ROADMAP TO REACH CARBON NEUTRAL CHEMISTRY IN FINLAND 2045

FINAL REPORT

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WHEN THE GOING GETS TOUGH…

“***J’ai le pessimisme de la réalité mais l’optimisme de la nécessité.***”

- Jacques Dubochet, Winner of Nobel prize in Chemistry 2017

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THE STRONG FOUNDATION

Progress is only possible, if …

The basic condition for success in all scenarios and all chemical industry sectors in Finland is a competitive, viable industry.

ROADMAP TO THE ROADMAP

POINTS TO REMEMBER: INTRODUCTION

Out of the ocean of facts, remember this

DOUBLE DISRUPTION: the industry is being disrupted both inside its process and electricity purchases (scopes 1 and 2) and feedstock (scope 3). The former disruption is less intense in outcome and conditionality.

FIVE CLUSTERS OF FINNISH CHEMICAL INDUSTRY: to manage analysis with reasonable time and effort, 400 companies have to be reduced to five clusters. The clusters differ notably in e.g. size, energy use and emissions. The changes in the global business environment will also affect them differently.

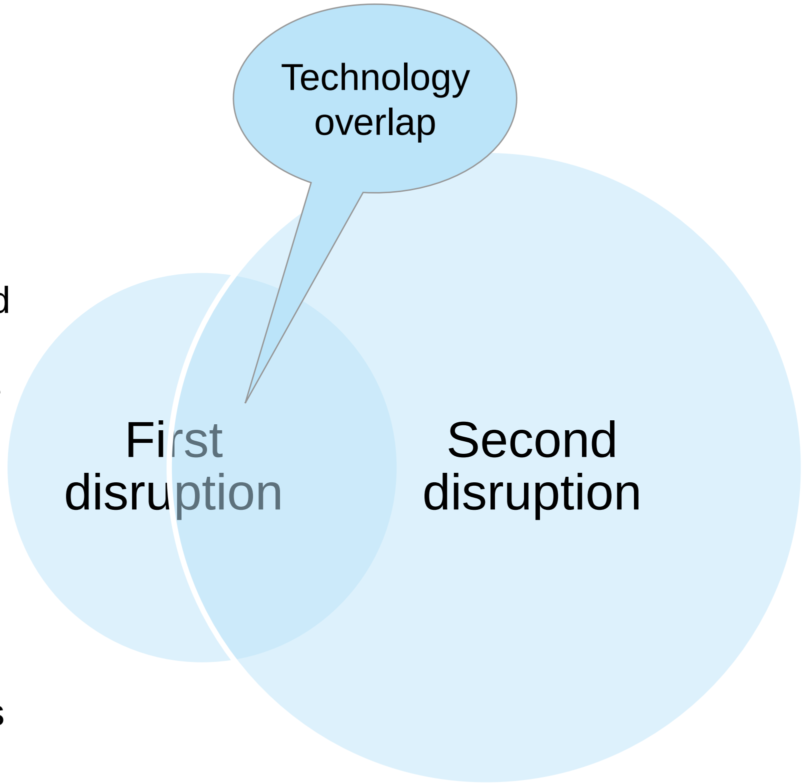
MANY VIEWPOINTS, ONE PICTURE : the overall analysis takes many viewpoints (clusters, development, technologies, different scopes, actions etc) and pulls together them into larger overall pictures of the emission reductions and conditionalities.

PURPOSE

THERE ARE TWO DISRUPTIONS

The road to carbon neutrality has two large cracks

- **The road**
  The route to *carbon neutrality* cannot be simple, when even the term needs explanation. There are two disruptions on the way, which have something in common – an increase in energy use.
- **The first disruption:** *processes and production.*
  To decarbonise processes and production (Scope 1 and 2), a toolbox of technical solutions is needed. Some exist, others need to be developed. Together, they have the potential to positively disrupt chemical production – at the expense of an *increase in energy use and costs*.
- **The second disruption:** *feedstock and end-of-life.*
  To *remove fossil feedstock (*Scope 3) is the second, larger disruption. The demanded change is much more extensive, meets problems in alternative feedstock availability – and may even increase process emissions to begin with. The increase in energy use overall would be *significantly higher*, likewise the cost, compared to the first disruption.



We have here looked at the both the first disruption and the second disruption (scenarios scopes 1 and 2, scenarios scope 3. The results are discussed in separate chapters.

IN BOTH, THE DEFINITION OF CARBON NEUTRALITY IS CENTRAL

Our chosen interpretation is orthodox

Terminology

- "**Carbon neutrality** means annual zero net anthropogenic (human caused or influenced) CO_2 emissions by a certain date. By definition, carbon neutrality means every ton of anthropogenic CO_2 emitted is compensated with an equivalent amount of CO_2 removed (e.g. via carbon sequestration), but this term has been used differently on occasion."
- **"Climate neutrality** is the same concept as carbon neutrality but rather than solely focusing on CO_2 emissions, it extends to zero net anthropogenic greenhouse gas emissions (i.e. including emissions beyond carbon dioxide)."

→ Carbon neutrality is here used according to the definition, taking into account all GHGs, considering the possibility of compensating emissions only as an option of last resort.

BOUNDARIES

WHAT CHARACTERISES THE GLOBAL CHEMICAL INDUSTRY?

As intense as many of its processes – and as intensely needed

Diversity

Globally, it has been estimated that there are over 85,000 different chemicals produced commercially. Value chains, raw materials, production processes and markets are vastly different.

Chemical industry includes everything from the largest (petro)chemical plants in the world to family businesses producing niche chemicals and products in small facilities.

Energy-intensity

High temperatures (400-1000˚C), pumping and drying are large energy uses in the chemical industry. High temperature heat is typically obtained through combustion of fossil fuels or other feedstock; electric furnaces to reach such high temperatures are expected to become widely available only in 2040s. The majority of GHG emissions (Scope 1&2) in the industry is energy-related; some CO_2 originates from chemical reactions (e.g. production of hydrogen through steam reforming of natural gas).

Capital intensity

Chemical industry is typically very capital intensive, and the investments are made with a time horizon of more than 30 years. Definitive indication of the direction of policy (market, RDD&D and other enablers) is needed in order to spark the investments, given the uncertainties of emerging technologies. Factories can suffer from technical lock-in effects, as incremental improvements throughout the years have made it hard to change the existing process without large stranded assets.

Global

Particularly in bulk chemicals, markets are global and value chains can be very large. In business-to-business, price and reliability are unfortunately often (the only) decisive factors, as bulk products are similar to each other. In specialized products, markets are small, driven by quality competition and higher margins. Price premium for environment-friendliness of products should be promoted.

Investment and RDD&D cycles

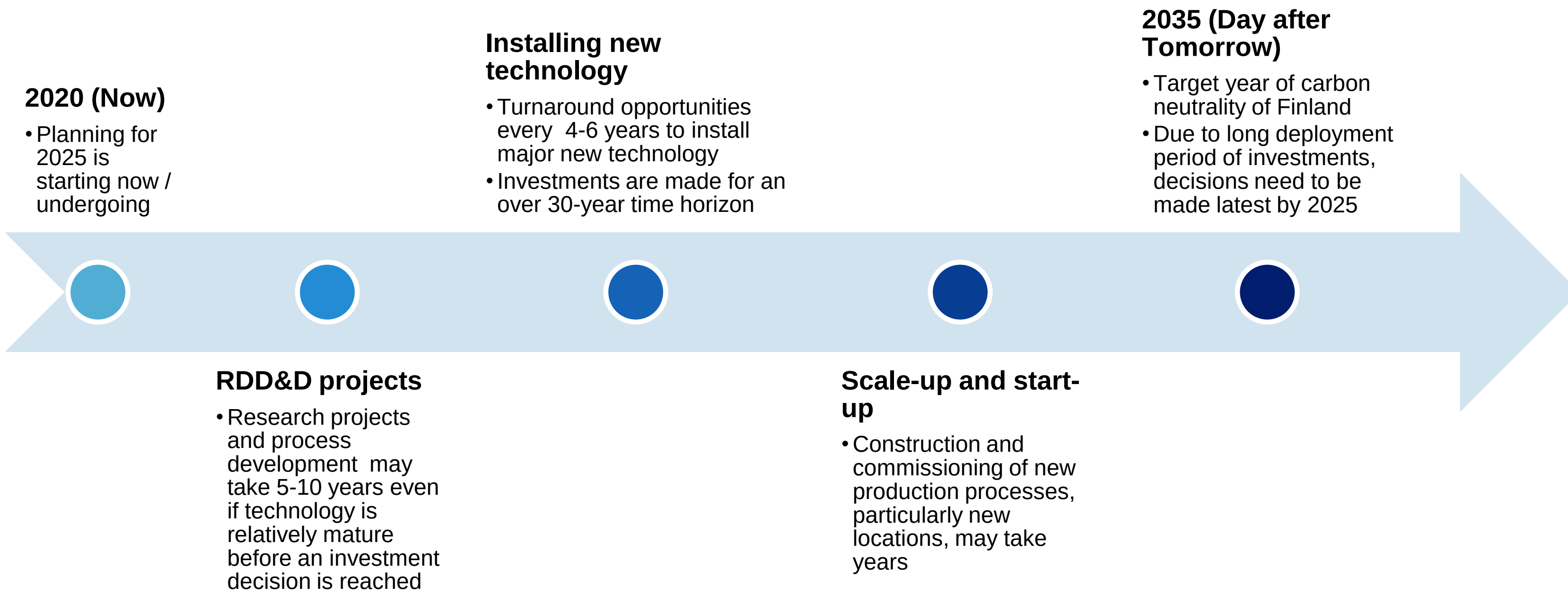
Large modifications to existing facilities are not possible without shutting down the plant. These turnarounds (maintenance breaks) occur typically every 4-6 years in a chemical plant. RDD&D projects may require 5-10 years of development before an investment decision is performed. From the investment decision, it may take another 5-10 years before the investment is fully operational. These characteristics emphasize the need for a stable, long-term operating environment and policies.

WHAT CHARACTERISES RDD&D IN CHEMICAL INDUSTRY?

It takes years to deploy new technology

Barriers of successful scale-up

- Long investment cycles, rare opportunities to change the underlying process.
- Perception of risks associated with RDD&D projects.
- Cyclical nature of business.
- Technical lock-in in current processes as a consequence of incremental investments/improvements throughout the years.
- Lack of customer-driven demand for low-carbon products.
- Overcoming the *Valley of Death,* few opportunities to scale up; the most radical innovations become stuck in pilot phase.



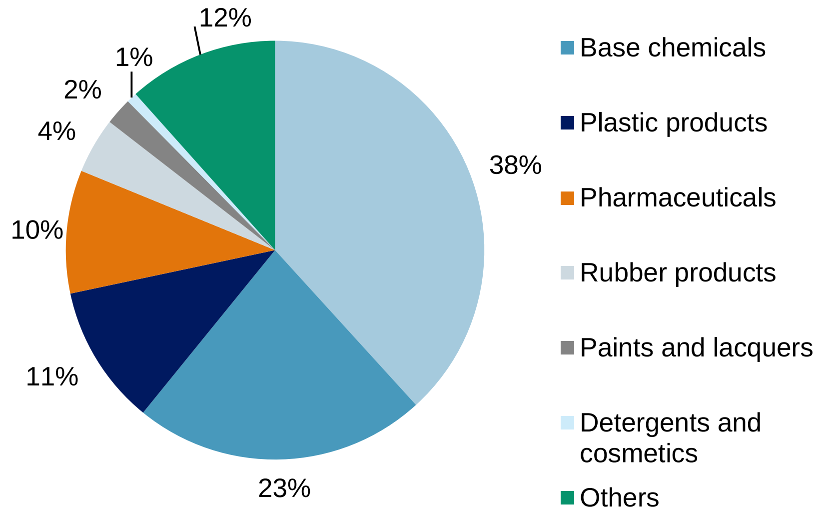
THE STARTING POINT IS FINNISH CHEMICAL INDUSTRY TODAY

An industry with strengths both in larger and smaller segments

Description

- The Finnish chemical industry is a rich combination of approximately 400 companies, employing directly over 34,000 people. The total turnover of the industry is 24 BEUR, and the industry accounts for almost a fifth of the total added value of Finnish industry sectors.
- In terms of production volume, the industry is characterized by oil refining and petrochemicals, base chemicals and minerals. Largest chemical industrial clusters are located in Porvoo, Kokkola, Harjavalta, Oulu and Turku.
- Local production has a reasonably high level of specialization in terms of processes and products and the industry is heavily integrated.
- Trade-wise, Finland is a “virtual island” and the industry is affected by high logistics costs and reliance on sea freight.
- Chemical industry also plays a key role in terms of security of supply, food and materials in Finland – notable in crisis times.

Main products by revenue (2018)

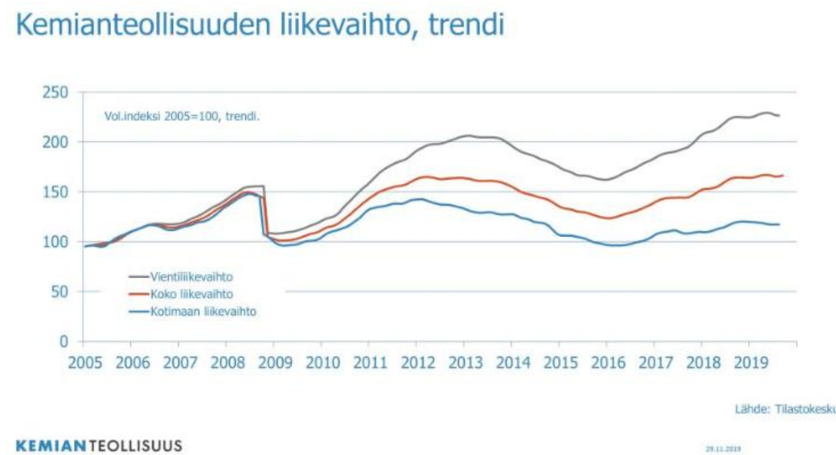


Source: Kemianteollisuus ry

THE STARTING POINT FOR EMISSION REDUCTION WAS A LONG TIME AGO

A durable trend of decreasing GHG emissions

- Total GHG emissions of the Finnish chemical industry have a decreasing trend, from nearly 8 $MtCO_2e$ (2008) down to 5.7 $MtCO_2e$ (2018).
  - The industry has succeeded in decreasing its specific emissions (tCO_2e / kg of product) by almost a third.
- Responsible Care program is the guiding principle of continuous improvement for the companies.
- The revenue of the industry is still closely linked to the oil price.



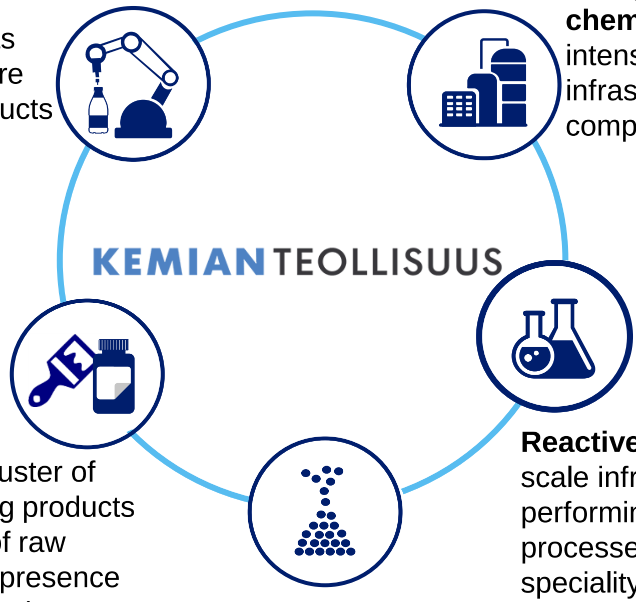
TO MANAGE THE COMPLEX WHOLE, A CLASSIFICATION OF COMPANIES OF CHEMICAL INDUSTRY IN FINLAND WAS MADE

Instead of 400 companies, 5 clusters of companies

- The chemical industry in Finland is a heterogeneous combination of companies which are often highly vertically integrated or may operate in completely different value chains.
- Many solutions, such as low-carbon fuels, are common to the whole sector, while some are very process-specific.
- Confidentiality of individual companies requires an anonymization of data. A division into five clusters was made to account for the heterogeneity while maintaining a holistic view.
- This classification is inherently flawed to a certain degree, as even a singly company may have operations that could be placed in several clusters. However, this classification makes the results more specific and yet easier to generalize.

Converters: Cluster of plants that manufacture consumer products

Energy-intensive chemical industry: Capital intensive large scale infrastructures performing complex processes



Reactive chemistry: Middle scale infrastructure performing complex processes, products including speciality chemicals and advanced materials

Formulating: Cluster of plants formulating products by mixing a set of raw materials (in the presence of a reaction or not)

Inorganic chemistry: Cluster of plants specialised in inorganic chemical products

WHAT IS THE ESSENCE OF THE CLUSTERS?

Compressing the diversity into a few key essentials

Energy-intensive chemical industry

- Large chemical facilities comprise the backbone of the chemical industry. Typical energy intensive unit processes include distillation, reforming, polymerisation. Products include transport fuels, petrochemicals, plastics, water treatment chemicals.
- Companies include Neste, Kemira, Borealis, etc.

Inorganic chemistry

- Inorganic chemistry is integrated to the metals and minerals sector. Energy intensive processes include crushing, grinding and electrolysis. Products include fertilizers, minerals, metals and salts and can be used in e.g. battery chemicals, pulp and paper industry, paints, construction industry and agriculture.
- Companies include Yara, Elementis, Freeport Cobalt, etc.

Reactive chemistry

- Middle scale infrastructure performing complex processes. Typical products include enzymes, dispersion polymers, resins, biochemicals, industrial gases to be used in various industries.
- Companies include Cabb, Linde Gas, Roal, etc.

Formulating

- Processes are primarily different types of mixing. Typical products include paints and coatings, pharmaceuticals, detergents, adhesives also in the customer product segment.
- Companies include Orion, Tikkurila, Kiilto, etc.

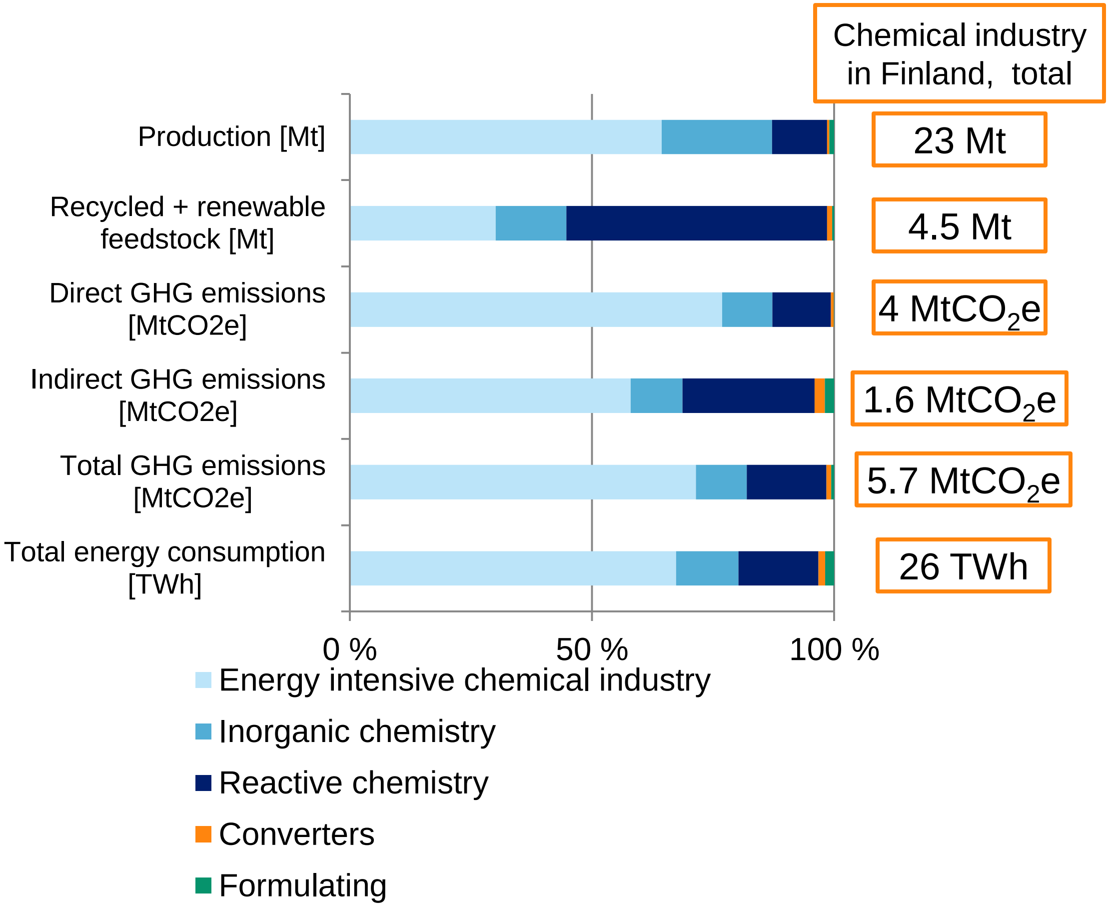
Converters

- Processes include molding and compounding. Typical products include plastic and rubber products.
- Companies include Exel Composites, Nokian Renkaat, ViskoTeepak, etc.

THE PROFILES OF THE CLUSTERS SHOW VARIETY

Here, key variables from input to production and emissions as differentiators

- The energy-intensive chemical industry cluster is the largest subsector of the Finnish chemical industry in terms of production volume, energy use and GHG emissions.
- Overall, total GHG emissions of the subsectors correlate with their total energy consumption.
- The share of total renewable or recycled feedstock (4.5 Mt total) currently covers 17% of the total raw material demand. The reactive chemistry subsector accounts for more than half of the Finnish chemical industry total recycled or renewable feedstock.



Direct GHG emissions include process originated and own energy production originated greenhouse gas (CO2, CH4, N2O, HFC) emissions as CO_2 equivalents. Indirect GHG emissions include greenhouse gas emissions of purchased energy. Sums may differ because of rounding of numbers. Geographical coverage of the analysis is limited to the production assets located in Finland. Source: Kemianteollisuus ry

ON THE LOOKOUT FOR THE FUTURE: COMING CHANGES IN THE GLOBAL MARKET ENVIRONMENT

A brewing larger disruption, growing through many means

Market changes in the past 10 years

- Protectionism and “trade wars” are a backlash against globalization (on global scale), which may be intensified by the pandemic. All this has introduced (unnecessary) uncertainty and made international cooperation harder possibly also in the field of climate politics.
- The shale boom, particularly in the US, has disrupted geopolitics and the global oil market, a key source of feedstock for chemical industry.
- Chinese industrial overcapacity in the chemical sector has tightened the margins.
- Market cycles have become shorter and price dynamics have changed during the last decade – “the cycles are broken”.
- Global chemical industry has undergone major restructuring and consolidation after the financial crisis. Financial engineering and divestment of non-core businesses have been used to increase profitability.
- The lowest interest rates on record have quickly become the new norm globally, creating a novel operating environment for capital-intensive business.

Selected drivers of change for next 10 years

- Climate change: the urge to act on the global scale has become apparent across the globe.
  - Regulation, such as EU ETS and EU Commission’s Green Deal
  - Certain companies have openly stepped up their ambition
  - Driven primarily by factors other than regulation, investors and sources of finance are becoming increasingly aware of
    1) Upside potential of business that is climate-consistent (virtually limitless demand for products)
    2) Downside potential of business that is based on fossils (a limited demand, future regulatory risks)
- Technology and energy sector
  - Low-carbon energy, particularly wind and solar energy, have become cost-competitive significantly faster than many expected. A major transition is underway in the European energy market. Cheap, low-carbon electricity enables new production routes to emerge
  - The Finnish energy system is expected to decarbonize rapidly. Electricity is expected to be low-carbon (ca. 10 kgCO_2/MWh) already by 2035*.

*Energiateollisuus ry BAU forecast of the energy sector

PÖYRY

COMPONENTS OF FUTURE CHANGE IN DIFFERENT CLUSTERS

The primary energy source is a common factor for the transition for all, and sector specifics are most visible in solutions relating to circular economy and feedstock

Energy-intensive chemical industry

- Feedstock, process and product-slate changes, including capital-intensive asset modification and circular / bio-origin feedstock.

Inorganic chemistry

- Feedstock solutions are mostly based on largely improved recycling, requiring new technology development and deployment.

Reactive chemistry

- Feedstock and product-slate changes. Regulatory drivers will impact specific monomers and raw materials due to health and environmental purposes.

Formulating

- It will be hard to switch the hundreds of different specialty chemicals, which may be obtained from non-fossil sources in the future.

Converters

- Growing share of recycled and bio-based materials as raw material.

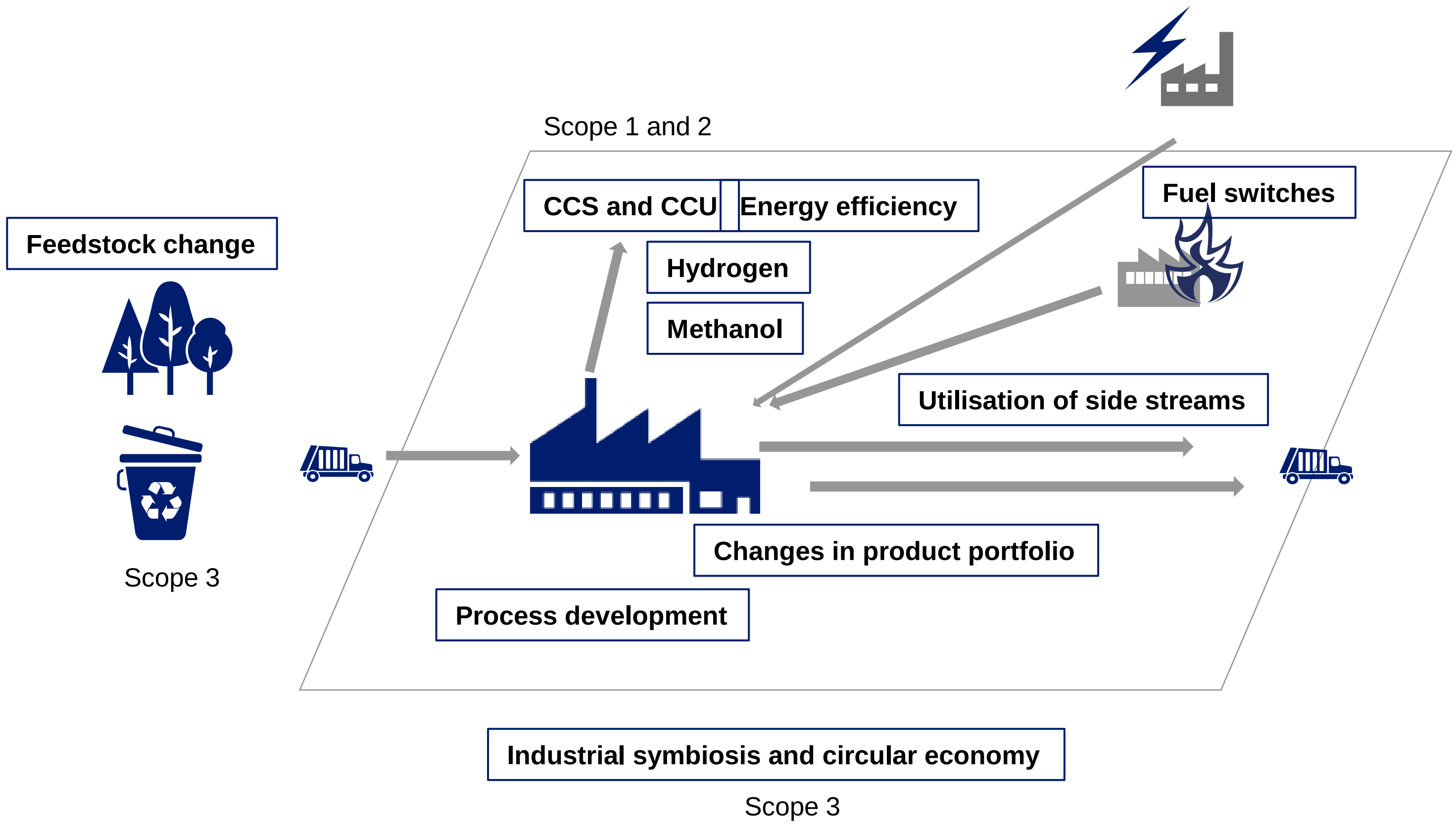
The most significant attribute for all groups

- Change the source of primary energy to low-carbon energy technologies (i.e. energy harvesting and nuclear energy).

APPROACH

VISUALISING THE FOCUS OF THE STUDY IS FAIRLY SIMPLE

Two sets of analysis: a scopes-1-and-2-scenario analysis, and a scope 3 analysis – as in the mentioned ”two disruptions”



ROAD MAP PUZZLE OF PIECING TOGETHER A LOGICAL WHOLE

Behind the big picture, there are many factors and sector-specific impacts

Technical means to reduce direct GHG emissions

- Product portfolio changes
- Improved technological solutions and process development
- Raw materials (renewable, recycling and CO_2 recovery)
- Energy sources
- Energy efficiency and waste heat recovery
- Recycling and side streams
- Circular economy and industrial symbiosis
- Hydrogen
- Methanol
- CCS and CCU
- Digitalization: process optimisation, inventory management, etc.

Grouping of players in the Finnish chemical industry

- Rough division into groups that may be considered to be subject to the same technical means with similar requirements

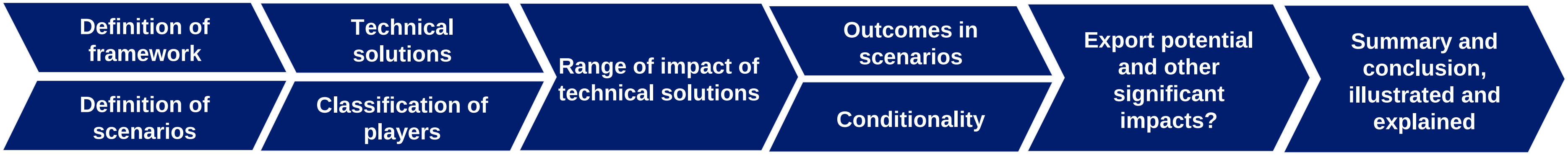
Spectrum of impacts of technical means

- An assessment of the impact of the applicable technical means by industry / operator category
  - Range for the reduction potential of carbon dioxide
  - The time span
  - Costs
  - Conditionality: e.g. required technological development and policy decisions

THE APPROACH OVERALL WAS BOTH TOP-DOWN AND BOTTOM-UP

Emphasis was laid on making both meet in the middle…

- *Which framework, assumptions and scoping define the work?*
- *What are technical means available between now and 2045/2050?*
- *Which policy measures will be applied?*
- *What level of GHG emissions reductions will be reached in different scenarios for two disruptions (scopes 1 and 2, scope 3)*



- *Which scenarios best correspond to the alternative futures?*
- *What is the meaningful way to classify and characterize the different plants?*
- *What is a realistic range for the costs and impacts of different solutions?*
- *Under what conditions would the scenarios be enabled?*

What impacts are there besides the GHG emissions reductions?

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POINTS TO REMEMBER: TECHNOLOGY

Out of the ocean of facts, remember this

- **TECHNOLOGY MENUS EASE THE TASK:** first a longlist, then a shortlist sorted under relevant technology type headings. Ideally, “pick from the menu”.

- **COST OF THE ITEMS ON THE MENU:** the technology items on the menu may be available now – or after a long time-to-market waiting period. The costs and impacts in emission reduction vary. Linked to export potential, some technologies may be both keys to domestic emission reduction and export winners.

- **NO SIMPLE “BEST” OR “ONLY” SOLUTION:** the “short” menu is long, the technologies have complex profiles and impacts – there is no “best technology” or “single solution”.

TECHNOLOGICAL MEANS

TECHNOLOGY IS A CENTRAL ELEMENT

It is both about reducing emission with technology – and exporting technology and products made with superior technology

Technology is, obviously, central in reducing emissions from processes, capturing carbon and adapting to new types of renewable and recycled feedstock.

Technology is also at the core of research, development, deployment and demonstration (RDD&D) and export potential: both technologies themselves and products produced with the technologies.

A TECHNOLOGY MENU DIVIDES THE DERIVED TECHNOLOGY SHORTLIST INTO DIFFERNT AREAS AND STAGES

For the shortlist worked out, the main types of means, and a sub-menu for each – classified by time-to-market (colour)

Power-to-chemicals

- Power-to-hydrogen
- Power-to-methane
- Power-to-methanol
- Power-to-ammonia

Energy efficiency

- Optimization and retrofits
- Advanced heat integration
- Process intensification
- More efficient equipment

Raw material and product portfolio changes

- Biofuels
- Biomethanol production
- Bioethanol production
- Bioethylene production
- Biopropylene production
- BTX production from biomass
- Biomethane production
- New materials

CCU & CCS

- Pre-combustion CO_2 capture
- Post-combustion CO_2 capture
- Oxyfuel combustion
- Direct air capture
- CO_2 to fuels
- CO_2 to chemicals
- CO_2 to mineralisation

Electrification & fuel switch

- Steam production by electric/hybrid boilers
- Steam production by electric furnaces
- Steam recompression
- Coal to natural gas to biogas

Synthetic biology & biochemistry

- Enzymatic process routes
- Genetic engineering
- Utilisation of C1-C4 and sugar platform
- Biomimicry, new materials
- Metabolic engineering and cell factories
- Artificial photosynthesis
- Microbial fuel cells

Circular economy

- Reuse of chemical industry products
- Reuse of materials (mechanical recycling)
- Use of chemical products as secondary raw materials (chemical recycling)
- Use of incineration related CO_2 and energy

Digitalisation

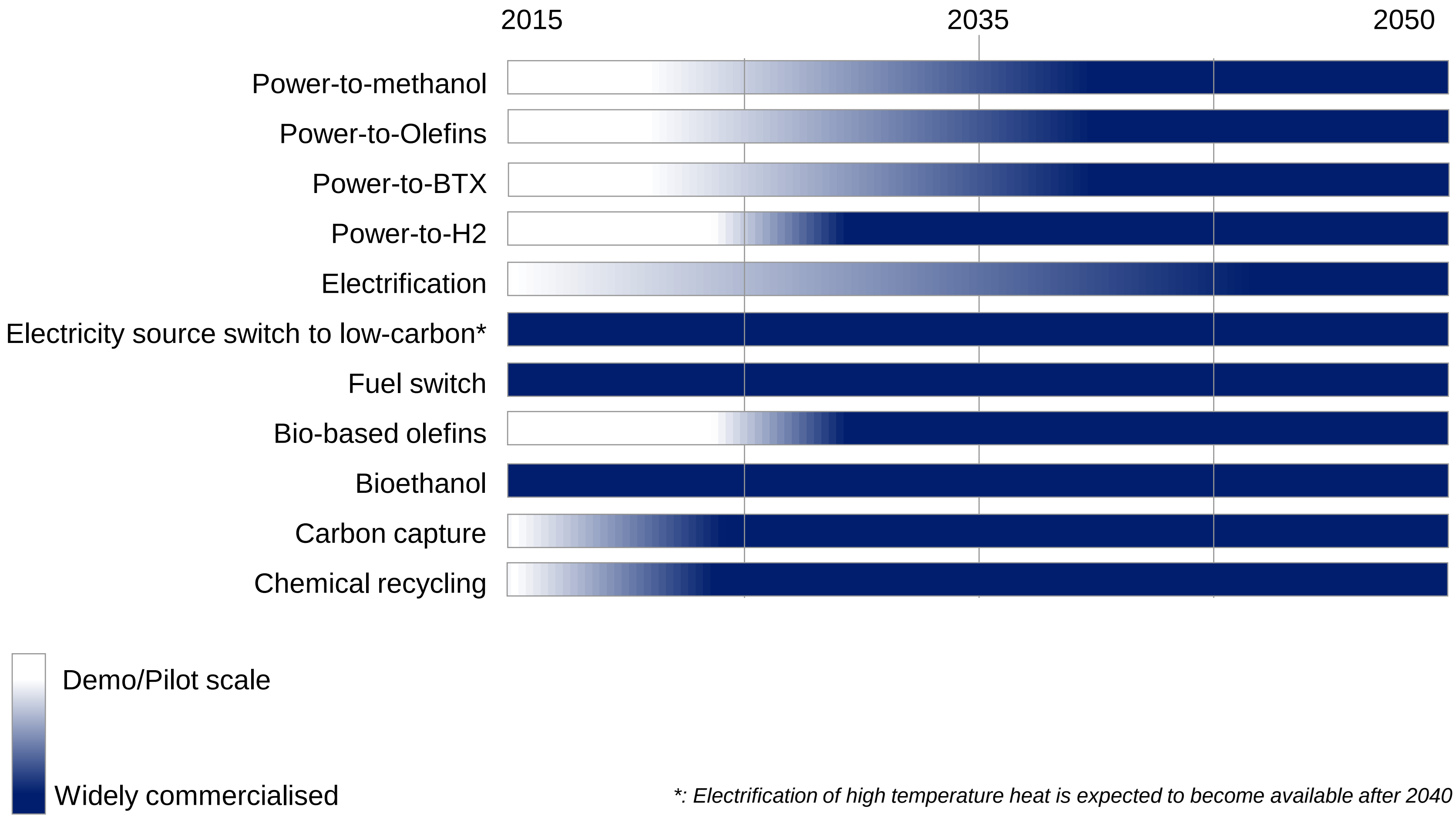
Bubbling under technologies

Process development

- Implemented in industrial scale
- Close to commercialisation
- Breakthrough needed

TECHNOLOGY READINESS OF SELECTED TECHNOLOGIES VARIES

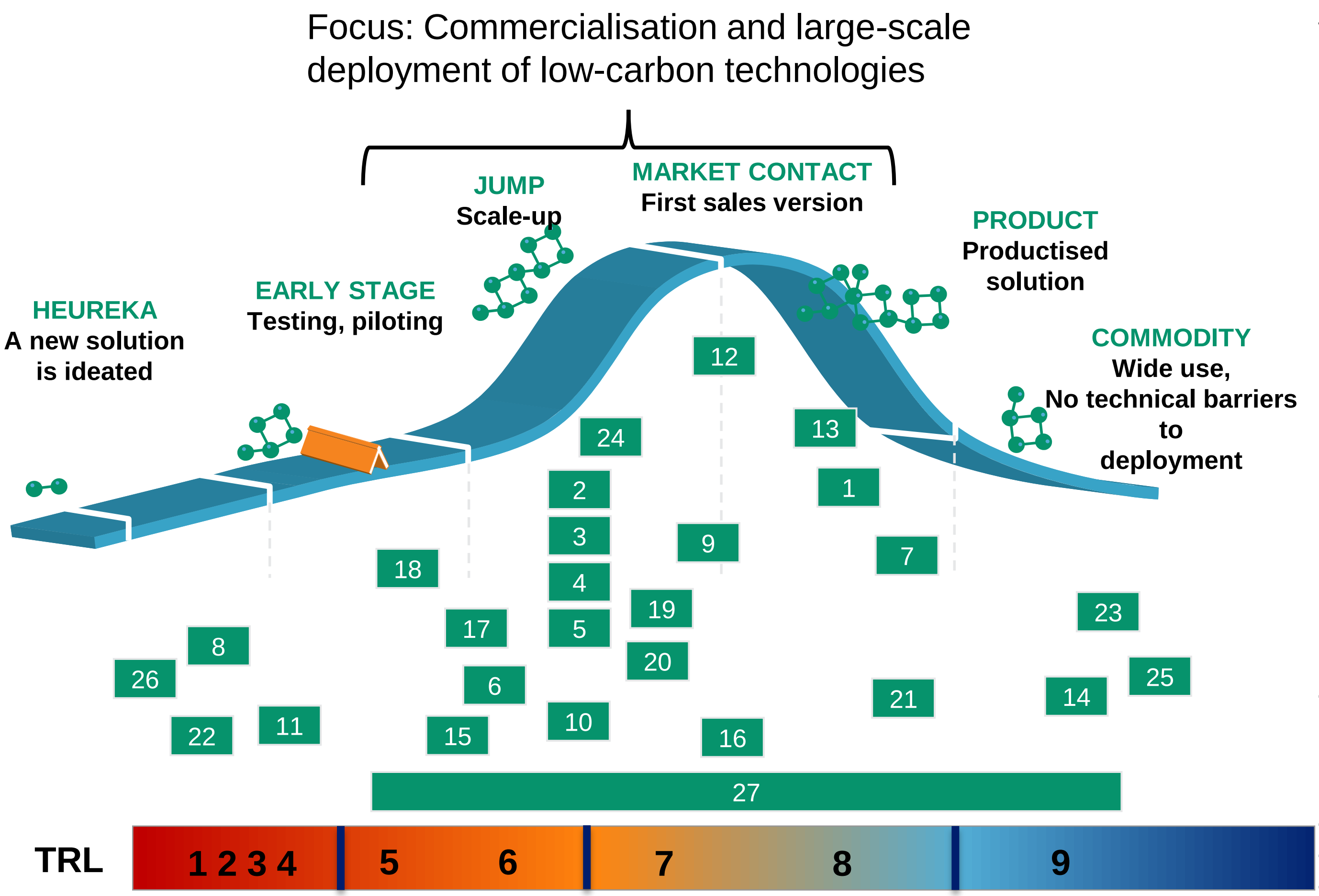
The colour gradient represents the development of commercialisation of key technologies over the years



**: Electrification of high temperature heat is expected to become available after 2040*

THE SPEED AND STATUS OF TECHNOLOGY SOLUTIONS FOLLOWS NORMAL DEVELOPMENT PATTERNS

R&D (Research and development) must be expanded to RDD&D (Research, development, demonstration and deployment) to speed up commercialisation of new technologies



Power-to-chemicals

1. Power-to-H2
2. Power-to-methanol
3. Power-to-olefins
4. Power-to-BTX
5. Power-to-ammonia

Raw material and product portfolio changes

6. Biomass to methanol
7. Biomass to bioethanol
8. Biomass to BTX (lignin-based)
9. Bionaphtha to olefins
10. Biomass to olefins
11. Hydrogen via methane pyrolysis
12. Biohydrogen
13. Biobased diesel (HVO)
14. **Energy efficiency**

CCU/CCS

15. Pre-combustion
16. Post-combustion
17. Oxyfuel combustion
18. CO_2 mineralisation

Electrification & fuel switch

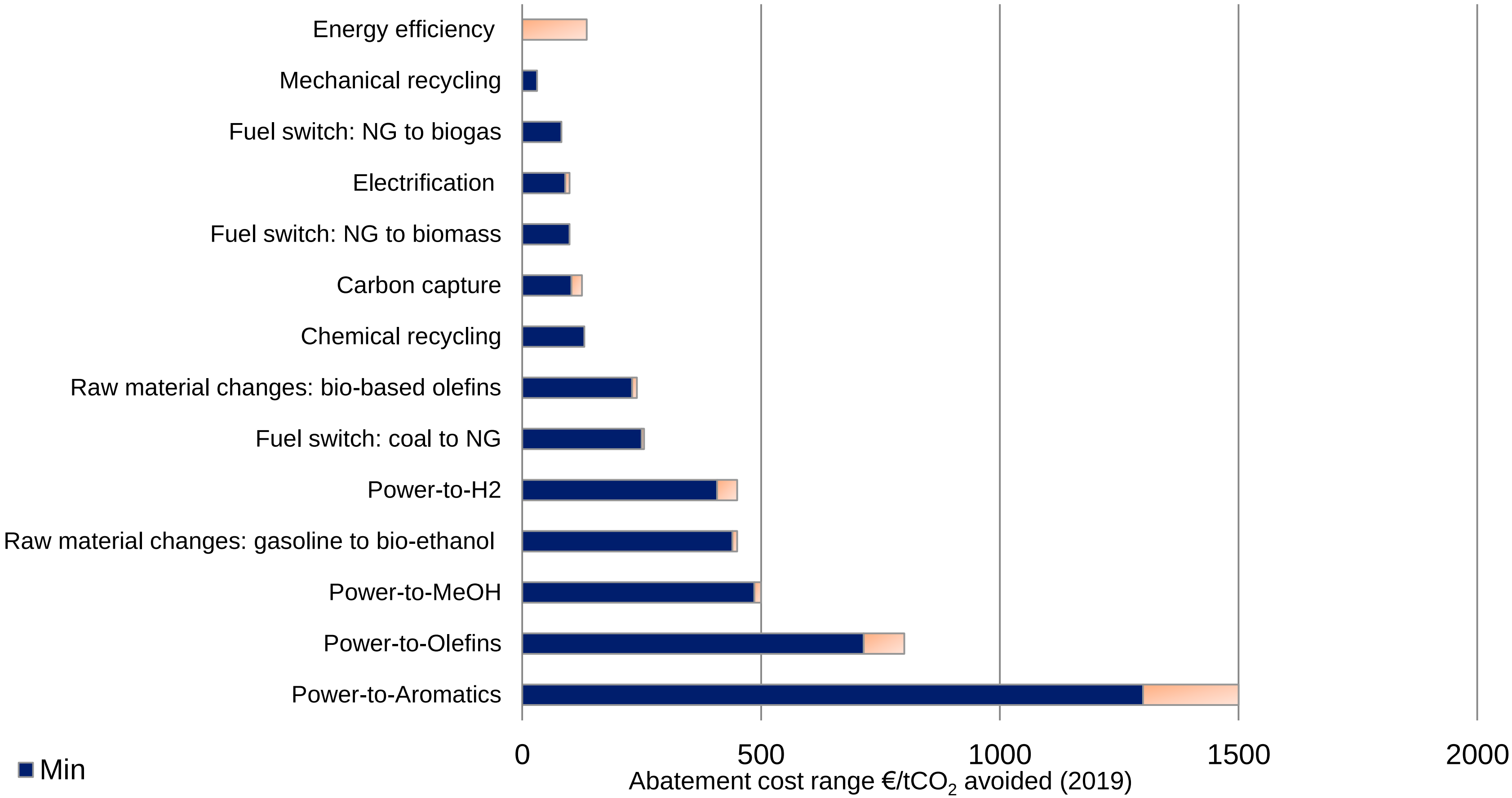
19. Steam production by electric/hybrid boilers
20. Steam production by electric furnaces
21. Coal to natural gas to biogas
22. **Synthetic biology & biochemistry**

Circular economy

23. Mechanical recycling
24. Chemical recycling
25. **Process development**
26. **Bubbling under technologies**
27. **Digitalisation**

THE ABATEMENT COST RANGE IS, LIKEWISE, WIDE

For new technologies such as Power-to-X the abatement costs are the highest. The abatement costs given below represent the current costs and are ranked by minimum.



The abatement costs are indicative and they are case dependent

FROM LONGLIST TO SHORTLIST – AND SELECTED PROFILES

In the following, some profiled technology areas with key aspects

*TRL refers to technology readiness level: lowest levels (1–3) relate to novel concepts and basic research, medium levels (4–6) to development and demonstration, and high levels (7–9) to proven systems and deployment towards commercialisation.

✓ Retrofits
✓ New installations

POWER-TO-CHEMICALS

General description

Power-to-chemicals (P2C) is a large family of technologies utilizing low-carbon electricity to produce raw materials for the chemical industry. Typical example includes production of hydrogen through electrolysis of water (ca. 50 MWh/t of H_2) which is the most electricity-intensive step in P2C production chains. Hydrogen can be used as a fuel or made into chemicals, e.g. hydrocarbons when combined with a source or carbon (e.g. CO_2): methanol is a promising platform chemical to produce olefins, BTXs and synthetic fuels. Currently, the yields to high value chemicals remain relatively low . Availability of low-carbon electricity and decreases in the capital costs of electrolysers are prerequisites for these technologies. Hybrid solutions with electrolysis and fuel cell can bring sources of flexibility to the power system.

Applicability to the chemical industry

Alkaline electrolysis and polymer electrolyte membrane (PEM) electrolysis are the most mature low-carbon H_2 production routes. Applicability of Power-to-Chemicals depends on the competitiveness of the technology, availability and price of low-carbon electricity. Competing solutions to make low-carbon hydrogen include use of biogas, steam methane reforming+ CCS, methane pyrolysis and biohydrogen routes.

Range of impact (GHG reduction)

Potential for significant reductions in GHG emissions or even negative emissions and closing of carbon loop by utilizing CO_2 emission streams. Impact is highly dependent on electricity source.

Power-to-X affects process emissions (currently a large source of process emissions is the steam methane reforming (SMR) of natural gas to produce hydrogen), but it increases electricity consumption (emissions in Scope 2). Power-to-X replaces fossil feedstock and affect emissions in Scope 3.

Impact beyond chemical industry

Enabler of decarbonisation of energy sector: Industry using P2C could provide flexibility to demand in the electricity system, which is required by the growth in intermittent renewables (RE). P2C can create a "price floor" for electricity, but much depends on the production dynamics.
Growth in electricity demand and reduction in fossil demand:
The technology serves to replace fossil feedstock but at the cost of rising power demand.
Use of hydrogen in the other sectors, such as steel production or transport is an opportunity.

Remaining obstacles

Industrial uses for P2C chemicals include material production or fuel

Technology development and scale-up are expected to decrease investment costs (up to tens of % by 2030), improve efficiency (few %), and lengthen the lifetime (up to tens of %) of electrolysers. Using CO_2 will require further innovation, as it is a chemically stable compound. Breakthroughs are needed in the synthesis yields to high-value-chemicals.

Policy could contribute to faster development by funding the RDD&D and industrial scale-up. Precondition of the technology is inexpensive, low-carbon electricity.

TRL* **3-9**

Cost (2015) **400-1500** €/tCO_2eq.

ENERGY EFFICIENCY (EE)

- ✓ Optimisation
- ✓ Retrofits
- ✓ New installations

General description

Energy efficiency (EE) has been a leading principle in the industry already for a long time. EE can come through incremental improvement (optimisation of performance and retrofit investments) or completely new configurations of heat economy. Feasibility of energy efficiency improvements is very case-specific.

Alternatives

- Optimization and retrofits : catalysts, steam systems, furnaces, boilers, electric motors, lighting, leak prevention, variable speed control systems.
- Advanced heat integration and energy cascading (plant and cross-industry).
- Process intensification: intensive mixing, heat-transfer and mass-transfer devices and integrated hybrid equipment such as reactive distillation, heat exchange reactors and membrane reactors
- (Biological process methods are considered separately).

Applicability to the chemical industry

Constant optimisation is already the industry standard, yet potential remains as waste heat: (recent estimate: 4 TWh of excess heat available in the Finnish chemical industry). Digitalisation, artificial intelligence and smart sensors and materials open new frontiers in EE.

Range of impact (GHG reduction)

Globally, EE measures could bring energy intensity down by 25% (implementation of BATs) and further 20% by additional innovation (IPCC, 2014). However, the BATs are increasingly approaching technical limits in the energy-intensive industry. In OECD Europe countries, the average energy intensity could improve by 6-46% compared to BPTs in selected processes (DECHEMA, 2017).

In this work, the BAU scenario includes EE improvement of 0.5% p.a., resulting in 7% reduction by 2030 and 16 % reduction by 2050 (vs. 2015) in energy intensity.

Impact beyond chemical industry

Best Practices are rather low-hanging fruits, if economically viable (local conditions). Technology spillovers to and from other industry sectors and power generation should be promoted.
Sector coupling may lead to higher interdependency between different industry sectors and e.g. district heating.
Energy consumption is reduced if the savings in specific energy consumption are achieved (uncertain) and if saved energy is not allocated elsewhere. Cleaner fuel mix reduces the GHG emissions reduction achievable through EE but does not reduce the cost incentive.

Remaining obstacles

In principle, there is no precondition for EE measures.
Capital costs. Although the average abatement costs are typically low, even negative, for EE measures, the capital investment may be significant. Costs may become "sunk", if the process configuration is envisioned to be changed drastically.
Uncertainties concerning the future price of energy and the savings potential of individual solutions may hinder investment. The quality and location of excess heat may make conventional uses (e.g. district heating infeasible).
Policy: EE contracts and audits , support for investments, role of electricity and energy taxation.

TRL **8-9**

Cost **<0-150** €/tCO_2eq

ELECTRIFICATION AND POWER-TO-HEAT

✓ Retrofits
✓ New installations

General description

Many chemical industry processes require an external heat source and often high temperatures. Most of the Scope 1 and 2 emissions of Finnish chemical industry are related to heat generation through the use of fossil fuels. Replacing fossils with low-carbon electricity enables a direct impact to decrease GHG emissions.

Alternatives

Steam production: Low carbon-electricity can be used for steam generation in electric boilers and/or hybrid boilers to replace e.g. fossil-fired boilers. Hybrid boilers reduce the risks related to high electricity price, but raise capital costs.

Steam recompression: Low and medium temperature (100-400°C) steam needs in a chemical plant can be met by upgrading residual steam through steam recompression, which also serves as a way to store inexpensive electricity as high-pressure steam.

Applicability to the chemical industry

Feasibility of electrification is affected by capital costs, feedstock use and the price of low-carbon electricity. Many process changes (e.g. pre-treatment of biomass, Power-to-Chemicals and biofuel production) may affect the heat requirement in the future.

Range of impact (GHG reduction)

GHG emissions reductions depend on the current fuels used and the source of alternative electricity as a heat source.

Current fuel mix of chemical industry in Finland results in emissions intensity of 250-300 kgCO_2e/MWh of own heat generation. In Finland, the current emissions intensity of district heating in ca. 150 kgCO_2e/MWh (2017) and it is expected to reduce to ca 50 kgCO_2e/MWh (2035, BAU forecast).

The electricity emission intensity is currently 90 kgCO_2e/MWh (2017) and will be reduced to 10 kgCO_2e/MWh (2035, BAU forecast).

Impact outside chemical industry

Excess steam produced by fuel combustion and some petrochemical processes will not be available in electricity-based low-carbon production processes. This may result in additional heat requirement.

Decarbonisation of the power sector plays a crucial role in positive reductions in GHG emissions.

Remaining obstacles

Power: Power-to-heat routes only have a positive impact on CO2 emissions if the electricity is coming from renewable sources. Therefore, generation of sufficient amounts of stable, low-carbon electricity is a significant challenge.

Technology: Currently, electrical heat pumps operate at temperatures below 250 °C. Electric furnaces that reach high temperatures are not expected to be widely in use before 2040s.

Steam recompression technologies for low-to-medium temperatures are investment intensive and overall efficiencies are not at desired levels. Therefore, these technologies have been considered for steam consumption of at least 25 t/h.

TRL **6-9**

Cost **50-150** €/tCO_2eq.
(sensitive to electricity price)

RAW MATERIAL CHANGES

To avoid overlapping, power-to-chemicals route is not considered here.

✓ Retrofits
✓ New installations

General description

Raw material changes are the key in the move from linear to circular economy. There are numerous possible streams of materials that could be used and many more possible products that can be made. Examples include biochemicals and biofuels, along with the closing of phosphate cycle. The reliability of available feedstock is a prerequisite for major investments.

Alternatives

Alternative feedstock of the future may include

- biomass (e.g. agri- forestry and biowaste)
- animal fats, vegetable oils (e.g. rapeseed, algae)
- recycled materials (waste materials, plastics, battery chemicals, composites, fibers, minerals extractions, waste mining)
- CO_2 from concentrated point sources or direct air capture, synthetic materials

Applicability to the chemical industry

It is very case-dependent what kinds of raw material changes are feasible . Routes from biomass to fuels are already commercial, but the expected biomass to high-value chemicals (e.g. lignin to aromatics) revolutions is yet to happen.

Range of impact (GHG reduction)

A majority of impact on GHG emissions comes through avoided emissions in feedstock production and end-of-life of materials (Scope 3). Emissions may grow in Scopes 1 and 2 as a result of an increased energy use. It is very important to communicate the system-level benefits to relevant stakeholders and not focus on direct emissions.

The level of emissions reductions depends on the materials used and substituted. Biomass is *currently* viewed as a carbon neutral raw material.*

Impact outside chemical industry

Competing uses for many alternative feedstock include energy use and other industries.

Energy consumption of production processes can change significantly from conventional production. Typically, processing of recycled feedstock may be more energy-intensive. However, this offers a potential opportunity for energy storage in the electricity system. Drying of biomass, carbon capture or gasification could be performed on electricity, when it is inexpensive, e.g. solar energy in the summer.

Remaining obstacles

Problems with *biomass*:

- Food and feed competition
- Costs of production processes, high oxygen content of biomass to make hydrocarbons
- The availability of agricultural and forestry residues

Infrastructure: most large-scale circular economy concepts require recycling and collection infrastructure on a scale which individual companies cannot provide. Public investments are necessary.

TRL **6-9** | Cost **0-300** €/tCO_2eq.

*Detailed study of the emissions reductions of feedstock changes is a focus of another chapter.

CO_2 CAPTURE AND UTILISATION OR STORAGE

✓ **Retrofits**
✓ **New installations**

General description

Carbon capture and storage (CCS) and carbon capture utilisation (CCU) have long been considered as silver bullets for mitigation of climate change. Carbon dioxide can be captured from concentrated point sources in the industry or even directly from air. The higher the CO_2 concentration, the more cost-efficient the capture is. Capture may happen via per-combustion, post-combustion or oxyfuel technologies. CCS projects have been initiated in past years, but they are mostly based on enhanced oil recovery (CO_2 EOR), and the total volumes are small. Storing CO_2 in large volumes in minerals or oceans requires transport infrastructure, revision of international agreements, fast development of storage technology (currently low TRL) and implies large costs.
CCU remains a more promising alternative, as it could close the societal carbon cycle through the production of synthetic hydrocarbons. Together, CCS and CCU are a prerequisite for negative GHG emissions of the future.

Applicability to the chemical industry

Carbon capture is most feasible to implement where large and concentrated CO_2 streams: processes such as cracking, fermentation and combustion. Clustering of sites avoids long-distance transport for CCU.

Range of impact (GHG reduction)

CCS contributes to eliminating GHG emissions, if the CO_2 remains permanently stored and will not escape over time. CCU technologies help to reduce the emissions similarly, and may help to avoid feedstock emissions.

IPCC has particularly emphasised the importance of Bioenergy CCS (BECCS) as a means to reach negative emissions in the latter part of 21st century.

Impact outside chemical industry

CO_2 sources in other sectors (esp. steel industry, energy, paper and pulp industry) provide additional potential for CCU, currently above 20 $MtCO_2e$ in Finland.

Increased electricity use due to carbon capture and compression (ca. 0.35 MWh/tCO_2).

Remaining obstacles

Both CCS and CCU technologies are currently too expensive to be considered attractive. Also the public acceptance of CCS remains a barrier.

The following components would make both CCS/U technologies more economically viable:

- A carbon tax and/or pricing
- Availability of cheap hydrogen and energy
- Cost of energy and fossil fuels
- Regulations around carbon storage infrastructure and transport

Commercialisation would additionally benefit from boosting investments in pilots, demos and scale-up.

TRL **6-9**

Cost **25-120** €/tCO_2eq.

PROCESS DEVELOPMENT

- ✓ **Optimisation**
- ✓ **Retrofits**
- ✓ **New installations**

General description

Process improvement and development takes place continuously in chemical industry. These practices focus on increasing efficiency of the process, reducing costs, waste generation and GHG emissions. Employing process optimisation and best available technologies also leads to overall improved energy efficiency.

Out of these varied process development practices, utilisation of catalysis has a significant role in reducing GHG emissions. Catalysts can be employed to increase conversion and process efficiency in innovative areas such as Power-to-chemicals or to improve existing processes. A good example for existing process improvement is the N_2O abatement technology implemented at a YARA site in Finland where a new pelleted catalyst implemented in all three existing sites resulted in a decrease of emissions by 85%.

Applicability to the chemical industry

Catalytic technologies to improve process efficiency and abate GHGs are employed throughout the industry. New catalysts with higher conversation efficiency are being developed that can convert CO_2 into fuels and chemicals.

Range of impact (GHG reduction)

Catalysts employed in CCU technologies where CO_2 is converted back into valuable chemicals and fuels has the potential to plays an important role in reducing CO_2 emissions.

In terms of, existing process improvements, apart from reducing GHG emissions, utilisation of durable catalyst system can lead to improvement of energy intensity in the range of 0.2% to 1% per year.

Examples of process development measures

- New reactor and process design
- Best practice technologies (BPT), especially in new installations
- Catalysis (e.g. valorisation of biomass, waste CO_2)
- Digitalisation
- Reduced flaring
- Advanced heat integration
- Improved separation and recovery processes

Remaining obstacles

Process development is a continuous process. Below, some of the major obstacles are listed.

- Energy saving potential of existing processes through process intensifying equipment
- Development and deployment of breakthrough technologies
- Advances in biocatalysts (e.g. production of fuels and chemicals under mild conditions)
- Reduction of non-CO_2 GHGs through novel catalysts
- Developing elective, active and/or durable catalyst systems that can provide a significant and durable yield

TRL **6-9**

SYNTHETIC BIOLOGY

General description

Synthetic biology is a multidisciplinary field combining life sciences and engineering. Synthetic biology refers to a set of concepts and tools within biotechnology. These tools are used to create specific microorganisms and cells aimed at producing desired products under certain process conditions. Synthetic biology could offer alternative ways of chemically synthesising variety of chemicals, fuels, pharmaceuticals, food-related products and products for agriculture. These processes are less mature compared to traditional chemical industry processes so more RDD&D is required for these technologies to become commercially viable.

Applicability to the chemical industry

Synthetic biology is already employed in chemical industry (e.g. biogas production from biomass, utilisation of enzymes for plastics recycling, utilisation of CO_2 to produce fuels). However, synthetic biology covers a wide range of potential applications where RDD&D is still needed for economically viable production and scale-up.

Range of impact (GHG reduction)

Biotechnological process can be utilised to capture and convert CO_2 from CO_2-intensive industrial point sources such as refineries, cement production plants, steel-mill off gases to produce chemicals and fuels (e.g. bioethanol)

Example of synthetic biology activities within chemical industry

-Microbial factories that can produce variety of novel and existing chemicals

-Enzymes or bacteria that produce chemicals and fuels from waste and/or biomass

-Gas fermentation of off-gas streams to produce chemical building blocks

- In vivo or in vitro chemical synthesis using catalysis and synthetic biology to produce pharmaceutical products

Remaining obstacles

As synthetic biology technologies are still developing (TRL1-5) there are significant obstacles to be solved. In general these relate to process intensification, engineering suitable microbial hosts and high costs

- Engineering industrial microbial hosts that can tolerate variable conditions and process-specific metabolic engineering
- Intolerance to contamination
- Low product yield and process efficiency
- Development of separation and purification technologies

TRL **1-7**

MESSAGES ON DIGITALISATION FOR FINNISH CHEMICAL INDUSTRY

A sword with two edges as regards energy and GHG emissions

Energy intensity on the rise in ICT also for chemical industry

- As opposed to most other sectors, digital developments are now accompanied by a very significant increase in energy use and also often energy-intensity.
  ➔ to reduce energy use and GHG emissions with digitalization, the chemical industry needs digital solutions. At the same time, these digital solutions are on a steep upwards curve in increasing consumption.

At the core for chemicals is data: gathering (5G, IoT), processing (datacenters, AI) and use (process, RD)

- The opportunities and problems are data-driven: data have to be gathered (5G, Internet of Things), processed (datacenters, AI) and used in process management and RD/innovation.
- ➔ Building a low carbon roadmap for chemicals in digital is equal to a low carbon roadmap around data.

"Circular data economy" for the chemical industry is needed

- A circular data economy built around the digital lifecycle of data is needed. Optimisation occurs around gathering, processing, use, end-of-life and repeating the cycle
  ➔ The potential amount of useful data in the chemical industry is such, that a painstaking "circular data economy" analysis would be very worthwhile.

DIGITALISATION

See Appendix for more information.

General description

Continued digitalisation creates a transformational change across practically all sectors. For the chemical industry, the whole value chain starting from RDD&D to supply chain and logistics to process control and management to product marketing will benefit from digital technologies and business models where data-driven innovation and implementation is the driver. In addition to bringing direct energy and cost savings, digitalisation may enable the use of many completely new technologies.

Four areas crystallise the impact
- data gathering via telecom and IoT (i.e. gathering and transferring data wirelessly)
- data processing (i.e. from AI to data centres)
- data use in process control
- data use in RDD&D and innovation

Applicability to the chemical industry

Digital tech can be expanded through out the chemical industry value chain to reduce CO_2 emissions and improve process development. The major segments that benefit from digitalisation are; RDD&D, maintenance, supply chain & logistics, industrial symbiosis, plant operations, and risk management.

Range of impact (GHG reduction)

Partly we are now dealing with an unfortunate coupling: it takes more energy to reduce energy. Two key elements are
- "The G-IoT cascade": transition from 4G to 5G triples the consumption, and enables technologies such as IoT that further consume energy

-"The AI Cascade": Artificial intelligence can already by used to find ways to reduce emissions and energy, but the energy costs of training AI are skyrocketing.

Examples of digitalisation measures

- **Data gathering**
- 5G transition
- Smart machinery, sensors, Internet of Things
- **Data processing**
- AI
- Edge/fog computing in addition to data centers/cloud
- **Data use process/RDD&D**
- Industrial symbiosis
- Increased process optimisation: IoT and AI
  - Predictive control
  - Predictive maintenance
  - Process analytics
- Enhanced simulation, VR and AR
- Energy system management
- Robot/automated laboratories
- Cybersecurity and data sharing
- Distributed-ledger (blockchain) technologies
- Automated chemicals innovation

Examples of breakthrough technologies

Automated labs
Automated compound and materials discovery (e.g. Chematica, ADA, already in 2010 "Adam").
Fog computing: sharing processing of gathered data between onsite resources and cloud.
Energy/resource-efficient AI algorithm teaching – has to be developed.

Circular data economy: mastering the lifecycle impacts of data.

TRL **2-9**

ICT AND CHEMICALS NUMBERS TO REMEMBER

AI	7:1	After 2012 breakpoint, most demanding AI models have needed 7 times more teaching capacity per task.
AI-2	300 000:1	After 2012 breakpoint, AI teaching has used 300 000 times more capacity.
5G	3.5:1	5G is estimated to use 3.5 times more electricity than 4G.
IoT	(75 bill) 3:1	By 2025, net-linked devices estimated to triple to 75 billion.
Anti-brexit	1.4:1	”Greater Britain” – one of the latest estimates of data centre electricity consumption is about 3 % of the world's power, 1.4 times that of current Great Britain.

ROADMAP TO THE ROADMAP

1 EXECUTIVE SUMMARY

2 INTRODUCTION: Purpose, boundaries, approach

3 TECHNOLOGY: A menu of options to reduce emissions

4 SCENARIOS: Direct emissions, purchased energy and sensitivity to circumstances

5 SCENARIOS EXPANDED:
A feedstock (r)evolution of defossilisation

6 TOOLBOX FOR CHANGE:
Chemical clusters and example action plans

7 HANDPRINT, EXPORT POTENTIAL AND KNOWLEDGE:
The global imprint of the Finnish chemical industry

8 CONCLUSIONS AND CONDITIONS:
The outcome and the preconditions

POINTS TO REMEMBER: SCENARIOS, SCOPES 1 AND 2

Out of the ocean of facts, remember this

REDUCTIONS ARE ACHIEVABLE GIVEN PRECONDITIONS: a viable industry, low-carbon electricity, an RDD&D supported program and export increase would seem to create a winning combination.

COMPETITIVELY PRICED LOW-CARBON ELECTRICITY IS ABSOLUTELY ESSENTIAL: with almost 5 times the current electricity use, all cards fall without available, competitive power also deliverable to the sites.

THE COSTS ARE VERY SIGNIFICANT, AND 2025-2035 IS CRUCIAL AS AN INVESTMENT PERIOD FOR THE WHOLE: be it emission reductions, export, competitiveness and knowledge to survive and prosper, the period 2025-2035 is likely to be decisive for the needed change.

SCENARIO METHODOLOGY

APPROACHING SCENARIOS WITH CLEAR LOGIC

Logic dictates a progress from assumptions and data to conclusions

Assumptions and definitions
- Definition of approach, system boundaries and general assumptions
- Definition of scenarios
- Data

Emissions reduction potential
- Technology identification: *What could be used?*
- Assessment of availability: *When could it be used?*
- GHG emissions reduction potential: *How much could it achieve?*

Cost assessment
- Assessment of abatement cost (€/tCO_2): *What is cost-efficient?*
- Assessment of investment need (€)

Scenario building
- BAU as a reference line, GHG emissions targets for other scenarios defined
- Construction of scenarios deploying different technologies

Results, iteration, conclusion
- Main results: emissions reductions, costs, electricity demand, raw material changes, conditionalities
- Iteration of scenarios
- Conclusions

PÖYRY

GENERAL ASSUMPTIONS

No "obvious" set of starting points: assumptions are a choice done carefully through many discussions

General assumptions

- Reference year: 2015
- Volume growth of production: 0.75%/a
- Consider product portfolio as it is currently
  - Only minor changes in emerging production
  - NB: e.g. possibly substantial needs of H_2 in steel manufacturing are not included

Energy

- Electricity source: grid mix, 7 TWh (2015)
- Heat source: on-site 15 TWh (2015), purchased 5 TWh (2015)
- Heat sources (own fuel mix): 45% NG, 45% HFO, 10% coal
- 35% of heat use is assumed to be low-T (<200 °C)
- Emission intensity of fuels from Statistics Finland (2019), includes only fossil carbon (bioenergy emissions assumed zero in chemical sector).

BAU development

- Gradual decarbonisation of power sector largely already by 2035, electricity from grid gets cleaner
- Coal phased out by 2029
- Energy efficiency: 0.5%/a

Specific emissions*	Electricity ($kgCO_2/MWh$)	District heating ($kgCO_2/MWh$)
2017	90	150
2035	10	50
2050	1	15

GHG emissions

- Emissions calculated for Scope 1 and 2
  - Scope 1: on-site emissions
  - Scope 2: emissions from off-site heat and power generation

*Energiateollisuus ry approved the BAU forecast of the energy sector

SCENARIOS AND COSTS

WHICH SCENARIOS CAPTURE THE FULL PICTURE?

A set of scenarios designed to give the answers needed

- Reference scenario
  1. **Baseline (BAU)** (underlying assumptions for all scenarios)
     - Volume growth +0.75%/a
     - Energy efficiency improvements 0.5%/a
     - Anticipated market and regulation-driven changes in the energy sector
       - Gradual decarbonisation of power sector (electricity generation) by 2035-2045
       - Coal use for energy to stop by 2029 (national legislation), fuel switches to alternative fuels (mostly bioenergy and alternative sources of low-carbon heat) in the medium term
     - No other measures in chemical sector

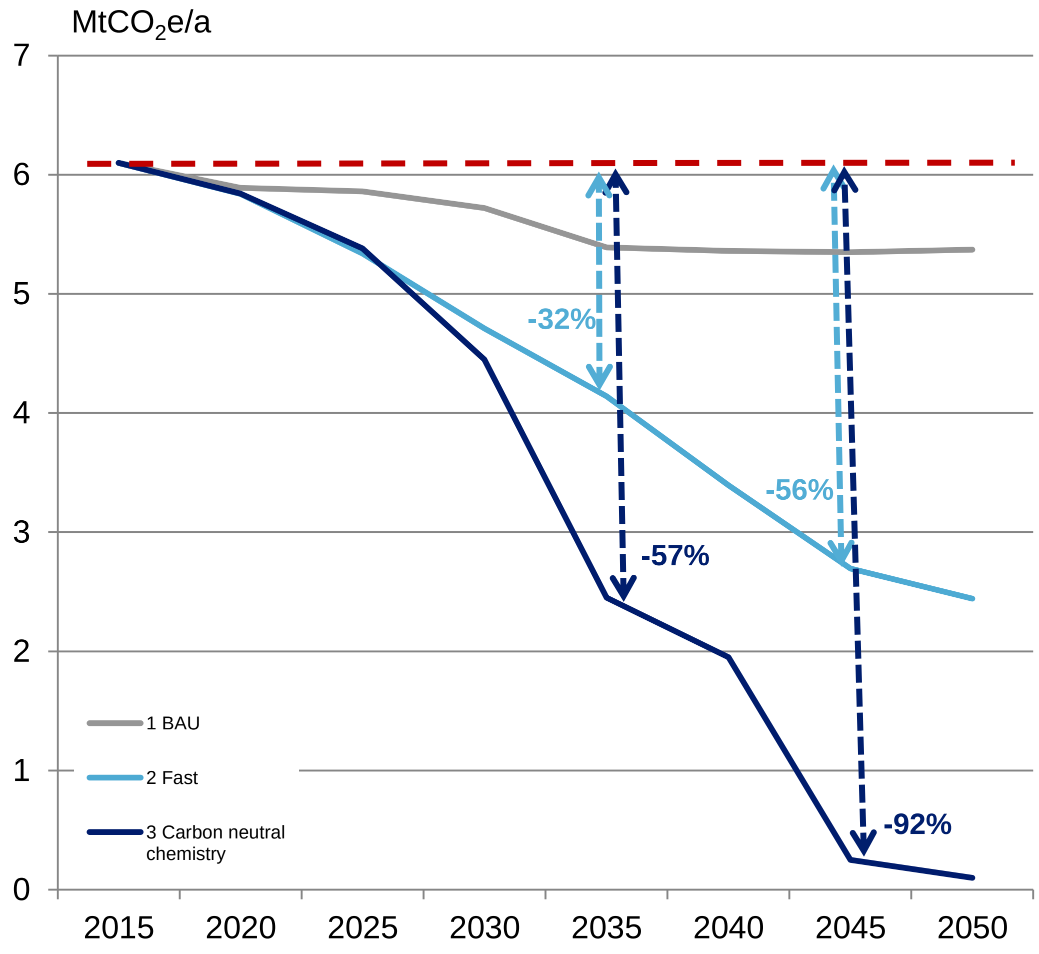
- Climate scenarios:
  2. **Fast development**
     - BAU + additional measures to reduce Scope 1 and 2 GHG emissions under constrained technology development

  3. **Carbon neutral chemistry**
     - Carbon neutral Finland 2035
     - BAU + additional measures to reduce Scope 1 and 2 GHG emissions under very positive technology development and additional resources

EMISSION REDUCTIONS FOR SCOPE 1 AND 2 ARE SIGNIFICANT

These are scenarios, where goals are reached

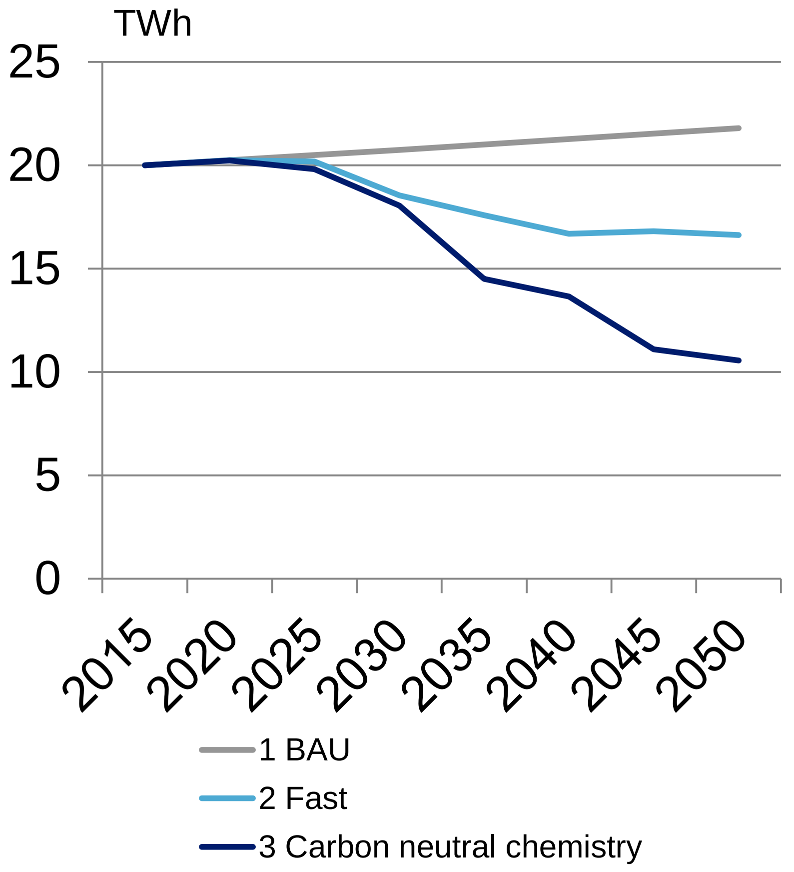
- Indirect GHG emissions reduce significantly in the *BAU scenario* and following scenarios due to development of power sector and energy efficiency measures.
- *Fast development scenario* reaches notable reductions in 2030s and 2040s, reducing the Scope 1 and 2 emissions by 56% by 2045 through new technology and investments. However, fossil energy and process emissions still remain in 2040s.
- *Carbon neutral chemistry scenario* reduces emissions by 92% in 2045, but requires breakthroughs in low-carbon technologies (and scale-up in the production) and wide utilisation of CCS & CCU in addition to a significant degree of electrification and fuel switches.



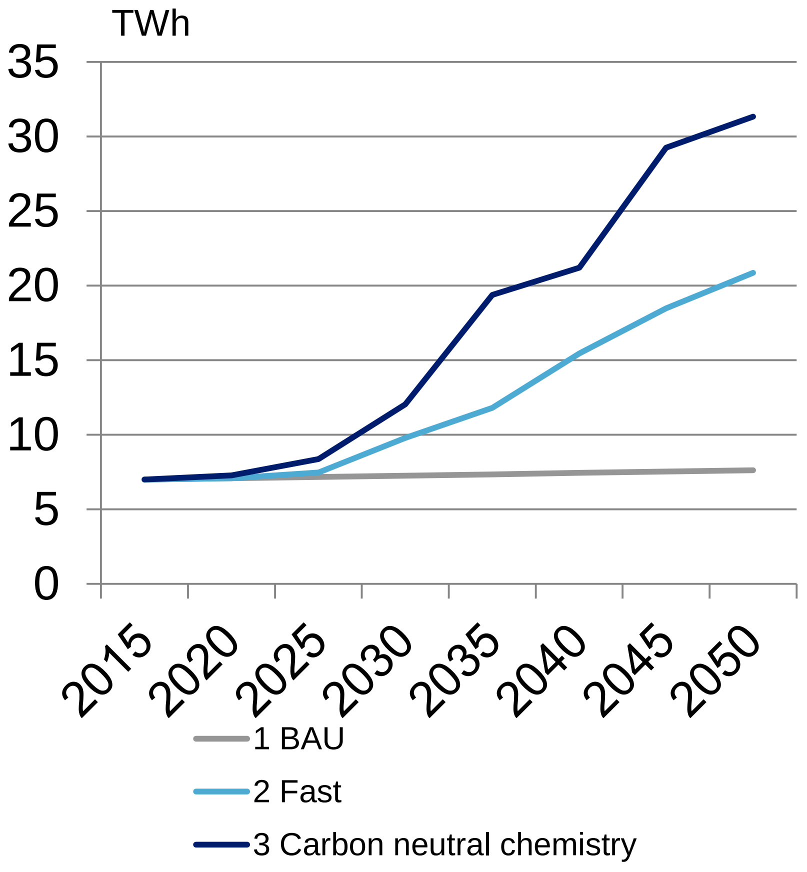
ENERGY CONSUMPTION IN THE SCENARIOS MOVES TO CONSIDERABLE ADDED ELECTRICITY DEMAND

A growing part of heat will be supplied through electrification, and electricity use is further driven by process changes, such as Power-to-X and carbon capture

Heat demand (after electrification)

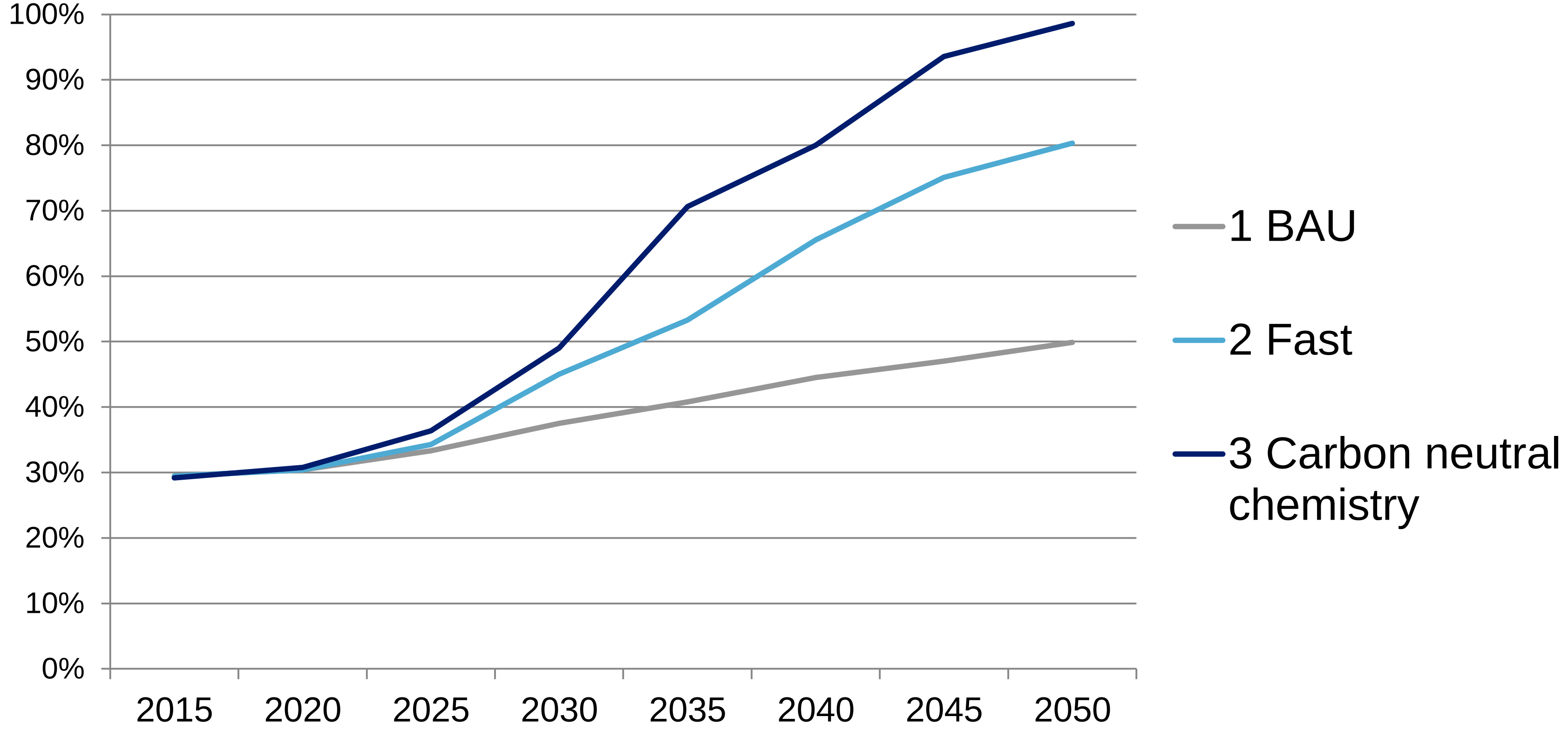


Electricity demand



SHARE OF LOW-CARBON ENERGY IN FINNISH CHEMICAL INDUSTRY INCREASES VERY NOTABLY

As can be expected, low-carbon energy provides major reductions



*Sources of purchased electricity and heat (Scope 2) are taken as averages of the Finnish energy system.
Starting point (2015) electricity is assumed to be 80 % renewable in the national energy mix and the electricity source is expected evolve according to the anticipated BAU development of power sector. Sources of purchased heat are presented according to the development of district heating. Additional energy demand foreseen in the scenarios comes from low-carbon sources.

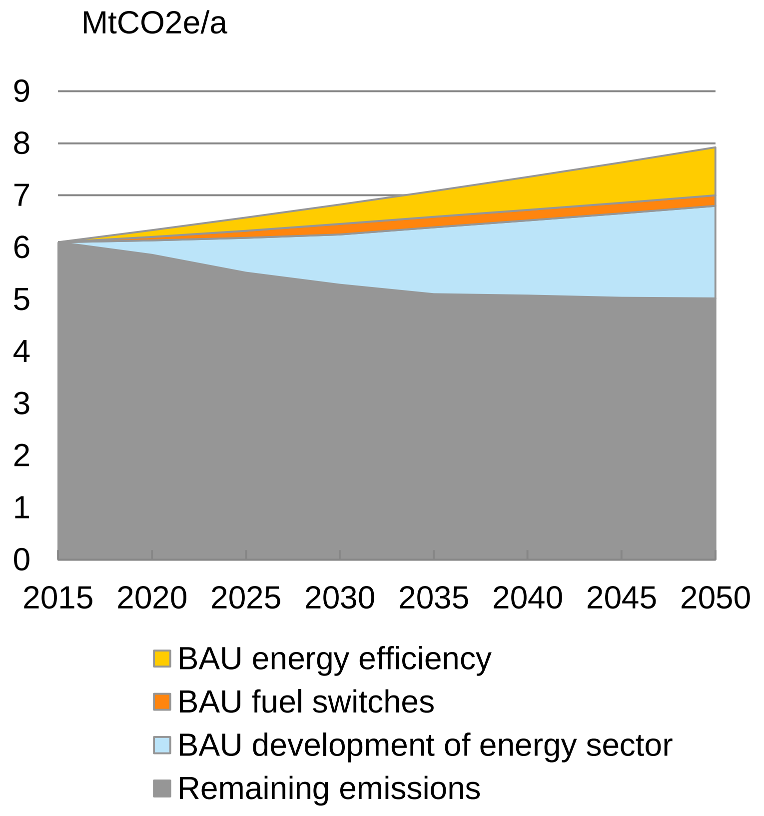
1ST SCENARIO: BASELINE (BAU) IS A REFERENCE LINE

No drastic process changes or significant investments are required. Chemical industry's GHG emissions* in 2050 remain largely unabated.

Description	Outcome

- In the *BAU* scenario, Scope 1 and 2 emissions of chemical industry in Finland decrease mostly through the market-based development of energy sector (Scope 2) already largely by the end of 2030s.
- Energy efficiency improvements (0.5%/a) bring significant emission reductions in direct emissions.
- Most of the investment need of the scenario is in the energy sector.
- Although Finnish chemical industry production grows by 25% by 2045, total emissions decrease 17% compared to 2015. Process-related emissions and emissions from own fuel combustion remain high in the BAU scenario.
- Electricity demand of Finnish chemical industry grows only marginally to less than 8 TWh (2050).

Specific emissions**	Electricity ($kgCO_2/MWh$)	District heating ($kgCO_2/MWh$)
2035	10	50
2050	1	15



*Emissions include Scope 1 and 2.

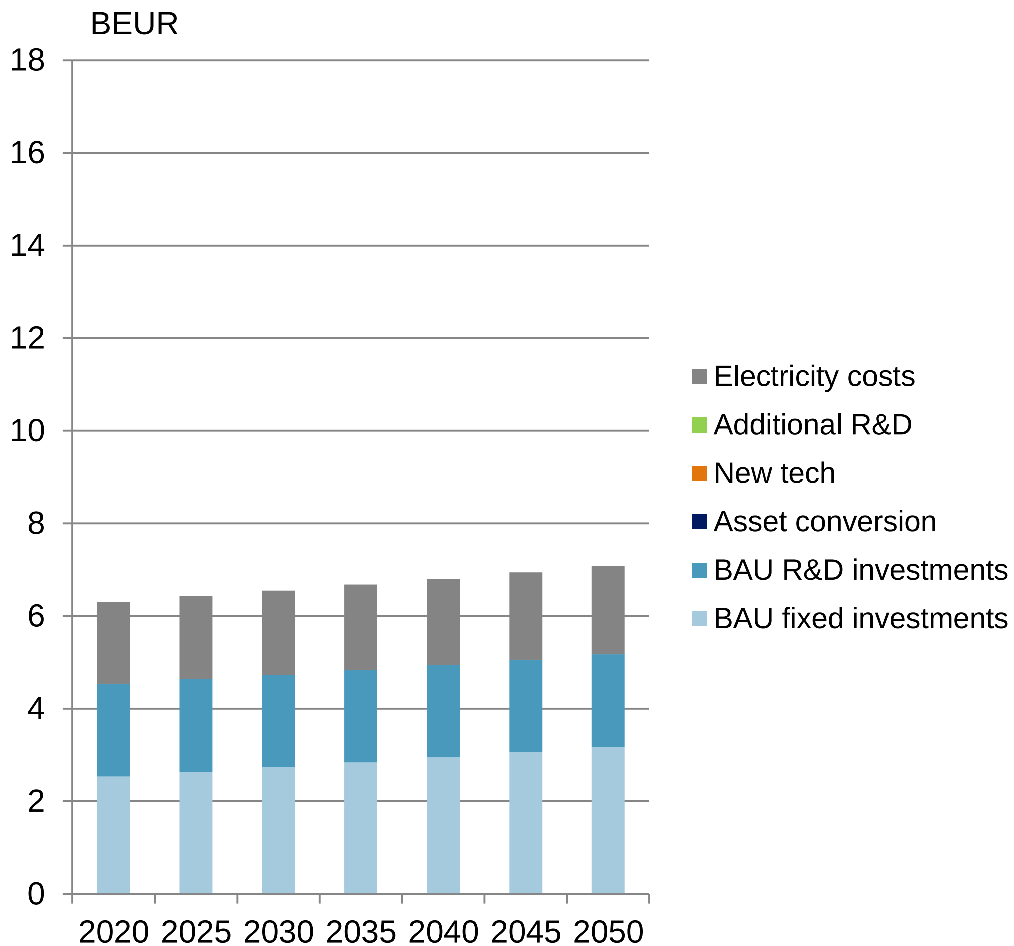
**Energiateollisuus ry approved the BAU forecast of the energy sector.

INVESTMENTS IN SCENARIO 1: BAU GROW MODERATELY

Growth in total production volume dictates growth in investments

- In the BAU scenario, the current level of investments is increased incrementally as the total production volume is expected to grow.
- No investments into new technology, asset conversion or additional R&D beyond the current levels take place in the BAU scenario.
- Electricity costs stay on approximately current levels.

2015-2050:
Total investment costs: **34 BEUR**
Electricity: **13 BEUR**



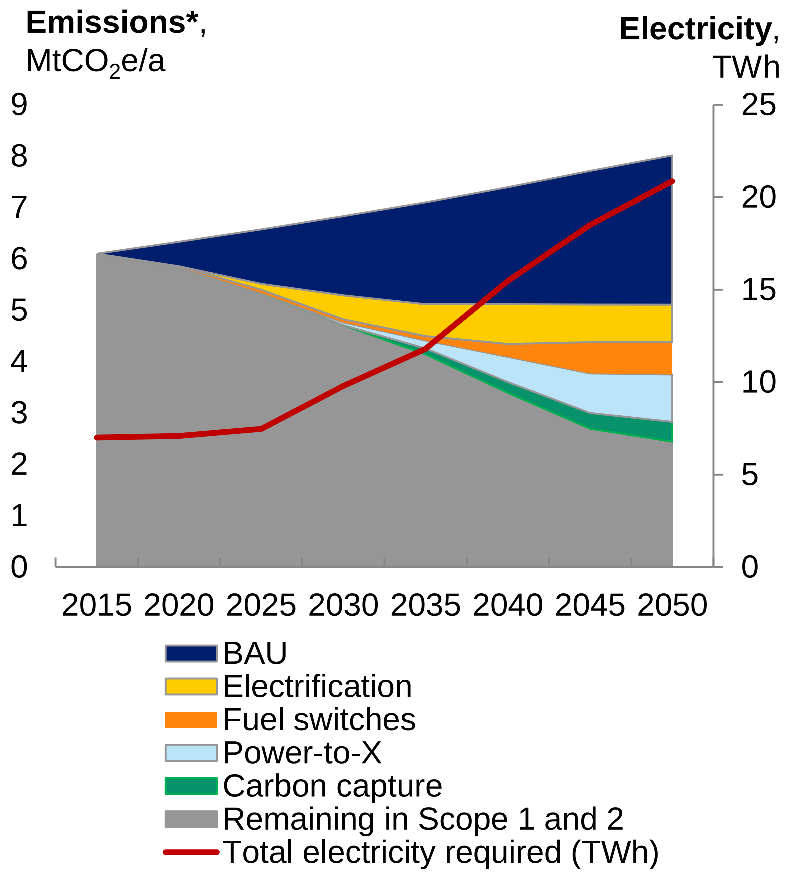
Each bar corresponds to the investments during the preceding 5-year-period.

2ND SCENARIO: FAST DEVELOPMENT, HIGHER AMBITION

An ambitious future for the GHG emissions reductions in the chemical industry in Finland

Description	Outcome

- In the *Fast development* scenario, additional measures are used on top of the anticipated BAU development.
- GHG emissions* are decreased from current 6.1 $MtCO_2e$ (2015) to 4.1 $MtCO_2e$ (2035).
- Electrification of a share low-temperature heat is performed in 2030s. Large-scale deployment of power-to-H_2 technology does not begin until late 2030s. Carbon capture brings minor reductions, mainly in 2040s.
- Natural gas is used as a transition fuel to replace more carbon-intensive fossil fuels. Energy is derived from additional biomass or biogas only in 2040s.
- Total demand of low-carbon electricity grows largely as a function of electrification and Power-to-H_2 almost doubling from current levels to 12 TWh by 2035 and close to 21 TWh by 2050.

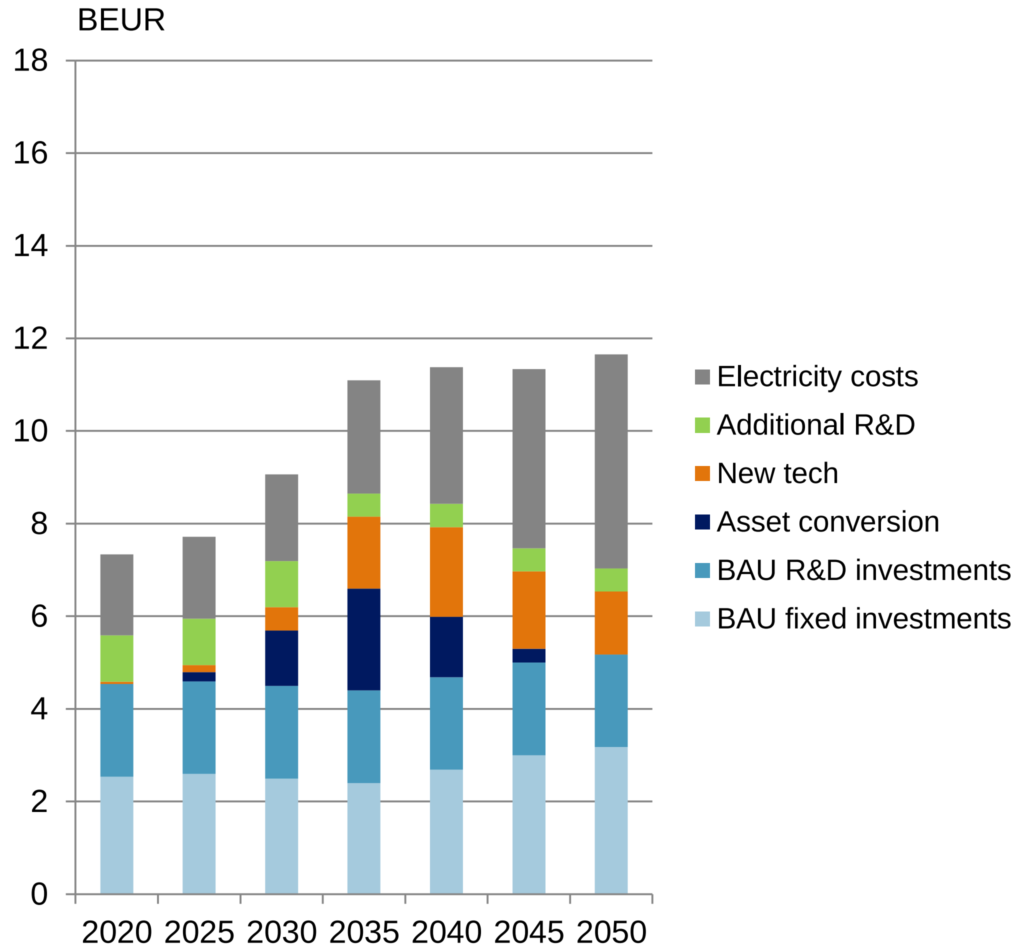


*Emissions including Scope 1 and 2.

INVESTMENTS IN SCENARIO 2: FAST DEVELOPMENT ARE SIGNIFICANTLY INCREASED, ALONG WITH ELECTRICITY COSTS

- Total investment costs are 48 % higher than in BAU, electricity costs are over 50% higher than in BAU.
- Main asset conversions (5.2 BEUR) and investments in new technology (7 BEUR) happen in 2030-2040.
- Additional annual R&D costs of 200 MEUR are allocated until 2030, representing a 50% increase from current levels.
- Main constituents of new technology investments are Power-to-Chemicals, bio-based feedstock production, chemical recycling and electrification of heat.

2015-2050:
Total investment costs: **50 BEUR**
Electricity: **19 BEUR**



Each bar corresponds to the investments during the preceding 5-year-period.

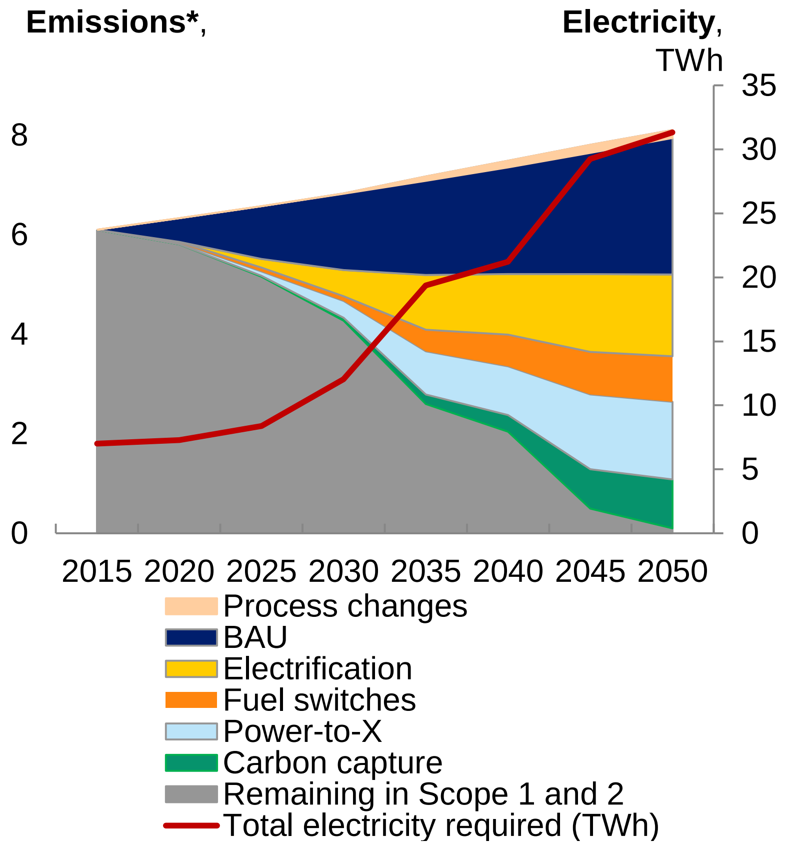
3RD SCENARIO: CARBON NEUTRAL CHEMISTRY 2045 REPRESENTS THE GOAL OF KEMIANTEOLLISUUS RY

A future combining an extremely ambitious target of 2045 with the supportive policies and a fast-tracked technology development

Description

- In the *Carbon neutral chemistry* scenario, GHG emissions* are decreased to 2.6 MtCO_2e (2035) and to 0.5 MtCO_2e (2045).
- Fossil fuels for heat generation play a minor role in 2040s, when electrification of high temperature heat becomes possible through electric furnaces.
- Residual GHG emissions from fossil combustion and processes are largely captured to be utilised as a feedstock of Power-to-Chemicals production.
- Electricity demand grows to 29 TWh by 2045 as a result of electrification (+11 TWh), Power-to-chemicals (+9 TWh), carbon capture technologies and process changes. Process changes to e.g. utilisation of biomass and recycled feedstock increase the energy demand, which is supplied primarily through low-carbon electricity.
- Remaining GHG emissions will include diluted CO_2 streams (e.g. fugitive emissions). If CCU becomes widely available, there could be a possibility of negative emissions through Bioenergy Carbon Capture and Use (BECCU).**
- The hardest-to-abate emissions are estimated to have significant additional costs compared to previous scenarios.

Outcome



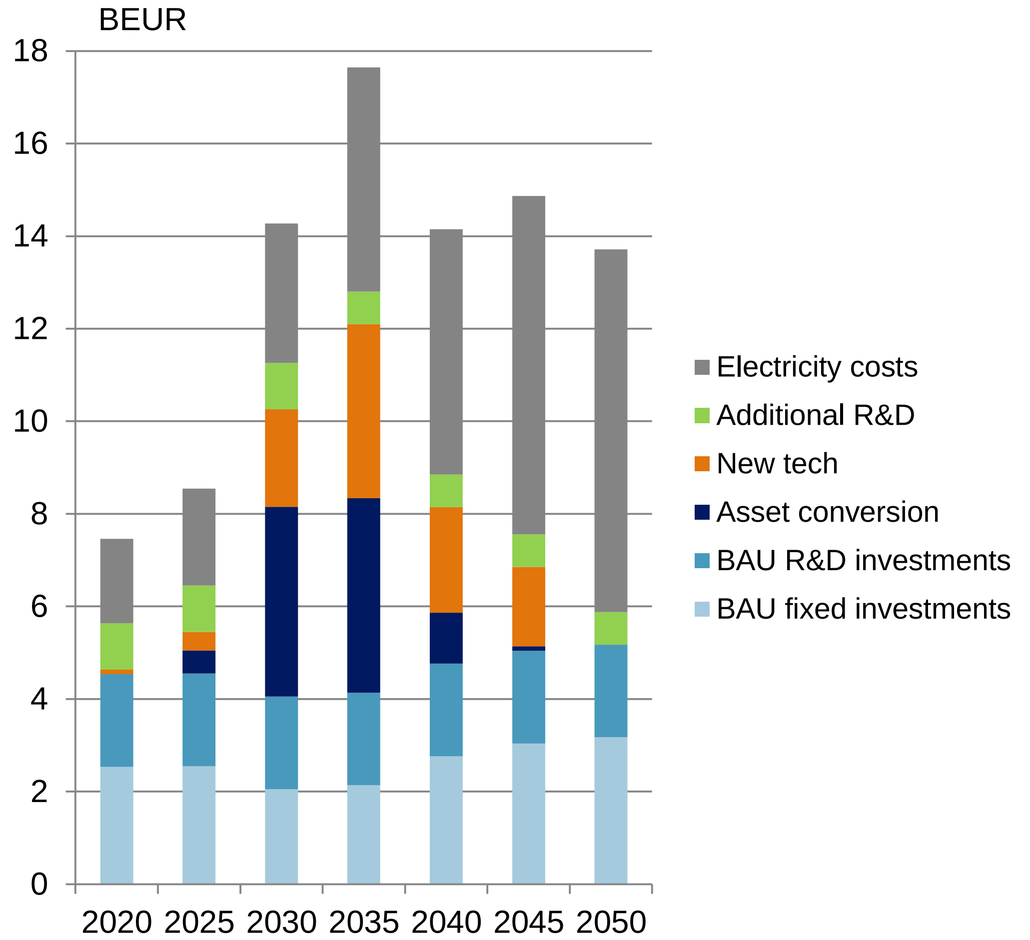
*Emissions including Scope 1 and 2. Reductions in emissions in Scope 3 are presented separately.
**BECCU not included in the scenario.

INVESTMENTS IN SCENARIO 3: CARBON NEUTRAL CHEMISTRY FOLLOW THE GENERAL PATTERN OF EARLIER SCENARIOS

However, instead of just domestic forced reduction, a goal to reach export and global handprint is built-in compensation

- Total investment costs are 72% higher than in BAU, electricity costs are 150% higher than in BAU.
- The total costs (investments and electricity) of the most ambitious scenario peak in 2030-2035 and again in 2040-2045, to account for the climate targets, respectively.
- In the timeframe of 2020-2040, investments into new technology and assets conversions exceed those of *Fast development scenario* by over 104%.
- The costs to mitigate the last remaining Scope 1&2 come with high uncertainty, as not all solutions are commercial yet.

2015-2050:
Total investment costs: **58 BEUR**
Electricity: **32 BEUR**



Each bar corresponds to the investments during the preceding 5-year-period.

INVESTMENT ALLOCATION IN THE TRANSFORMATION OF WHOLE INDUSTRY FITS INTO KEY CATEGORIES (1/2)

The right mix of smart spending for emission reduction and export is needed

Investment categories

- **BAU investments:** Approximate level of BAU investments is based on the data provided publicly by Kemianteollisuus. Annual own investments of Finnish Chemical Industry (fixed and R&D) is around 1 BEUR. Overall BAU investment in the future is scaled up by considering the volume growth in the industry.
  - **BAU fixed investments** (i.e. maintenance, process development)
  - **Maintenance** investments are expected to gradually reduce, as existing assets are being replaced and the overall production facilities become newer via increased new capacity.
  - **BAU R&D investments:** Apart from BAU R&D investments, additional investment into R&D is added to each scenario. The additional investment into R&D is expected to replace a portion of BAU R&D investments, as R&D is partly redirected.
- **Asset modification:** This includes retrofit and replacement investments to existing production that requires be modification (as much as possible) to adapt to new feedstock. These modifications include;
  - Revamping refineries to use plastic hydrocarbon as feedstock
  - Furnace electrification (e.g. coil replacement)
  - Demolishing

INVESTMENT ALLOCATION IN THE TRANSFORMATION OF WHOLE INDUSTRY FITS INTO KEY CATEGORIES (2/2)

The right mix of smart spending for emission reduction and export is needed

Investment categories

- **New technology:** Capital investment cost necessary to implement low-carbon technologies (i.e. Power-to-X, product portfolio changes, CCU and CCS).
- **Electricity costs:** This is calculated as procurement of electricity by considering the electricity demand in each scenario at the electricity price of 50 EUR/MWh. The overall investment costs *per se* are not assigned to a specific industry (i.e. chemical industry or energy sector). This illustration is presented to account for the significant share of costs related to electricity.

Costs related to raw material procurement are in feedstock scenarios.

FACTORS CONTRIBUTING TO ELECTRICITY DEMAND RISE ARE MANY

Many drivers, one impact

- The most significant drivers of electricity demand rise include
  - Electrification of heat: heat pumps, electric boilers, hybrid boilers, coils and electric furnaces; (uncertainty of reduced availability of excess steam with new processes)
    - Ca. 10 TWh/a in 2050 in *Carbon neutral chemistry* scenario
  - Power-to-X, particularly Power-to-Hydrogen
    - Ca. 10 TWh/a in 2050 in *Carbon neutral chemistry* scenario
- Other drivers include
  - Utilisation of biomass (drying and pre-treatment)
    - Ca. 4 TWh/a in *Carbon neutral chemistry* scenario
  - (Uncertainty about the effect of new feedstock on the energy demand)
  - CO_2 capture of process and combustion emissions and compression of CO_2 for storage
    - Less than 0.5 TWh/a in *Carbon neutral chemistry* scenario

- Electricity demand is decreased through
  - Energy efficiency measures (wide range of different technologies and incremental improvements, see *Energy efficiency* technology card)

- *Significant changes to feedstock are not included in the electricity demand of these scenarios.*

COMPARISON: TOTAL INVESTMENTS IN 2015-2050 EXCLUDING ELECTRICITY

Even under business-as-usual (BAU) development, investments needs are high; in carbon neutral scenarios they almost double during the next decades

Current level as the baseline

- As the current level of investments is scaled up with the growth of production volume, the BAU investments (equal ca. 1 BEUR/year), including fixed assets and R&D. BAU development results in investment need of 34 BEUR in 2015–2050.

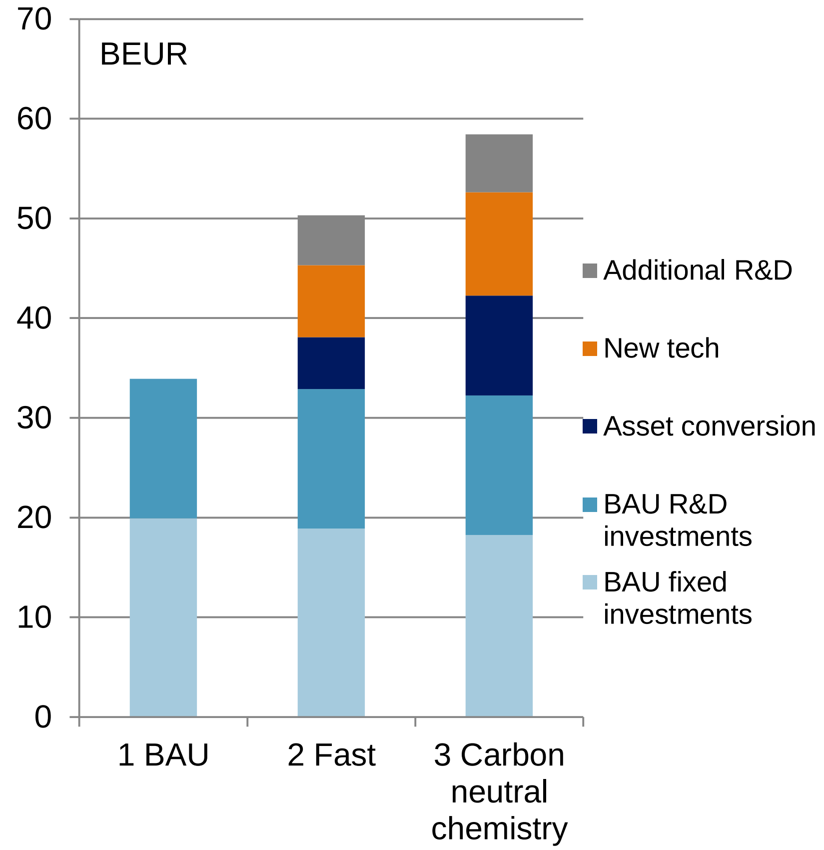
Additional investment need in the scenarios

- Total additional investment requirement (excl. energy) in the climate scenarios is 16-24 BEUR in 2015–2050, equal to 48-72% increase from current levels. Additional investments have to be for increased R&D, asset conversions and new technology.

Interconnections of investments

- Through asset conversion, a part of BAU fixed investments will be avoided, as new assets will lower some of the maintenance costs, for example.

As a comparison:
Total cost of crude oil in 30 years: **195 BEUR**
(60 €/bbl, 15 Mt/a crude oil demand)



COMPARISON: TOTAL INVESTMENTS IN 2015-2050 INCLUDING ELECTRICITY

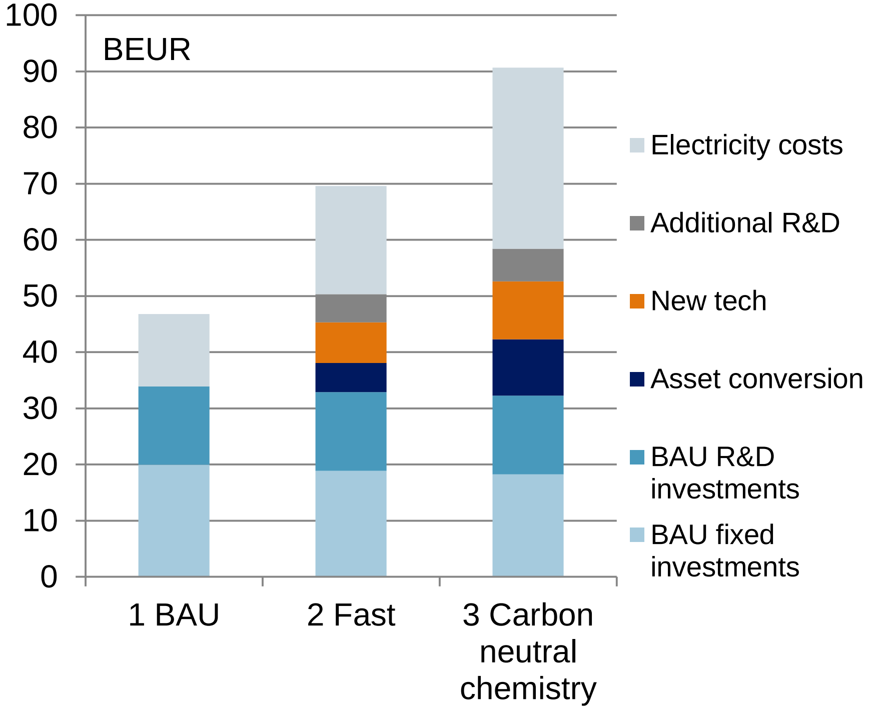
Costs of energy transition will also be borne at least partly by the chemical industry

Electricity costs

- Indication of the significant electricity costs in the scenarios is illustrated in the figure through the estimated cost of electricity procurement. The investments into low-carbon electricity generation (wind, nuclear, etc.) will also be performed by actors outside the Finnish chemical industry, and capacity must be built up prior to the consumption can increase. Electricity costs constitute the largest individual cost category in the three climate scenarios.

Additional investment need in the scenarios

- Total additional investment requirement (incl. energy) in the climate scenarios is 23–44 BEUR in 2015–2050, equal to 49–94 % increase from current levels.

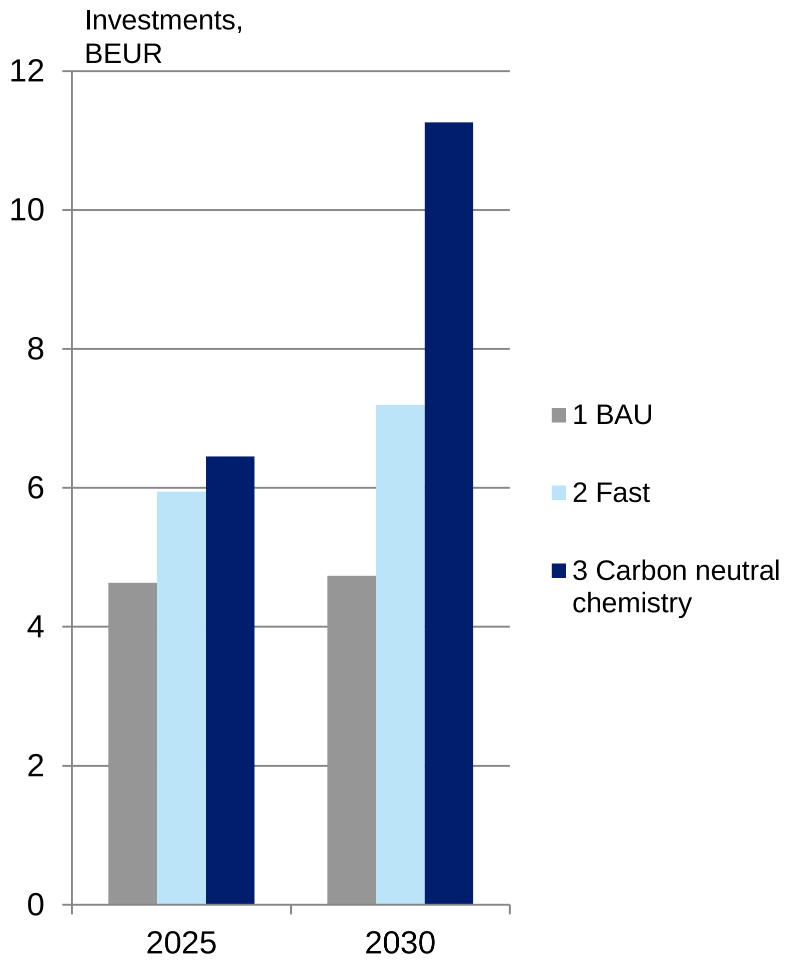


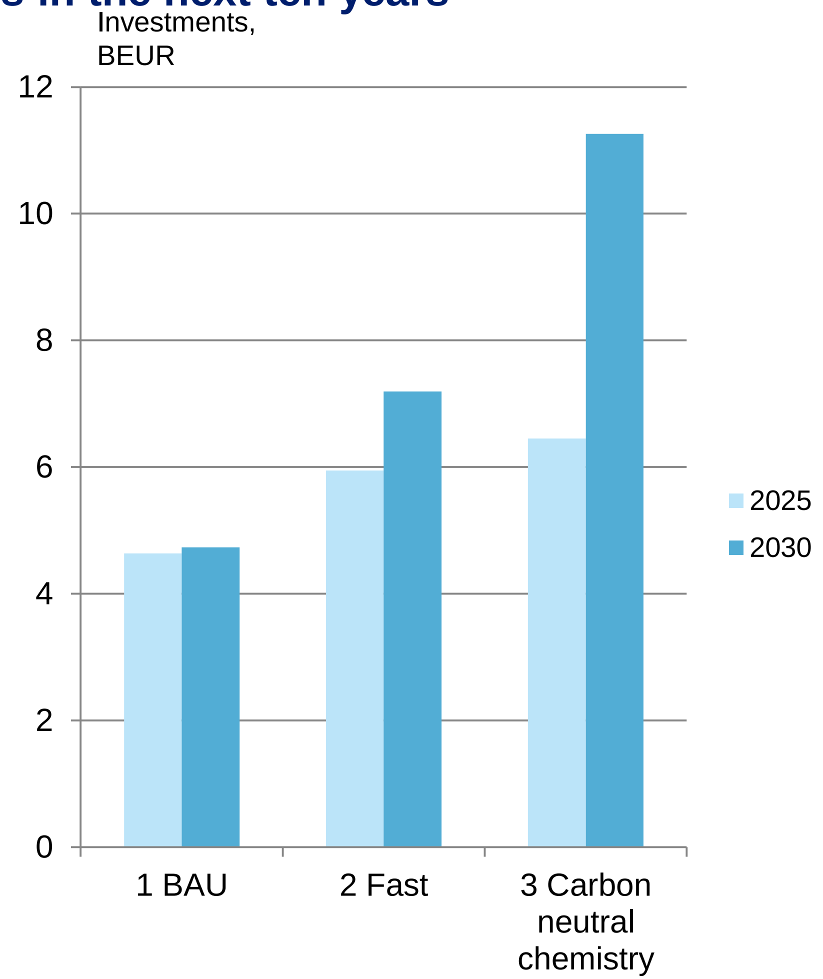
As a comparison:
Total cost of crude oil in 30 years: **195 BEUR**
(60 €/bbl, 15 Mt/a crude oil demand)

Electricity costs are based on the assumed price of 50 €/MWh for electricity and the cumulative electricity consumption of the scenarios. This is only a preliminary estimate of the energy costs, and it is sensitive to assumptions in the energy sector. Possible savings as a consequence of reduced use of fossil-derived heat are not accounted for in the calculation.

INVESTMENTS IN 2020-2030 SHOW THE INTENSE PILOTING SPEEDUP NEEDED

Investments into fixed assets, R&D, new technology and asset modifications require a doubling of total investment levels in the next ten years





Each bar corresponds to the total investment need during the preceding 5-year-period. Possible investments into public infrastructure, energy infrastructure and cross-industry integration are excluded.

LEFT: HARDEST OF GHG EMISSIONS TO REMOVE

Some emissions always present special problems

In the current scenarios, Scope 1 and 2 emissions were targeted.

Scope 1: Process emissions and emissions by own heat and power generation

Scope 2: Emissions from external heat and power generation

Analysis of reduction in Scope 3-related emissions is in the next chapter.

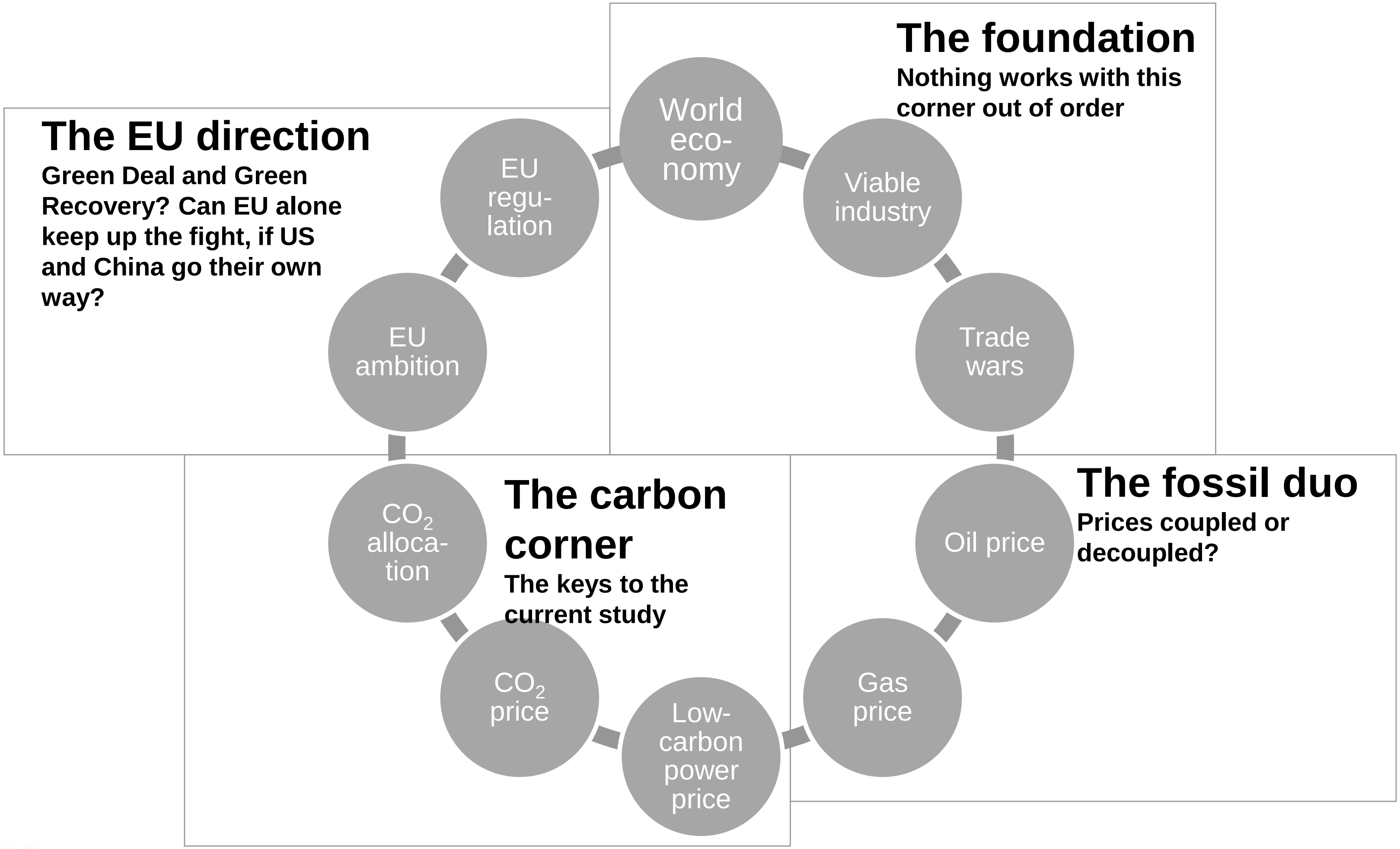
There are some processes and sources of CO_2 that are the hardest to tackle:

- High heat (electric furnaces likely to be available in the 2040's)
- Reducing flaring
- Fugitive emissions
- Back-up, start-up, reserves (energy)
- Certain process emissions
  - e.g. CaO (quicklime)
  - Use of imported specialty chemicals (feedstock of Finnish industry)
- These "hardest of emissions to remove" will require breakthrough technologies to be developed. The overall investment needs come with significant uncertainties.

SENSITIVITY ANALYSIS

GAME CHANGERS WITH THE GREATEST EFFECT

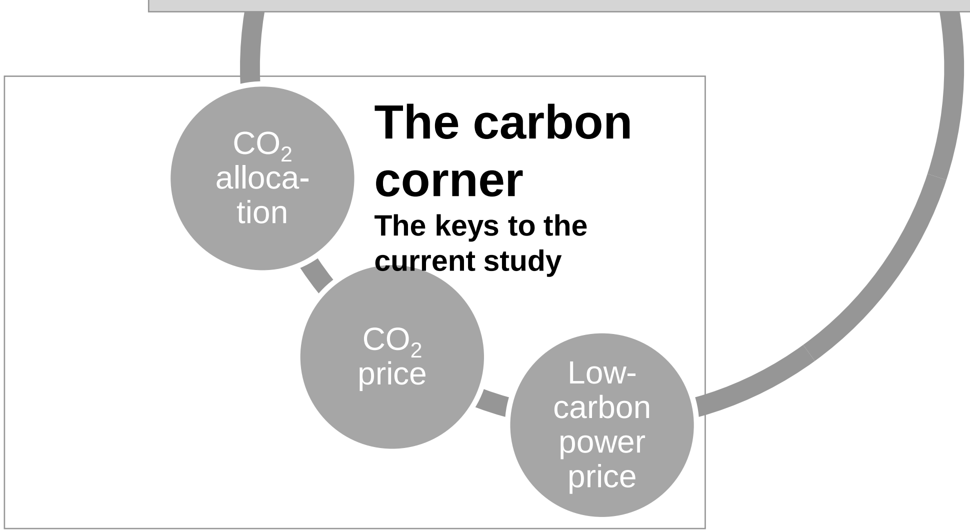
In a comprehensive sensitivity analysis, one should look at a considerable amount of interlinked change factors. However, that would be a "world economy model", and the goals are simpler here



GAME CHANGERS ANALYSED

The focus here is on the impact of CO_2 price and low-carbon electricity price on emission scenarios – allocation is assumed to change so that all emissions cost

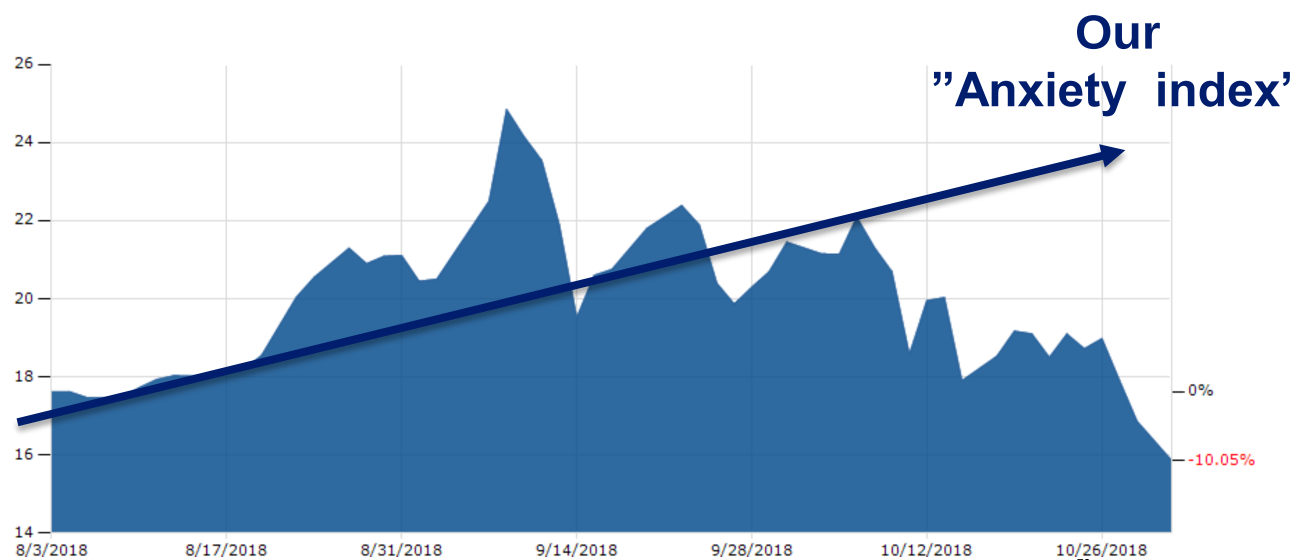
The sensitivity of the scenarios (scopes 1 and 2, with scope 2 of very low importance) to CO_2 and (assumed low-carbon) electricity is analysed. All emissions are assumed to cost – how large the amount of free CO_2 will be in later years is very unclear and probably not worth speculating about.



MOODSWINGS HAVE A ROLE: CO_2 HAS BEEN A VERY EMOTION-DRIVEN MARKET

Real example of mood/fear analysis – CO_2 price in 2018. Raw market emotion in action.

- The graph on the side shows an AFRY analysis on the link between sentiment on the markets and CO_2 price. In a period of a sudden rise in said price, in August-October 2018 AFRY took a large slice of Internet discussion and news on this topic, data mined it for emotion, and the result was as above.
- For every two weeks, a specific mood on the markets, from doom to volatile moodswings. What was interesting, further, was that the calculated "AFRY Anxiety Index" kept growing (i.e. anxiety increasing), while the prices took a downturn.



ETS mood calendar

Confident of risk and negative feelings

Insecure, mood swings pos/neg

Confident of low rewards, anxiety growing

Insecure, volatile pos/neg, anxiety still growing

STARTING POINT: CHANGE IN POWER AND CO_2

Costs of energy transition will also be borne at least partly by the chemical industry

Electricity costs

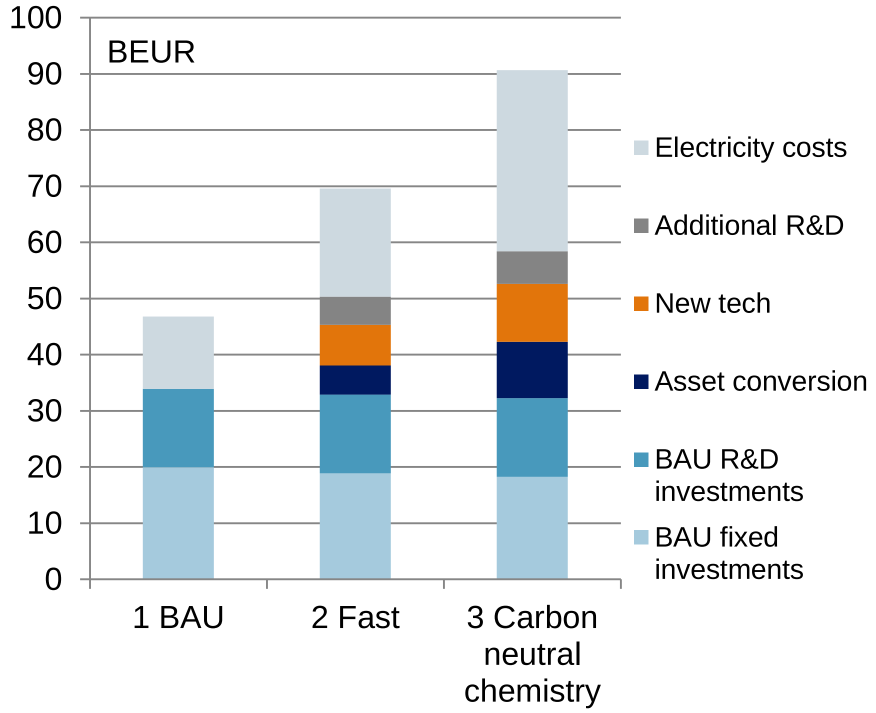
- The figure illustrates the cumulated costs in the different scope-1-and-2 scenarios. There is an electricity cost (no emission costs).

Emission costs

- Obviously, we have the emissions data overall at five year intervals.

Procedure

1) **Varying electricity and CO_2 prices**
We pick a range for both, and create a matrix of all combinations of selected prices in the ranges.
2) **Means to reduce emissions reacting to prices**
We have the different means in the scenarios used to reduce emissions. We use the information gathered and expertise to determine reasonable price cut-off points, when the use of a technology starts to go down (and emissions are not reduced).
3) **Outcome**
As an outcome, we get “increase in emissions” as function of CO_2 and electricity prices.

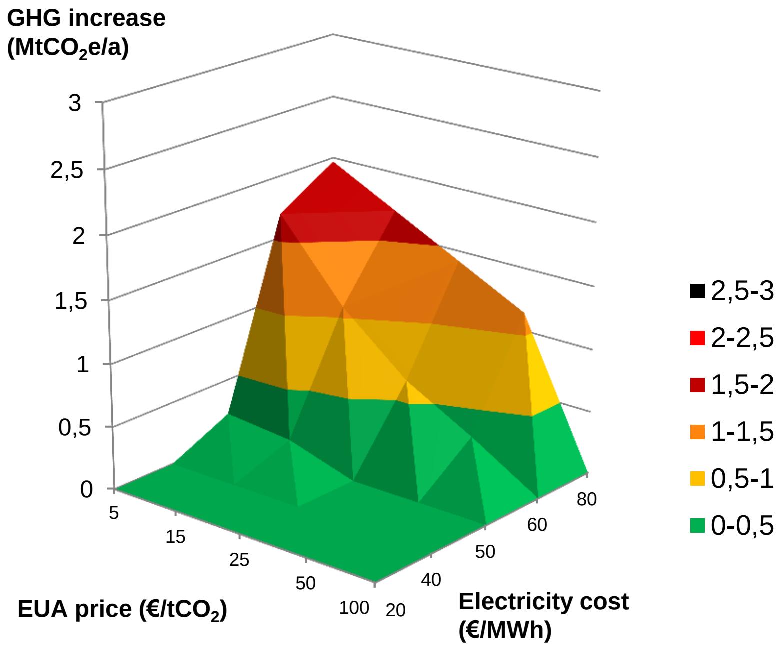


Electricity costs are based on the assumed price of 50 €/MWh for electricity and the cumulative electricity consumption of the scenarios. This is only a preliminary estimate of the energy costs, and it is sensitive to assumptions in the energy sector. Possible savings as a consequence of reduced use of fossil-derived heat are not accounted for in the calculation.

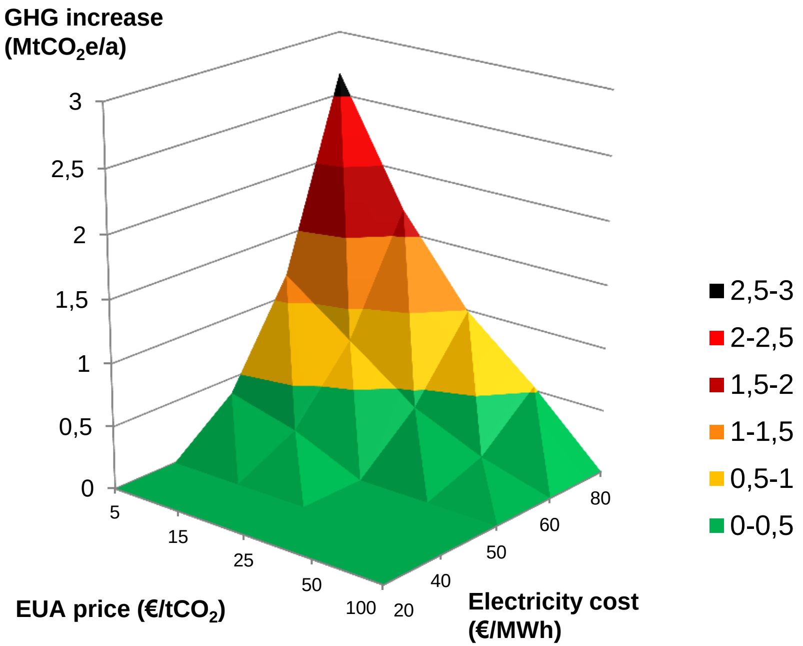
SENSITIVITY OF CARBON NEUTRAL SCENARIO TO ELECTRICITY AND CO_2 PRICES

Emission reductions are estimated to be heavily affected by electricity and CO_2 prices

Additional annual scope 1 emissions compared to Carbon neutral scenario in 2035: 2.4 $MtCO_2/a$



Additional annual scope 1 emissions compared to Carbon neutral scenario in 2045: 0.4 $MtCO_2/a$



Electricity costs

- A combination of high electricity prices and low price of CO_2 allowances reduces the economic attractiveness of emissions reductions substantially. In contrast, low electricity prices and high prices of CO_2 allowances are estimated to make the emission mitigation technologies relatively more competitive.
- Electricity prices are estimated to bring a stronger impact to the scenarios.

Results are indicative only.

TO KEEP IN MIND IN THE INTERPRETATION OF THE RESULTS OF THE SENSITIVITY ANALYSIS

CO_2 and electricity do not tell the whole story – and the plot is thickening

A global market, and plans for e.g. carbon border tax in Green Recovery

- The chemical industry operates in a global market, and carbon pricing schemes should be extended to cover more of the global GHG emissions to ensure the cost-efficiency of climate change mitigation and the competitiveness aspects of the industries already under such schemes, as in the EU. In May 2020, the presented plans from the Commission for post-COVID19 recovery contain a "carbon border tax", planned to standardize the carbon emission price between the EU and its imports. What shape, if any, this carbon border tax will take, and what its impact on e.g. CO_2 price is, will be a geopolitical decision with intense intra-EU negotiation and lobbying. That cannot reasonably be modelled, especially in a highly tense international political climate (in addition to record-warm years).

Energy transition linked to oil and natural gas prices

- The current (May 2020) oil price war, and the anticipated transition from (in a simplified turn of words) coal and oil via natural gas to renewable fuels, are part of another global geopolitical issue, with an impact on emission reduction. If the wisdom to anticipate all turns in this game existed, one would certainly use it. But it doesn't.

Technology development

- Technology commercialisation and development will define the exact capital expenditure levels required by the emission reduction. This development, along with operating parameters, such as load, scale and efficiency are paramount factors for the whole.

A viable industry as a foundation

- Current operations and future investments into low-carbon technologies necessitate the economic viability of the industry, also in Europe and Finland. However, electricity price and price of CO_2 allowance are only two parameters that affect corporate decision-making. An enabling environment includes these aspects, as well as a plethora of others.

The meaning of the analysis

- Trying to model the development of the world and all its driving forces during the next 30 years is being tried by many but will fail – too many wheels within wheels, too many surprises. What the indicative analysis with two variables points at is that the message in this study of the need for cost-competitive low-carbon electricity truly weighs heavy on the success of carbon neutrality.

ROADMAP TO THE ROADMAP

1 EXECUTIVE SUMMARY

2 INTRODUCTION: Purpose, boundaries, approach

3 TECHNOLOGY: A menu of options to reduce emissions

4 SCENARIOS: Direct emissions, purchased energy and sensitivity to circumstances

5 SCENARIOS EXPANDED:
A feedstock (r)evolution of defossilisation

6 TOOLBOX FOR CHANGE:
Chemical clusters and example action plans

7 HANDPRINT, EXPORT POTENTIAL AND KNOWLEDGE:
The global imprint of the Finnish chemical industry

8 CONCLUSIONS AND CONDITIONS:
The outcome and the preconditions

POINTS TO REMEMBER: SCENARIOS EXPANDED TO FEEDSTOCK

Out of the ocean of facts, remember this

DEFOSSILISATION OF FEEDSTOCK WOULD BE AN EXERCISE OF VERY DRAMATIC CONSEQUENCES: breakthroughs in renewable feedstock are not enough, investments and quite dramatic electricity needs accompany the feedstock defossilisation scenarios.

HOWEVER, HAVING A FEEL FOR WHAT FULL DEFOSSILISATION WOULD MEAN HELPS ALSO IN PARTIAL DEFOSSILISATION: in the extreme scenario, we go down to less than 10 % fossil feedstock – even notably less would be a second disruption.

CARBON-NEGATIVITY WOULD BE POSSIBLE, BUT WITH VERY DRAMATIC CHANGES: reaching total significant carbon-negativity comes with the extreme scenario, but the amount of investments, renewable feedstock generation and recycling and electricity would require very significant changes in our global industrial ecosystem.

SCENARIOS (FEEDSTOCK)

BACKGROUND AND APPROACH

DEEP TRANSFORMATION OF CHEMICAL INDUSTRY

PERSPECTIVES

DEEP TRANSFORMATION OF CHEMICAL INDUSTRY: WHAT WOULD BE NEEDED?

Completing the picture with Scope 3, the second disruption

What is it?

- Measures and scenarios in the previous chapter target mainly direct GHG emissions and energy-related indirect emissions (Scope 1 and 2).
- The most ambitious scenarios reduce these emissions close to zero by mid-century.
- However, most of the climate impact (positive and negative) of chemical industry could be said to happen outside the chemicals plant: feedstock production, use of products and their end-of-life solutions.

What drives it?

- Demand for oil products depends heavily on the development e.g. the transportation sector.
- Cost efficiency of solutions, scale of impact and the maximisation of the global handprint of Finnish chemical industry (via export) may favour large-scale circular economy solutions.
- Alternative products of future may include green hydrocarbons, methanol, ethanol, HVO, HTL.
- Alternative feedstock of the future include
  - Algae oils, vegetable oils, animal fats
  - Agri-, forestry and biowaste
  - CO_2 from point sources or direct air capture
  - Heat could be obtained from waste heat
- Electricity demand and investment need would grow very *significantly* compared to the presented scenarios (e.g. artificial light and pumping in algae oil production, electrolysis, CO_2 capture).
- Significant implications on national export/import balance, security of supply of energy (*huoltovarmuus*), etc.

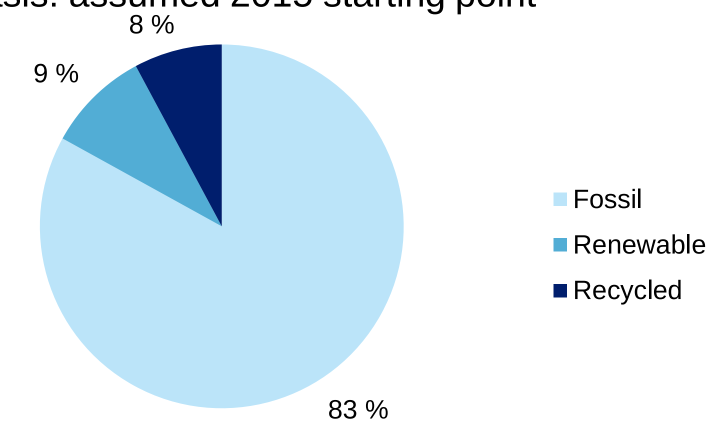
THREE FEEDSTOCK SCENARIOS COMPLEMENT THE PICTURE

Again, with feedstock, a reference line and variations

1. Baseline
2. Fast development
3. Carbon neutral chemistry 2045

- Feedstock composition development in scenarios
  - Fossil
  - Renewable
  - Recycled
  - Synthetic hydrocarbons (P2X)
- Fossil materials, such as fossil hydrocarbons and minerals, create the material backbone of all modern societies. Replacing these large material volumes with sustainable alternatives is a true grand challenge necessitating changes in and impacting value chains much beyond chemical industry boundaries.

Basis: assumed 2015 starting point

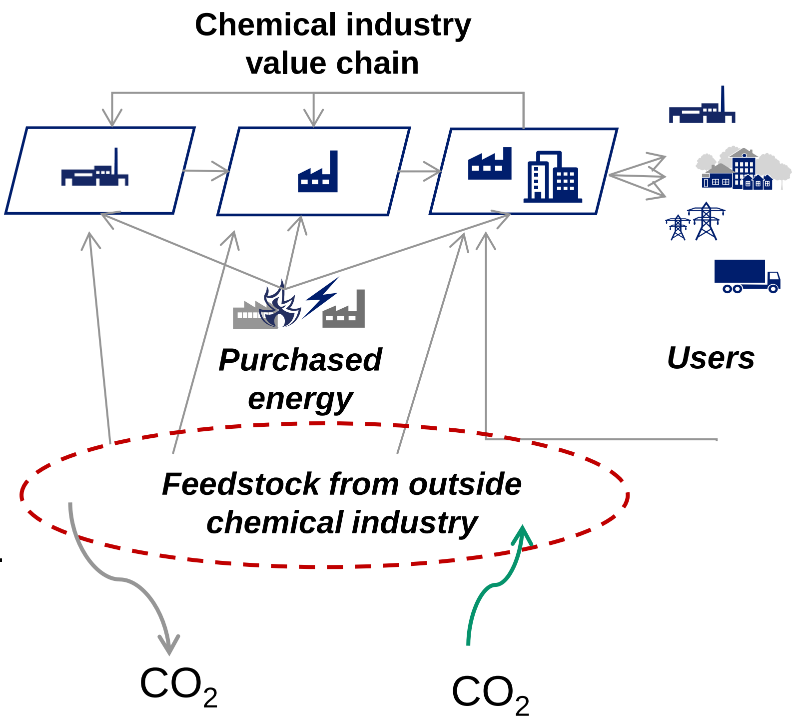


Diversity of chemicals and intermediate use
The global chemical industry is estimated to produce close to 100 000 different substances for commercial use. Single Finnish chemical companies may use dozens, even hundreds of different chemicals as their raw materials. Many of those are intermediates, whose climate impact depends primarily on the origin of primary raw material (fossil/renewable/recycled) of the corresponding value chain. Not only do companies serve all other sectors of the economy, but they also are each others' clients. Entire value chains (globally) will thus be impacted by the choice of raw material origin, which justifies the scope of the study limited to main raw materials. Main product categories of focus include fuels, plastics and fertilizers.

WHAT ARE GHG EMISSIONS RELATED TO FEEDSTOCK?

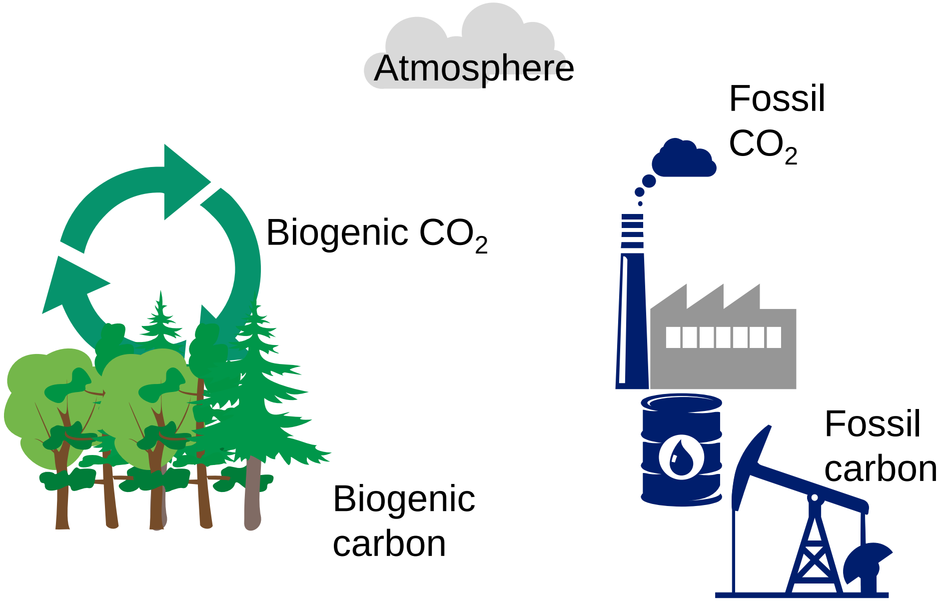
The role of feedstock in the full GHG picture is considerable

- *Feedstock* means the raw materials of the industry.
- In this chapter, the focus is to analyse means to reduce the carbon footprint of the feedstock of chemical industry (cradle-to-gate), as this is the way for chemical industry to have the most influence on GHG reductions.
- The generation, harvesting, extraction and production of raw materials have GHG impacts
  - These GHG emissions are a part of Scope 3 emissions of chemical industry. The related emissions do not occur within chemical industry, maybe not even in the same country.
  - Nevertheless, the impact can be very significant.
  - The impact can be *emissions* (CO_2 emissions to atmosphere) or *CO_2 uptake* (CO_2 absorption or uptake from atmosphere)
  - On the other hand, *end-of-life emissions* are also mostly impacted by circular economy solutions related to feedstock.
  - Of other notable Scope 3 emissions, solutions for reducing *emissions from transportation* are discussed in the Toolbox section of the report.
- For many of the emerging, sustainable alternatives, there is not yet data available. Estimates presented here are based on literature references, publicly available LCA studies and expert estimates. Results are preliminary and should be interpreted with due caution.



FOSSIL AND BIOGENIC GHG EMISSIONS OF FEEDSTOCK ARE NOT EQUAL

At least so far, biogenic GHG is treated based on its renewable/recyclable nature

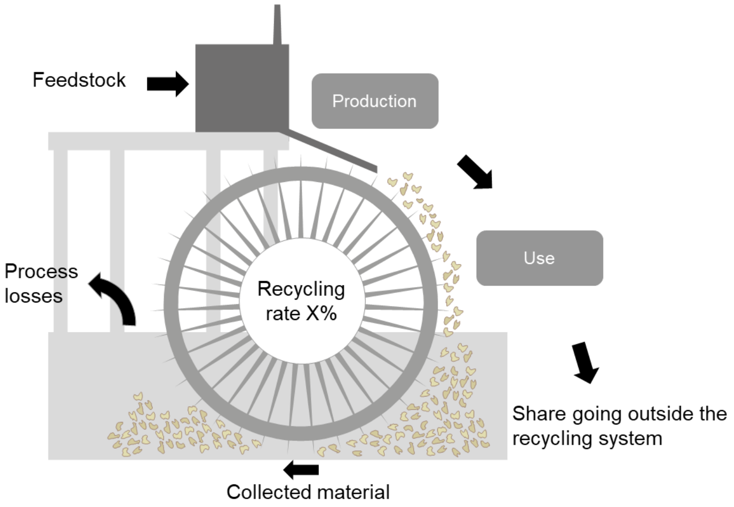


- The total GHG impact of the feedstock includes fossil CO_2 emissions and (biogenic) CO_2 intake of renewable materials.
- Renewable and recycled raw materials may function as carbon *sinks*, absorbing CO_2 from atmosphere. The feedstock may thus become carbon-negative.
- In the case of synthetic hydrocarbons, the feedstock use of captured CO_2 also functions as a carbon sink.
- If this carbon (synthetically captured or of bio origin) is not later released back into atmosphere, the products can be carbon-negative, functioning as carbon *storage*.

RECYCLED FEEDSTOCK AND RELATED GHG EMISSIONS FORM A CYCLE

The "water wheel of recycling" for greenhouse gases is our way of illustrating it

- For virgin raw materials, GHG emissions from cradle (cultivation, extraction, etc.) to chemical industry gate are taken into account.
- In case of side or waste streams, a reasonable share of GHG emissions of the total is allocated to the studied feedstock.
- The GHG emissions related to **recycled feedstock** are the share of the GHG emissions of virgin feedstock, plus the possible impact of recovered material treatment as recycled material replaces virgin material.
- The share is determined case-specifically based on how many times the studied material can stay in the loop, what the recycling rate is and what the process losses in each loop are.
- Currently, a large GHG impact comes from the end-of-life of chemical industry products, e.g. currently incinerated products. Although not quantified in this study, the recycled feedstock and circular economy solutions significantly reduce these end-of-life emissions. Required measures and policies are specific.



PÖYRY

SCENARIOS

IDENTIFYING THE OPPORTUNITIES OF NEW FEEDSTOCKS

ALTERNATIVE FEEDSTOCKS CONSIDERED TO SUBSTITUTE FOSSIL ARE NUMEROUS

The focus of the feedstock analysis has been on recycled, renewable and synthetic raw materials

Recycled materials

- Biocomposite waste
- Textile waste
- Plastic waste
- Concrete waste
- Pigments (Fe-oxide, TiO_2)
- Gypsum
- Bitumen
- Ceramics and glass
- Mining waste (e.g. phlogopite)
- Battery waste

Renewable materials

- Algae oil
- Plant-based oils
  - Rapeseed oil, palm oil, soybean oil, tall oil
- Waste oils
  - Plant-based oils and waste animal fats
- Hemicellulose
- Lignin
- Sugars
- Agri waste
- Bio waste
- Forest and bio waste
- Mixed waste

Synthetic hydrocarbons

- Power-to-H_2
- Carbon from CO, CO_2

Diversity of chemicals and intermediate use

The global chemical industry is estimated to produce close to 100 000 different substances for commercial use. Single Finnish chemical companies may use dozens, even hundreds of different chemicals as their raw materials. Many of those are intermediates, whose climate impact depends primarily on the origin of primary raw material (fossil/renewable/recycled) of the corresponding value chain. Not only do companies serve all other sectors of the economy, but they also are each others' clients. As an example, notable chemicals used by Finnish industry include sulfates, sodium chloride, chlorine, sodium hydroxide, styrene, butadiene, pentaerythritol, MCAA, polyvinylalcohol, phenol, anthaquinone, maleic anhydride, phtalic anhydride, starch, natural/synthetic rubber, soot, polyester resins, epoxy resins, carbon and glass fibers, solvents and other specialty chemicals. Entire value chains (globally) will thus be influenced by the choice of raw material origin, which justifies the scope of the study limited to main raw materials.

RECYCLED FEEDSTOCK: A RICH MENU, AGAIN

Maturing technology enables the use of materials that are not recycled nowadays

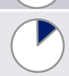
General description

Recycled feedstock is based on the concepts of circular economy and it includes many attractive alternatives to chemical industry. Using waste materials from all sectors of economy necessitates sector integration and effective recycling infrastructure. Many waste streams are currently landfilled or combusted for energy. Thus, alternative heat sources help in increasing the material efficiency.

Applicability: an example of recycled plastics

Plastics waste is estimated to yield the highest volumes of the recycled feedstock. Significant investments and innovation are required in the following areas:

- collection, sorting and storage of waste plastics (including imports),
- additional hydrogen capacity,
- possible feedstock and product tanking and piping changes,
- processes, such as pyrolysis or gasification, hydrotreatment of pyrolysis oil, filtration with mineral filters and distillation.

Feedstock material	Quan-tity	Example products	Techno-economic potential	Remarks
Plastic waste		Hydrocarbons, (plastics, fuels, chemicals)	+++	Mechanical, physical and chemical recycling. Already under intensive research in chemical industry.
Textile waste		Textiles, plastics	++	Cooperation with the garments industry needed.
Composite waste		Hydrocarbons	++	Some of the hardest waste to recycle currently.
Battery waste		Recycled battery materials	+++	A future high-value recycling business will emerge due to growth of electric vehicle market.
Concrete waste		Concrete and composites	+/-	Cement and concrete production is one the world largest GHG emitters.
Gypsum		Fertilizers, new gypsum products	+	Potential for future slow-release fertilizer, large-scale trials already on-going in agricultural use.
Mining waste		Minerals	+	Quantities of waste material are large, but mineral concentration levels vary. Some (Fe, Al-containing) waste is already being used.
Ceramics and glass		Ceramics and glass	+	Already recycled successfully.
Bitumen		Asphalt	+	Potential to feed into asphalt production.
Pigments		Pigments (e.g. Fe-oxide, TiO_2)	+	Potential to extract pigments from construction waste and reuse them.

Note: *Quantity* illustrates the assumed techno-economically feasible availability, or the assumed quantities of novel feedstocks in the scenarios in reference to each other.

RENEWABLE FEEDSTOCK: LIKEWISE, A RICH BLEND

Renewable feedstock base could be widened from numerous sources

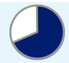
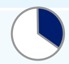
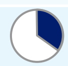
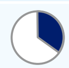
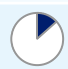
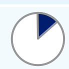
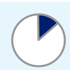
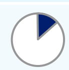
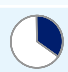
General description

Utilization of renewable feedstock reduces the dependence on fossil raw materials. On a molecular level, a significant difference is the high oxygen-content in the bio-based raw materials. The most potential in the long term in estimated in completely novel sources, such as algae oil. Most other renewable materials discussed here are not utilized for materials currently. Biodiversity, water and land use must be considered for renewable feedstock.

Applicability: an example of algae oil

Algae can provide a significant substitution to fossil feedstock, particularly as the required quantities become very large in the scenarios. Species of algae can be cultivated in open raceway ponds or photobioreactors to yield novel biomass consisting of up to 40 m-% oils. Investments and innovation are needed in e.g. the following areas:

- Possible feedstock and product tanking and piping changes
- Extraction of oil,
- Removal of algae cell walls
- Filtration with mineral filters
- HVO process: hydrotreatment (and isomerization)
- Distillation

Material	Estimated quantity	Example products	Techno-economic potential	Remarks
Algae oil		HVO (plastics, fuels, chemicals)	++	High potential for the largest volumes (high growth rate, high lipid content). Different process configurations exist. Nutrients, artificial/synthetic light and processing affect GHG impact and feasibility. Land use issues must be considered. Currently not commercialised, and "algae fever" has passed but could return.
Plant-based oils and waste oils		HVO	+++	Many alternatives, already mature applications. Land use and availability issues may curb the potential.
Hemi-cellulose		MEG, MPG (chemicals)	++	Potential to cooperate with agri and forestry sectors
Lignin		Phenolics (chemicals)	+	Intense research on-going; cooperation with agri and forestry sectors
Sugar		PDO, (chemicals)	++	Cooperation with sugar producers
Agri waste		Biogas	+	Collection and transportation are the main hurdles
Bio waste		Biogas	++	Already a mature technology, but significant volumes end up in mixed waste
Forest waste		Ethanol	+	Cellulosic ethanol production
Mixed waste		Methanol, hydrocarbons	+	Relatively large amounts currently combusted for energy

Quantity illustrates the assumed techno-economically feasible availability, or the assumed quantities of novel feedstocks in the scenarios in reference to each other.

HYDROGEN ECONOMY AND SYNTHETIC HYDROCARBONS

H_2

General description

Hydrogen economy became a "thing" due to energy considerations – from fusion reactors to low carbon fuels. However, the lightest element is not just a fuel or a storage, it is an important raw material for chemicals, for new compounds – and possible to produce in large quantities.

Fossil-based hydrogen can be produced from fossil fuels through e.g. steam methane reforming (SMR) or auto thermal reformation (ATR), which remain the cheapest options. Low-carbon options include blue hydrogen and green hydrogen. Blue hydrogen refers to methane use coupled with CCS or pyrolysis, while green hydrogen is produced by utilising low-carbon electricity for the electrolysis of water.

For hydrogen economy to truly realize 1) commercial and technical challenges must be solved, 2) cost competitiveness reached and 3) end use applications found.

Work is well under way through learning-by-doing and scale-up projects in Europe and beyond.

Applicability – spearheads for hydrogen:

- **Climate impact through use**

Low carbon fuel, no CO_2 emissions, possible transport and storage infrastructure needed.

- Flexibility in the production

Being able to adapt and adjust between energy (storage) and chemicals production. Opportunities to use as synthetic raw material of hydrocarbons and links to carbon capture and utilisation (CCUS) processes .

- New markets

Hydrogen – future end use sectors of hydrogen in addition to chemicals include other industries (e.g. new steel manufacturing technologies), transportation and potentially others.

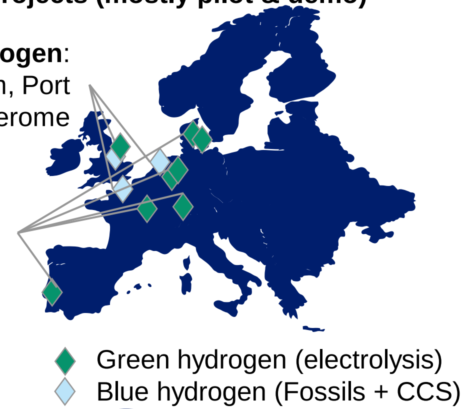
Examples of existing low-carbon hydrogen projects (mostly pilot & demo) are numerous

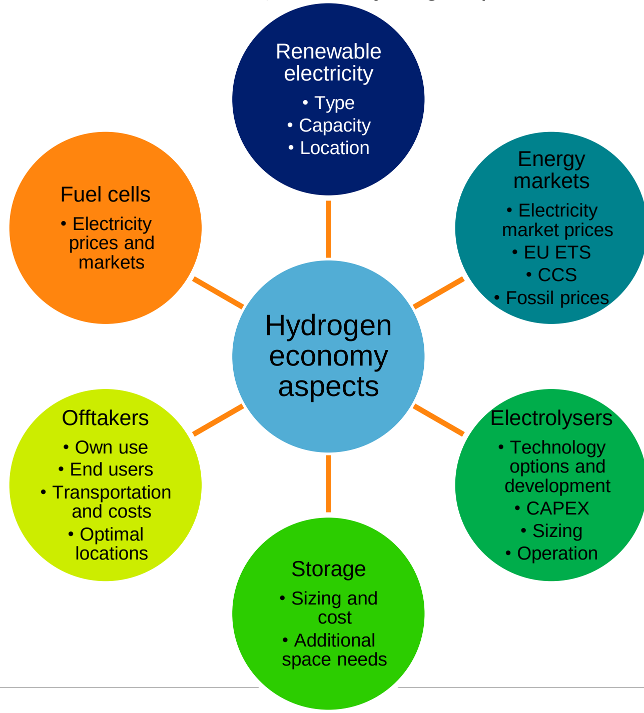
Interest in hydrogen is currently extremely intense. Several commercial projects are under planning and being performed, as new value chains and business models are sought, sometimes across new wide industrial consortia.

Several EU countries, such as Germany, the Netherlands and Portugal, have outlined their hydrogen strategies, envisaging significant growth in the 2020s. In Central Europe, hydrogen is seen to hold potential for sector integration through existing gas infrastructure much in a similar manner that integration through electricity networks holds in the Nordics.

Blue hydrogen: HyNet NW, Magnum, Port Jerome

Green hydrogen: Fredericia, H2RES, NorthH2, Hybridge, REFHYFNE, H2 Energy, H2V, Gigastack, Sines





INTERLINKAGES OF HYDROGEN, BIO AND CIRCULAR ECONOMY

Importance of new business models and value chains

- All new commercial activities in the fields of bioeconomy, hydrogen economy and circular economy share the need for completely new value chains to emerge. The problems are not simply technical or related to resources of individual companies. Knowledge (in the development phase) and money and products (in the execution phase) must start switching hands for the sustainable solutions to be sustained.

Importance of RDD&D and scale-up

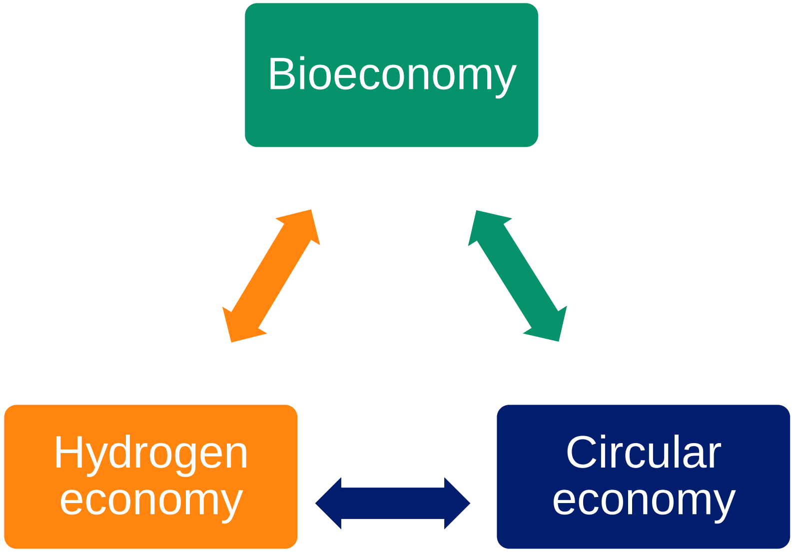
- Many of the new raw materials of tomorrow's economy have to intensively researched to clear the remaining technical barriers. Learning-by-doing in the pilot and demonstration projects and scale-up is absolutely essential for industrial-size operations to emerge.

Importance of trade, enabling regulation and new markets

- Materials must be able to flow effortlessly across the borders for new business to emerge, as scale is essential also in circular economy. New waste hierarchy implementation to ensure that "waste" becomes valuable feedstock and is utilised is crucial.
- Markets of conventional products can be regulated and government procurements used to promote the formation of new markets.

Complementary, but focus is needed

- None of the three entities can solve the climate crisis on its own, instead they complement each other even in the scope of chemical industry defossilisation and the scenarios in this work. However, focus is needed to estimate the core strengths and bottlenecks in each category from with viewpoint of single nation states. No country or company can perform the transformation on its own and sector integration much beyond energy is essential for all.



SCENARIOS (FEEDSTOCK)

RESULTS

ASPECTS TO CONSIDER WHEN INTERPRETING THE RESULTS

The warning overlap with those for scope 1 and 2 scenarios

Only an economically successful industry can make the climate transformation happen

- It comes as no surprise that the transformation of chemical industry towards carbon neutrality requires tireless work in research and developing new products and processes, and significant investments in production assets, energy (production and infrastructure) and recycling infrastructure. Economic viability of the large investments, access to finance and new value chains will, to a large extent, decide how quickly and to what extent the transformation will happen. *From an industry point-of-view, environmental sustainability necessitates economic sustainability, albeit new business opportunities are also numerous along the way.*

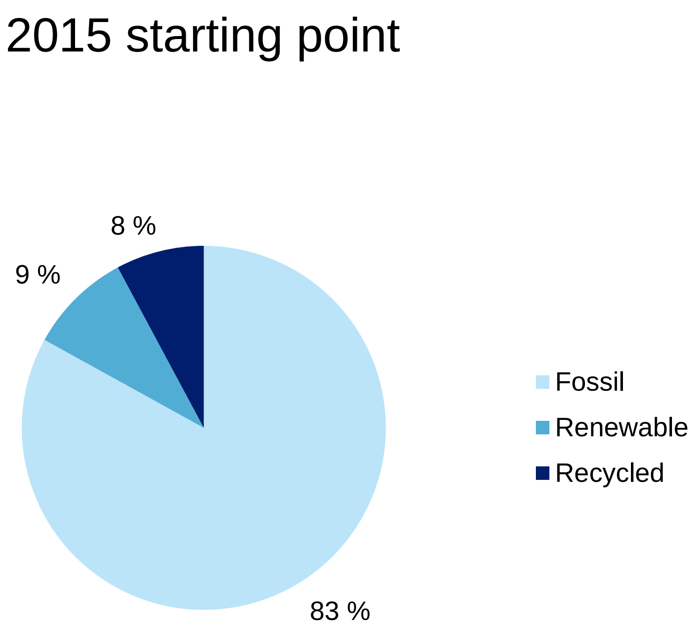
Global market, global players

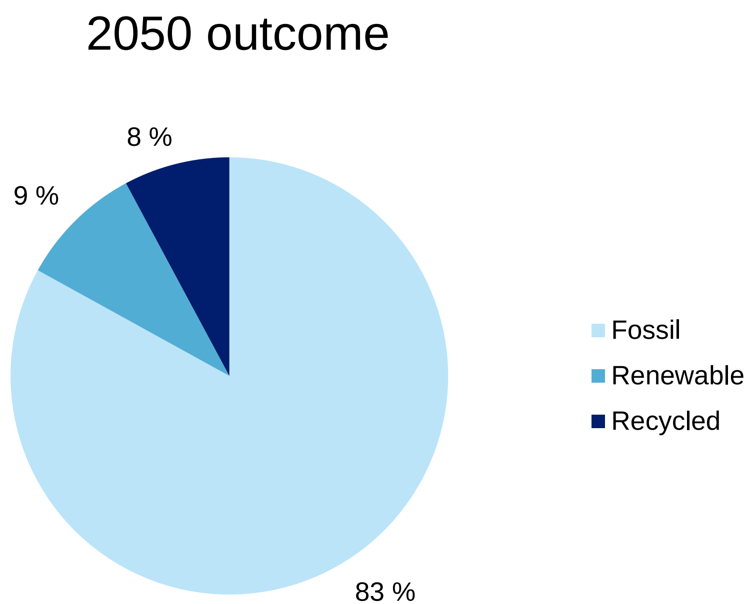
- *Chemical industry operates in a highly globalized market*. Companies have production assets in many countries on different continents. Raw materials and products of the industry flow effortlessly across country borders. From a company point-of-view, focusing on national boundaries is not necessarily natural, whether it is a question of production investments or climate change mitigation, for example.
  - This is particularly true for the feedstock scenarios and GHG impact in scope 3 (indirect emissions). When interpreting the results, it is essential to keep in mind that *these scenarios (not forecasts!) are sensitive to a range of assumptions* and with a focus primarily on Finland. However, Finland will not be an island in the future, either, and the scenarios rely on continuation of imported raw materials
- Keeping the above in mind, the following scenarios aim to depict a realistic, yet extremely ambitious transformation of what the chemical industry of Finland could look like in the future as a part of the national roadmap work of Finnish main industries.

1. BASELINE SCENARIO AS A REFERENCE LINE

Simplifying the variety of materials to two “changing pies”

- Total material consumption of chemical industry is 26 Mt/a in 2015.
- Volume growth of production for all industry: 0,75%/a.

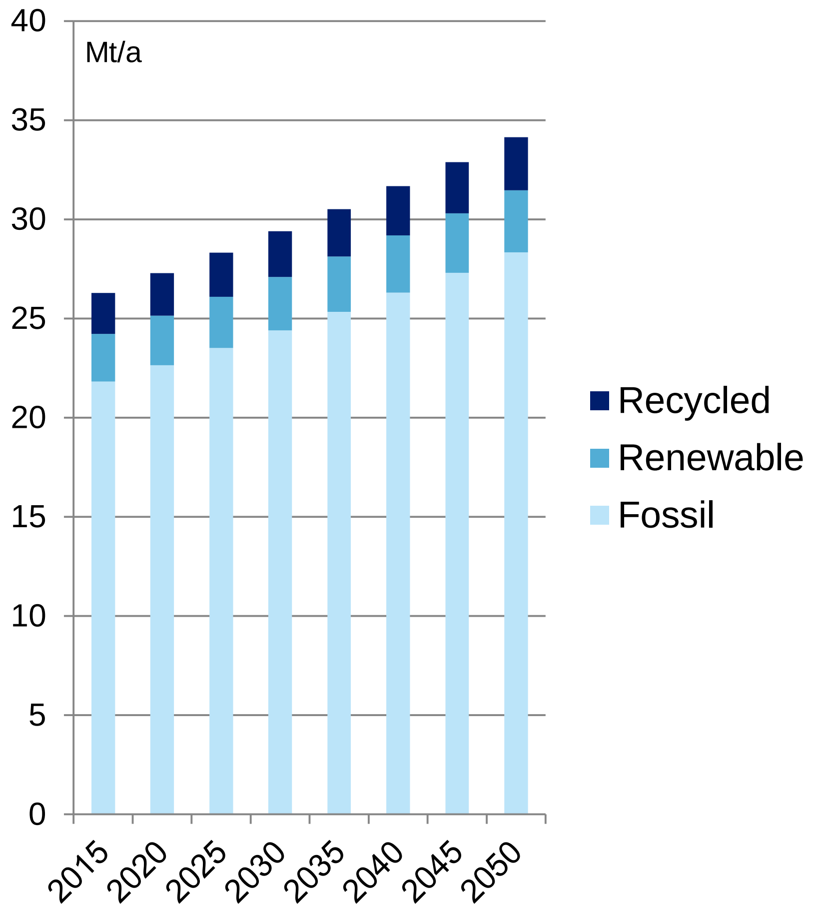




1. BASELINE SCENARIO: FEEDSTOCK VOLUME INCREASES

With production growth and no dramatic material efficiency change envisioned, more feedstock needed

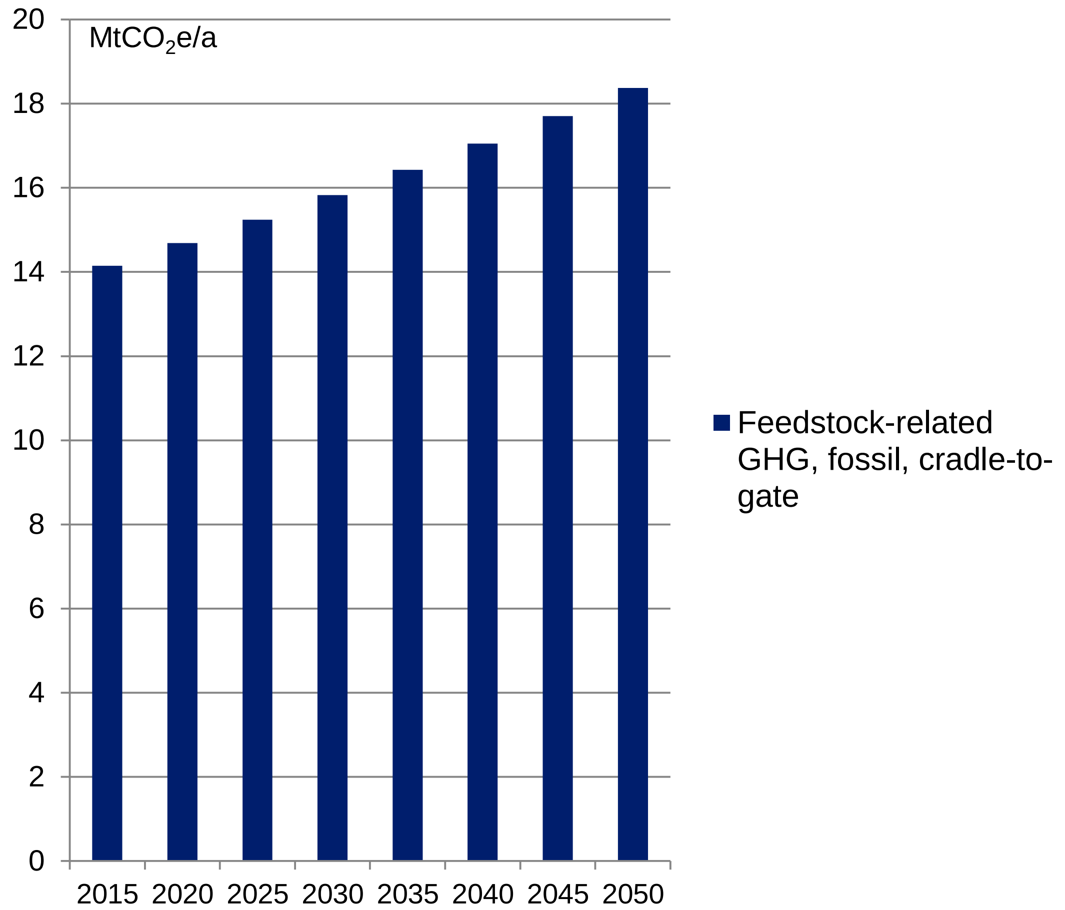
- Here, assuming the same composition as in 2015, scaling up with volume growth, and
  - Assuming the same +0,75%/a industry-wide volume growth
  - Achieving as a result a reference line for other scenarios
  - The output is not the most likely future or a prediction of the development of the chemical industry, but only a static reference line.



1. BASELINE SCENARIO: FEEDSTOCK EMISSIONS INCREASING

Again, a reference line, this time for emissions from feedstock

- Only feedstock emissions are analysed for Scope 3 GHG emissions. These emissions originate from the generation, harvesting, extraction and production of raw materials that the chemical industry utilizes.
- No changes in the feedstock composition are assumed in creating the baseline scenario, resulting in a volume-driven growth of the feedstock GHG impact.



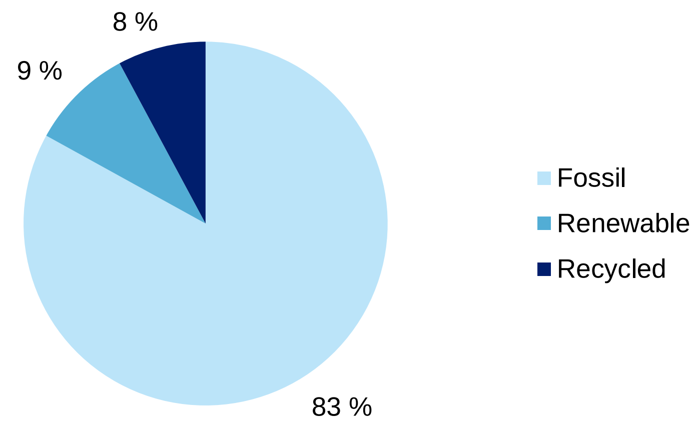
Results are estimates based on published LCA information.

2. FAST DEVELOPMENT SCENARIO BOOSTS RENEWABLE AND RECYCLED FEEDSTOCK

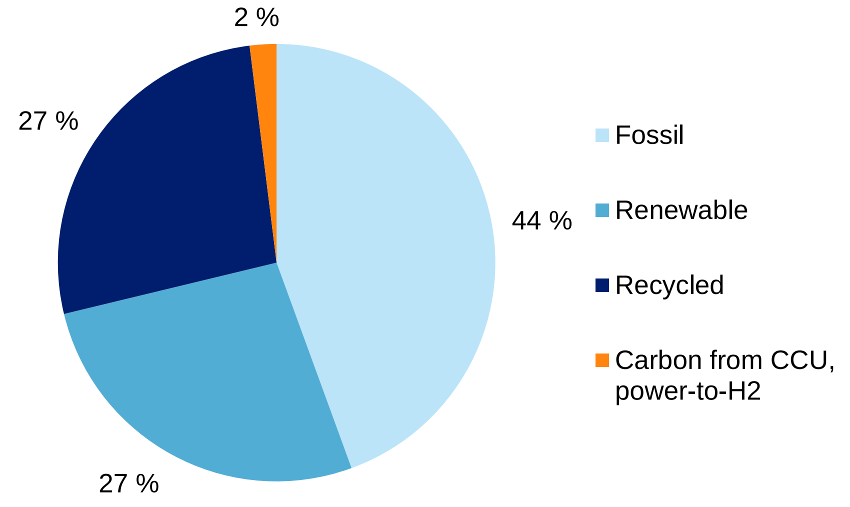
Same production, but renewable and recycled feedstocks cross the 50 % line

- Total material consumption of chemical industry: 26 Mt/a.
- Volume growth of production for all industry: 0,75%/a.
- Renewable and recycled feedstocks assumed account for over 50 % in 2050.
- Fossil still the largest single raw material source.
- Power-to-hydrogen estimated to reach ca. 130 kt/a in 2050, while synthetic hydrocarbon production requires CO_2 capture of ca. 2 $MtCO_2$/a.

2015 starting point



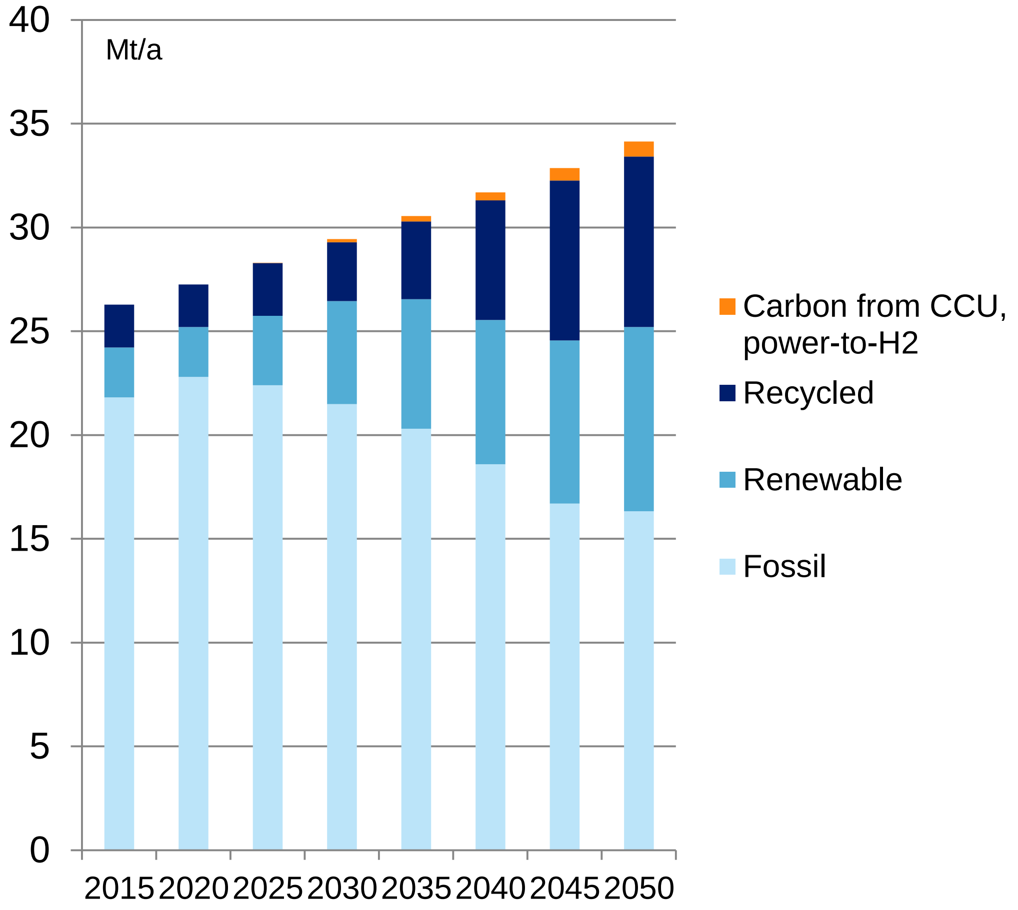
2050



2. FAST DEVELOPMENT SCENARIO WITH A NOTABLE SCALE-UP OF RENEWABLE AND RECYCLABLE FEEDSTOCK

A fairly constant decrease of fossil feedstock

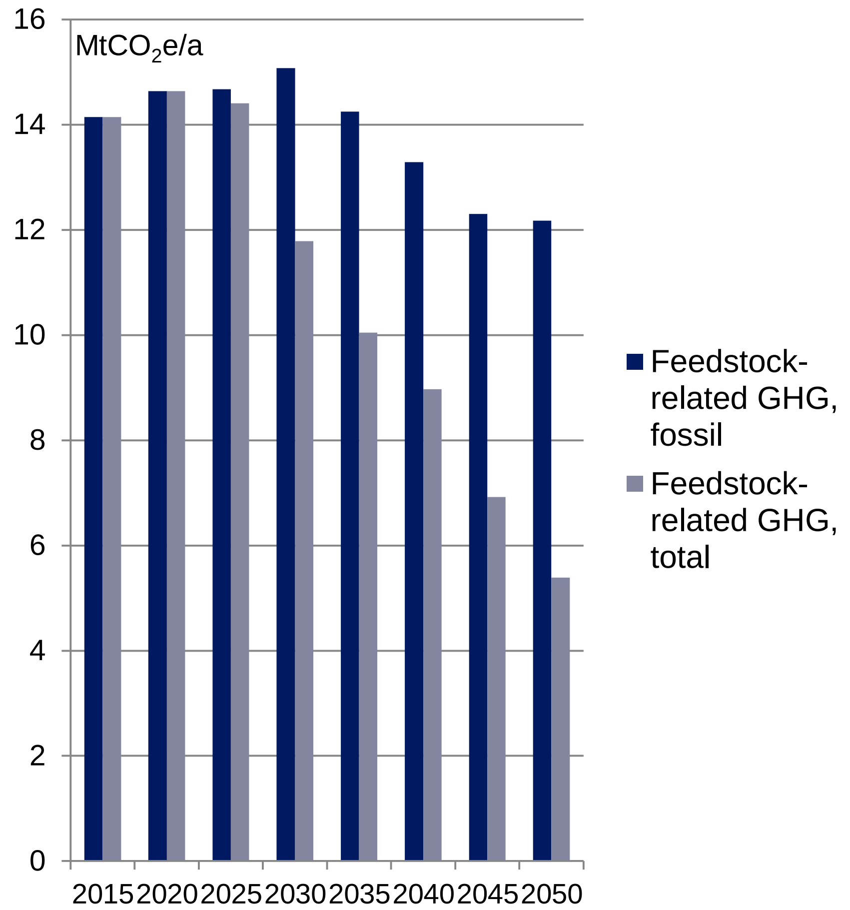
- Fossil content in the feedstock starts to gradually decrease after 2020.
- Largest volumes in the new raw materials come from recycled plastic waste and from renewable algae oil.
  - Sources of currently underutilized feedstock (like plastics, waste oils and mixed waste) are expected to scale up first and faster.
  - Completely novel feedstock (like algae oil, green hydrogen and CO_2 capture) is estimated to start with pilot and demonstration projects. They will contribute to significantly to the whole after 2030 and in 2040s, after the lower-hanging fruits of alternative feedstock have been picked (and technology has evolved).



2. FAST DEVELOPMENT SCENARIO AND DECREASING FEEDSTOCK EMISSIONS

A decrease of total emissions from 14 to 6 MtCO2

- This analysis is a comparison of GHG emissions related to feedstock up until the inbound gate of chemical industry.
- Total GHG impact includes fossil and (biogenic) CO_2 intake of renewable materials.
- Increasing share of renewable and recycled raw materials starts decreasing the feedstock GHG emissions fast after 2030.
- With current GWP data and estimates of the feedstock,
  - annual feedstock-related fossil emissions would be decreased from ca. 14 to 12 $MtCO_2$ and
  - annual total emissions (accounting for biogenic carbon) would decrease from 14 to ca 6 $MtCO_2$



Results are estimates based on published LCA information.

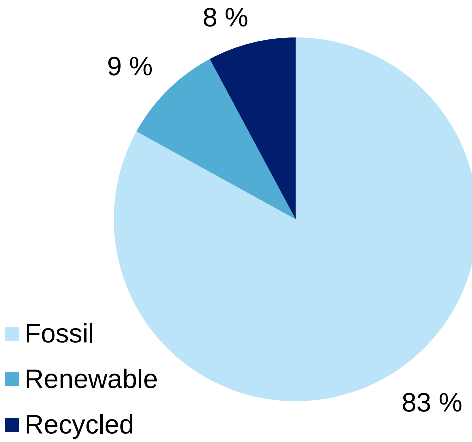
3. CARBON NEUTRAL CHEMISTRY 2045: THE GOLD STANDARD

Now, in keeping with the ambition level of “2045”, fossil down to less than 10 % of the feedstock

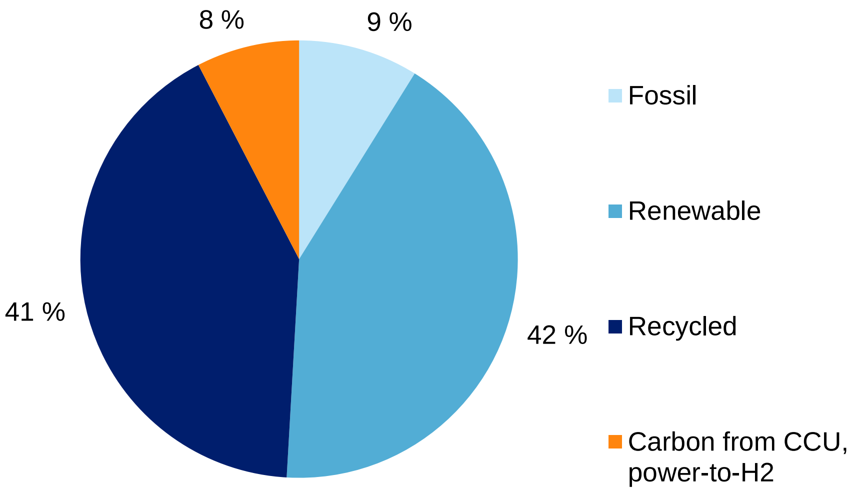
- Total material consumption of chemical industry: 26 Mt/a.
- Volume growth of production for all industry: 0,75 %/a .

- In 2050, fossil less than 10 % of the feedstock.
- Renewable and recycled cover over 80 %.
- Synthetic hydrocarbon production requires CO_2 capture of 7-8 $MtCO_2$/a and ca. 500 kt/a of green hydrogen.

2015 starting point



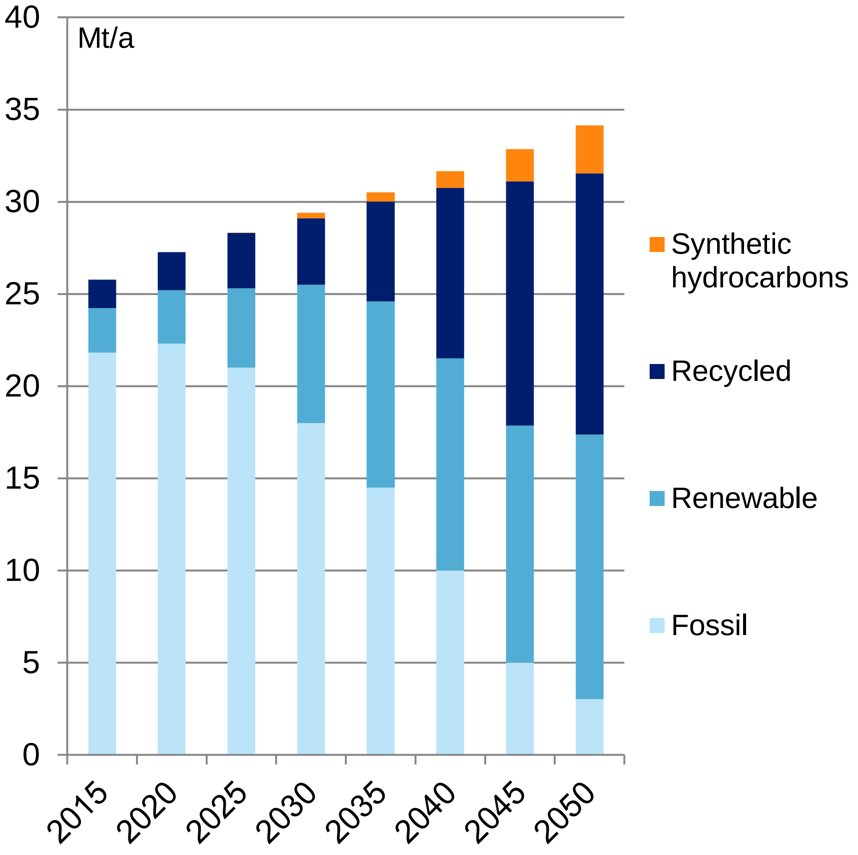
2050



IN FEEDSTOCK ANALYSIS, CARBON NEUTRAL CHEMISTRY 2045 SCENARIO HAS AN INCREASING DEFOSSILISATION

This admittedly very tough goal picks up speed after 2025 and accelerates

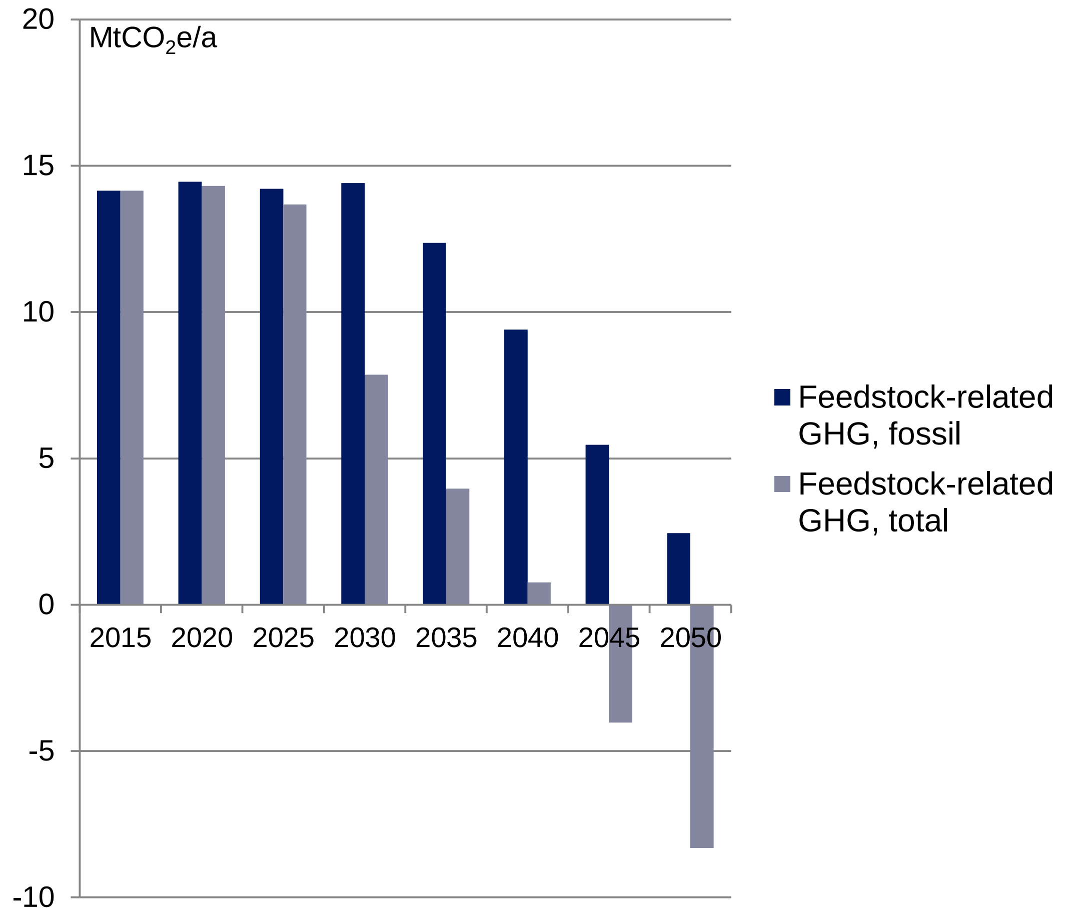
- Targeting a chemical industry with less than 10% fossil content in 2050.
- A rapid shift towards renewable and recycled raw materials starts after 2025.
- Quantities of novel raw materials are based on actual estimates for their availability. Imports would play a significant role in the future, as they do currently. A change of this magnitude is, however, conceived as possible (again, given many conditions fulfilled).
- The amount of recycled and renewable amounts grow 6-10 fold compared to current situation.
  - A large part of the feedstock is completely novel to chemical industry. Adding complexity and flexibility into process operations would enable using new raw materials and producing a wider array of products.
  - Synthetic hydrocarbons estimated to require 7-8 MtCO_2/a captured in 2050.
- As a comparison, the amount of renewable materials is equal to twice the current pulp production in Finland, albeit the largest part of renewables come from algae oil production.
- **It is imperative that entire value chains and dynamics of key material flows of modern society get transformed for this scenario to come true.**
  - Preconditions: recycling infrastructure, deep sector integration, strategic and synergistic locations, supporting legislation, large-scale investments, technology advancement and changes in consumer behaviour.



IN FEEDSTOCK ANALYSIS, CARBON NEUTRAL SCENARIO 2045 REACHES CARBON NEGATIVITY FOR FEEDSTOCK EMISSIONS

A tough goal, and dramatic impacts, from 14 to -8 MtCO2

- This analysis is a comparison of GHG emissions related to feedstock up until the inbound gate of chemical industry.
- Total GHG impact includes fossil and (biogenic) CO_2 intake of renewable materials.
- Increasing the share of renewable and recycled raw materials starts decreasing the feedstock GHG emissions fast after 2030.
- By 2050, with current GWP data and estimates of the feedstock,
  - annual feedstock-related fossil emissions would be decreased from ca. 14 to 2 $MtCO_2$ and
  - annual total emissions (accounting for biogenic carbon) would decrease from 14 to ca -8 $MtCO_2$.



Results are estimates based on published LCA information.

SCENARIOS (FEEDSTOCK)

COMPARISON OF RESULTS

COMPARISON OF FEEDSTOCK COMPOSITION IN 2050

A very significant defossilisation in two variants

1 BAU

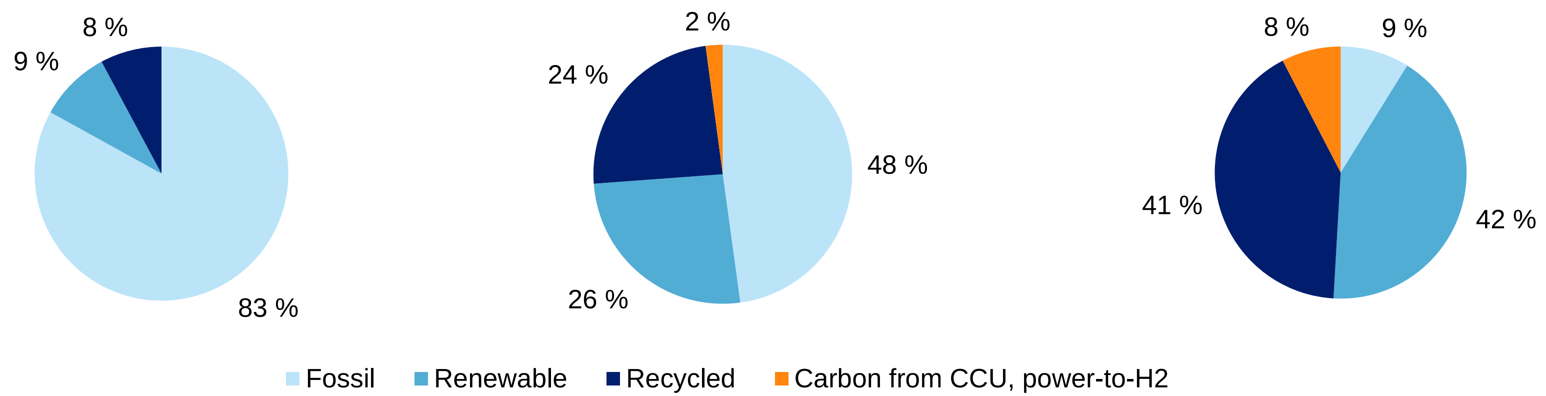
- No changes to current composition
- Amounts grow due to volume growth
- Fossil remains the major source of feedstock
- No additional investment, electricity or biomass demand

2 Fast development

- Recycled and renewable feedstock streams grow significantly
- Additional investments
- Significantly reduced GHG impact for Scope 3 emissions

3 Carbon neutral 2045

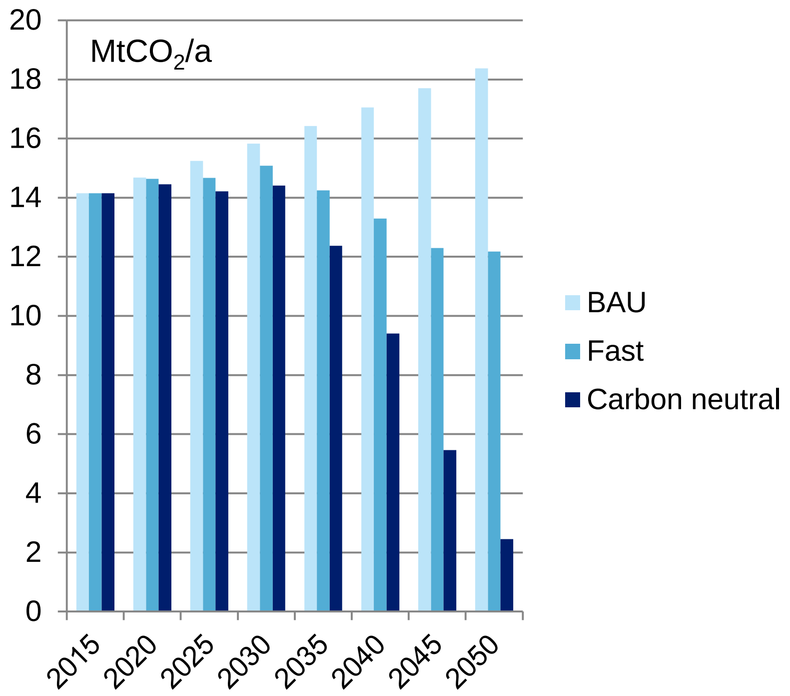
- A complete transformation of the feedstock portfolio by 2050
- Chemical industry could become carbon-negative
- Significantly increased demand for recycling infrastructure, energy demand and investments



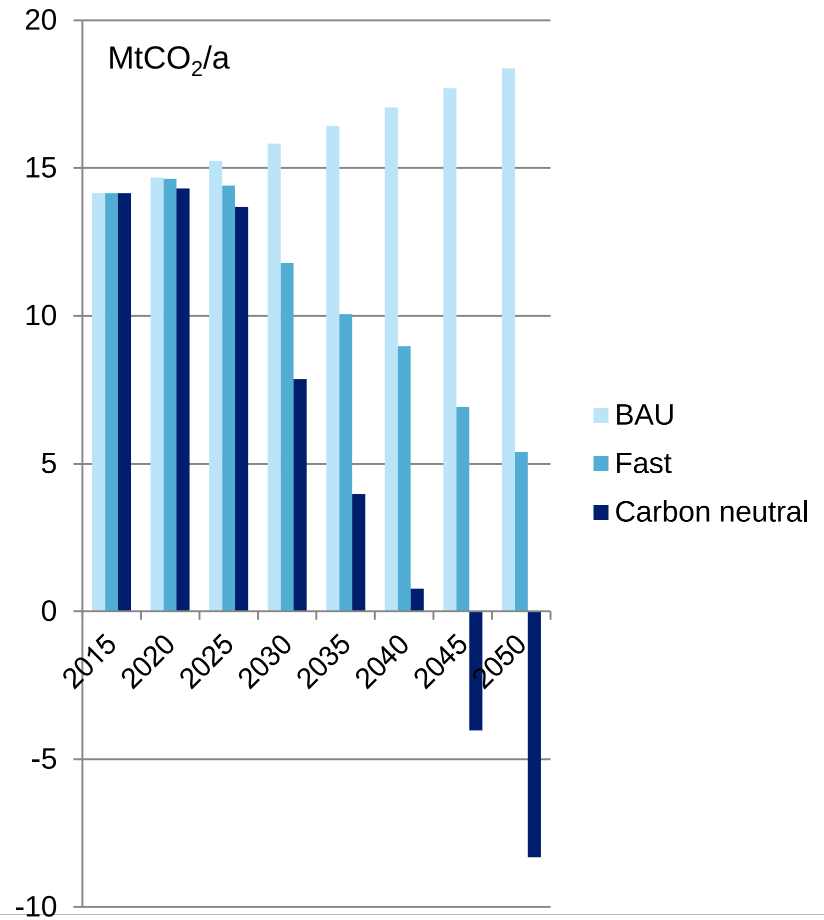
COMPARISON OF FEEDSTOCK GHG EMISSIONS WITH VERY NOTABLE CHANGES

In the extremely ambitious scenario, the feedstock of the industry is estimated to become a carbon sink, absorbing CO_2 as it is prepared or cultivated

Fossil GHG of feedstock



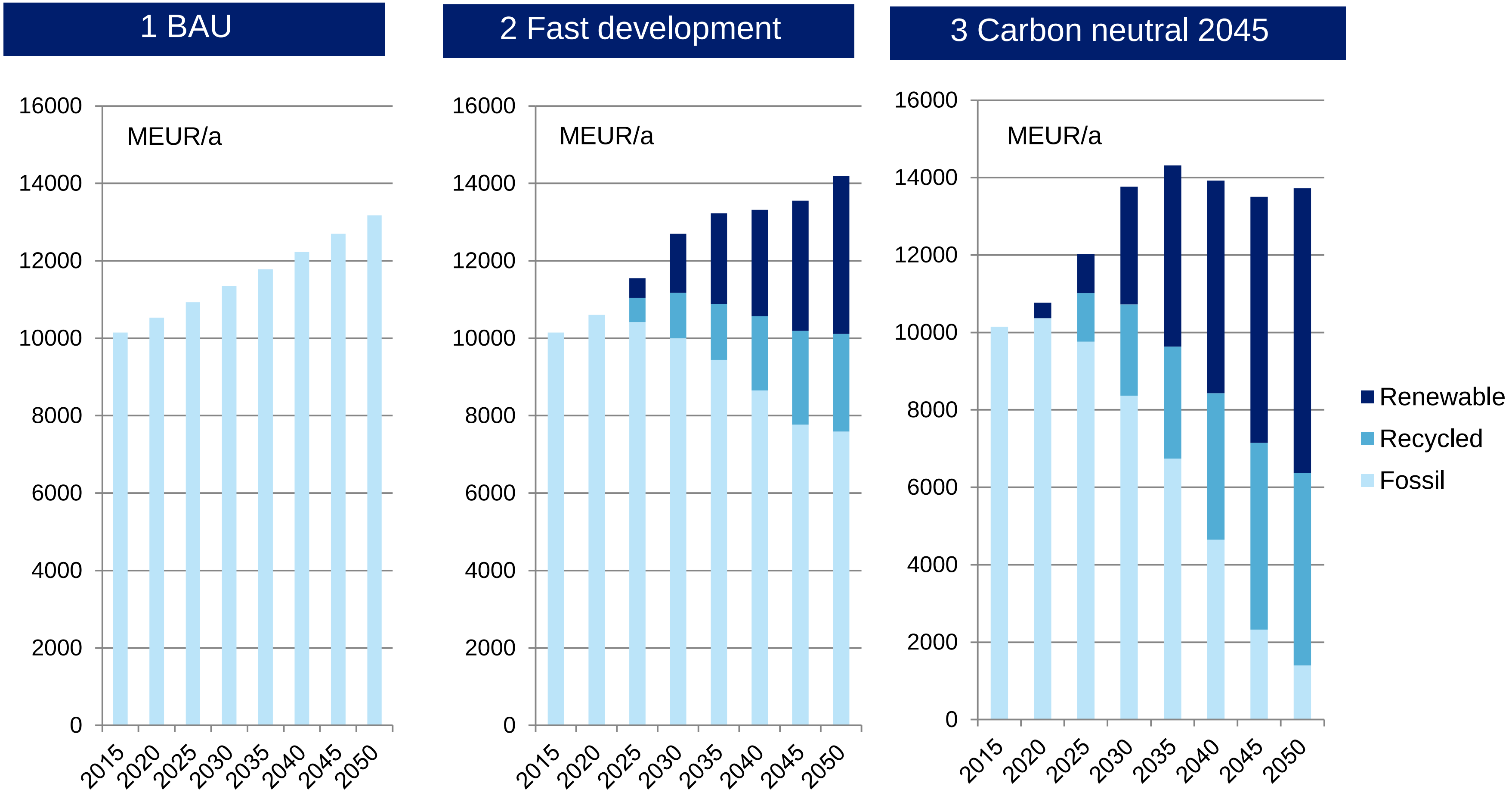
Fossil and biogenic GHG of feedstock



Results are estimates based on published LCA information.

COMPARISON OF MAIN RAW MATERIAL COSTS GIVES SOMEWHAT SIMILAR RESULTS WITH LARGE UNCERTAINTIES

Procurement costs to obtain the bulk raw materials at the gate of chemical facility are estimated similar across the scenarios, albeit uncertainties are large



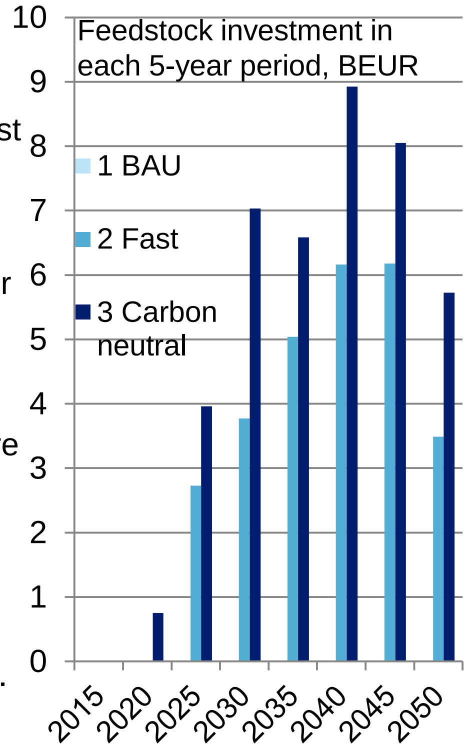
Note: Estimates of raw material costs only include the industry-level main bulk raw materials which are studied in the feedstock scenarios. Crude oil price of $60 US/bbl is assumed.

COMPARISON SHOWS VERY SIGNIFICANT INVESTMENT AND ELECTRICITY INCREASES

Defossilisation has its costs

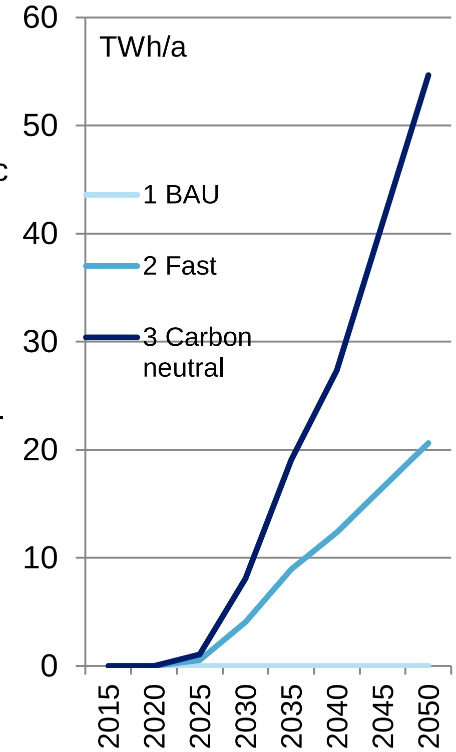
Additional investments due to new feedstock

- Additional asset investments due to feedstock changes total 27 BEUR in Fast development scenario and 41 BEUR in Carbon neutral scenario over the period 2015-2050.
- Considering that no large investments are estimated before 2025, annual feedstock investments would average close to 1 BEUR in 2025-2050.



Additional electricity demand due to new feedstock

- The most electricity-intensive feedstocks include the manufacturing of algae oil and synthetic hydrocarbons.
- Electricity increases must be from low-carbon sources for feedstock changes to yield GHG reductions.
- *Currently*, chemical industry in Finland consumes annually 7 TWh of electricity.
- *Currently*, total electricity production capacity of Finland is 65 TWh.



Note: Amounts of investments only include investments required for new production assets capable of processing the new feedstock. Investments into recycling infrastructure, energy infrastructure or manufacturing of feedstock are not included. A part of the investments overlaps with the asset investments of the scope 1 and 2 scenarios and the numbers are not directly additive.

ROADMAP TO THE ROADMAP

POINTS TO REMEMBER: TOOLBOX FOR CHANGE

Out of the ocean of facts, remember this

- **NO SOLUTION FITS 400 FINNISH CHEMICAL INDUSTRY COMPANIES:** first we have five clusters for the companies, then examples of what could be done in that cluster – which differs by company.

- **CHECKLISTS USUALLY HELP:** the items to do and action plan examples may at the very least serve as checklists of "have we done that/do we need to consider it".

- **A TOOLBOX IS FOR ALL:** and the roadmap is for all members. Some are further, some less far, all have to face the climate challenges.

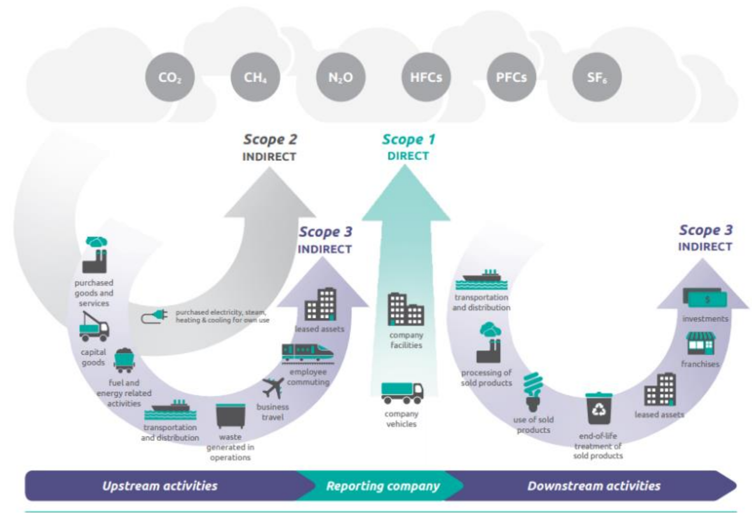
TOOLBOX

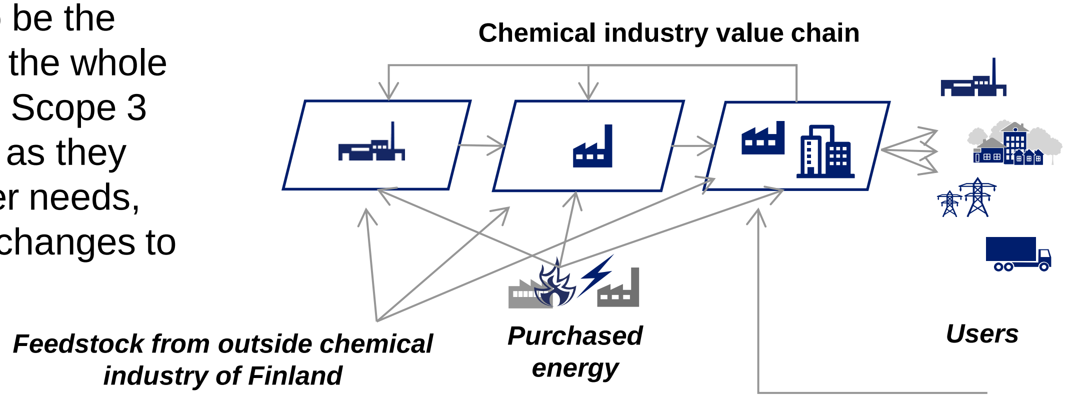
INTRODUCTION:
OVERVIEW OF SOURCES OF EMISSIONS AND GENERAL SOLUTIONS TO REDUCE THEM IN CHEMICAL COMPANIES

WHERE DO GHG EMISSIONS OF A COMPANY COME FROM?

Process emissions and own energy-related emissions are the tip of the iceberg, energy and raw materials constitute the majority of indirect GHG emissions

- Greenhouse gas (GHG) emissions are reported separately for
  - **Scope 1**: direct emissions from own processes and energy generation
  - **Scope 2**: indirect emissions related to purchased heat and electricity
  - **Scope 3**: indirect emissions upstream and downstream: feedstock, transportation, use and end-of-life of products
- The significance of Scope 1, 2 and 3 emissions in relation to each other varies across different companies. For most, Scope 3 emissions (including feedstock, end-of-life, etc.) are estimated to be the largest, as they potentially cover the whole value chain. However, mitigating Scope 3 emissions are often the hardest, as they depend on supplier and customer needs, as well as potentially significant changes to the manufacturing processes.





WHAT ARE THE MAIN TECHNICAL ALTERNATIVES TO REDUCE DIFFERENT EMISSIONS?

There are clearly defined options to pick from

Direct emissions

- Change the source of heat
  - Fuel switch from CO_2-intensive fuels to low carbon heat sources (e.g. from coal and oil to natural gas, biofuels, synthetic fuels, electrification, waste heat, geothermal)
- Process emissions
  - Process changes
    - Catalysts, new pathways, low-temperature processes
  - Process optimisation
    - Advanced control systems, reduction of down-time an off-spec, automation, AI, etc.
  - Process specificity

CO_2 from purchased energy

- Change the source of heat
  - Fuel switches at source
- Change the source of electricity
  - Power purchase agreements (PPAs) to secure low-carbon electricity
  - Joint venture with energy companies to invest in new energy generation (and storage capacity, e.g. P2X)

Other indirect emissions

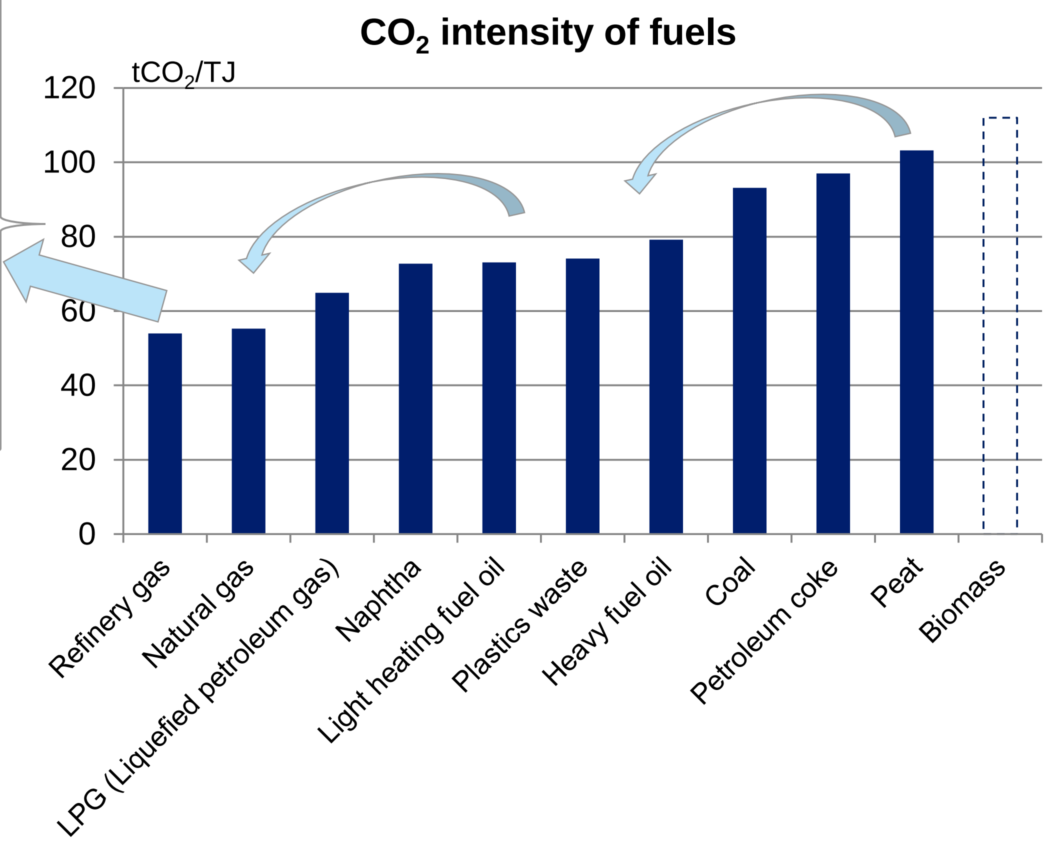
- Feedstock
  - Sourcing: from fossil-based to utilisation of recycled, waste, bio-based and synthetic alternatives
- End-of-life
  - Contribute to recycling systems
- Transportation
  - Transportation shifts: low-carbon transportation fuels, road-to-rail,
  - Logistics optimisation

Note: *The solutions are very process-, plant- and company-specific*. Some locations already exhibit state-of-the-art energy and material efficiency solutions, and optimising their current processes much further is challenging. The potential of other sites to adapt new solutions may be limited by external factors (e.g. availability of feasible low-carbon energy solutions) or sheer physical space required for retrofits (e.g. cannot fit new equipment to current property or process configuration)

ENERGY: FUELS AND A WHOLE CHAIN OF SWITCHES

Many processes require high temperatures – low-carbon heat can come in many forms

- Low-carbon alternatives to fossil fuels include:
  - Synthetic fuels
  - Biofuels
  - Geothermal
  - Waste heat
  - Electrification (heat pumps, hybrid boilers, direct electric heating)
    - Solar, wind, hydro, nuclear, etc. as a low-carbon electricity source
- Changes within fossil energy carriers may be feasible in the transformation. However, risk of stranded assets should not be overlooked.
- Combustion of biomass (in its various forms) may constitute a seemingly easy remedy, as biogenic CO_2 is counted as zero in the current calculation rules. However, calculation changes may be employed in the future since combustion of biomass as fuel is a controversial topic.



Source: Statistics Finland, Fuel classification 2020

ENERGY: ELECTRICITY FROM A FAST DECARBONISING ENERGY SECTOR

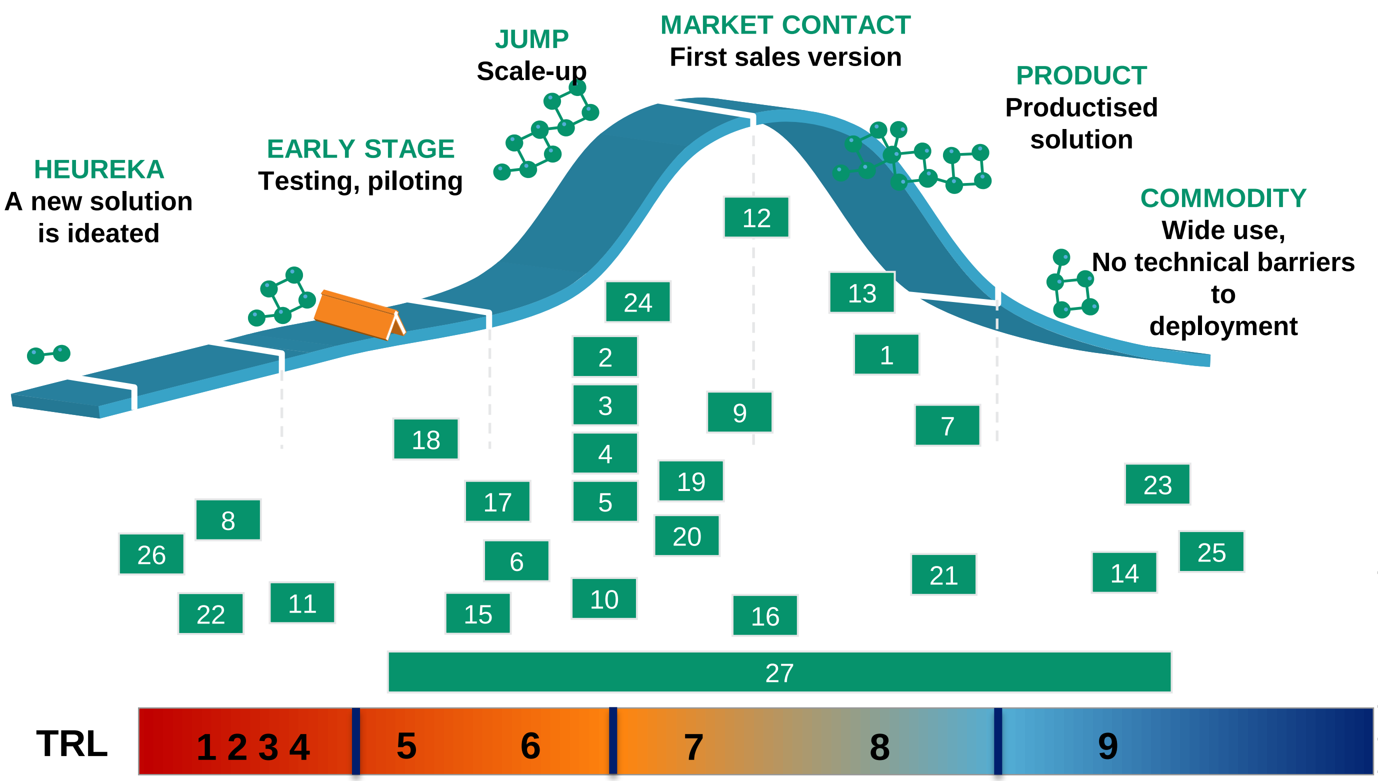
The electricity sector is decarbonising fast in Finland

- Electricity used in Finland is expected to decarbonize by the 2030s.
- The Finnish power market is influenced by the Nordic electricity market (characterized by abundant hydro energy).
- The Nordic electricity market is becoming more integrated to Central European electricity markets through new connections in early 2020s.
- Low-carbon electricity has already been recognized as a scarce, key resource of the 21st century by global technology companies.
  - e.g. Google investing purchasing the production of entire wind farms to be used in data centres.
- Investments into demand flexibility and low-carbon energy are preconditions for the development
  - New business opportunities for the chemical sector include Power-to-chemicals, synthetic fuels, flexible production modes, energy and electricity storage.
  - New investments in planning into wind energy farms in Finland equal 19 GW (current Finnish power capacity 15 GW).

Specific emissions in Year	Electricity ($kgCO_2/MWh$)	District heat ($kgCO_2/MWh$)
2017	90	150
2035	10	50
2050	1	15

THERE IS A RICH TIMELINE OF EMERGING TECHNOLOGIES

New process technologies are emerging on a wide scale to provide GHG emissions reduction alternatives



Power-to-chemicals

1. Power-to-H2
2. Power-to-methanol
3. Power-to-olefins
4. Power-to-BTX
5. Power-to-ammonia

Raw material and product portfolio changes

6. Biomass to methanol
7. Biomass to bioethanol
8. Biomass to BTX (lignin-based)
9. Bionaphtha to olefins
10. Biomass to olefins
11. Hydrogen via methane pyrolysis
12. Biohydrogen
13. Biobased diesel (HVO)
14. **Energy efficiency**

CCU/CCS

15. Pre-combustion
16. Post-combustion
17. Oxyfuel combustion
18. CO_2 mineralisation

Electrification & fuel switch

19. Steam production by electric/hybrid boilers
20. Steam production by electric furnaces
21. Coal to natural gas to biogas
22. **Synthetic biology & biochemistry**

Circular economy

23. Mechanical recycling
24. Chemical recycling
25. **Process development**
26. **Bubbling under technologies**
27. **Digitalisation**

TOOLBOX:

EXAMPLE COMPANIES AND THEIR SOLUTIONS

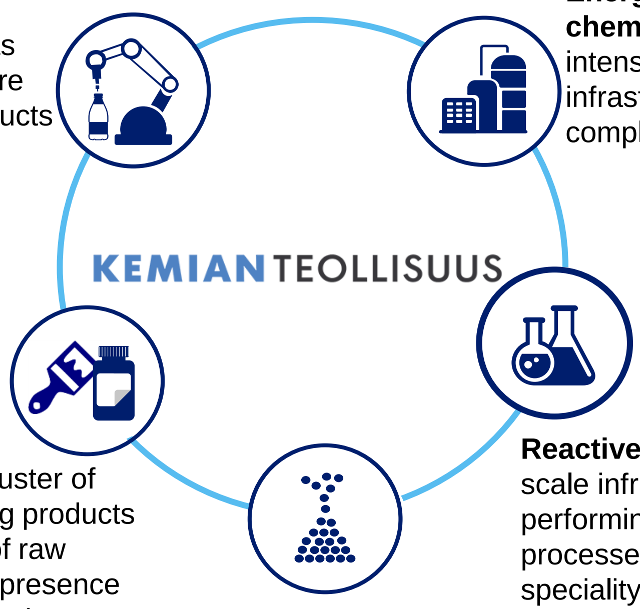
TO MANAGE THE COMPLEX WHOLE, A CLASSIFICATION OF COMPANIES OF CHEMICAL INDUSTRY IN FINLAND WAS MADE

Instead of 400 companies, 5 clusters of companies

- The chemical industry in Finland is a heterogeneous combination of companies which are often highly vertically integrated or may operate in completely different value chains.
- Many solutions, such as low-carbon fuels, are common to the whole sector, while some are very process-specific.
- Confidentiality of individual companies requires an anonymization of data. A division into five clusters was made to account for the heterogeneity while maintaining a holistic view.
- This classification is inherently flawed to a certain degree, as even a singly company may have operations that could be placed in several clusters. However, this classification makes the results more specific and yet easier to generalize.

Converters: Cluster of plants that manufacture consumer products

Energy-intensive chemical industry: Capital intensive large scale infrastructures performing complex processes



Reactive chemistry: Middle scale infrastructure performing complex processes, products including speciality chemicals and advanced materials

Formulating: Cluster of plants formulating products by mixing a set of raw materials (in the presence of a reaction or not)

Inorganic chemistry: Cluster of plants specialised in inorganic chemical products

ENERGY-INTENSIVE CHEMICAL INDUSTRY

What is it and how does it look like?

Average company in Energy-intensive chemical industry

> 1 Mt	3,500 GWh	1 : 4	620 ktCO_2	190 ktCO_2	2,400,000 m^3	< 10%
Total production volume	Total energy consumption	Energy from electricity : fuels	GHGScope 1 (direct emissions)	GHGScope 2 (purchased energy)	Total water consumption	Share of renewable and recycled feedstock

Typical raw materials:
Crude oil, natural gas, naphtha, hydrogen, sodium chloride, chlorine, sodium hydroxide, ferrosulfate

Typical energy sources:
heavy fuel oil, heating fuel oil, wastes, hydrocarbons (side products and natural gas), propane, LNG, coal, wood, black liquor, bioenergy, hydrogen, electricity…

Typical products
Transport fuels (gasoline and diesel), solvents, plastics, large volume specialty chemicals, intermediates…

Note: the numbers are based on aggregate Responsible Care data by Kemianteollisuus ry. Average numbers do not strictly correspond to any individual companies and they should be understood as indicative only.

EXAMPLE COMPANY: ENERGY-INTENSIVE CHEMICAL INDUSTRY

A profile that may not exactly match a real company, but represents the cluster

Description

Average company

620 ktCO_2
GHGScope 1 (direct emissions)

190 ktCO_2
GHGScope 2 (purchased energy)

1 : 4
Energy from electricity : fuels

3,500 GWh
Total energy consumption

> 1 Mt
Total production volume

2,400,000 m^3
Total water consumption

< 10%
Share of renewable and recycled feedstock

- Large chemical facilities comprise the backbone of the chemical industry. Facilities are capital-intensive and operational for long periods of time. Major investments and retrofits to reduce emissions are only possible during a turnaround (typically every 4 – 6 years).
- Typical energy-intensive unit processes include distillation, reforming, polymerization. Products include transport fuels, petrochemicals, plastics, large volume specialty chemicals.
- Operating largest plants in the industry, and most of energy is obtained from fossil fuel combustion. Own emissions (Scope 1) are very large.
- The share of recycled and renewable raw materials of all feedstock remains very low. Changing sources for feedstock in this category is very challenging, but results in massive GHG reduction throughout the value chain.
- Companies are large multinationals, and include Neste, Kemira, Borealis, etc.

Main solutions

In the short term

- Fuel switches to low-carbon fuels; gain supply agreements for low-carbon electricity; invest in heat pumps, enhance efficiency

In the long term

- New process technology, e.g. through synthetic biology, catalysts, reaction engineering and low-temperature processes (e.g. crackers)
- Substitute fossil-origin feedstock with low-carbon alternatives: synthetic chemicals, biomass and recycled materials. Capture and utilisation of CO_2 as feedstock.

Specific drivers and challenges

Drivers

- Shifts and pressure from transportation sector affect product portfolio

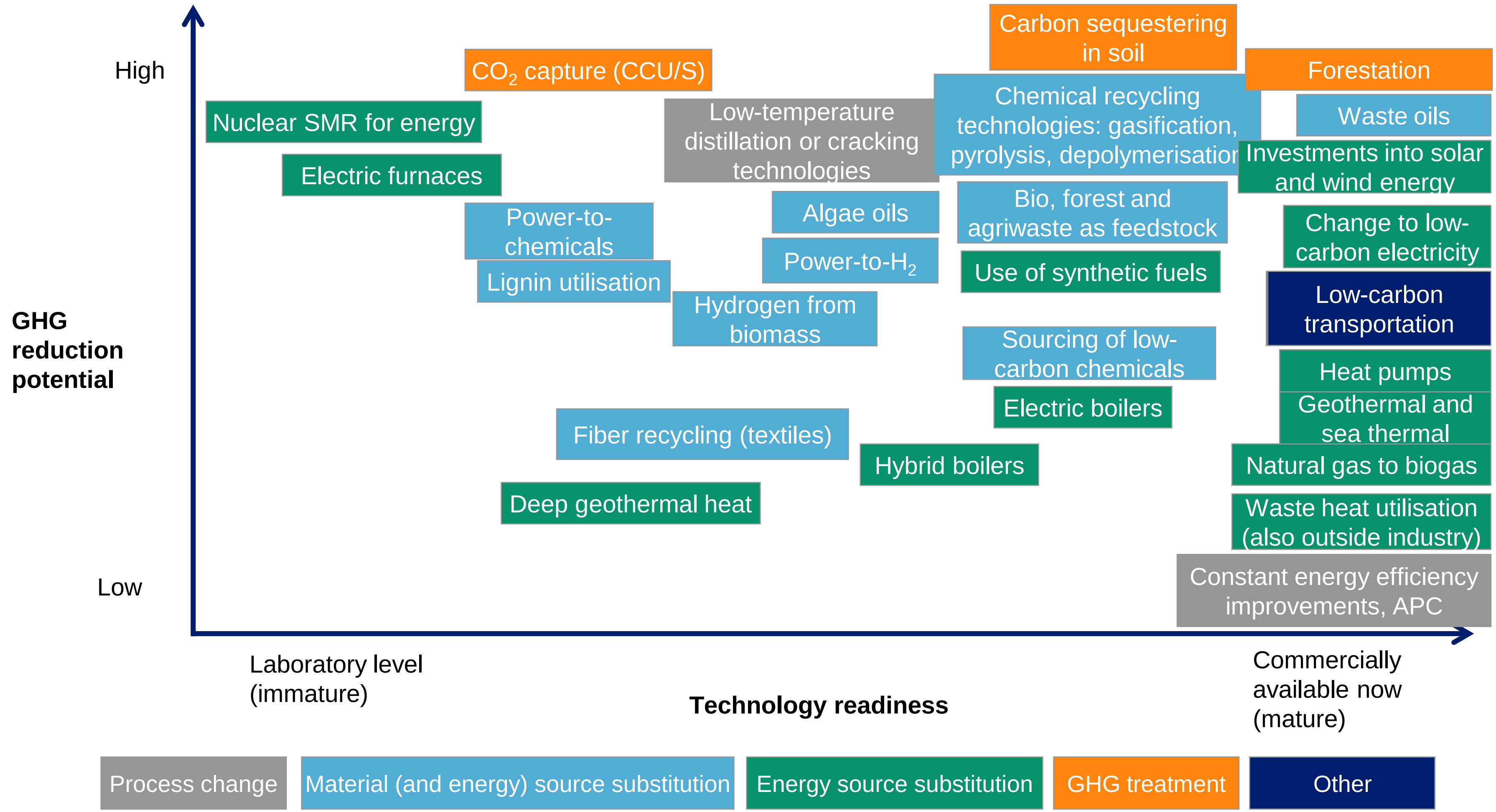
Challenges

- Complex facilities are old and require heavy investment, if process is significantly altered.
- Feedstock volumes are large (e.g. 15 Mt of crude oil); alternative feedstock is not as abundantly available.
- Further focus required on recycling and material efficiency

TOOLBOX TECH FOR ENERGY-INTENSIVE CHEMICAL INDUSTRY

A classified selection to pick from

The toolkit below covers GHG emissions in Scope 1, 2 and 3 and additional means to offset emissions through compensation scheme, e.g. forestation projects.



REACTIVE CHEMISTRY

What is it and how does it look like?

Average company in Reactive chemistry cluster

> 100 kt	170 GWh	1 : 2,5	20 ktCO_2	17 ktCO_2	160,000 m^3	80%
Total production volume	Total energy consumption	Energy from electricity : fuels	GHGScope 1 (direct emissions)	GHGScope 2 (purchased energy)	Total water consumption	Share of renewable and recycled feedstock

Typical raw materials:
Styrene, butadiene, pentaerythritol, MCAA, polyvinylalcohol, phenol, anthaquinone, maleic anhydride, phtalic anhydride

Typical energy sources:
heavy fuel oil, heating fuel oil, natural gas, biomass, wastes, electricity

Typical products
Enzymes, dispersion polymers, resins, biochemicals, industrial gases, specialty chemicals

Note: the numbers are based on aggregate Responsible Care data by Kemianteollisuus ry. Average numbers do not strictly correspond to any individual companies and they should be understood as indicative only. Image sources: Roal, Woikoski.

EXAMPLE COMPANY: REACTIVE CHEMISTRY

A profile that may not exactly match a real company, but represents the cluster

Description

Average company

20 ktCO_2
GHGScope 1 (direct emissions)

17 ktCO_2
GHGScope 2 (purchased energy)

1 : 2.5
Energy from electricity : fuels

170 GWh
Total energy consumption

> 100 kt
Total production volume

160,000 m^3
Total water consumption

80%
Share of renewable and recycled feedstock

- Middle scale infrastructure performing complex processes. Typical products include enzymes, dispersion polymers, resins, biochemicals, industrial gases to be used in various industries.
- Processes are typically rather energy-intensive, and a majority of energy is derived from fuels.
- Share of recycled and renewable feedstock is the highest in all the clusters, up to 80 % of all feedstock.
- Companies include Cabb, Linde Gas, Roal, etc.

Main solutions

In the short term

- Purchase electricity via wind and solar power PPA
- Purchase own solar panels onto rooftops
- Invest in geothermal energy and heat-pumps
- Gain a supply agreement for biogas
- Initiate marketing of new products based on recycled and renewable raw materials
- Research, develop and pilot products and solutions based on non-fossil, recycled and renewable raw materials

In the long term

- Develop own mechanical and chemical recycling processes, value chains and partnerships
- Integrate into raw material supply chain

Specific drivers and challenges

Drivers

- Pressure from downstream partners. Large part of the business is B-to-B.

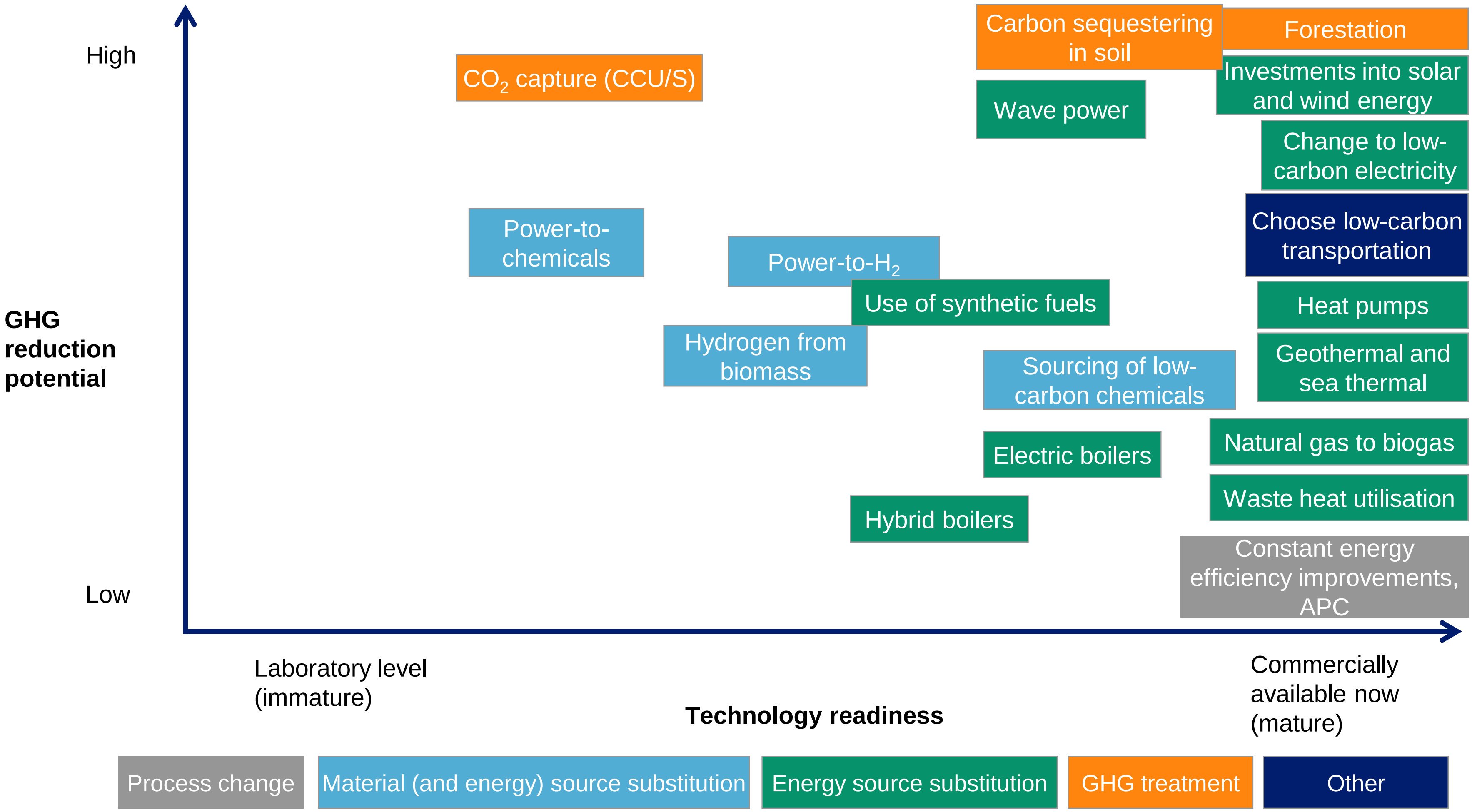
Challenges

- A lot of imported specialty chemicals are used as raw materials, fossil origin may be hard to substitute

SOLUTIONS FOR REACTIVE CHEMISTRY

A classified selection to pick from

The toolkit below covers GHG emissions in Scope 1, 2 and 3 and additional means to offset emissions through compensation scheme, e.g. forestation projects.



INORGANIC CHEMISTRY

What is it and how does it look like?

Average company in Inorganic chemistry cluster

1 Mt	430 GWh	1 : 3	53 $ktCO_2$	22 $ktCO_2$	1,100,000 m^3	12%
Total production volume	Total energy consumption	Energy from electricity : fuels	GHGScope 1 (direct emissions)	GHGScope 2 (purchased energy)	Total water consumption	Share of renewable and recycled feedstock

Typical raw materials:
Nitric acid, ammonia, KCl, K_2SO_4, apatite, sulfates, gypsum, biotite, calcium chloride, calcium carbonate, Na silicate, sulphuric acid, hydrochloric acid, phosphoric acid

Typical energy sources:
heavy fuel oil, heating fuel oil, wastes, electricity

Typical products
Fertilizers, minerals, metals and salts

Note: the numbers are based on aggregate Responsible Care data by Kemianteollisuus ry. Average numbers do not strictly correspond to any individual companies and they should be understood as indicative only. Image sources: Cision News, Recycling International

EXAMPLE COMPANY: INORGANIC CHEMISTRY

A profile that may not exactly match a real company, but represents the cluster

Description

Average company

53 ktCO_2
GHGScope 1
(direct emissions)

22 ktCO_2
GHGScope 2
(purchased energy)

1 : 3
Energy from electricity : fuels

430 GWh
Total energy consumption

1 Mt
Total production volume

1,100,000 m^3
Total water consumption

12%
Share of renewable and recycled feedstock

- Inorganic chemistry is integrated to the metals and minerals sector. Energy intensive processes include crushing, grinding and electrolysis. Products include fertilizers, minerals, metals and salts and can be used in e.g. battery chemicals, pulp and paper industry, paints, construction industry and agriculture.
- Processes are highly energy-intensive, and energy is primarily derived from fuels. Water is also used in vast quantities.
- Raw materials include only 12 % renewable and recycled content. The largest potential in replacing raw materials comes from recycling of existing materials, which is the only way to replace virgin mineral flows.
- Companies include Yara, Elementis, Freeport Cobalt, etc.

Main solutions

In the short term

- Purchase electricity via wind and solar power PPA
- Purchase own solar panels onto rooftops
- Invest in geothermal energy and heat-pumps
- Gain a supply agreement for biogas
- Initiate marketing of new products based on recycled raw materials
- Research, develop and pilot products and solutions based on non-fossil, recycled and renewable raw materials

In the long term

- Develop own mechanical and chemical recycling processes, value chains and partnerships
- Integrate into raw material supply chain

Specific drivers and challenges

Drivers

- Pressure from downstream partners and environmental groups

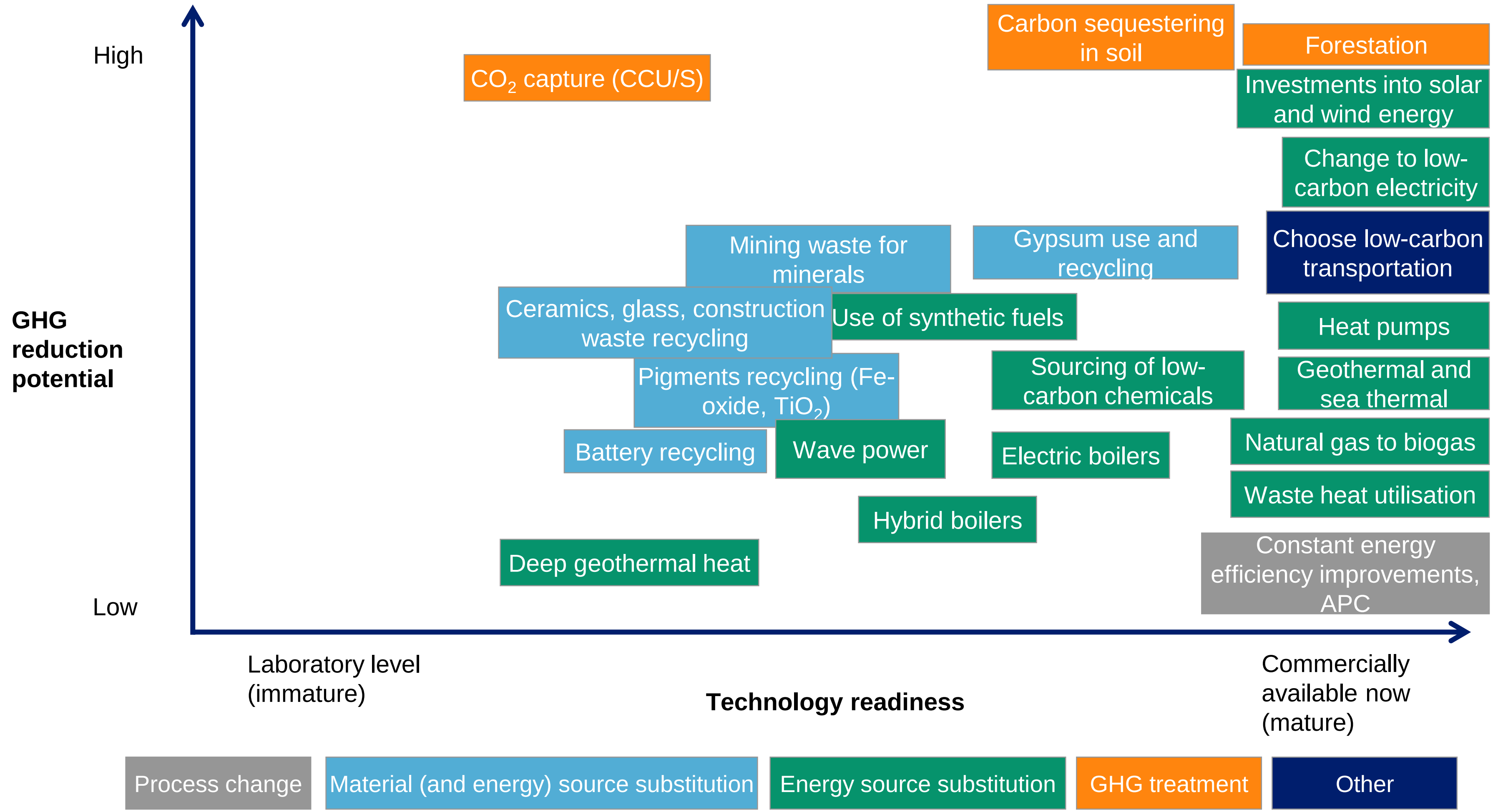
Challenges

- Perceived difficulties in changing the feedstock

SOLUTIONS FOR INORGANIC CHEMISTRY

A classified selection to pick from

The toolkit below covers GHG emissions in Scope 1, 2 and 3 and additional means to offset emissions through compensation scheme, e.g. forestation projects.



FORMULATORS

What is it and how does it look like?

Average company in Formulator cluster

20 kt	35 GWh	1.4 : 1	0.2 ktCO_2	2 ktCO_2	90,000 m^3	< 10%
Total production volume	Total energy consumption	Energy from electricity : fuels	GHGScope 1 (direct emissions)	GHGScope 2 (purchased energy)	Total water consumption	Share of renewable and recycled feedstock

Typical raw materials:
Pharmaceutical ingredients, specialty chemicals, pigments, organic solvents (e.g. ethanol toluene, xylene, alcohols), resins, polyesters, carboxylic acids, binders, fillers

Typical energy sources:
Electricity, heavy fuel oil, heating fuel oil

Typical products
Paints and coatings, pharmaceuticals, detergents, adhesives

Note: the numbers are based on aggregate Responsible Care data by Kemianteollisuus ry. Average numbers do not strictly correspond to any individual companies and they should be understood as indicative only. Image sources: Vantaan Sanomat, SoftwarePoint

EXAMPLE COMPANY: FORMULATOR

A profile that may not exactly match a real company, but represents the cluster

Description

Average company

0.2 ktCO_2
GHGScope 1 (direct emissions)

2 ktCO_2
GHGScope 2 (purchased energy)

1.4 : 1
Energy from electricity : fuels

35 GWh
Total energy consumption

20 kt
Total production volume

90,000 m^3
Total water consumption

< 10%
Share of renewable and recycled feedstock

- Processes are primarily different types of mixing. Typical products include paints and coatings, pharmaceuticals, detergents, adhesives also in the customer product segment.
- Own emissions of a typical company are very small. Most the of the energy demand is met by electricity.
- Share of renewable and recycled feedstocks remains low, under 10 % of all feedstock.
- Companies include Orion, Tikkurila, Kiilto, etc.

Main solutions

In the short term

- Purchase electricity via wind and solar power PPA
- Purchase own solar panels onto rooftops
- Invest in geothermal energy and heat-pumps
- Gain a supply agreement for biogas
- Change packaging materials to recyclable, recycled and bio-based materials
- Initiate marketing of new products based on recycled and renewable raw materials
- Research, develop and pilot products and solutions based on non-fossil, recycled and renewable raw materials

In the long term

- Develop own mechanical and chemical recycling processes, value chains and partnerships
- Integrate into raw material supply chain

Specific drivers and challenges

Drivers

- Consumers and downstream partners demand solutions

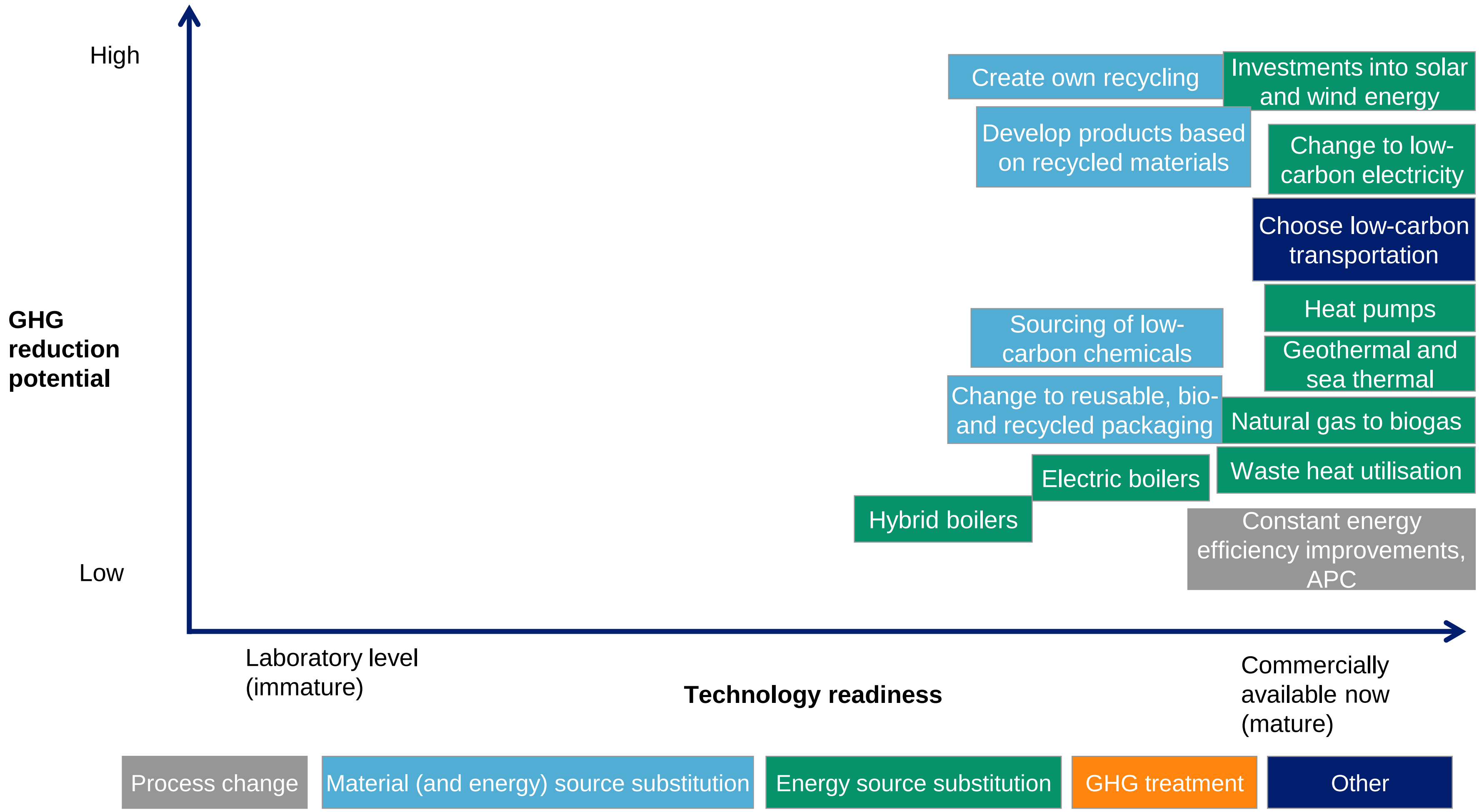
Challenges

- A wide variety of specialties as raw materials

SOLUTIONS FOR FORMULATORS

A classified selection to pick from

The toolkit below covers GHG emissions in Scope 1, 2 and 3 and additional means to offset emissions through compensation scheme, e.g. forestation projects.



CONVERTERS

What is it and how does it look like?

Average company in Converter cluster

< 10kt	22 GWh	1.2 : 1	1.5 ktCO$_2$	2 ktCO$_2$	24,000 m^3	33%
Total production volume	Total energy consumption	Energy from electricity : fuels	GHGScope 1 (direct emissions)	GHGScope 2 (purchased energy)	Total water consumption	Share of renewable and recycled feedstock

Typical raw materials:
Plastic intermediates, natural/synthetic rubber, specialty chemicals, soot, polyester resins, epoxy resins, carbon and glass fibers, solvents

Typical energy sources:
Electricity, heavy fuel oil, heating fuel oil, wastes

Typical products
Plastic, rubber products, tires, composite products.

Note: the numbers are based on aggregate Responsible Care data by Kemianteollisuus ry. Average numbers do not strictly correspond to any individual companies and they should be understood as indicative only. Image sources: Nokian Renkaat Oyj, , Exel Composites Oyj

EXAMPLE COMPANY: CONVERTER

A profile that may not exactly match a real company, but represents the cluster

Description

Average company

1.5 ktCO_2
GHGScope 1 (direct emissions)

2 ktCO_2
GHGScope 2 (purchased energy)

1.2 : 1
Energy from electricity : fuels

22 GWh
Total energy consumption

< 10 kt
Total production volume

24,000 m^3
Total water consumption

33%
Share of renewable and recycled feedstock

- Processes include molding and compounding. Typical products include plastic and rubber products.
- Energy consumption of a typical company is the lowest of all clusters. Majority of energy consumption is in the form of electricity, not fuels.
- Share of recycled and renewable feedstock is higher than some other clusters, but still only 33 % of all feedstock. Procurement of raw materials is the major option to alter the feedstock base. Green packaging solutions present an opportunity.
- Companies include Exel Composites, Nokian Renkaat, ViskoTeepak, etc.

Main solutions

In the short term

- Purchase electricity via wind and solar power PPA
- Purchase own solar panels onto rooftops
- Invest in geothermal energy and heat-pumps
- Gain a supply agreement for biogas
- Develop own mechanical and chemical recycling processes, value chains and partnerships
- Initiate marketing of new products based on recycled and renewable raw materials
- Research, develop and pilot products and solutions based on non-fossil, recycled and renewable raw materials

In the long term

- Integrate into raw material supply chain
- Gain a supply agreement for electrolysis or hydrogen to replace biogas

Specific drivers and challenges

Drivers

- Consumers and downstream partners demand solutions

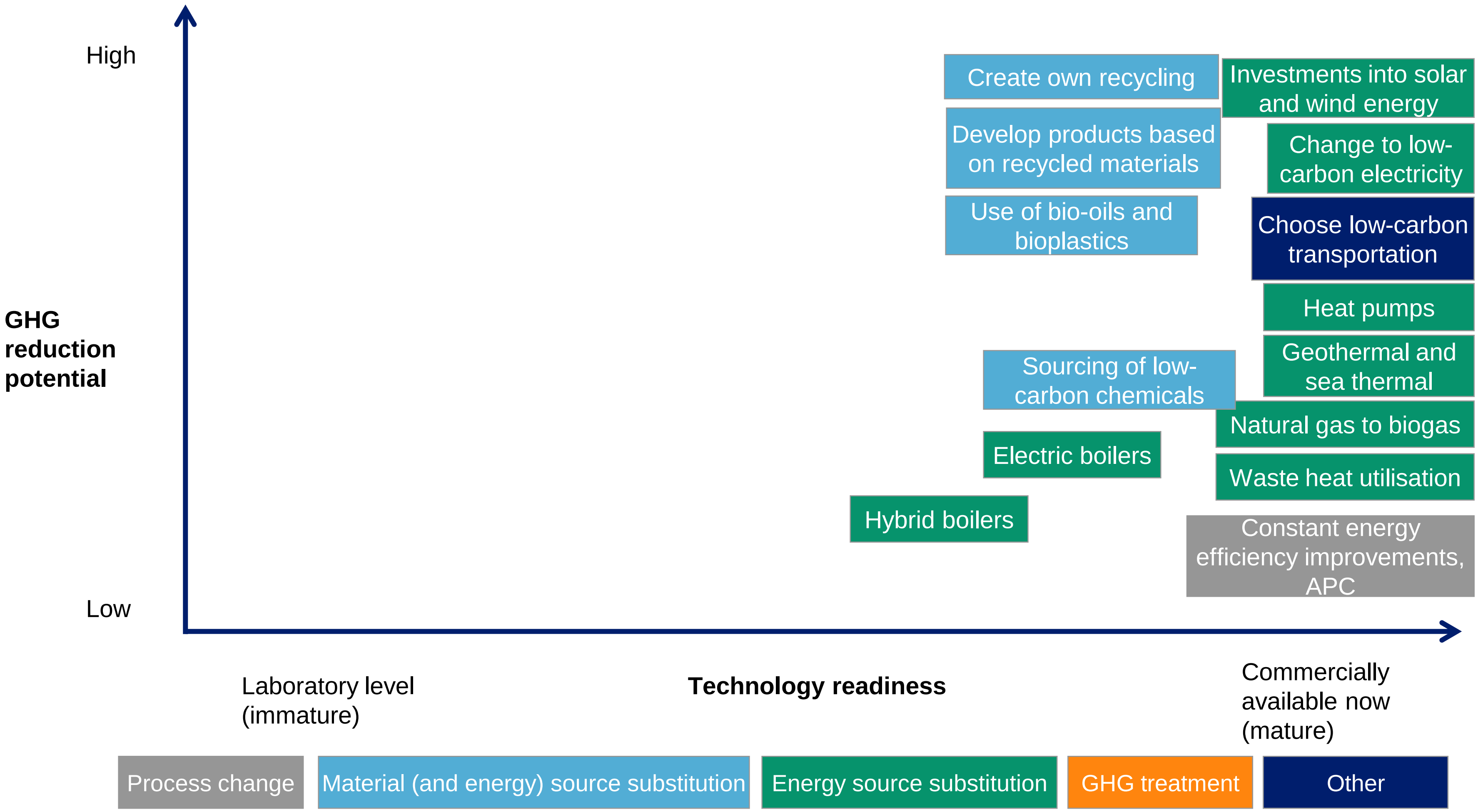
Challenges

- A wide variety of specialties as raw materials

SOLUTIONS FOR CONVERTERS

A classified selection to pick from

The toolkit below covers GHG emissions in Scope 1, 2 and 3 and additional means to offset emissions through compensation scheme, e.g. forestation projects.

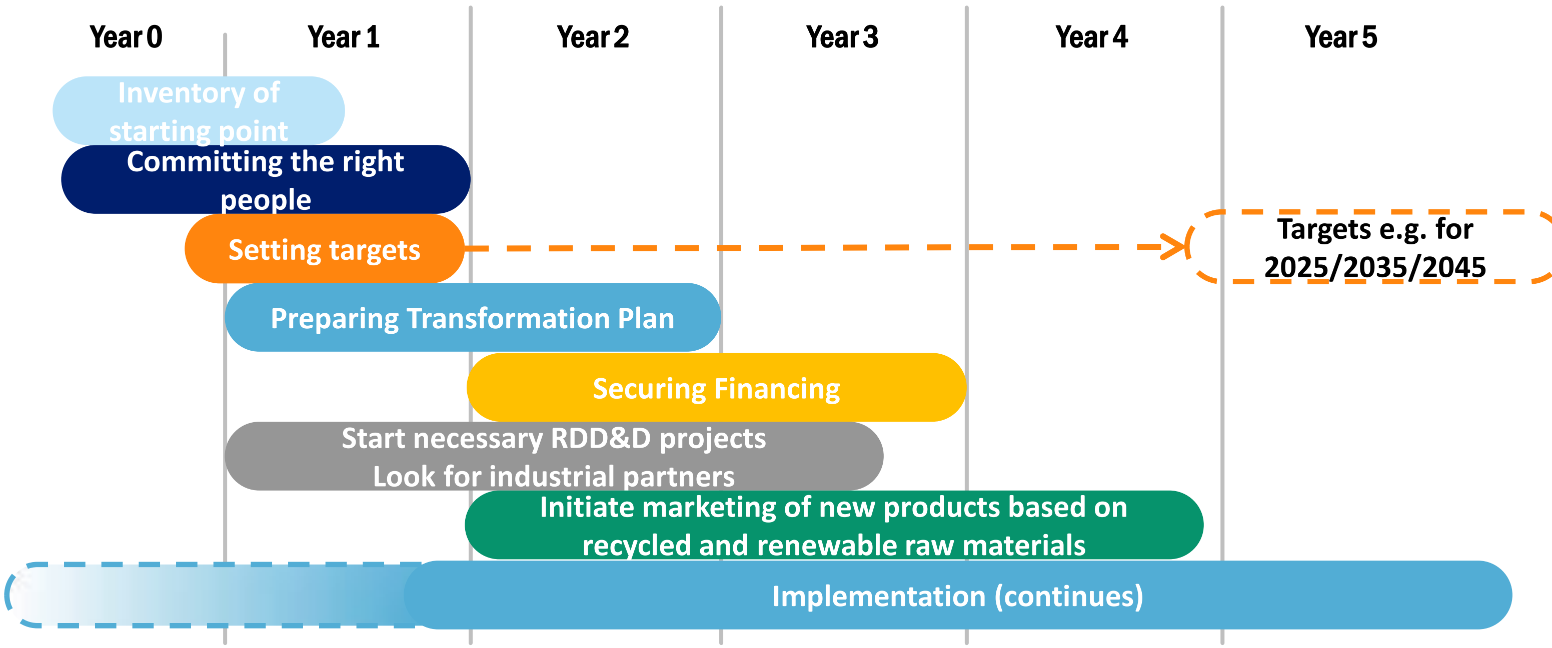


TOOLBOX:

CONCRETE EXAMPLE OF AN ACTION PLAN

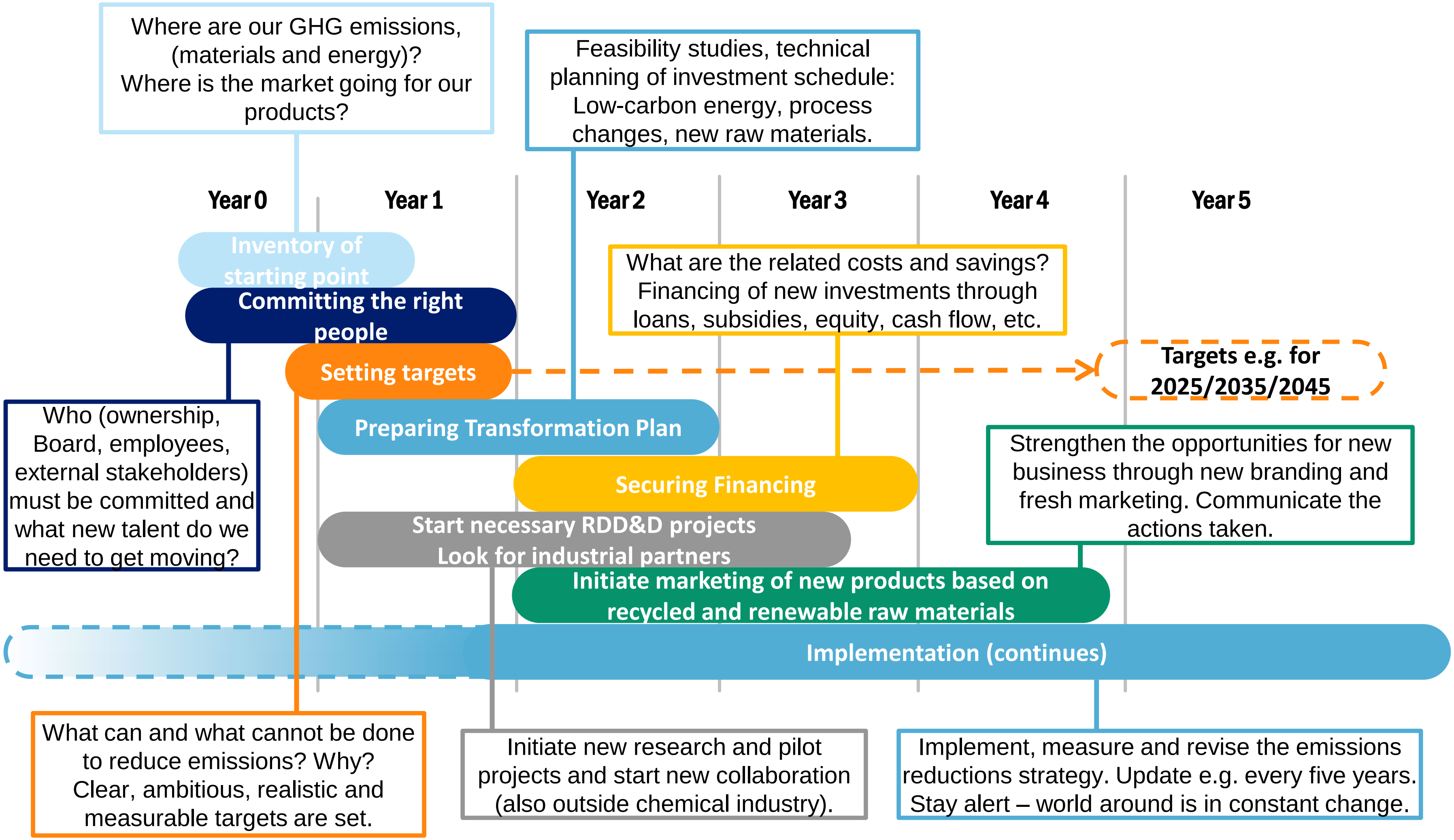
ACTION PLAN: HOW TO GET MOVING

A logical, possible schematic for an action plan



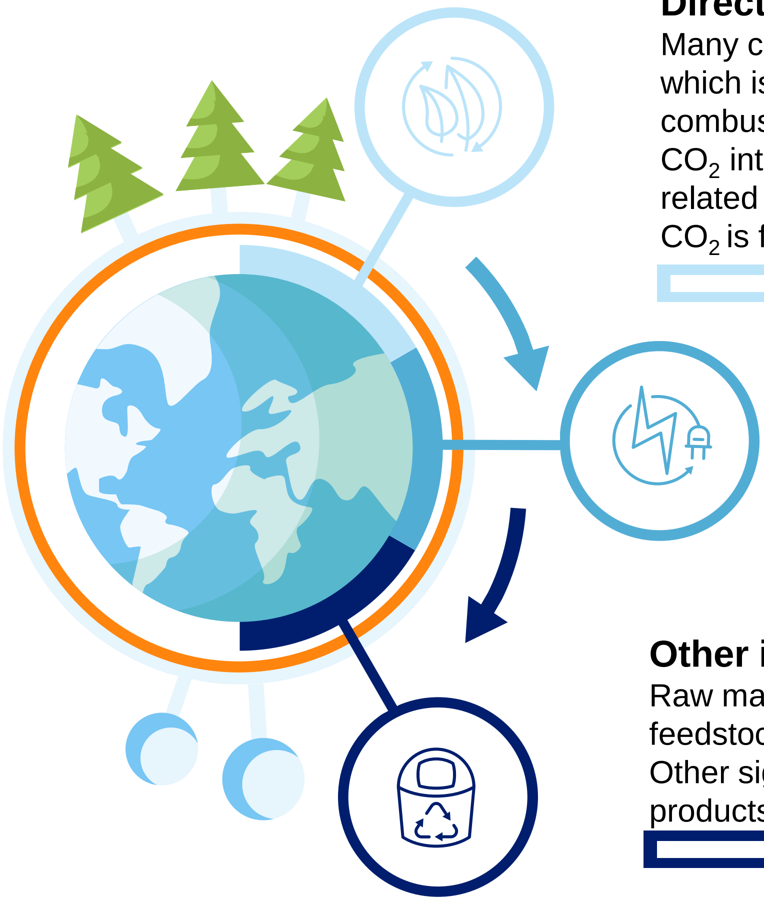
ACTION PLAN: HOW TO GET MOVING

Examples of concrete actions



A TRANSFORMATION PLAN WITH THREE KEY COMPONENTS

GHG emissions of a company come from different sources that should all be covered



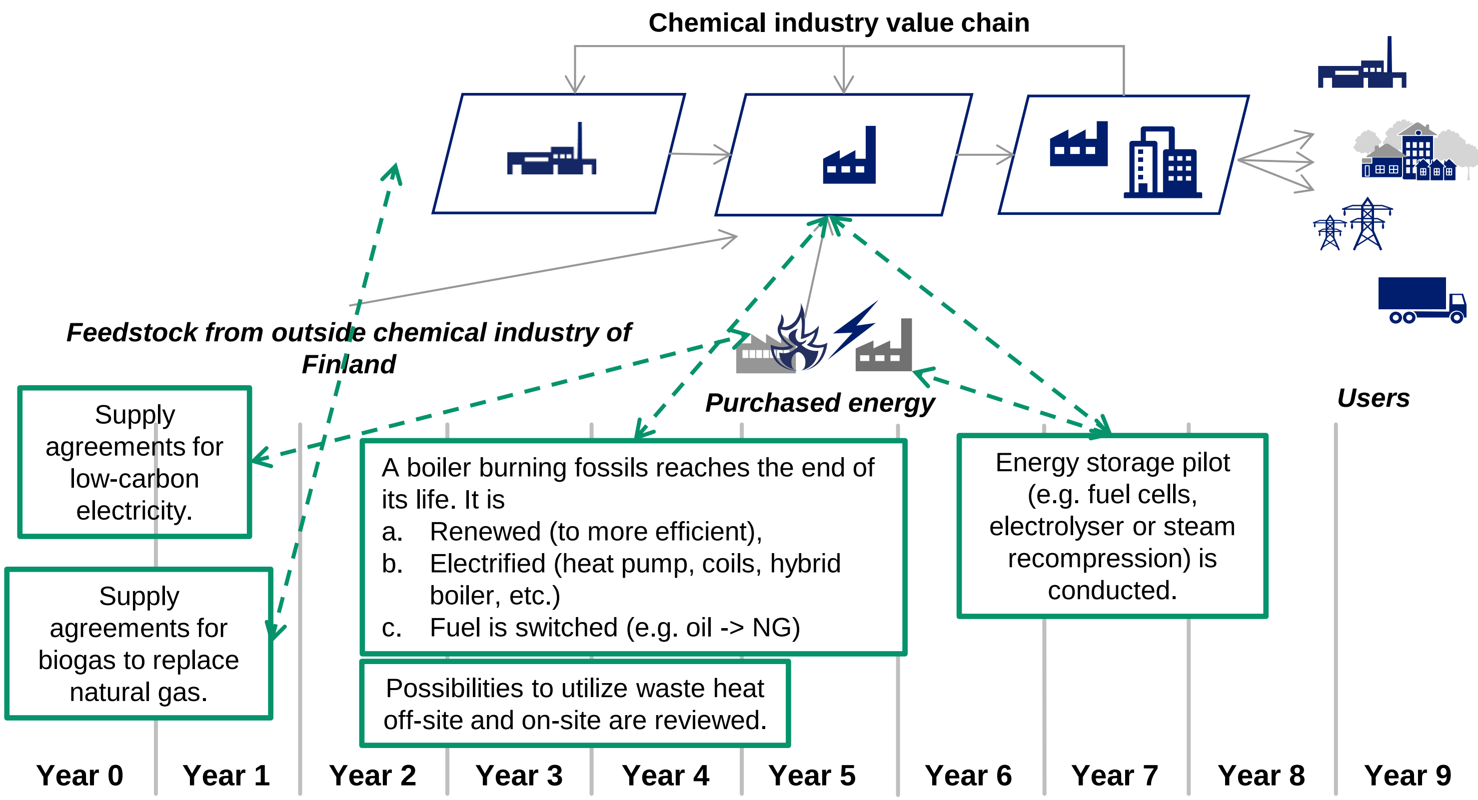
Direct emissions, energy and processes (scope 1)
Many chemical processes require heat and high temperature which is often obtained from combustion of fossil fuels. Once combusted for energy, fossil materials release their carbon as CO_2 into the atmosphere, which contributes to on-site energy-related emissions. Some process emissions may also result, if CO_2 is formed in the reactions from the materials.

Indirect energy-related emissions (scope 2)
Heat and electricity which are used by the industry may be purchased from energy sector. This off-site generation also has a CO_2 impact that is counted as scope 2 emissions.

Other indirect emissions (scope 3)
Raw materials are often based on fossil sources, resulting in feedstock already having a CO_2 footprint.
Other significant sources of GHG emissions include end-of-life of products and travel, transportation and logistics of the company.

EXAMPLE OF TRANSFORMATION PLAN 2020-2030: ENERGY-RELATED EMISSIONS

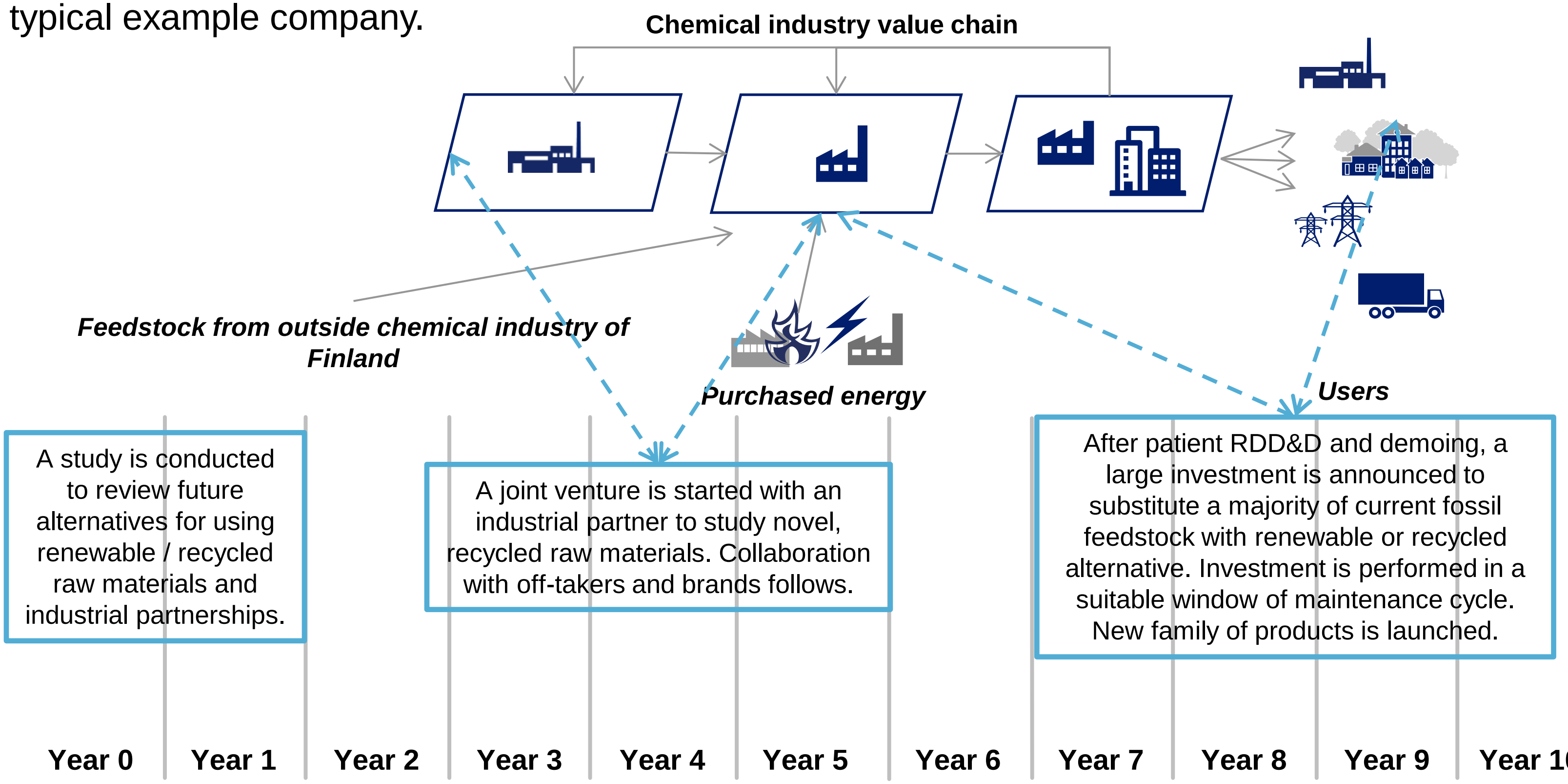
Company X has not really considered GHG emissions reductions in the past. Here's what it could do in the next ten years to reduce emissions from energy use



EXAMPLE OF TRANSFORMATION PLAN 2020-2030: MATERIAL-RELATED EMISSIONS

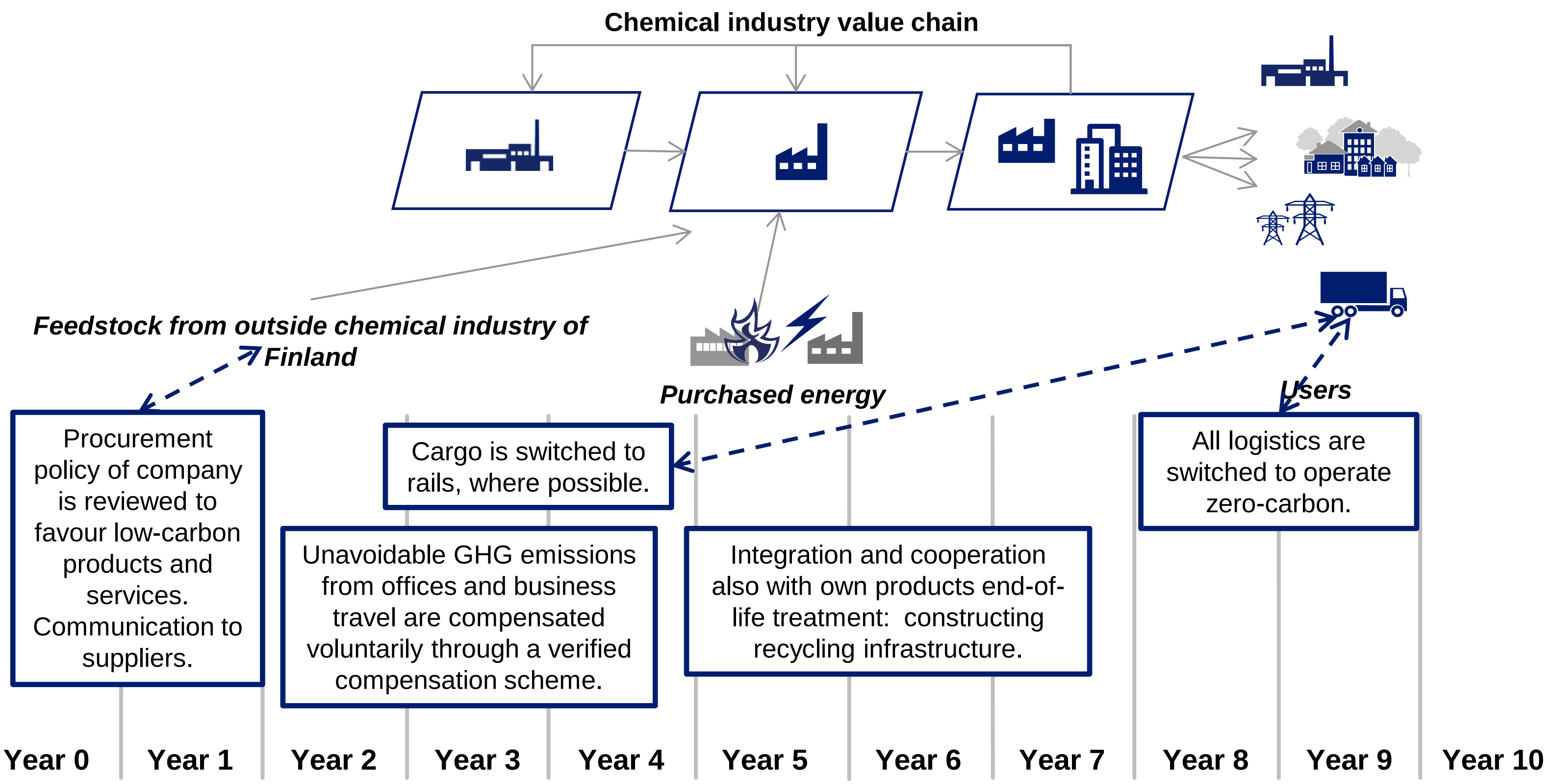
Company X has not really considered GHG emissions reductions in the past. Here's what it could do in the next ten years to reduce emissions from materials use

- Material use can also cause direct process emissions as a result of CO_2-releasing reactions. Solutions to these emissions are highly process-specific (e.g. alternative synthesis routes, catalyst use, reaction engineering, carbon capture, etc.) and are not included in these actions taken by a typical example company.



EXAMPLE OF TRANSFORMATION PLAN 2020-2030: INDIRECT EMISSIONS OTHER THAN FEEDSTOCK

Company X has not really considered GHG emissions reductions in the past. Here's what it could do in the next ten years for other Scope 3 emissions apart from feedstock materials



TOOLBOX:

INCENTIVES AND BARRIERS FOR TRANSFORMATION

WHY TO ACT?

Transformation to low-carbon chemical industry in Finland – Why?

- **Climate change as the fundamental Grand Challenge of the 21st century**
- **We cannot do it without chemistry**
  - Chemical industry, as diverse as it is, forms the material backbone of modern societies, providing products to all walks of life. Responding to the threat of climate change requires a deep transformation of society.
- **Growing pressure to inaction**
  - Customers demand new solutions
  - Legislation adds pressure
  - Investors are concerned about the future profits and stranded assets
  - Activists and NGOs are already keeping global industrial giants on their toes – not yet on their knees.
- **New business opportunities emerge**
  - the demand of low-carbon products is globally virtually unlimited.

A JOURNEY INTO PARTLY UNKNOWN COMES WITH SOME KNOWN OPPORTUNITIES AND THREATS TO CONSIDER

Depending on the company, the challenges can be very different

Opportunities

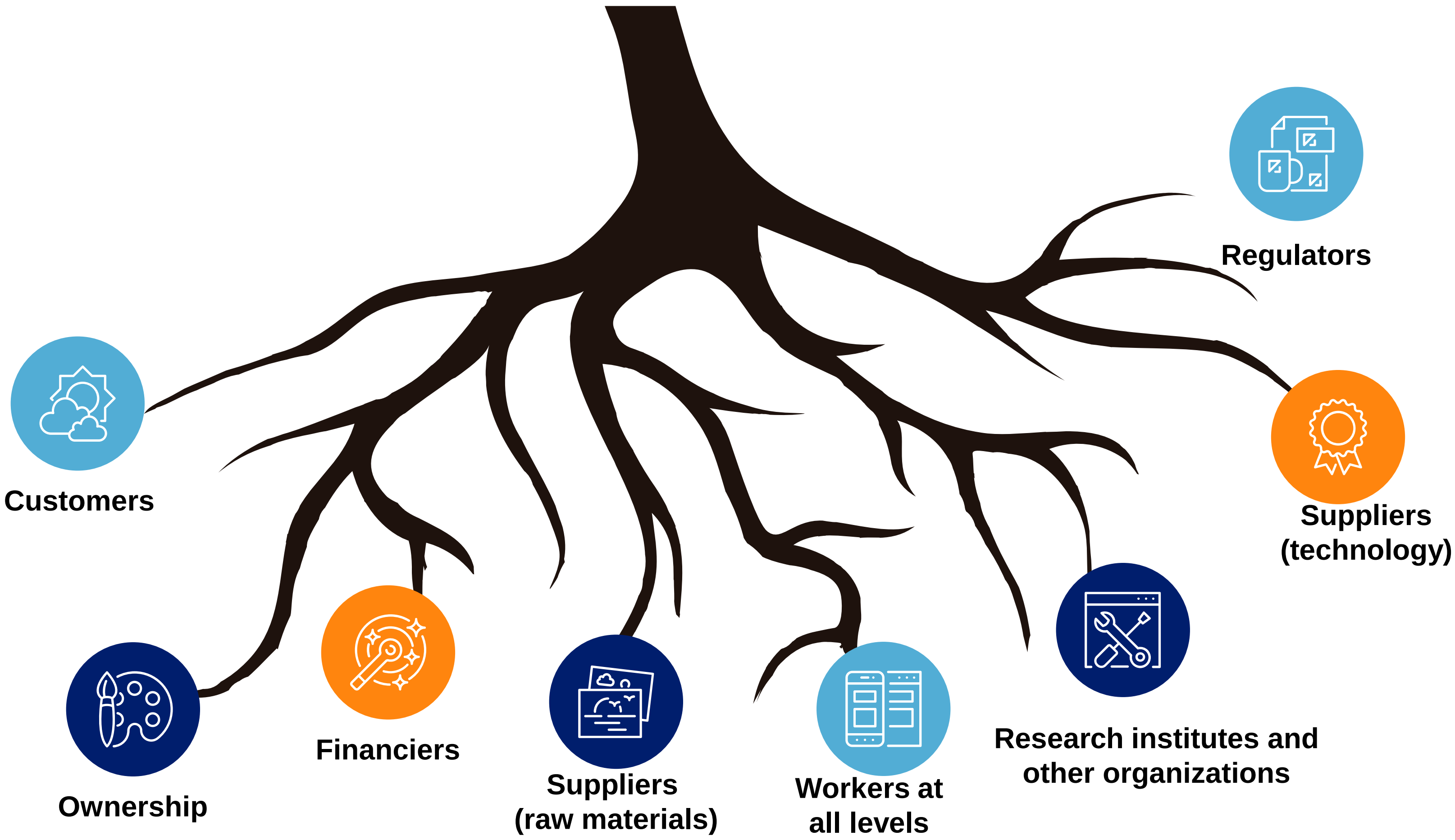
- Financing support for bio- and circular economy solutions and products
- Technology development
  - Economical wind, solar and wave power solutions launched
  - Technologies developed faster than expected
- Fast-mover advantages
  - Securing raw materials and supply chains
  - Securing low-carbon energy sources
  - Learning-by-doing, competitiveness
  - Spillover effects to other parts of organisation
  - Unexpected innovation and emergence of novel markets
- Wide NGO support for actions
- Media coverage and good-will increase brand-value

Threats

- Lack of financing
- Regulatory risks
  - Regulation making certain technologies unfeasible, e.g. nuclear power
  - Regulation changes increase emissions of burning of biomass
  - Environmental permitting of new facilities
- Uncertainties related to energy
  - Slow nuclear energy construction
  - Availability of solar panels and wind turbine generators and parts
- Failure to catch management attention
  - Management too focused on everyday problems – energy exhausted with putting out constant fires
  - Lack of decision-making body on national level
- Knowledgeable workforce
  - Lack of design workforce
  - Lack of construction workforce
  - Lack of education

STAKEHOLDERS TO CONSIDER ARE MANY

Fundamentally, this transformation is about people and all must be kept aboard – roots of sustainable change lie deep



ROADMAP TO THE ROADMAP

1 EXECUTIVE SUMMARY

2 INTRODUCTION: Purpose, boundaries, approach

3 TECHNOLOGY: A menu of options to reduce emissions

4 SCENARIOS: Direct emissions, purchased energy and sensitivity to circumstances

5 SCENARIOS EXPANDED: A feedstock (r)evolution of defossilisation

6 TOOLBOX FOR CHANGE: Chemical clusters and example action plans

7 HANDPRINT, EXPORT POTENTIAL AND KNOWLEDGE: The global imprint of the Finnish chemical industry

8 CONCLUSIONS AND CONDITIONS: The outcome and the preconditions

POINTS TO REMEMBER: HANDPRINT, EXPORT AND KNOWHOW

A HANDPRINT LARGER THAN THE NATIONAL EMISSIONS: using a set of "spearhead" technologies and products that either exist or where Finland is developing or has the knowhow to develop offerings, we get a handprint estimate about four times larger than the chemical industry emissions in Finland.

A BROAD SPECTRUM OF POTENTIAL: the 10 "spearhead" cases chosen from a longlist represent Finnish chemical industry across the board.

THERE IS A WIN-WIN – THE "GREEN RATIO": to illustrate the win-win of economic potential, climate change mitigation and consequent social benefits, we introduce the "green ratio", the ratio of export potential by GHG emission avoided. For our analysis, this ratio approaches 200 EUR, i.e. a potential 200 EUR export for Finnish industry for every ton GHG avoided through the export.

HANDPRINT

HANDPRINT

SUMMARY OF MAIN RESULTS

FINNISH CHEMICAL INDUSTRY, PUNCHING ABOVE ITS WEIGHT GLOBALLY

Small country, big global handprint

Product solutions

- **PRODUCTS AND SOLUTIONS** Smart circularity, good processes and practices make winning solutions possible. Many products from different parts of the chemical industry form parts of very complex solutions – which opens possibilities for multiple categories of special knowhow with large impact.

Climate change

- **PROBLEM** Cutting to the core, climate change as a global problem is mainly due to humankind harnessing fossil-based technologies, especially in energy, with great impacts across the globe.

Technology solutions

- **ADOPTION OF TECHNOLOGIES** Starting from technologies instead of products, climate change mitigation and adaptation are based on an as-fast-as-rational switch from fossil to low-carbon technologies. This is common for all sectors.

Finnish solutions

- **EXPORT** Finnish chemical industry's potential to combat climate change can fully be used by developing and exporting both solutions and parts of solutions (new business models, industrial processes, new raw materials, material efficiency and circular economy, energy efficiency, low-carbon energy, carbon capture storage and utilisation…)

Global scale-up

- **PUNCHING ABOVE ONE'S WEIGHT The** Finnish chemical industry is not the world's biggest heavyweight, but it punches far harder than it looks capable of. Finnish chemical industry solution potential for climate change far exceeds what can be seen with focus inside Finland's border.

THE POTENTIAL FROM SELECTED HANDPRINT SOLUTIONS FAR EXCEEDS CHEMICAL INDUSTRY FINNISH EMISSIONS

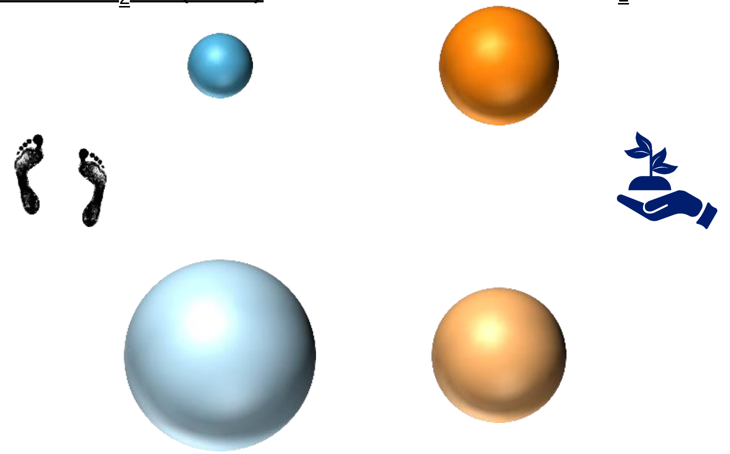
By estimating the handprint potential of key solutions, we can estimate a handprint of at least 4 times that of chemical industry CO_2 emissions in Finland

Outcome	Comparison

- The chosen, representative and varied key technologies and products represent both current and under-development products and technologies. Many of them still require scale-up for the handprint potential to be fully realized.
- The key solution sample's potential handprint is estimated at 26 $MtCO_2e/a$, of which 5 $MtCO_2e/a$ represents solutions further from market today.
  - Closer to market solutions refer to products and processes that are considered already commercial or close to commercialisation. Investments in Finland are primarily not constrained by technical immaturity.
  - Further from market solutions refer technologies that are still relatively immature but hold considerable potential for future.
- *The analysis represents only a very small part of the thousands of chemical industry products,* and in reality the impact is probably significantly greater. It should be noted that all estimates have uncertainties regarding e.g. market share, comparison solution and low-carbon impact.
- However, the estimate shows the great potential Finland has and which can be realised if innovative RDD&D is implemented and exported.

Chemical industry own CO_2-emissions in Finland (scope 1 and 2), 5.4 $MtCO_2e/a$ (2019)

Estimates for export solutions closer to market, potential global handprint of about 21 $MtCO_2e/a$



Finnish national GHG emissions, 53 $MtCO_2e/a$ (2019)

Estimate including solutions further from market, potential global handprint of about 26 $MtCO_2e/a$

INTRODUCTION TO HANDPRINT AND ITS IMPLICATIONS FOR CHEMICAL INDUSTRY

HANDPRINT ANALYSIS AS A PART OF THIS STUDY

For an analysis lacking a standard, a pragmatic solution linked to export and knowhow

As a part of the roadmap of chemical industry of Finland

- **BASED UPON AND COMPLEMENTARY TO SCENARIOS:** Scenarios have been formed as a core part of the roadmap to reach carbon neutral chemical industry of Finland in the timeframe of 2015-2050 by identifying measures to reduce the GHG emissions of own production.
- **GLOBAL IMPACT:** For many chemical companies, the GHG emissions of own production are already very limited. Many companies focus on providing solutions to reduce global GHG emissions through a positive handprint impact.

Approach

- **GLOBAL MARKET AND GLOBAL IMPACT:** The approach is driven by global markets and impacts: as a starting point of the work, the key markets were identified and main sources of global GHG emissions were studied.
- **CURRENT, DEVELOPING AND ”GAPS”:** For each of the five clusters of Finnish chemical industry, current key export products were assessed. In addition, new products under development were identified along with potential gaps in the market with high GHG impact and export potential.
- **KEY PRODUCTS AND TECHNOLOGIES:** The current and potential handprints of the industry were demonstrated through key products and technologies. Estimates of emission reduction potentials must be viewed as indicative.

WHAT IS A HANDPRINT?

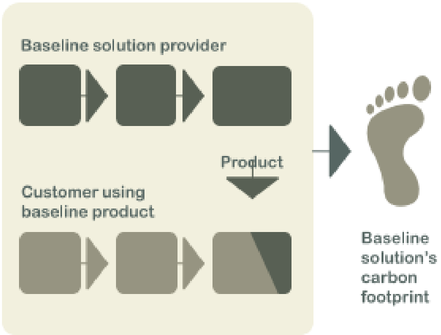
Still an unestablished method to present the positive climate change mitigation impacts

Definition

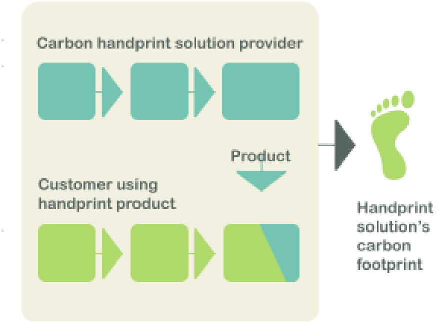
- A *Carbon footprint* includes the GHG emissions emitted in the manufacturing of a product or a service, whereas a *carbon handprint* is used to analyse the positive impact that a product or a service may have in the mitigation of climate change.
- Below, *handprint* is used to refer to the climate change impact of a product or a service as tons of CO_2 equivalents (tCO_2e).

Principles

- The reduction of one's own GHG emissions does not affect a carbon handprint as such. *Carbon handprint* refers to the reduction of GHG emissions of *another actor.*
- *Positive handprint impact does not and is not meant to compensate for the footprint.* Mitigation of industry's own emissions is the priority and widely discussed in the scenarios section of the roadmap.
- *Principles* of handprint quantification *remain partly unestablished*, and different *actors report their handprints based on heterogeneous methodologies*.
- The basic principle is that a handprint effect may be created through two ways:
  1. ***Avoidance of an existing footprint by providing a better solution to the same need***
     By using a product or a service, a carbon footprint (which would happen otherwise) is avoided.
  2. ***Emergence of new method to create a positive impact***
     By using a product or a service, a positive impact (which would not otherwise materialise) is created.



Handprint is the difference of two footprints



Sources: Norris (2015), VTT, LUT: Carbon Handprint Guide (2018)

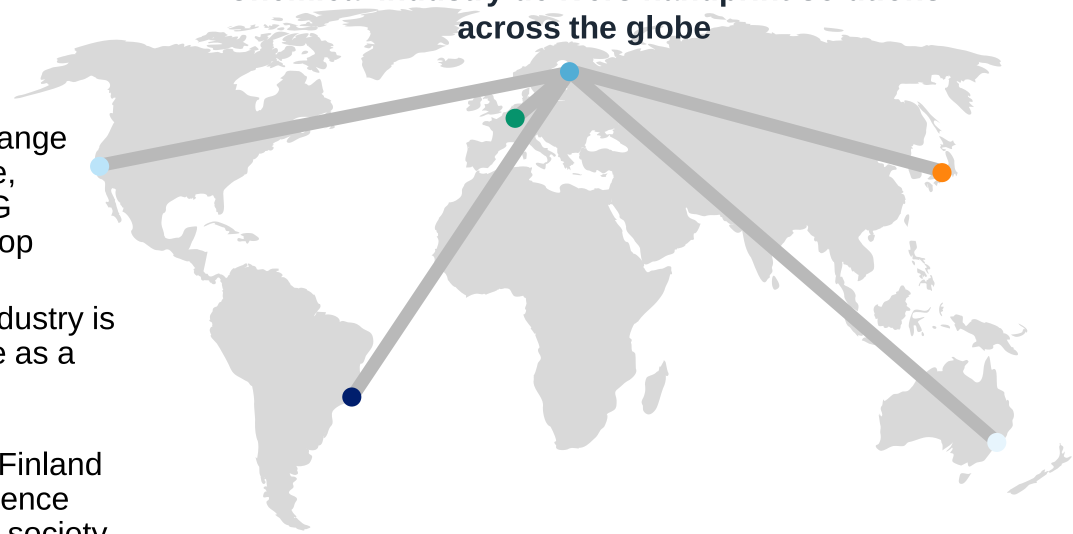
WHAT DOES THE HANDPRINT MEAN FOR CHEMICAL INDUSTRY?

Global industry, global handprint

Implications from handprint thinking

- Focusing also on the handprint can help to *significantly increase* the overall climate change mitigation impact that the industry can have, compared to only focusing on national GHG emissions reductions (which still remain a top priority).
- The market environment of the chemical industry is *global*. The same applies to climate change as a phenomenon.
- Finnish companies are the *forerunners* of technological development in many areas. Finland has many strengths (green energy, competence and knowledge, challenging climate, stable society, etc.) as a *pilot and demonstration platform* to develop new global solutions.
- The *full potential of Finnish innovations can only be realised* by scaling up and exporting the products and technologies abroad.
- The *market* for true handprint solutions offers *sizeable export opportunities* for Finland.
- The solutions of the future (also concerning handprint) necessitate *concrete resources allocated to research, development, regeneration and knowledge.*

Chemical industry delivers handprint solutions across the globe

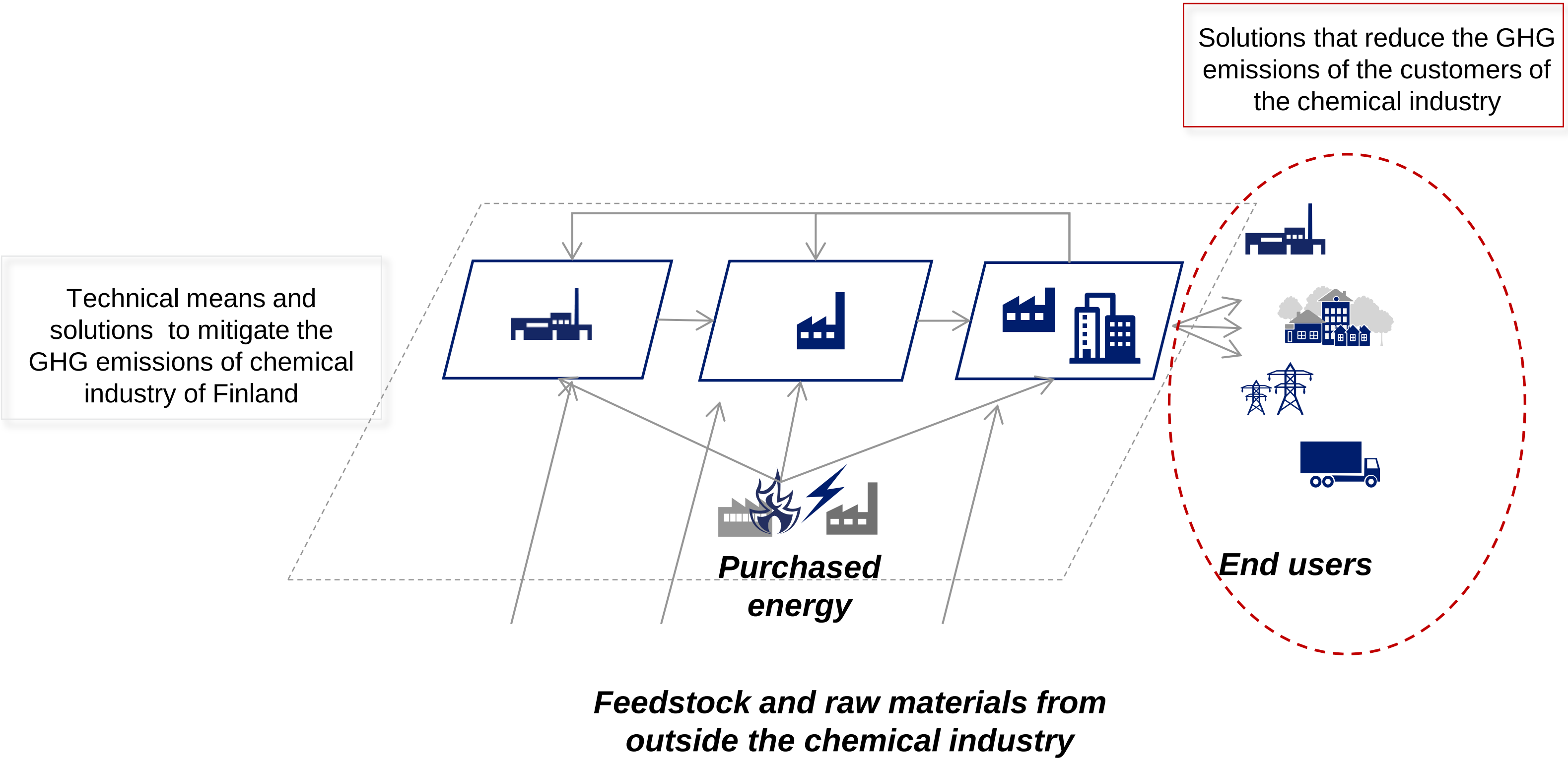


A handprint impact can be created through many ways

- Improvements in material efficiency and new materials
- Improvements in energy efficiency and new energy sources
- Lengthening of product lifecycle and new services
- Waste avoidance and treatment, recycling and reuse
- Carbon capture, sequestration and recycling

HOW DOES THE HANDPRINT WORK IN THE VALUE CHAIN?

Handprint analysis aims to illustrate the impact of solutions that chemical industry provides to other sectors



HANDPRINT

APPROACH

THE HANDPRINT ANALYSIS HERE HAS MULTIPLE TARGETS

Many birds with one stone, in a (climate-and-biodiversity-)friendly way

Multiple targets

- With the same analysis, starting from markets and innovation, objects for RDD&D-focus, spearheads for export potential, key technologies and their handprint.

Representativity

- Key products/technologies covering as well and representatively as possible the Finnish chemical industry.

Long list

- Promising products/tech that exists, is close or a bit further from markets – all united by climate change reduction potential. Finnish knowhow, market promise and climate impact part of long list criteria.

Short list

- Chosen from long list, diverse list of spearheads of climate combat in different stages of development.

Export potential

- Export potential estimation also based on the key technologies/products working together in climate solutions (if relevant).

Handprint

- No ”official” standard way of doing handprint. Likewise, products/tech very different in climate impact. For each case above, estimation adapted to the special characteristics.

WHAT DOES NOT MAKE SENSE?

The Finnish chemical industry is a complex construct. Many of the technologies and products are not yet on the markets – and for some, markets do not exist yet, only a pent-up demand.

IMPOSSIBLE TO DO AN EXHAUSTIVE PRODUCT-BY-PRODUCT ESTIMATE

The chemical industry has tens of thousands of products (educated guess). A systematic attempt to cover this is doomed to fail – apart from time and resources needed, GIGO. Garbage In, Garbage Out = data does not exist for most of it, the more guesses, the worse the result.

(R)EVOLUTION IN THE MARKETS AND COMPETITION CHANGE DYNAMICALLY

Even the progress of globalisation is an object of speculation especially with COVID19: achieving and keeping a Finnish advantage is not done by following a ready-made rulebook.

MARKET SHARES FOR PRODUCTS THAT DO NOT EXIST ARE NOT PARTICULARLY PRECISE

So we aim at transparency and explanations, common sense, rather than "black box" models.

ASPECTS TO CONSIDER IN THE INTERPRETATION OF THE RESULTS OF HANDPRINT ANALYSIS

Finding the balance between pragmatic assessment and future opportunities

Coverage and exclusivity of the studied cases

- The handprint potential of the chemical industry of Finland is illustrated by fitting together the exports portfolio of the industry and Finnish key expertise areas with the global end use markets based on both economic attractiveness and CO_2 mitigation potential. This is how the presented example cases were selected. These cases can in no regard fully capture the rich diversity of the product portfolio of the industry, nor does this analysis (cl)aim to do so. Rather, the analysis aims to illustrate the large potential that the chemical industry strives for in delivering solutions to mitigate climate change as a global problem. Due to the complexity of the value chains of chemical industry, it should be noted that similar resources could be used to produce many different solutions (e.g. low-carbon fuels, plastics or chemicals).

Estimates of the handprint potential (CO_2)

- The handprint potentials of selected key products that were assessed includes many new, innovative products that do not exist yet in the market. Naturally, such estimates are inaccurate by definition. Even if individual companies publish their own company-level handprint estimates, their geographical allocation (what is the share of Finland) is not straightforward, as production locations exist across the globe. Exact numerical values cannot cover the whole industry (thousands of product streams). Estimates of the selection of examples should be understood indicative and sensitive to many assumptions (presented in a transparent way). This being said, the assumptions are inclined to ,the conservative side to depict a realistic, yet visionary approach to the potential climate change mitigation solutions of the Finnish chemical industry.

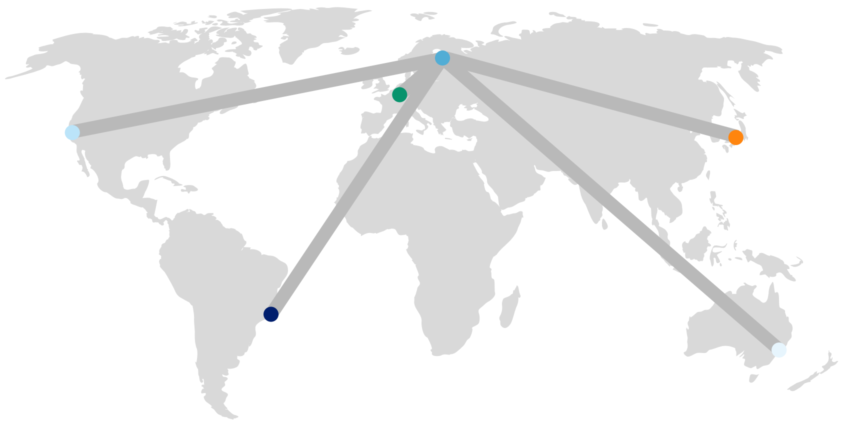
HANDPRINT

CHEMICAL INDUSTRY IN THE CONTEXT OF GLOBAL MARKETS AND SOURCES OF GHG EMISSIONS

HANDPRINT ANALYSIS WITH A GLOBAL BUSINESS APPROACH

Exporting the solutions – a business handprint of climate mitigation

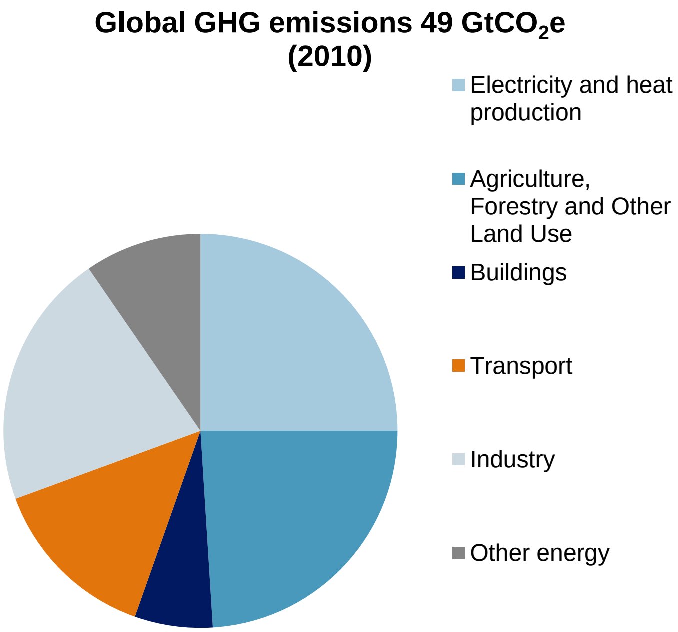
- The question from the global handprint point-of-view could be phrased: ***how could the chemical industry of Finland deliver most impact for climate change mitigation through its products and services?***
- The answer depends on:
  1. Where the global GHG emissions come from (economic sectors and the underlying needs)
  2. What are the relevant markets that can be won
     - National competitiveness aspects
     - Existing expertise and current market position
     - Development of markets, technologies and products



WHAT TO MITIGATE: GLOBAL GREENHOUSE GAS EMISSIONS

The goal is clear: GHG reduction

- The majority of global GHG emissions come in the form of CO_2 from fossil fuel use and industrial processes.
- Globally, *electricity and heat production* is the sector with the largest GHG emissions. However, the electricity and heat generated is mostly delivered to industry and building sectors (and contributes to their indirect emissions).
- Agriculture, forestry and other land use (AFOLU) and industry both contribute more than 20% to global GHGs emitted, while the share of transport stood at 14% in 2014.



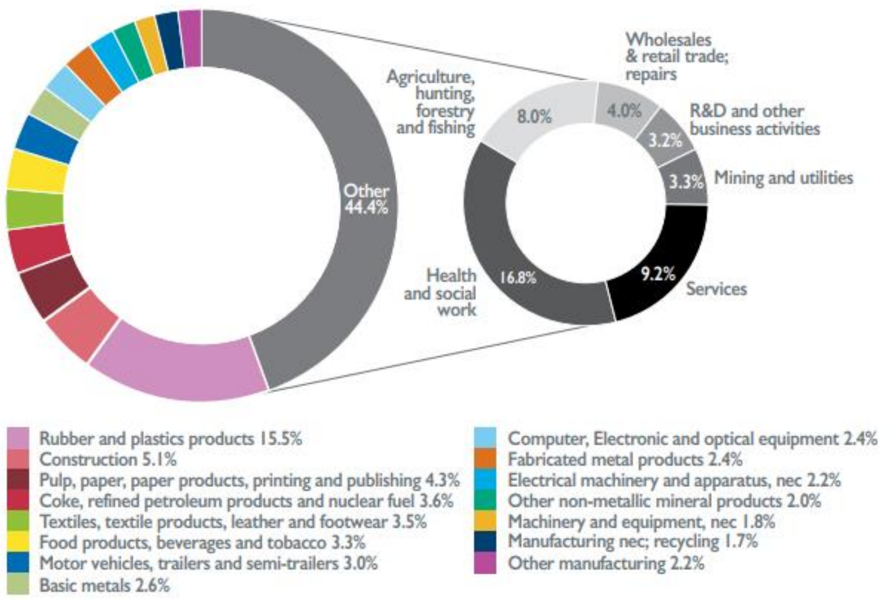
Lähde: IPCC (2014)

WHERE TO DELIVER THE SOLUTIONS: CUSTOMER MARKETS OF CHEMICAL INDUSTRY

Although new markets need to be conquered, it is easiest to start where there is a foothold

- Products of the chemical industry serve countless needs across numerous sectors of the economy.
- Different industrial sectors consume more than 50% of the EU chemical industry outputs. Other notable sectors include health and social work, services and primary production.
- Through this EU-level example, it is illustrated that the possible handprint solutions may end up used and benefited by almost any sector of the economy.
- The chemical industry of Finland is also very diverse (see next page).

Key end use markets of the EU chemical industry



Source: CEFIC (2020)

<u>HOW</u> TO MITIGATE: LONG LIST OF PRODUCTS AND TECHNOLOGIES OF FINNISH CHEMICAL INDUSTRY

Current production

- Transport fuels (e.g. gasoline and diesel; fossil and renewable-based)
- Oil products, tall oil, monophenols, hydrocarbon mixtures
- Solvents
- Plastics (intermediates and products)
  - Ethylene, propylene, polymers
- Water treatment chemicals, chlorates
- Intermediates
- Basic chemicals (e.g. sulphates)
- Enzymes
- Cellulose derivatives
- Acrylic ethers and derivatives
- Dispersion polymers
- Resins
- Biochemicals
- Industrial gases
- Specialty chemicals
- Fertilizers
- Minerals (e.g. cobalt oxides)
- Metals
- Salts (e.g. calcium carbonate)
- Rubber products, tires
- Synthetic rubber
- Composite products
- Paints and coatings
- Pharmaceuticals (and contraceptives)
- Nucleic acids and heterocyclics
- Detergents
- Adhesives and adhesive products

Under development

- **<u>Synthetic</u>** fuels and chemicals based on CCU and P2X
- Materials, chemicals and fuels from **<u>renewable / bio-based</u>** raw materials
  - e.g. bio-based plastics
- Materials, chemicals and fuels from **<u>recycled</u>** raw materials
  - e.g. battery recycling and chemically recycled plastics

Gaps in the market

- New circular & recycling-based value chains
  - Pigments, gypsum, biocomposites, wood products, composites, mining waste and side rock, construction waste, concrete and cement, advanced industrial biotechnology
- Electricity and energy storage options
  - Also flexible production modes

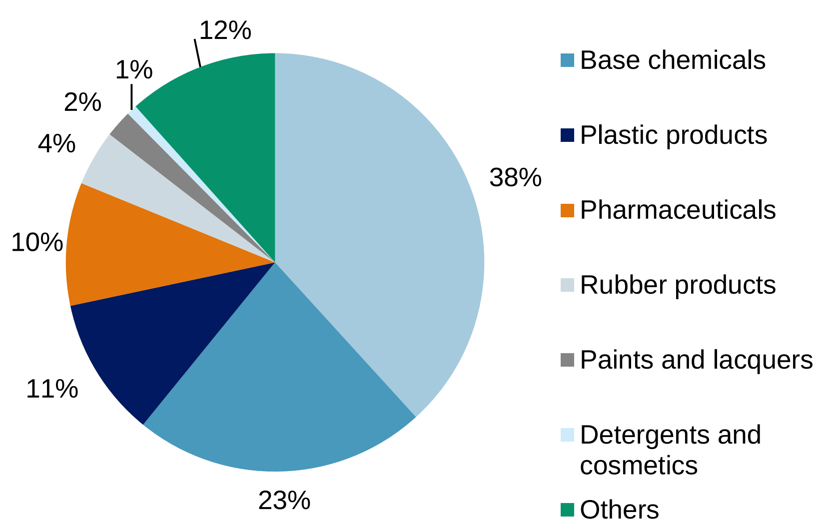
THE FINNISH CHEMICAL INDUSTRY HAS A DIVERSE PRODUCT PORTFOLIO

There is no simple way to estimate the full handprint of such a diverse industry, even for the current situation, let alone for forecast scenarios

Description

- Finnish chemical industry is a rich combination of approximately 400 companies, employing directly over 34,000 people. The total turnover of the industry is 24 BEUR, and the industry accounts for almost a fifth of the total added value of Finnish industry sectors.
- In terms of production volume, the industry is characterized by oil refining and petrochemicals, base chemicals and minerals. Largest chemical industrial clusters are located in Porvoo, Kokkola, Turku, Oulu and Harjavalta.
- The complete product portfolio of the chemical industry of Finland is highly diverse.

Main products by revenue (2018)



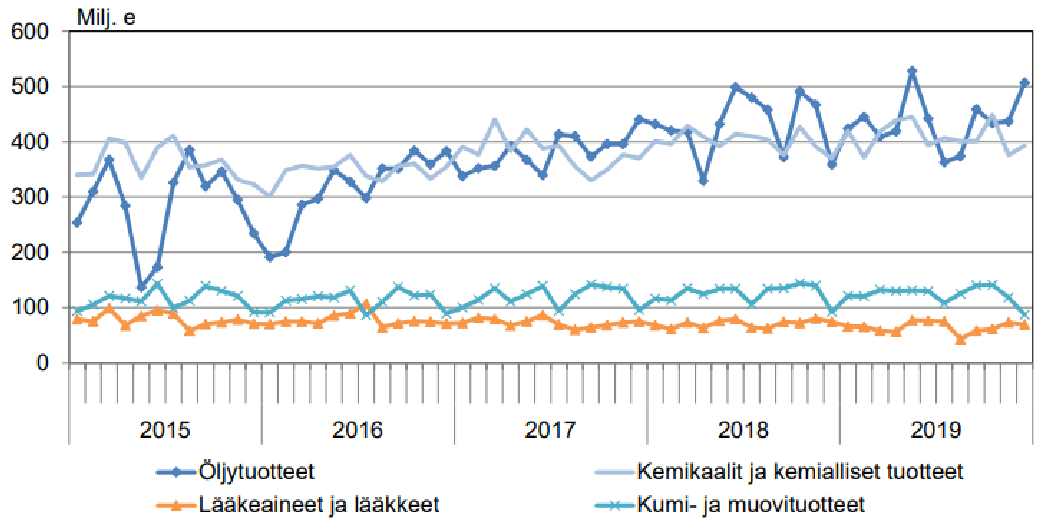
Source: Kemianteollisuus ry

EXPORTS OF FINNISH CHEMICAL INDUSTRY OF FINLAND DIFFER IF THE PERSPECTIVE IS TONS OR VALUE

Because of the diversity, volume does not directly correspond to value or emissions, either

- The main categories of Finnish chemical industry exports are dominated by oil products and chemicals (by export value), while pharmaceuticals and rubber and plastic products are other significant export categories.
- This level does not give the full picture.

KEMIAN TEOLLISUUDEN TUOTTEIDEN VIENTI KUUKAUSITTAIN 2015-2019(1-12); Milj. e; (CPA 19,20,21,22)



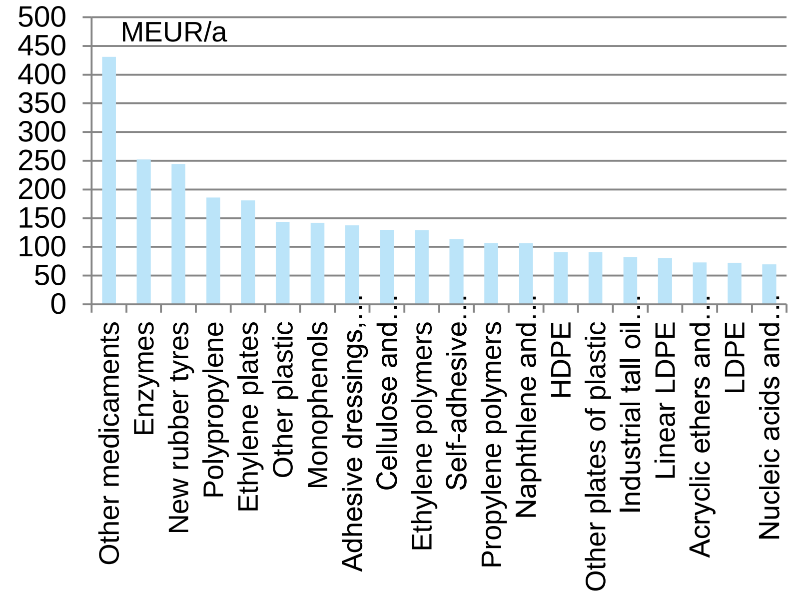
Source: Tulli (2019)

EXPORTS OF CHEMICAL INDUSTRY OF FINLAND BY INDIVIDUAL PRODUCTS FURTHER ILLUSTRATES THE DIVERSITY

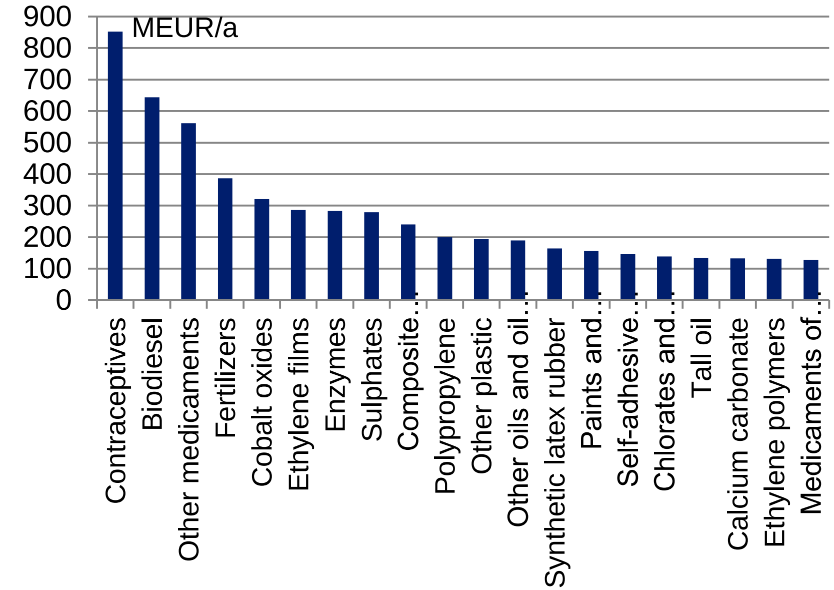
The top export list is quite hard to guess even for experts

- In Eurostat trade statistics, the top 20 product categories *by export value* constituted 57 % of all production value in 2018.
- In Eurostat trade statistics, top 20 product categories *by production value* constituted 59 % of all production value in 2018.

Top 20 products by export value



Top 20 products production value



Source: Eurostat, International trade statistics (2018). Data covers the production codes in main categories 19–22. Note that the granularity of classification affects the results; if there are no subcategories, the value of the reported category is larger than in the opposite case.

CHOSEN PRODUCTS AND PROCESSES

The long value chains within the chemical industry mean that cooperation between all clusters is needed to materialize the handprint opportunities

	Products (current / potential) = manufacturing and selling a material product	**Processes** (current / potential) = researching, developing and licensing IPR	**Others**
Energy-intensive chemical industry	- **Chemical recycled plastic** - **Bio-based plastics** - **Renewable transport fuels** - **Water treatment solutions**	- **Chemical recycled plastic technology** - **Water purification technology (membranes)** - **Synthetic fuels / CCU / BECCU**	Other examples: - **Utilisation of own waste heat** in Helsinki district heating - **Utilisation of own waste heat in other industry** - Low-carbon **packaging** - Zero-carbon **transportation** - **Waste avoidance** - **Creating own recycling infrastructure**
Inorganic chemistry	- **Battery chemicals** - **Recycled battery chemicals**	- **Gypsum use**	
Reactive chemistry	- **Resins** - **Bioethanol**	- **Biotechnology**	
Formulating			
Converters			

HANDPRINT CASE 1: CHEMICAL PLASTICS RECYCLING

A rising area, with pressure from markets and legislation, and also Finnish tech

Under development

Potential handprint impact: 2.2 $MtCO_2e/a$

- Chemical recycling of plastics refers to a family of technologies that will enable wide-ranging recycling of different plastics. Currently, only a fraction of all plastic waste is recycled mechanically.
- The GHG benefit of plastics recycling comes through two ways:
  - Using recycled raw materials to make new products substitutes the use of fossil feedstock and the associate GHG emissions
  - Recycling the plastic avoids its incineration as waste and the release of CO_2 to atmosphere
- Handprint impact quantification:
  - Assume volume of plastics waste in Finland to be recycled to be 300 kt/a
  - Assume: recycling avoids 72% of the CO_2 emissions of plastics incineration, equalling 678 $ktCO_2/a$
    - GHG impact through *avoided incineration* of waste: 0.7 $MtCO_2/a$
  - Assume a 80 % efficiency for plastics waste collection* and a 90 % process efficiency for the recycling process of plastics and that plastics are recycled 6 times
    - GHG impact through *recycling* effect: due to the recycling loop, 1 ton of recycled plastics avoids 2.2 tons of virgin plastic
    - Virgin material use that can be avoided is 660 kt/a plastic and the corresponding avoided GHG impact is ca. 1.5 $MtCO_2/a$
  - **Total handprint impact would thus be 2.2 $MtCO_2/a$**

*Based on current estimates of theoretical maximum levels of paper recycling

HANDPRINT CASE 2: RENEWABLE FUELS

An established area with Finnish world leadership

- A result of successful R&D work of Finnish chemical industry is the NEXBTL technology. In the NEXBTL process, vegetable oils and waste animal fats are treated with hydrogen to produce hydrotreated vegetable oil (HVO). HVO can then be used to substitute fossil-based fuels, chemicals or plastics. Currently, *Neste* produces 3 Mt of HVO at its sites in Finland, the Netherlands and Singapore, and has also licensed parts of the technology to other companies. The capacity is expected to increase to 4.5 Mt by 2022.
- Handprint impact quantification:
  - Assume a future HVO capacity of 5 Mt/a to be sited in Finland. Assume a calorific value of 43.1 MJ/kg for the biodiesel, which substitutes fossil diesel 1:1. Assume well-to-wheel emissions of 99 gCO_2/MJ for fossil diesel.
  - The footprint of 5 Mt/a fossil diesel consumption is ca. 21,3 $MtCO_2e$/a. Assume renewable fuels comes with 70% lower GHG impact than fossil diesel (estimates range between 60–90 %).
  - **The avoided GHG emissions would thus be 14.9 $MtCO_2e$/a**

Current product

Potential handprint impact: 14.9 $MtCO_2e$/a

Sources: Eriksson and Ahlgren (2013); Neste (2020) reports that the current HVO refining capacity of 3 Mt/a to yield a 9.6 MtCO2/a reduction in GHG emissions of its customers across Neste's portfolio of different renewable products. Neste's quantification method of life cycle emissions and emissions reduction is consistent with the Directive on the promotion of the use of energy from renewable sources (2009/28/EC)

HANDPRINT CASE 3: BIOPLASTICS FROM BIOCRUDE

Answering the pull from the markets based on Finnish strong knowhow

- Plastics produce 5 tCO_2 / ton of plastic over the life cycle, of which 2.3 tCO_2 relate to feedstock production and manufacturing of plastics, while the end-of-life treatment (dominantly the incineration of plastic waste) releases ca. 2.7 tCO_2
- Globally, over 300 Mt of plastics are produced every year, primarily from fossil feedstock. However, plastics could also be made using bio-based feedstock.
- Handprint impact quantification:
  - Assume that Finnish plastic precursor capacity (ethylene and propylene) is transformed to use bio-based feedstock, for example HVO, to make renewable polypropylene and renewable polyethylene. Assume a total PP and PE capacity of 1 Mt/a.
  - Range of estimated greenhouse warming potentials of different fossil-based plastics ($kgCO_2e$/kg plastic) for upstream and production phase:
    - PE/PP 1.7-1.8 and PET/ABS 3.5-4; average 2.5
  - Range of estimated greenhouse warming potentials of different bio-based plastics for upstream and production phase:
    - Bio-PE/PP ca. -2 and bio-PET/ABS ca. 0-0.5; average -0.5
  - Handprint impact per ton of plastic is ca. 3 tCO_2/t of bio-based plastic
  - **Total handprint impact would thus be ca. 3 $MtCO_2$/a**

Under development

Potential handprint impact: 3 $MtCO_2e$/a

Source: Material Economics (2019), Braskem, Plastics Europe, Moretti et al (2020)

HANDPRINT CASE 4: BATTERY CHEMICAL RECYCLING

A rising area with Finnish production on the way

- The electric vehicle (EV) market is anticipated to grow tremendously in the 2020s (CAGR 20 %), as the automotive industry seeks to reduce GHG emissions of transportation through electrification.
- Finnish chemical industry is seeking and developing solutions to build recycling infrastructure of the EV batteries and their chemicals, critical components in the EV market.
- Handprint impact quantification:
  - Estimates of greenhouse warming potential of Li-ion battery manufacturing from virgin materials vary between 30-270 kgCO_2e/kWh, and 61–106 kg CO_2e/kWh is considered a likely range in 2019.
    - Assume virgin production to be 65 kgCO_2e/kWh battery.
    - Assume battery capacity of an average car to be 40 kWh.
    - Battery manufacturing of the car would results in a footprint of 2600 kgCO_2e/car
  - In Europe, assume 10 million new EVs coming to market every year in 2020s. The battery manufacturing for annual EV sales is equal to a global 26 MtCO_2 footprint.
    - Assume that the footprint of recycled batteries is significantly lower than from virgin materials. As the value chains and recycling schemes do not exist yet, no definitive values can be given. One estimate presented is that recycling Li-ion battery cathode materials yields 51% natural resource savings. Assume a 30 % reduction in specific emissions over the lifecycle here.
    - Assume a growing share to be provided through recycling. On average, assume 10 % of battery market to be supplied by Finnish battery chemical recycling cluster.
  - **This would corresponds to a ca. 800 ktCO_2/a handprint impact.**

Under development

Potential handprint impact: 0.8 MtCO_2e/a

Sources: Emilsson and Dahllöf (2019); Romare and Dahllöf (2017); Liikenne- ja viestintäministeriö (2018); Notter et al. (2010); Statista (2020)

HANDPRINT CASE 5: LOW-EMISSION DESALINATION, E.G. REVERSE OSMOSIS

The need for clean water is approaching climate in urgency

- As the global population grows, water demand and consecutively the need for water reuse and desalination systems grows.
- Desalination systems can be categorised into two: membrane or thermal technologies.
- The dominant thermal technologies include multistage flash (MSF) and multi-effect distillation (MED). These systems take fossil fuel as primary energy, but also use significant amounts of electrical energy for water circulation. Therefore, these technologies have higher CO_2 emissions, on average between 10-20 $kgCO_2/m^3$.
- Membrane technology for desalination is dominated by reverse osmosis (RO), which is a highly scalable process. The scale of applications range from small systems for household use to as large as 600,000 m^3/day. RO for desalination driven by electrical energy and these technologies have significantly lower CO_2 emissions compared to thermal technologies, between 2-3.5 $kgCO_2/m^3$.
- The difference is largely due to the energy required for the high pressure pump needed to overcome osmotic pressure in RO systems (4.0–4.5 kWh/m^3) is lower than the energy required to provide heat for thermal technologies (6.0–23.5 kWh/m^3).
- The carbon footprint of RO desalination systems can be further reduced by using low-carbon or renewable energy sources; solar, wind, geothermal, nuclear and waste-heat utilisation.
- Main assumptions in the handprint calculation include;
  - Water consumption on average is taken as 75 lt/person
  - The handprint is calculated for 1 million people
- **The handprint of desalination systems therefore becomes 356 $ktCO_2e/a$.**

Current product

Handprint impact: 356 $ktCO_2e/a$

Source: Lienhard et al. (2016); Cornejo et al. (2014)

PÖYRY

HANDPRINT CASE 6: SYNTHETIC FUELS / CCU /BECCU

Synthetic diesel (FT) representing a family of products around CCU – where e.g. BECCU (BioEnergyCCU) is a rising Finnish technology

- Synthetic fuels are produced from a carbon source via chemical conversion. Carbon sources for synthetic fuels are coal, carbon dioxide, natural gas biogas or biomass. Hence, synthetic fuels include conventional fossil-based processes.
- Synthetic fuels produced through low-carbon technologies are;
  - Methanol as substitute and/or additive in gasoline
  - Bioethanol as gasoline additive
  - Synthetic diesel as drop-in fuel
  - Synthetic kerosene as drop-in jet fuel
- As the handprint of HVO technology to produce diesel fuel is shown under "renewable fuels" section, here production of synthetic diesel via low-carbon syngas, carbon capture and utilisation (CCU) and Fischer-Tropsch synthetic is taken as the basis point.
- In this technology, hydrogen is produced via electrolysis and carbon dioxide is captured either from a point source or via direct ait capture. The point source for carbon dioxide can be biomass operations. Finally, synthetic diesel is produced through Fischer-Tropsch synthesis.
- Unlike methanol and/or ethanol which are blended into gasoline to reduce carbon footprint of the product, synthetic fuels are drop-in fuels with almost same chemical composition as fossil fuels and therefore could replace them completely.
- Main assumptions in the handprint calculation include;
  - Synthetic diesel production capacity; 200 kton/a
  - Low carbon electricity is used in hydrogen production and carbon capture
  - Well to wheel emissions of conventional and synthetic diesel are adapted from publically available sources
  - **The handprint (i.e. avoided CO_2) of synthetic diesel is; 480 ktCO_2e/a**

Under development

Potential handprint impact: 480 ktCO_2e/a

HANDPRINT CASE 7: BIOTECHNOLOGY AND MODIFIED METABOLIC ROUTES TO ENHANCE USE OF GASEOUS RAW MATERIALS

Harnessing Finnish biotech knowhow to climate mitigation

- Artificial sequestration of greenhouse gases directly from the atmosphere or CO_2 from industrial point sources may become viable options to obtain carbon feedstock in the future. For example, synthetic hydrocarbons and algae oil necessitate CO_2 as a raw material.
- As an example of numerous different opportunities within in the field of biotechnology, modified metabolic pathways is analyzed here as a potential future solution. Improved CO_2 fixation would open the door for numerous new applications.
- Handprint impact quantification:
  - Recently, scientists have developed a biological pathway (type of artificial photosynthesis) which fixes CO_2 at a greater efficiency than the Calvin cycle in plants. The pathway is up to five times more efficient than the in vivo rates of the most common natural carbon fixation pathway.
  - Assume further advances in biotechnology to reduce the specific energy consumption required to fix CO_2 and produce algae oil by 10 %.
  - Firstly, this would enable a commercialisation of the new technology faster, substituting fossil feedstock, leading to great CO_2 benefit.
  - Assume: European microalgae biomass annual potential of 50 Mt/a, requiring approximately 1 EJ of energy. Assume the technology to be exported and improve the algae oil process correspondingly, resulting in annual 0,1 EJ (28 TWh/a) energy savings.
  - Assume: Algae cultivation uses relatively low-carbon energy (100kgCO_2/MWh, compared with current average of EU electricity 296 kgCO_2/MWh)
  - **Handprint impact would be ca. 2,8 MtCO_2e/a through just savings of energy** (of what is assumed to be relatively low-carbon energy) obtained through improved metabolic pathways

Potential handprint

Potential handprint impact: 2.8 MtCO_2e/a

Source: Schawander et al. (2016); Ort et al. (2015), Skarka (2012); EEA (2018)

HANDPRINT CASE 8: GYPSUM USE FOR FERTILIZERS

Using something that just lies there for climate mitigation

- Fertilizers are used to enhance crop productivity. Their production, transportation and use releases GHGs (CO_2 and N_2O). Finland has significant NPK-fertilizer production, and fertilizers are typically manufactured from ammonia and nitric acid. *Yara* reports that its Nordic factories with BAT technology could have almost 40 % lower carbon footprint than European average without BAT.
- What if in the future, gypsum from the side-product of phosphate production or recycled waste materials could be used as a possible slow-release fertilizer? Currently, the largest supplier of phosphorus to Europe is Morocco, from where 22 % of all phosphate-based products are imported.
- Quantification
  - Using gypsum avoids the emissions from the mining and processing phase
    - Emissions of mining and emissions of phosphate processing: 0,35-0,7 $kgCO_2$/kg phosphate (triple super phosphate, di-ammonium phosphate). Assume pure phosphorus to make up 20 % of the fertilizer by mass on average.
    - Finnish pilot of gypsum use in agriculture: 4 t gypsum per hectare, reduces the phosphorus need by 50 % for five years.
    - Assume fertilizers to contribute ca. 10 Mt of phosphorus annually in Europe
    - Assume 1 % of European croplands adopt gypsum-based technology to supply phosphorus to the fields, reducing their phosphorus need by 50 %. This would correspond reduce phosphorus need by 54 kt of phosphorus annually. This corresponds to reduction of fertilizer demand by 270 kt/a.
    - Assuming average emissions of 0,5 $kgCO_2$/kg phosphate, **this would avoid 135 $ktCO_2$/a** released in mining and manufacturing of phosphates*.

Potential handprint

Potential handprint impact: 135 $ktCO_2e$/a

Sources: Yara (2020); Fertilizers Europe; Ledgard et al. (2011); Universidad Politécnica de Madrid (2015); Varsinais-Suomen ELY-keskus (2020); Withers et al. (2015)

*not accounting for gypsum transportation, etc.

HANDPRINT CASE 9: RESINS, BIO-BASED

Representing, again, a family of Finnish feedstock knowhow developed to global impact

- Bio-based resins can be produced from natural oils (e.g. glycerol), carbohydrates (e.g. chitosan for adhesives) and natural phenol compounds (such as tannin and lignin).
- Glycerol that is released in the production of biodiesel can be converted into epichlorohydrin, acrylic acid, or propylene glycol, for the production of epoxy, acrylic, and unsaturated polyester resins, respectively.
- Lignin, a by-product of pulping processes can be used to produce resins such as phenol formaldehyde, polyurethanes and epoxy resins.
- In order to calculate the handprint of bio-based resins, glycerol based epoxy and unsaturated polyester resin and lignin-based phenolic resins are taken as the basis point.
- For the selected resins, the production capacity in Finland is around 655 kton/a.
- Cradle-to-gate emission figures for both bio-based and fossil-based resins are adapted from publically available sources.
- Considering most commercially available bio-based resins are bio-based up to a maximum of fifty per cent, **the handprint of bio-based resins would be 1.5 MtCO_2e/a.**

Current product

Potential handprint impact: 1.5 MtCO_2e/a

HANDPRINT CASE 10: BIOETHANOL

Something that is already there, but done better

- First generation bioethanol is widely produced from crops such as corn and other cereals. However, due to issues such as food consumption and land use 1st generation biofuels are perceived critically, especially in Europe.
- Advanced ethanol production utilises, lignocellulosic biomass waste (e.g. straw) and residues from forestry and forest-based industries (e.g. sawdust). Although advanced ethanol represent around 4% of the total European ethanol production in 2018, the industry is moving away from 1st generation biofuels towards advanced ethanol.
- Advanced ethanol typically has lower GHG emissions as emissions from the recovery of lignocellulosic residues are included but emissions related to upstream biomass production are not.
- Apart from transport fuels, bioethanol can be used to produce bioethylene and biopropylene. As handprint for low-carbon routes to plastics are covered under ‘chemical recycling for plastics’ and ‘bioplastics from biocrude’, therefore in this calculation bioethanol is used as transport fuel.
- Main assumptions in the handprint calculation include;
  - Bioethanol production capacity assumed to be 150 kt/a
  - Low carbon electricity is used in hydrogen production and carbon capture
  - Well to wheel emissions of conventional gasoline and advanced bioethanol production are adapted from publically available sources
  - Lignin produced is utilised as fuel, but it can also be utilised to produce higher value chemicals. Moreover, the carbon footprint can be significantly decreased by employing CCS and CCU methods.
- **The handprint (i.e. avoided CO_2) of bioethanol would be 240 ktCO_2e/a**

Current product

Potential handprint impact: 240 ktCO_2e/a

EXAMPLES OF OTHER HANDPRINT SOLUTIONS

Chemical industry can deliver solutions through its products and technologies – but also through cooperation with other sectors

Energy

- **Utilisation of own waste heat in district heating**
  - E.g. the on-going project to study the feasibility of utilizing industry waste heat in Helsinki metropolitan area as residential district heat, which would reduce the GHG emissions of energy sector. The project requires large investments with no direct CO_2 benefit to the industry.
- **Utilisation of own waste heat in other industry**
  - Examples of successful cooperation exist already, where excess energy of chemical industry is utilised efficiently by partners in completely different industries.

Materials

- **Beneficial products**
  - New products in the industry can contribute to the customer's material efficiency by dramatically reducing their raw material consumption.
- Low-carbon **packaging**
  - Choosing and creating low-carbon packaging solutions.
- **Waste avoidance**
  - Industry with a long record of high material efficiency can further reduce waste and wastewater treatment efforts.
- Creating own **recycling infrastructure**
  - Some examples have already surfaced: companies start their own recycling scheme (possibly in collaboration with e.g. retail) to improve circularity of packaging solutions.

Transport

- **Beneficial products**
  - Highly concentrated products or products with a novel operating mechanism reduce the volumes (tons) that need to be transported. For example, certain products under development could serve the customer need with only 1/30 share of old volumes, dramatically reducing transportation emissions.
- Zero-carbon **transportation**
  - Opting for zero-carbon transportation reduces transport sector GHG emissions, while the industry continues to enable the transition also through its low-carbon fuels.

THE POTENTIAL FROM SELECTED HANDPRINT SOLUTIONS FAR EXCEEDS CHEMICAL INDUSTRY FINNISH EMISSIONS

By estimating the handprint potential of key solutions, we can estimate a handprint of at least 4 times that of chemical industry CO_2 emissions in Finland

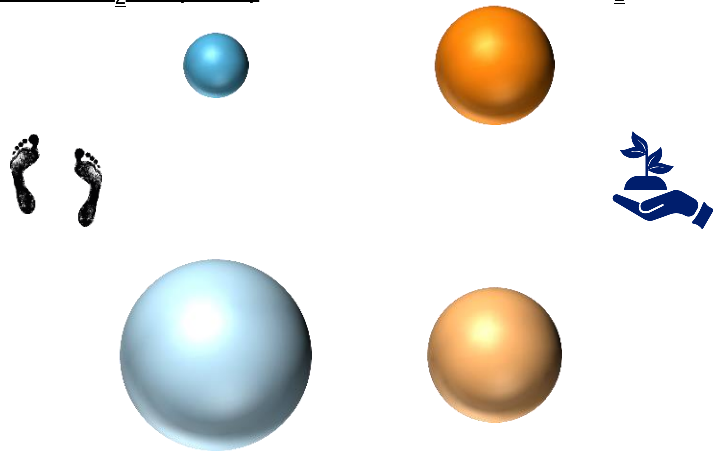
Outcome

- The chosen, representative and varied key technologies and products represent both current and under-development products and technologies. Many of them still require scale-up for the handprint potential to be fully realized.
- The key solution sample's potential handprint is estimated at 26 $MtCO_2e/a$, of which 5 $MtCO_2e/a$ represents solutions further from market today.
  - Closer to market solutions refer to products and processes that are considered already commercial or close to commercialisation. Investments in Finland are primarily not constrained by technical immaturity.
  - Further from market solutions refer technologies that are still relatively immature but hold considerable potential for future.
- *The analysis represents only a very small part of the thousands of chemical industry products,* and in reality the impact is probably significantly greater. It should be noted that all estimates have uncertainties regarding e.g. market share, comparison solution and low-carbon impact.
- However, the estimate shows the great potential Finland has and which can be realised if innovative RDD&D is implemented and exported.

Comparison

Chemical industry own CO_2-emissions in Finland (scope 1 and 2), 5.4 $MtCO_2e/a$ (2019)

Estimates for export solutions closer to market, potential global handprint of about 21 $MtCO_2e/a$



Finnish national GHG emissions, 53 $MtCO_2e/a$ (2019)

Estimate including solutions further from market, potential global handprint of about 26 $MtCO_2e/a$

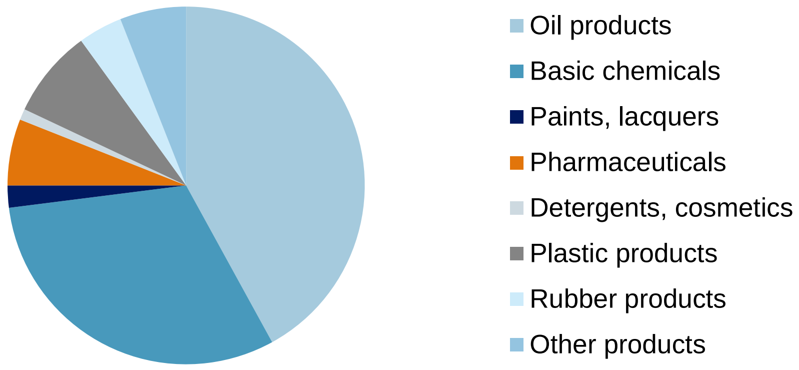
EXPORT POTENTIAL

FINNISH CHEMICAL INDUSTRY EXPORTS HAVE BEEN 10–12 BILLION EUROS IN THE LAST FEW YEARS

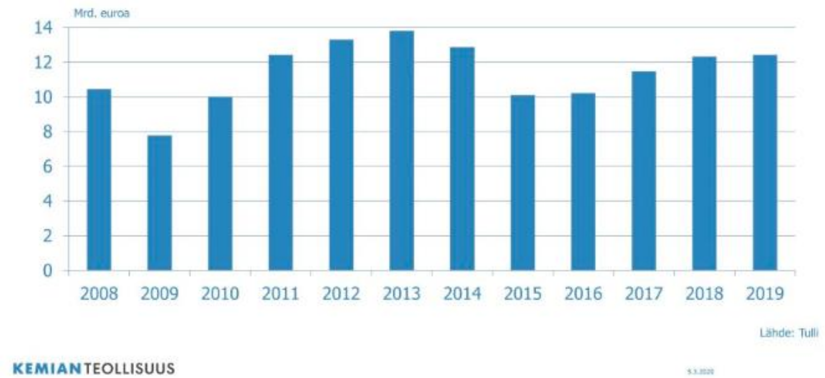
A very significant national contribution to be grown

- To put the export potential analysis in perspective, historical export statistics reveal that the chemical industry is one of the major exporting sectors of Finland.
- Annual material exports of chemical industry were slightly higher than 12 BEUR/a in 2018 and in 2019.
- The largest export categories were oil products and basic chemicals, followed by plastic products, pharmaceuticals and rubber products.
- The value of exports fluctuates strongly depending on commodity prices, such as oil price.
- Imports of the industry were equal to 11.4 BEUR/a in 2019.

Exports of chemical industry by value



Value of material exports of chemical industry of Finland, BEUR/a

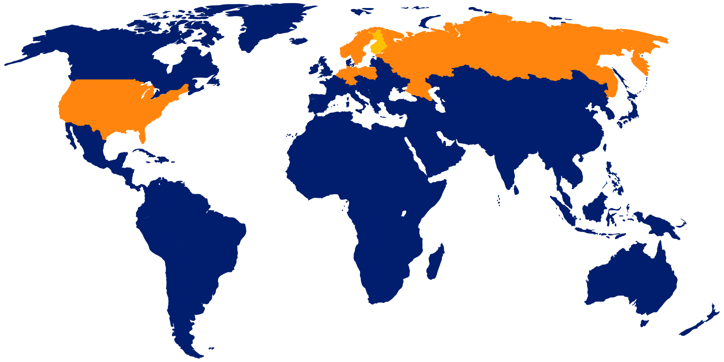


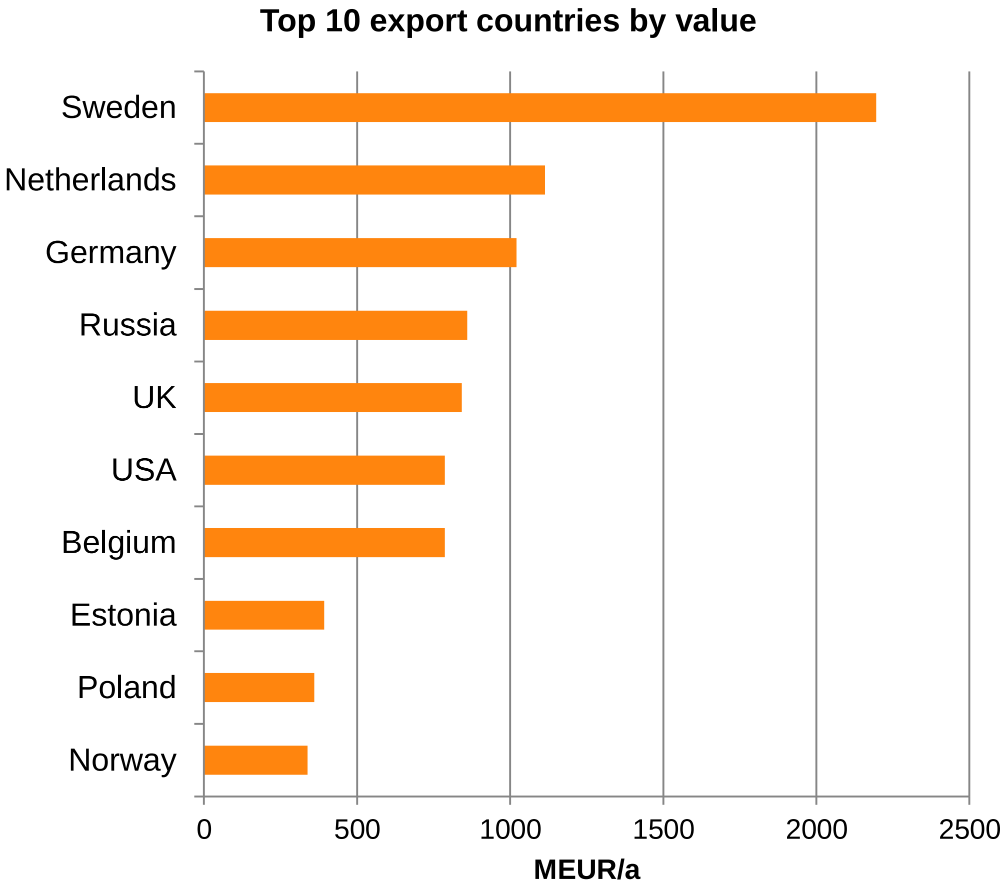
Source: Kemianteollisuus ry, Tulli

WESTERN EUROPE IS THE MAIN EXPORT MARKET

The geographical spread is already wide – and can be widened

- Western Europe is the main export market of Finnish chemical industry, while also Russia and USA make the top 10 list.
- Top 10 export countries make up 72% of the industry exports by value, led by Sweden.



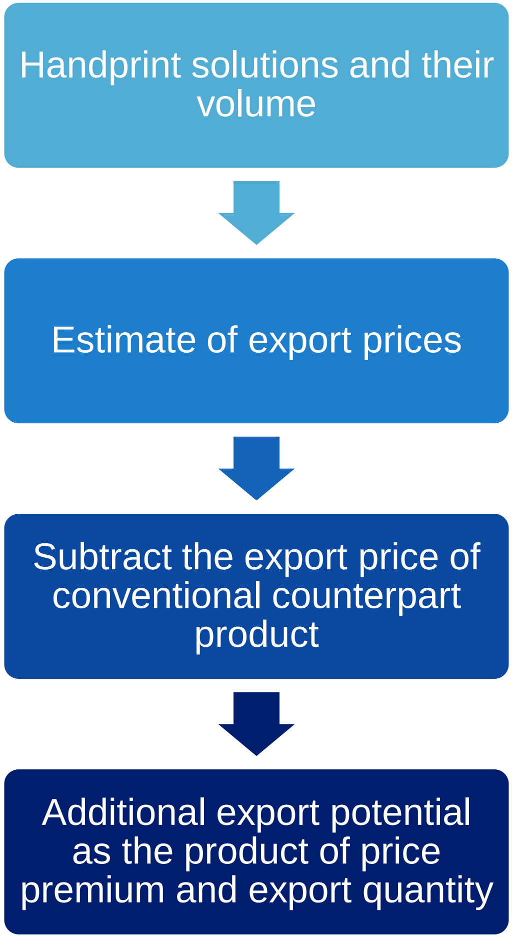


Source: Kemianteollisuus ry, Tulli

METHODOLOGY OF THE ANALYSIS OF EXPORT POTENTIAL

A business-driven method linking spearhead products, research need and resulting export potential

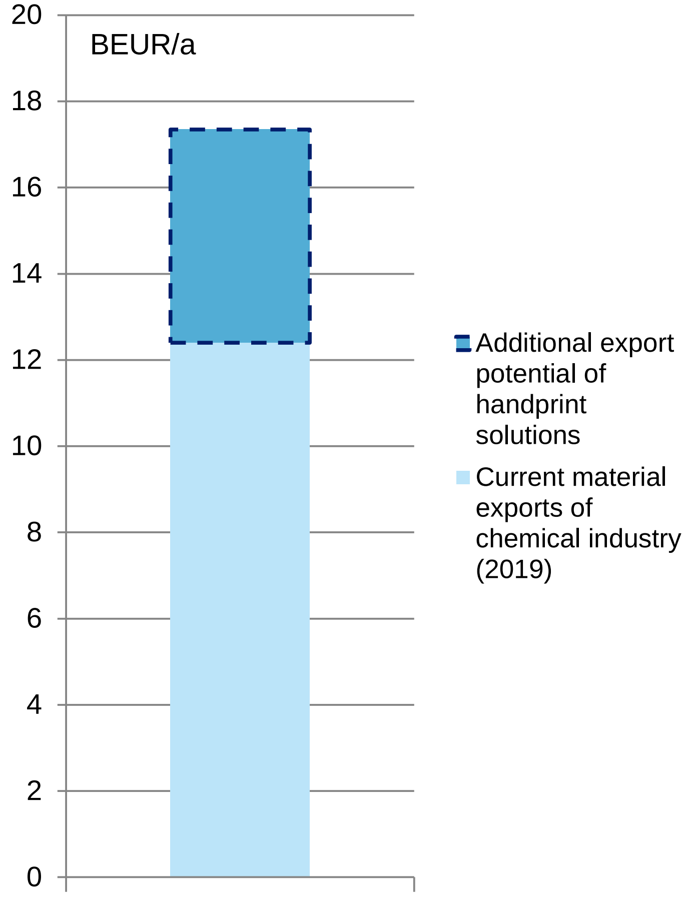
- The ten handprint examples identified and studied as a part of this work were also assessed for their future export potential.
- The analysis of export potential is based on current estimates of global market prices of novel products and solutions.
  - The handprint solutions were compared to current export products that the solutions could partly substitute. For some, there is no functioning market yet, and the analysis is grounded on best estimates available today. Some of the products are completely novel to the chemical industry, and they could thus open completely new export markets.
  - The analysis is based on quantities identified in the handprint cases, presented above.
  - The result of the analysis is the additional export potential of the new products compared to the current situation, assuming new products substitute some of the old product portfolio of the industry. This additional potential is a result of *higher value products* and *completely new products.*
  - It must be emphasized that the assessment only covers the analysed set of handprint cases. In reality, there are hundreds of products that contribute to the total export potential. If the substitution effect (new versus old products) is not as strong (signifying notable production volume growth), the exports could grow significantly more for existing top products and their variants.



ADDITIONAL EXPORT POTENTIAL OF HANDPRINT SOLUTIONS IS CLOSE TO 5 BILLION EUROS ANNUALLY

The “spearhead analysis” reaches a 40 % added export potential

- The additional export potential of the handprint solutions is ca 4.95 BEUR annually. This represents a 40% increase to the current exports of chemical industry.
  - Compared with the exports growth of ca. 2 BEUR/a between 2008–2019, this would mean a very notable increase compared to past trends.
  - The solution is based on current estimates of price premiums of handprint products. These premiums are still relatively moderate, as many companies and consumers have only in recent years become aware of the added value of low-carbon products. Therefore, the price premiums of low-carbon products may increase further compared to fossil products in the future through changes in consumer behaviour and regulatory requirements.
- Additional potential benefits of the handprint cases include reduced imports, avoided incineration and waste treatment costs – and of course the very significant CO_2 mitigation in addition to other environmental benefits.



INTRODUCING ”THE GREEN RATIO”

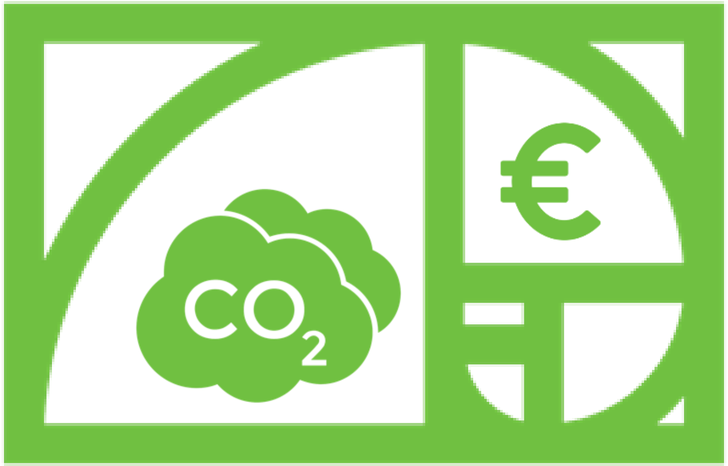
From the ”golden ratio” to the ”green ratio” – how many EUR of export potential is created per ton of avoided CO_2?

- The golden ratio is a number, about 1.618, describing proportions. It appears amazingly often in nature, and is used also intentionally to create aesthetically pleasing structures/pictures.

- By **”green ratio”,** with the symbol (!) on the right, we mean the ratio of

  Green ratio = **EUR of export potential/ tons of reduced CO_2**

- There is no ”right golden number for this”, but we can use the ratio to get a feel for how business potential connects to climate change mitigation.

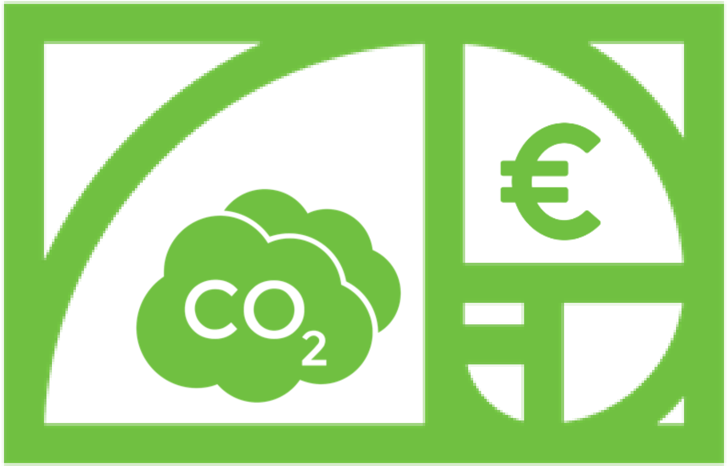


GREEN RATIO OF 187 EUR IN EXPORTS PER TON OF CO_2 AVOIDED

Win-win as a number – environmental, economic and social gains from climate tech

- The handprint analysis of a representative sample of cases revealed a handprint potential of 22–26 MtCO_2e/a through this selection of new products.
- The additional export potential of these cases is estimated to be ca. 4.9 BEUR/a.
- Through this analysis, a *green ratio* can be computed: each ton of CO_2 reduction delivered through the selected handprint solutions creates an additional 187 EUR in exports value for Finnish chemical industry.
- Although indicative only, the analysis truly reveals how attractive business opportunities lie in the low-carbon solutions.
  - Several companies in the industry have realised this long ago, and are currently economically benefiting from their forerunner position.
  - This highlights that importance of enabling framework conditions and the impact that investments into handprint solutions can create domestically.

187 EUR/tCO_2

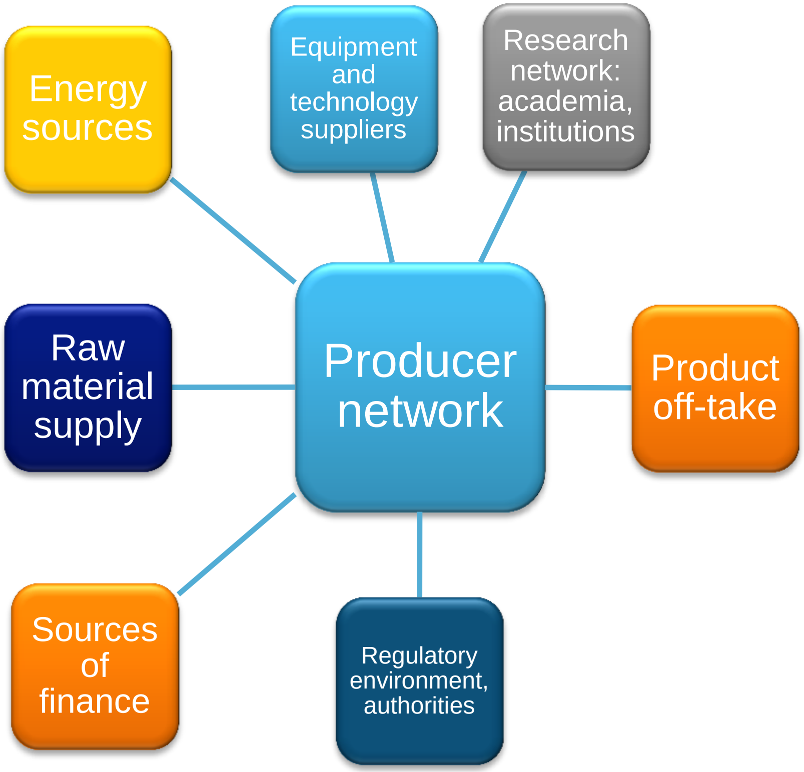


RDD&D AND KNOW-HOW

NETWORK OF INNOVATION ACROSS INDUSTRY BOUNDARIES

Innovation has never happened in a vacuum, and most of the radical technological advances do not respect industry boundaries

How to promote cooperation



Examples

- Future interdependencies and further integration between energy sector and industry
- Required public infrastructure for circular economy
- New financial instruments to drive low-carbon innovation across industry and national boundaries
- Research consortia covering the whole value chain, aiming to reduce systemic and operational costs is key in the innovation channel

MAPPING MEANS OVERCOMING TECHNOLOGY DEPLOYMENT BOTTLENECKS

Alternatives for policy support of low-carbon alternatives

Conventional approach: push & pull

- Technology push
  - Direct financing of RDD&D, public-private partnerships and industrial demos
    - Defragmentation of sources of finance in national R&D system to enable radical innovation
  - Indirect financing of RDD&D: preferred loans, tax credits
  - Human capital: training and education of scientists
- Demand pull
  - Standards and mandates
  - Public procurement, infrastructure investments
  - Market incentives: taxation, environmental legislation across society
  - Intellectual property aspects: acquisition and security of rights

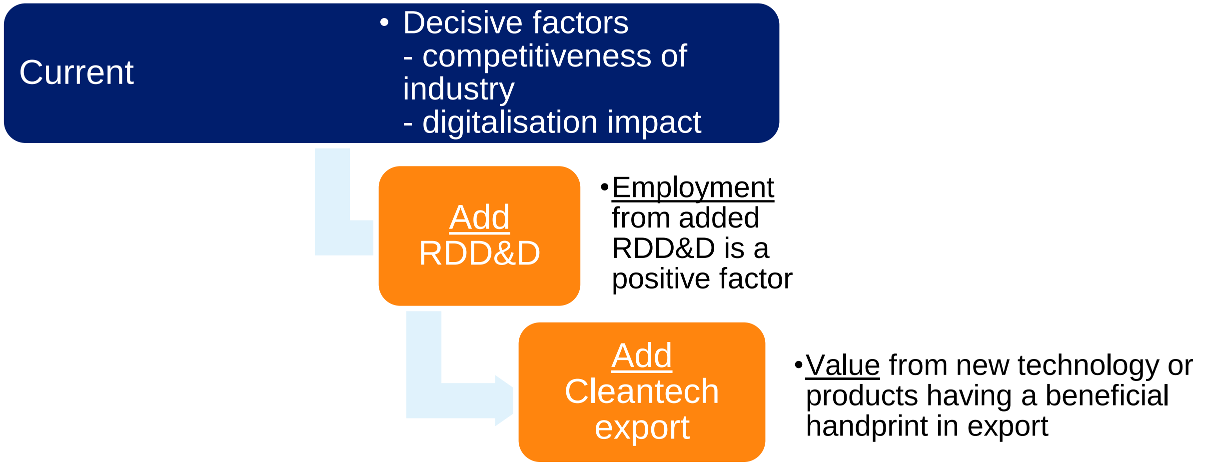
Network approach

- Awareness
  - Knowledge brokers
  - Search of partners
  - Clear communication of vision and mission, while avoiding winner-picking of technologies
- Promoting cooperation
  - Network formation
  - Vertical integration partnerships (across value chain)
  - Horizontal integration partnerships (across industries)

PERSONNEL CHANGES AND EXPORT POTENTIAL

Describing the positive change from added RDD&D.

Climate tech is not the decisive factor in chemical industry employment. The **competitiveness of the industry,** and the **impact of digitalization are the absolutely dominant factors.** Two positive changes can be estimated roughly in scenarios: **added employment from RDD&D, and from added cleantech export.** What the other, decisive competitive and digital impacts could be is outside this scope**.**



ESTIMATING ADDED EMPLOYMENT

What to use as basis for a rough estimate

Added RDD&D: employment

Factors:

- background:
***** RDD&D-intensity of basic chemicals, plastics and pharma is tracked by e.g Eurostat
* proportion of investments and RDD&D to turnover tend to form characteristic patterns for industry sectors – which are tracked

- scenarios:
- for the scenarios, we have a mixture of technologies of different types, and sizes of investments in the technologies and asset restructuring
- for each scenario, the investments, the RDD&D -proportion and the RDD&D -intensity of the types of investment form the basis of added RDD&D -employment in each scenario, which can be compared to CO_2 saved and EUR spent,

The change in RDD&D *-labour intensity is assumed to be in increased productivity and potential for more advanced research rather than a reduction in employment*

ROADMAP TO THE ROADMAP

1 EXECUTIVE SUMMARY

2 INTRODUCTION: Purpose, boundaries, approach

3 TECHNOLOGY: A menu of options to reduce emissions

4 SCENARIOS: Direct emissions, purchased energy and sensitivity to circumstances

5 SCENARIOS EXPANDED: A feedstock (r)evolution of defossilisation

6 TOOLBOX FOR CHANGE: Chemical clusters and example action plans

7 HANDPRINT, EXPORT POTENTIAL AND KNOWLEDGE: The global imprint of the Finnish chemical industry

8 CONCLUSIONS AND CONDITIONS: The outcome and the preconditions

IMPLICATIONS FOR THE NATIONAL FRAMEWORK…

Chemical industry can deliver decarbonisation reaching the core of modern societies, given the enablers are in place

Knowhow, innovations, RDD&D

- Additional resources into education, knowhow and interdisciplinary expertise targeted at climate solutions and low-carbon technologies are essential to be dealt immediately.
- Funding of research and development must be secured, while extending the channels of finance to cover demonstration and deployment phases, supporting industrial scale-ups and technology commercialization.

Promoting exports

- Paths to commercialisation and to global markets will be ever more important in the future, as the industry scales up low-carbon solutions.
- Promoting a supporting international framework is a key aspect even from national perspective.
- All human activity comes with environmental impacts, which should not limit the most innovative sustainable solutions being manufactured in Finland.

Industrial and technology policy

- Seeing the industry as a part of the solution or a part of the problem impacts the policy toolbox. Chemical industry embraces the Paris Agreement – how can domestic industrial and technology policy speed up the transformation, considering global competitiveness aspects?
- Reliable, inexpensive and low-carbon energy is key, as well as the necessary recycling infrastructure of materials.

New business models

- Handprint solutions are based on the use of the product or service.
  - Technology as an export product, licensing; need for enabling IPR environment
  - Piloting environment as a export product
  - Enabling sector integration through circularity

PÖYRY

…EMPHASIZING THE GLOBAL LEVEL

Solutions must be reached on the global level

European Union level

- EU is the most significant channel of Finland to impact global affairs, while the decisions made in Europe also fix the operating environment of Finnish industry to a great degree.
- From the view point of climate initiatives in the industry, the core areas in EU include the Green Deal and Green Recovery, mechanisms to set the CO_2 price and development of the EU ETS and the taxonomy of sustainable finance.

Trade politics

- Trade policy is the tool to reach a level playing field for industry.
- The transformation of industry towards climate neutrality can only be performed if it is also sustainable economically to the participating companies.
- The global uptake of Finnish handprint solutions could be leveraged also through trade policy.

International climate politics

- International climate negotiations have a key role for reaching the Paris Agreement goals.
- Increasing the global coverage of strict environmental and climate regulation and their further development could be very beneficial from the viewpoint of European industry's competitiveness.

Broader Sustainability Agenda

- Climate change is only one (though a key) aspect of environmental problems, which also include e.g. loss of biodiversity, water scarcity issues and overuse of natural resources.
- Chemical industry provides not only environmental solutions, but also serves core societal needs in the fields of food and pharma, for example.
- Other aspects of sustainable development (economical, social, cultural) cannot be sacrificed on the altar of the climate change – rather, they must be considered absolutely essential for succeeding in global efforts to mitigate and adapt to climate change.

CONDITIONALITIES

Presented scenarios depict a very ambitious future that will only materialize if certain systematic changes support the transition

Energy and feedstock

- Availability of low-carbon electricity at a competitive price
- Infrastructure enabling circular economy solutions
- Availability of alternative feedstock

Regulation and policies

- Market incentives and competitiveness: EU ETS, carbon border taxation
- Waste hierarchy
- Higher recycled and renewable content in the products

RDD&D system

- Heavy focus and support for low-carbon technologies
- Promotion of cross-industry collaboration and synergies
- De-risking scale-up
- IPR – import and export of technologies

GUIDELINES FOR GENERAL POLICY RECOMMENDATIONS ON NATIONAL LEVEL

Guidelines can be given on for supporting national policy, but EU-level policy and regulation may be more decisive also for the transition of Finnish industries

Energy policy

- Ensure the availability of low-carbon electricity at a competitive price
  - Avoid the chicken-egg problem: industry sectors need to secure electricity sources, energy sector needs to secure sufficient electricity off-take for low-carbon energy investments to take place
- Incentives to companies for switching to low-carbon energy

New markets policy

- Incentives to produce low-carbon products
  - Public procurement and other means to create new markets and demand
  - Links to larger, international framework: markets are global, and highly impactful, sector-cutting climate policy is crafted on EU level

Circular economy policy

- Incentives to companies to invest in circular economy options and solutions
  - Legislation, but also enabling infrastructure and incentives

Technology policy

- Incentives to invest in pilots, trials, demos and industrial production in Finland
  - Scale-up projects are a precondition for industrial solutions!
  - Projects provide a reference for Finnish companies
  - Projects will build new competitiveness and IPR assets for Finnish industry
    - Export potential both in new products and via technologies (“handprint”)
  - Projects will have spillover effects in Finnish society beyond Finnish chemical industry (see slides on Sector coupling)
  - But not at the expense of basic research!

Education and knowhow

- Incentives for both public and private sector to educate and re-educate the workforce
- Knowledgeable workforce
  - Designing workforce
  - Construction workforce
  - Education
- Attracting also international top talent is essential.

APPENDIX 1

ADDITIONAL CONTENT ON IMPACT OF DIGITALISATION ON FINNISH CHEMICAL INDUSTRY

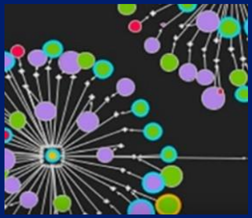
IT'S ALL ABOUT THE DATA AND WHAT THE CHEMICAL INDUSTRY DOES WITH IT – "CIRCULAR DATA ECONOMY FOR CHEMICALS"

Get it, process it, use it in an energy- and emission-efficient way

The **"circular data economy" for chemicals** notes that
- data has a lifecycle with also resource impacts along with handprint.
- data has a source
- it is processed
- the product, insight, is used for control and innovation.
- data needs an end-of-life solution.
- after that and during the cycle, new data gathering begins or is ongoing.

A-TO-C OF AUTOMATED LAB/DISCOVERY EXAMPLES

Picking Adam, ADA and Chematica for energy/emission saving digital tool types



Adam

Already in 2010, “Adam” received attention: this automated “scientist” had a database on the enzymes, chemicals, reagents and yeast cultures needed for a task. Adam could not do the simple tasks (waste removal, refill) but with a human “cleaner”, it solved a yeast genetic problem.

For chemical industry: automated labs with more data, more AI, and optimised resource consumption.

Ada

Named after Ada Lovelace, the 19th century computing pioneer, Ada is a Developing Materials Acceleration Platform that optimised and automates the materials discovery cycle.

For chemical industry: materials discovery speeded up, resource-efficiently, with resource goals.

Chematica

Chematica is a software long in development by Prof. B.A. Grzybowski. It is available, and the company sold to Merck in 2017. It is an extensive database of compounds and reactions, enabling search for new routes. Discovery of routes to target molecules have been successfully implemented in reality.

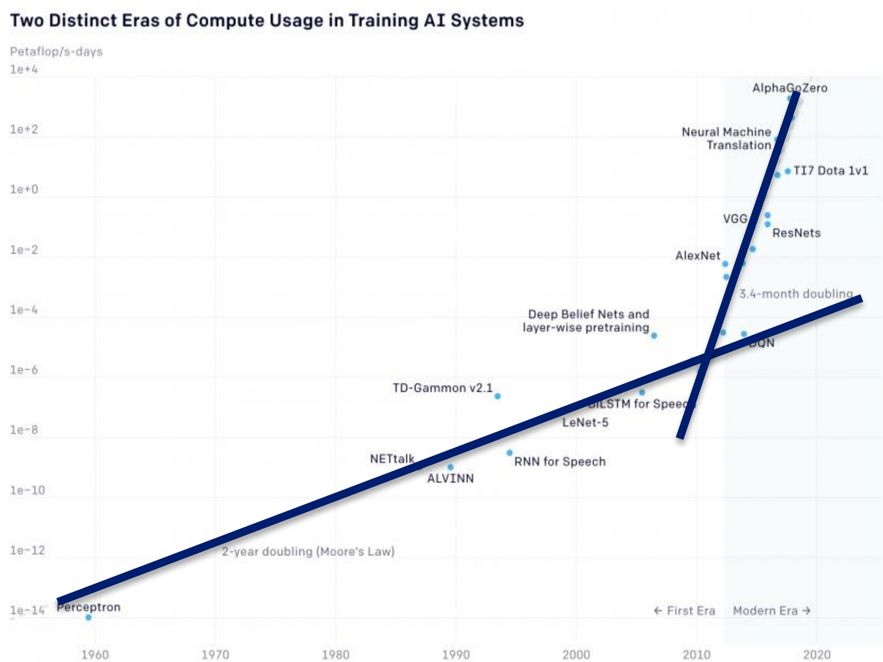
For chemical industry: materials discovery speeded up with a first phase of e.g. less steps and less resources.

AI DISRUPTION: MOORE'S LAW VS NEW LAWS

Old law: chemical industry could count on double the capacity at same cost in two years. Now…automated discovery of chemicals and process insight face this.

New law?	Consequences for chemical industry

The OpenAI-foundation stated in 2018 that the capacity needed to teach the most demanding AI models has doubled every 100 days since the breakpoint 2012. And, the models continue to get more complicated.



"7x"
Needed AI teaching capacity for one demanding task has (at a minimum) increased seven times since the breakpoint 2012

"300 000x"
Used capacity has increased 300 000 times in the same seven years

Source: Karen Hao, MIT Technology Review 2019

ARTIFICIAL PERPETUUM MOBILE?

AI fighting itself in chemical industry

Data centres, devices consume

About 3 % of the world’s energy is now consumer in data centres also used by the chemical industry, and the number is increasing. With own data centre increase in also chemical industry (incl. fog computing), the increase continues further.

AI increases consumption

The breakpoint in AI teaching 2012 (7 times more capacity per problem, 300 000 times more capacity) is only one of the many consumption-increasing aspects.

AI reduces consumption, invents new compounds, does automated labwork

Google estimates that its new specialised services can reduce on average 30 % of data centre energy consumption. E.g. Chematica looks for new compounds and shorter, more energy-efficient process routes.

LONGLIST – DIGITALISATION

Counter current area – increasing energy- intensity

Background

- Using extensive technology mapping, a global longlist on technical emission reduction possibilities.

Solutions

- Some are part of chemical industry development, some are items where the chemical industry has to know what it needs and make the supply chain and services provide it as part of digital investments.

Data gathering

- Right sensors developed for the right missing data with best impact

  5G solutions, e.g. mobile fog computing, carefully deployed and planned

Data use in process management

- Fast deployment of insight from processing to plants

  Trade-offs: weighing quality/cost/energy use of new solutions in sustainable way

Data processing

- Aiming for capacity-efficient own algorithms in process and RDD&D

  Choice of most energy-efficient cloud/fog service providers

Data use in RDD&D and innovation

- Going for resource-efficient algorithms both in teaching and use

  Using automated labs and discovery to improve process

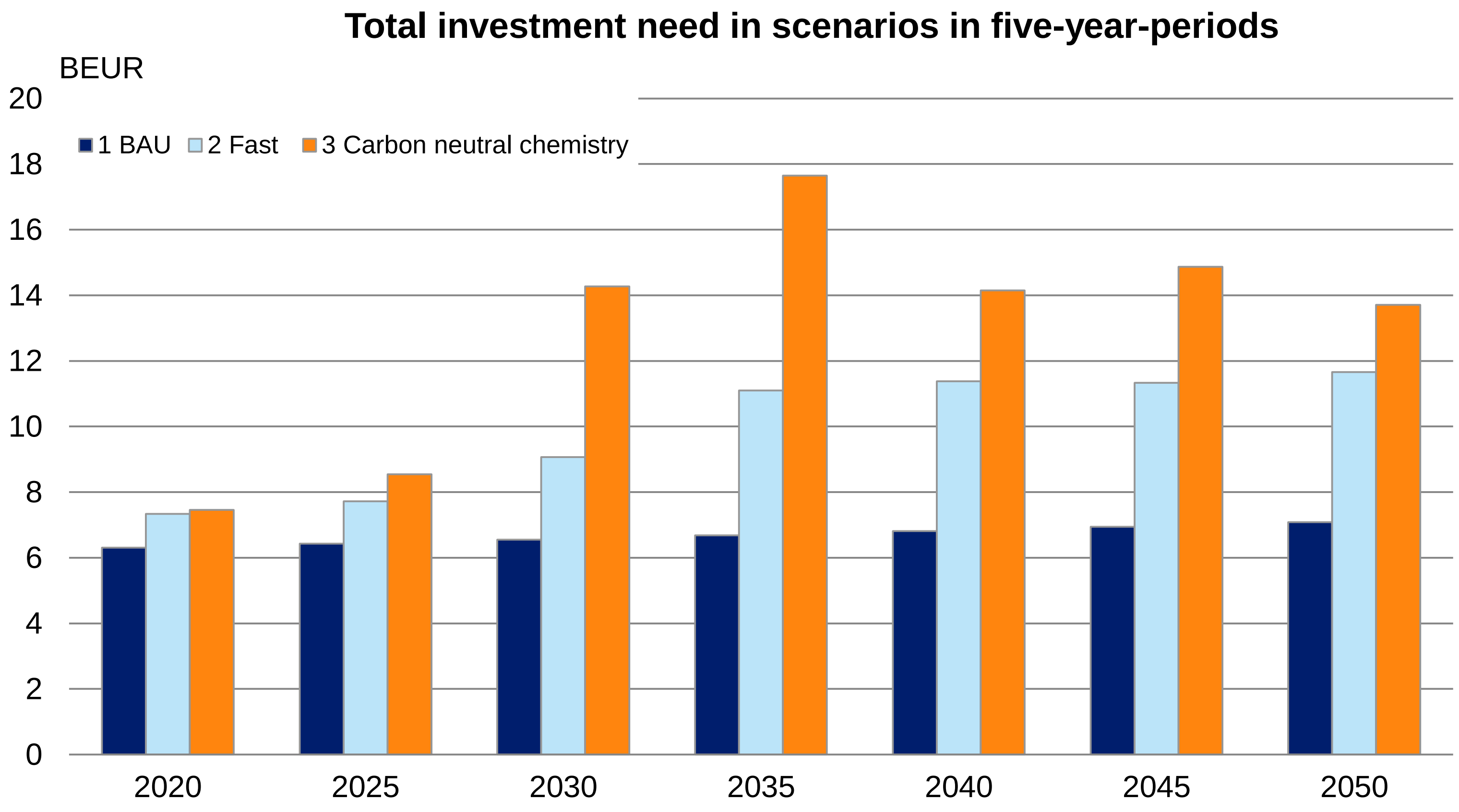
● Suits Finland, potential not exhausted

APPENDIX 2

INVESTMENT COSTS 2015-2050

INVESTMENTS 2015-2050 (INCLUDING ENERGY COSTS)

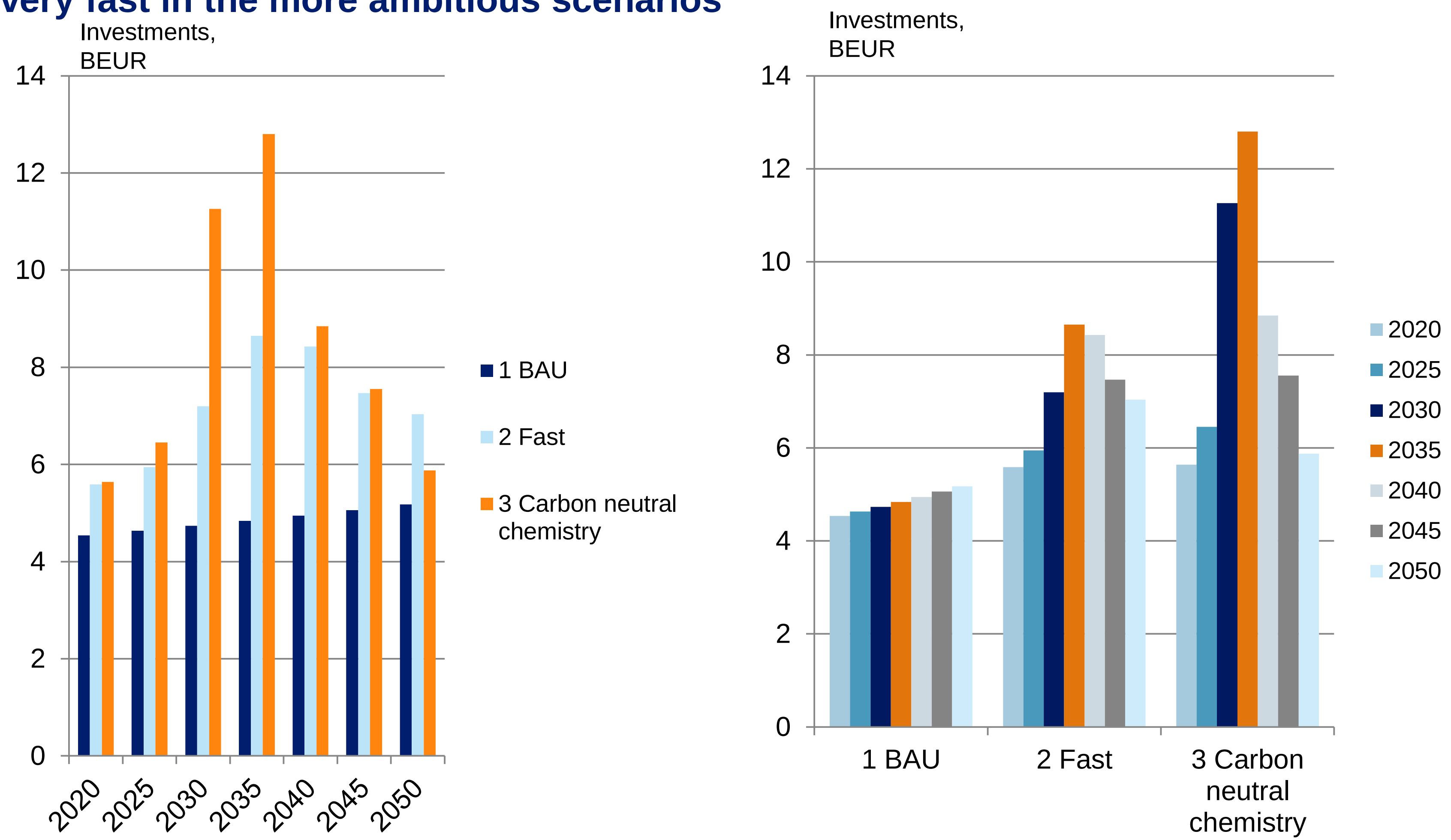
Five-year periods of scenario costs (scopes 1 and 2) peaking in the middle



Each bar corresponds to the investment need (including electricity costs at 50 €/MWh) during the preceding 5-year-period.

INVESTMENTS 2015-2050 (EXCLUDING ENERGY)

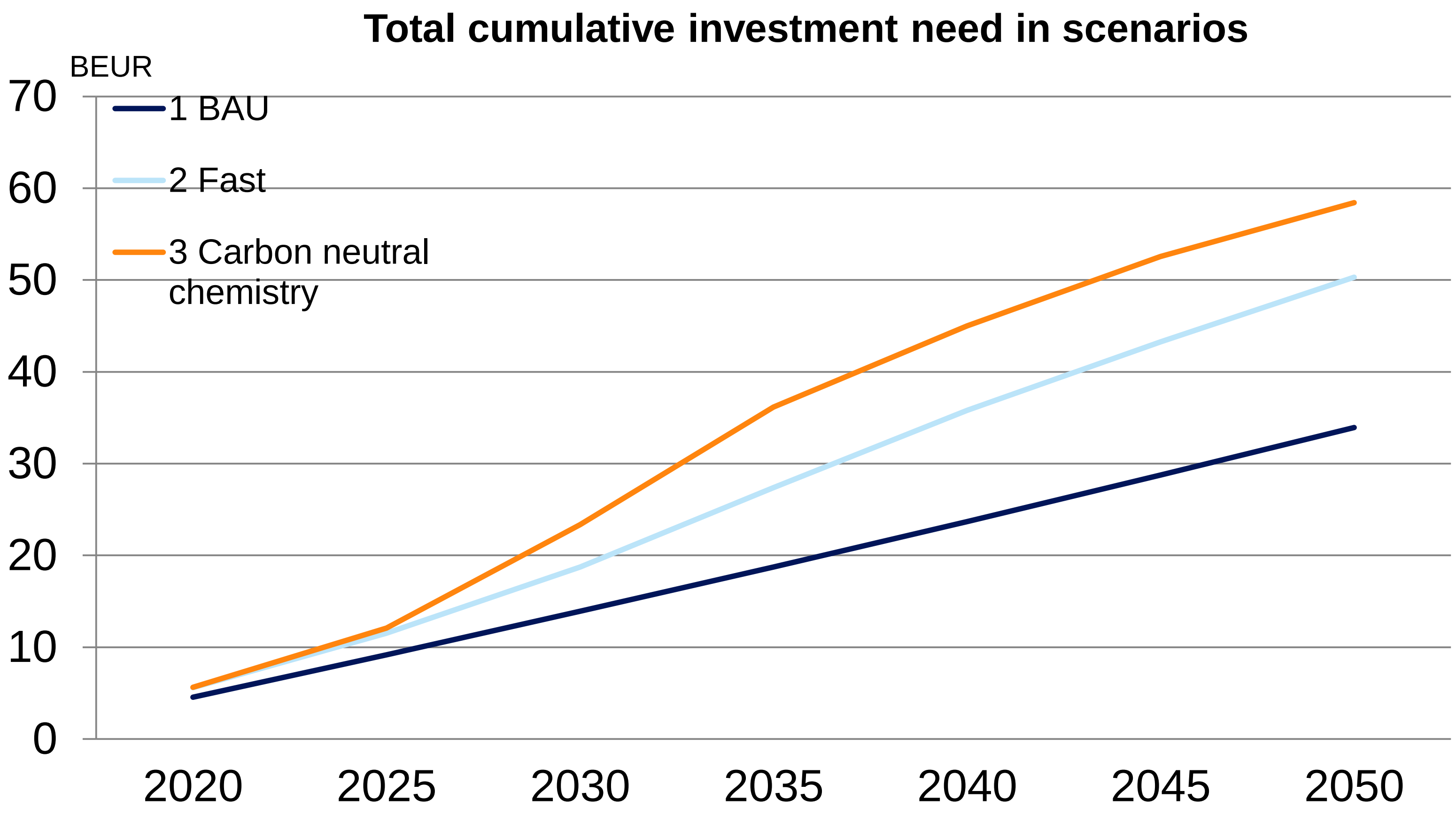
Investments into fixed assets, R&D, new technology and asset modifications climb very fast in the more ambitious scenarios



Each bar corresponds to the investment need during the preceding 5-year-period. Possible investments into public infrastructure, energy infrastructure and cross-industry integration are excluded.

CUMULATIVE INVESTMENT NEED 2015-2050 (EXCLUDING ENERGY)

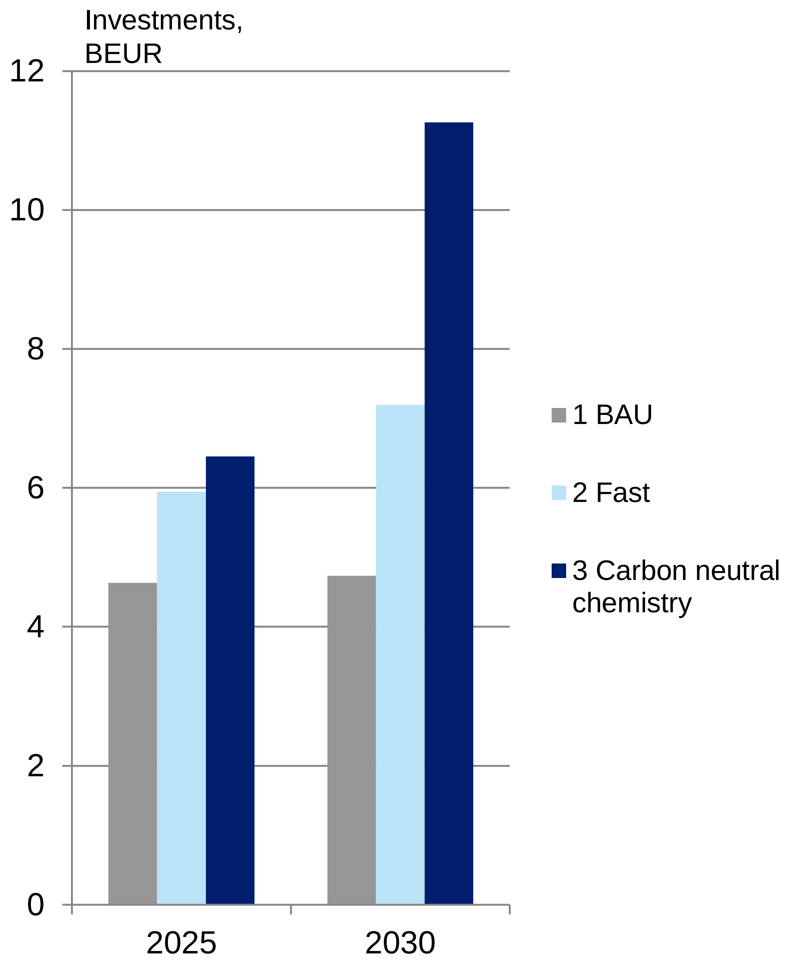
A significant sum with a steep beginning, evening out slightly towards the end

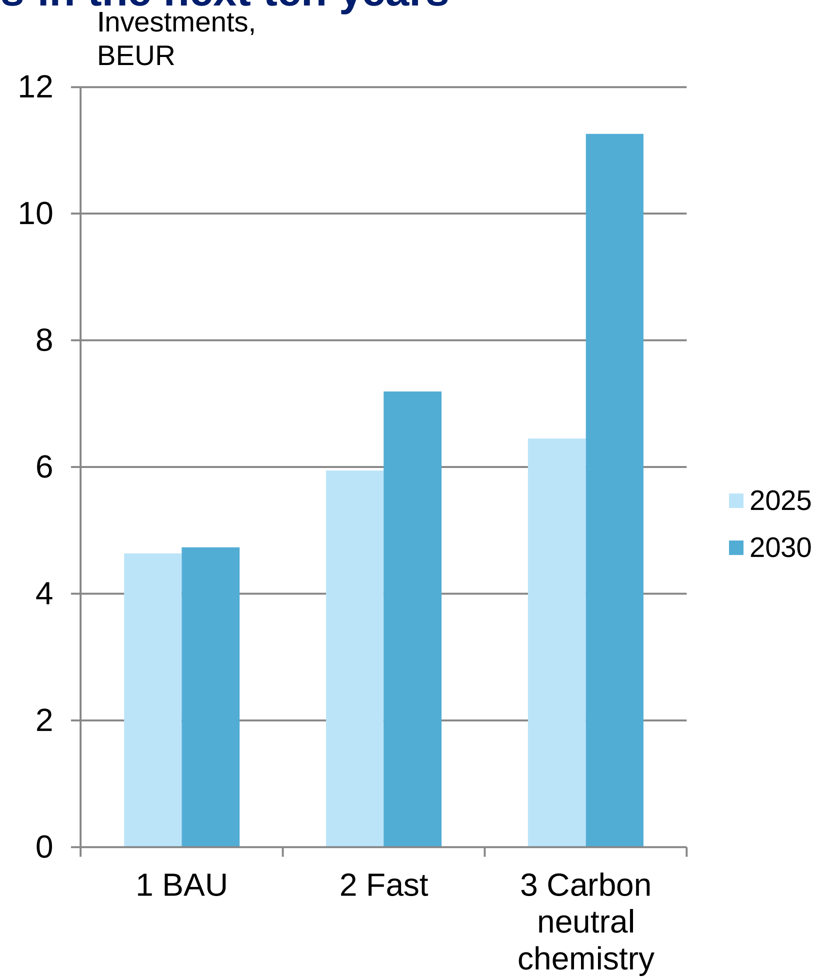


The graph corresponds to the cumulative investment need, starting from 2015. Possible investments into public infrastructure, energy infrastructure and cross-industry integration are excluded.

INVESTMENTS IN 2020-2030 : DOUBLING UP

Investments into fixed assets, R&D, new technology and asset modifications require a doubling of total investment levels in the next ten years



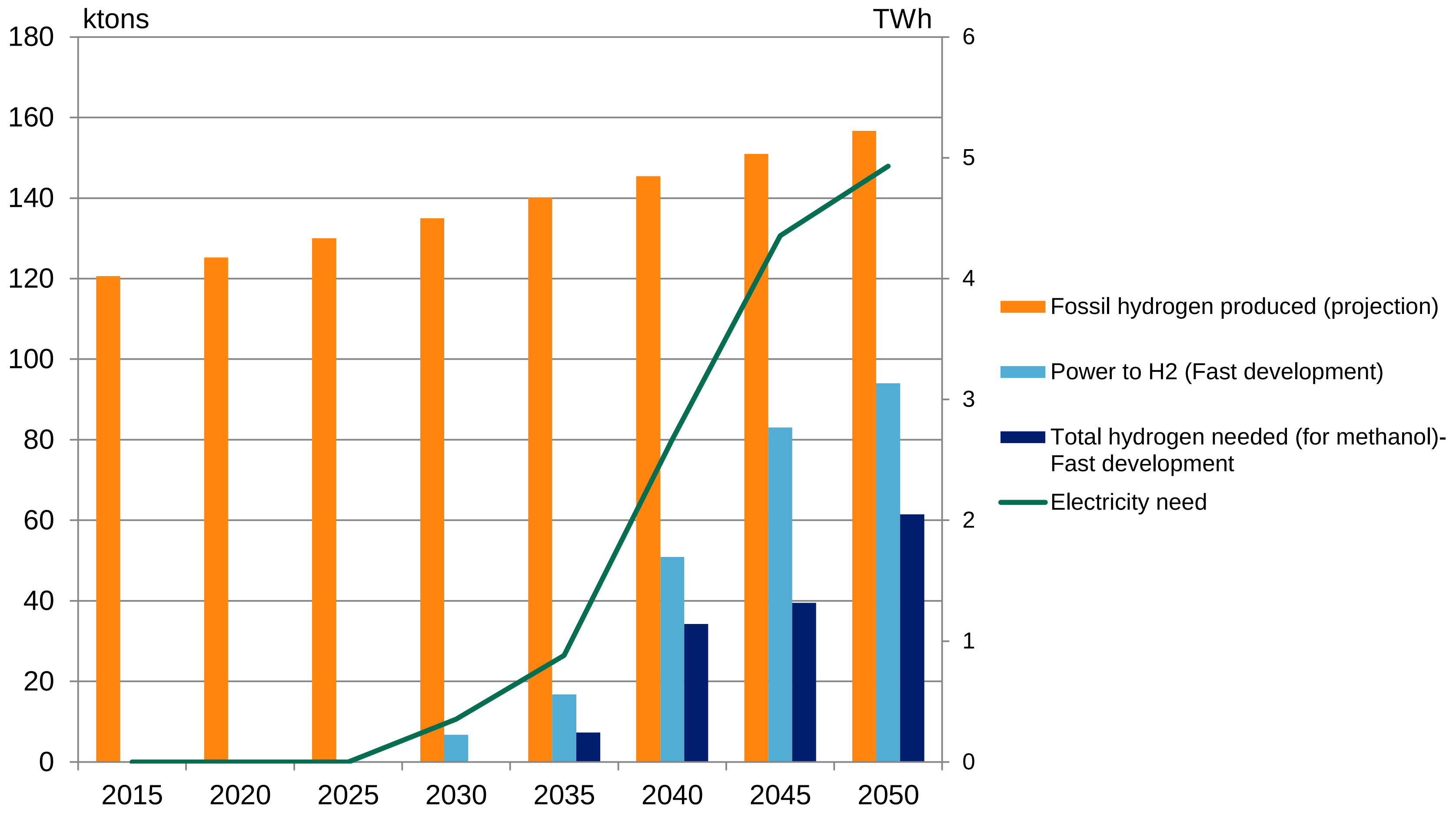


Each bar corresponds to the total investment need during the preceding 5-year-period. Possible investments into public infrastructure, energy infrastructure and cross-industry integration are excluded.

APPENDIX 3

HYDROGEN PRODUCTION AND USE IN SCENARIOS CONCERNING SCOPE 1 AND 2 ONLY

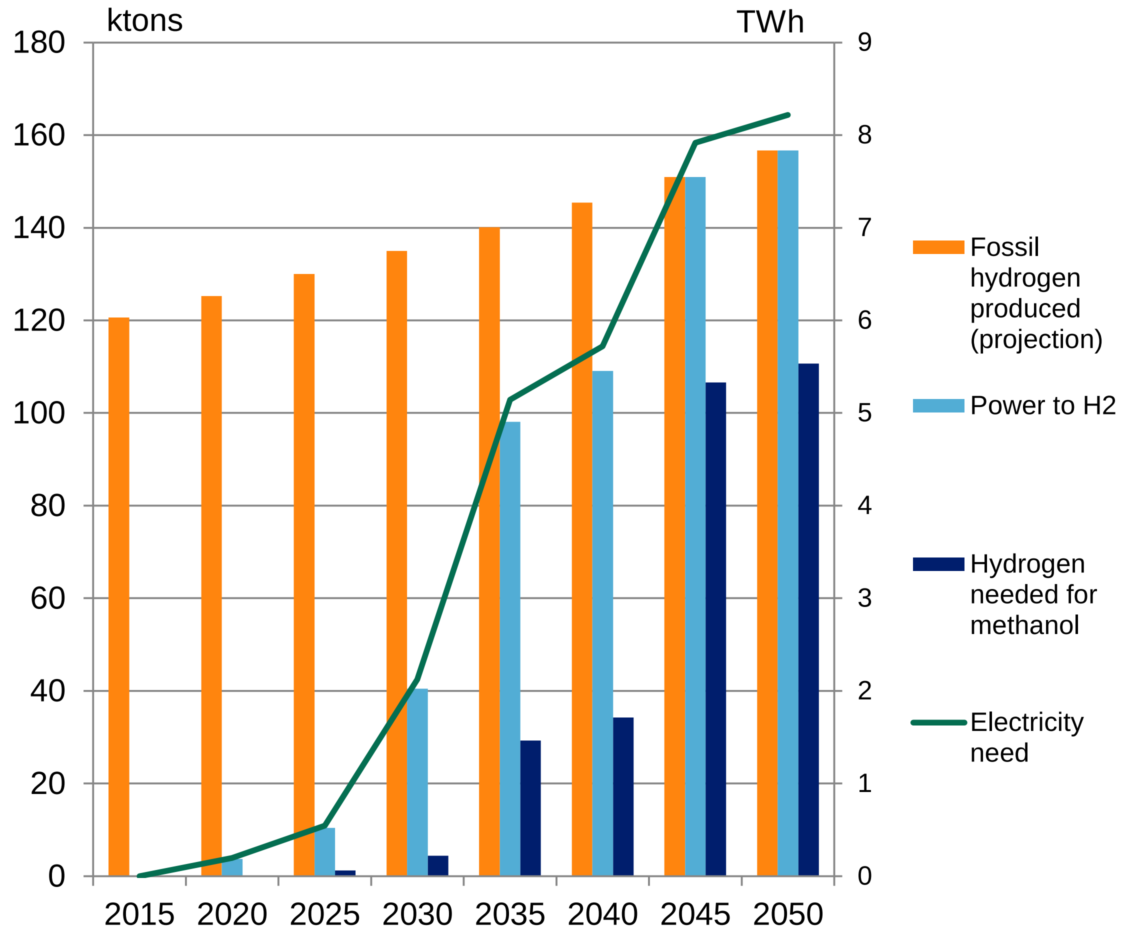
FAST DEVELOPMENT AND HYDROGEN



CARBON NEUTRAL CHEMISTRY 2045 AND HYDROGEN

Hydrogen and electricity are closely linked

- Hydrogen produced by Power-to-H2 technologies is projected to reach almost 160 kton by 2050. This projection is a result of current production level and the agreed volume growth (0,75%/a).
- The development and deployment scale of Power-to-hydrogen technologies is different in each scenario. Slow development and fast development scenario figures are presented in Appendix 3.
- Hydrogen used to produce methanol through the Power-to-methanol route comes from Power-to-H2. Methanol is then used in the Power-to-Olefins and Power-to-BTX routes.
- Overall hydrogen demand for the whole chemical industry in Finland is addressed partly by low-carbon hydrogen production and partly fossil-hydrogen production.



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