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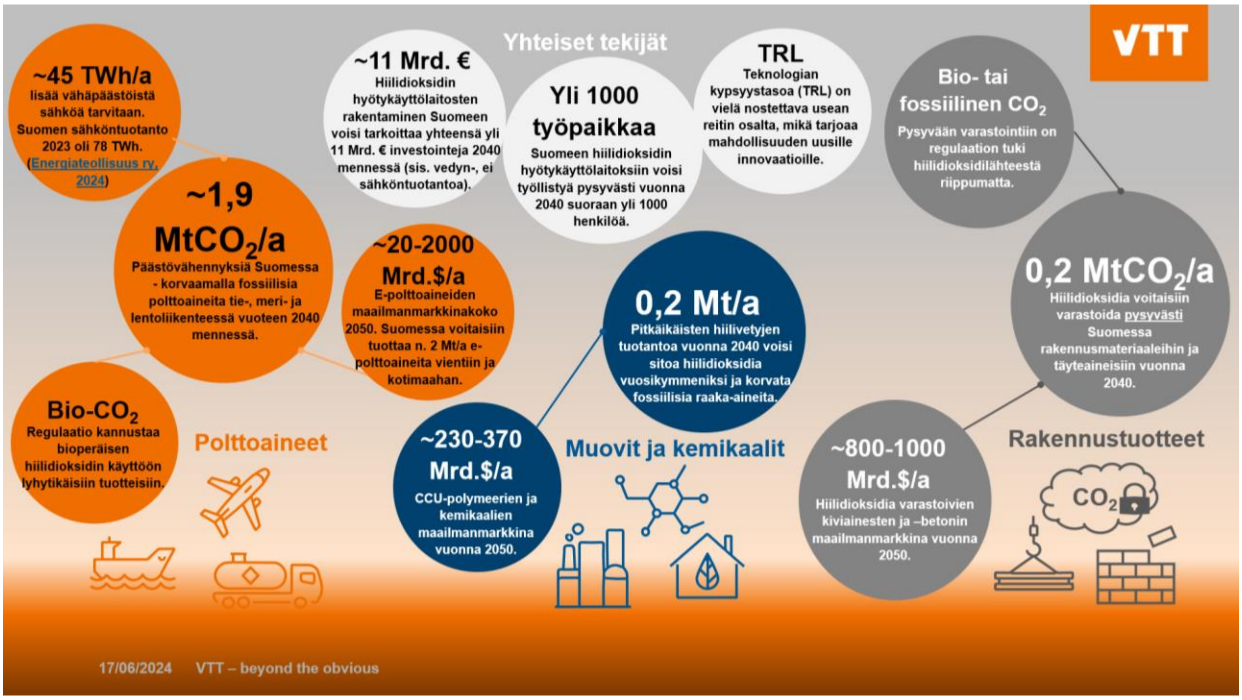


Projektiraportti: Selvitys hiilidioksidin talteenoton ja hyötykäytön kansallisesta ilmasto- ja talouspotentiaalista

Kirjoittajat: Sampo Mäkikouri, Lauri Kujanpää, Juha Lehtonen, Niko Heikkinen, Onni Linjala, Eveliina Jutila, Kati Koponen, Matti Reinikainen

Luottamuksellisuus: VTT Public

Versio: 21.8.2024

beyond the obvious

Projektiraportti: Selvitys hiilidioksidin talteenoton ja hyötykäytön kansallisesta ilmasto- ja talouspotentiaalista

Asiakkaan nimi, yhteyshenkilö ja yhteystiedot	**Asiakkaan viite**
Teknologiateollisuus ry, Annukka Saari, annukka.saari@teknologiateollisuus.fi Energiateollisuus ry, Petteri Haveri, petteri.haveri@energia.fi Kemianteollisuus ry, Tuomas Tikka, tuomas.tikka@kemianteollisuus.fi Metsäteollisuus ry, Ahti Fagerblom, ahti.fagerblom@forestindustries.fi	
Projektin nimi	**Projektin numero/lyhytnimi**
Selvitys hiilidioksidin talteenoton ja hyötykäytön kansallisesta ilmasto- ja talouspotentiaalista	139402 / CCU-potentiaali

Tiivistelmä

Teknologiateollisuus ry, Energiateollisuus ry, Kemiantelisuus ry sekä Metsäteollisuus ry tilasivat tämän selvityksen koskien hiilidioksidin talteenoton ja hyötykäytön kansallista talous- ja ilmastopotentiaalia. Työn tavoitteena oli kerätä ja tuottaa teknistaloudellista tietoa yritysten ja päättäjien tueksi, koskien Suomen ilmastotavoitteiden saavuttamiseksi vaadittavien toimenpiteiden mittakaavaa, kustannuksia ja edellytyksiä. Työ tukee toimialojen ilmastotiekarttojen päivitystä, mikä puolestaan luo pohjaa Suomen hallituksen ilmastotoimille ja strategialle.

Selvitys jaettiin kolmeen Toimenpiteeseen (Work package) ja on raportoitu niiden mukaisesti englanniksi. Näiden lisäksi raportin alkuun on koottu keskeisimpien viestien tiivistämiseksi Yhteenveto suomeksi sekä Executive Summary. Toimenpiteet ovat:

1) Hiilidioksidin talteenoton ja etenkin hyötykäytön liiketoimintamahdollisuudet Suomessa / Business opportunities of carbon capture and utilisation in Finland
2) Tuotteet, markkinat ja arvonmuodostus / Products, markets and value
3) Vaikutukset Suomelle, investointinäkymät, mahdolliset ohjauskeinot sekä ehdotukset pelisäännöiksi. / Implications for Finland, investment prospects, possible policies and proposals for code of conduct

Toimenpiteessä 1 koottiin tiedot Suomen hiilidioksidin päästölähteistä, hiilidioksidin hyötykäyttöä koskevasta regulaatiosta ja teknologiareiteistä. Lisäksi valittiin keskeisimmiksi tarkasteltaviksi tuotteiksi polttoaineet lento-, laiva- tieliikenteessä; polyolefiinit ja polyolit/polyuretaanit; sekä kiviainekset ja esivaletut betonituotteet. Kartoitusta tehtiin myös keskeisestä hiilidioksidin hyötykäyttöä ja varastointia koskevasta EU-sääntelystä. Toimenpiteessä 2 tehtiin markkinakatsaus näihin tuotteisiin, arvioitiin markkinoiden muodostumista vuoteen 2050 mennessä sekä tarkasteltiin ansaintamahdollisuuksia hiilidioksidipäästöjen poistamisen kautta. Toimenpiteessä 3 arvioitiin mahdollisen hiilidioksidin hyötykäyttöskenaarion vaikutuksia Suomen päästövähennyksiin, sähkönkulutukseen, investointeihin ja työllisyyteen.

Hiilidioksidista valmistetuille tuotteille tulee Euroopassa kysyntää matkalla kohti hiilineutraaliutta. Teollisuuden uudistamisen edellytyksinä ovat uusiutuvan energian lisäksi suuret investoinnit ja teknologiakehitys. Nämä edellytykset eivät täyty itsestään, vaan tarvitaan riittävät kannustimet ja sääntelyä, joka mahdollistaa uudet markkinat. Tähän selvitykseen perustuen keskeisimmät politiikan suosituksemme ovat:

- **Korkea jalostusaste ja pysyvät varastot**: Hiilidioksidin hyötykäytössä tulisi panostaa korkean jalostusasteen tuotteisiin sekä pysyviä hiilidioksidivarastoja luoviin tuotteisiin.
- **Puhdas sähkö ja vety – tuotanto ja siirto**: Puhdas sähkö ja vety ovat edellytyksiä hiilidioksidin korkean arvon jatkojalostukselle, joten investoinnit näihin liittyvään tuotantoon ja infrastruktuuriin olisi turvattava hiilidioksidin hyötykäyttöhankkeiden lisäksi.
- **Suuret investoinnit ja juoksevat kulut**: Sähkön- ja vedyntuotannon lisäksi hiilidioksidin talteenotto, kuljetus ja hyötykäyttö vaativat kokonaisuudessaan miljardien eurojen investoinnit. Investointien lisäksi toiminnan juoksevat kulut on katettava CCU-tuotteiden myyntikatteilla tai toimivilla hiilenpoistomarkkinoilla.
- **EU-politiikkaan vaikuttaminen Suomelle suotuisan hiilienpoistomarkkinan luomiseksi:** Markkinat kaipaavat ennakoitavuutta, ja bioperäisen hiilidioksidin varastoinnilta puuttuu vielä vakaa taloudellinen kannustin.
- **Valtion esimerkillä myös yksityistä rahoitusta:** Toistaiseksi yksityistä rahoitusta on kyetty saamaan hiilidioksidin poistoon merkittävässä mittakaavassa vain maissa, joissa on valtiovetoista taloudellista kannustinpolitiikkaa talteenottoon ja varastointiin.
- **Edellytettävä perusteellisia tapauskohtaisia tarkasteluja:** Hiilidioksidin hyötykäyttöhankkeiden kannattavuus talous-, ilmasto-, ympäristö- ja työllisyysnäkökulmista on tapauskohtaista ja hankkeiden vaikutusten perusteellista arviointia kannattaa edellyttää ja tukea.
- **Tahtotila ja yhteiskunnan hyväksyntä**: Yhteiskunnan eri toimijat on otettava mukaan valmisteluun varhaisessa vaiheessa CCU-hankkeita suunniteltaessa erilaisten vaikutusten huomioimiseksi, avoimen keskustelun luomiseksi ja yhteiskunnan edun varmistamiseksi.

Tampereella 21.8.2024	
Laatija	**Tarkastaja**
Sampo Mäkikouri Erikoistutkija	Harri Latonen Asiakkuusvastaava
Confidentiality	VTT Public
VTT:n yhteystiedot Sampo Mäkikouri, sampo.makikouri@vtt.fi +358 40 152 9658	
Jakelu (asiakkaat ja VTT) Sähköinen jakelu tilaajille (Teknologiateollisuus ry, Annukka Saari; Energiateollisuus ry, Petteri Haveri; Kemianteollisuus ry, Tuomas Tikka; Metsäteollisuus ry, Ahti Fagerblom) ja VTT:n arkistoon. Tämä raportti on julkaisuun kelpaava muokattu versio alkuperäisestä luottamuksellisesta projektiraportista.	

Hyväksyminen

TEKNOLOGIAN TUTKIMUSKESKUS VTT OY

Päivämäärä:	21.8.2024
Allekirjoitus:	
Nimi:	Lauri Kujanpää
Asema:	Tutkimustiimin päällikkö

Selvitys hiilidioksidin talteenoton ja hyötykäytön kansallisesta ilmasto- ja talouspotentiaalista – ”CCU-potentiaali”

Yhteenveto & Executive Summary

Sampo Mäkikouri, Lauri Kujanpää, Niko Heikkinen, Juha Lehtonen, Kati Koponen, Onni Linjala, Matti Reinikainen, Eveliina Jutila

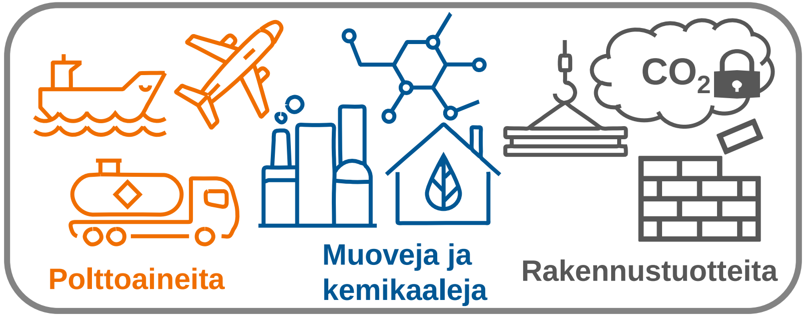
VTT:n projektinumero 139402

Tiivistelmä

Hiilidioksidin hyötykäyttöön tarvitsemme paljon puhdasta energiaa – mitä me hyödymme siitä?

- Hiilidioksidin talteenotto ja hyötykäyttö (CCU) tuotteiksi vaatii paljon vähäpäästöistä energiaa, mutta näin voimme luoda **korvaajia fossiilisista raaka-aineista valmistetuille tuotteille**. Osa tuotteista voi toimia myös eri ikäisinä varastoina hiilidioksidille.
- Tämä tarkoittaa suurta uudistumista monelle teollisuudenalalle, mikä puolestaan luo **uusia liiketoimintamahdollisuuksia.**

- Tässä työssä selvitettiin **hiilidioksidin hyötykäytön vaikutuksia** koko Suomen tasolla, keskittyen **liiketoimintamahdollisuuksiin, markkinoihin ja ohjauskeinoihin.**



Kuva 1. *Hiilidioksidia hyödyntäen voidaan valmistaa mm. polttoaineita, muoveja, kemikaaleja ja rakennustuotteita. Rakennuksiin käytettävät muovit ja eristeet voivat varastoida hiilidioksidia vuosikymmeniksi, mineraaliset tuotteet jopa pysyvästi.*

VTT

Kannattaako hiilidioksidin hyötykäyttö?

Ilmasto- ja muut ympäristö-vaikutukset?

Investointien suuruus?

Teknologian kypsyys ja uudet innovaatiot?

Vaikutukset työllisyyteen ja teollisuuden uudistumiseen?

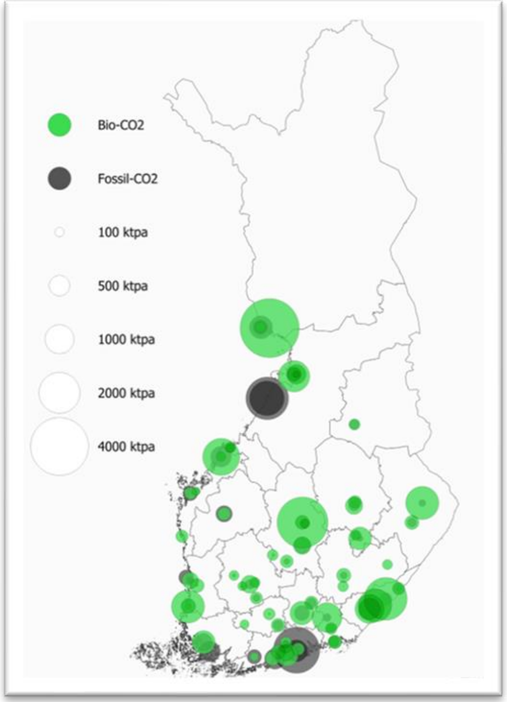
Kuinka suuret markkinat ja mille tuotteille?

Hiilidioksidin saatavuus?

Mitä regulaatio mahdollistaa?

Suomen lähtökohdat hiilidioksidin hyötykäyttöön ja varastointiin

- Suomella on Euroopassa erityisluontoinen asema **merkittävänä bioperäisen hiilidioksidin lähteenä** ja toisaalta maana, jolla ei ole hiilidioksidin varastointiin sopivia geologisia muodostumia. Lisäksi uusi teknologia voi mahdollista hiilidioksidin varastoinnin kaivosjätteisiin.
- **Suomessa syntyy teollisuuden CO_2-päästölähteistä (>0,1 Mt/vuosi) n. 30,1 Mt/vuosi bioperäistä ja n. 15,2 Mt/vuosi fossiilista hiilidioksidia.** Jätteenpoltosta hiilidioksidipäästöjä syntyy n. 1,4 Mt/vuosi (fossiilista ja bioperäistä sekaisin). Tulevaisuudessa CO_2-päästöt voivat olla laskemassa materiaalihyötykäytön lisääntyessä (esim. ligniinin talteenotto, muovin kierrätys) ja vastaavasti polton osuuden pienentyessä.
- **Hiilidioksidia on saatavilla Suomessa ympäri vuoden.** Vaikka esimerkiksi kaukolämmön tuotanto ja päästöt vaihtelevat kausittain, on valmistavassa teollisuudessa ja jätteenpoltossa vaihtelu selvästi vähäisempää.
- Suomen **hiilidioksidipäästöt ovat suuria verrattuna moniin kotimaisiin materiaalivirtoihin**; jos suuri osa tästä halutaan jalostaa korkean arvon tuotteiksi, on tähdättävä **myös Euroopan markkinoille**.
- **Suomessa sähköntuotannon CO_2-päästöt ovat alhaiset, keskimäärin n. 70 gCO_2/kWh** (2020-2022 ka. Tilastokeskus, 2024.), mikä on on keskeinen edellytys päästövähennyksille hiilidioksidin hyötykäytön avulla. Vastaava 2020-2022 ka. EU-tasolla on n. 240 gCO_2/kWh. (EEA, 2023) Hyötykäyttö vaatii lisäksi investointeja puhtaaseen energiantuotantoon.



***Kuva 2.** Hiilidioksidin pistemäiset päästölähteet Suomessa, >100 kt/a eli > 0,1 Mt/a.*

Keskeisimmät tulokset

- **Hiilidioksidista valmistetuille tuotteille tulee kysyntää Euroopassa** matkalla kohti hiilineutraaliutta. Teollisuuden uudistamisen edellytyksinä ovat uusiutuvan energian lisäksi suuret investoinnit ja teknologiakehitys.
- Keskeisimpien CCU-tuotteiden globaalin markkinan odotetaan olevan vuoteen 2050 mennessä suuruudeltaan yhteensä **$1000 – 3400 Mrd./vuodessa**.
- CCU on tunnustettu keskeiseksi teknologiaksi EU:n ilmastonmuutoksen hillintäkeinojen joukossa, mutta **CCU-regulaatiota on toistaiseksi kehitetty pääasiassa liikennepolttoaineiden osalta**, ja on jäänyt vielä vaillinnaiseksi muiden tuotteiden kannalta.
- **Mahdollinen CCU-skenaario voisi toteutuessaan tarkoittaa Suomelle vuoteen 2040 mennessä**:
  - Tarvittaisiin ~50 TWh/a lisää vähäpäästöistä sähköä. Koko sähköntuotanto Suomessa oli ~78 TWh vuonna 2023.(Energiateollisuus ry, 2024).
  - CCU-tuotteiden valmistamiseen tarvittaisiin ~1,2 Mt/a vetyä, josta pääosa menisi sähköpolttoaineisiin.
  - Kokonaisinvestointien suuruus olisi yhteensä ~11 000 milj. €
  - CCU-tuotteiden tuotannon arvo liki ~7 000 milj. €/a
  - Hiilidioksidipäästöt vähenisivät Suomessa ~2,5 MtCO_2/a, josta ~1,9 MtCO_2/a sähköpolttoaineiden korvatessa fossiilisia polttoaineita. Lisäksi vientituotteet vähentäisivät päästöjä merkittävästi muissa maissa.
  - Raakaöljyn tarve pienenisi ~2 Mt/a, ja ~0,7 Mt/a fossiilisiin raaka-aineisiin pohjautuvia tuotteita korvattaisiin CCU-tuotteilla. Mineraaliset rakennustuotteet voisivat sitoa pysyvästi ~0,2 MtCO_2/a.
  - CCU-tuotantolaitokset voisivat työllistää suoraan ~1 100 henkilöä.

Yhteiset tekijät

~45 TWh/a
lisää vähäpäästöistä sähköä tarvitaan. Suomen sähköntuotanto 2023 oli 78 TWh. (Energiateollisuus ry, 2024)

~11 Mrd. €
Hiilidioksidin hyötykäyttölaitosten rakentaminen Suomeen voisi tarkoittaa yhteensä yli 11 Mrd. € investointeja 2040 mennessä (sis. vedyn-, ei sähköntuotantoa).

Yli 1000 työpaikkaa
Suomeen hiilidioksidin hyötykäyttölaitoksiin voisi työllistyä pysyvästi vuonna 2040 suoraan yli 1000 henkilöä.

TRL
Teknologian kypsyystasoa (TRL) on vielä nostettava usean reitin osalta, mikä tarjoaa mahdollisuuden uusille innovaatioille.

Bio- tai fossiilinen CO_2
Pysyvään varastointiin on regulaation tuki hiilidioksidilähteestä riippumatta.

Polttoaineet

~1,9 $MtCO_2/a$
Päästövähennyksiä Suomessa - korvaamalla fossiilisia polttoaineita tie-, meri- ja lentoliikenteessä vuoteen 2040 mennessä.

~20-2000 Mrd.$/a
E-polttoaineiden maailmanmarkkinakoko 2050. Suomessa voitaisiin tuottaa n. 2 Mt/a e-polttoaineita vientiin ja kotimaahan.

Bio-CO_2
Regulaatio kannustaa bioperäisen hiilidioksidin käyttöön lyhytikäisiin tuotteisiin.

Muovit ja kemikaalit

0,2 Mt/a
Pitkäikäisten hiilivetyjen tuotantoa vuonna 2040 voisi sitoa hiilidioksidia vuosikymmeniksi ja korvata fossiilisia raaka-aineita.

~230-370 Mrd.$/a
CCU-polymeerien ja kemikaalien maailmanmarkkina vuonna 2050.

Rakennustuotteet

0,2 $MtCO_2/a$
Hiilidioksidia voitaisiin varastoida pysyvästi Suomessa rakennusmateriaaleihin ja täyteaineisiin vuonna 2040.

~800-1000 Mrd.$/a
Hiilidioksidia varastoivien kiviainesten ja –betonin maailmanmarkkina vuonna 2050.

CO_2

Mitä on tehtävä, jotta Suomessa saataisiin toteutettua hiilidioksidin hyötykäytön mahdollisuudet?

- **Korkea jalostusaste ja pysyvät varastot:** Hiilidioksidin hyötykäytössä tulisi panostaa korkean jalostusasteen tuotteisiin sekä pysyviä hiilidioksidivarastoja luoviin tuotteisiin.
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Executive Summary

Utilising carbon dioxide requires a lot of low-emission electricity – what's the benefit?

- Carbon capture and utilisation (CCU) requires a lot of low-emission electricity but **enables replacing products based on fossil raw materials**. Some products can also act as a carbon storage for various durations.
- This means a grand renewal for many industries, which in turn creates **new business opportunities.**

- In this work, the **impacts of carbon capture and utilisation** for Finland were assessed, focusing on **business opportunities**, **markets** and **regulation.**

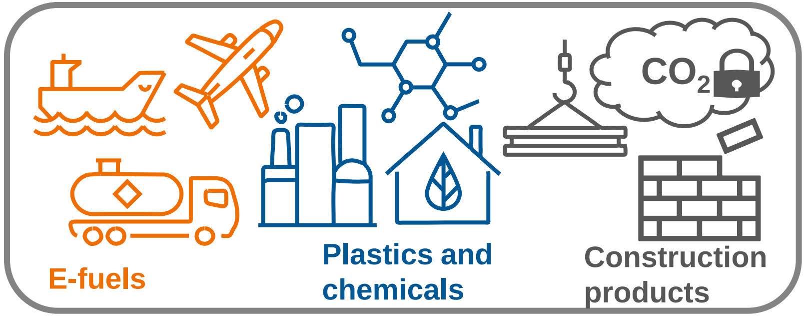

Figure 1. *By using carbon dioxide as a feedstock, products like e-fuels, plastics, chemicals and construction products can be manufactured**.** Plastics and insulation materials used for construction can store carbon for decades and mineral products even permanently.*

Is CCU worth it?

Climate and other environmental impacts?

Needed investments?

Maturity of the technology, new innovations?

Impacts on employment and industrial renewal?

Market volume? Which products?

Availability of carbon dioxide?

What does the regulation enable?

The Finnish starting point for carbon capture, utilisation and storage

- Finland has a special position in Europe as **a significant source of biogenic carbon dioxide**, and on the other hand as a country with no suitable geological formations for storgin it. However, new technology may enable the storage of carbon dioxide in mining wastes.
- **From the industrial point sources of CO_2 (>0.1 Mt/year), Finland produces ca. 30.1 Mt/year biogenic and ca. 15.2 Mt/year fossil carbon dioxide.** Municipal waste incineration produces ca. 1.4 Mt/year carbon dioxide emissions (a mixture of fossil and biogenic).). In the future the CO_2 amounts may decrease due to growth in material recovery (e.g. lignin, plastic recycling) and diminished share of combustion.
- **Carbon dioxide is available from Finland all year round.** Although for example district heating production fluctuates seasonally quite significantly, the manufacturing industry and municipal waste incineration fluctuate much less.
- The **carbon dioxide emissions in Finland are large volumes compared to many domestic material flows**; if a major part is to be upgraded to high-value products, **export to European markets** must be included.
- **The CO_2 emission intensity of electricity production is low in Finland, on average ca. 70 gCO_2/kWh** (2020-2022 average, Tilastokeskus, 2024.), which is a central prerequisite for emission reductions via carbon dioxide utilisation. The respective EU average 2020-2022 was ca. 240 gCO_2/kWh (EEA, 2023). In addition, CO_2 utilisation requires further investments in low-emission electricity production.

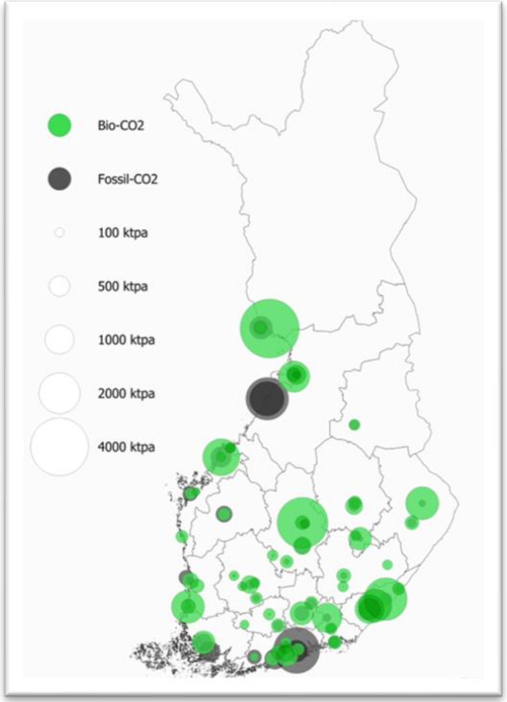

Figure 2. CO_2 point source in Finland, >100 kt/a i.e. > 0,1 Mt/a.

Main results

- Towards our path to carbon neutrality **there will be a European demand for CCU-products**. In addition to renewable electricity, this industrial renewal requires large investments and techonology development.
- The global market volume of the most relevant CCU products is expected to grow to **$1000 – 3400 Bn./year** by 2050.
- CCU is acknowledged as an essential technology in EU's climate action portfolio, but **regulation on CCU has mostly been advanced regarding transport fuels**, remaining inadequate for other products.
- **A possible scenario for the implementation of CCU in Finland might mean by 2040:**
  - An increase of ~50 TWh/a in renewable electricity demand. Electricity production in Finland in 2023 was 78 TWh (Energiateollisuus ry, 2024).
  - About ~1.2 Mt/a hydrogen would be needed for CCU, mainly for e-fuel production.
  - Total investments of about ~11 000 M€
  - Value of annual CCU-production close to ~7 000 M€
  - CO_2 emission reductions of ~2.5 $MtCO_2$/a in Finland, of which ~1.9 $MtCO_2$/a from e-fuels replacing fossil fuels. In addition, exported products would significantly reduce emissions in other countries.
  - Lowering the need of crude oil by ~2 Mt/a and the replacement of ~0.7 Mt/a fossil-based products with CCU-products. Storage of ~0.2 $MtCO_2$/a permanently in mineral construction products.
  - Employing ~1 100 people directly in the CCU-production facilities

VTT

Common factors

~45 TWh/a
Additional low-emission electricity is needed. Electricity production in Finland in 2023 was 78 TWh. (Energiateollisuus ry, 2024)

~11 Bn. €
Construction of carbon dioxide utilisation plants in Finland could mean investments of ca. 11 Bn. € by 2040 (incl. H_2 but, not electricity production).

Over 1000 jobs
The carbon dioxide utilisation plants in Finland could employ directly over 1000 people by 2040.

TRL
Technology readiness level (TRL) must be increased for many utilisation routes, which offers a possibility for innovation.

Biogenic or fossil CO_2
Permanent storage of CO_2 is supported by regulation irrespective of CO_2 origin.

~1.9 $MtCO_2/a$
Emission reductions in Finland by replacing fossil fuels in road, maritime and aviation transport by 2040.

~$20-2000 Bn./a
Global e-fuel market volume by 2050. Finland could produce ca. 2 Mt/a e-fuels for domestic use and exports.

Bio-CO_2
Regulation encourages the use of biogenic CO_2 for short-lifetime products.

E-fuels

0.2 Mt/a
Finnish long-lifespan hydrocarbon production could be ca. 0.2 Mt/a by 2040, storing carbon for decades and replacing fossil raw materials.

~$230-370 Bn./a
Global market of CCU-polymers and chemicals by 2050.

Plastics and chemicals

0.2 $MtCO_2/a$
Carbon dioxide might be stored permanently in Finland into construction products and fillers by 2040.

~$800-1000 Bn.$/a
Global market of CO_2-storing aggregates and concrete products by 2050.

Construction products

CO_2

What must be done, for Finland to be able to realise the possibilities of carbon dioxide utilisation?

- **High degree of upgrading and permanent carbon sinks:** Carbon dioxide utilisation efforts should focus on products of high degree of upgrading and on products creating permanent carbon sinks.
- **Low-emission electricity and hydrogen – production and logistics:** Low-emission electricity and hydrogen are necessary prerequisites for high-value upgrading, and thus investments on their production and infrastructure should be secured in addition to carbon dioxide utilisation projects.
- **Large investments and operating expense:** In addition to electricity and hydrogen, carbon dioxide capture, transportation and utilisation require investments in billions of euros. In addition to the investments, the operating expense must be covered with the profit from CCU-products and/or functioning carbon removal markets.
- **Influencing EU-regulation to create a favourable carbon removal market for Finland:** Markets need predictability and biogenic carbon dioxide storage is still lacking a stable financial incentive.
- **Leading example from the government boosting private sector funding:** For the moment, large private sector funding for carbon removals has been granted only in countries, where the state has shown a leading example for financial support for carbon dioxide capture and storage.
- **Thorough case studies must be required:** The benefits of carbon dioxide utilisation projects regarding economic, climate, environmental and labour impacts are case-dependent, and thorough impact assessment studies of proposed projects should be both required and supported.
- **Political will and social acceptance:** Various stakeholder of the society must be invited into the preperation at an early stage of developing CCU projects, so that different impacts can be taken into account, open discussion is enabled and the benefit to the society is secured.

Picture: Pyynikki esker in Finland, Sampo Mäkikouri.
In addition to their natural beauty, eskers provide ecosystem services, such as filter water, but they are also an important source of natural aggregates.

beyond the obvious

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Work package 1:
Business opportunities of carbon capture and utilisation in Finland

Table of Content

Terms and acronyms

AEL	Alkaline electrolyzer, water electrolysis to produce hydrogen
BECCU/BECCS	Biomass-based CCU/CCS
Biogenic CO_2	CO_2 released from renewable resources, such as biomass
CAGR	Compound Annual Growth Rate
CCU	Carbon Capture and Utilisation
CCS	Carbon Capture and Storage
DH	District heating
e-	Prefix ”e-”, electricity, e.g. e-methane is synthetic methane produced from emission CO_2 and renewable electricity (sometimes ”electro-fuels”)
FT	Fischer-Tropsch synthesis, CO + H_2 conversion to hydrocarbons
Mt/a	Mass per annum, metric megatonnes per annum, billion kilograms per annum
MTO	Methanol-to-olefins process, conversion of methanol to olefins (alkenes)
P2X	Power-to-X, conversion of renewable electricity (power) into products (X)
PSA	Pressure swing adsorption, e.g. H_2 separation from a gas mixture
RFNBO	Renewable fuels of non-biological origin, e.g. e-fuels belong to this category
RWGS	Reverse water-gas shift reaction, conversion of CO_2 to CO
SAF	Sustainable aviation fuel
SNG	Synthetic natural gas (methane)
SOEL/SOEC	Solid oxide electrolysis, high temperature electrolysis for H_2 production
Syngas	Synthesis gas (mixture of CO + H_2)
TWh	Energy, terawatthour

Term	Explanation
CCU - Carbon Capture and Utilisation	The whole chain of processes when CO_2 is captured from an industrial pipeline or captured from air. After capture, CO_2 is typically purified and led into a chemical conversion to valueable products, such as, fuels, chemicals and materials.
BECCU – Biomass-based Carbon Capture and Utilisation	Carbon Capture and Utilisation, where the CO_2 is specifically originating from biomass. For example, the utilisation of biogenic CO_2 from an pulp mill.

CO_2 sources and CO_2 quality specifications

CO_2 supply for CCU (Carbon Capture & Utilization)

- CO_2 can be captured from many types of sources such as flue gases, process emissions or even from the atmosphere.
- Source properties and the desired capture performance determine the feasibility of carbon capture, suitable capture technology options and CO_2 capture cost.
- Industrial emission point sources, where CO_2 occurs as somewhat concentrated, are the most potential CO_2 supply options for CCU regarding cost-effectiveness.

Key factors affecting the feasibility of carbon capture

Source properties and operating environment

- Scale
- Feed gas properties: composition, CO_2 concentration and its fluctuation, impurities, temperature, pressure
- Origin of CO_2 (fossil, biogenic, atmospheric)
- Utilizable energy supply and energy integration options
- Site restrictions, e.g., for equipment size
- Location and readiness for CO_2 logistics
- Stability of operation / seasonal variation

Desired capture performance

- Capture efficiency
- Product-CO_2 purity

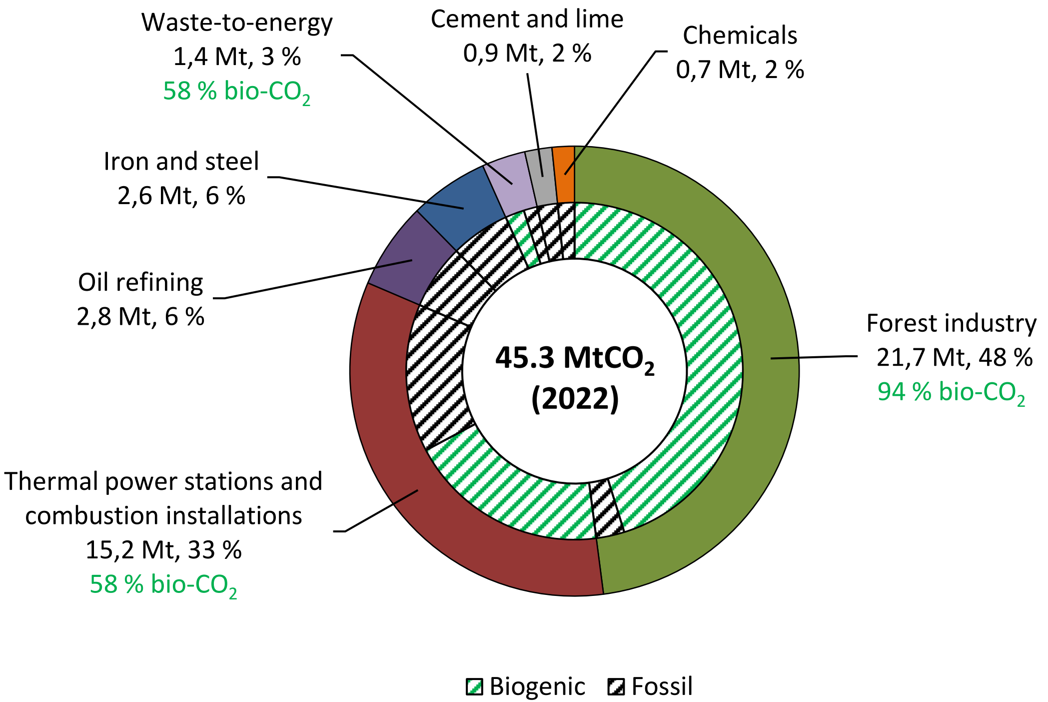
Capture technology

- Technological readiness
- Energy demand and the form of energy needed
- Utility and auxiliary demands, e.g., water, waste handling
- Retrofittability
- Scalability
- Emissions of the capture process
- Flexibility

Industrial CO_2 emissions in Finland

- Significant portion (66 %) of the Finnish industrial CO_2 emissions are biogenic, i.e., originating from biomass.
- Due to renewability of biomass, bio-CO_2 is seen as carbon-neutral and can therefore be a valuable feedstock for utilisation or storage of CO_2.

Industrial CO_2 emissions from facilities with emissions of >100 ktCO_2/a

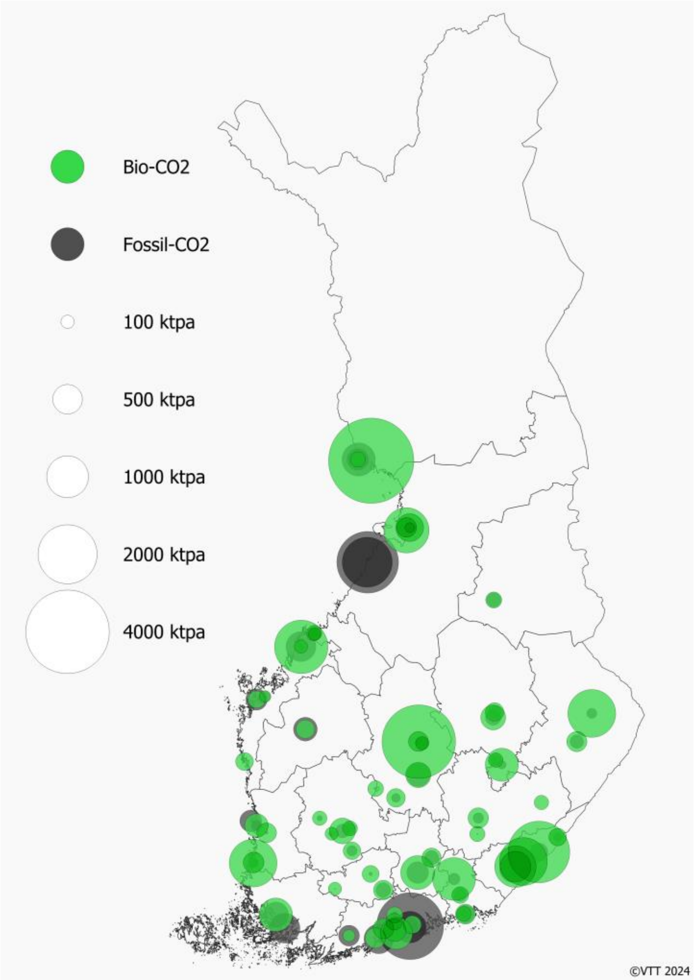


Based on 2022 data of the European Pollutant Release and Transfer Register (EEA 2023, published on 12/2023), which has been updated manually in terms of missing data.

Industrial CO_2 emissions in Finland

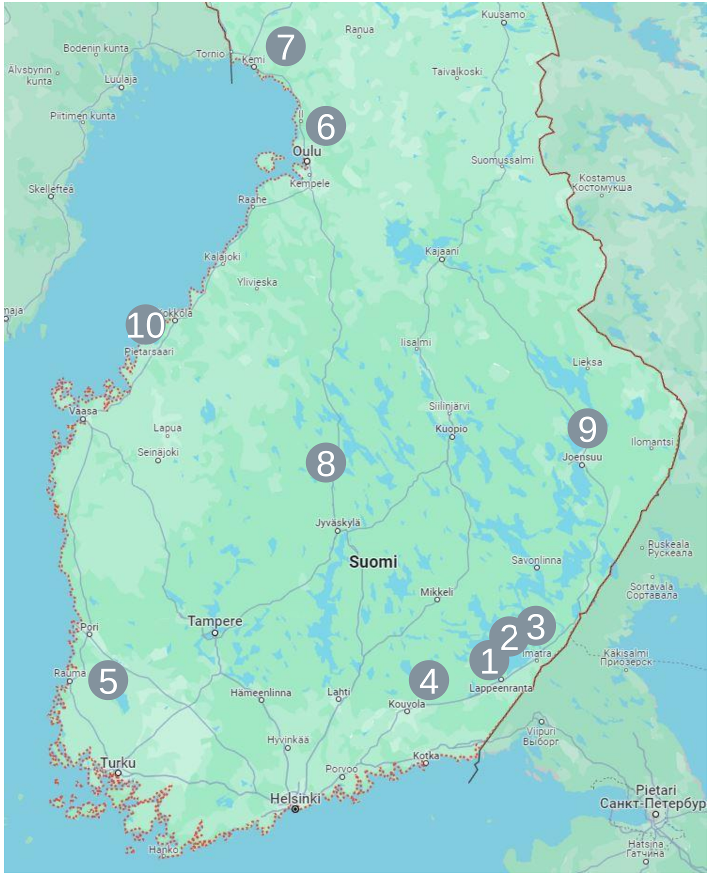
CO_2 emissions in industrial facilities with annual emissions of >100 ktCO_2

- 72 facilities
- Total: 45.3 MtCO_2
- Biogenic: 30.1 MtCO_2
- Fossil: 15.2 MtCO_2



Based on 2022 data of the European Pollutant Release and Transfer Register (EEA 2023, published on 12/2023), which has been updated manually in terms of missing data.

Biogenic CO_2 sources



Industry sector	Total CO_2 [$MtCO_2$]	Bio CO_2 [$MtCO_2$]	Fossil CO_2 [$MtCO_2$]	Share of bio CO_2 [%]	Share of fossil CO_2 [%]	Share of all [%]
Forest industry	21.7	20.5	1.2	94	6	48
Thermal power stations and combustion installations	15.2	8.7	6.4	58	42	34
Iron and steel	2.8	0.0	2.8	0	100	6
Oil refining	2.6	0.0	2.6	0	100	6
Waste-to-energy	1.4	0.8	0.6	58	42	3
Cement and lime	0.9	0.0	0.9	0	100	2
Chemicals	0.7	0.0	0.7	0	100	2
Total	45.3	30.1	15.2	66	34	

	Forest industry plant	Biogenic CO_2 availability (Mt/a)
1.	UPM, Lappeenranta	1.0
2.	Metsä Fibre, Joutseno	1.3
3.	Stora Enso, Imatra	2.2
4.	UPM, Kuusankoski	1.1
5.	Metsä Fibre, Rauma	1.3
6.	Stora Enso, Oulu	1.2
7.	Metsä Fibre, Kemi	4.2
8.	Metsä Fibre, Äänekoski	3.1
9.	Stora Enso, Joensuu	1.3
10.	UPM, Pietarsaari	1.6

Based on 2022 data of the European Pollutant Release and Transfer Register (EEA 2023, published on 12/2023), which has been updated manually in terms of missing data.

Seasonal variation of industrial CO2 sources in Finland

Industry: low seasonal variation

Industrial CHP: low seasonal variation

Waste-to-energy: low seasonal variation

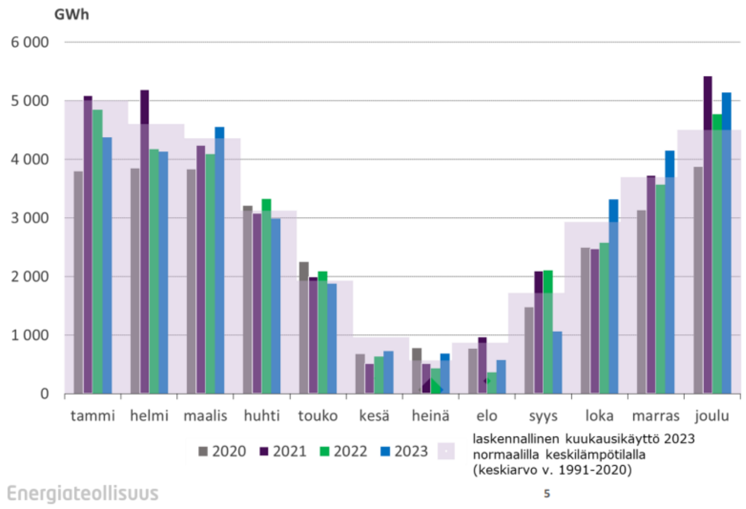
District heating CHP: high seasonal variation

- winter ~ 90-100 % load
- spring and autumn ~ 40-70 % load
- summer ~ 0-20 % load

Separate production of electricity in combustion installations: high seasonal variation

- Mainly used for power reserve in Finland with little use only at peak loads. Not reasonable for carbon capture.

Monthly district heating demand in Finland
(Energiateollisuus 2024)



CO_2 sources and purity

Most CO_2 sources have low concentrations. A typical CO_2 concentration from a forest industry source is 15-20 vol.-%. CO_2 concentration from combustion processes is typically 8-20 vol.-% for solid fuel, 3-10 vol.-% for gaseous fuel, and 15-25 vol.-% for lime and cement kilns.

- Generally, the CO_2 stream must be concentrated for synthesis processes. This is done using CO_2 separation processes. In general, high CO_2 concentration lowers the cost of recovery.
- In some CO_2 mineralisation processes, flue gas can be used as such, but there may be penalties to the efficiency or reaction rate of the process compared to purified CO_2.
- Alternatively, electrification of processes (e.g. electrically heated cement kiln) or oxygen combustion concentrates CO_2 sources, and separation processes may not be necessary. These technologies are still under development.

Different CO_2 sources contain different impurities that must be removed before further processing.

- There are varying CO2 purity grades for different applications (See, e.g., CO2Meter CO2 Purity Grade Chart)
- EIGA Doc. 70 provides recommendations for carbon dioxide use in beverage and food applications.
- In catalytic processes, impurities cause premature deactivation (process deterioration).
- There are also reference values and limits for CO_2 purity for CO_2 pipeline transport, geological storage, and liquefied CO_2 shipping.
- In products aimed at the concrete industry, the sulphur and chloride content of the end product must be controlled, but lower CO_2 source purity in general may be tolerated.

Carbon capture technology

- Several types of technologies have been developed for carbon capture such as liquid absorbents, solid sorbents, membranes, chemical looping systems, cryogenic separation and electrochemical separation.
- Liquid absorbents (e.g, amines and carbonate salts) are the most mature technology for post-combustion capture that is an end-of-pipe technology where the CO_2 is captured from process or flue gases deriving from the core process. Generally around 90 % of the CO_2 is captured with a purity of >99 %.

Schematic diagram of a CO_2 capture process based on a liquid absorbent

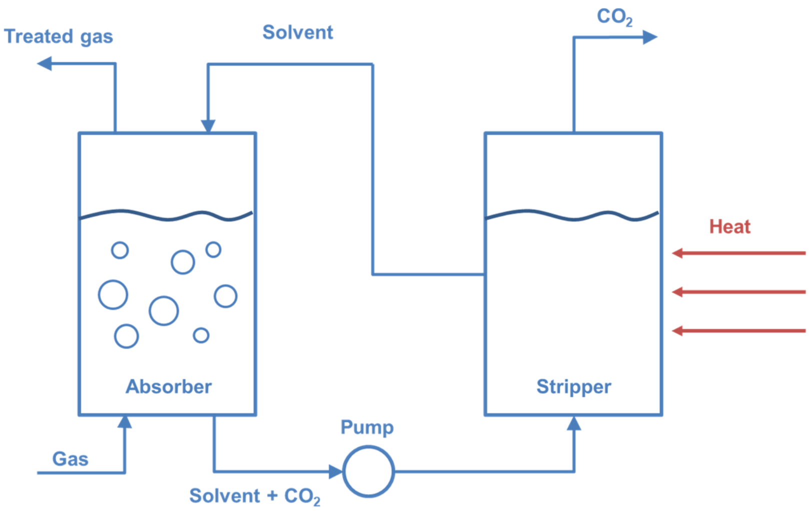
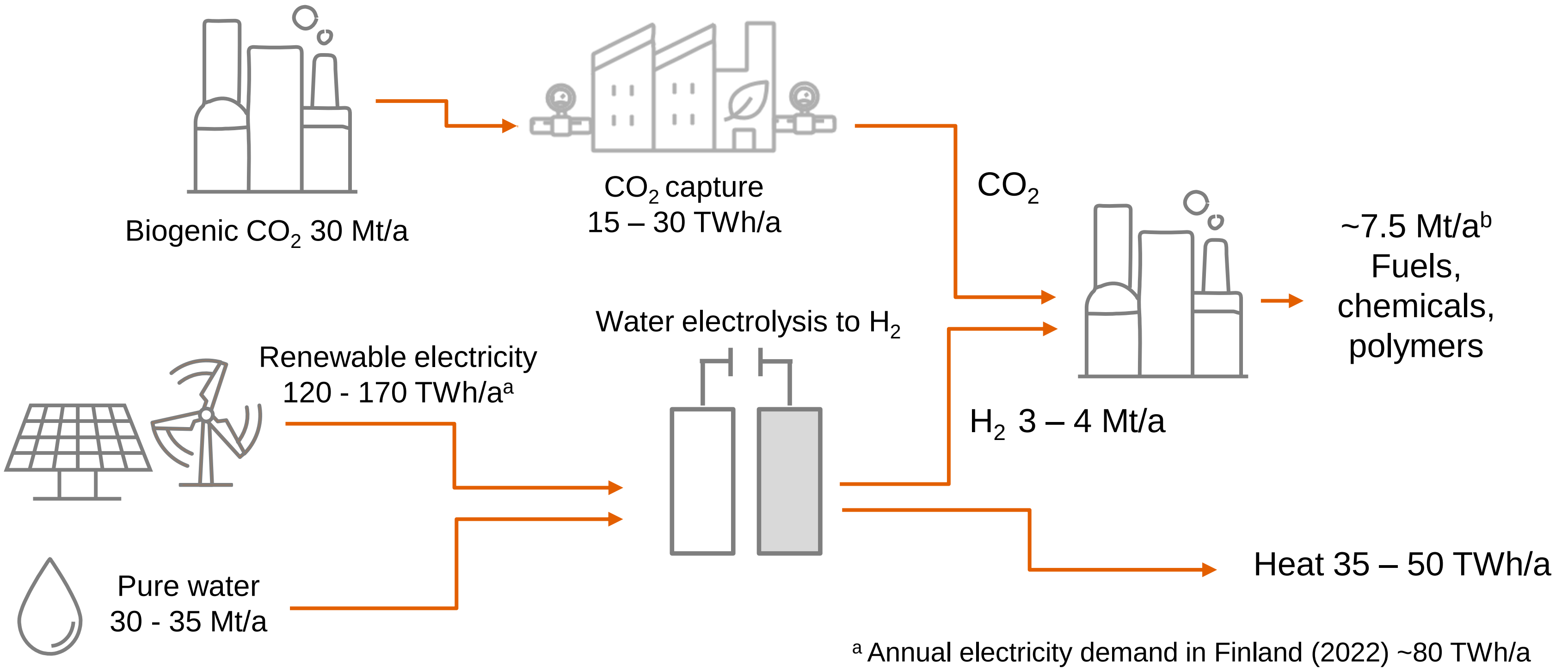


Image: IDTechEx

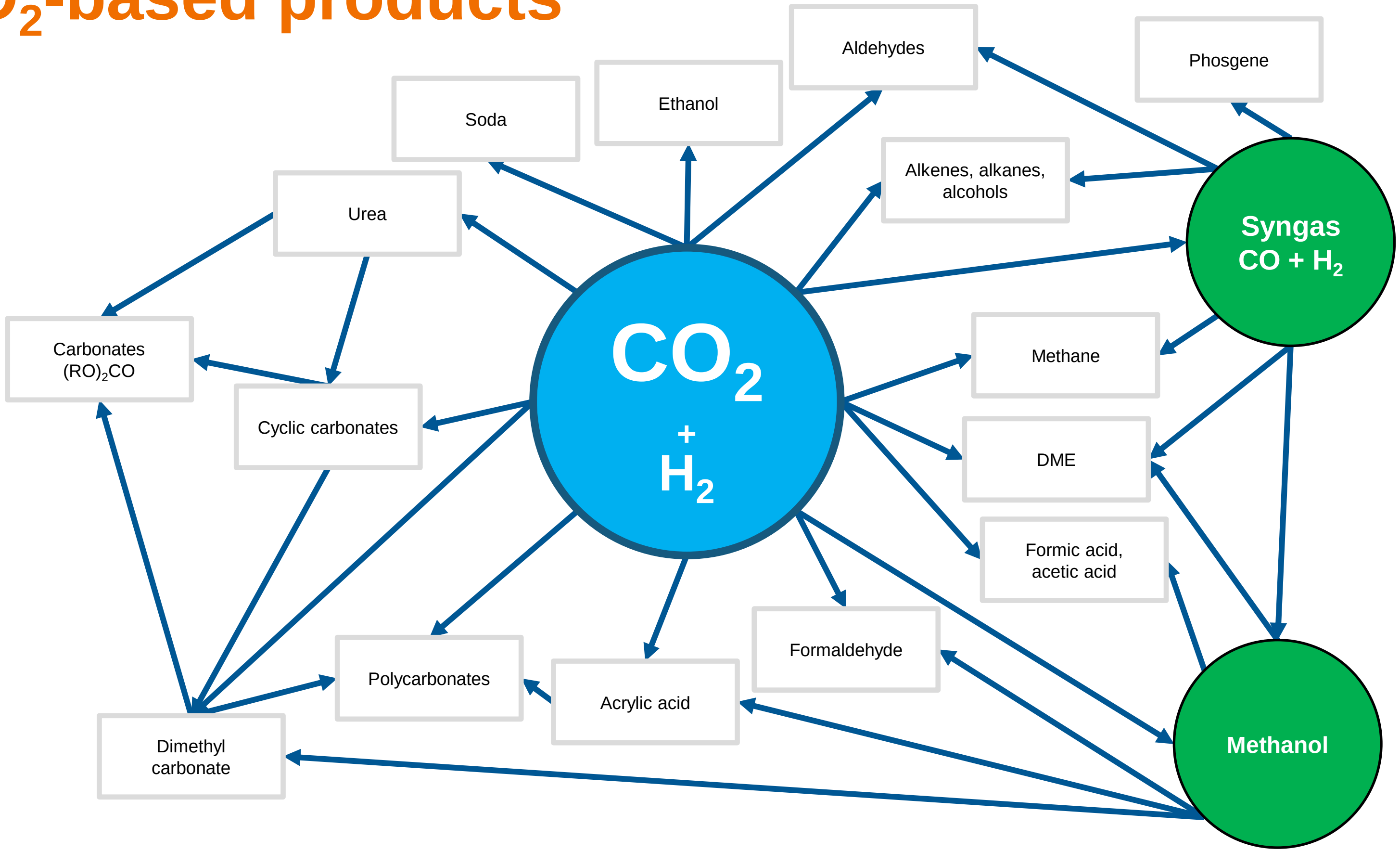
Biogenic flue gas CO_2 to CCU products



[a] Annual electricity demand in Finland (2022) ~80 TWh/a
[b] Annual diesel fuel consumption in Finland (2023) 2.4 Mt/a
[b] Annual Finnish aviation fuel consumption (2019) 1.0 Mt/a

CCU technology routes for hydrocarbon products

CO_2-based products



Adapted from: Krishnamurthy, Linde Presentation at Carbon Management Technology Conference (2013)

CO_2-based intermediate and final products

VTT

Technology readiness level

Research ← → Industrial

Product	Example products
DME	Fuel additives, liquified fuel gases
Aldehydes	Polymers, solvents, colourants, cosmetics
Organic acids	Surfactants, food supplements, medicines
Alcohols	Solvents, detergents
Organic carbonates	Pecticides, polymer precursors, farming chemicals, isosyanate precursors, preservative chemicals, cosmetics

Product	Example products
Polypropylene carbonate polyols	Polyurethane
Polycarbonates	Packaging
Formic acid	Precervatives, glues
Inorganic carbonates	Mineral fillers, cement, concrete, soil improvement
Cyclic carbonates	Solvents, battery material, polymers

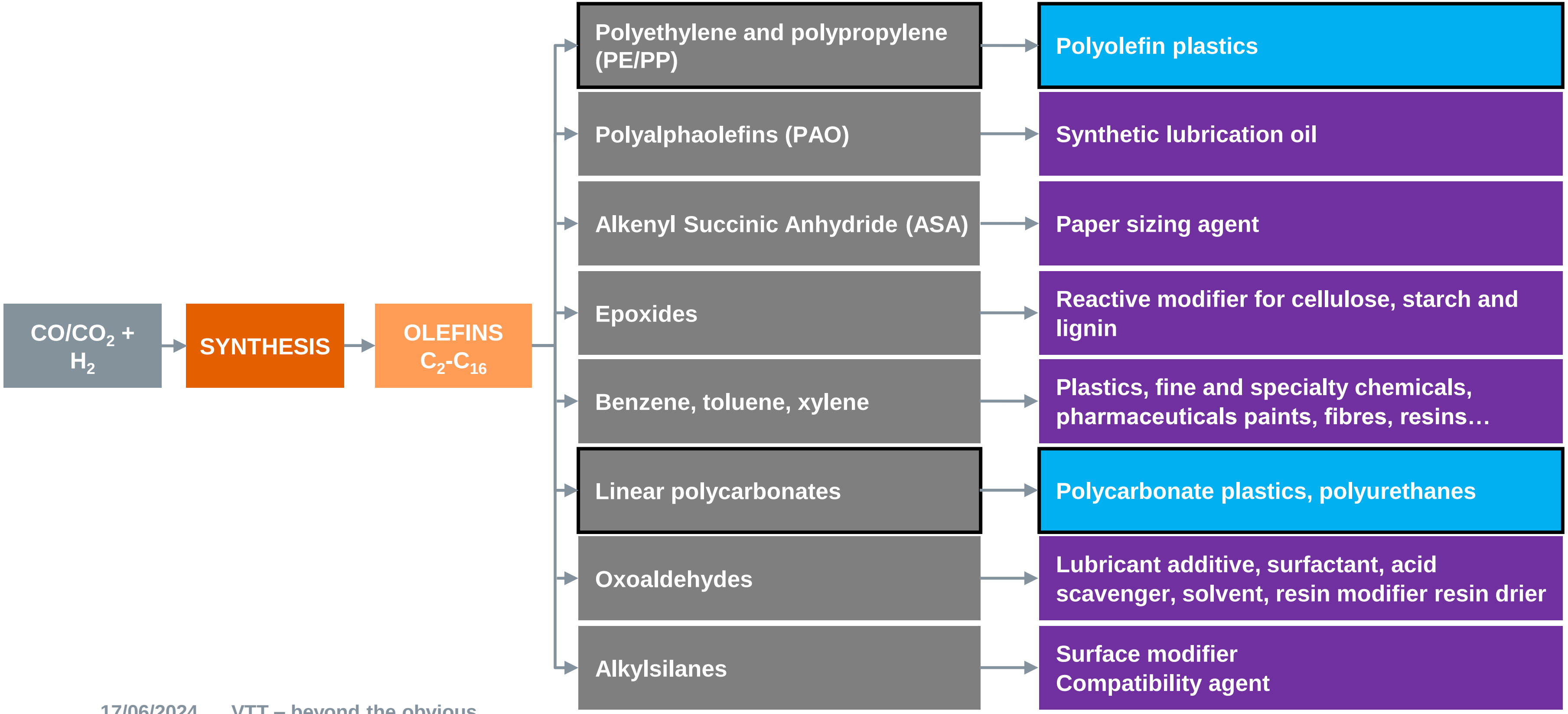
Product	Example products
Methanol	Acetic acid, ethene, propene, polymer precursors, DME, fuels
Salicylic acid	Medicine
Urea	Fertilizers, resins
Fosgene	Polycarbonate plastics, polyurethane plastics, pecticides
Alkanes and alkenes	Fuels, polymers

Case: CO_2 based polymers

Introduction

- There are several different technology routes to produce various kinds of polymers from CO_2
- One key intermediate is olefins (alkenes) that can be converted to many polymer products
- In this section, we present most relevant technology routes from CO_2 to olefins and finally to plastics and polyurethane

Example: Products from CO_2-based olefins (alkenes)



Example: Markets for CO_2-based polymers

Light olefins from e.g. Fischer-Tropsch-to-olefins or methanol-to-olefins process

Polyolefins (PE, PP)
Global volume: 180 Mton/a
CAGR: 4-5 %

Light epoxides (EO, PO)
Global volume: 40 Mton/a
CAGR: 5-6 %

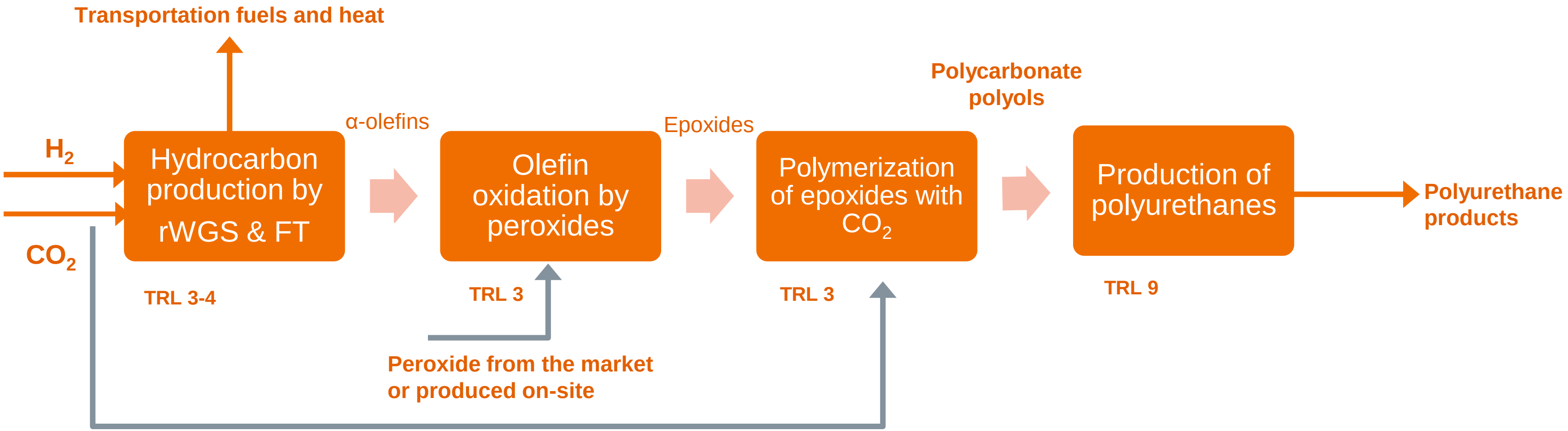
Polyols
Global volume: 15 Mton/a
CAGR: 8 %

Polyurethanes
Global volume: 16 Mton/a
CAGR: 5 %

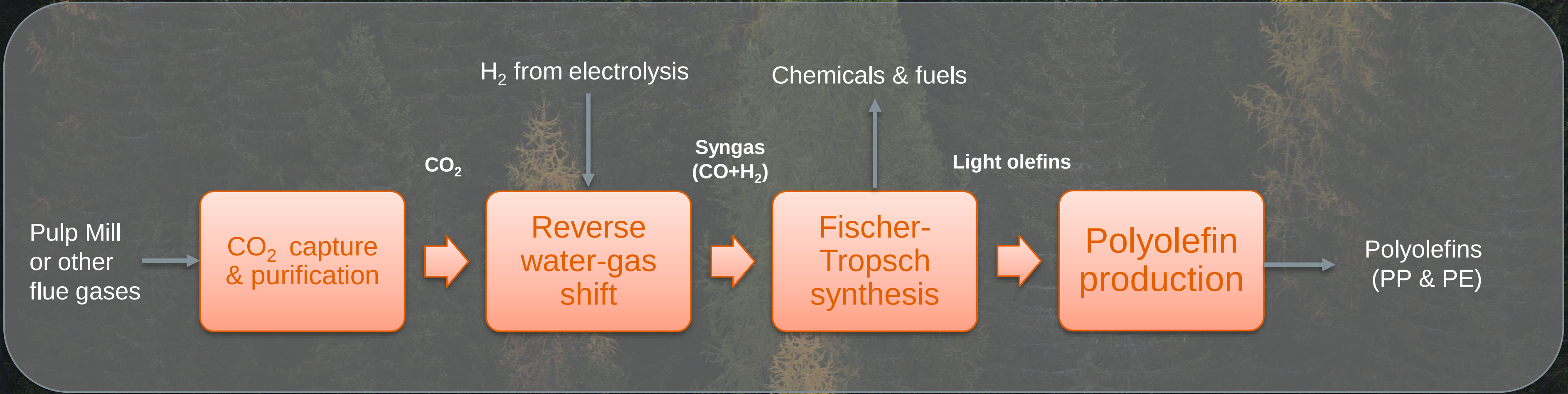
Polyols and polyurethanes from CO_2

A process concept based on the CO_2 to hydrocarbons technology

- The yield of C_2-C_4 olefins is maximised to be used in chemicals production
- Heavier hydrocarbons applied for transportation fuels (gasoline, diesel, jet fuel)

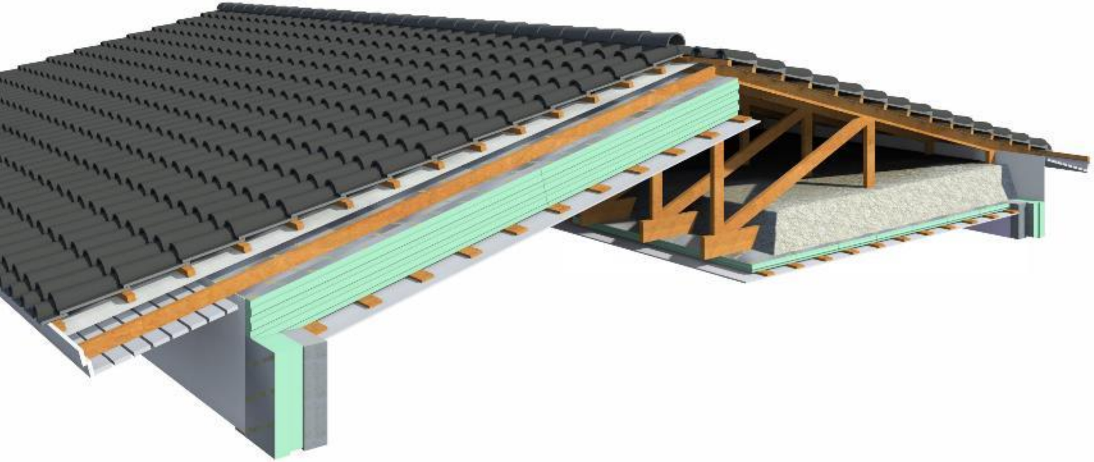


Polyolefins from CO_2



Case: Techno-economic feasibility of polycarbonate polyols from CO_2

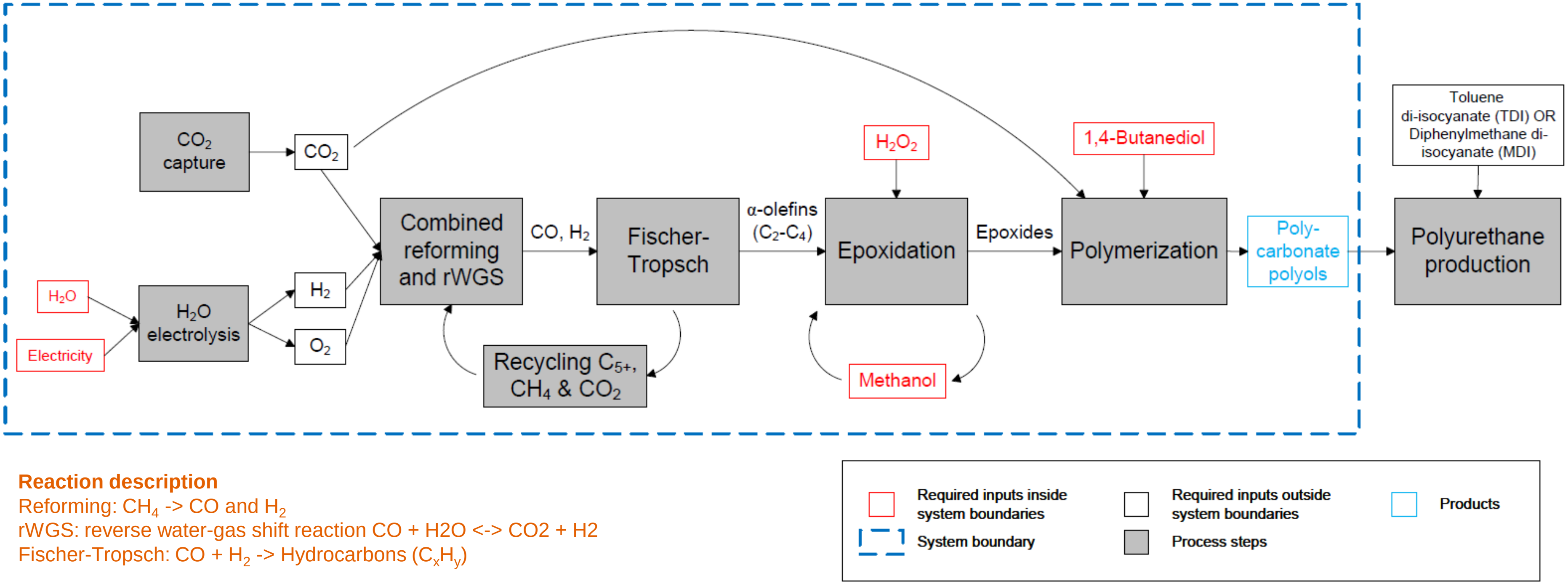
Versatile polyurethanes in the spotlight



Polyurethane can be used in various long lifetime applications such as insulation materials
Figure: Finnfoam

Polyurethanes are widely used in adhesives for such applications as woodworking glues
Figure: Kiilto

Polyols from biogenic CO_2 & green H_2



Reaction description

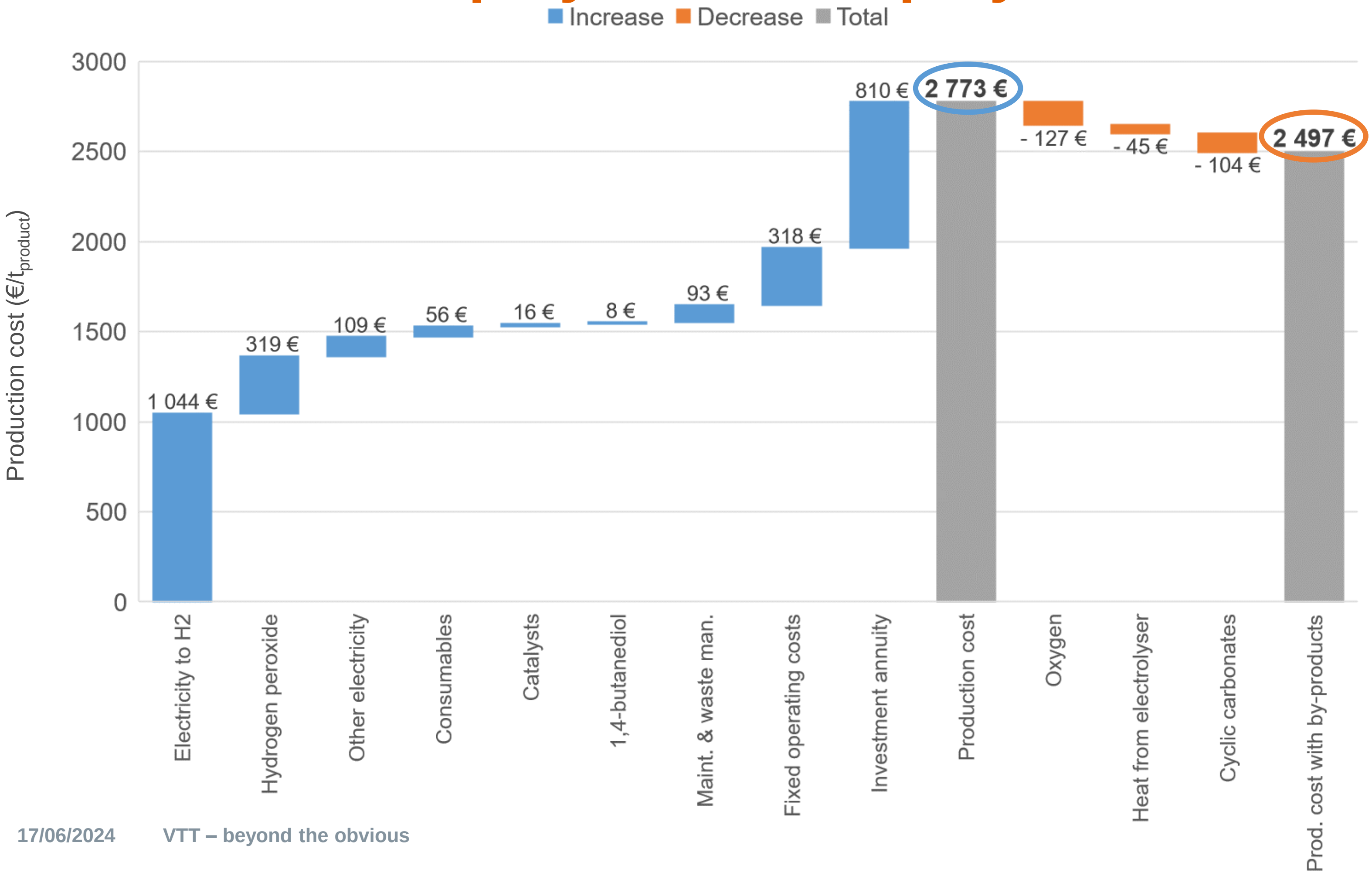
Reforming: CH_4 -> CO and H_2

rWGS: reverse water-gas shift reaction CO + H2O <-> CO2 + H2

Fischer-Tropsch: CO + H_2 -> Hydrocarbons (C_xH_y)

Production cost - polycarbonate polyols

VTT



Polyether -, polyethercarbonate - & polycarbonate polyols

Calculated production cost: ~2500 €/t

Image: Sonnenschein (2015)

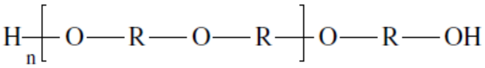


Image: Bian et al. (2016)

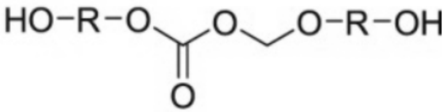
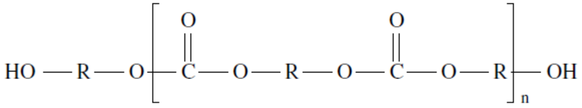


Image: Sonnenschein (2015)



Polyether polyols

- Conventional polyols
- Global production: 9,4 Mt in 2016 [1)]
- Lower viscosity and faster diffusion compared to polyethercarbonate polyols
- Market price around 1 700 €/t [2)]

Polyethercarbonate polyols

- New products
- Larger market potential, as they can replace traditional polyether polyols
- Market price closer to polyether polyols? Probably some premium for improved properties and sustainability.

Polycarbonate polyols

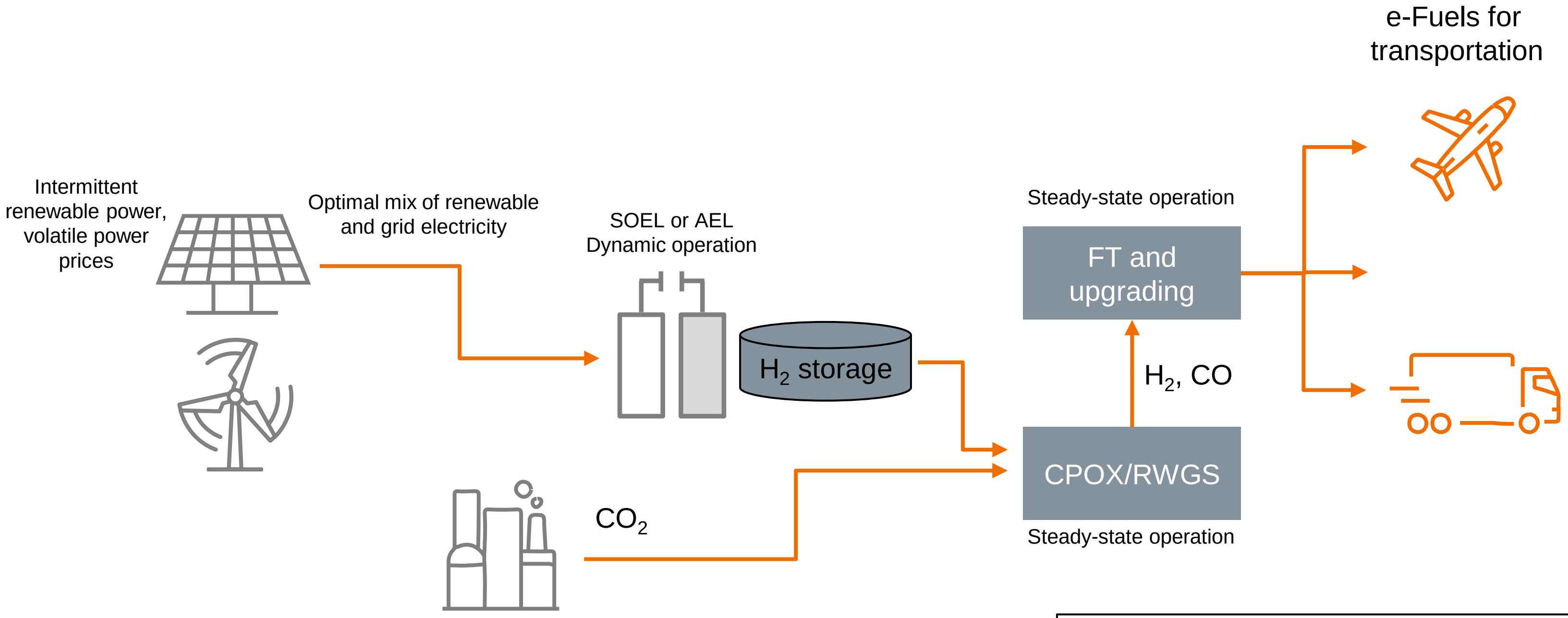
- Specialty products - smaller markets and production volumes, around 30 kt/a [3)]
- Higher market price, can be even 6 000 €/t [3)]

Can be produced from CO_2 using the studied technology

References: [1)] Covestro (2017) [2)] Fernández-Dacosta et al. (2017) [3)] QYResearch (2021)

Case: Techno-economic feasibility of CO_2 based aviation fuels

e-Fuel project (Business Finland) – Studied PLANT Concept



SOEL: Solid oxide electrolysis (Hydrogen production)
AEL: Alkali electrolysis (Hydrogen production)
CPOX: Catalytic partial oxidation (Hydrocarbon reforming)
RWGS: Reverse water-gas shift (CO_2 conversion to CO)
FT: Fischer-Tropsch synthesis (hydrocarbon production)

Efuel project target products

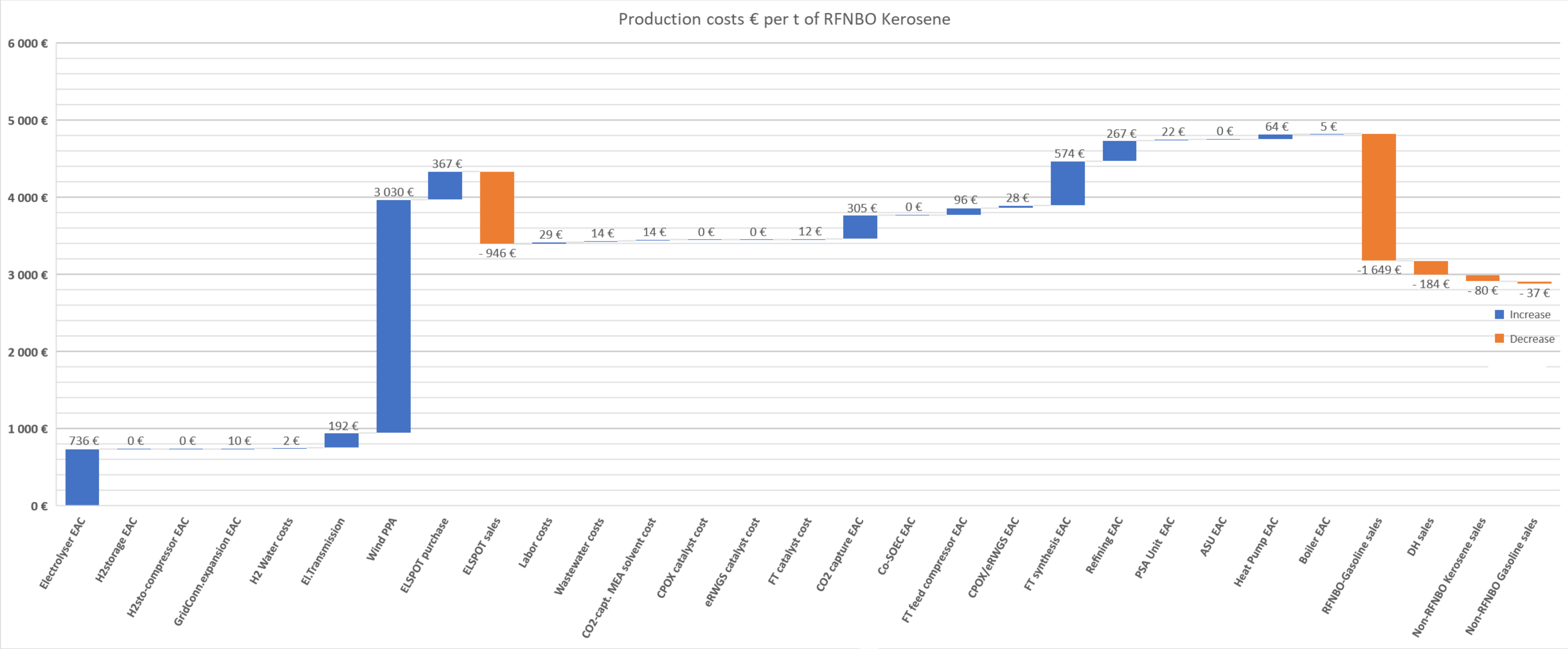
VTT

- **Main product: Jet fuel C9-C16**
  - **SAF: RFNBO-kerosene** according to EU Delegated Act 2/2023
  - Non-RFNBO-kerosene assumed to be priced as fossil kerosene (600 €/t)

- By-products
  1) Light paraffinic hydrocarbons C5-C9 (compared to gasoline)
     - **RFNBO-gasoline** according to EU Delegated Act 2/2023. Assumed sales price 2400 €/t
     - Non-RFNBO-gasoline assumed to be priced as fossil gasoline (600 €/t)
  2) District heat,
     - Supply temperature 85 °C, assumed sales price 25 €/MWh
     - Heat sources:
       i. Electrolyser cooling load
       ii. Downstream units' cooling Load, using High-Performance Heat Pumps
       iii. Remaining purge gas (prioritizing internal use such as steam needs)

C9-C16: Hydrocarbons fuel range with carbon number 9 to 16
SAF: Sustainable aviation fuel
RFNBO: Renewable fuels of non-biological origin, e.g. e-fuels belong to this category

SAF Production cost distribution example detailed



Summary and conclusions

Techno-economic analysis for e-fuels were modelled and calculated in the Business Finland funded e-Fuel project, having an example site at Finland, using Finnish power system and land-based wind power.

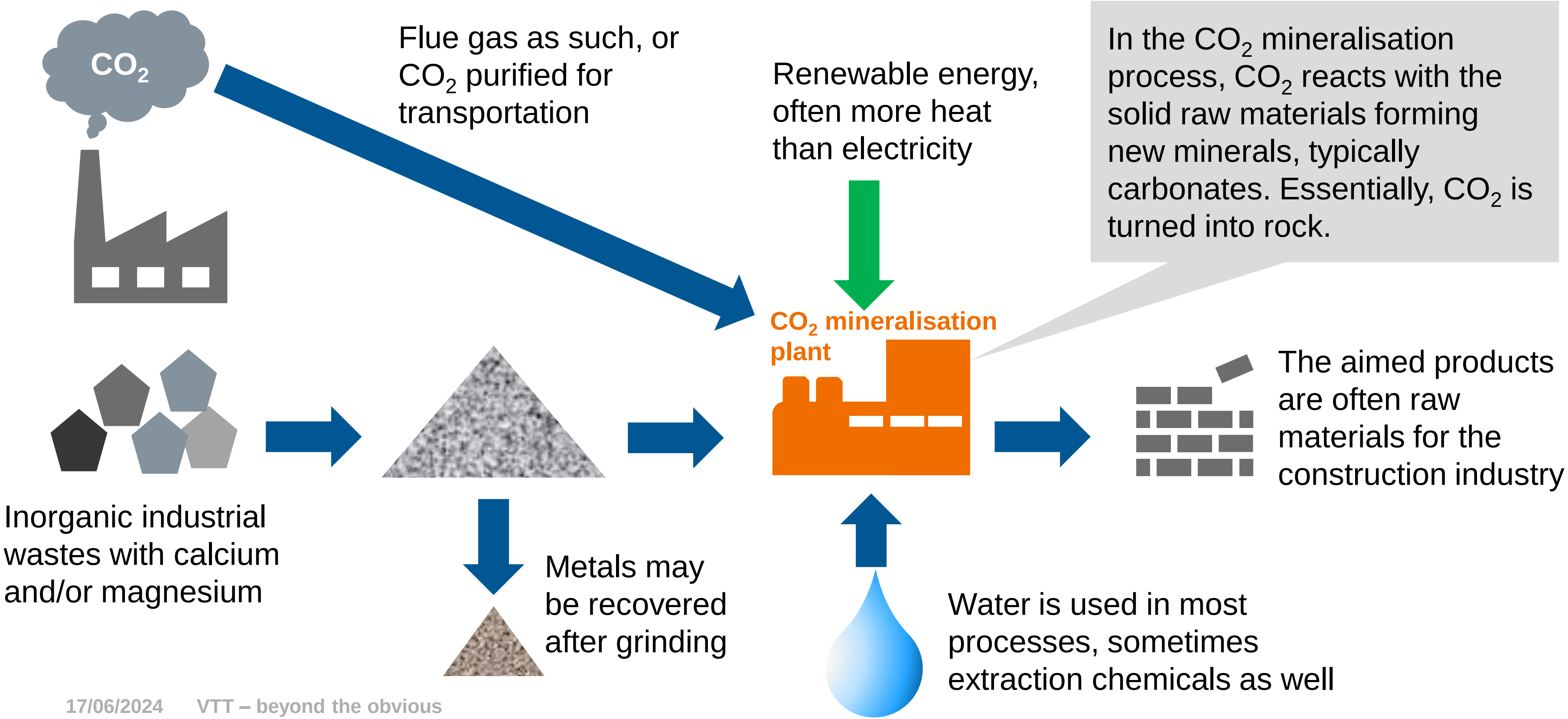
Results based on hydrocarbon related processes Aspen steady-state simulations, VTT's optimization tools for Power-2-X Optimization and Power System Forecasts 2025-30:

- A realistic cost for RFNBO-eKerosene was ~3000€/ton
- Cost estimates range from 2400 – 9 600 €/ton RFNBO-eKerosene, depend on
  - optimal unit dimensioning of the plant (electrolysers, H_2 storage, compressors etc)
  - optimal long-term contracting of renewable power
  - optimal long term and intraday power trading strategy
  - Rules applied from the Delegated 2/2023: prior 2030 (montly correlation to RE) or after 2030 (hourly correlation to RE) .

- Specific GHG-emissions 9-12 gCO_2eqv/MJ RFNBO-eKerosene
  - which is a **reduction of 87-90% in GHG-emissions** (fossil kerosene is ~94 gCO2eqv/MJ)

Mineralisation of CO_2 - or *"CO_2 rock"*

What is CO_2 mineralisation?



Background for CO_2 mineralisation in Finland

- Reacting CO_2 with suitable minerals, like mining wastes, ashes or slags from the metals processing industry **can offer a permanent storage for CO_2** without monitoring requirement (Olajire, 2013), unlike geological storage of CO_2.
- Finland has no suitable geological formations for the storage of CO_2 (Teir et al., 2016). However, the **Finnish mining industry produces about 90 Mt/a mining wastes** (Vasara et al. 2023). *Some* of those wastes are suitable for CO_2 storage by mineralisation, such as mine tailings from Kemi Elijärvi, Hitura (Mälkki & Mäkikouri, 2024) or Kevitsa mine (Veetil & Hitch, 2021). These mining wastes could enable the storage of approximately **0.5-2.0 $MtCO_2$/yr in Finland**, if the suitable technology is commercialised (Kujanpää et al. 2023).
- In addition, such processes can produce products, like mineral **fillers for plastics, paper or construction** industry, **aggregates** (sand and gravel) for earth construction and building materials, **or pre-cast concrete products** (blocks, elements etc.). Moreover, **valuable metals could be recovered** from the mining wastes as well.

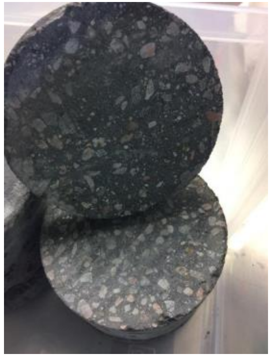


Figure 1. A carbon-negative concrete-like material sample from VTT in 2019 was made using biomass ash, blast furnace slag and green liquor dregs cured with CO_2. The technology is now commercialised by a VTT spin-off Carbonaide.

CO_2 mineralisation does not require hydrogen and offers permanent CO_2 storage – but lower value products

- CO_2 mineralisation requires
  - electricity for grinding and crushing,
  - energy for transporting the CO_2 or the minerals and
  - in the large scale, a lot of heat is needed for thermal activation of solids and for drying and possible chemical recovery
- Energy use and process is greatly dependent on the raw material used (ashes, slags, magnesium-rich or calcium-rich mining wastes), and **implementation is limited by the availability of suitable raw materials**.
- In general, compared to e-fuels and platform chemicals made of CO_2 and hydrogen, CO_2 mineralisation is less energy-intensive, but produces lower value products. It can offer an alternative to geological CO_2 storage.

The potential environmental benefits must be assessed case-by-case

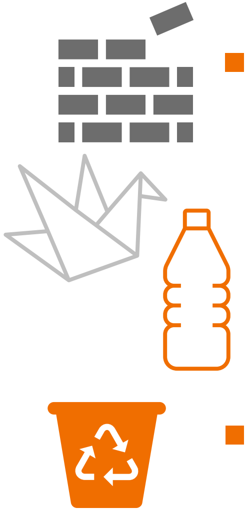
Key questions include:

- **What is the current use of the mineral raw material?**
- **How fast would the mineral form carbonates without intervention?** This can range from weeks (thin layer of ashes) to millenia (coarse waste rock from mining).
- **What is the annual CO_2 storage potential?** Construction product plant **~1-10 kt/a** scale, storage potential in a large mine **~0.1-1 Mt/a** scale
- **What is the end of the product's life-cycle?** Typically permanent storage, but Combustion can release the CO_2, otherwise not likely.
- **What is the logistical solution and related emissions?** In general, the mass of minerals is much higher than the mass of CO_2 used, e.g. ~ 5:1 (storage-focus), ~25:1 (artificial aggregates).
- **How efficient is the process?** Consumed energy and chemicals may lead to more emissions than what is removed.

Mining wastes: CO_2 storage with metals recovery

- Products & value:
  - Permanent CO_2 storage → EU ETS for fossil CO_2, voluntary CDR or similar for biogenic CO_2
  - Recovered metals
  - Silicate filler by-product
  - Magnesium and/or calcium carbonate filler (with/without impurities)
  - Reduced mining waste
- Product value chain / CO_2 storage duration: Permanent (as long as no acid leaching occurs)
- Potential climate benefit: **Very high, if technology can be commercialised** – Large volumes of raw, material, slow carbonation with ambient CO_2 (millenia)
- **TRL: 6-7**

Fillers: fine powders for many uses



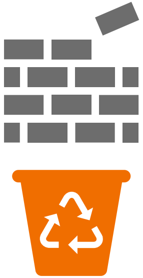
- Products & value:
  - Fine aggregates for concrete industry
  - Reactive calcium carbonate for cement blending
  - PCC for plastics, paper industry
  - Reduced industrial waste
- Product value chain / CO_2 storage duration:
  - **Paper: short (a few years)**
  - **Plastics: short to long (years to decades)**
  - **Concrete: permanent (with current end-of-life)**
- Potential climate benefit: Moderate – a modest fraction of calcium carbonate filler can easily replace emission-intensive and virgin raw materials in but global markets are large
- TRL: 7-9

Aggregates: Replacing natural sand and crushed stone

- Products & value:
  - Sand and gravel for concrete
  - Reduced landfill amounts
- Product value chain / CO_2 storage duration: Permanent (as long as no acid leaching occurs)

- Potential climate benefit: Moderate – **large market volumes in tonnes**, but alternative is not very energy-intensive either (crushed natural stone and sand)
- TRL 9

Pre-cast concrete products: replacing emission-intensive concrete products



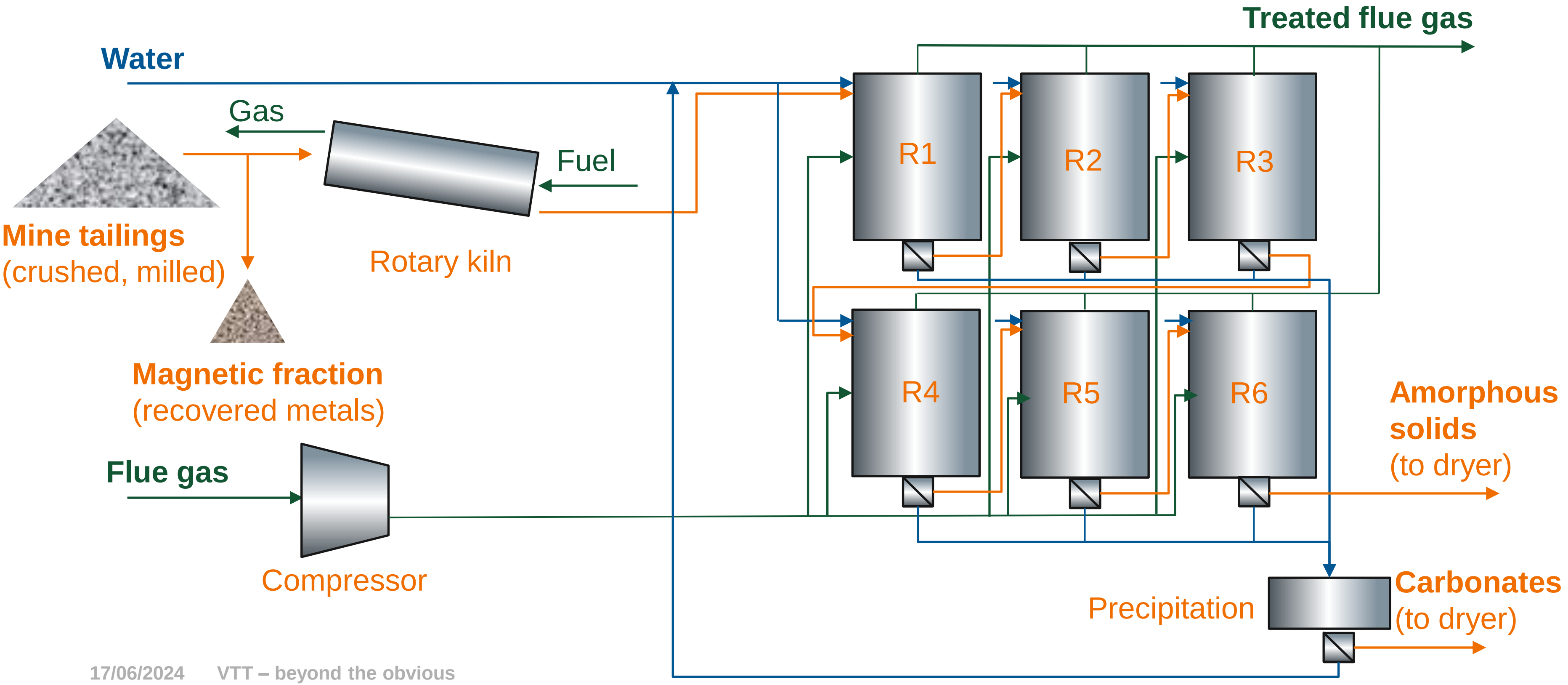
- Products & value:
  - Pre-cast concrete products (bricks, railroad pavers, wall elements…)
  - Reduced landfill amounts
- Product value chain / CO_2 storage duration: Permanent (as long as no acid leaching occurs)

- Potential climate benefit: High – readily reactive wastes, but **replacing emission-intensive** conventional concrete; large market eventually – **but safe applications emerge slowly**
- TRL 8-9

Case: Magnesium carbonate filler and metals recovery from mine tailings

Based on:
L.-C. Pasquier, G. Mercier, J.-F. Blais, E. Cecchi, S. Kentish. 2016. Technical & economic evaluation of a mineral carbonation process using southern Québec mining wastes for CO2 sequestration of raw flue gas with by-product recovery, International Journal of Greenhouse Gas Control, Vol. 50, 2016, pp. 147-157, https://doi.org/10.1016/j.ijggc.2016.04.030.

Process diagram – modified based on Pasquier et al. 2016



Notes on the *direct aqueous carbonation* process example

- **Inputs:** flue gas, crushed mining wastes (="rock") and recycled water
- **Outputs:** Treated flue gas, magnetic metal fraction, amorphous solids, carbonates
- **~4,27 t of rock needed to store 1 t CO_2**
- **Flue gas (18 vol% CO_2) as such** used as input → Compression to 10.2 bar
- **Energy use:**
  - 1124 MJ/tCO_2 electricity, 6880 MJ/tCO_2 heat
  - ⇔ ~0.31 TWh/MtCO_2 electricity, 1.91 TWh/MtCO_2 heat
- **Investment** for a 387 000 tCO_2/year plant: 167 M$ (2016)

- Flue gas flow split to 6 parallel reactors:
  - Ambient temperature
  - 30 min reaction time
  - Water to solids –ratio = 20:1
- Thermally treated solids pass through all reactors sequentially
- Recycled water-solids slurry enters the reactors; water recovery to precipitation after each reactor
- Some of the magnesium is dissolved and is recovered by precipitation, while some remain with the solid flow

Energy use as [MJ/t rock] and as [MJ/t CO_2]

Conversion using: 234 kg CO_2 stored per tonne of rock

Process step	Power (MJ/t rock)	Power (MJ/t CO2)	Heat (MJ/t rock)	Heat (MJ/t CO2)
Crushing/Grinding and Magnetic Separation	83	355		
Heat Activation			1143	4885
Total gas compression	68	291		
Carbonation Reactors (R1-6)	0.4	2		
2nd grinding	36	154		
Precipitation			467	1996
Others (pumps, conveyors etc)	76	325		
Total	**263**	**1124**	**1610**	**6880**

Most relevant CCU products for further investigations

Relevant CCU products for furher investigation

- **Aviation**
  - JET A-1 fuel according to standard ASTM D7566
    - Fischer-Tropsch to jet route
    - Alcohols (methanol) to jet route
- **Marine transport**
  - e-methanol
  - e-marine diesel oils according to standard ISO 8217 (marine distillate fuels)
- **Road transport (+non-road ground transport)**
  - e-methane (compressed or liquefied)
  - e-Gasoline according to standard EN228
  - e-Diesel according to standards EN590/EN15940

Relevant CCU products for furher investigation

- **Polymers (long term carbon storage):**
  - Polyolefins
  - Polyols/polyurethanes

- **Inorganic products (long term and permanent carbon storage)**
  - Mineralization to aggregate products (replacing sand and gravel)
  - Pre-casted concrete and cement products

Regulation on CCU

Onni Linjala, Kati Koponen

Introduction: CCU regulation

- In this section, we review and analyse existing and upcoming EU regulation that is relevant for CO_2 utilisation and evaluate regulation readiness regarding the different product categories of CCU.

- Key results of the review are:
  - Summary of targets and drivers to increase demand of CCU
  - Summary of quality criteria and production rules for CCU
  - Timeline and expected content of upcoming relevant regulation
  - Conclusions on the status of CCU regulation in EU and in Finland

Examined regulation relevant for CO_2 utilisation

- European Climate Law
- Fit-for-55
- Green Deal Industrial Plan
- Industrial Carbon Management Strategy
- 2040 Climate Target
- Sustainable Carbon Cycles
- Renewable Energy Directive
- Net-Zero Industry Act
- ReFuelEU Aviation
- FuelEU Maritime
- Delegated Act's on RFNBO and RCF production (2023/1184) and GHG methodology (2023/1185)
- Delegated Act on permanent CCU
- Carbon Removal Certification Framework
- Hydrogen and decarbonised gas market package
- Monitoring and Reporting Regulation

EU policy packages relevant for the development of CCU regulation

Policy package	Description
European Climate Law	A legal obligation for EU Institutions and the Member States to be carbon neutral by 2050 and reduce GHG emissions at least 55 % by 2030 compared to 1990 levels.
Fit-for-55	A legislative climate package aiming for 55 % reduction in EU's GHG emissions by 2030 compared to the level of 1990.
Green Deal Industrial Plan	Plan to support competitiveness and implementation of net-zero technologies and products to achieve climate targets by simplifying regulations, accelerating funding, developing skills, and ensuring resilient supply chains.
Sustainable Carbon Cycles	Initiative to promote drastic reduction of carbon reliance, recycling of carbon originating from sustainable sources, and importance of carbon removal solutions in climate action.
2040 Climate Target	An intermediate climate target between the 2030 and 2050 targets aiming for 90 % reduction in GHG levels relative to 1990.
Industrial Carbon Management Strategy	Strategy that covers the role of carbon management technologies (CCS, CCU, CDR) in EU, bringing together the related policy and regulatory measures.

Targets / drivers to increase demand for CCU

STATUS:	Adapted legislation			Proposal / in preparation		Communication (non-binding)		
Product category	**Renewable Energy Directive (RED)**	**ReFuel EU Aviation**	**Fuel EU Maritime**	**Net Zero Industry Act**	**Hydrogen and decarbonised gas market package**	**Industrial carbon management strategy**	**EU 2040 Climate Target**	**Sustainable Carbon Cycles**
SAF	• General target for RNFBO's • RFNBO reward factor of 1.5x	• SAF and synthetic fuel targets for 2025-2050		• CCU and CCS are chosen as a *stragic net-zero technologies*, benefitting from priority status at national level, accelerated permitting processes, and facilitated access to public tenders and support schemes.		• Outlines the EU strategy for carbon management (CCU, CCS, CDR). • Development of new policies, e.g., CO2 quality standards, CO2 demand and aggregation platform and accounting rules for carbon management.	• CCU is noted as necessary to achieve the 2040 climate target among other zero and low carbon energy solutions.	
Marine fuels	• Share of RNFBO's 1.2 % by 2030 • RFNBO reward factor of 1.5x		• GHG intesity reduction targets for ships with a 2x reward factor for RFNBO's (2025-2034)					
E-fuels for road transport	• Share of RNFBO's 1 % by 2030 • RFNBO reward factor of 2x							
CCU chemicals								• By 2030, at least 20 percent of the carbon used in chemical and plastic products should come from sustainable, non-fossil sources.
CCU plastics								
CCU construction materials / CCU concrete								
Hydrogen	• Article 22a: Contribution of RFNBO's used for final energy and non-energy purposes shall be at least 42 % of the hydrogen used for final energy and non-energy purposes in industry by 2030, and 60 % by 2035.				• Aims for decarbonised gas sector in Europe.			

Quality criteria for CCU products

VTT

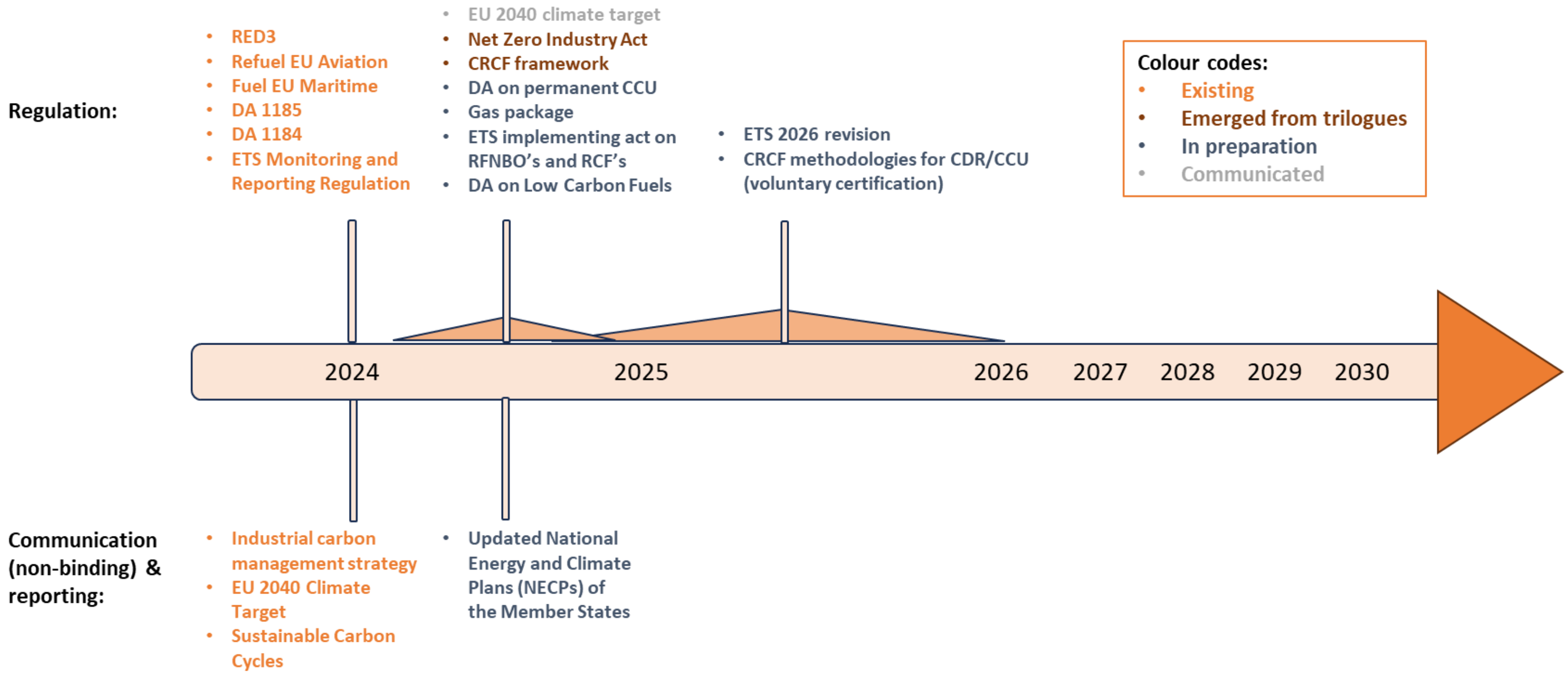
STATUS:	Adapted legislation	Proposal / in preparation

Product category	DA1185	DA1184	ETS Monitoring and Reporting Regulation	Carbon Removal Certification Framework	Delegated act on permanent CCU (draft version)
SAF	• 70% emission saving threshold for RFNBOs and RCFs • Origin of the CO2 • GHG calculation criteria	• Determines when hydrogen, hydrogen-based fuels or other energy carriers can be considered as RFNBOs • Sets rules for the origin of renewable electricity (additinality, temporal and geografic correlation)			
Marine fuels					
E-fuels for transport					
Hydrogen					
CCU chemicals					
CCU plastics					
CCU construction materials / CCU concrete			• Fossil CO2 used to produce precipitated calcium carbonate (or stored in long-term geological storage) can be subtract from the installation’s emissions that are accounted for in the ETS.	Definition for carbon removals: • Temporary carbon storage in long-lasting products: stores atmospheric or biogenic carbon for at least 35 years in long-lasting products • Permanent carbon removals: storage time several centuries, (DACCS, BECCS, biochar, including permanently chemically bound carbon in products) • Life-cycle emissions to be accounted for and reduced from the removal, Additionality • Certification systems, Union wide registry Detailed methodologies to be developed.	• Definition of permanent CCU and eligible products listed: a) carbonated aggregates; (b) carbonated supplementary cementitious materials used in cement or concrete; (c) pre-cured (wet) concrete; (d) carbonated clay bricks • Permanence at least several centuries • Products that have a significant share of end-of-life disposal through incineration are not applicable
CDR: Permanent removals (BECCS/DACCS)					

Upcoming regulation

Policy / regulation	Estimated timeline	Content
Updated National Energy and Climate Plans (NECPs) of the Member States	06/2024	Outlines how the Member States aim to reach EU's energy and climate goals
Climate Law: 2040 Climate Target amendment	After the EU elections of summer 2024	Legal obligation for 90 % reduction of GHG emissions by 2040 compared to 1990 level
Delegated act on permanent CCU	Published on summer 2024, adoption before end of 2024	Defines permanent CCU products that are eligible to avoid surrendering ETS allowances and under what conditions
ETS 2026 revision	By 31.7.2026	Assessment of accounting negative emissions and integrating those to the ETS, emission accounting and double counting regarding non-permanent CCU, role of WtE
Gas package: Delegated act for GHG assessment methodology for the certification system for low-carbon gases, including hydrogen	By 31.12.2024	Detailed rules on the methodology and assessment of greenhouse gas reduction of hydrogen will be determined in a delegated act
CRCF Delegated Acts for BECCS and DACCS, Carbon removals via permanent CCU / mineralisation	Likely 2024-2026	Detailed rules for various CDR and CCU options developed with the CDR expert group
ETS implementing act on RFNBO's and RCF's	2024	Will detail how RFNBO's and RCF's are accounted for in the ETS (pursuant to Article 14 of the EU ETS Directive)
Delegated Act on Low Carbon Fuels (Gas package Article 8)	By 31.12.2024	Details the methodology for assessing greenhouse gas emissions savings from low carbon fuels

Timeline on upcoming EU CCUS regulation



Review on regulation with targets / drivers to increase demand for CCUS

Renewable Energy Directive (RED3)

- **2023/2413, in force, implementation by 21.5.2025**

- Definition of RNFBO = “renewable fuels of non-biological origin”
- Share of RNFBO’s in transport sector at least 1 % by 2030
- Share of RFNBO’s in the total amount of energy supplied to maritime transport sector is at least 1.2 % by 2030
- For calculating the minimum shares 2x multiplier is used for RNFBO’s and 1.5x in aviation and maritime transport

- Delegated acts of RED2 (DA1184, 1185)

ReFuelEU Aviation

- 2023/2405, in force

- Sets SAF (sustainable aviation fuels) and synthetic fuels targets for airlines, airports and aircraft fuel suppliers in EU from 2025 to 2050

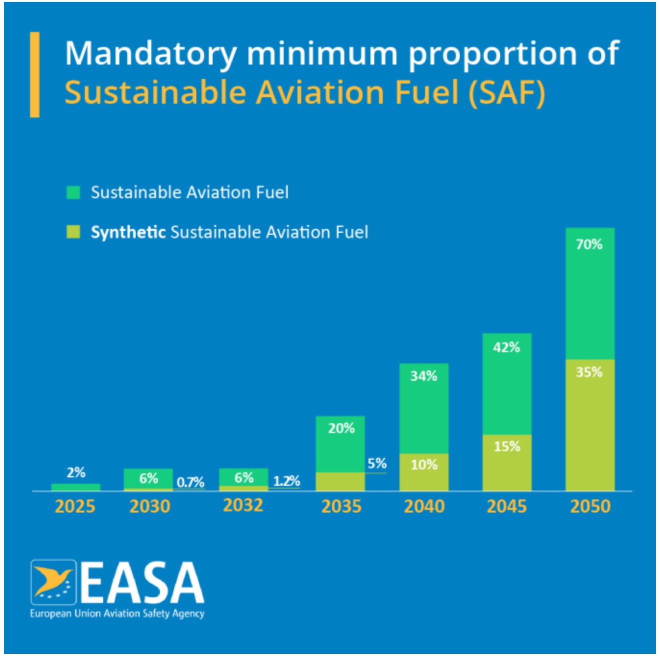


Figure: EASA

FuelEU Maritime

- **2023/1805**, **in force**
- Sets GHG intensity reduction targets for vessels above 5000 gross tonnage calling at European ports from 2025 to 2050
- Incentive for RFNBO use with a 2x reward factor in GHG intensity calculation (2025-2034)

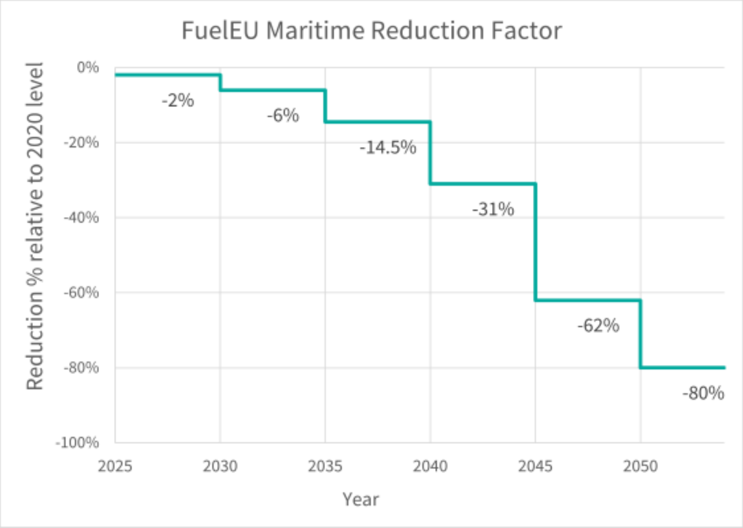


Figure: Lloyd's Register

Net Zero Industry Act

- **2023/0081/COD, emerged from Trilogues 20.2.**

- CCS and CCU are listed as *strategic net-zero technologies*, benefitting from priority status at the national level, accelerated permitting processes, and facilitated access to public tenders and support schemes. CCU was not initially included, but was added after trilogue agreement.

- Article 18: The proposed Net Zero Industry Act requires oil and gas companies holding licenses for the prospection, exploration, or production of hydrocarbons in the European Union to contribute to the annual injection capacity of at least 50 million tonnes of CO_2 by 2030 under
  - could increase the storage potential also for BECCS / DACCS

Hydrogen and decarbonised gas market package

- 2021/0424(COD), provisional agreement (proposal here)

- Aims for a long-term planning of a decarbonised gas sector in Europe
- Facilitates the emergence and operation of a well-functioning and transparent wholesale market in natural gas and hydrogen
- National network development plans
- A certification system for low-carbon gases, including hydrogen, is also established complementing the certification of renewable gases and hydrogen foreseen in the RED3

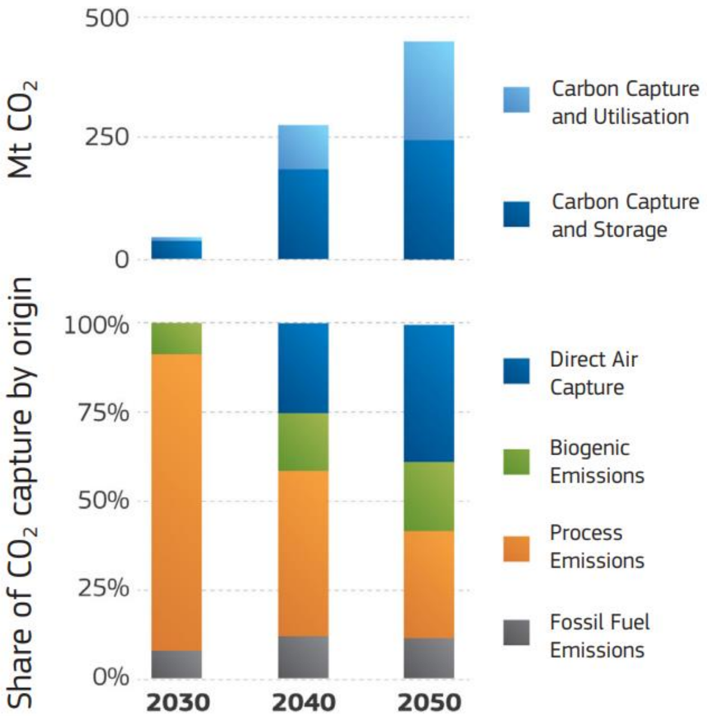
Industrial Carbon Management Strategy

- Communication (COM/2024/62 + Q/A) published on 6.2.2024

- Covers the role of carbon management technologies (CCS, CCU, CDR) in EU and brings together the related policy and regulatory measures, aiming to:
  - enable creation of viable business cases
  - building comprehensive regulatory framework across the entire value chain with necessary incentives
  - improving cross-border coordination and planning

- Does not identify specific sectors for carbon management, leaving the best applications at national level for the Member States to decide

- The communication outlines several topics for development of further policies such as CO_2 quality standards, CO_2 demand and aggregation platform and carbon management accounting rules



Vision of the Industrial Carbon Management Strategy in EU

VTT

By 2030

Deployment of CO_2 storage capacity of at least 50 million tonnes per year, together with related transport infrastructure consisting of pipelines, ships, rail and road. First CO_2 infrastructure hubs and industrial clusters are expected to emerge. Investments in these hubs will be facilitated by new EU-wide CO_2 transport infrastructure interoperability rules, including minimum CO_2 quality standards to ensure it can flow freely across the EEA.

By 2040

Most regional carbon value chains should become economically viable to meet EU climate objectives and CO_2 should become a tradable commodity for storage or use within the EU's single market. Up to a third of the captured CO_2 could be used. Requires EU-wide transport and storage infrastructure with pipelines and shipping being the main means of transport.

After 2040

Industrial carbon management should be an integral part of EU's economic system, and biogenic or atmospheric carbon should become the main source for carbon-based industrial processes or transport fuels. Any remaining fossil-based CO_2 would need to be captured, and a strong business case for negative emissions would be in place.

Side note

- Industrial-scale CO_2 storage projects have taken place in Europe since 1996 in Sleipner and 2008 in Snøhvit, but not without difficulties. (Hauber, 2023)
- CO_2 injection capacity is about to emerge quickly during the next 5 years based on current project pipeline. (The Finnish Climate Change Panel, 2023)

EU 2040 Climate Target

- Communication (COM/2024/63) and impact assessment report (SWD/2024/63) published on 6.2.2024, legislative proposal is expected by the next commission after the EU elections of summer 2024.

- Sets an intermediate target between the climate goals of 2030 (-55%) and 2050 (carbon neutral), aiming to reduce greenhouse gas emissions by 90% from 1990 levels.

- Energy system modelling for the impact assessment indicate that approximately 280 million tonnes of CO_2 would need to be captured by 2040 and around 450 Mtpa by 2050.

- CCS, CCU and carbon removals are identified as essential parts of the climate action portfolio
  - *”All zero and low carbon energy solutions (including renewables, nuclear, energy efficiency, storage, CCS, CCU, carbon removals, geothermal and hydro-energy, and all other current and future net-zero energy technologies) are necessary to decarbonise the energy system by 2040.”*
  - *”In line with the international commitment to transition away from fossil fuels, policies should ensure that any remaining fossil fuel combustion will be coupled as soon as possible with carbon capture (utilisation) and storage.”*

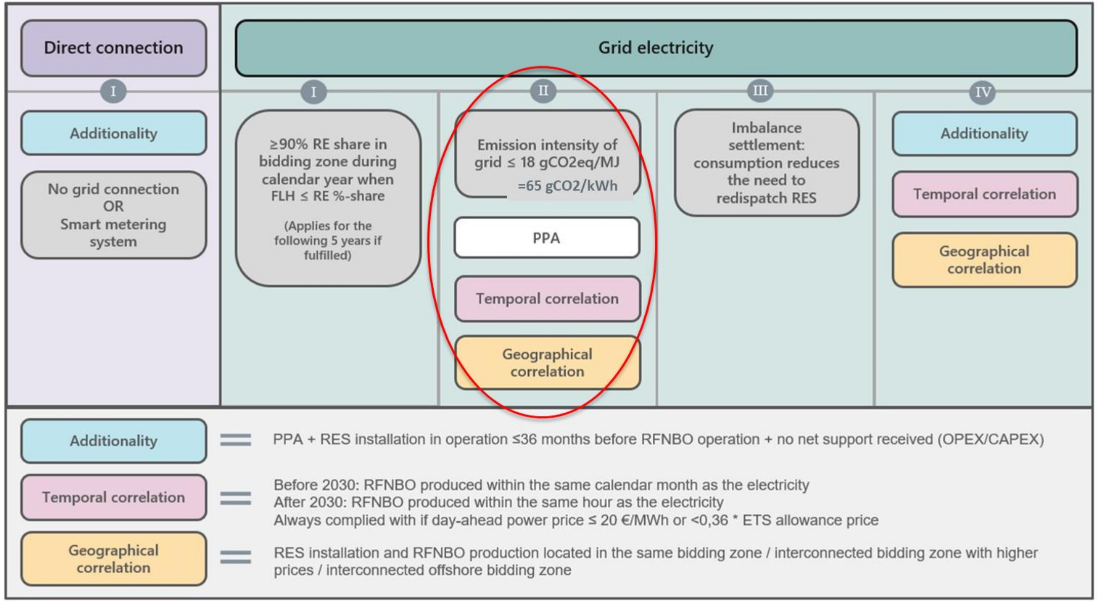
Sustainable Carbon Cycles

- Communication (**COM/2021/800**) published on 15.12.2021
- Initiative to promote drastic reduction of carbon reliance, recycling of carbon originating from sustainable sources, and importance of carbon removal solutions in climate action.
- The objectives presented in the communication:
  - By 2028, any ton of CO_2 captured, transported, used and stored by industries should be reported and accounted by its fossil, biogenic or atmospheric origin;
  - At least 20% of the carbon used in the chemical and plastic products should be from sustainable non-fossil sources by 2030, in full consideration of the EU's biodiversity and circular economy objectives and of the upcoming policy framework for bio-based, biodegradable and compostable plastics.
  - 5 Mt of CO_2 should be annually removed from the atmosphere and permanently stored through frontrunner projects by 2030.
- Expert group on carbon removals has been running since 2023

Review on regulation with quality criteria for CCU products

DA1184: Delegated act on RFNBO production rules

- 2023/1184, in force
- Defines when hydrogen, hydrogen-based fuels or other energy carriers can be considered as RFNBO
- Definition of fully renewable electricity
- Case two relevant for Finland



Summary by Aleksandra Saarikoski VTT

DA1185: Delegated act on GHG methodology for RFNBO's and RCF's

- 2023/1185, in force

- A minimum greenhouse gas emission saving threshold of 70 % for recycled carbon fuels
- Defines the methodology to calculate GHG emissions savings from RFNBOs and recycled carbon fuels
- Criteria for the origin of the CO2 for RNFBOs
  - CO_2 from e-fuel combustion is fully accounted despite the origin of the CO_2.
  - However, captured CO_2 incorporated in the chemical composition of the e-fuel can be considered as "avoided emission" when the origin of the CO_2 is one of the following:
    - Until 2035: Fossil CO_2 which has been captured from electricity production under ETS
    - Until 2040: Fossil CO_2 which has been captured from other source under ETS
    - CO_2 captured from the air
    - CO_2 from production of bioenergy complying with the EU sustainability and GHG criteria
    - CO_2 captured from the combustion of RNFBOs complying with the EU GHG criteria

→ Emissions from the capture process need to be included.

ETS Monitoring and Reporting Regulation

- 2018/2066, in force
- Lays down rules for the monitoring and reporting of greenhouse gas emissions and activity data pursuant to the ETS directive (2003/87/EC)
- Article 49 1(b): fossil CO_2 used to produce precipitated calcium carbonate can be subtract from the emissions of the installation that are accounted for in the ETS

CRCF: Carbon Removal Certification Framework

- 2022/0394/COD, emerged from Trilogues 20.2.

- Aims to facilitate and encourage the deployment of permanent carbon removals, carbon farming and carbon storage in products as a complement to sustained emission reductions across all sectors to meet the objectives of European Climate Law

- Establishes a voluntary Union framework for the certification of carbon removals and soil emission reductions by laying down:
  - quality criteria for activities that take place in the Union
  - rules for the verification and certification of carbon removals and soil emission reductions generated by activities
  - rules for the functioning and recognition by the Commission of certification schemes
  - rules on the issuance and use of certified units

- Defines the categories Carbon removals based on permanent storage (BECCS, DACCS), temporary storage in long-lasting products, temporary carbon storage from carbon farming and soil emission reduction (from carbon farming).
  - Detailed methodologies to be developed in Delegated Acts

Delegated act on permanent CCU (draft 3.5.)

- A new Article 12(3b) is introduced to ETS directive 2003/87/EC to remove the obligation to surrender allowances for greenhouse gas (GHG) emissions that are captured and utilized permanently.
- Legal elements of the delegated act:
  - Supplementing criteria for determining if GHG's are permanently chemically bound in product so that it is not emitted to atmosphere during or after product lifetime under any normal activity.
  - Detailing the requirements necessary for products to be considered as meeting the criteria
  - Listing the CCU products (in annex) that are considered to fulfil the requirements and thus qualify for the derogation from the obligation to surrender allowances.
  - Establish a procedure for reviewing and updating the list of compliant CCU products, based on technological developments, new evidence or practical experience with CCU products, including the possibility to remove products.

- Regarding permanence: *"[GHG's shall] remain permanently chemically bound in a product so as to not enter the atmosphere under normal use of the product, including any normal EN 8 EN activity taking place after the end of the life of the product, for* ***a period of at least several centuries****. In case of products with multiple normal use and end of life pathways, all such pathways need to be taken for the purposes of this paragraph. Products that during normal use, including any normal end of life activity, may be exposed to high temperature combustion, such as occurring in incineration, shall not qualify as permanently chemically bound."*

- Products included in the draft version of 3.5.2024:
  - **Mineral carbonates used in the following construction products: (a) carbonated aggregates used bound or unbound; (b) carbonated supplementary cementitious materials used in cement or concrete; (c) carbonated concrete; (d) carbonated clay bricks or tiles**

Open questions related to waste regulation

- Waste regulation could affect the availability of CO_2 by encouraging recycling of raw materials rather than CO_2?
- Packaging/ecodesign regulation could affect the biogenic/renewable carbon content in waste materials?
- How to ensure that there is no double counting for recycled $CO_{2,}$ e.g. in case where CCU products end up in waste incineration?
- Possibly relevant regulations
  - **EU Waste Framework Directive**
  - **Single use plastics directive**
  - **Packaging and packaging waste directive / regulation / act**
  - **Ecodesign for sustainable products regulation (ESPR)**

Preventing waste is the preferred option, and sending waste to landfill should be the last resort.

Conclusions on CCU regulation

Conclusions on CCU regulation (1/2) – outlook on CCU pathways

- **CCU is acknowledged as an essential technology in EU's climate action portfolio** among other zero and low carbon energy solutions. It has been selected as one of the strategic net-zero technologies and therefore should benefit from streamlined regulation and supportive investment environment.

- So far, **regulation on CCU has mostly been advanced regarding transport fuels**, for which there are capacity targets and sustainability rules in place. However, clarification is still needed, for instance, regarding non-transport use of these fuels and ETS accounting.

- **For non-fuel products, such as chemicals and materials, CCU regulation is currently largely inadequate** to enable farsighted planning and to generate investments. Some strategic but non-binding targets have been set suggesting that these products will be promoted in the future – but for now the necessary incentives and rules are lacking. Product categories (e.g. regarding the CCU storage permanence) are still to be clearly defined and accounting methodologies to be clarified.

- Carbon removals are defined in the CRCF but not incentivized, with **market uptake relying on voluntary carbon markets**. Also, the upcoming act on permanent CCU focuses only on fossil-CO_2 with ETS being the driver – although a similar act regarding carbon removals is expected to follow.

Conclusions on CCU regulation (2/2) – Finnish perspective

- **RNFBO's for transport (road, aviation, maritime) were recognised as high potential options of CCU for Finland within the current regulatory framework.** The legislation concerning these products is the most mature and includes detailed guidance e.g. on the origin of CO_2 and hydrogen used in the process.
  - The rules of DA1184 for defining the renewable hydrogen likely require Finnish actors to make a PPA agreement for purchasing e.g. wind electricity for their electrolyser.

- Although regulation for non-fuel CCU products is yet largely missing, strategic policies suggest that they will be relevant in the EU. Therefore, **Finnish actors should actively promote the development of an extensive portfolio of CCU products and participate in formulating the policies for various CCUS products in the EU** (e.g. under the CRCF framework).

- **Finland has a significant potential for bio-CO_2 utilisation**, which is major strength as EU policies acknowledge sustainable biogenic CO_2 as key feedstock for CCU.
  - This is a benefit as the DA1185 sets biogenic CO_2 from sustainable biomass according to RED criteria as an acceptable source of CO_2 for CCU in long-term.
  - However, at the same time the carbon sink in the Finnish forest sector has radically reduced. This could cause some impacts on the land use sector regulation and thus availability of wood and CO_2 in future.

Work package 2:
Products, markets and value

Lauri Kujanpää, Juha Lehtonen, Eveliina Jutila

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Global CCUS outlook

Key insights

- The global CCUS revenue is expected to increase from $1.68 billion in 2022 to $ 38.18 billion in 2040 with a CARG of 18.9 % (2022-2040). The European CCUS market is expected to grow from $0.21 billion in 2022 to $13.63 billion in 2030 and fall to $11.20 billion by 2040 with a CARG of 24.9 % (2022-2040).
- The demand of CO_2 as raw materials is approaching about 634 Mtpa in 2030, 3241 Mtpa in 2040 and 6076 Mtpa in 2050. The annual capacity for captured CO_2 utilization is expected to increase dramatically from 1.4 million tonnes per annum (Mtpa) in 2022 to 171.2 Mpta in 2040.
- It has been forecasted that the CO_2 capture per annum will increase from 0.9 $GtCO_2$ in 2030, to 6.3 $GtCO_2$ in 2050 and to 12.6 GtCO2 in 2070. It has been estimated that by 2070 92 % of the CO_2 is stored, while only 8 % of it is utilized. Most of the CO_2 utilized is used to produce synthetic fuels and the rest are used in the chemical sector.
- The main categories of CCU products are fuels, chemical and materials. The highest potential for CO_2 utilization lies in construction materials and fuels, both in terms of market opportunity and CO_2 consumption. For example, the theoretical volume of CO_2 utilization for 2040 (assuming 100% market penetration) is estimated at 0.5-2 Gtpa for construction aggregates, 130-280 Mtpa for e-methanol, 50-150 Mtpa for e-kerosene and 70 Mtpa for CO_2 cured concrete. The market opportunity of construction materials in 2050 is estimated to reach USD 800-1000 billion, while the market opportunity of fuels is expected to reach USD 21-2060 billion.
- CO_2 utilization technologies are at various stages of maturity. The most mature utilization technologies are in the cement industry (mineralization, concrete), followed by fuel production (methanol, synthetic methane). Power generation related technologies and synthetic liquid hydrocarbons are still in the pilot scale.
- Barriers for CO_2 utilization include the cost of CO_2 capture, high cost of CCU products compated to traditional alternatives and lack of harmonized regulatory support.

Market potential for CCU products in 2040 1/2

Product	CO_2 utilization in 2040	Price	More information
Construction aggregates	0.5-2 Gt CO_2 per year (~2-25 % market penetration)	4-5 times more expensive than conventional aggregates without landfill tax rates	Largest potential market in terms of CO_2, but low product value makes competing with low-cost conventional aggregates challenging. Currently two or four times more costly than incumbent (conventional alternative) and requires landfill tax of ~$50-100 to incentivize using waste streams for constructions aggregates instead of putting them in landfills.
CO_2-cured concrete	40-70 Mtpa CO_2 per year (30-50 % market penetration)	1.3-1.5 times more expensive compared to conventional concrete	A small market in terms of overall CO_2 required, but the technology is nearly ready for scaling. The economics can be challenging, given high capex requirements for a low-value product..
E-kerosene	50-150 Mtpa CO_2 per year (3-10 % of the overall jet fuel market)	$6-$7 per gallon	Medium-sized market and technology is nearly ready for scaling. However, overall cost is expected to stay well above conventional and other bio-based kerosene prices without significant regulatory incentives; the scarcity of biogenic CO_2 and the cost of direct air capture (DAC) could be a limiting factor. Two to four times more expensive than regular jet fuel. Existing or new fuel mandates could make E-SAF profitable before 2040.
E-methanol	130-280 Mtpa CO_2 per year (10-60 % of the overall methanol market for both fuels and chemicals)	$900-$1200 per ton	Medium-sized market and technology is nearly ready for scaling. However, given that high energy requirements drive the bulk of production costs, the business case is likely to be negative without financial incentives or suffifient low-cost hydrogen; scarcity of biogenic CO_2 and the cost of DAC could be a limiting factor. Two to four times more expensive than regular methanol. e-methanol reguires higher carbon prices of $200-$450 to break even. Technology close to scaling in shipping, e-methanol for shipping could make up 40 % of the methanol market in 2040.

Source: The Oil and Gas Climate Initiative (OGCI): Carbon capture and utilization as a decarbonization lever (2024)

Market potential for CCU products in 2040 2/2

Product	Market potential in 2040	Price	More information
Polyolefins	60-120 Mtpa CO_2 (100 % of green olefin produced via green MTO process are polyolefins and green penetration of 3 %),	N/A	Highest potential market, but the expectation for penetration is relatively low due to alternative bio-options.
Polyols/polyurethanes	10-15 Mtpa CO_2 (100 % market penetration)	N/A	Highest maturity, but have a smaller market size.

Source: The Oil and Gas Climate Initiative (OGCI): Carbon capture and utilization as a decarbonization lever (2024)

Market potential estimations for CCU products in 2030, 2040 and 2050 (best case scenario)

- Precast Concrete and Aggregates: These materials show the highest volumes and CO_2 utilization potential, especially by 2050.
- Polyurethane and Methanol: Although the volumes are smaller compared to construction materials, they still represent a significant market and CO_2 utilization growth.
- Jet Fuel and Methane: These sectors, while starting with negligible values in 2030, show dramatic increases in market value and CO_2 utilization by 2050.

	2030			2040			2050		
Product	**Market value (US$ billion)**	**Market volume (annual billion or million tonne)**	**CO_2 utilization (annual Gt of CO_2)**	**Market value (US$ billion)**	**Market volume (annual billion or million tonne)**	**CO_2 utilization (annual Gt of CO_2)**	**Market value (US$ billion)**	**Market volume (annual billion or million tonne)**	**CO_2 utilization (annual Gt of CO_2)**
Precast conrete	15	1.5 Bt	0.02	233	12 Bt	0.18	666	27 Bt	0.39
Aggregates	~0	~0 Bt	~0	100	7.5 Bt	4.2	337	22.5 Bt	7.3
Polyurethane	20	5 Mt	0.0006	110	32 Mt	0.0048	191	53 Mt	0.0075
Methanol	3	5 Mt	0.01	47	110 Mt	0.15	183	410 Mt	0.55
Jet fuel	0	0	0	0	0	0	1880	1.7 Bt	8
Methane	0	0	0	25	0.7 Bt	0.7	214	4 Bt	4

Source: University of Michigan: Implementing CO2 capture and utilization at scape and speed (2022), values estimated from the figures of the document.

Market volume estimation for 2020 and projected growth to 2050 by Lux Research

- Lux Research estimated a starting market volume in 2020 and projected growth to 2050 to establish the total addressable market & estimated starting product price in 2020 to project the cost tipping point between incumbent and CCU end products. Sources and comments related to estimates by Lux Research can be found from the original source, pages 151-155.
- Price of CCU products are higher than those of incumbent products in 2020.

Market	2020 market volume (tonne)	2050 market volume (tonne)	Market growth rate (CARG %)	Incumbent 2020 price (US$/tonne)	Incumbent price change (%/year)	CCU end product 2020 price (US$/tonne)
Precast concrete	7 billion	32 billion	5.2 %	19	1.1 %	26
Aggregates	45 billion	119 billion	3.3 %	10	1.5 %	50
Polyurethane	24 million	58 million	3 %	3200	0.5 %	4160
Methanol	100 million	432 million	5 %	350	1 %	1381
Methane	32 billion	79 billion	3 %	17	3.5 %	170
Jet fuel	305 million	3.1 billion	8 %	450	3 %	2250

Source: University of Michigan: Implementing CO2 capture and utilization at scape and speed (2022)

Other global market estimates

Product	Market size and CARG	Source
Fischer-Tropsch Synthetic Paraffinic Kerosene	USD 2546.9 million in 2023 and is forecast to a readjusted size of USD 4463.4 million by 2030 with a CAGR of 8.3% during review period.	360 Market Updates (2024)
Fischer-Tropsch Synthetic Paraffinic Kerosene	USD 19 billion in 2023 and is expected to reach USD 32 billion by the end of 2036, growing at a GARC of 8 % during the review period.	Research Nester (2024)
E-fuels	USD 28.16 billion in 2024 and expected to reach 90.85 billion by 2030 with a CARG of 21.4%.	ResearchAndMarkets (2024)
E-methanol	Expected to reach $2.5 billion by 2027 with a CARG of 5.8 % between 2022 and 2027.	EINPresswire (2024)
E-methanol (renewable)	USD 3.6 billion in 2023 and is expected to reach USD 5.6 billion by 2032 with a CARG of 5.03 %.	ValueSpectrum (2024)
Polyolefins	Estimated to grow by USD 70.6 billion from 2023 to 2027 with a CARG of approximately 5 % during the review period.	PR Newswire (2024)
Polyols	USD 25.84 billion in 2023 and is expected to reach USD 44.78 billion by 2030 with a CARG of 6.3 %.	WhaTech (2024a)
Polyurethanes	USD 82.2 billion in 2023 and is expected to reach 117.5 billion by 2031 with a CARG of 4.5 % during the review period.	WhaTech (2024b)
Precast concrete	USD 100.68 billion in 2022 and is expected to withness a CARG of 5.4 % from 2023 to 2030.	WhaTech(2024c)
Precast concrete (Europe)	USD 28,014.25 million in 2022 and expected to reach USD 44,978.37 by 2028 with a CARG of 7.1 % during review period.	Statzon / The Insights Partners: Europe Prevast Concrete Market to 2028.

Note: The market size estimates on this slide are mostly from advertisements of market reports, which might not be as reliable as reports produced by consultancy companies. Also note that the market might be scoped in a different way thus leading to varying market estimates.

Market outlook for the main product categories

E-fuels

Key insights

- The e-fuels are the least mature of the technologies included in this market study indicating that synthetic fuels still need significant development. However, they have the highest market potential, though reaching it can take some time. The e-fuels market is mainly in the aviation and marine industry.
- The annual e-fuel production capacity should reach 1.1 million metric tons by 2028, including all forms of e-fuels targeting automotive, aviation, and marine applications. Europe is the most important region for e-fuel production, followed by the United States and Australia.
- The global carbon dioxide segment of the carbon-neutral fuel market as feedstock for carbon-neutral fuels is expected to grow from USD 10,839.36 million in 2022 to USD 18,002.97 million in 2030 at a CARG of 6.55 % between 2022 and 2030. By volume the global market is expected to increase from 7,800.7 kilotons in 2022 to 12,3315.2 kilotons in 2030 with a CARG of 5.87 %.
- **Marine:** The increase of dual-fueled vessels is increasing demand for alternative fuels from the maritime industry, but the demand and supply of fuels do not match and thus there is a yearly shortfall of up to 20 million tonnes of alternative fuels. The price of renewable and synthetic fuels have significantly higher projected prices than fossil fuels. Furthermore, synthetic fuels are currently the most expensive to produce compared to bio-based fuels.
- **Aviation:** The aviation industry is projected to undergo a significant shift from reliance on fossil fuels to synthetic hydrocarbon fuels and biofuels. By 2070, almost half of the global energy demand for aviation is met with synthetic fuels, requiring capture of approximately 830 MT of CO_2 to be used as feedstock. It has also been estimated that over 10 Gt of CO_2 can be potentially utilized annually by 2050 as CO_2-derived jet fuel take up 55% market share. A substantial gap in SAF supply is anticipated, indicating a need for continued advancements and investments in sustainable fuel technologies. Barriers include high production cost and limited supply of resources.

CCU chemicals and materials

Key insights

- There are various chemical synthesis pathways for the utilization including methanol and polyurethane. The technologies are quite mature, but the market is much smaller than that for building materials or e-fuels.
- In 2020 the share of CO_2-based chemicals was approximately 0.165 million tonnes of embedded carbon (Mt C) and it is expected to increase to approximately 288 Mt C by 2050 amounting to 25 % of the carbon embedded chemicals and materials. In 2050, 20% of the carbon in plastics is expected to be sourced from captured CO_2.
- A complete defossilisation of the chemical industry can only be achieved by combining the three different sources (bio-based, CO2-based and recycling).
- **E-methanol:** The global methanol market is expected to grow to US$204 billion by 2050 with a CAGR of 5% as demand for commodity chemicals continues to rise. Nearly 0.6 Gt of CO_2 can be potentially utilized annually by 2050 as CO_2-derived methanol is expected take up 90% market share. E-methanol is projected to contribute approximately 300 Mt to the total methanol production of 500 Mt by 2050. The current production cost of e-methanol depends on where the CO_2 is sourced from. Main barrier is related to higher cost compared to fossil-fuel based alternatives.
- **Polyurethane:** The global polyurethane market is expected to grow to US$217 billion by 2050 with a CAGR of 3% Projected market volume of polyurethane is 58 million MT by 2050 based on a 24 million MT market volume in 2020 and an estimated CAGR of 3%. Less than 0.02 Gt of CO_2 can be potentially utilized annually by 2050 as CO_2-derived polyurethane is expected to take up 88% market share.

Note: Key insights are drawn from CCUS potential and CCU chemicals and materials slides.

CCU building materials

Key insights

- The main utilization pathways for building materials are construction aggregates and CO_2 cured concrete (used for precast concrete). These are also referred to as mineralization technologies. These technologies are in the early adaptation or deployment phase.
- The market potential for construction aggregates is around 500 Mt CO_2 by 2040, compared to CO_2 cured concrete which is expected around 40-70 Mt CO_2 by 2040. According to another estimate, the market size for construction aggregates has been estimated at 0.5-2 Gtpa and co2 cured concrete at 70 Mtpa in 2040. The price of the aggregates is estimated to be 4-5 times higher than conventional alternatives, while the price of CO_2 cured concrete is estimated to be 1.3-1.5 times higher than the conventional alternative making the high price as one of the barriers for utilization.
- **Aggregates:** The global aggregates market is expected to grow to US$1.8 trillion by 2050 with a CAGR of 3.3% as demand rises with rapid urbanization and global development. Projected market volume of aggregates is 119 billion MT by 2050 based on a 45 billion MT market volume in 2020 and an estimated CAGR of 3.3%. Over 7.3 Gt of CO_2 can be potentially utilized annually by 2050 as CO_2-derived aggregates expected to take up 18% market share.
- **Precast concrete:** The global precast concrete market is expected to grow to US$830 billion by 2050 with a CAGR of 5.2%. Projected market volume of precast concrete is 32 billion MT by 2050 based on a 7 billion MT market volume in 2020 and an estimated CAGR of 5.2% Despite rapid adoption leading to 80% market share, curing's low utilization potential only utilizes 1.3 Gt of CO_2 in 2050.

Note: Key insights are drawn from CCUS potential and CCU building materials slides.

Good sources for CCUS

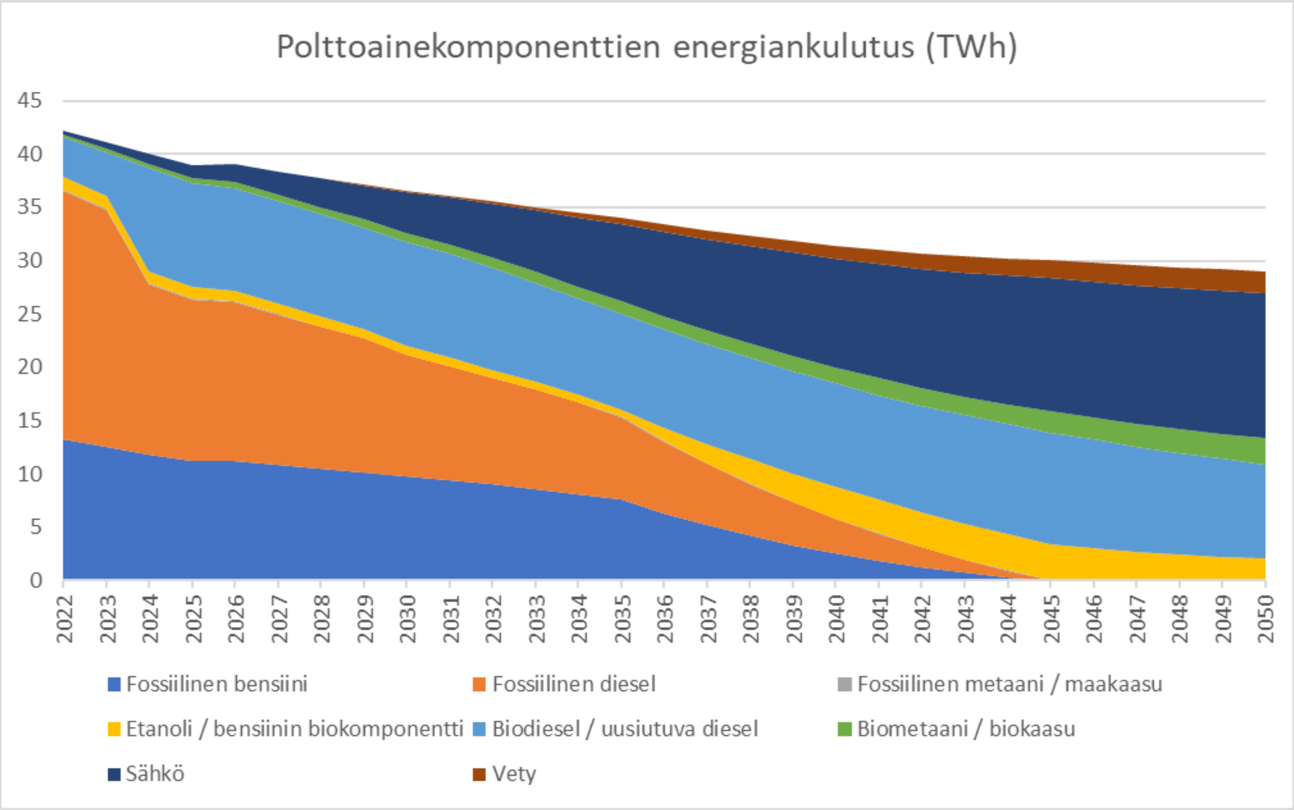
- Global CO_2 Initiative by University of Michigan
  - Implementing CO2 capture and utilization at scale and speed (2022)
  - Implementing CO2 capture and utilization at scape and speed, data and analysis amendment (2022)
- International Energy Association (IEA)
  - Special Report on Carbon Capture utilization and Storage (2020)
- nova institute
  - Renewable carbon publications
    - Carbon Dioxide (CO_2) as Feedstock for Chemicals, Advanced Fuels, Polymers, Proteins and Minerals (2,500 € – 10,000 € ex. tax)
    - RCI's scientific background paper: "Making a case for Carbon Capture and utilization (CCU) – It is much more than just a carbon removal technology" (July 2023) (free)
    - CO2-based Fuels and Chemicals Conference 2024 (150 € ex. tax)
- Kearney Energy Transition Institute: Carbon capture utilization and storage (2021)
- The Oil and Gas Climate Initiative (OGCI) Carbon capture and utilization as a decarbonization lever (2024)

Status and outlook of CCUS in Finland

CCU product market by 2040 in Finland – some assumptions

- The amount of biogenic CO_2 emitted in Finland will remain constant (~ 28 Mton/a) or decline by some extent by 2040.
- Of that amount ~ 8 Mton/a could be utilized for CCU products by 2040.
- Out of 8 Mton/a of 2 - 3 Mton/a of CCU products could be produced (based mainly on organic products i.e. e-fuels and polymers)
- Production will start with quite small scale e-methane for road transport in 2026 – 2028 and probably with methanol production for marine transport before 2030 (e.g. P2X Solutions and RenGas).
- Aviation fuels production will be much more investment intensive but we expect to have some production in Finland by 2035 .
- Some inorganic materials production by 2030 and organic chemicals and polymers by 2035.

Transportation energy consumption by propulsion in Finland with additional measures (WAM)



ELIISA-malliajojen tulostaulukot. Tausta, ks. Markkanen, J. 2022. Tieliikenteen toimenpiteiden khk-päästövähennysvaikutusarviot. Muistio 30.8.2022

E-fuels market in Finland - assumptions

- Aviation
  - Liquid hydrocarbon fuels will be fully prevailing propulsion option in aviation in 2040
  - EU demand of e-fuel for aviation 3 – 5 Mton/a by 2040 (10 % total demand) (EASA, 2024)
  - In Finland, we could assume that by 2040 ~ 20 % aviation fuels consumption replaced with e-fuels (200 kton/a)
  - In addition , we can set a target for the production in Finland to cover 20 % of EU:n demand by 2040 => production ~ 1 Mton/a
  - Main routes to e-jet: Fischer-Tropsch hydrocarbons ja methanol-to-jet

E-fuels market in Finland - assumptions

- Maritime
  - Liquid and gaseous fuels will be fully prevailing option in maritime in 2040.
    - Current marine fuels consumption in the EU ~ 50 Mton/a (FuelsEurope, 2022)
    - In Finland ~ 1,5 Mton/a (Traficom, 2021)
  - Demand to be based on FuelEU Maritime (31% reduction in carbon intensity by 2040).
  - E-fuels to be one important solution to reduce carbon intensity.
  - Methanol the most potential e-fuel for maritime, ammonia as questionmark (non-carbon e-fuel).
  - Let's assume ~ 3 Mton/a demand for maritime e-fuels by 2040 in the EU:
    - 20 % of that amount to be produced in Finland ~ 0,6 Mton/a
    - 50 % of that amount consumed in Finland ~ 0,3 Mton/a

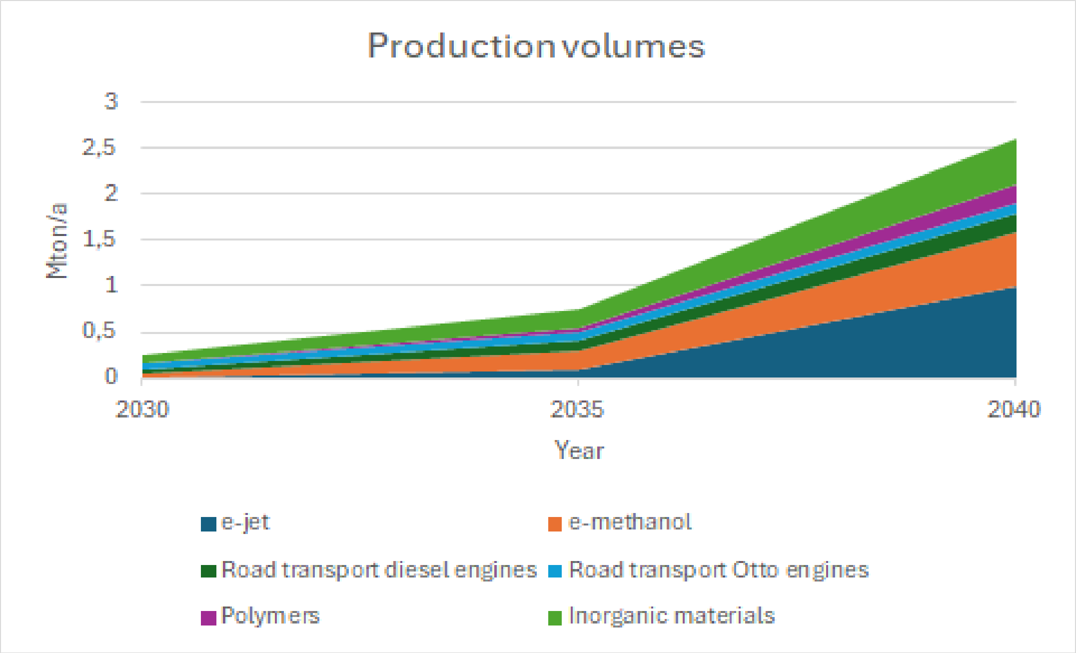
E-fuels market in Finland - assumptions

- Road transport
  - To be based on blending obligations.
  - ICE:s to be banned for new passanges cars and vans beyod 2035, however, engines with e-fuels allowed beyod 2035.
  - However, electrification of light road transport expected to a great extent in the EU => Demand of road transport e-fuels is expected to focus on heavy road transport.
  - Relatively small scale production of e-methane starting 2026 – 2028 in Finland.
  - Some by-product e-gasoline production expected from the production of aviation e-fuels.
  - Let's assume e.g. following domestic demand 20 % of current consumption for diesel engines (~ 0,2 Mton/a e-diesel + e-methane) and 10 % demand of current consumption for otto engines (~ 0,1 Mton/a). (Autoalan Tiedotuskeskus, 2024)
  - Those amounts to be produced in Finland.

CCU chemicals and materials market in Finland - assumptions

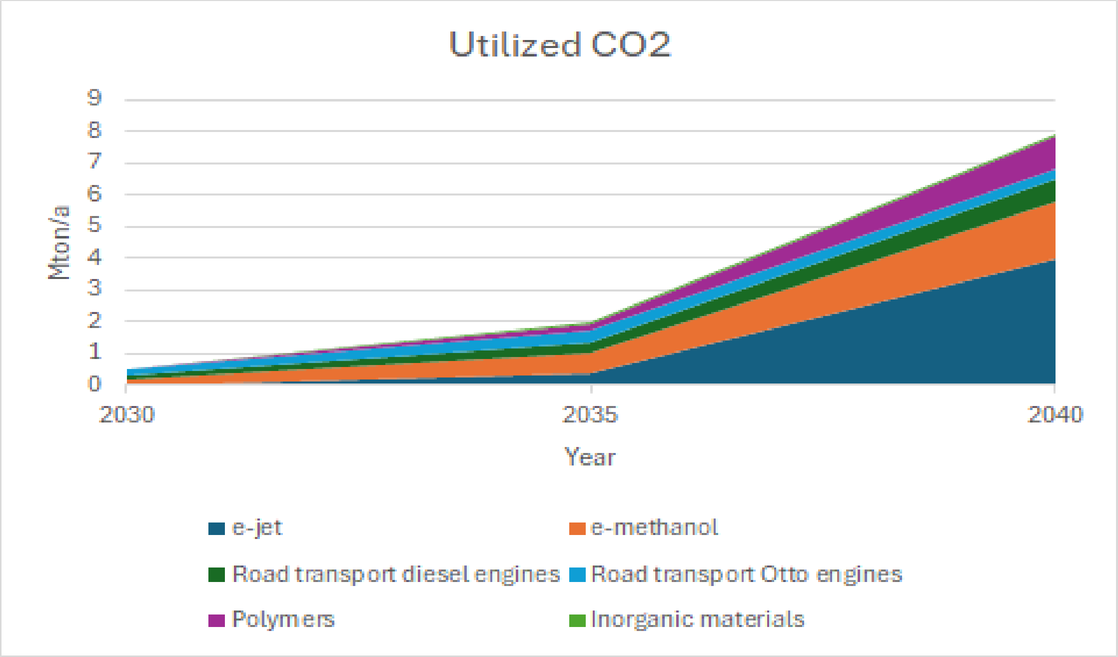
- Regulations poorly established for CCU chemicals and materials.
  - Difficult to make scenarios based on regulations and policies.
- However, regulations steer industry to more sustainable products and there is already as well some voluntary market based on the premium of sustainable products.
- Some production of inorganic materials by 2030.
  - Production volume could be ~ 0,5 Mton/a by 2040.
- Production of organic polymers from 2035.
  - Production volume could be ~ 0,2 Mton/a by 2040.

Scenarios of production volumes of CCU products in Finland 2030 – 2040



- With a stronger growth after 2035, e-jet could be the CCU product of highest production volumes in Finland.
- Most of the captured CO_2 would be utilized for e-jet and e-methanol in the assumed outlook.

Scenarios of captured CO_2 volumes for CCU products in Finland 2030 – 2040



- Following factors used (ton CO_2/ton product):
  - e-jet: 4
  - e-methanol: 3
  - Road diesel engine: 3,5
  - Road Otto engine: 3,5
  - Polymers: 5
  - Inorganic fillers: 0,45
  - Concrete & aggregates: 0,05

EU's Industrial carbon management policy and markets carbon dioxide removal

Key policy initiatives in the EU and options for value creation

VTT

Key policy inititatives in EU

- CCUS is gaining substantial role in reaching the EU's carbon neutrality target. Below are two key policy initiatives in the EU, which will affect the business environment of CCUS and CDR in the coming years.
- Certification framework for permanent carbon removals, carbon farming and carbon storage in products (CRCF-regulation) (2022/0394 (COD))
  1. establishes EU quality criteria for carbon removals
  2. outlines monitoring and reporting processes
  3. addresses greenwashing
  - Provisional agreement on 20.2.2024
- Industrial carbon management strategy (COM/2024/62)
  - A comprehensive approach for the EU to scale up carbon management.
  - Identifies a set of actions to be taken, at EU and national level, to establish a single market for CO_2 in Europe and to create a more attractive environment for investments in industrial carbon management technologies.

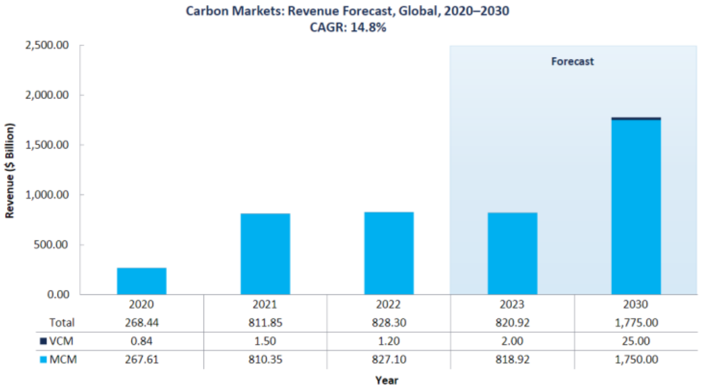
Carbon removals covered by the CRCF Regulation (Articles 1 and 2)

Carbon farming	Carbon storage in products	Permanent carbon removals
• Rewetting peatlands or more efficient use of fertilizers. • Temporary carbon removals in soil and forests. • Monitoring time of at least 5 years.	• Temporary carbon storage in products such as building materials for more than 35 years.	• Storage for several centuries. • Contains permanently chemically bound carbon in products.

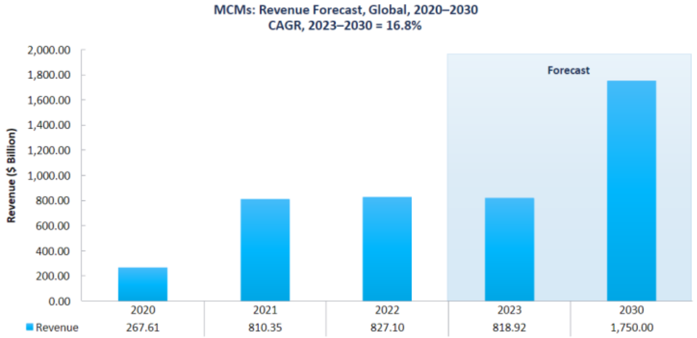
Opportunities to create value through the emission allowance market

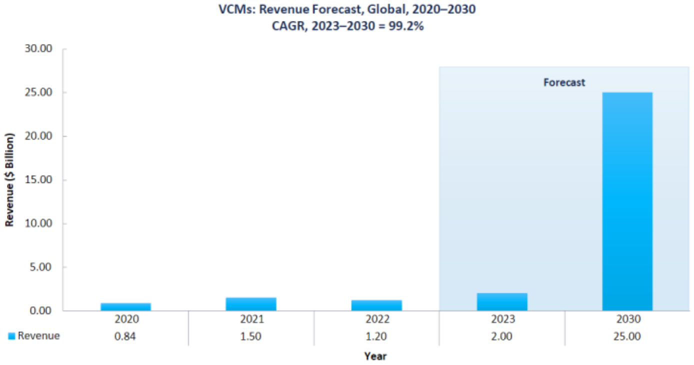
- Currently, only utilization of fossil CO_2 in products, where the carbon remains permanently chemically bound, is accounted within the EU mandatory carbon market EU ETS.
- No compliance markets yet for carbon removals in EU: Inclusion of permanent removals of biogenic or atmospheric carbon to ETS will be discussed in 2026.
- One perspective to allowing participants in the EU ETS to use BECCS credits (Möllersten et al 2023):
  - With the reforming of the EU emissions trading system in 2023, the EU ETS cap will be reduced by 4.3 – 4.4 % per year. -> the last emission allowance would be issued in Year 2039. Residual emissions likely, from hard to abate processes, capture residuals, aviation.
  - An emissions trading system with no further allocation of emission allowances could still be possible if CDR can be used to offset the residual emissions.

Global revenue forecast for carbon storage and removal markets



- While both markets are expected to grow, the global mandatory carbon markets (MCM), which is currently worth $818.92 billion, is much larger than the global voluntary carbon markets (VCM), which is worth $2.00 billion.
- MCM: market growth linked to rising carbon prices driven by increased demand and new government regulations to attain climate targets. Concerns regarding energy affordability and security temper the growth.
- VCM: Very small compared to MCM. Tighter regulations focused on supply and demand may transform the offset market into a burgeoning commodity market.





Source: Frost & Sullivan: Carbon Markets: Trends and Growth Opportunities (2024)

Demand for voluntary carbon markets and foreseeable unit price levels

- International carbon markets are potentially a very powerful tool for mobilizing carbon dioxide removal (Honegger et al. 2023).
- Carbon removal certification framework is laying the foundation for high quality removals in the voluntary markets.
- To date, Microsoft (6.6MtCO_2) and the state of Denmark (1.1MtCO_2) are the biggest buyers of permanent carbon removals (CDR.fyi)
  - Largest sellers are Stockholm Exergi (3.3MtCO_2) and Ørsted (2.7MtCO_2), both BECCS projects.
  - Around 10 suppliers for removals based on mineralization.
- Cost indices of removal units are not always reliable. CDR.fyi report that only 15% of the cases the price is public.
  - In 2023, price of BECCS was 300$/t$CO_2$ and price of DACCS $715/t$CO_2$.

Article 6 of the Paris Agreement as a possible framework for value creation

- Article 6 of the Paris Agreement recognizes that Parties can pursue voluntary cooperation to the ambition of their Nationally Determined Contributions (NDCs) to climate change mitigation (UNFCC, 2024)
- Under Paris Agreement Article 6, Parties may authorize International Transferred mitigation outcomes (ITMO), such as carbon removals.
- Authorization includes a commitment by the first transferring Party (or project host country) to make a corresponding adjustment to their emissions balance, as well as reporting requirements for participating Parties, who obtain the removal units as ITMOs (OECD 2022).
- In practise, this mechanism links national interests to the voluntary emission trading markets within the context of the UN climate agreement targets.

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Financial models to incentivise high quality carbon removals

- Möllersten et al 2023 discuss the four main options to support BECCS in the Nordic setting, which in principle applies also to other permanent carbon removal options:
  - **State guarantees**: The state buys the mitigation outcome, for instace using reverse auctioning of removal units.
  - **Quota obligation for selected sectors with GHG emissions**: The State gives obligation to companies to purchase an amount of carbon removal credits proportionate to their fossil emissions.
  - **Allowing participants in the EU ETS to use BECCS credits**: Emissions within ETS can be off-setted by carbon removal credits. Would require further adjustments to avoid mitigation deterrence.
  - **Private entities for voluntary use of carbon credits**: Carbon removals are voluntarily paid by companies and individuals purely by will to contribute to climate change mitigation.
  - **Other states as buyers**: States directly or indirectly purchase Internationally Transferred Mitigation Outcomes (ITMOs) from another Paris Agreement.

Experiences and plans for government auctions for carbon removals

Experiences and plans for government auctions for carbon removals - Sweden

The main principle:

- Sweden aims to conduct a reverse auctioning, where the state pays subsidies to the operator that produces negative emissions at the lowest cost.
- Only bio-CCS projects where carbon dioxide is stored in geological reservoirs will initially be accepted for the reverse auction in Sweden.
  - Companies with bio-based carbon dioxide emissions from CHP plants, paper or pulp production or other industrial plants can participate in the transaction.
  - The inclusion of biochar in the deal had also been investigated, but it had been excluded for the time being due to the small size of the project and difficulties in verification.
- A 15-year support period is planned.
- The Energy Authority's preliminary recommendation is that the bids in the first auction amount to at least 50,000 tonnes of carbon dioxide.

Timetable:

- The transaction was supposed to start in 2022, but the start has been delayed due to the preparation and study of the support scheme and the necessary approval from the European Commission.
- At the moment, it is estimated that the transaction can be started no later than 6 months after the EU Commission has announced its decision on the state aid scheme.

Experiences and plans for government auctions for carbon capture - Denmark

- State of Denmank is funding CCUS and BECCS through two connected funds CCUS Fund and NECCS Fund.

CCUS Fund (Ministry of foreign affairs of Denmark)**:**

- In first phase, DKK 8 billion to achieve an annual reduction of 0.4 million tons of CO2 from 2025/2026 and onwards. A maximum of DKK 815 million per year can be disbursed to recipients.
- The CCUS Fund is a technology-neutral fund aimed at supporting carbon capture, storage and utilization in two phases. The first disbursement from the fund is planned to be from 2025/2026.
- The funding would cover the costs of CCS at all stages of the value chain from capture to storage. Funding is given per tonne of CO_2 captured and permanently stored.
- Energy company Ørsted was awarded to establish carbon capture at its wood chip-fired Asnæs Power Station in Kalundborg in western Zealand and at the Avedøre Power Station's straw-fired boiler in the Greater Copenhagen area.

Negative Emissions Carbon Capture and Storage (NECCS) Fund:

- DKK 2.5 billion to achieve 0.5 million tons of CO_2 reductions annually from 2025 to 2032.
- Open for bidding until 1 December 2023, focused on realizing negative CO_2 emissions through support to biogenic CO_2 sources.
- $24 million of financial support annually between 2026 and 2032 was awarded to three companies for carbon capture and storage projects that aim to handle 160,350 tonnes per annum of CO_2.

Green Transformation Scheme (GSR) + CCUS Fund Phase 2:

- Bidding rounds in June 2024 and June 2025, to achieve capture of a minimum of 0.9 million tons (June 2024) and 1.4 million tons annually (June 2025).

Summary

General summary

- **CCUS Market:** The global carbon capture, utilization and storage technology market is growing. Based on the market forecast review, stored volumes of CO_2 are anticipated higher than utilized volumes globally.
- **CCU Products:** The most promising CCU pathways include construction aggregates, CO_2-cured concrete, e-kerosene and e-methanol.
- **CCU Adoption:** The high cost of CCU products compared to conventional alternatives is a major barrier to adoption. Investments and efforts are needed to advance the commercial viability and large-scale deployment of the technologies.
- **Policy Support:** Effective policy measures, including financial incentives, regulatory frameworks, and market-based mechanisms, are critical in advancing CCUS technologies towards commercial deployment. The EU Commission’s communication on Industrial Carbon Management strategy and the introduction of the Carbon removal and carbon farming certification framework are show the ambition to make a business case for both utilization and storage of biogenic CO_2 in Europe.
- **CCU Potential:** Estimates of the size of the CO_2 utilization market in the future vary widely, from between 10%-33% of total captured carbon. In EU, climate and carbon management targets increase the predictability of CCU demand in especially synthetic fuels.

CCU potential from the product market size and volume aspect

- CCU products provide vast opportunities in the future, the annual capacity for captured CO_2 utilization is expected to increase dramatically from 1.4 Mtpa in 2022 to 171.2 Mpta in 2040 growing with a CARG of 30.8 % between 2022 and 2040. Depending on the sources, the CCU market's projected value is expected to reach USD 10.75 -USD18 billion by 2030-2032.
- Building materials (aggregates & precasted concrete) and fuels (e-kerosene & e-methanol) demonstrate the highest market potential and CO_2 utilization potential. The building materials are already in the early adoption / deployment stage while synthetic fuels and methanol still need significant development. For example, producing synthetic fuels from CO_2 requires significant energy inputs and infrastructure limiting its near-term adoption.
- According to estimates, the majority of the globally captured CO_2 will be most likely stored rather than being used in 2050 and 2070 due to factors such as the volume of emissions, technological maturity of CCS technologies over CCU technologies and due to economic viability as storing CO_2 is often more cost-effective than converting it into products. Furthermore, the market for products derived from CO_2 is still emerging. This became also evident during this market analysis, as far more market information is available for CCS than CCU.

Sources: Market Data Driven Decisions (2024), Verde.ag (2023)

CCU potential in Finland

- Based on conservative assumptions, approximately 8 Mton/year of CO_2 could be utilized for CCU products by 2040.
- The amount would equal 2 - 3 Mton/a of CCU products, consisting mainly of organic products i.e. e-fuels and polymers)
- Due to Refuel Aviation and Maritime regulations, a strong market pull for e-jet and e-methanol is assumed.
- With a stronger growth after 2035, e-jet could be the CCU product of highest production volumes in Finland.
- Most of the captured CO_2 would be utilized for e-jet and e-methanol in the assumed outlook.

Work package 3:

Implications for Finland, investment prospects, possible policies and proposals for code of conduct

Juha Lehtonen, Sampo Mäkikouri, Lauri Kujanpää

Objectives

1. Estimate the emission reduction potential in Finland and other climate impacts based on Work package 2 scenarios for production volumes of CCU-products in 2030, 2035 and 2040.
2. Estimate the impacts of CCU-production on reduced fossil raw material imports, hydrogen demand and renewable electricity required for CCU. Review the geographic distribution of green hydrogen production and large CO_2 point sources in Finland.
3. A light assessment on the impact on national economy and employment. An in-depth analysis is not possible given the time and budget constraints.

Scenarios of production volumes - Assumptions

- A target for the production of jet fuel in Finland to cover 20 % of EU:n demand by 2040 => production ~ 1 Mton/a
- Let's assume ~ 3 Mton/a demand for maritime e-fuels by 2040 in the EU
  - Methanol used in the calculations
  - 20 % of that amount to be produced in Finland ~ 0,6 Mton/a
- Road transport: domestic demand 20 % of current consumption for diesel engines (~ 0,2 Mton/a e-diesel + e-methane) and 10 % demand of current consumption for otto engines (~ 0,1 Mton/a e-gasoline + emethane)
- Some production of inorganic materials by 2030
  - Production volume could be ~ 0,5 Mton/a by 2040
- Production of organic polymers from 2035
  - Production volume could be ~ 0,2 Mton/a by 2040

Scenarios of production volumes of observed products 2030 - 2040

Fuels		2030	2035	2040
e-jet	Produced amount Mton/a	0	0,1	1
e-methanol	Produced amount Mton/a	0,05	0,2	0,6
Road transport diesel engines	Produced amount Mton/a	0,05	0,1	0,2
Road transport Otto engines	Produced amount Mton/a	0,05	0,1	0,1
Chemicals and materials				
Polymers	Produced amount Mton/a	0	0,05	0,2
Inorganic fillers	Produced amount Mton/a	0,1	0,2	0,4
Concrete & aggregates	Produced amount Mton/a	0,02	0,06	0,24
	Production total Mton/a	**0,2**	**0,6**	**2,3**

Domestic use of CCU products and emission reduction potential and other climate impacts

Domestic use of CCU products and domestic emission reduction potential - Introduction

- Following domestic use assumed by 2040:
  - ~ 20 % aviation fuels consumption replaced with e-fuels (200 kton/a)
  - Marine fuels: 50 % of the amout of produced marine e-fuels consumed in Finland ~ 0,3 Mton/a (methanol)
  - Road transport: domestic demand 20 % of current consumption for diesel engines (~ 0,2 Mton/a e-diesel + e-methane) and 10 % demand of current consumption for otto engines (~ 0,1 Mton/a e-gasoline + e-methane)
  - All produced inorganic materials for domestic use (~ 0,5 Mton/a)
  - 50 % organic polymers for domestic use (0,1 Mton/a)
- Replacement of fossil products:
  - 100 % replacement assumed for fuels expect for methanol ~ 40 % (due to lower energy content of methanol

Domestic use of CCU products and domestic emission reduction potential - Introduction

Replacement of fossil products:

- 100 % replacement assumed for fuels expect for methanol ~ 40 % (due to lower energy content of methanol)
- 100 % replacement assumed for polymers
- 0 % replacement assumed of inorganic products

- GHG savings in Finland
  - GHG intensities of the fossil products obtained from the litterature
  - GHG intensities of CCU-products from the litterature and from VTT projects
  - Different heating values of the fuels taken into account (when converting from MJ-based intensities to ton-based intensities)

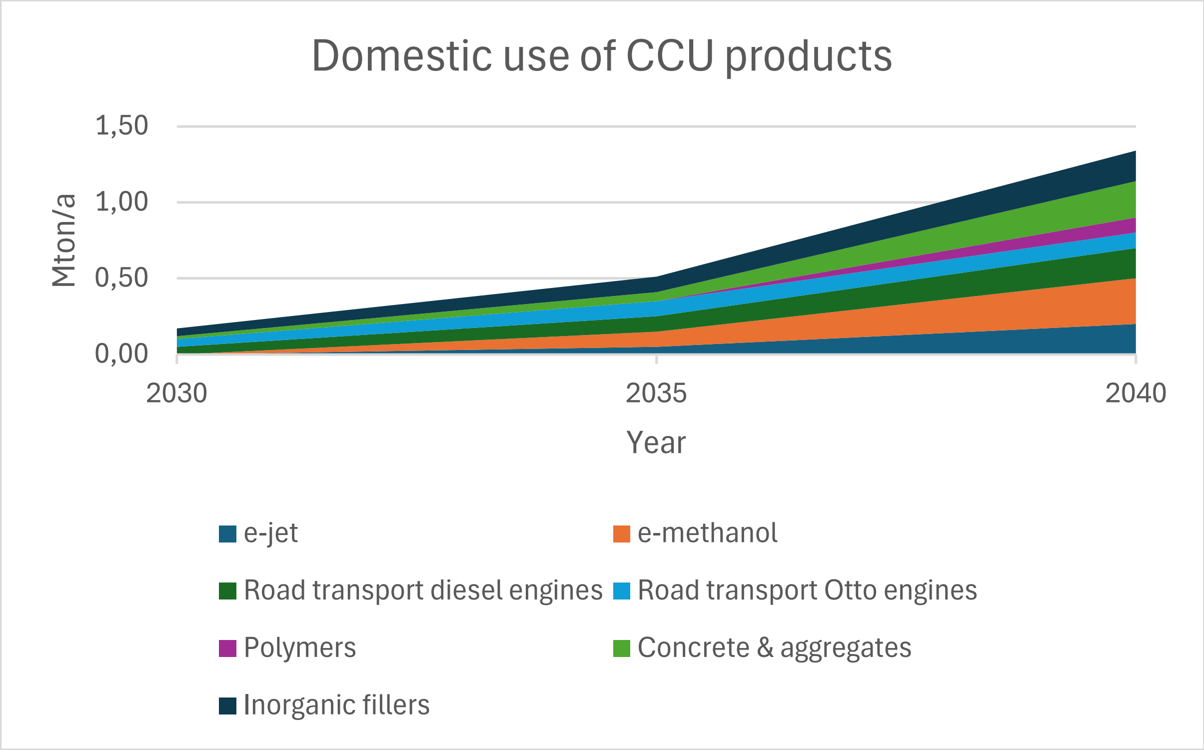
Assumptions used in the calculations

- Heating values:
  - Diesel: 45,6 MJ/kg
  - Gasoline: 46,4 MJ/kg
  - Jet fuel: 43,0 MJ/kg
  - Methanol: 19,7 MJ/kg
- GHG intensity:
  - Fossil diesel: 95,1 gCO2eq/MJ
  - Fossil gasoline: 93,3 gCO2eq/MJ
  - Fossil jet fuel: 94, 0 gCO2/MJ
  - Fossil polyolefins: 2,5 kgCO2/kg
  - E-diesel: 10 gCO2eq/MJ
  - E-gasoline: 10 gCO2eq/MJ
  - E-jet: 10 gCO2eq/MJ
  - CCU-polyolefins: 2,5 kgCO2/kg
  - Methanol: 4,4 gCO2eq/MJ

- Correspondence of the products:
  - Fossil diesel => e-diesel (similar properties assumed)
  - Fossil gasoline => e-gasoline (similar properties assumed)
  - Fossil jet fuel => e-jet (similar properties assumed)
  - MDO (Marine diesel oil, properties of EN590 diesel assumed) => e-methanol (different heating values and thus consumptions taken into account)
  - Fossil polyolefins => CCU-polyolefins (similar properties assumed)

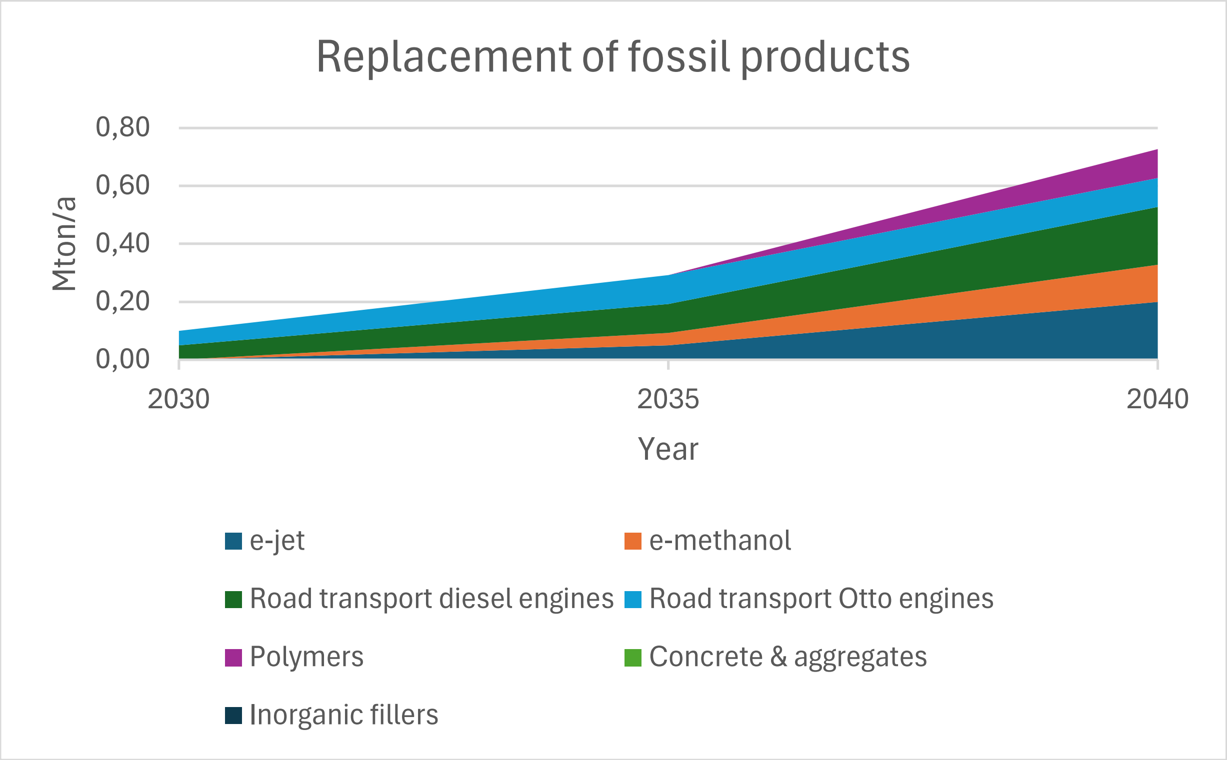
Sources:
https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emission-intensity-of
https://www.methanol.org/wp-content/uploads/2022/01/CARBON-FOOTPRINT-OF-METHANOL-PAPER_1-31-22.pdf
Previous VTT studies

Scenario of domestic use of CCU products

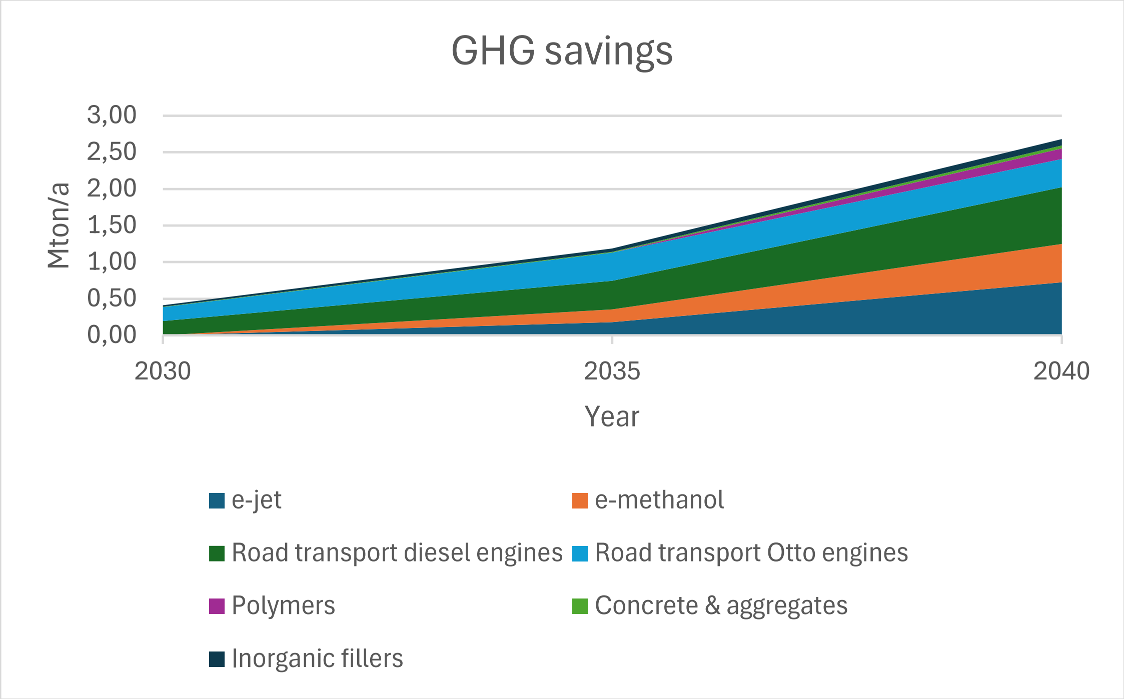


- Assumptions of the domestic use were given at the end of WP2

Scenario of domestic replacements of fossil products



Scenario of GHG savings in Finland



Domestic replacement of fossil products & GHG savings

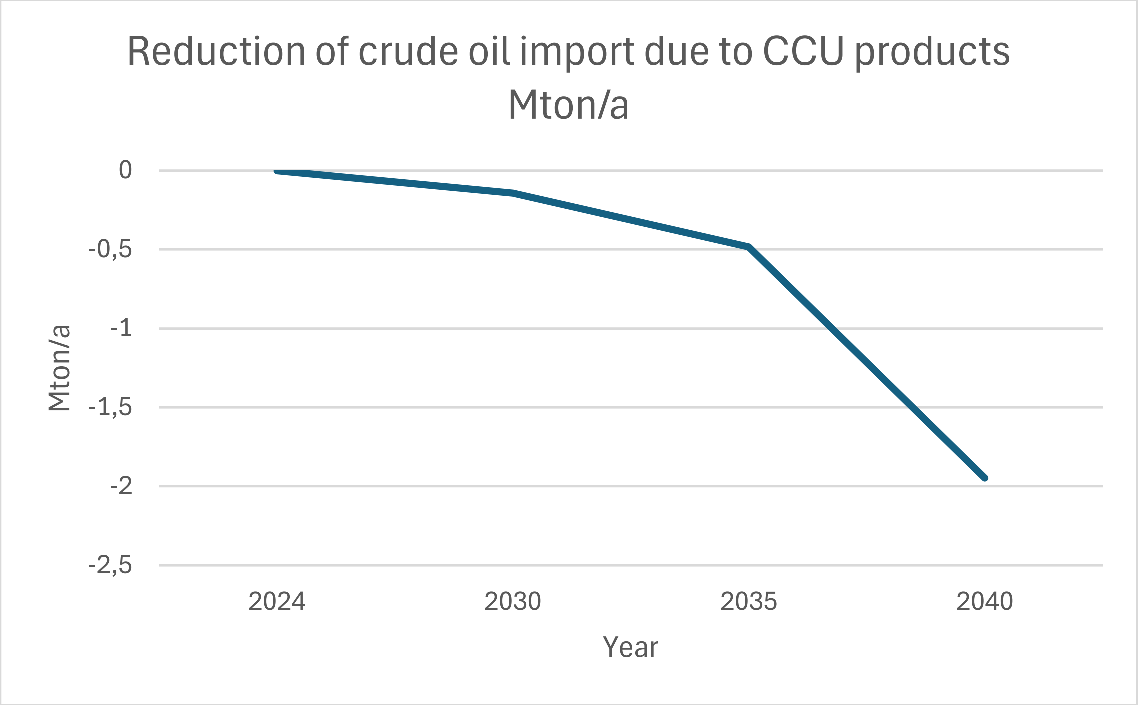
- Replacement of fossil products 2040 e.g. ~ 20 % of current use of fuels in road transport (Autoalan Tiedotuskeskus, 2024)
  - However, there will be many other reasons why fossil products will be replaced as well by 2040 (some of those reasons same as presented on page 16)
- GHG savings due to use of CCU products will be ~ 9 % of current fossil CO_2 in Finland (Motiva, 2024).
- Exported CCU-products can have a large carbon handprint towards lowering CO_2 emissions in the EU/global markets.

Impact of CCU-production on reduced import of fossil raw materials, hydrogen demand and transportation of H_2 and CO_2

Impact of CCU-production on reduced import of fossil raw materials and hydrogen demand - Introduction

- Reduced import of crude oil based on CCU-products volumes replacing fossil-based
  - Assumptions on the next page
- Hydrogen demand for CCU-products calculated based on recent projects by VTT
- Green hydrogen and electricity production regionally compared to hydrogen demand
- Pipeline transportation needs of hydrogen vs. carbon dioxide in Finland

Scenario - Impact on the demand of imported oil products (crude oil)



Assumptions:

- All e-fuels and polymers in the scenarios included
- All production of e-fuels and half of the production of CCU-polymers will directly replace corresponding fossil production
- For fossil fuels and polymers 0,85 ton of a product is assumed from 1 ton of crude oil

Impact on the demand of imported oil products

- Impact by 2040 15 – 20 % of current import of fossil oil products (10 – 12 Mton/a)
- However, the import of the oil products will probably decrease also by other reasons:
  - Electrification of (light) road transport => highest reduction in gasoline demand
  - Improved energy efficiencies of ICE vehicles
  - Abandoning fossil fuels in heat & power
  - Abandoning fossil feedstocks in oil refining industry (Porvoo refinery)

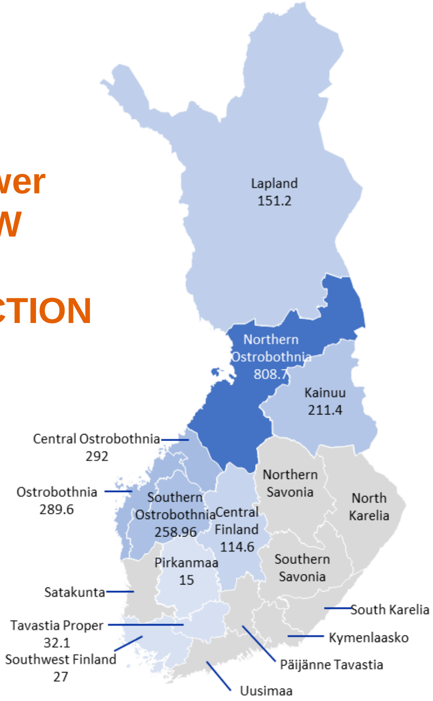
Renewable electricity and hydrogen production, hydrogen and CO_2 transportation

NEW WIND POWER GENERATION IN FINLAND

New Wind Power Capacity in MW

IN CONSTRUCTION OR ON-LINE

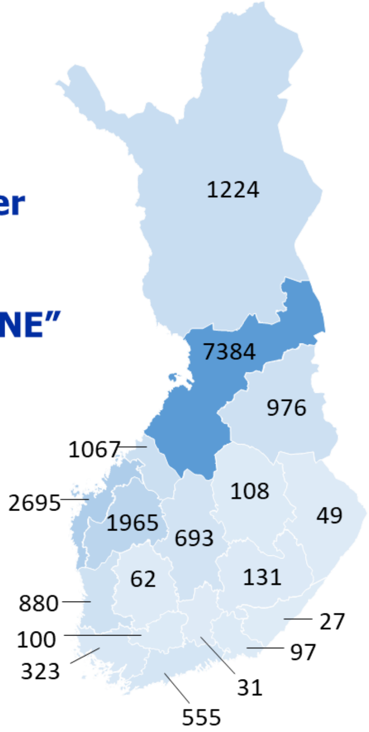
2019-2023



New Wind Power Capacity in MW

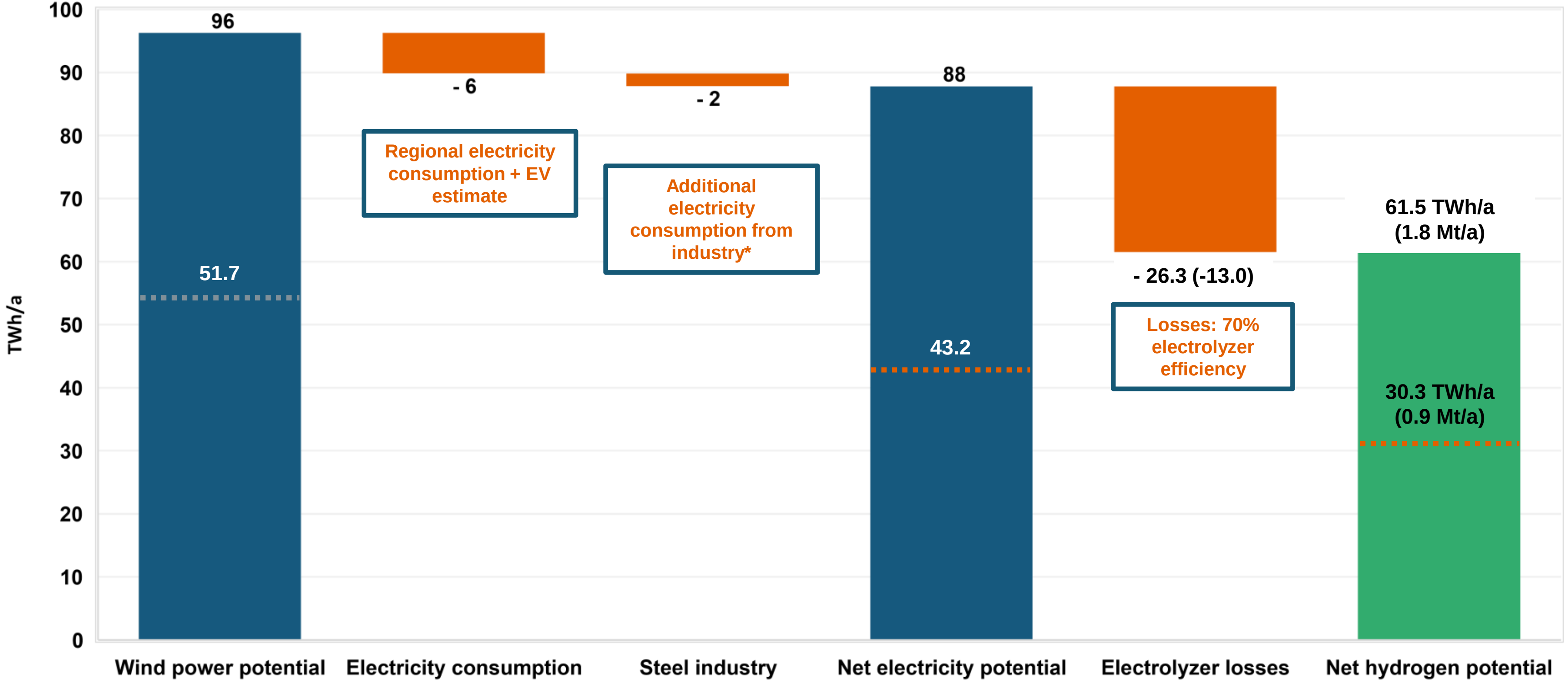
IN THE "PIPELINE"

	GW
Onshore	15.8
Offshore	2.7
in Total	18.5



Laurikko, J., Hydrogen roadmap for Finland, November 2020

Example: Hydrogen production potential in the Northern Ostrobothnia region

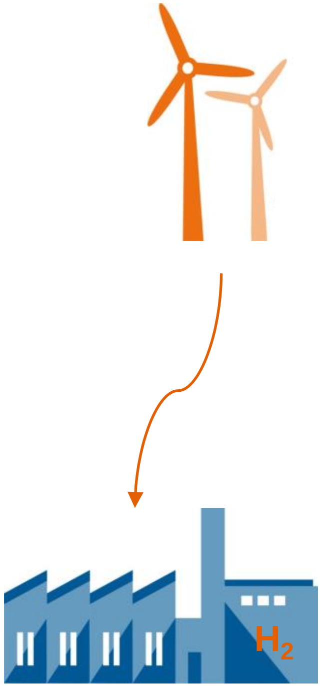


Kiviranta, K. Hopsu, J., Kanto, T., Saarikoski, A., Kärki, J., Lehtonen, J., 2023, Pre-study on transition to hydrogen economy in Finland, specifically in Northern Ostrobothnia, VTT

* Includes additional electricity consumption from electric arc furnaces in SSAB Raahe steel mill, it is expected that there will be further electrification in industry > not in the scope of this study

Example: Hydrogen production and demand potential in Northern Ostrobothnia

- Based on the applied assumptions, hydrogen production potential **(30-62 TWh/a** and **0.9-1.8 Mt/a)** in Northern Ostrobothnia is significant
  - Current hydrogen production in Finland and Northern Ostrobothnia is app. **5 TWh/a** and **0.2 TWh/a**
- Hydrogen production requires demand. The regional demand estimated to be **0.4 Mt/a (15 TWh)**
- Finnish Government adopted a resolution on hydrogen with the target to produce 10% of EU's renewable hydrogen in 2030 : **1 Mt/a (33.6 TWh/a)** of hydrogen in 2030 [1]
  - This amount of hydrogen could potentially be produced in Northern Ostrobothnia
- Northern Sweden's hydrogen demand to exceed **20 TWh** by 2030, while the hydrogen production in the region is estimated to only reach 7.7 TWh by 2030 [2]
  - Hydrogen demand in Northern Sweden could accelerate hydrogen production also in Northern Ostrobothnia and in Finland



[1] Ministry of Economic Affairs and Employment, 2023. Government adopts resolution on hydrogen – Finland could produce 10% of EU's green hydrogen in 2030 Available: https://valtioneuvosto.fi/en/-/1410877/government-adopts-resolution-on-hydrogen-finland-could-produce-10-of-eu-s-green-hydrogen-in-2030
[2] Vendt, M., Wallmark, C. (2022). Prestudy H2ESIN: Hydrogen, energy system and infrastructure in Northern Scandinavia and Finland. RISE Research Institute of Sweden & Luleå University of Technology Available: http://urn.kb.se/resolve?urn=urn:nbn:se:ri:diva-61532

Hydrogen pipelines

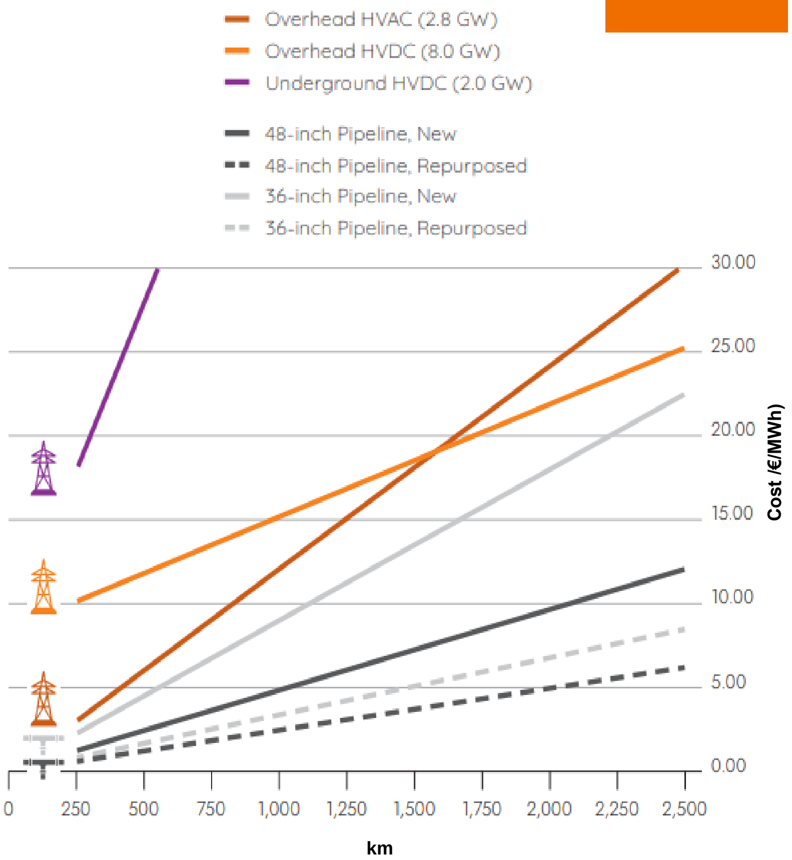
- Can be constructed in the same way as natural gas pipelines
  - Hydrogen more challenging for materials =>investment of hydrogen pipelines 10 – 50 % more expensive than natural gas pipelines
- Typical diameter: 500 – 1200 mm
- Typical pressure: 50 – 80 bars
- When using large pipelines (1200 mm), transportation cheaper than transmission of electricity

https://urn.fi/URN:NBN:fi:oulu-202207123249

Pre-study on transition to hydrogen economy, specifically in Northern Ostrobothnia (vtt.fi)

Hydrogen transmission

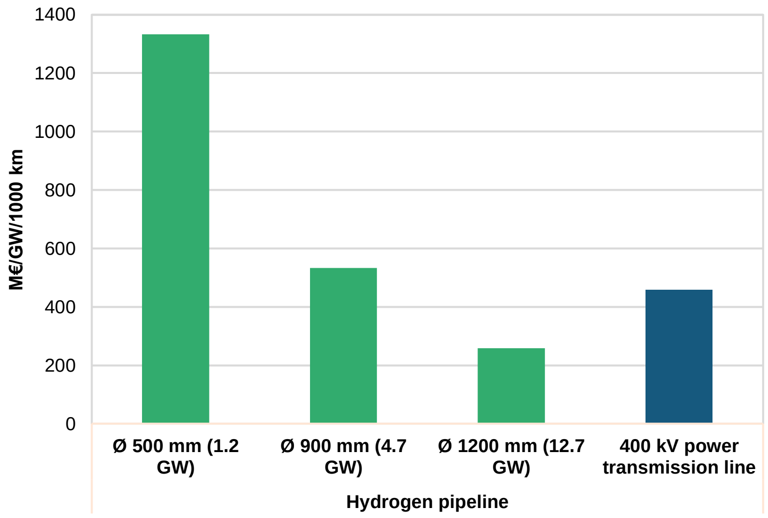
- Hydrogen production via electrolysis can take place either at the site where electricity is generated or at the site where hydrogen demand exists
  - Energy can be transmitted to the demand site as electricity or as hydrogen
- The size of hydrogen main pipelines is **1200 mm**
  - Large-scale hydrogen transmission via new pipeline is more cost-effective at any distance for a 1200 mm pipeline in comparison to new power lines



EHB, 2021. Analysing future demand, supply, and transport of hydrogen. Available: https://ehb.eu/files/downloads/EHB-Analysing-the-future-demand-supply-and-transport-of-hydrogen-June-2021-v3.pdf

Hydrogen transmission

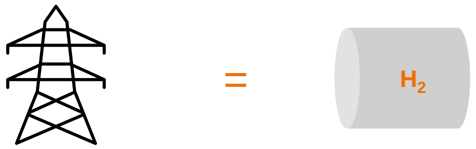
- Calculations by Fingrid and Gasgrid suggest that investing to a **1200 mm pipeline** results in a lower cost compared to a **400 kV power transmission line**
- However, wind power projects are scattered and can be far away from main pipelines
- Producing hydrogen at the locations of wind power plants, a branching pipeline could be connected to the main pipeline on the coast
  - However, this pipe would be smaller with higher relative CAPEX



Source: Adapted from Fingrid Oyj & Gasgrid Finland Oy (2022). Väliraportti: Energian siirtoverkot vetytalouden ja puhtaan energiajärjestelmän mahdollistajina.

Hydrogen transmission

- Large-scale hydrogen transmission is more **land-use efficient** than power grid transmission, which can impact **social acceptance**
- According to Fingrid and Gasgrid one pipeline of 1200 mm can transmit energy equivalent to 15 pcs of 400 kV power lines
- **By-product utilisation**: hydrogen production via electrolysis also produces oxygen and heat as a by-product
  - Generating revenue from heat from electrolysis can affect the siting of hydrogen production, potentially impacting transportation needs



15 pcs 400 kV lines = 1200 mm pipeline

Fingrid Oyj & Gasgrid Finland Oy (2022). Väliraportti: Energian siirtoverkot vetytalouden ja puhtaan energiajärjestelmän mahdollistajina. Available: https://gasgrid.fi/wp-content/uploads/Fingrid-Gasgrid_Valiraportti_Energian-siirtoverkot-vetytalouden-ja-puhtaan-energiajarjestelman-mahdollistajina.pdf

CO_2 pipelines

- Typically transported in dense or in supercritical phase (a highly compressed fluid that demonstrates properties of both a liquid and a gas)
- Typical conditions: 110 – 150 bar pressure and temperature close to ambient (dense) or above 40 ºC (supercritical)
- Typical diameters of pipelines: 150 – 900 mm

https://urn.fi/URN:NBN:fi-fe2023062057124

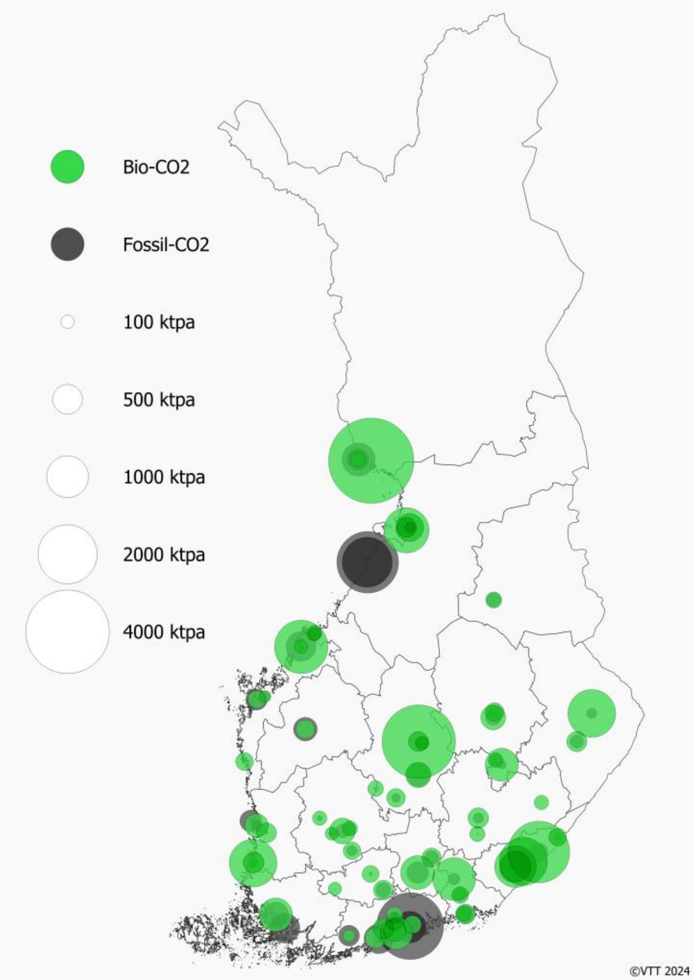
Transportation of carbon dioxide vs. hydrogen

- Case example:
  - Green hydrogen production in Kokkola region and CO_2 capture in Äänekoski, distance ~ 200 km
  - 200 kton/a e-fuel production either in Kokkola or Äänekoski
    - CO_2 demand: ~ 800 kton/a
    - H_2 demand: ~ 100 kton/a
- Estimation of annual transportation costs based on Oona Tuomisto master’s thesis
  - CO_2: 9,3 MEUR/a
  - H_2: 11,4 MEUR/a

https://urn.fi/URN:NBN:fi-fe2023062057124

Many large point-sources of CO_2 at the coast of Finland

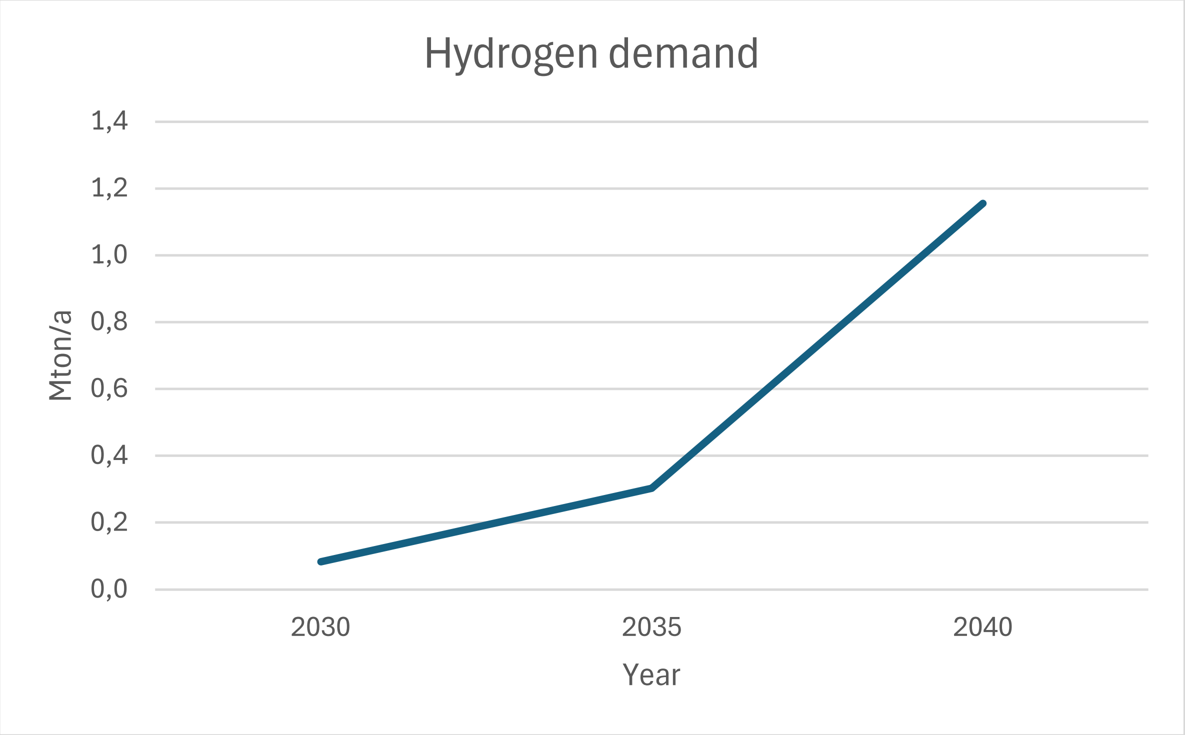
- The coastal location of a CO_2 point source gives the advantage of considering shipping for transportation.
- Especially in the mid-term, shipping of CO_2 is the likely alternative for long-distance tranportation of large volumes of CO_2, especially regarding CCS.
- Many projects in Europe form "CO_2 hubs", connecting emitters from a region to a CO_2 utilisation and/or storage site.
- In addition to pipelines, transportation by rail and truck can be considered for inland transportaion.



CO2 emissions in industrial facilities with annual emissions of >100 ktCO2.
Based on 2022 data of the European Pollutant Release and Transfer Register (EEA 2023, published on 12/2023), which has been updated manually in terms of missing data.

Scenarios for hydrogen and power demand

Scenario – Green hydrogen demand 2030 - 2040

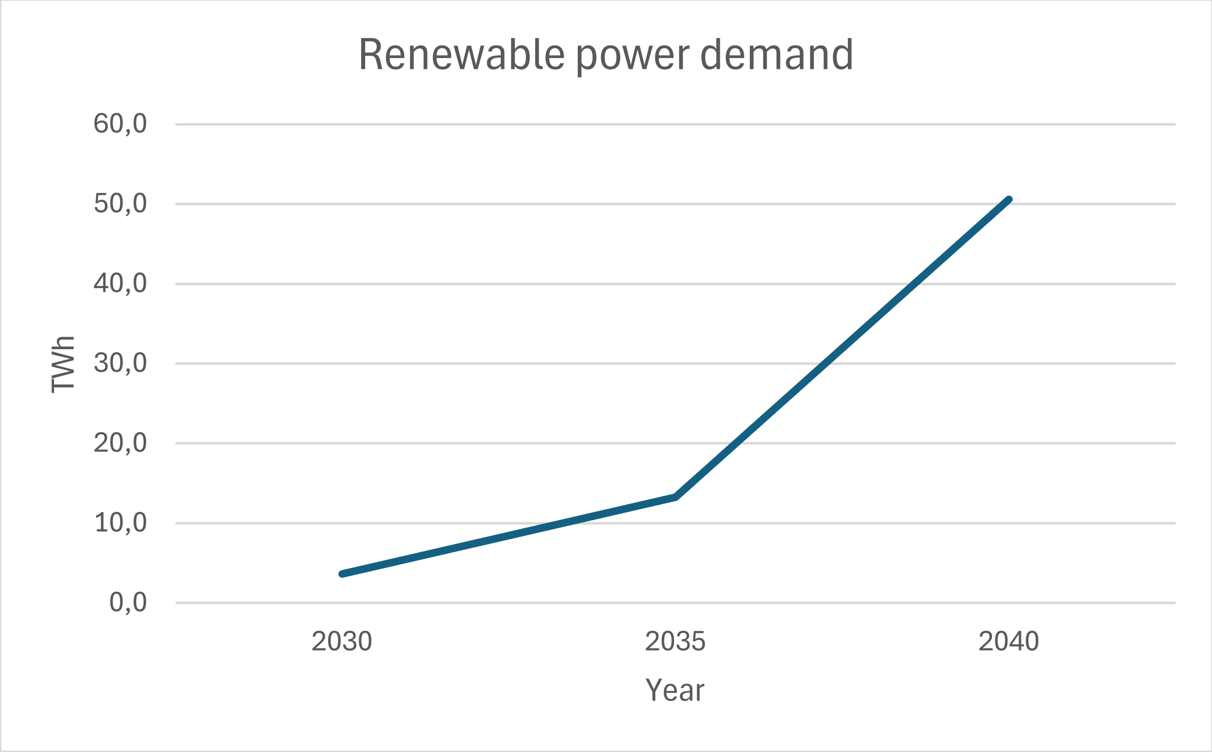


Assumptions:

- Hydrogen needed for e-fuels and CCU-polymers: 0.55 ton H_2 / ton product

Source: Based on values calculated for e-jet and e-gasoline in the E-fuel Business Finland project.

Scenario – Renewable power demand 2030 - 2040



Assumptions:

- Power needed for e-fuel and CCU-polymer products: 24.1 TWh / Mton product

Source: Based on values calculated for e-jet and e-gasoline in the E-fuel Business Finland project.

- Precast concrete, aggregates and fillers not included in power demand (no need for hydrogen, low energy demand).

Green hydrogen and renewable power demand - Summary

- There is a high expected potential of renewable wind power and green hydrogen production being enough for the production anticipated CCU-product volumes by 2040
- However, realization of new renewable power investments will require PPA contracts between renewable power vs. green hydrogen/P2X/CCU production investors
  - Realization of green hydrogen investments also require contracts between green hydrogen vs. P2X/CCU production investors
- Green hydrogen production (assumed close to wind power) and large biogenic CO_2 sources does not fully meet each other geographically in Finland
  - Pipeline transportation of either hydrogen or CO_2 needed
  - Cost of those options seem to be quite equal => Selection to be made case by case

Impacts on national economy

Impacts on national economy

- Number of new or retro-fitted production facilities based on production volumes in the scenarios
- Two plant sizes (”Plant size 1” and ”Plant size 2”) included with separate production volumes and investment costs
- Direct employment effects of the new facilities and a rough estimate for impact along the value chain based on construction work
- Economic impact of the required CCU and hydrogen production investments (investments on renewable electricity production excluded) and value of annual production
- The presented numbers of plants, production volumes, investment costs and numbers of employees should be considered as indicative rough estimates.

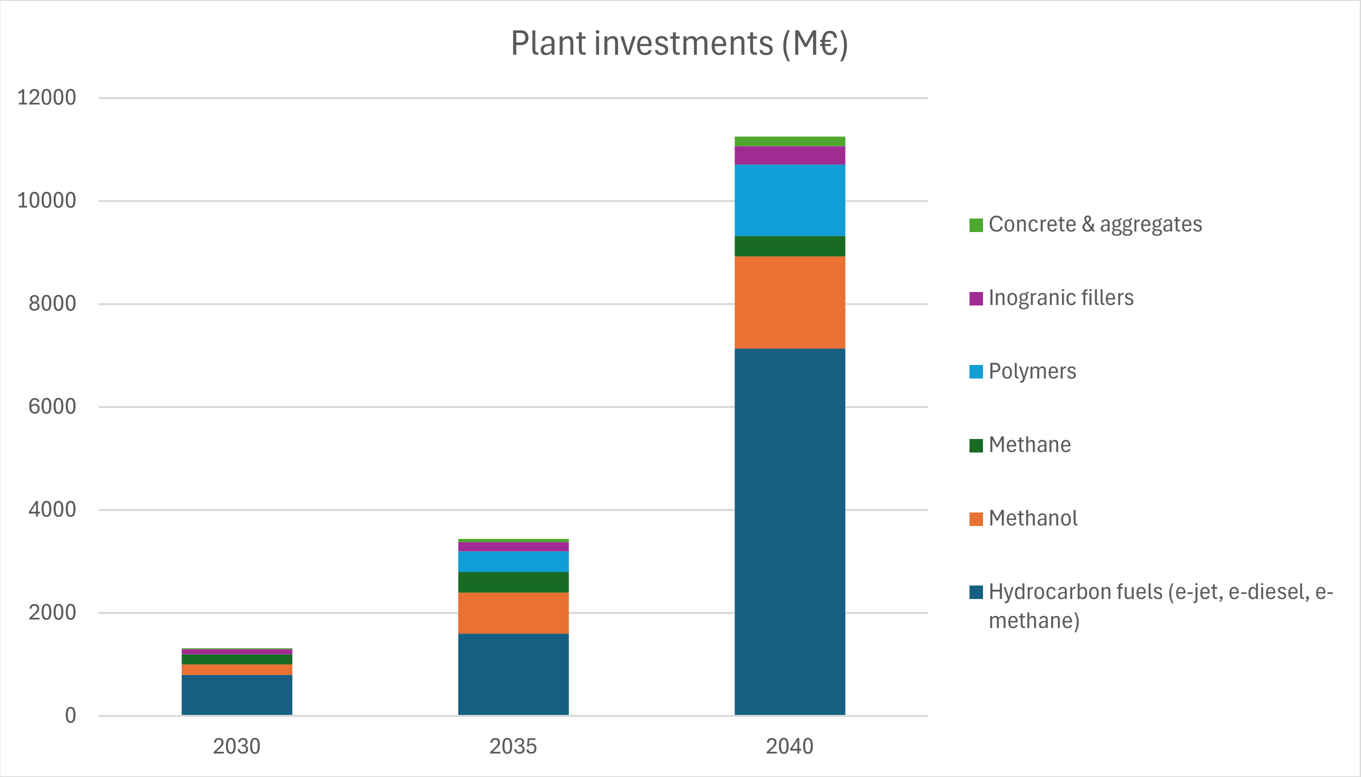
Assumed plant sizes, investment costs and personnel count per plant

	Plant size 1 Mton/a	Plant size 2 Mton/a	Plant investment, size 1, MEUR	Plant investment, size 2, MEUR	Personnel, plant size 1	Personnel, plant size 2
Hydrocarbon fuels (e-jet, e-diesel, e-methane)	0,1	0,4	800	1970	40	90
Methanol	0,05	0,2	200	492	30	60
Methane	0,05	0,1	200	314	30	40
Polymers	0,05	0,2	400	985	30	60
Inorganic fillers	0,05	0,1	50	78	30	40
Concrete & aggregates	0,02	0,05	20	36	20	30

Assumed total number of plants

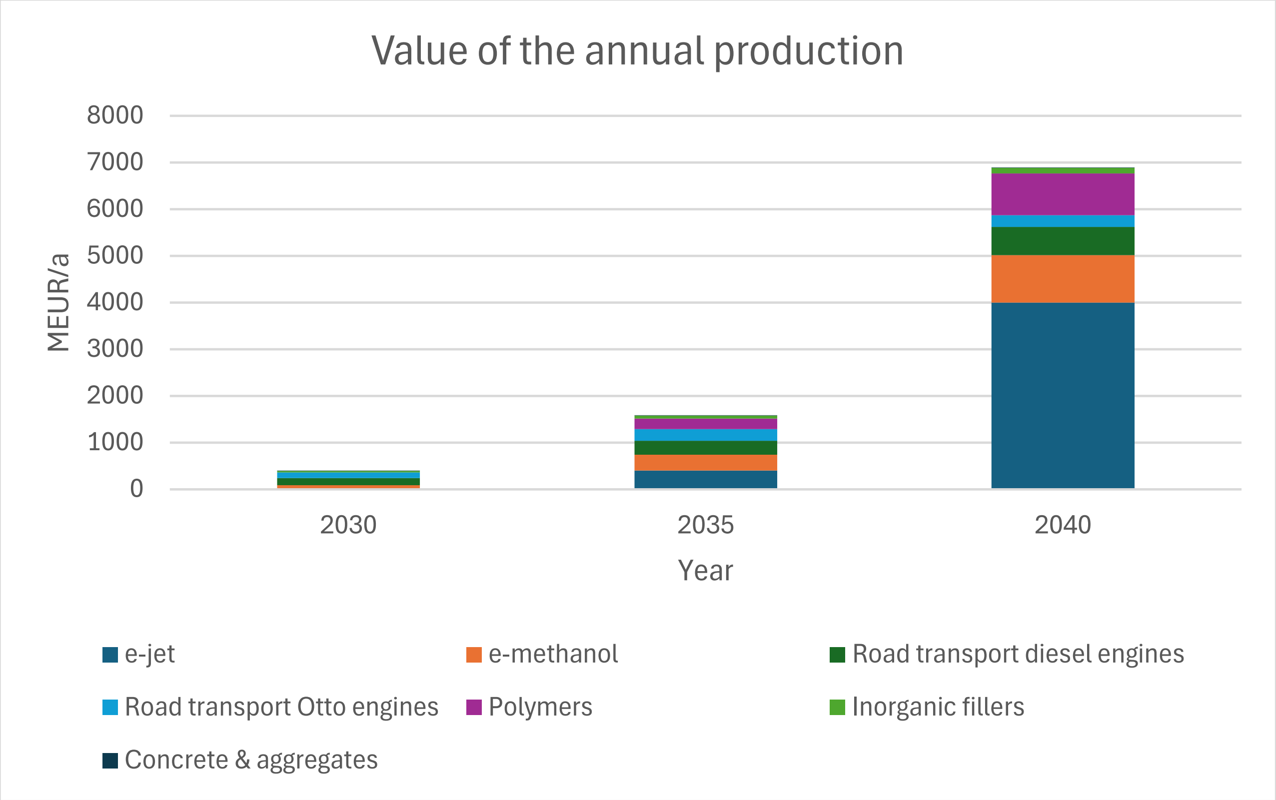
	Plant size 1 (2030)	Plant size 2 (2030)	Plant size 1 (2035)	Plant size 2 (2035)	Plant size 1 (2040)	Plant size 2 (2040)
Hydrocarbon fuels (e-jet, e-diesel, e-methane)	1	0	2	0	4	2
Methanol	1	0	4	0	4	2
Methane	1	0	2	0	2	0
Polymers	0	0	1	0	1	1
Inorganic fillers	2	0	2	1	4	2
Concrete & aggregates	1	0	3	0	4	3
	6	**0**	**14**	**1**	**19**	**10**
Plants total number		**6**		**15**		**29**

Plant investments



- CCU and hydrogen production investments
- Investments on renewable electricity production excluded

Value of the manufactured CCU products



Assumed product prices (EUR/ton):

- e-jet 4000
- methanol 1700
- Road diesel 3000
- Road gasoline 2500

- Polymers 4500
- Inorganic fillers 300
- Concrete & aggregates 30

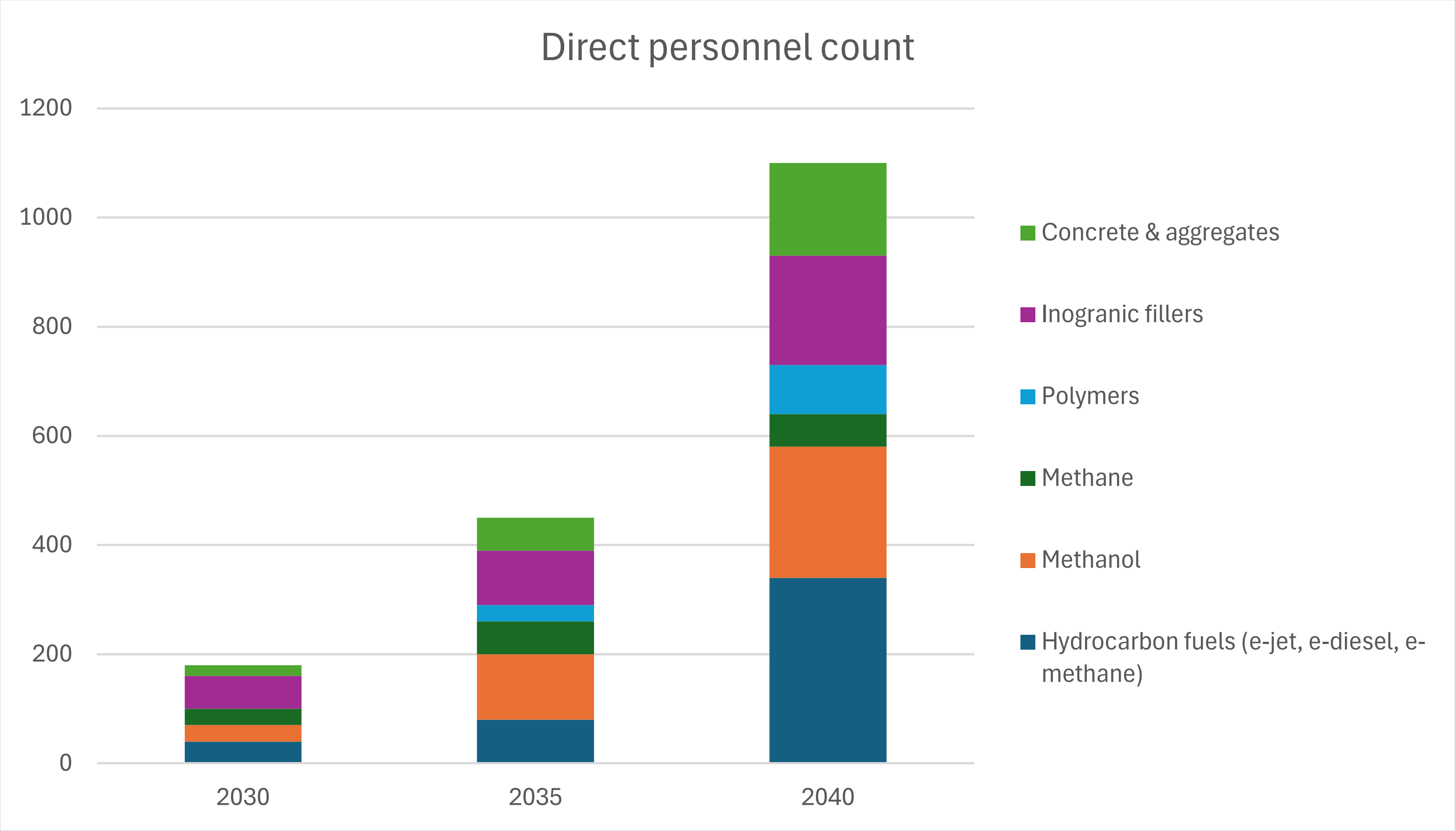
Key assumption and observations on investments and annual production value

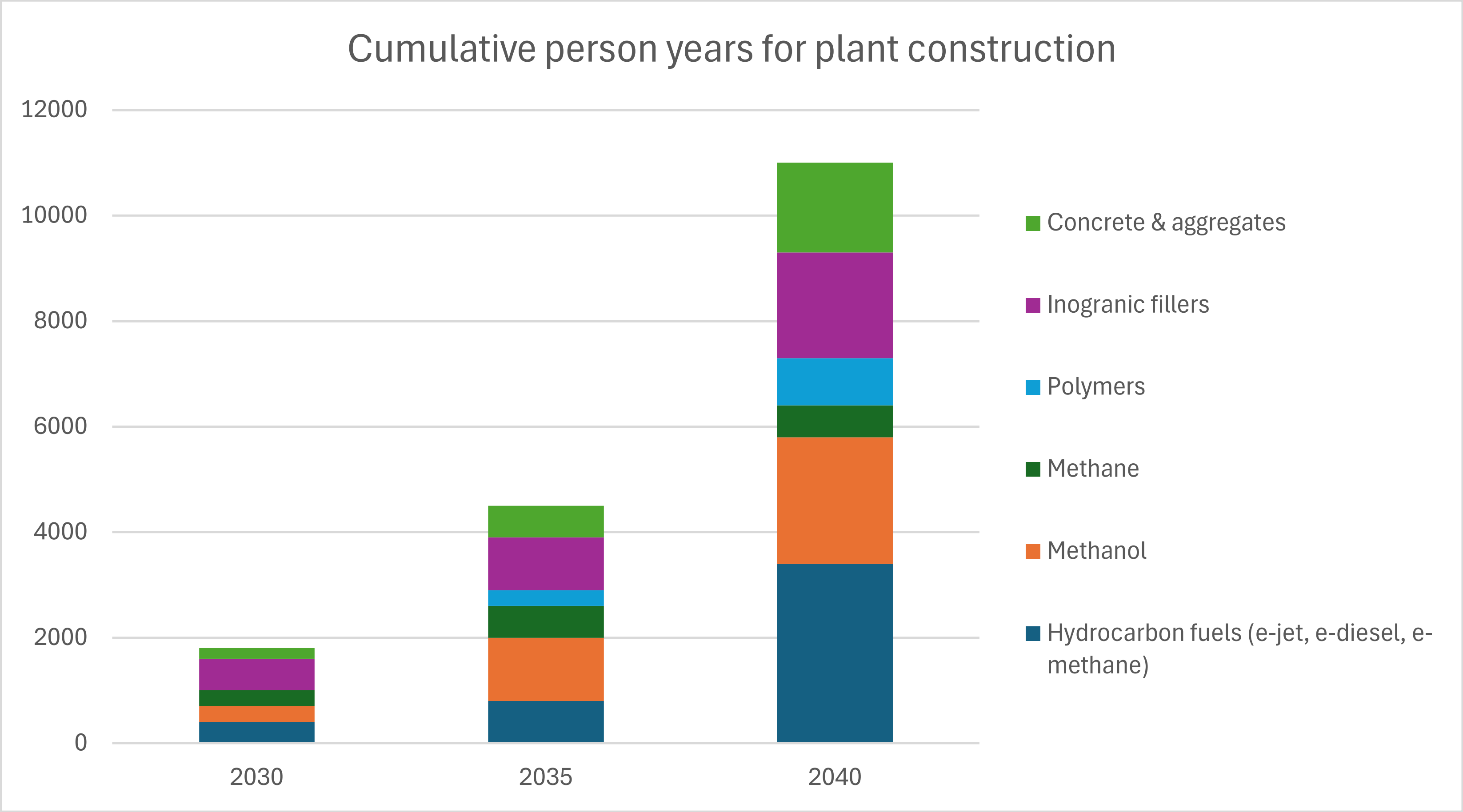
Assumptions:

- Production will start by constructing smaller plants (plant size 1)
- Assumed investment cost of plant size 1 based on VTT know-how from recent projects on e-fuels and CCU-chemicals
- Bigger plant size (plant size 2) based on feasible size ”economy of scale”. Investment cost of plant size scaled from the plant size 1 using exponent 0.65

Observations:

- Average investment/100 kton product ~ 500 MEUR
- Due to regulations (e-fuels) ”real start” of the investment after 2035, even faster growth in the investments expected beyond 2040
- Value of the production high (~7000 MEUR/a) compared to required investments (~11 000 MEUR in total), but operational expenses will also be significant.


Direct personnel count
1200
1000
800
600
400
200
0
2030
2035
2040
Concrete & aggregates
Inogranic fillers
Polymers
Methane
Methanol
Hydrocarbon fuels (e-jet, e-diesel, e-methane)


Cumulative person years for plant construction
12000
10000
8000
6000
4000
2000
0
2030
2035
2040
Concrete & aggregates
Inogranic fillers
Polymers
Methane
Methanol
Hydrocarbon fuels (e-jet, e-diesel, e-methane)

Key assumptions and observations on direct personnel count and costruction labor

Assumptions:

- Direct personnel count of the plants assumed based on VTT know-how from recent projects
- Person years of construction labor assumed to be 10 times the direct personnel count

Observations:

- Impact of direct personnel count of the plants relatively moderate but the indirect impact will be significant
- However, the production by the new plants may replace current production e.g. in Kilpilahti area

Conclusions on WP3

Implications for Finland, investment prospects, possible policies and proposals for code of conduct

Assumptions

- CCU-products and technology development were explored in WP1 and respective markets in WP2. The included products were:
  - Hydrocarbon fuels (e-jet, e-diesel, e-methane)
  - Methanol
  - Methane
  - Polymers
  - Inogranic fillers
  - Concrete & aggregates
- A scenario for the production volumes CCU-products in Finland was created for 2030, 2035 and 2040 based on market and technology development.
- The production volumes were used to estimate electricity and hydrogen demand, numbers of plants, investments and direct employment effects.

Results

Requirements (by 2040)

- Renewable electricity
  - ~50 TWh/a electricity needed for CCU-production
  - Of that ~45 TWh/a for e-fuel production, the rest for polymers.
  - Electricity production in Finland in 2023 was 78 TWh (Energiateollisuus ry, 2024),
- ~1.2 Mt/a hydrogen, mainly for e-fuel production
- Total investments ~11 000 M€ (incl. hydrogen production, excl. renewable electricity prodcution)

Benefits (by 2040)

- CO_2 emission reductions in Finland
  - ~2.5 MtCO_2/a, of which ~1.9 MtCO_2/a from e-fuels replacing fossil fuels
  - Exported CCU-products → large emission reductions globally
- ~2 Mt/a less fossil crude oil needed, ~0.7 Mt/a fossil-based products replaced
- ~1 100 directly employed in CCU-production facilities
- Value of annual CCU-production ~7000 M€ and permanent storage of CO_2 in mineral construction products

Conclusions

- European and global markets for CCU-products are emerging and scenarios contain great uncertainties.
- In the presented scenario, e-fuel production has the major role, assuming a faster market development driven by EU-regulation.
- High-value products require very large increases in renewable electricity production, hydrogen production and investments, but offer a large export potential for Finland.
- Precast concrete and aggregates have a lower export potential, but offer a possibility for permanent carbon dioxide storage within Finland.
- CCU could be a large business and innovation opportunity for Finland, help reduce the depency on fossil fuels and achieve climate goals, but it requires large investments, electricity production, technology development and policies to support the CCU-market.

Picture: Pyynikki esker in Finland, Sampo Mäkikouri.
In addition to their natural beauty, eskers provide ecosystem services, such as filter water, but they are also an important source of natural aggregates.

VTT

beyond the obvious

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