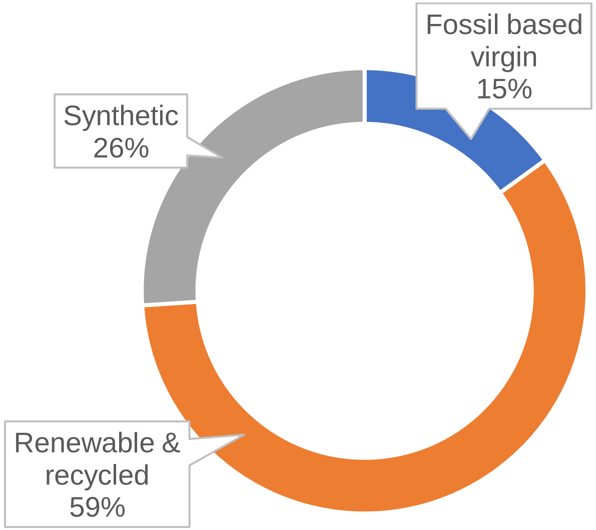
Green growth potential

- In the current scenarios, the focus was on potential means for reducing GHG emissions.
- Reducing virgin fossil feedstock and switching towards renewable and recycled raw materials could mean significant decline in production volumes after 2035 (~ 8 Mt).
- Additional new investments would be needed for creating green growth. These could include for example investments in biogenic carbon capture and production of green ammonia.
- It has been estimated that the maximum biogenic CCU potential in Finland would be ca. 20-30 Mt CO_2 These potentials are in industrial facilities within the forest and energy sectors (Arasto et al., 2024).
- Production of 1Mt of new high-value products like e-fuels would require ca. 4 Mt CO_2 and ca. 5 billion euros of new investments, on top of those needed in the climate neutrality scenario (See Mäkikouri et al., 2024).
- In addition to major investments, clarification of regulations for non-fuel CCU-products like chemicals and materials is still needed.

Green growth with biogenic CCU (max)

- Carbon capture from forest and energy sector could create significant new raw material base for the chemical industry.
- Large-scale utilisation of CCU could allow reaching production volumes close to current situation, with new, high-value products like e-fuels and new materials.
- Refining ~20 Mt of captured biogenic CO_2 together with hydrogen to polymers, chemicals and fuels, would require 100-160 TWh of electricity and 2-3 Mt H2.
- This amount of CO_2 represents roughly 2/3 of current biogenic emissions from large industrial facilities in Finland.
- It could create additional 5 M tons of new synthetic feedstock for the chemical industry.

For more information related to CCU, see: Arasto et al. (2024); Mäkikouri et al. (2024)



Assumed feedstock 2045 with estimated maximum capacity of CCU

Summary of assumed feedstock composition in different scenarios

Shifting to renewable & recycled feedstock

- In 2022, the total production of the Finnish Chemical Industry was ca. 21 Mt.
- From all the raw materials used, 87% were from virgin fossil sources, and 13% from renewable and recycled sources.
- Several efforts and plans for moving towards new raw materials have already been made. However, millions of tons of new raw materials are needed, together with investments in new process technologies and energy transition.
- When successful, transition in the chemical industry provides new more sustainable raw materials and products also for other sectors, enabling significant GHG emission savings, as discussed in this study.
- Despite the transition, a small share of virgin fossil-based raw materials will remain in use due to lack of reasonable substitutes. There are raw materials (such as sands) which are difficult or even unfeasible to recycle.

Sources of alternative raw materials

Bio-based raw materials

- Lignocelluloses
- Sugars
- Vegetable oils
- Fungus
- Algae
- Cyanobacteria
- Reeds

Main challenges

- Availability
- Cost
- Required process changes
- Potentially increasing impacts related to land-use & biodiversity

Circular raw materials

- Organic
  Recycled oils
- Recycled plastics
- Recyclates from organic & sevage waste

Inorganic

- Recycled metals & minerals

Main challenges

- Availability & quality
- Cost
- Unclear regulatory status
- New recycling technologies and value chains needed

Synthetic raw materials

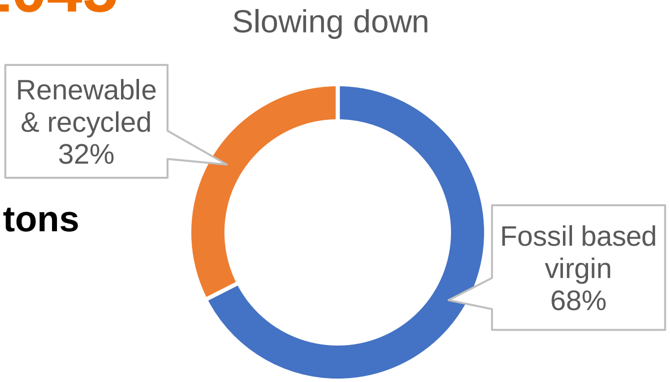
- CO_2
- H_2

Main challenges

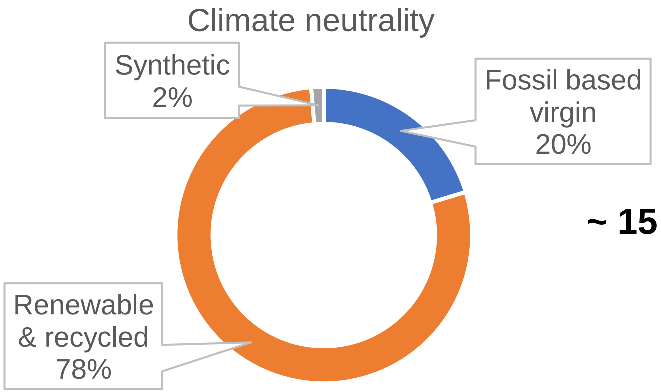
- Major investments needed
- Cost
- Unclear regulatory status
- Need for significant amounts of clean eletricity

Additionally, a small share of virgin fossil raw materials is expected to remain in use.

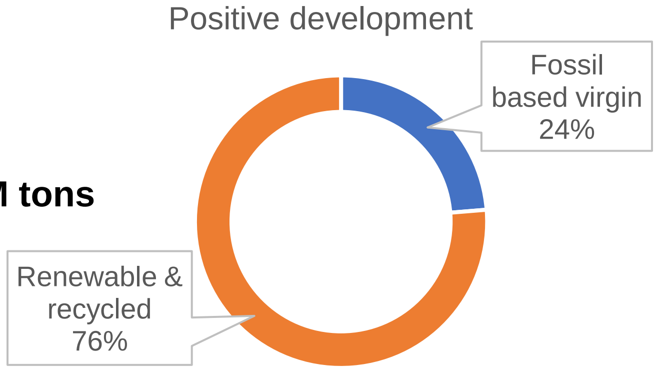
Assumed feedstock base in different scenarios by 2045



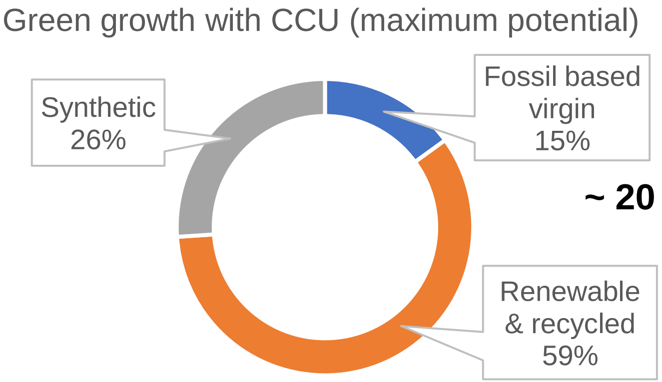
~ 22 M tons



~ 15 M tons



~ 15 M tons



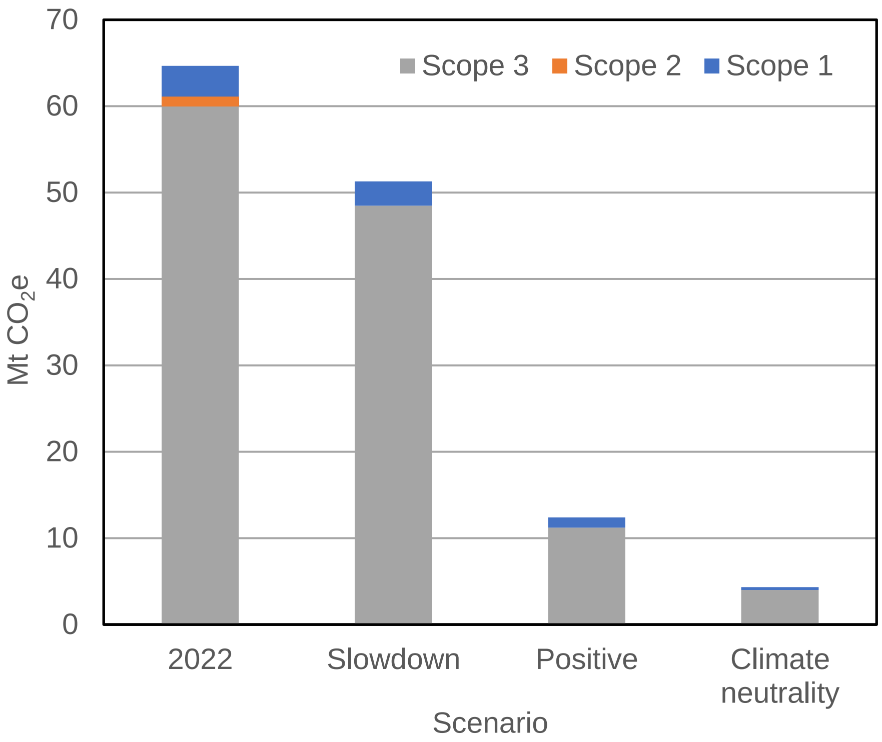
~ 20 M tons

Estimated development of value chain (Scope 3) GHG emissions

Value chain emissions (Scope 3)

- Chemical companies that have calculated their Scope 3 emissions have announced that Scope 3 emissions form up to 90% (or more) of their total emissions.
- Thus, assumed Scope 3 GHG emissions from the value chain multiply considered total (Scope 1 & Scope 2) emissions. A rough estimate of the Scope 3 emissions created for this study was ca. 60 Mt CO_2e.
- Due to the global nature of the chemical industry value chains these emissions take place in several countries. Overlaps and double-counting within Scope 3 and between the Scope 1-3 emissions occur when chemical industry companies purchase products and services from each other.
- For many companies, significant share of Scope 3 emissions originates from production of used raw materials and fuels, and emissions related to the use stage of sold products.
- Transition away from fossil raw materials and energy reduces estimated Scope 3 emissions significantly. However, impacts related to biodiversity and land use may increase due to increasing share of renewable raw materials.

Potential development of Scope 1-3 GHG emissions in different scenarios



- Estimated amount and development of fossil Scope 3 GHG emissions is a rough estimate (indicative only)
- Overlaps and some double-counting between the Scopes, and within Scope 3 take place within the sector, causing some uncertainty to the results.
- Scope 3 emissions occur in different countries, whereas Scope 1-2 emissions occur in Finland.

Examples of potential means and technologies for achieving GHG emission reductions

Examples of potential means and technologies enabling emission reductions

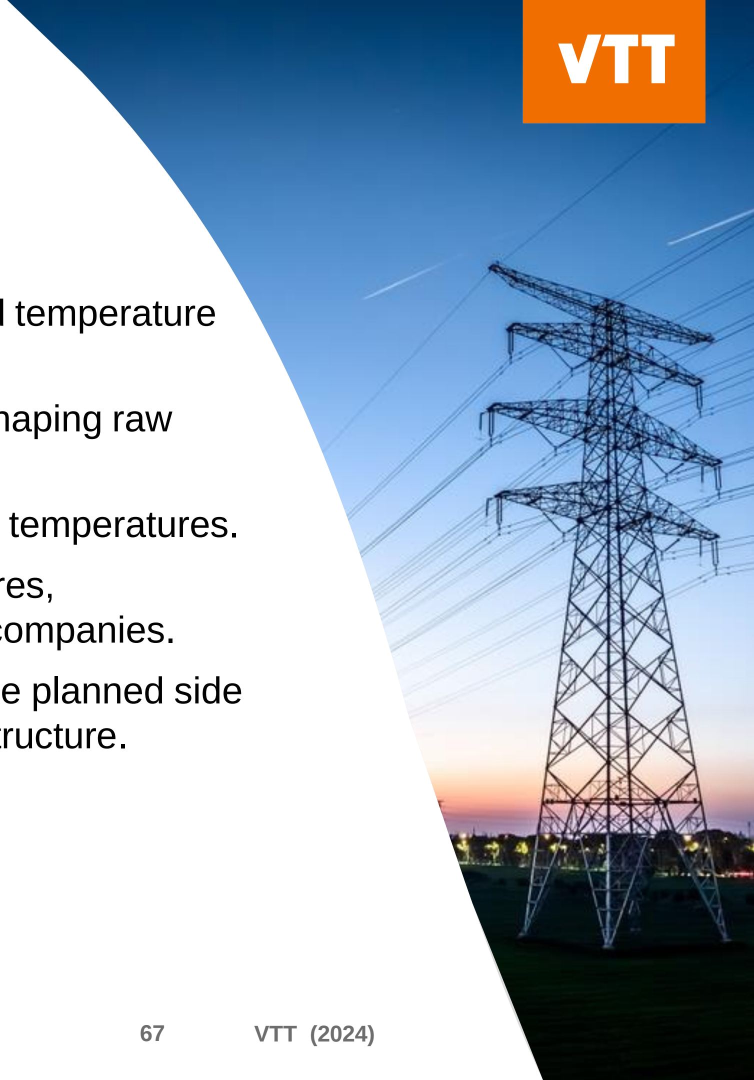
- Due to the versatile composition of the chemical sector, several different energy and process technologies are required for achieving GHG reductions and for preparing the necessary switch in applied feedstocks.
- Technological means must be combined with education, training, supplier and customer cooperation, sustainability assessments and environmental management tools.
- Out of the already available technological solutions, electrification is one of the central means for improving production efficiency, possibly also enabling cost savings if affordable clean electricity is simultaneously available.

Means for GHG reductions (Scope 1-3)

Scope	Source of GHG emissions	Potential means for GHG reductions, e.g.
Scope 1 Direct GHG emissions	Direct GHG emissions from processes and fuels and potential removals	Improvements in energy and material efficiency Fuel switches, process and raw material changes Electrification Carbon capture/removal
Scope 2 Energy indirect GHG emissions	Indirect GHG emissions from purchased energy	Switching to renewable electricity and heat Purchased Power Agreements (PPAs)
Scope 3 Other indirect GHG emissions	Indirect GHG emissions from purchased raw materials and services Indirect GHG emissions from products (goods and services) used by organization Indirect GHG emissions from the use of sold products Indirect GHG emissions from other sources	Switching to renewable and recycled or synthetic raw materials Waste handling: Increasing re-use, recycling and reducing incineration Including sustainability criteria for purchases (goods and services) Knowledge sharing, training and cooperation with value chain actors Regular GHG calculations and target setting

Different levels and means of electrification

- When defining industrial electrification options, the required temperature in the processes is a key factor.
- Heat is used in industry to bring energy to the process of shaping raw materials or products into the desired shape.
- Industrial processes need heating at low, medium and high temperatures.
- Depending on the applied process and required temperatures, electrification can mean many different things for different companies.
- It may require several rounds of investments that need to be planned side by side with other investments in existing production infrastructure.



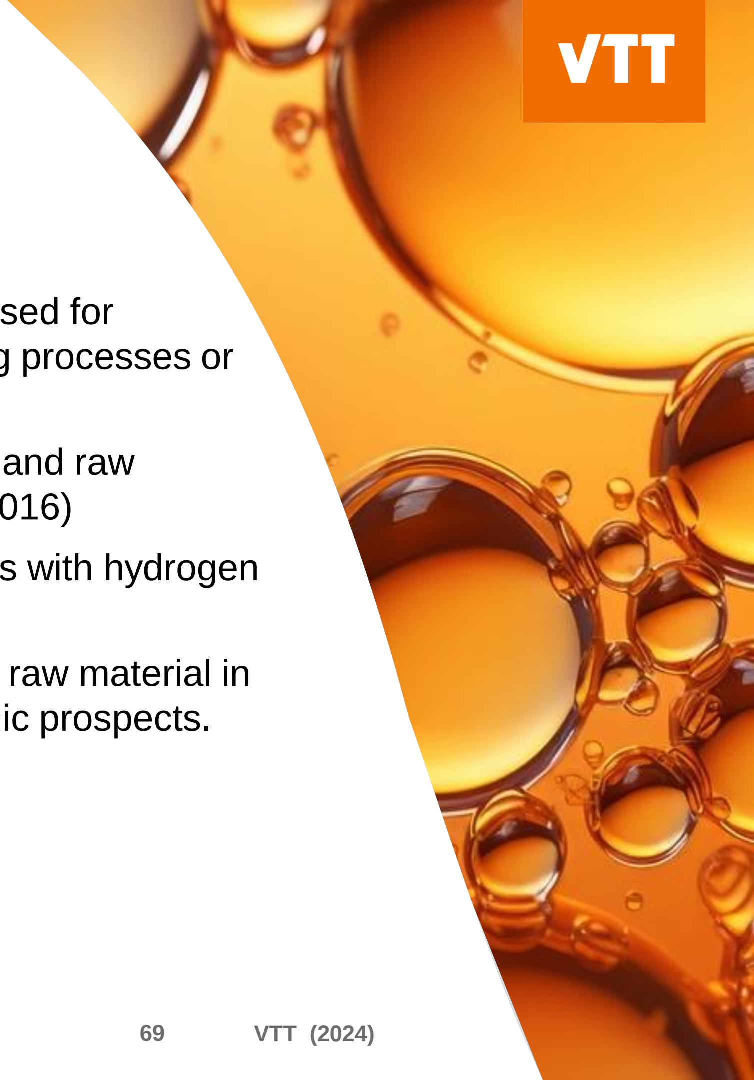
Different levels of electrification

The electrification of an industrial process can take place at four different levels (adapted from Bühler et al. 2019):

1. ***Exchange of a consumable (e.g., fuel) with electric fuel*** – Replacement of the fuel used to generate process heat with electro-fuels from renewable sources, such as hydrogen
2. ***Changing the production process of a consumable*** – Replacement of a central fossil fuel-fired boiler with e.g., electric boiler or a central heat pump
3. ***Making changes to the production process*** – For example replacing the process energy supply with and an electric technology, e.g. heat pump, resistance or infrared (IR) heating while keeping the process operation identical
4. ***Replacing current process with an electric process*** – Replacement of a current unit operation with a fully electric one, e.g. mechanical separation instead of evaporation

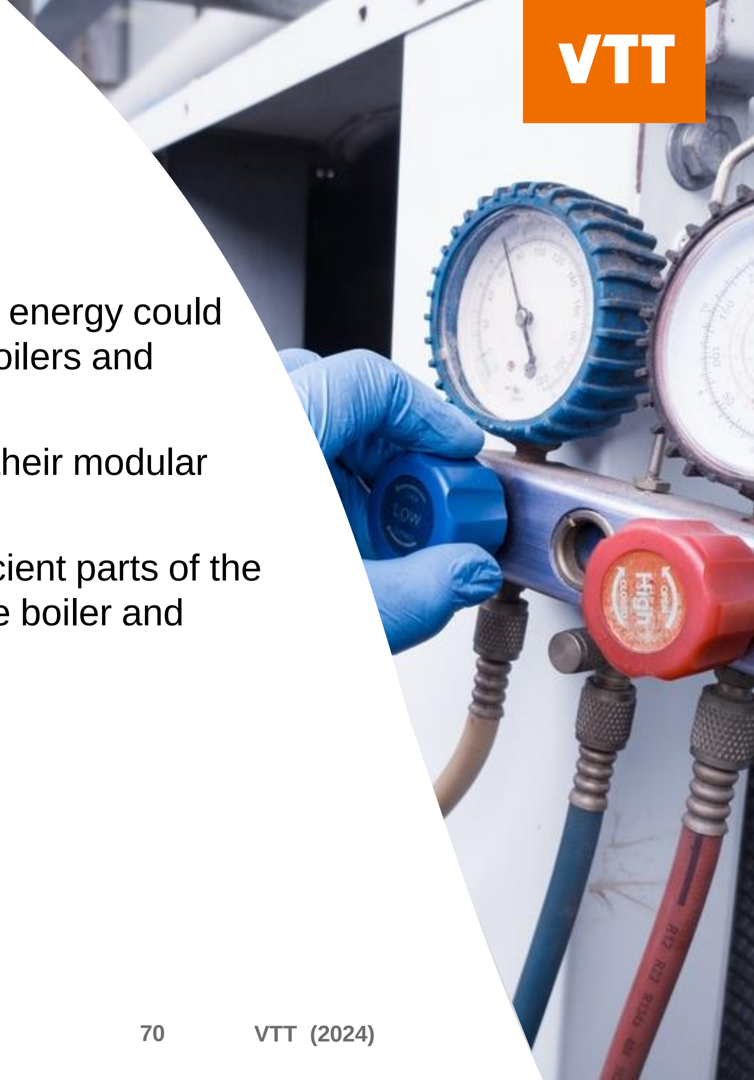
1) Exchange of a consumable, i.e., fuel with electric fuel

- Electricity is a very versatile form of energy, and it can be used for industrial heating either directly with various electric heating processes or indirectly using hydrogen as an energy carrier.
- The goal is often to replace fossil fuel used as both energy and raw material with renewable electricity. (Lechtenböhmer et al. 2016)
- As an example, replacing natural gas fuel and raw materials with hydrogen or its derivatives produced with renewable energy.
- Among all hydrogen applications, the use of hydrogen as a raw material in the production of ammonia, for example, has good economic prospects. (Irena 2019)



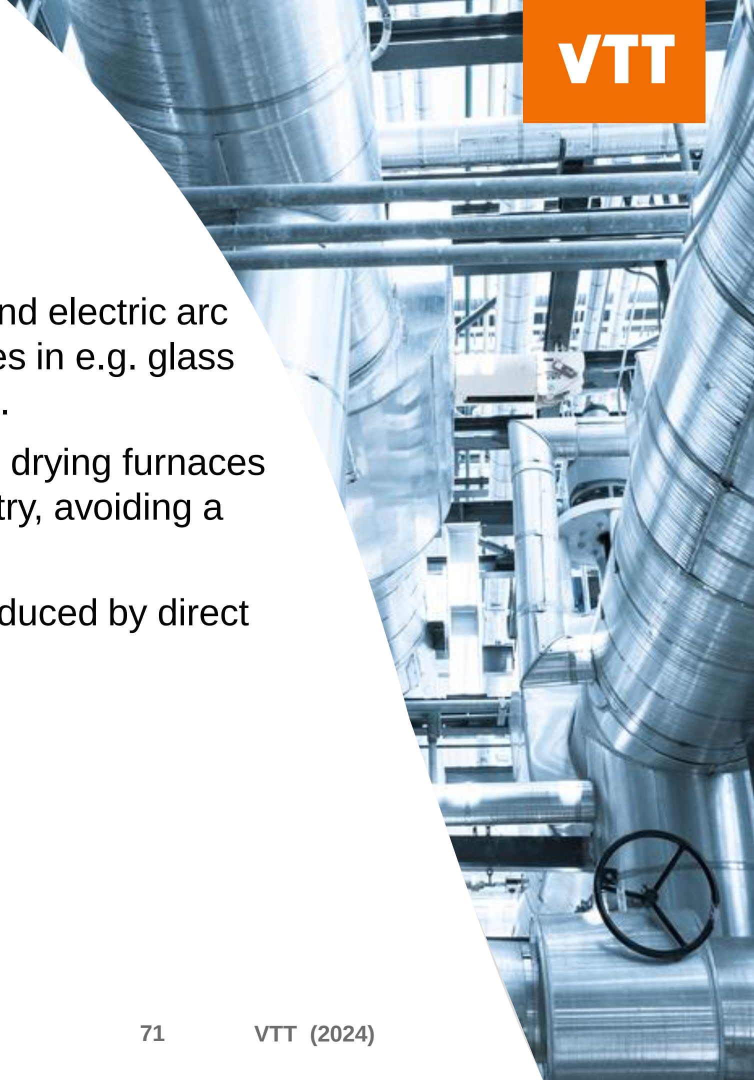
2) Changing the production process of a consumable

- In Finnish conditions, traditional heating boilers using fossil energy could be replaced by e.g., in the chemical industry with electric boilers and industrial heat pumps.
- The suitability and usability of heat pumps is increased by their modular installation.
- In most cases, it is sufficient to replace only the most inefficient parts of the boiler or distribution system, rather than replacing the entire boiler and steam system. (Lord et al. 2018.)



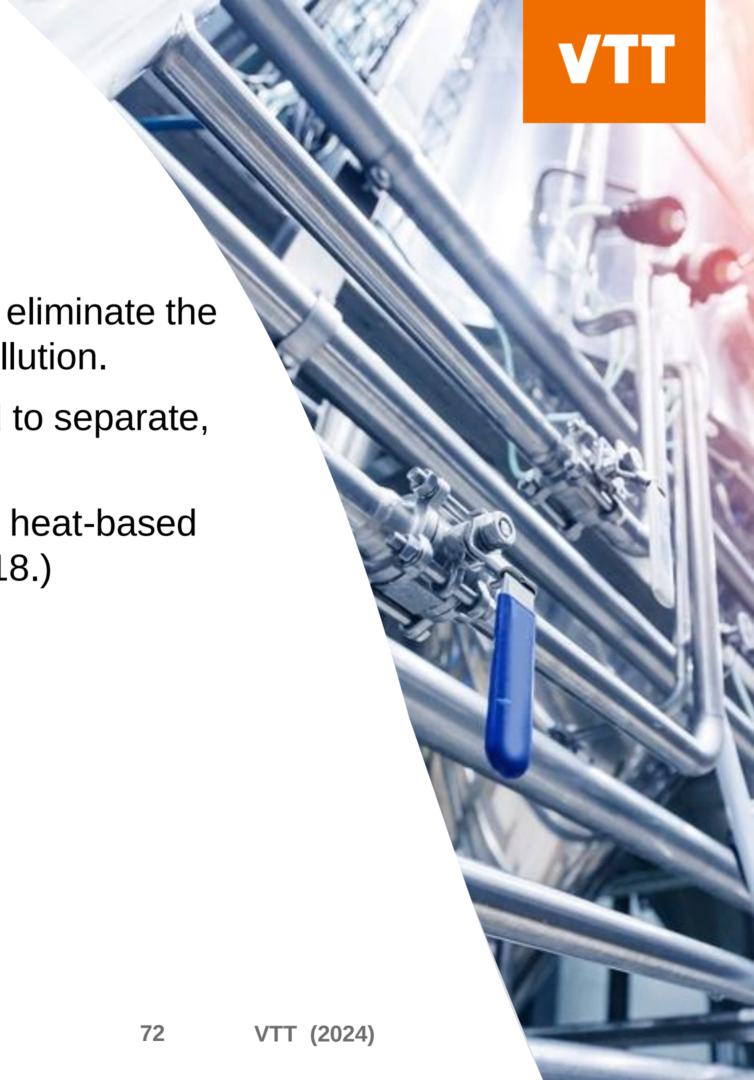
3) Making changes to the production process

- Induction heating, electrolytic heating, resistance heating and electric arc technologies are seen as possible replacement technologies in e.g. glass and metal manufacturing and non-ferrous metal production.
- It has been estimated that electric ovens, e.g. smelting and drying furnaces could displace a large amount of fossil fuel energy in industry, avoiding a significant amount of carbon dioxide emissions.
- Part of the heat needed to produce chemicals could be produced by direct resistance heating.



4) Changing the production process to another

- There are technologies that can be used to reduce or even eliminate the need for heat and at the same time the generation of air pollution.
- Membrane technologies such as reverse osmosis are used to separate, purify or remove water from a liquid.
- They are low-energy, non-thermal alternatives to traditional heat-based separation techniques such as evaporation. (Lord et al. 2018.)



Examples of potential technologies enabling emission reductions: electrification

- Coolbrook’s rotodynamic reactor could reach 1700 C heating with solely using rotational kinetics and electricity. This could revolutionise e.g. steam cracking and other process steps requiring heating.
- Would delete most of the scope 1 emissions for heating, but also influence scope 2, as electricity is transitioning towards being solely renewable or low carbon.
- Nefco finances Coolbrook to accelerate decarbonisation of heavy industries | Nefco

Examples of potential technologies enabling emission reductions: CCU/CCS

- New technologies with a higher capture rate and lower capital cost are constantly being researched – one worth mentioning is an adsorption based solution – metal organic frameworks (MOFs)
- MOFs could revolutionise carbon capture, as they are tunable, highly porous and have a large surface area.

- Process intensification technologies for CO_2 capture and conversion – a review | BMC Chemical Engineering | Full Text (biomedcentral.com)

Handprint potential

Handprint definition

Handprint has been defined as “beneficial environmental impacts that organizations can achieve and communicate by offering products and services that reduce the footprints of others.” (Carbon handprint guide, v.2.0)

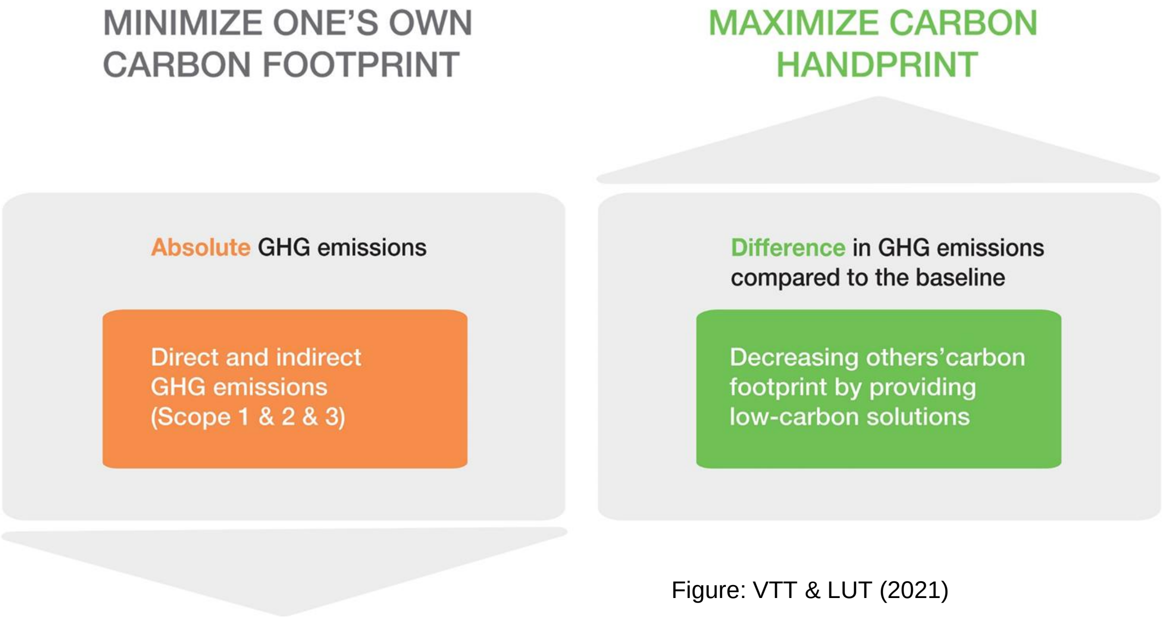


Figure: VTT & LUT (2021)

Mechanisms for creating carbon handprint

- According to the Carbon handprint guide v. 2.0, handprint can be created via various mechanisms that include for example:
  - Less GHG intensive material use
  - Less GHG intensive energy use
  - Increased lifetime and performance of products
  - Reduced waste and losses
  - Carbon capture and storage
- All these mechanisms should be applied within the chemical sector, to reduce GHG emissions and to create handprint potential.

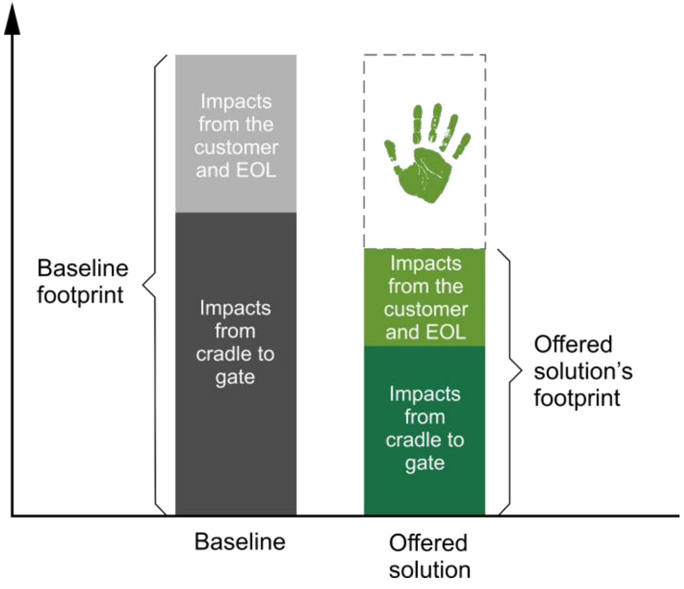
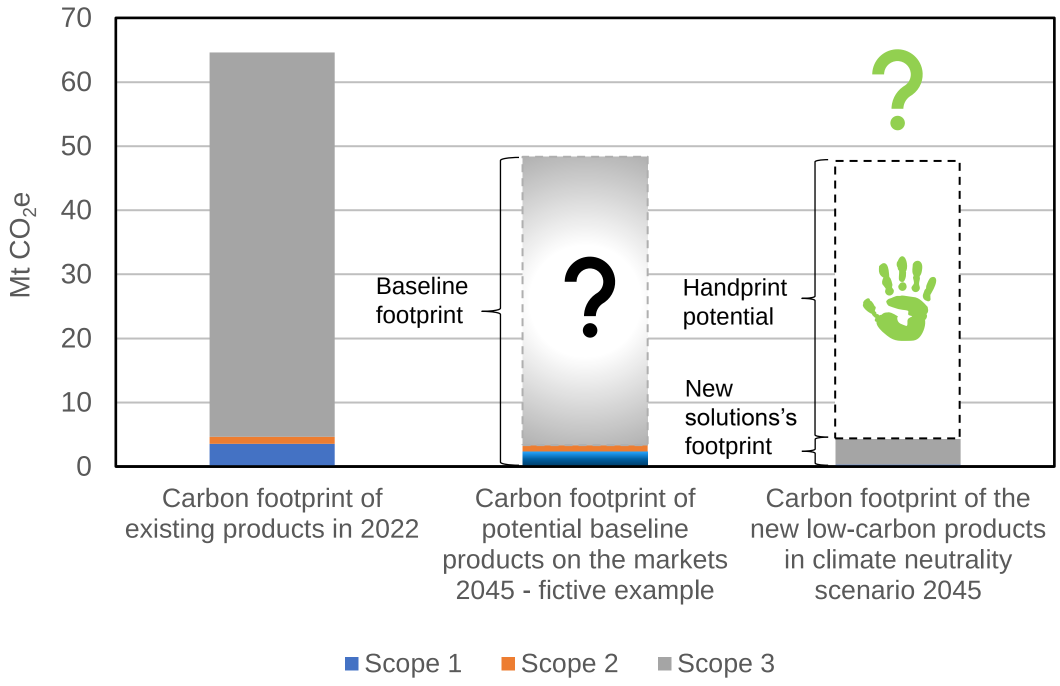


Figure: VTT & LUT (2021)

How carbon handprint is calculated?

- First, a reduction in organisation's Scope 1-3 emissions is required, reducing the carbon footprint of the selected product or solution.
- Carbon footprint of the new, low-carbon product is then compared with the footprint of a baseline product (or solution).
- Carbon handprint is created, if the new low-carbon product replaces existing product which has higher GHG emissions, or provides a completely new solution to the markets
  - Carbon handprint is the difference between offered solution's and baseline solution's carbon footprint.
- Transparency is required in reporting selected baseline and other assumptions.
- Selected baseline must be regularly updated to reflect 'business-as-usual' situation in the target markets.

Carbon handprint is specific for products and depends on the baseline

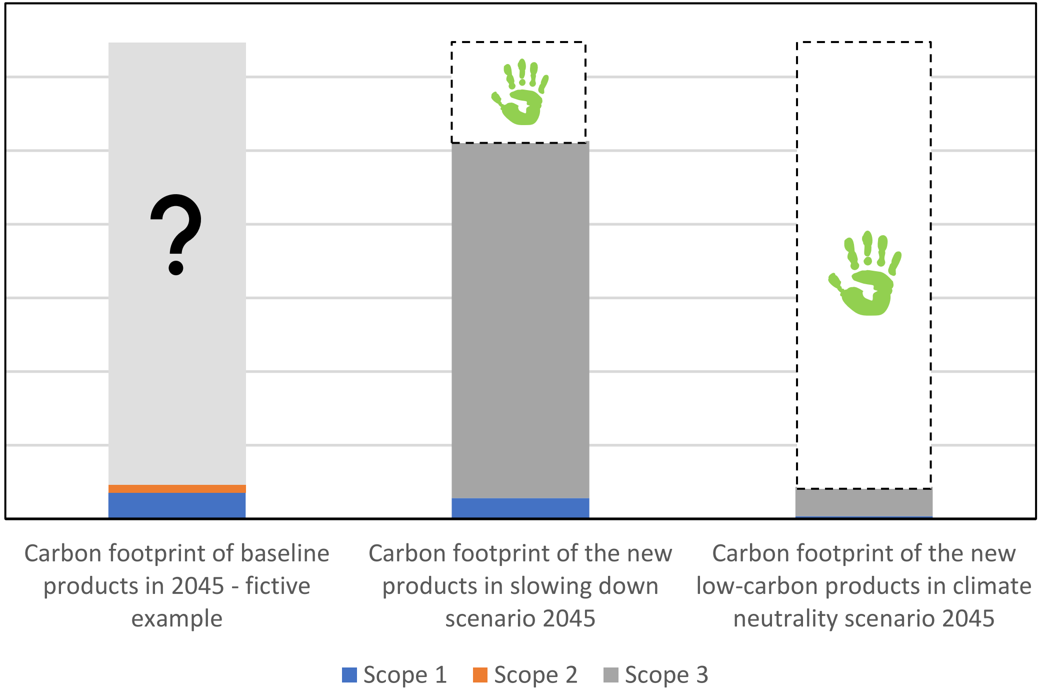


Reductions in Scope 1-3 GHG emissions create potential for carbon handprints.

Actual handprint is defined in relation to selected baseline product that can be either internal or external.

Biggest handprint potential is available for forerunner companies that bring new less-GHG intensive products to the markets.

Future handprint is uncertain

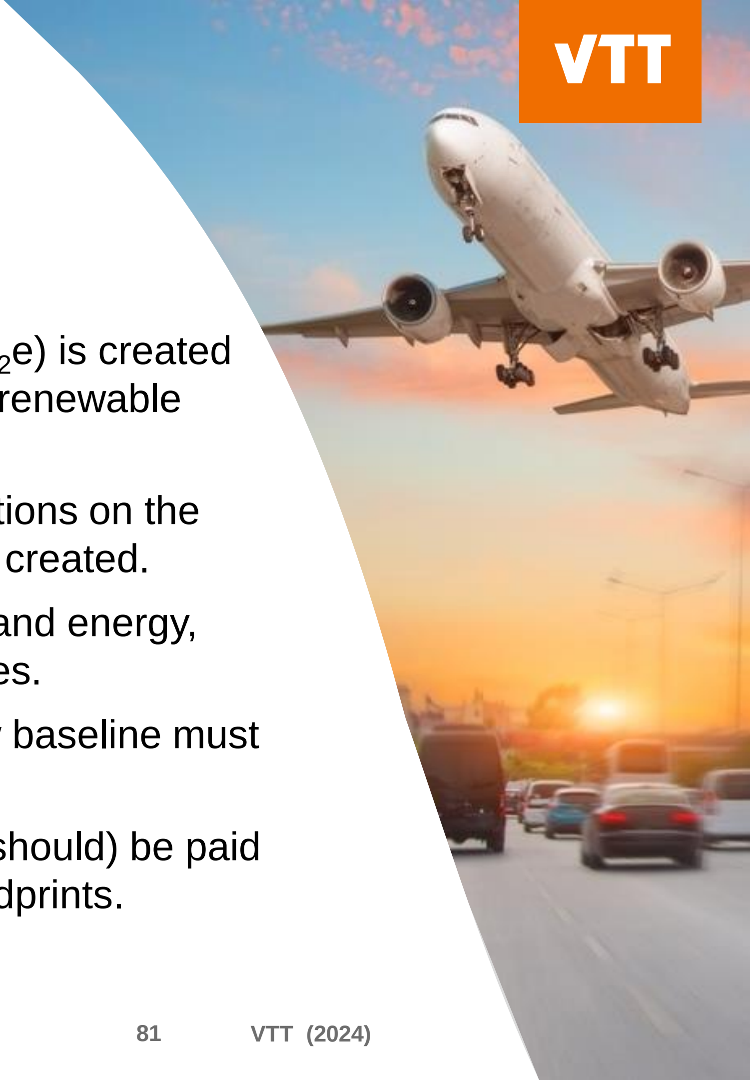


Estimated carbon handprint for exported Finnish goods in 2019 varied between 13 - 23 Mt CO_2e, depending on the assumed target markets and product groups (SYKE, 2024).

Carbon handprint for chemical products in 2045 is highly uncertain. It depends on the estimated GHG emission reductions, assumed baseline markets and products.

In this study, future handprint potential could vary between 4 - 60 Mt CO_2e, depending on the scenario. Its realisation depends on assumed future baseline (=how much others reduce their emissions).

Example of a carbon handprint created with renewable fuels



- As an example, significant carbon handprint (11 Mt CO_2e) is created annually by replacing fossil fuels with new circular and renewable solutions (Neste, 2023).
- By further increasing the share of new low-carbon solutions on the markets, it is possible to increase the carbon handprint created.
- In future, when moving away from fossil raw materials and energy, also the baseline definition for carbon handprint changes.
- When renewable fuels become business as usual, new baseline must be defined.
- In addition to the carbon handprint, attention can (and should) be paid to other environmental impacts and environmental handprints.

Example of carbon handprint potential – Green ammonia production

- Investing in green ammonia production could reduce mineral fertilizer production related GHG emissions in food production and improve security of supply. It could also create significant emission reductions in maritime transport.
- Currently, ammonia used in Finland is imported. It is one of the GHG intensive raw materials used by the chemical industry.
- An estimated reduction of ca. 1 Mt CO_2 in Scope 3 emissions could be created by producing 0.5 Mt green ammonia in Finland
- Domestic production of green ammonia would require clean electricity (5.8 TWh/a) and significant investments (ca. 1.0-1.2 billion €) (Ikäheimo et al. 2023).
- Since a large share of fertilisers produced in Finland are exported, new low-carbon fertilisers could create significant handprint potential in different markets.
  - Within the food sector, estimated carbon handprint potential could be ca. 5-15% from the carbon footprint of selected agricultural products.

Summary, main conclusions and recommendations

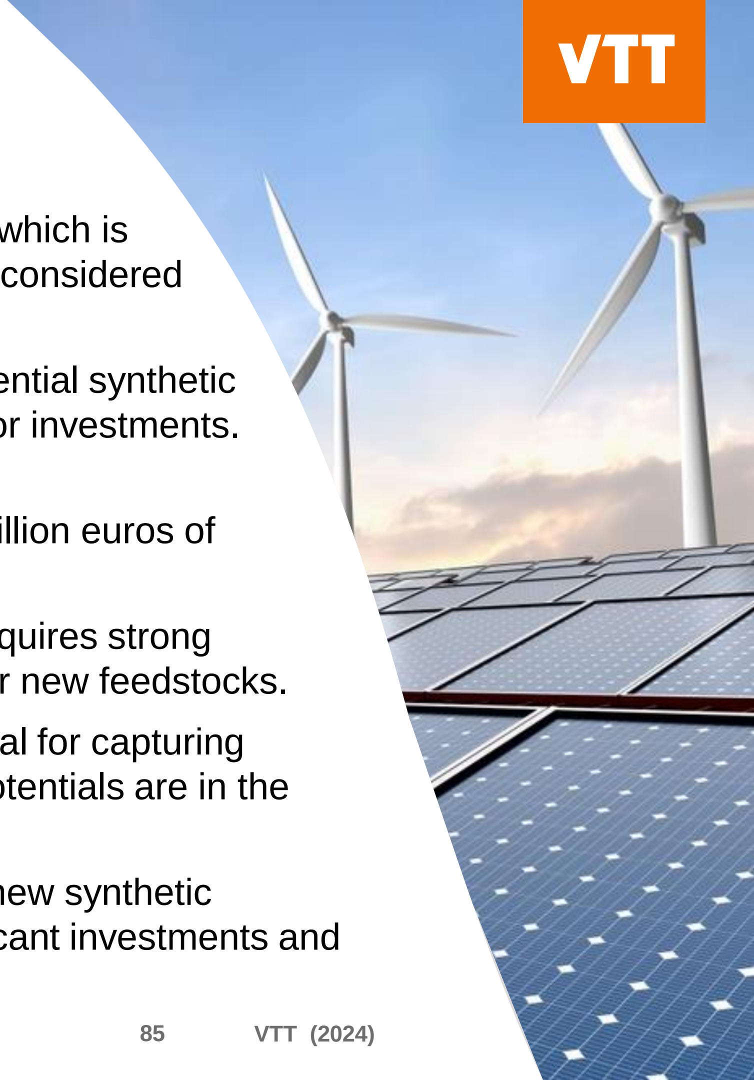
Limitations

Main conclusions 1/3

- In 2022, the direct and indirect fossil GHG emissions from the Finnish chemical industry were 4.5 Mt CO_2e.
- Since 2018, a reduction of 0.6 Mt CO_2 (~11%) has been achieved.
- Chemical industry companies have set climate targets and announced several investments which enable significant reduction in sector’s GHG emissions. However, not all companies have been able to specify their plans. Internationally operating companies are considering different options and locations for their investments.
- The biggest future challenge in the chemical sector relates to the raw material transition that is required for reaching climate neutrality.
- The biggest source of GHG emissions for most chemical industry companies is their value chain, especially the emissions related to acquired raw materials and sold products. Value chain (Scope 3) emissions are currently the most difficult to evaluate and provide the biggest GHG emission reduction potential.

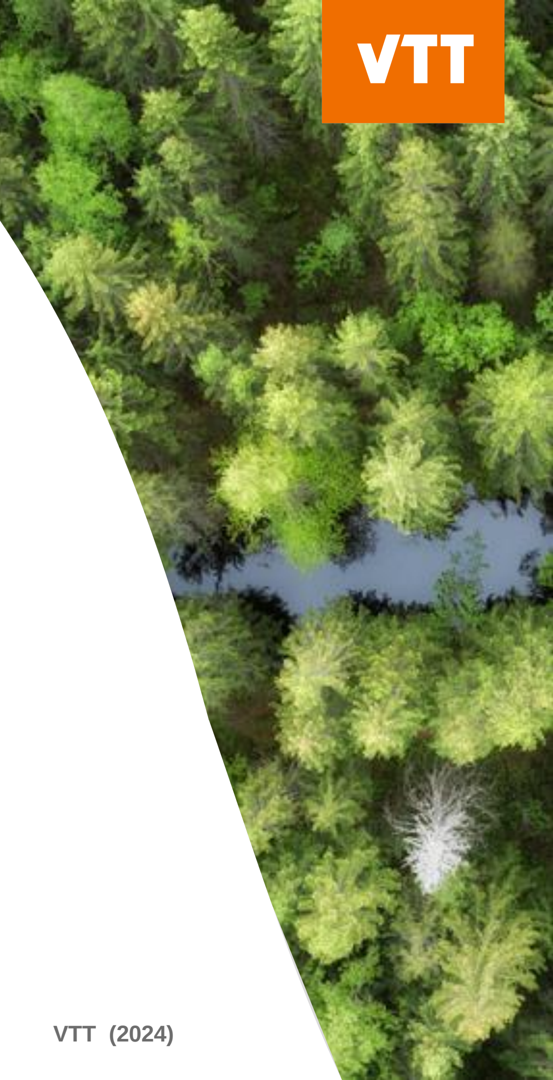
Main conclusions 2/3

- Becoming biodiversity positive is another ambitious target, which is closely related to the raw material transition. It needs to be considered and integrated in all plans.
- Move from fossil resources to renewable, recycled and potential synthetic raw materials increases production costs and requires major investments. In addition, a decline in production volumes is foreseen.
- Reaching climate neutrality by 2045 would require over 3 billion euros of investments during the next ten years.
- Achieving planned reductions and raw material switches requires strong demand for new, climate neutral products and incentives for new feedstocks.
- Switching to renewable raw materials creates some potential for capturing biogenic CO_2 from the chemical sector, but biggest CCU potentials are in the forest and energy sectors.
- Biogenic CO_2 from forest and energy sectors could create new synthetic feedstock for the chemical industry, but this requires significant investments and clear regulatory frameworks.



Main conclusions 3/3

- In this study, means for achieving GHG emission reductions in include
  - Switching to renewable or emission-free energy (e.g. PPA-agreements) (ca. 1.1 Mt CO_2e)
  - Moving away from crude oil refining (ca. 1.6 Mt CO_2e)
  - Electrification and switching to renewable fuels in industrial processes (ca. 0.4 Mt CO_2 e)
  - Direct, process-related emissions need to be reduced using various mechanisms, such as improving efficiency and switching to less GHG intensive raw materials (ca 1.1 Mt CO_2e)
  - To reduce direct emissions close to zero by 2045, carbon capture and/or removal is most likely needed (ca. 0.5 Mt CO_2e)
- When successful, the combined climate and raw material transition of the chemical sector creates significant handprint potential in other sectors, promoting green transition in Finland.
- To reach climate neutrality by 2045, activities must start now.



Key factors enabling climate and raw material transition in the chemical industry

- Clean electricity
- Alternative raw material sources
- Carbon leakage protection
- Incentives for the new products
- R&D and funding
- Permitting

Key factors enabling climate and raw material transition in the chemical industry

Clean electricity

- The demand for clean electricity increases significantly
- The price of electricity will be crucial
- A stable supply of electricity and energy security are important
- Investments in national grid are crucial

Alternative raw material sources

- Legislation must recognize and support all alternative raw material sources. Chemical legislation must support alternative raw materials entering the market.
- Relevant legislative sectors should be harmonized
- Clear rules for the use of new raw materials (including emission-free hydrogen) are needed.
- Necessary infrastructure must be in place

Carbon leakage protection

- Sufficient carbon leakage protection is necessary when aiming towards ambitious climate goals
- Especially ETS, ETS compensation and CBAM are relevant

Incentives for the new products

- There are already new solutions but no markets for new products which are based on alternative raw materials
- Incentives will be required for the new climate friendly products
- Clear definitions and sustainability criteria for new products and raw materials are needed

R&D and funding

- Well-functioning R&D environment is important
- Investments that aim for climate neutrality are expensive and risky and the market is yet under development
- The R&D environment should support new solution creation, and the landscape should be predictable as new product development takes 10-15 years
- RDI funding is required all the way from R2B, commercialization to pilot plant funding

Permitting

- Efficient, smooth and predictable permitting procedures are crucial, especially at national level
- Stakeholder engagement is needed as part of the process

Limitations & uncertainties

- All the results presented in this study are based on the made assumptions.
- The scenarios and other results include a lot of uncertainty – they aim to present potential future development paths based on current knowledge and expert estimations.
- The most important assumptions are
  - amounts of total production (not increasing due to required major shift in feedstocks)
  - share of fossil feedstock (especially assumptions related to crude oil refining)
  - future development of the Finnish energy system (GHG emissions reaching zero after 2030) and availability of clean electricity,
  - ability of the industry to invest in various process and energy technologies, to conduct necessary raw material and fuel switches and reach GHG emission reductions.
- Due to high variety and number of companies and raw materials included in the sector, potential impacts and development paths were evaluated on a high level, focusing especially on the most energy and emission-intensive clusters.
- Despite uncertainty included in the study, required change in production systems and raw materials is massive. Planning and implementing all the different activities aiming towards GHG emission reductions need to start now.

Summary of key numbers from the scenarios

Summary of key numbers from the scenarios

	Scope 1						Scope 2	Scope 3
Scenario	GHG-emissions, Mt CO_2	Investments, million/a	H_2 demand, Mt	H_2 demand, TWh (LHV)	Electricity demand (H_2 prod), TWh	Total electricity demand, TWh	GHG-emissions, Mt CO_2	GHG-emissions, Mt CO_2
Slowing down	2.8	+ 0 (BaU = 1 000)	0.2	6.7		5.7	0	48.5
Positive development	1.2	+ 300	0.2	6.7	9.9	14.7	0	11.2
Climate neutrality	0.3	+ 400	0.2	6.7	9.9	19.2	0	4

Note! The total production volumes decrease in Positive development and Carbon neutrality scenarios. However, there is a significant green growth potential. All presented numbers are dependent of the background assumptions made for specific scenarios.

Summary of key numbers from the scenarios and beyond

Green growth potential estimates	Description	Synthetic products, kt	Additional H_2, kt	Addtional H_2, TWh (LHV)	Additional electricity demand (H_2 prod), TWh	Additional CO_2 demand, Mt	Additional electricity, TWh/a	Additional investment, billion
CCU+S, 130 t products	As assumed in carbon neutrality scenario	130	70	2.4	3.6	0.5	3.7	1.0
*CCU increase / 1 Mt product	How much more is needed for 1 Mt growth	1000	550	18	27	3.8	28	7.7
*CCU Max potential	Maximum CCU potential in Finland is 20 Mt,CO_2	5200	2900	96	143	20	147	40
*Ammonia Max / 0.5 Mt	If current imported ammonia would be produced in FI	500	80-90	2-4	4-5	-	5.8	1.0-1.2

Note: Presented numbers are dependent on the background assumptions made for specific scenarios.
*Estimations based on other available studies and expert estimations (See Arasto et al. 2024, Mäkikouri et al. 2024 and Ikäheimo et al. 2023).

List of references

References

- AFRY (2022) The Scope 3 Substitution study. Carbon neutral chemical industry – possibilities to expand raw material base. Final report, autumn 2022. Authors: Vasara, Lehtinen, Le.
- Arasto, A. et al. (2024). Päästäjästä tuottajaksi – Hiilidioksiditaloudella arvonlisää Suomen metsäsektorille. VTT Technical Research Centre of Finland. https://publications.vtt.fi/julkaisut/muut/2024/VTT_Luke_Hiilidioksiditalous.pdf
- Bühler F. et al. (2019) Potentials for the electrication of industrial processes in Denmark, Proceedings of ecos 2019 - The 32nd international conference on efficiency, cost, optimization, simulation and environmental impact of energy systems June 23-28, 2019 Wroclaw, Poland.
- Ikäheimo, J. et al. (2023) Impact of Climate and Geological Storage Potential on Feasibility of Hydrogen Fuels. Applied Energy 342 (July 2023): 121093. https://doi.org/10.1016/j.apenergy.2023.121093
- Irena (2019) Electrification with Renewables: Driving the transformation of energy services, 2019, ISBN: 978-92-9260-108-9, Copyright © IRENA.
- Koljonen, Tiina et al. (2024) Perusskenaariot energia- ja ilmastotoimien kokonaisuudelle kohti päästöttömyyttä (PEIKKO). Valtioneuvoston selvitys- ja tutkimustoiminnan julkaisusarja 2024:26. http://urn.fi/URN:ISBN:978-952-383-219-0
- Lechtenböhmer S. et al. (2016) Decarbonising the energy intensive basic materials industry through electrification - Implications for future EU electricity demand, Energy 115 (2016) pp. 1623-1631.
- Lord M. et al. (2018) Zero Carbon Industry Plan: Electrifying Industry, Beyond Zero Emissions Inc., 2018, Melbourne Australia.

References continue

- Mäkikouri, S. et al. (2024). Selvitys hiilidioksidin talteenoton ja hyötykäytön kansallisesta ilmasto- ja talouspotentiaalista. Teknologiateollisuus ry. VTT Asiakasraportti No. VTT-CR-00468-24 https://teknologiateollisuus.fi/fi/ajankohtaista/tiedote/vttn-selvitys-teollisuudessa-talteen-otetusta-hiilidioksidista-valmistetuilla
- Neste (2023) Annual report - Sustainability https://www.neste.com/files/pdf/3SiB5xKRfcL3dDDJvA73aD-Neste_Sustainability_2023.pdf
- Savolainen, H. et al. (2024) Suomen kansantalouden materiaalivirrat ja niiden vaikutukset. Toteutunut kehitys ja kiertotalouden skenaariot vuodelle 2035. Valtioneuvoston julkaisuja 2024:8. https://urn.fi/URN:ISBN:978-952-383-759-1.
- Pöyry (2020) Roadmap to reach carbon neutral chemistry in Finland 2045. Final report. Authors: Vasara, Nyman, Lehtinen, Aktüre, Laukkanen.
- Sustainability reports of chemical industry companies (from years 2022 & 2023)
- SYKE (2024) News 25.9.2024
- Q&A on the provisional agreement on the Regulation establishing an EU-wide voluntary framework for certifying permanent carbon removals, carbon farming and carbon storage in products (CRCF Regulation) (V.10, 05.04.2024), https://climate.ec.europa.eu/document/download/a8abe1c4-a3c6-4c94-be0e-4b76f7fd0308_en?filename=policy_carbon_faq_crcf_regulation_en.pdf
- VTT (2024) Future directions through strategic foresight. Confidential Customer report to Chemical Industry Federation of Finland.
- VTT & LUT (2021) Carbon handprint guide v. 2.0 Applicable for environmental handprint. Authors: Pajula T. et al. https://publications.vtt.fi/julkaisut/muut/2021/Carbon_handprint_guide_2021.pdf

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