BioCCU - Arvonluontia biopohjaisesta hiilidioksidista

Julkinen loppuraportti

BioCCU - Tunnusluvut

- Projektin tyyppi: Co-innovation (Business Finland)
- Projektin kesto: 10/2022 – 9/2024
- Kokonaisbudjetti: 8,3 M€
- Julkaisut, patentit ja sovellukset: 20 +
- Hankekumppanit: 5 + 8

CO_2
BioCCU

Hankekumppanit

UNIVERSITY OF OULU

Tampere University

LUT University

HELSINGIN YLIOPISTO

Luke
NATURAL RESOURCES INSTITUTE FINLAND

fortum

Sumitomo
SHI FW

Fimpec

OULUN ENERGIA

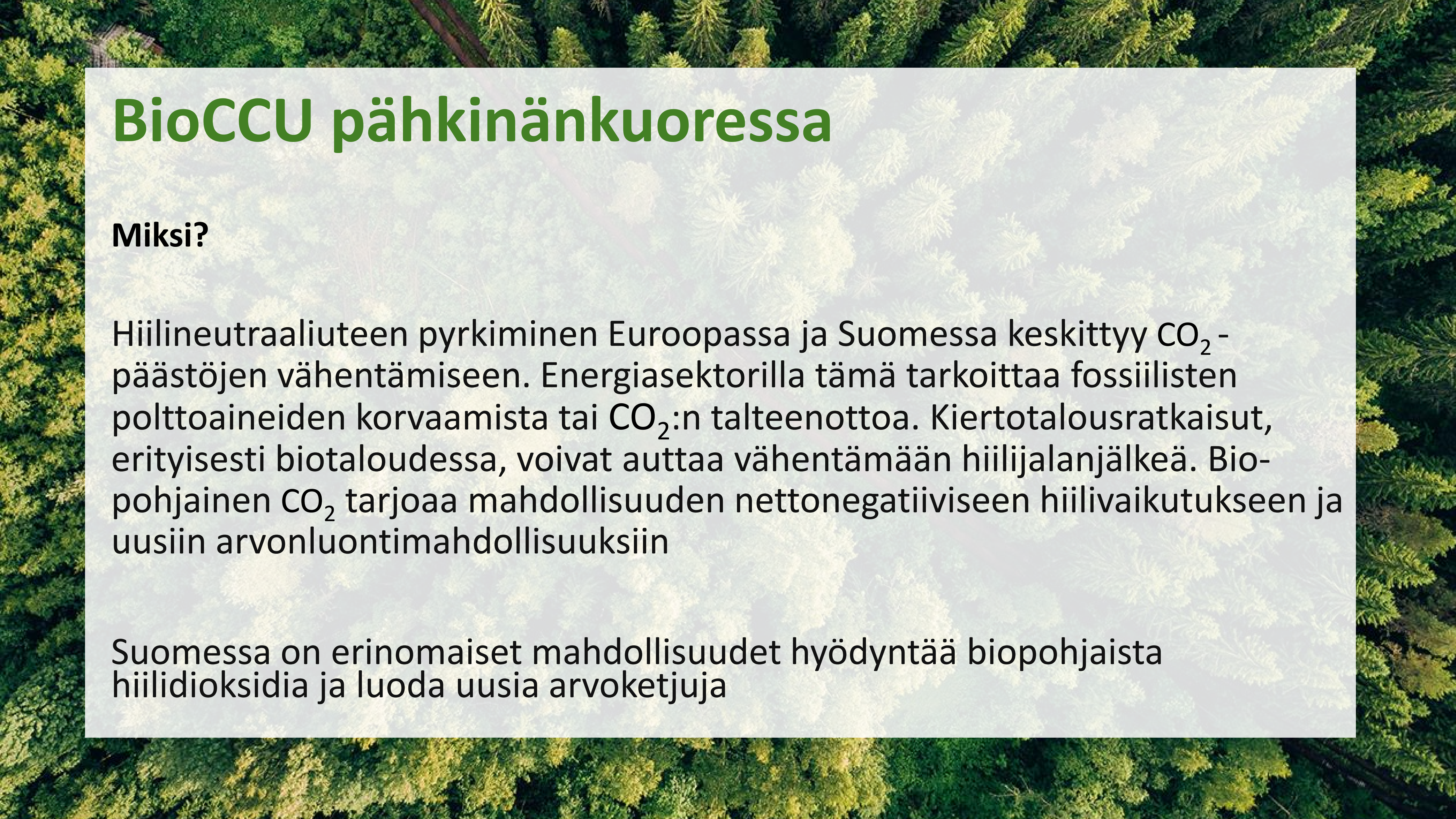
storaenso

Kiertokaari
Kestävän kiertotalouden edistäjä

P2X
solutions

GBW

CLIC



BioCCU pähkinänkuoressa

Miksi?

Hiilineutraaliuteen pyrkiminen Euroopassa ja Suomessa keskittyy CO_2-päästöjen vähentämiseen. Energiasektorilla tämä tarkoittaa fossiilisten polttoaineiden korvaamista tai CO_2:n talteenottoa. Kiertotalousratkaisut, erityisesti biotaloudessa, voivat auttaa vähentämään hiilijalanjälkeä. Bio-pohjainen CO_2 tarjoaa mahdollisuuden nettonegatiiviseen hiilivaikutukseen ja uusiin arvonluontimahdollisuuksiin

Suomessa on erinomaiset mahdollisuudet hyödyntää biopohjaista hiilidioksidia ja luoda uusia arvoketjuja

BioCCU pähkinänkuoressa

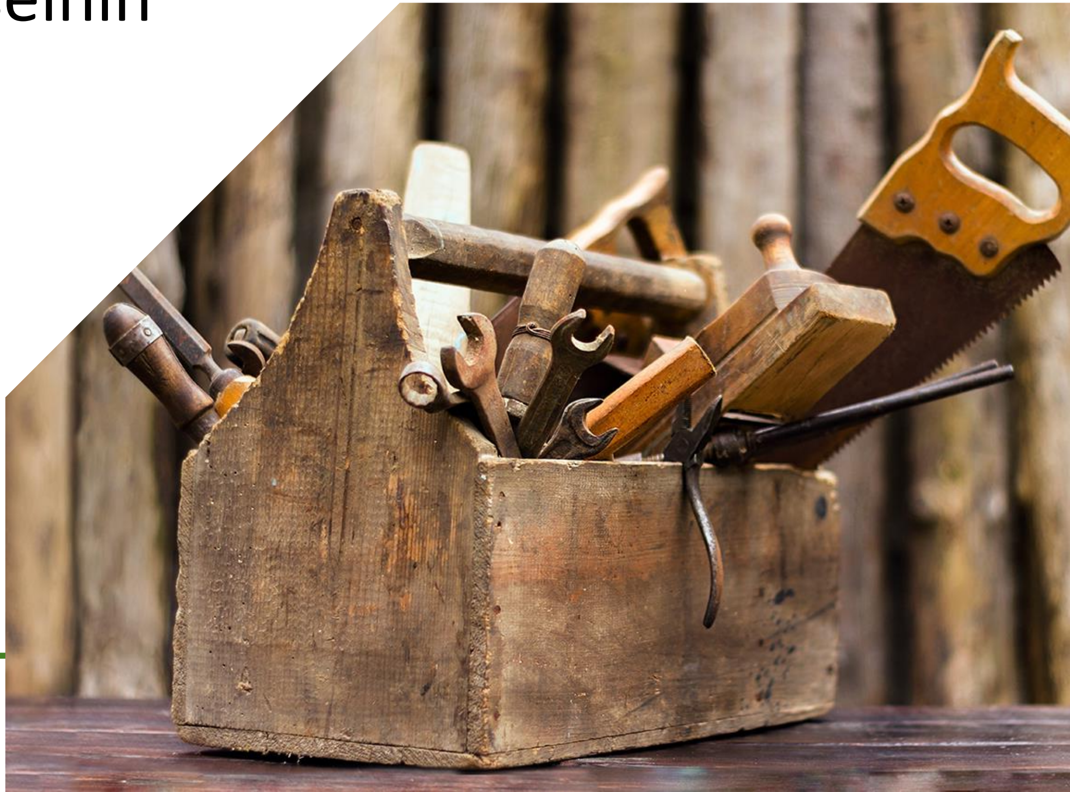
Tavoite 1

Tunnistaa biopohjaisen hiilidioksidin kannattavat liiketoimintamallit ja arvoketjut ja lisätä ymmärrystä prosessien ja tuotteiden kaupallistamisesta ja arvonluonnista

BioCCU pähkinänkuoressa

Tavoite 2

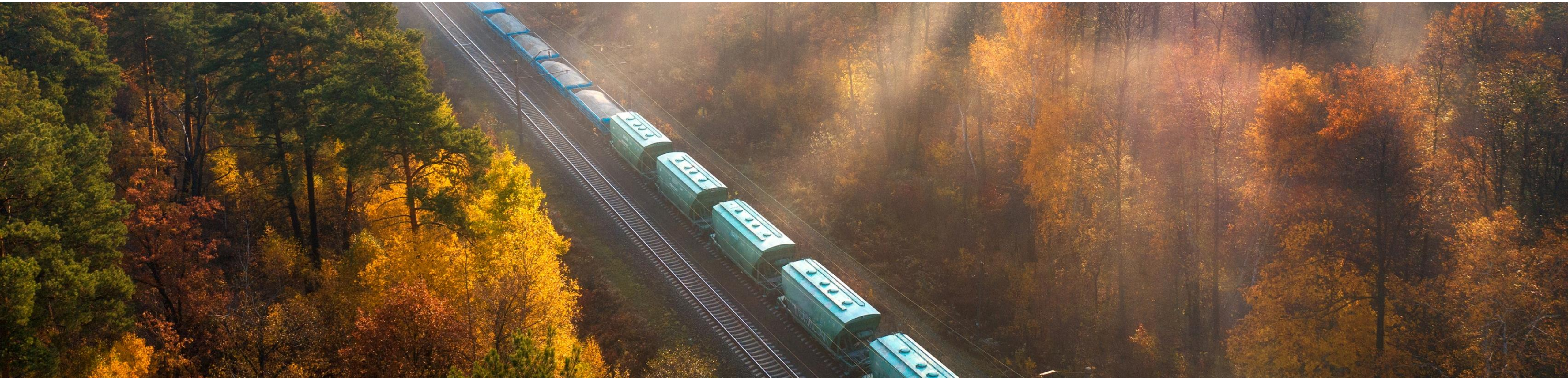
Tunnistaa parhaat teknologiat CCU-prosesseihin



BioCCU pähkinänkuoressa

Tavoite 3

Identifioida paras mahdollinen teknoekonominen polku derivatiivien ja tuotteiden kehittämiseksi



BioCCU pähkinänkuoressa

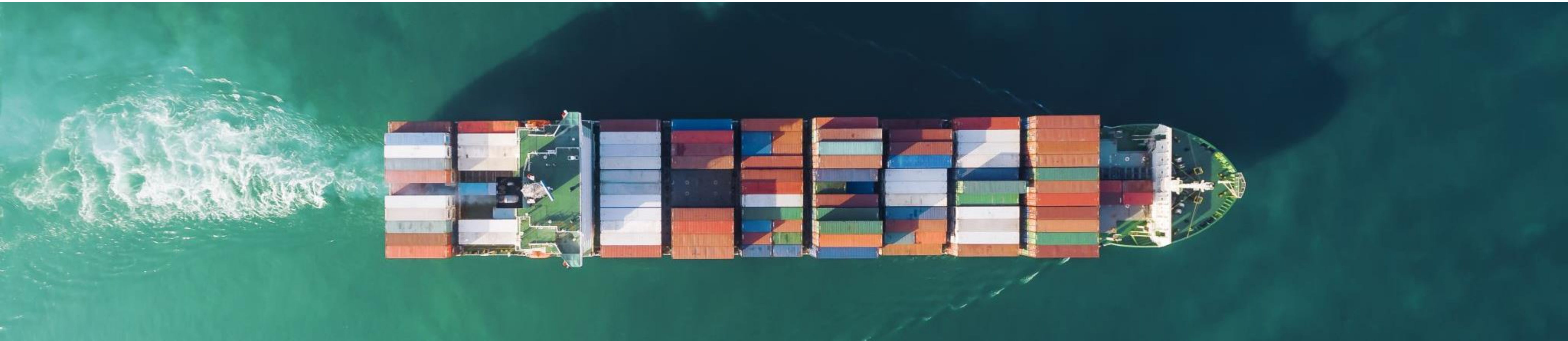
Tavoite 4

Kannustaa kiertotaloudellisten ratkaisujen kehittämiseen bio- ja jätepohjaisen hiilidioksidin hyödyntämiseksi

BioCCU pähkinänkuoressa

Tavoite 5

Edistää tulosten avulla suomalaisten yritysten ja teollisuuden kilpailukykyä ja vientimahdollisuuksia



BioCCU - Työpaketit

Tärkeimmät löydökset ja oivallukset

WP1 - Applications, technology, quality requirements and sustainability of CO2 capture

- Kehitetty uusi teknologia hiilidioksidin matalan lämpötilan adsorptio-erotukseen. Erinomainen prosessitehokkuus yhdistettynä yksinkertaiseen rakenteeseen takaa matalan CAPEXin ja OPEXin sekä luotettavan toiminnan. Kaupallistamiseen tähtäävä tuotekehitys jatkuu.
- Huippututkimusta hiilidioksidin kalvoerotusteknologioista. Työ luo pohjan demolaitteiston rakentamiselle seuraavissa hankkeissa ja mahdollistaa uusien membraanimateriaalien kehittämisen erilaisia käyttöolosuhteita silmällä pitäen.
- Elokuussa 2023 toteutetun biokaasun mittauskampanjan tuloksia voidaan hyödyntää arvioitaessa biokaasun ja kaatopaikkakaasun sisältämän hiilidioksidin soveltuvuutta jatkojalostukseen. Tavoitteena on, että biokaasun ja erityisesti kaatopaikkakaasun arvo lisääntyy.

WP2 - Co-optimized component dimensioning and system control of alkaline and PEM water electrolysis process

- Suuren mittakaavan prosessi- ja systeemitason mallinnukset teollisen kokoluokan alkalielektrolyysereistä (AWE) ja PEM-elektrolyysereistä. Mallien avulla tutkittiin vihreän vedyn tuotannon kustannuksiin ja tehokkuuteen vaikuttavia seikkoja sekä kartoitettiin keinoja prosessien parantamiseen.
- Tri-reformoinnin soveltuvuus biovedyn tuotantoon. Tutkittiin mm. että minkälainen katalyytti on lämpöstabiili, hiilenkestävä ja sietää biokaasun sisältämiä epäpuhtauksia. Lisäksi selvitettiin minkälaisilla reaktio-olosuhteilla vedyn saantoa ja vety-hiilimonoksidisuhdetta (H_2/CO) voidaan parantaa ja samalla katalyytin pinnalle muodostuvan hiilen määrää voidaan vähentää.

WP3 - Conversion technologies and product applications

- Kirjallisuuskatsaus hiilidioksidin katalyyttisen konversion TRL-tasoihin
- Uusien katalyyttien tunnistaminen ja kehittäminen RWGS- ja metanointiprosessiin
- Biokaasun hiilidioksidipitoisuuden laskeminen metanointiprosessilla
- Jatkuvatoiminen sulasuolaelektrolyyseri teknisen hiilen tuotantoon
  - jatkuva ja tasainen prosessi, kestävät elektrodit ja laitekomponentit
  - tasalaatuinen ja puhdas lopputuote, jonka pysyvyys maaperässä erinomainen
- Uutta tietoa kolmesta hiilidioksidin arvoketjusta
  - Kemiallinen, biologinen ja kiinteän hiilen arvoketju

WP4 – Evaluation, Optimisation and Integration of concepts

- Mallit P2X-prosessiketjuille luotu ja simuloitu
- Herkkyysanalyysissa löydetty useita tekno-ekonomisiin analyyseihin vaikuttavia parametrejä
- Systeemitason tutkimuksia Bio-CO2-hubille huomioiden energiavirrat, markkinat, voitto-odotteet ja kustannukset
  - ➢Systeemitason kustannusarvio tuotetulle biopohjaiselle hiilidioksidille
  - Tulokset hyödyntäiskelpoisia muun muassa ympäristövaikutusten arvioinnissa ja tarvittavan sääntelykenttämallin rakentamisessa

WP5 - Regulation, Sustainability, Market Drivers and Value mining

- Tunnistettu 12 erilaista pääliiketoimintamallia CCU:lle.
- Identifioitu ja arvioitu neljää yrityksille tärkeää toisiinsa kytkeytyvää arvonmuodostumisajuria arvoketjuissa:
  - poliittiset linjaukset ja sääntely, teknologia, eri liiketoimintamallien käyttökelpoisuus ja kestävyys.
- Todettu Suomen CCU-toimintojen kehittämisellä olevan vaikutusta markkinamuotoiluun myös laajemmin EU-alueella.
- BioCCU sovellusten ilmastohyödyt ovat merkittävät, mikäli tuotteilla korvataan neitseellisiä fossiilisia raaka-aineita.
- Kyse sellaisessa hyödyntavoittelussa on samalla hiilenkiertotaloudesta.
- Regulaatiotutkimus myös yksittäisten arvoketjujen osissa tärkeää - muutokset arvoketjuissa vaikuttavat eri sääntelyn soveltuvuuteen ja ohjausvaikutukseen.

Yhteenveto verkostoitumis- ja tiedotusaktiviteeteista

- Project collaborations, *e.g.* ForestCUMP, HYGCEL, FinH2, MarineCO2, and new initiatives created during the BioCCU project
- Active dissemination of research results in different platforms
  - In total 32 publication and 6 theses
    - 11 published, 17 under progress, 4 internal reports
    - Seven theses published (1 doctoral thesis, 6 diploma theses)
  - In total 29 events participated
- International co-operation throughout the world
  - In total 21 international matters listed

UUTISET

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Business model innovations for carbon capture and utilization

Mikko Sairanen*

Leena Aarikka-Stenr

Emma Nykänen

* Corresponding author

Renewable Energy

Influence of shunt currents in industrial-scale alkali plants

Georgios Sakas*, Alejandro Ibáñez-Rioja, Santeri Pöyhönen, Ant Pertti Kauranen, Jero Ahola

Applied Energy 345 (2023) 121277

Applied Energy

Off-grid solar PV–wind power–battery–water electrolyzer plant Simultaneous optimization of component capacities and system

Alejandro Ibáñez-Rioja*, Lauri Järvinen, Pietari Katja Hynynen, Jero Ahola, Pertti Kauranen

Optimizing E-Methanol Production: Effect of Electricity Price and Renewable Energy Volatility on Optimum Dimensioning and Operation

Jaakko Hyypiä[1,*] Hannu Karjunen[1] Nashmin Hosseinpour[1] Eero Inkeri[1] Tero Tynjälä[1]

[1] *Lappeenranta-Lahti University of Technology LUT, School of Energy Systems, Lappeenranta, Finland*

**Corresponding author. Email: Jaakko.Hyypia@lut.fi*

ABSTRACT

Renewable energy can significantly reduce global CO_2 emissions, both directly by reducing the use of fossil-based energy sources and indirectly through power-to-X pathways. These pathways facilitate the production of various fuels and chemical feedstocks, offering alternatives to fossil-based products. This study focuses on optimizing e-methanol production chain to determine the most economically viable dimensioning of main process components and selection of operation strategy. The optimization task is executed with an open-source energy system modelling framework, considering different electricity supply alternatives, such as grid, wind power and combined wind and solar power. The analyzed system incorporates essential process components for hydrogen, methanol and CO_2 production, along with intermediate storages and alternative power supply profiles. The main finding of the study is that allowing flexible operation and over-dimensioning of the methanol synthesis plant, considerable, up to 46% cost savings can be achieved already in current market scheme. Moreover, the dynamic operation of the e-methanol plant may benefit electricity

Hank et al. and Sollai et. al [1], [2] summarise the reasons why e-methanol manufacturing holds great potential. An

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P. Droege and L. Quint (eds.), *Proceedings of the International Renewable Energy Storage and Systems Conference (IRES 2023)*, Atlantis Highlights in Engineering 32,

sanoma

Keskiviikkona 20.12.2023 Perustettu vuonna 1881

AAMULEHTI

PÄÄSTÖT. HIILIDIOKSIDISTA NANOHIILTÄ HERVANNASSA

TAMPEREEN YLIOPISTOSSA RAKENNETTIIN MAAILMAN ENSIMMÄINEN JATKUVATOIMINEN SULASUOLAELEKTROLYYSILAITTEISTO.

Tampere University

CONSTRUCTION AND FORMU CALCULATION MO THERMAL SWING AD REACTOR M

Application in Post-Combustion C

University Lecturer Henrik Tolvanen

September 2023

Ennallistaminen ympäristöoikeuden sektoreilla – luonnonsuojelu

Kokko, Kai

Ympäristöjuridiikka 4/2023 s. 47–64

3.1.2024

Asiantuntija-artikkeli

Tiivistelmä

Euroopan unionissa on valmistumassa luonnon ennallistamisesta annettu asetus. Tämän ennallistamisasetusehdotuksen tavoitteita ja keinoja peilataan artikkelissa luonnonsuojelulain (LSL 9/2023) tavoitteisiin ja keinoihin turvata luonnon monimuotoisuutta. Luonnonsuojelulain tavoite luonnon monimuotoisuuden turvaamisesta mahdollistaa uudet aktiiviset ja dynaamiset, EU:ssa tavoiteltua ekosysteemien suojelua tukevat sääntelykeinot. Luonnon monimuotoisuuden turvaamisessa yksi keskeinen taso on ekosysteemien suojelu ja sen alatavoite, heikentymisen estäminen, toimii lähtökohtana ekosysteemien ennallistamiselle.

Varsinaisista luonnonsuojelulain mukaisista suojelukeinoista aluesuojelu on keskeinen toteutettaessa ekosysteemien ennallistamista. Natura 2000 -alueiden ohella valtion ja yksityisten suojelualueet mahdollistavat ekosysteemien ennallistamisen suunnittelua ja toteuttamista. Myös luonnonsuojelulain kohdesuojelu, lajien elinympäristöjen ja luontotyyppien suojelu, täydentää luonnon monimuotoisuuden turvaamista varsinaisten suojelualueiden ulkopuolella. Ennen EU:n ennallistamisasetuksen voimaantuloa alue- ja kohdesuojelusta poikkeamista voidaan joutua arvioimaan uudelleen. Lisäksi luonnonsuojelulain mukaiset tuet voivat edistää ekosysteemien ennallistamista. Sen sijaan uusien suojelukeinojen, ekologisen kompensaation ja lajien avustetun leviämisen, suhde ennallistamiseen on epäsuorempi. Niiden vaikutus ennallistamiseen ratkeaa lopulta soveltamiskäytännössä.

Luonnonsuojeluoikeuden näkökulmasta Suomessa on hyviä valmiuksia ennallistamisasetusehdotuksen mukaisten jäsenvaltion velvoitteiden toimeenpanoon. Siitä huolimatta luonnonsuojelulakia joudutaan tarkistamaan joiltakin osin ennen lopullisen asetuksen voimaantuloa. Yleisesti biodiversiteetin turvaamis- ja ekosysteemien ennallistamissääntely tulisi nähdä osana yhteiskunnan kestävyysmurrosta, kun päämääränä on esimerkiksi biopohjaisen kiertotalouden saavuttaminen ja ylläpitäminen. Luonnonsuojelulain ohella tarvitaan muiden kansallisten säädösten, mukaan lukien

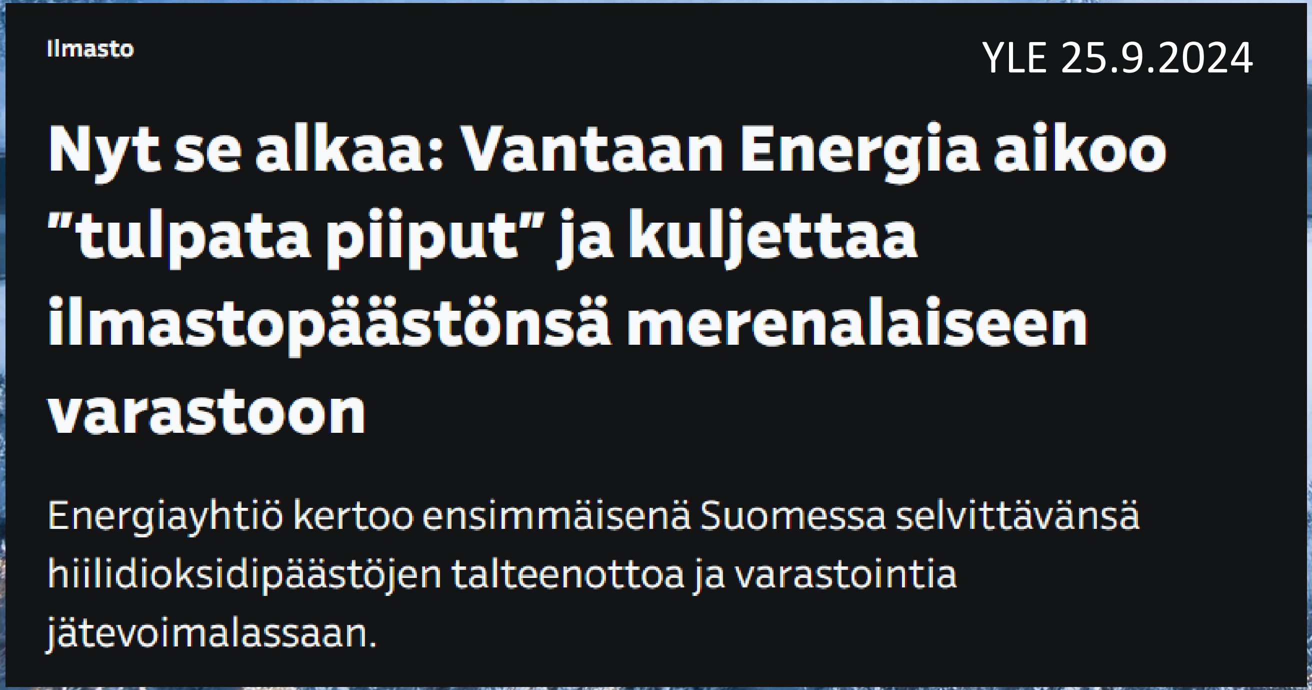
Ajankohtaista?

Ilmasto

YLE 25.9.2024

Suomi voi saada tuottoisan bisneksen hiilidioksidin talteenotosta ja hyödyntämisestä

VTT kiittelee Vantaan Energian hanketta edelläkävijyydestä ilmastonmuutosta lisäävän kaasun varastoinnissa.



Ilmasto

YLE 25.9.2024

Nyt se alkaa: Vantaan Energia aikoo ”tulpata piiput” ja kuljettaa ilmastopäästönsä merenalaiseen varastoon

Energiayhtiö kertoo ensimmäisenä Suomessa selvittävänsä hiilidioksidipäästöjen talteenottoa ja varastointia jätevoimalassaan.

WP1. Main achievements

Applications, technology, quality requirements and sustainability of CO2 capture

Tero Joronen, TAMK Applied Research Center ARC

Contents of the presentation

- Need and business potential
- HALT technology, benefits
- Benchmarking of technology
- Upgrading of low grade biogas
- Conclusion

Sustainability requirements

- Bio-CO_2 for reducing emissions
- In Finland, bio-CO_2 alone has 2,500 M€ value in emission credits
- Would fulfill gap in the carbon neutrality target of Finland in 2035

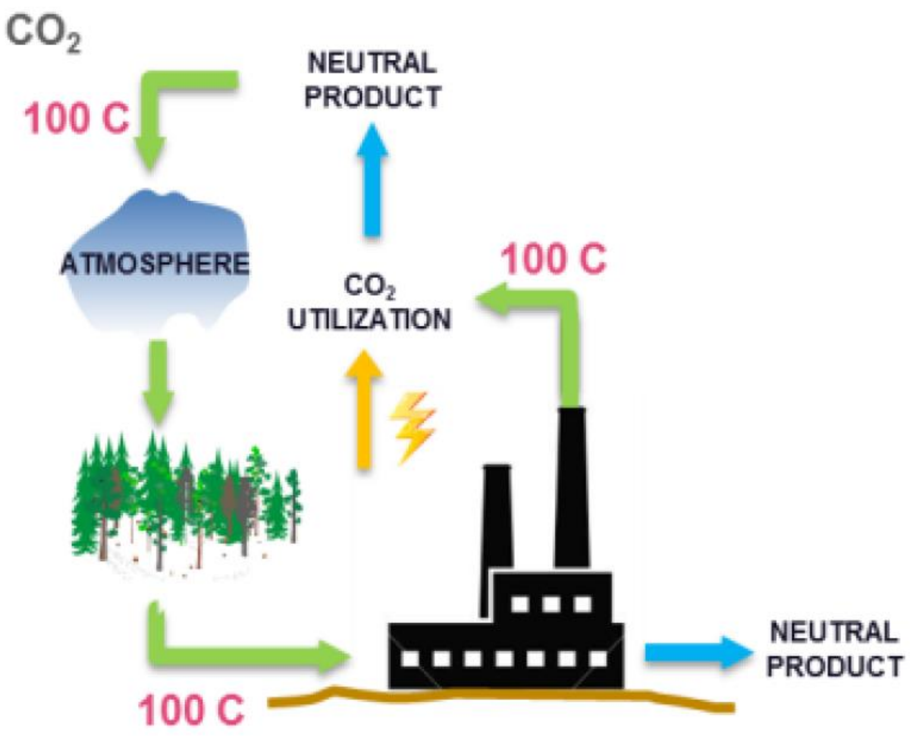


Figure IEA

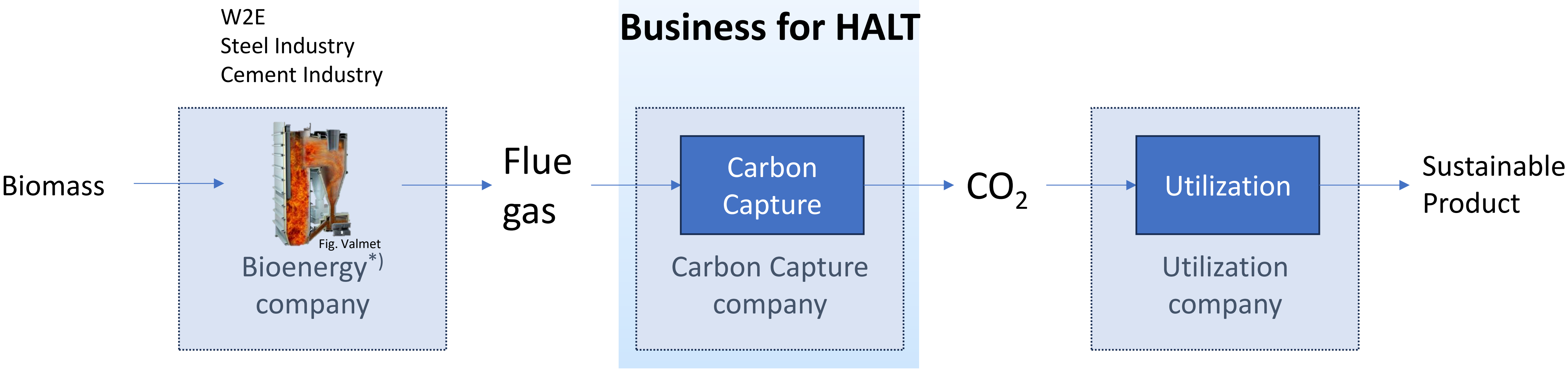
Oulu CC case studies - TEA model

- **Stora Enso Oulu, Oulun Energia,** Kiertokaari, Global Boiler Works
- General interest to CC business. Limiting factors:
  - Maturity of technology (WP1)
  - Legislative unclarity (WP5)
  - Utilization of CO_2 undefined (WP3)
- Literature review of different technologies
- Alternative technologies give benefits as simple and low energy alternatives
- Potential for large scale applications ~ 2 Mt/a

	Stora Enso Oulu	**Oulun Energia**
CO_2 total potential (t/a)	926 320	1 100 000
CO_2 captured (t/a)	787 372	935 000
CO_2 captured cost (€/t CO_2)	63.9	62.8

Meri Salo, TAU 2023

CC position in the value chain



*)
Forest Industry
W2E
Steel Industry
Cement Industry

Business for HALT

Biomass → Bioenergy*) company → Flue gas → Carbon Capture (Carbon Capture company) → CO_2 → Utilization (Utilization company) → Sustainable Product

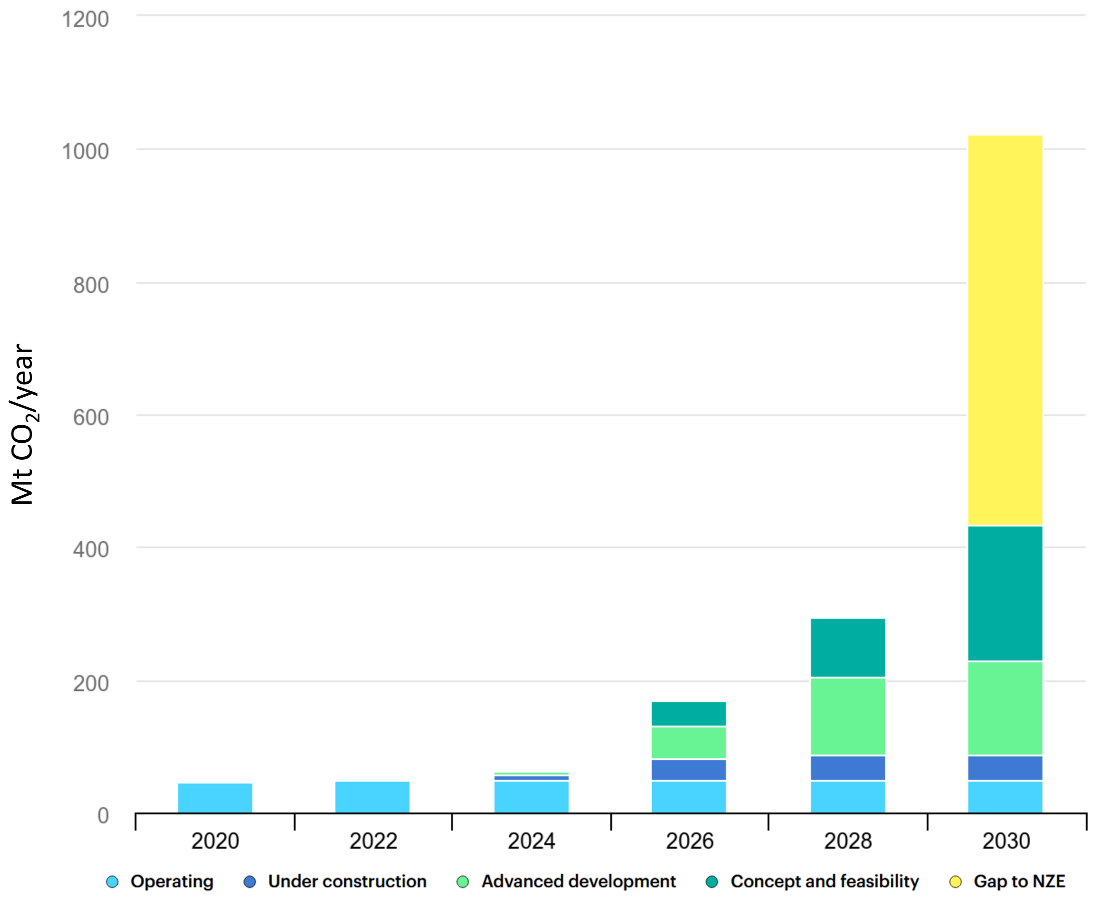
Fig. Valmet

Big and feasible business potential

BioCCU

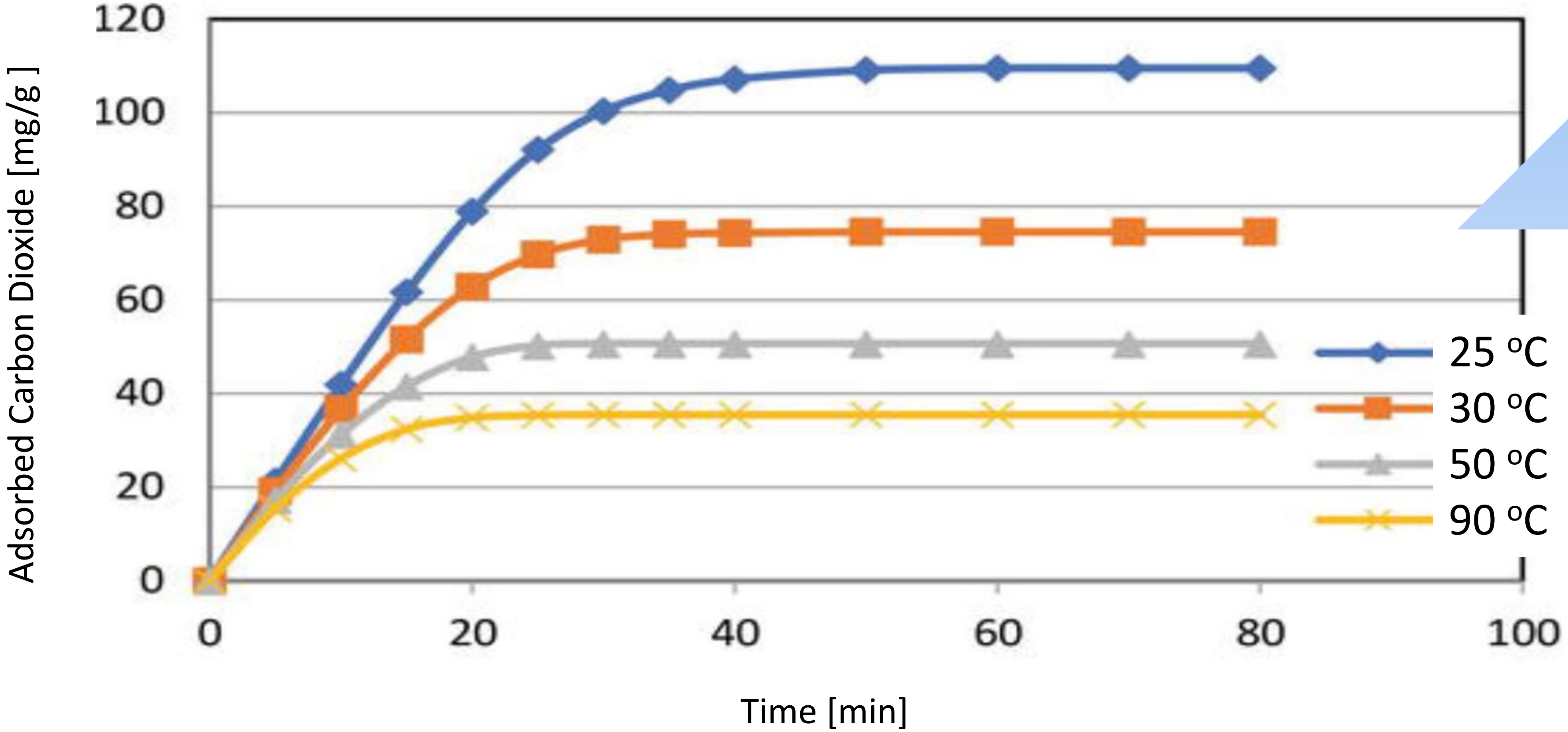
- CCUS market is growing fast, and the target market size in 2030 is globally 5-20 milliard euros
- Yearly business potential is at least 300 million euros
- Forest industry has concentrated bio-CO_2 streams available
- Scalable without technological limitations
- Capture from flue gas consumes only 1/4 power compared to Direct Air Capture

Focus on the large scale industrial bio-CO_2 in flue gases



IEA (2024) CCUS Projects Database

Hybrid Adsorption and Low Temperature (HALT)



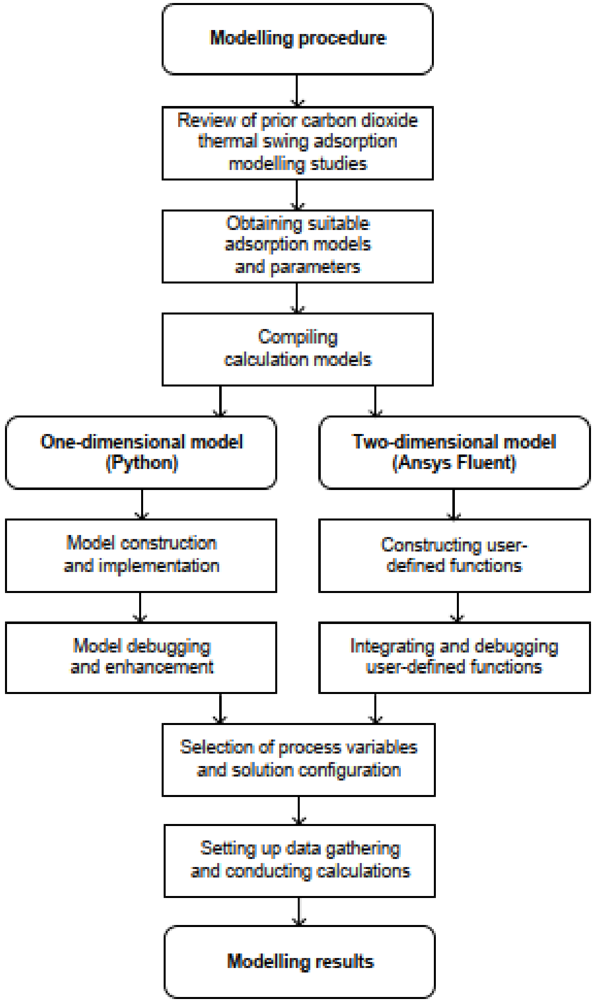
Low Temperature increases the capacity

Adsorption to activated carbon by time on different temperatures (Adapted from Parkkila 2022, TAU)

HALT

- Two reactor models
  - Python 1D
  - CFD 2D
- Bench scale experiments

→ Process simplified



Modelling procedure

Review of prior carbon dioxide thermal swing adsorption modelling studies

Obtaining suitable adsorption models and parameters

Compiling calculation models

One-dimensional model (Python)

Model construction and implementation

Model debugging and enhancement

Two-dimensional model (Ansys Fluent)

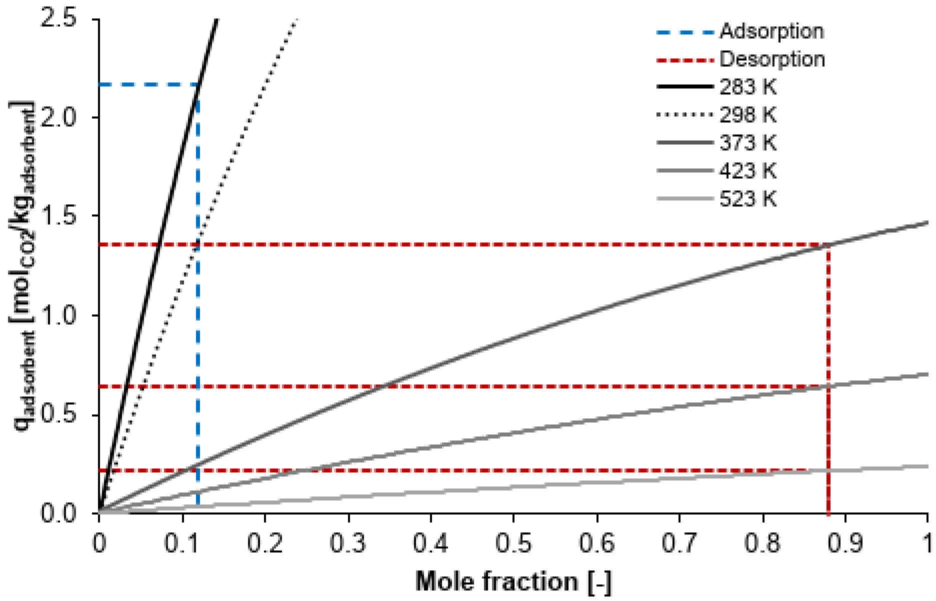
Constructing user-defined functions

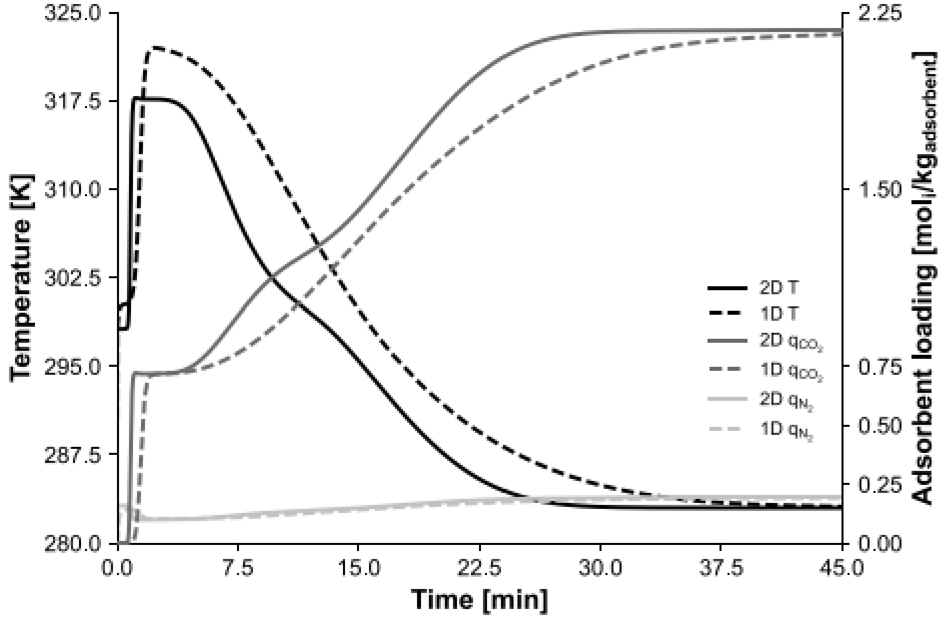
Integrating and debugging user-defined functions

Selection of process variables and solution configuration

Setting up data gathering and conducting calculations

Modelling results





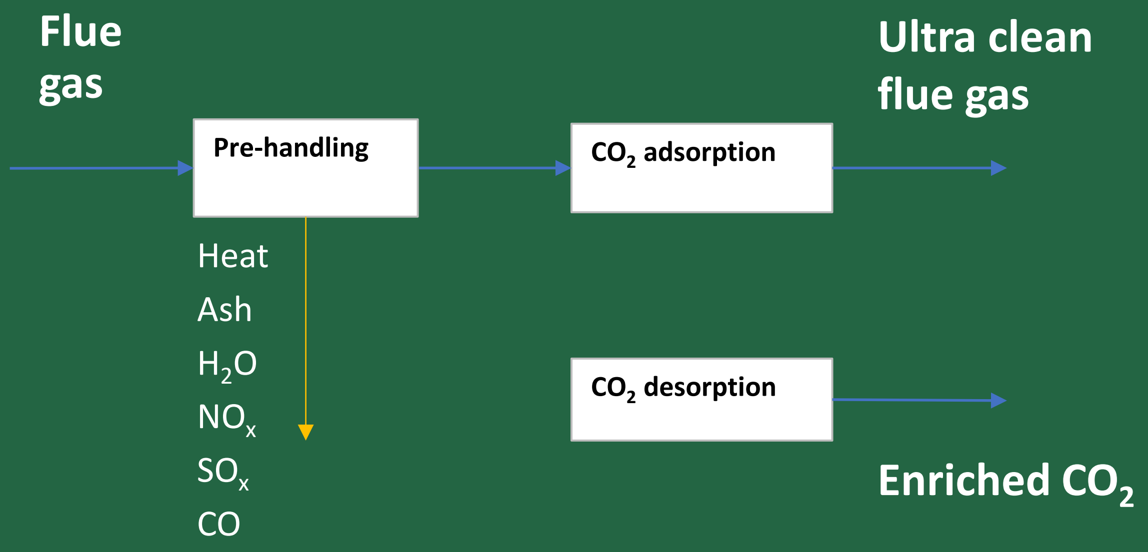
Jesse-Eemeli Viljanen, TAU 2023

What we have accomplished

Developed in BioCCU project:

- Business study
- Experimental verification
- Process optimization
- Robust and simple solution

→ **Invention declaration**



Flue gas

Pre-handling

Heat
Ash
H_2O
NO_x
SO_x
CO

CO_2 adsorption

CO_2 desorption

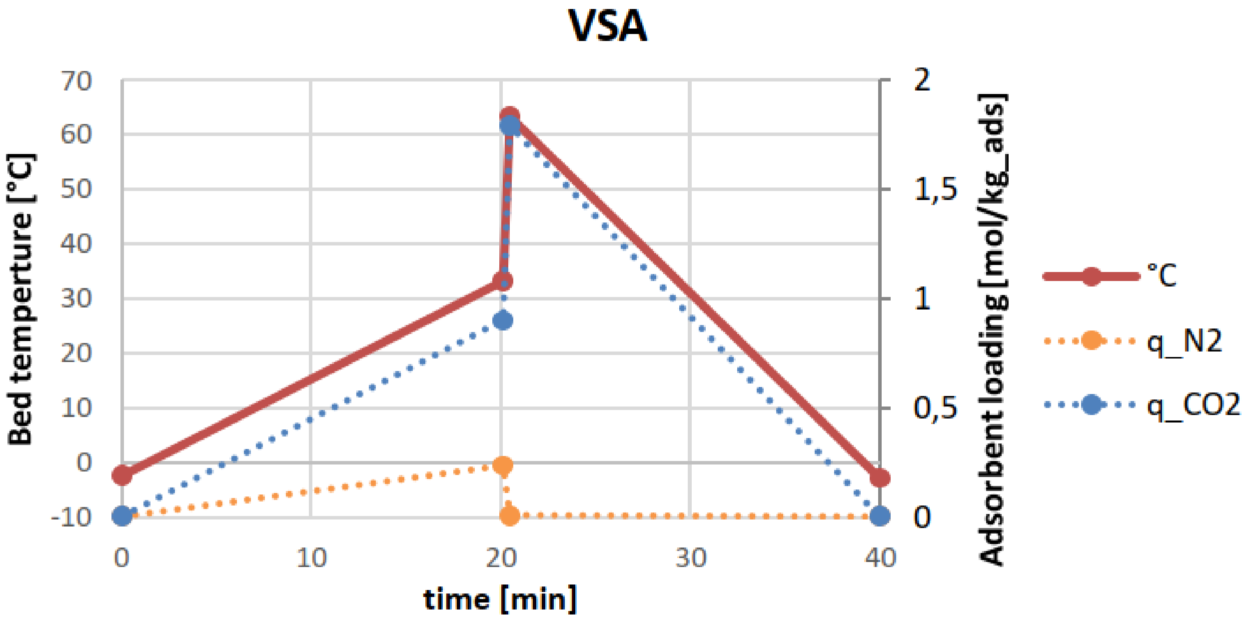
Ultra clean flue gas

Enriched CO_2

Excellent results

- *Heat recovery → High energy efficiency*
- *Autonomous cooling by desorption*
- *Simple solution*
- *No moving parts, no pumping*
- *No chemicals*

Estimated CO_2 capture price based on the process modelling is
15 €/tCO_2
Fraction of current cost level of 60 – 80 €/tCO_2[1]



Huila and Joronen, 2024

Feasible technology for Carbon Capture

[1] Kearns, D., Liu, H., & Consoli, C. (2021). Technology readiness and costs of CCS. *Global CCS institute*, *3*.

Bench marking - VSA by HyGear

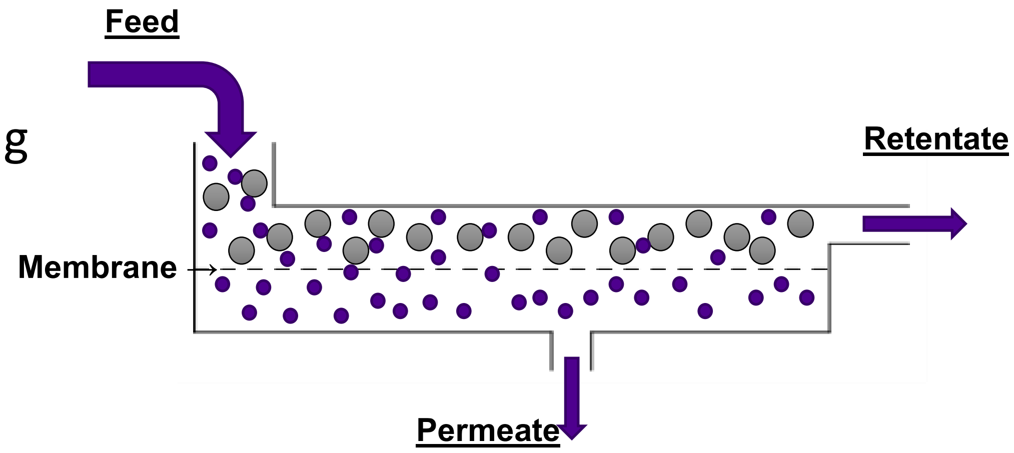
Located in Arnhem, NL

- Small scale VSA solution
- Two stage approach by Vacuum Swing Adsorption
- Recovery > 85 %
- CO_2 purity > 98 %
- Electricity consumption 150 kWh/tCO_2
- Scale < 2000 Nm^3/h flue gas

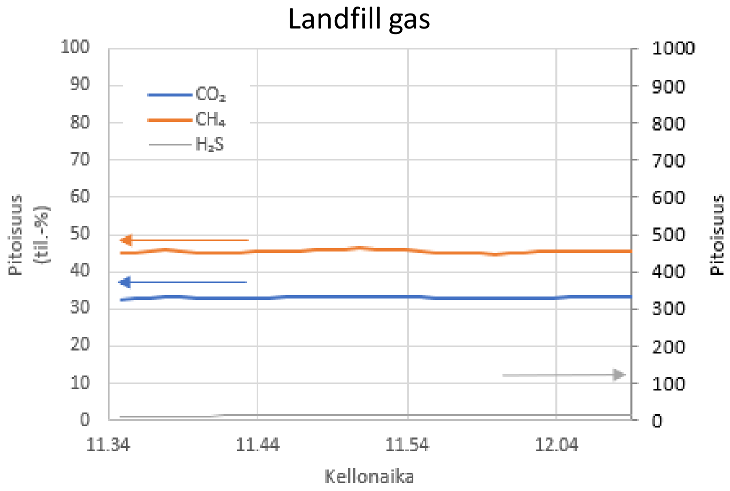
Figure HyGear, https://hygear.com/technologies/carbon-capture/

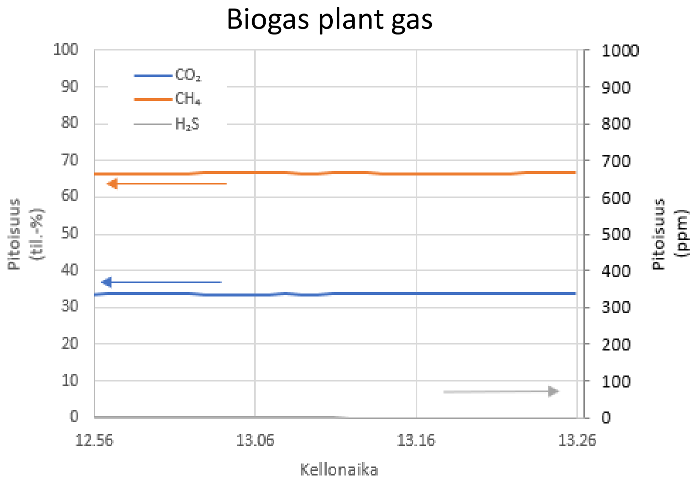
T1.3. Low grade gas upgrading: Literature study on membrane separation and gas measurements

- CO_2 from small gas compounds, e.g. H_2, N_2, CO
- Polymeric membranes dominate, but new promising membrane materials are developed
- Requires multi-stage membrane separation and/or hybrid separation technologies



- Gas measurements at Kiertokaari
- Feed to WP4 membrane separation modelling





Conclusion

- BioCCU has great potential
- BioCCU project has enhanced all the issues of technology, legislation, and utilization
- HALT technology has showed excellent performance; simplicity, costs and performance
- Technology will be commercialized in next phase
- Membrane separation studied for low grade gases and modelled in WP4

WP2: Electrolytic hydrogen production in BioCCU

Presentation held in BioCCU & ForestCUMP joint seminar 20.3.2024

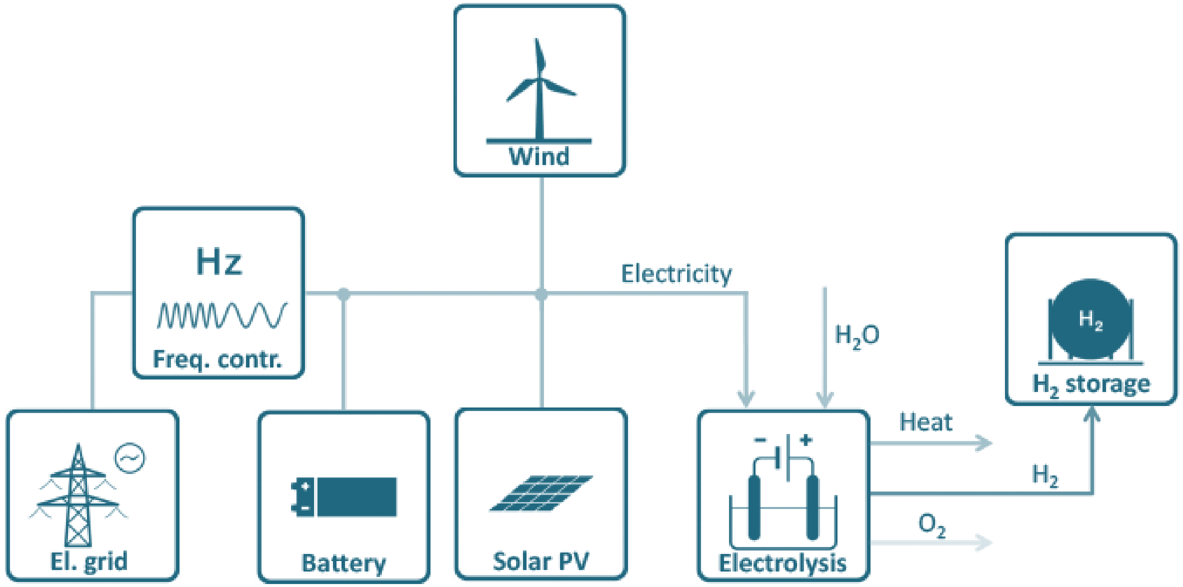
Antti Kosonen, LUT Universíty

Cost optimized hydrogen production and storage systems

BioCCU

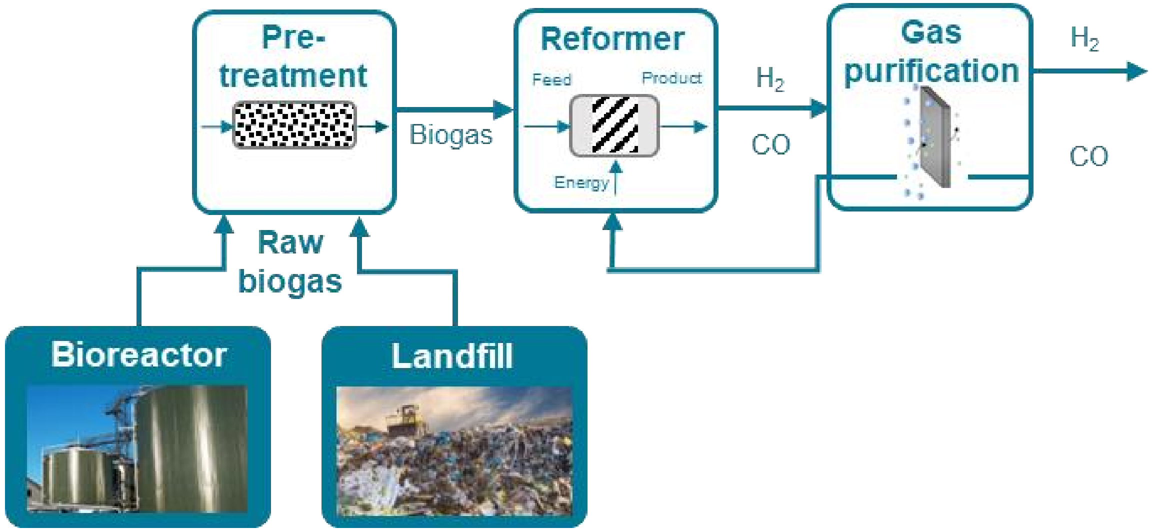
LUT University

Electrolytic hydrogen production



UNIVERSITY OF OULU

Hydrogen production from biogas plants



How to produce cheap green hydrogen?

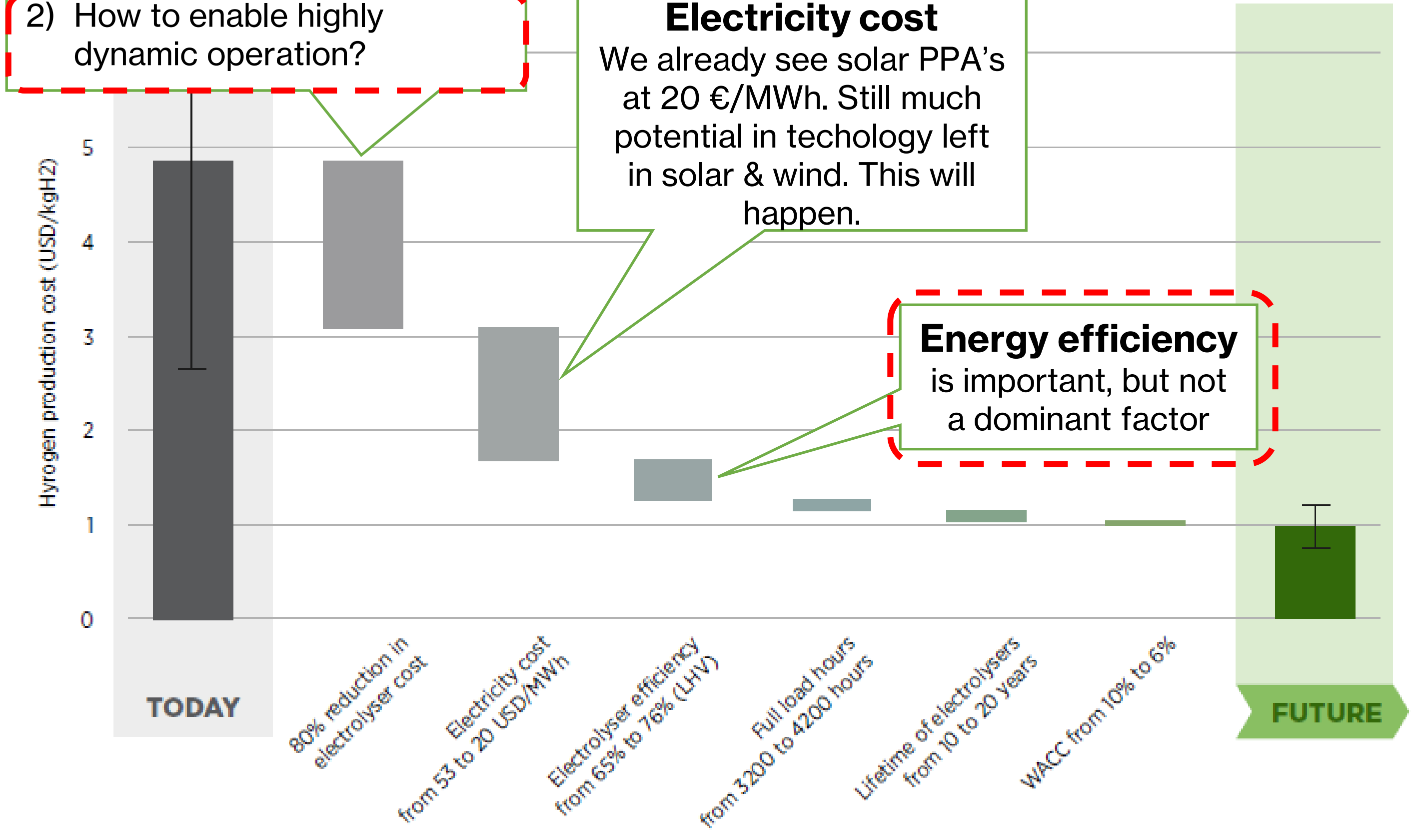
Electrolyser cost

1) How to get electrolyser cost down by 80 %?
2) How to enable highly dynamic operation?

Electricity cost

We already see solar PPA’s at 20 €/MWh. Still much potential in techology left in solar & wind. This will happen.

Energy efficiency is important, but not a dominant factor



Note: ‘Today’ captures best and average conditions. ‘Average’ signifies an investment of USD 770/kilowatt (kW), efficiency of 65% (lower heating value – LHV), an electricity price of USD 53/MWh, full load hours of 3200 (onshore wind), and a weighted average cost of capital (WACC) of 10% (relatively high risk). ‘Best’ signifies investment of USD 130/kW, efficiency of 76% (LHV), electricity price of USD 20/MWh, full load hours of 4200 (onshore wind), and a WACC of 6% (similar to renewable electricity today).

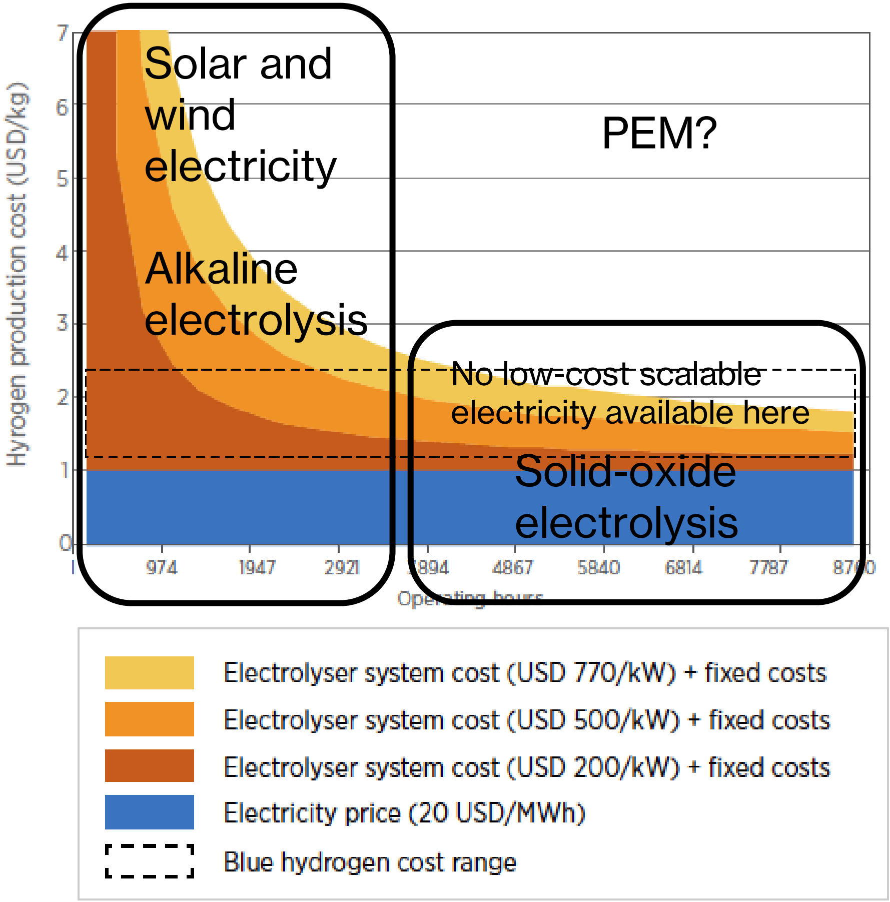
Main research tasks:

1) Production of hydrogen based on wind and solar power
2) Understanding of parameters that affect the energy efficiency and control range

IRENA (2020), Green hydrogen cost reduction: Scaling up electrolysers to meet the 1.5 °C climate goal, International Renewable Energy Agency, Abu Dhabi.

Green hydrogen production based on wind and solar electricity

Effect of intermittency of electricity supply



Solar and wind electricity

Alkaline electrolysis

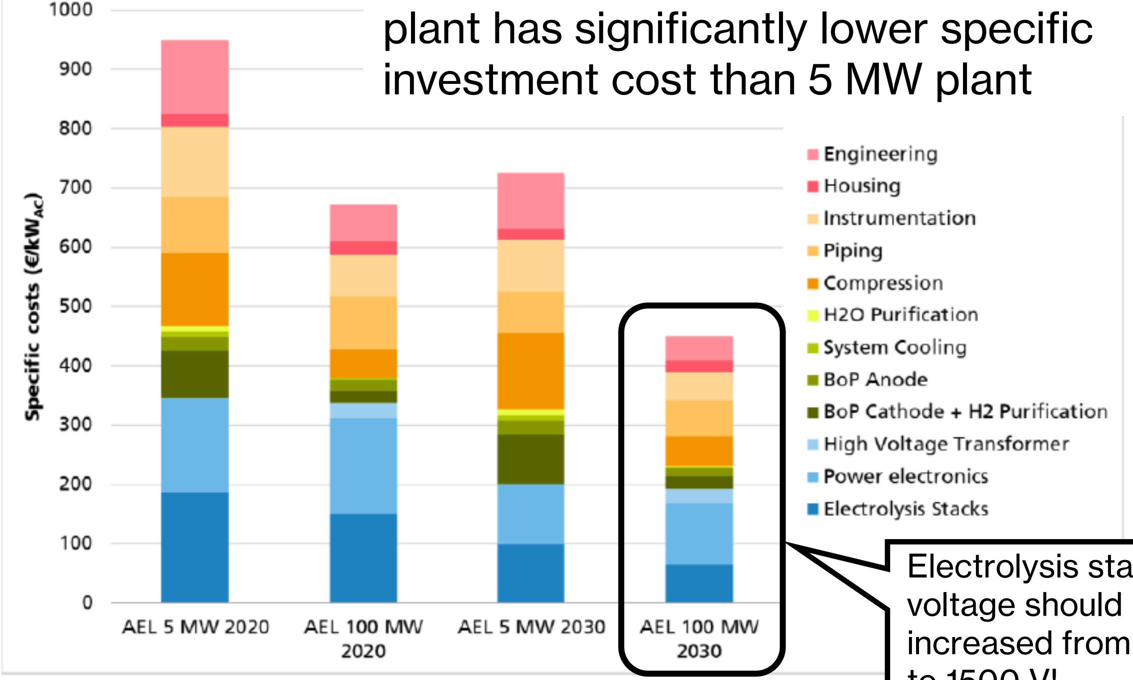
PEM?

No low-cost scalable electricity available here

Solid-oxide electrolysis

Cost composition of alkaline water electrolysis (AWE)

Electrolyzer plant size matters. 100 MW plant has significantly lower specific investment cost than 5 MW plant



Electrolysis stack voltage should be increased from 300 V to 1500 V!

Figure 3-6: Specific costs of 5 MW and 100 MW next generation AEL systems (including mechanical compressors) for the design scenarios 2020 and 2030

Source: M. Holst, S. Aschbrenner, T. Smolinka, C. Voglstätter, G. Grimm, Cost forecast for low-temperature electrolysis – Technology driven bottom-up prognosis for PEM and alkaline water electrolysis systems, Fraunhofer ISE, Oct. 2021.

Off-grid green hydrogen production

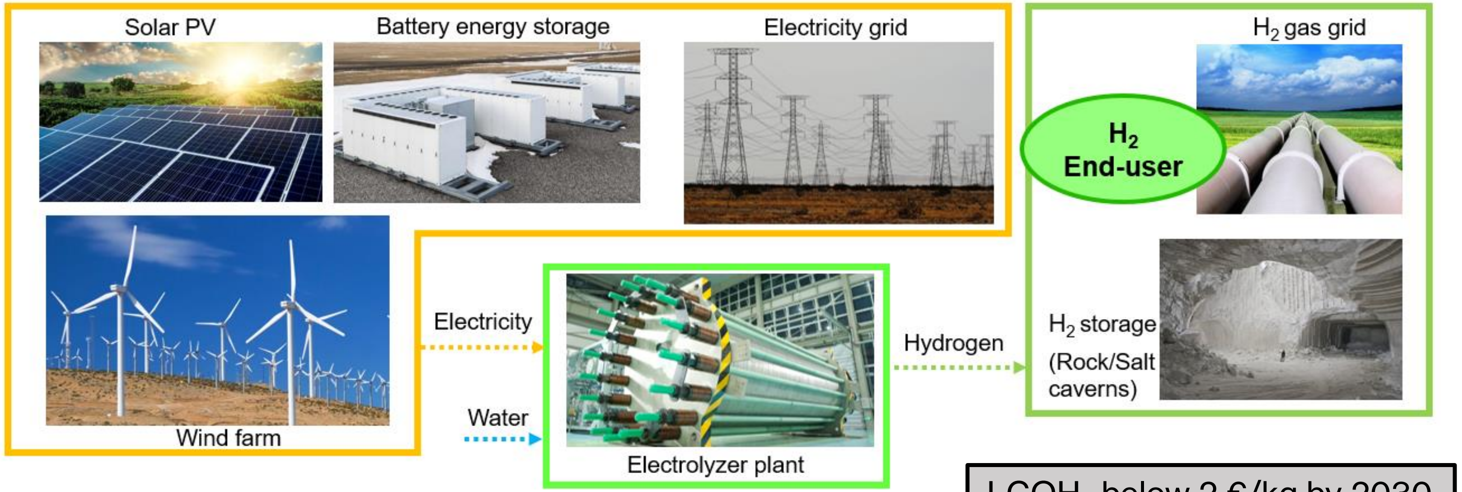


Figure: typical green hydrogen production system

LCOH$_2$ below 2 €/kg by 2030

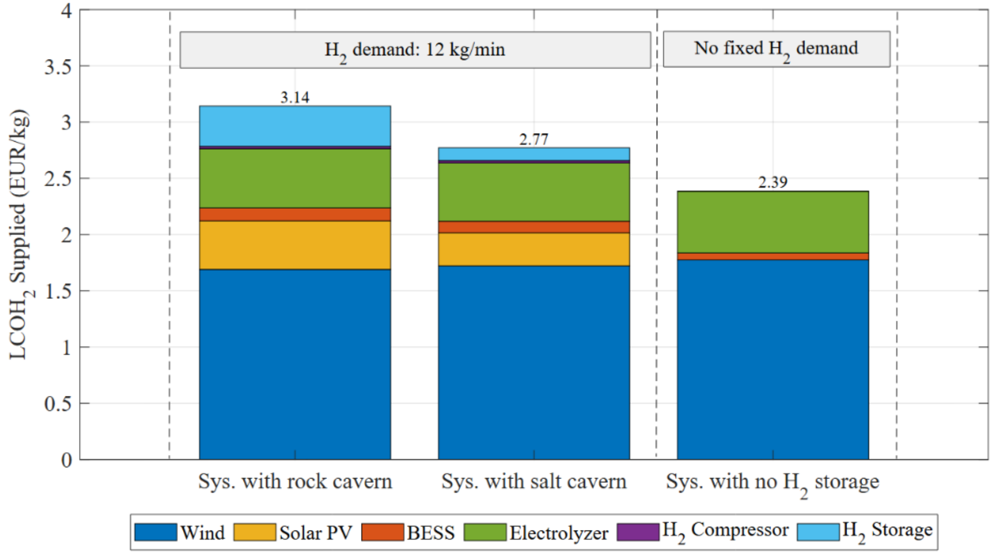


Figure: Levelized cost of Hydrogen (LCOH2) for a plant located in southeastern Finland in the year 2025 and 5% discount rate.

Press release: https://www.lut.fi/en/news/wind-most-cost-effective-power-source-hydrogen-economy-southeast-finland

A. Ibáñez-Rioja, L. Järvinen, P. Puranen, A. Kosonen, V. Ruuskanen, K. Hynynen, J. Ahola, P. Kauranen, [Off-grid solar PV-wind power-battery-water electrolyzer plant: Simultaneous optimization of component capacities and system control](), Appl. Energy. 345 (2023), Article 121277.

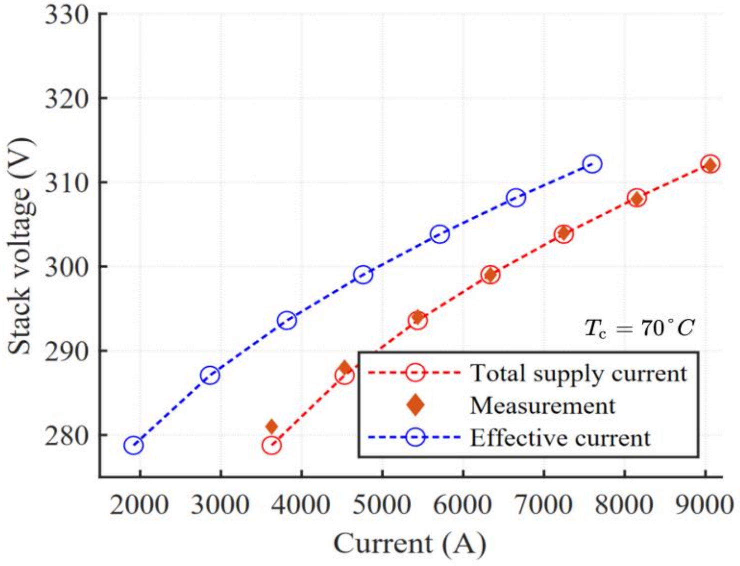
In review: Baseload hydrogen production by solar and wind power-based electricity → compression & storage included

Preprint: A. Ibáñez-Rioja , P. Puranen, L. Järvinen, A. Kosonen, V. Ruuskanen, K. Hynynen, J. Ahola, P. Kauranen. [Baseload hydrogen supply from an off-grid solar PV-wind power-battery-water electrolyzer plant](). Energy, 2024.

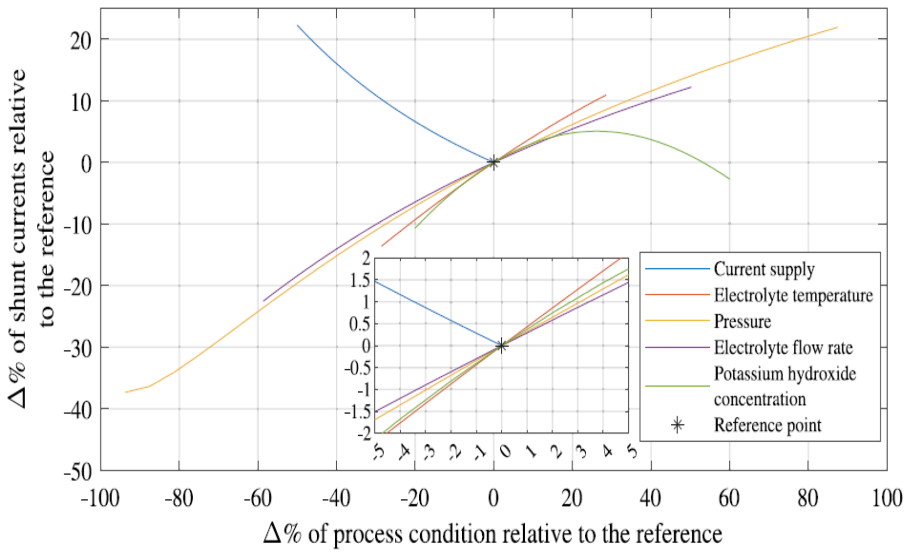
Shunt current analysis in pressurized AWE

Simplified definition: Shunt current is defined as the current that is lost in secondary low resistance paths. The shunt currents corrode the manifold ducts and cause loss of current in secondary electrochemical reactions, thus loss of hydrogen production.

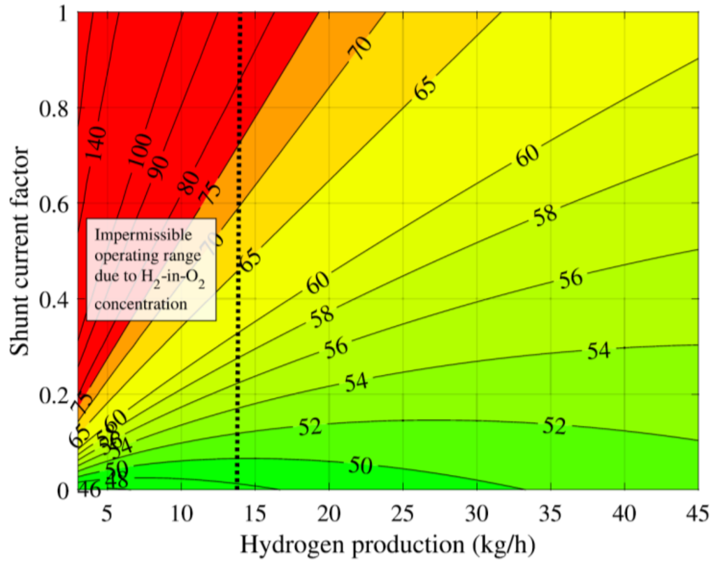
UI curve



Parameter sensitivity



SEC and shunt currents



G. Sakas, A. Ibáñez-Rioja, S. Pöyhönen, L. Järvinen, A. Kosonen, V. Ruuskanen, P. Kauranen, J. Ahola, Sensitivity analysis of the process conditions affecting the shunt currents and the SEC in an industrial-scale alkaline water electrolyzer plant, Appl. Energ. 359 (2024), Article 122732.

G. Sakas, A. Ibáñez-Rioja, S. Pöyhönen, A. Kosonen, V. Ruuskanen, P. Kauranen, J. Ahola, Influence of the shunt currents in industrial-scale alkaline water electrolyzer plants, Renew. Energy 225 (2024), Article 120266.

Dynamic energy and mass balance model of a 50 kW PEM electrolyzer

The methodology and model showed excellent accuracy and proved to be a promising approach for dynamically modelling the behavior of PEM plants.

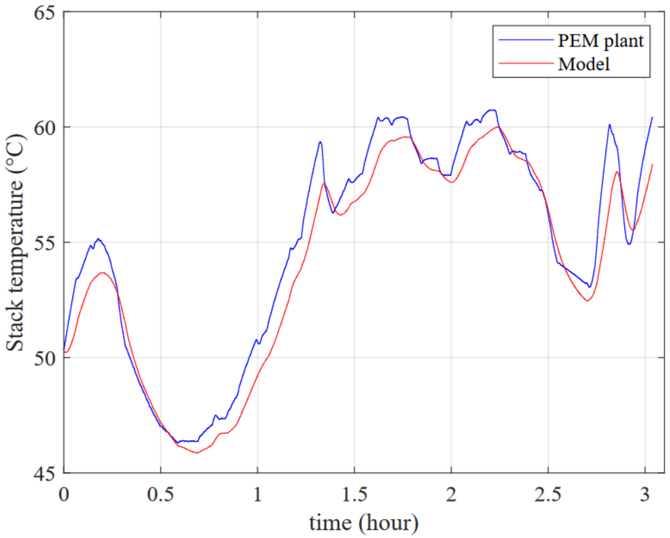


Figure: Dynamic stack temperature comparison between model and real PEM plant.

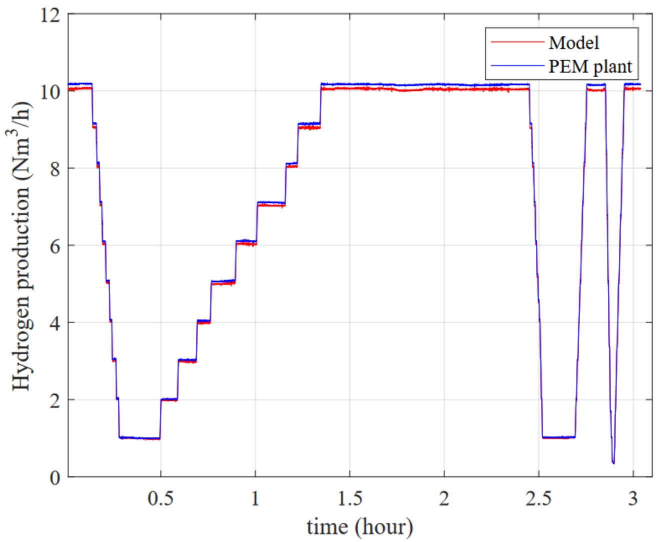


Figure: Dynamic hydrogen production comparison between model and real PEM plant.

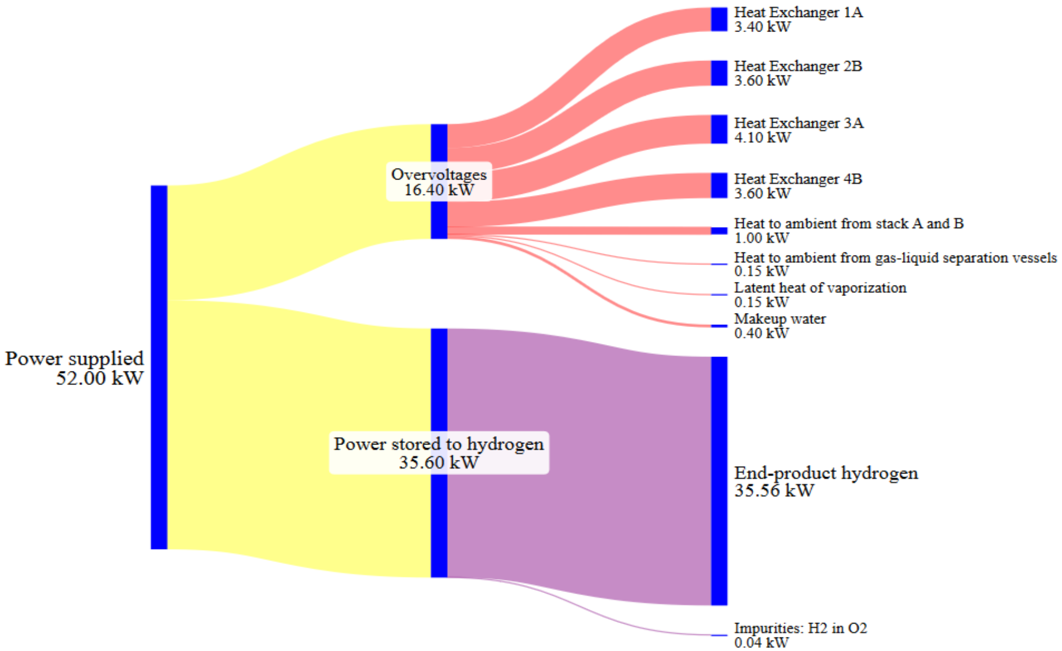


Fig. System-level power consumption during steady-state and nominal operation.

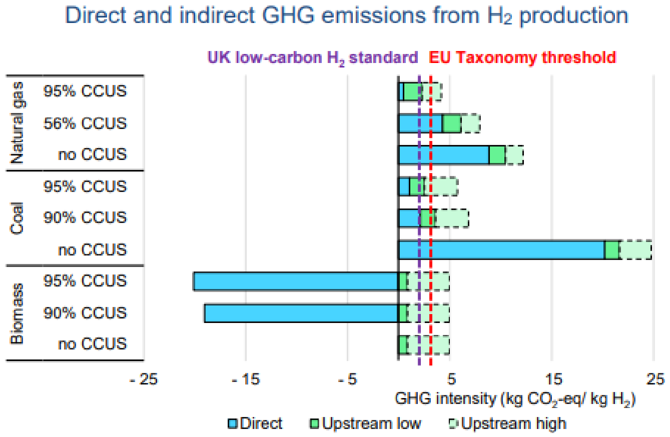
In review, preprint: G. Sakas, P. Rentschler, A. Kosonen, P. Holtappels, V. Ruuskanen, P. Kauranen, J. Ahola, R. Dittmeyer, Dynamic Mass and Energy Balance Model of a 50 Kw Proton Exchange Membrane Electrolyzer System. Applied Energy, 2024.

Towards added value of biogas – carbon capture and biohydrogen production

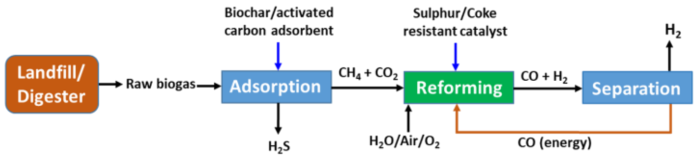
UNIVERSITY OF OULU

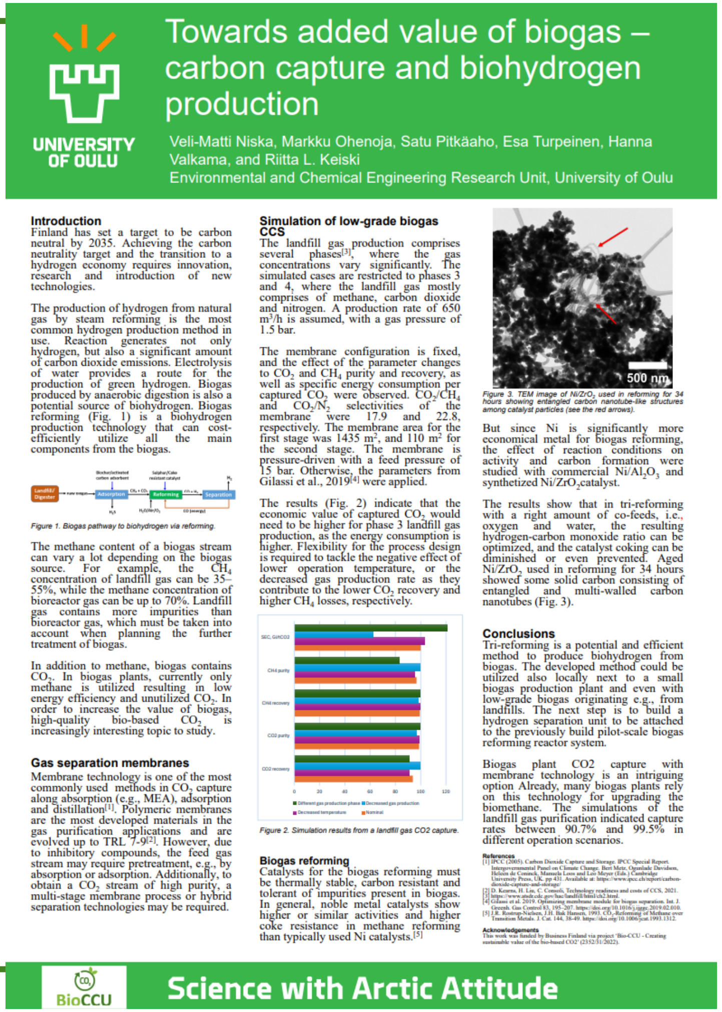
BioCCU

- Biogas plant can be equipped with membrane technology for CO_2 capture to lower the GHG emissions.
- **Simulation results of low-grade biogas CCS were presented.**
- Tri-reforming is a potential and efficient method to produce biohydrogen from biogas.
- **The effect of reaction conditions on activity and carbon formation was studied with 2 catalysts in tri-reforming and journal manuscript was submitted.**



GlobalHydrogenReview2022





Towards added value of biogas – carbon capture and biohydrogen production

UNIVERSITY OF OULU

Veli-Matti Niska, Markku Ohenoja, Satu Pitkäaho, Esa Turpeinen, Hanna Valkama, and Riitta L. Keiski
Environmental and Chemical Engineering Research Unit, University of Oulu

Introduction

Finland has set a target to be carbon neutral by 2035. Achieving the carbon neutrality target and the transition to a hydrogen economy requires innovation, research and introduction of new technologies.

The production of hydrogen from natural gas by steam reforming is the most common hydrogen production method in use. Reaction generates not only hydrogen, but also a significant amount of carbon dioxide emissions. Electrolysis of water provides a route for the production of green hydrogen. Biogas produced by anaerobic digestion is also a potential source of biohydrogen. Biogas reforming (Fig. 1) is a biohydrogen production technology that can cost-efficiently utilize all the main components from the biogas.

Figure 1. Biogas pathway to biohydrogen via reforming.

The methane content of a biogas stream can vary a lot depending on the biogas source. For example, the CH_4 concentration of landfill gas can be 35–55%, while the methane concentration of bioreactor gas can be up to 70%. Landfill gas contains more impurities than bioreactor gas, which must be taken into account when planning the further treatment of biogas.

In addition to methane, biogas contains CO_2. In biogas plants, currently only methane is utilized resulting in low energy efficiency and unutilized CO_2. In order to increase the value of biogas, high-quality bio-based CO_2 is increasingly interesting topic to study.

Gas separation membranes

Membrane technology is one of the most commonly used methods in CO_2 capture along absorption (e.g., MEA), adsorption and distillation[1]. Polymeric membranes are the most developed materials in the gas purification applications and are evolved up to TRL 7-9[2]. However, due to inhibitory compounds, the feed gas stream may require pretreatment, e.g., by absorption or adsorption. Additionally, to obtain a CO_2 stream of high purity, a multi-stage membrane process or hybrid separation technologies may be required.

Simulation of low-grade biogas CCS

The landfill gas production comprises several phases[3], where the gas concentrations vary significantly. The simulated cases are restricted to phases 3 and 4, where the landfill gas mostly comprises of methane, carbon dioxide and nitrogen. A production rate of 650 m^3/h is assumed, with a gas pressure of 1.5 bar.

The membrane configuration is fixed, and the effect of the parameter changes to CO_2 and CH_4 purity and recovery, as well as specific energy consumption per captured CO_2 were observed. CO_2/CH_4 and CO_2/N_2 selectivities of the membrane were 17.9 and 22.8, respectively. The membrane area for the first stage was 1435 m^2, and 110 m^2 for the second stage. The membrane is pressure-driven with a feed pressure of 15 bar. Otherwise, the parameters from Gilassi et al., 2019[4] were applied.

The results (Fig. 2) indicate that the economic value of captured CO_2 would need to be higher for phase 3 landfill gas production, as the energy consumption is higher. Flexibility for the process design is required to tackle the negative effect of lower operation temperature, or the decreased gas production rate as they contribute to the lower CO_2 recovery and higher CH_4 losses, respectively.

Figure 2. Simulation results from a landfill gas CO2 capture.

Biogas reforming

Catalysts for the biogas reforming must be thermally stable, carbon resistant and tolerant of impurities present in biogas. In general, noble metal catalysts show higher or similar activities and higher coke resistance in methane reforming than typically used Ni catalysts.[5]

Figure 3. TEM image of Ni/ZrO_2 used in reforming for 34 hours showing entangled carbon nanotube-like structures among catalyst particles (see the red arrows).

But since Ni is significantly more economical metal for biogas reforming, the effect of reaction conditions on activity and carbon formation were studied with commercial Ni/Al_2O_3 and synthetized Ni/ZrO_2catalyst.

The results show that in tri-reforming with a right amount of co-feeds, i.e., oxygen and water, the resulting hydrogen-carbon monoxide ratio can be optimized, and the catalyst coking can be diminished or even prevented. Aged Ni/ZrO_2 used in reforming for 34 hours showed some solid carbon consisting of entangled and multi-walled carbon nanotubes (Fig. 3).

Conclusions

Tri-reforming is a potential and efficient method to produce biohydrogen from biogas. The developed method could be utilized also locally next to a small biogas production plant and even with low-grade biogas originating e.g., from landfills. The next step is to build a hydrogen separation unit to be attached to the previously build pilot-scale biogas reforming reactor system.

Biogas plant CO2 capture with membrane technology is an intriguing option Already, many biogas plants rely on this technology for upgrading the biomethane. The simulations of the landfill gas purification indicated capture rates between 90.7% and 99.5% in different operation scenarios.

References
[1] IPCC (2005). Carbon Dioxide Capture and Storage. IPCC Special Report. Intergovernmental Panel on Climate Change. Bert Metz, Ogunlade Davidson, Heleen de Coninck, Manuela Loos and Leo Meyer (Eds.) Cambridge University Press, UK. pp 431. Available at: https://www.ipcc.ch/report/carbon-dioxide-capture-and-storage/
[2] D. Kearns, H. Liu, C. Consoli, Technology readiness and costs of CCS, 2021.
[3] https://www.atsdr.cdc.gov/hac/landfill/html/ch2.html.
[4] Gilassi et al. 2019. Optimizing membrane module for biogas separation. Int. J. Greenh. Gas Control 83, 195–207. https://doi.org/10.1016/j.ijggc.2019.02.010.
[5] J.R. Rostrup-Nielsen, J.H. Bak Hansen, 1993. CO_2-Reforming of Methane over Transition Metals. J. Cat. 144, 38-49. https://doi.org/10.1006/jcat.1993.1312.

Acknowledgements
This work was funded by Business Finland via project 'Bio-CCU - Creating sustainable value of the bio-based CO2' (2352/31/2022).

BioCCU

Science with Arctic Attitude

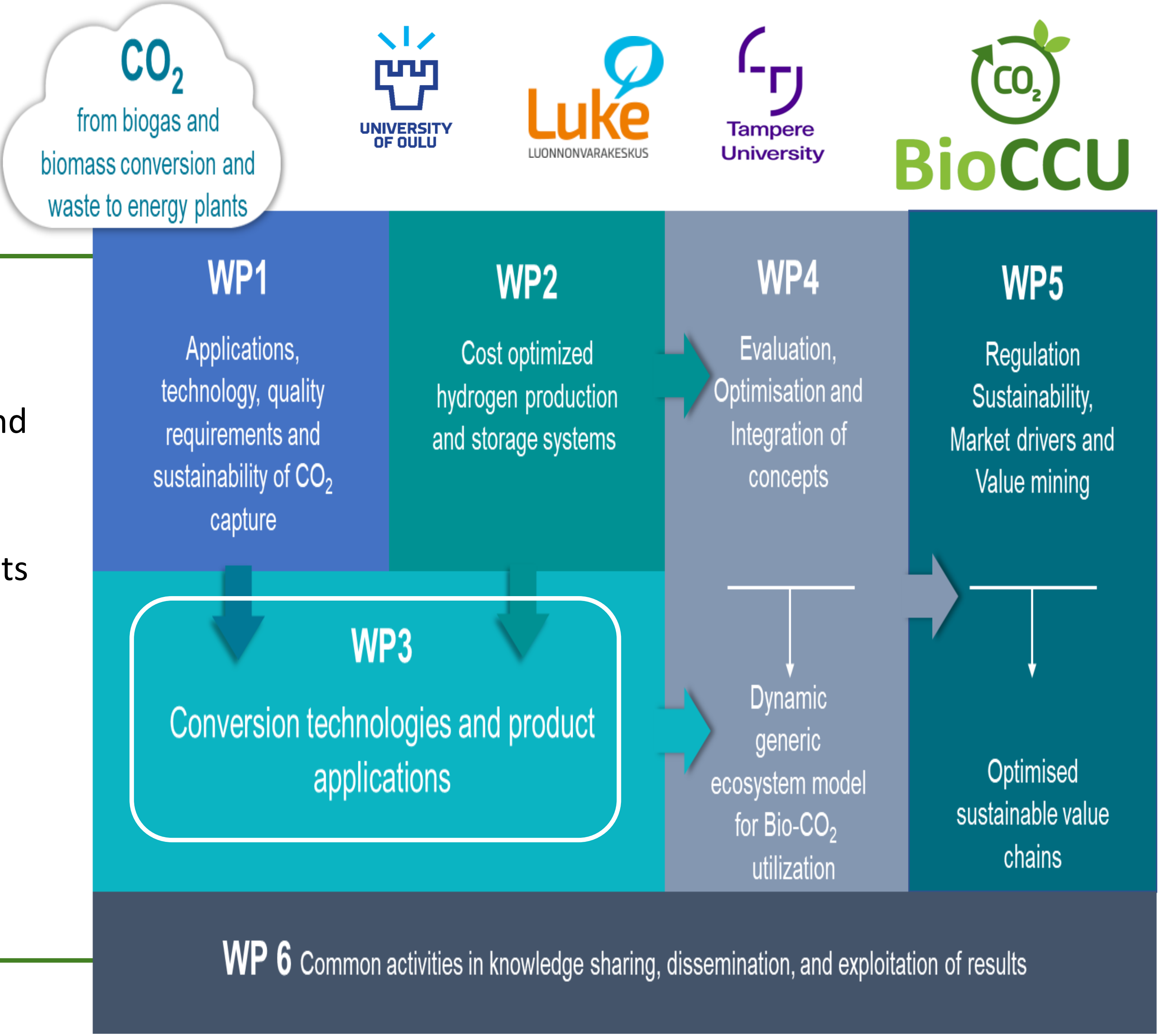
BioCCU-tutkijoiden esitykset:

WP3: Conversion Technologies and Product Applications

Riitta Keiski (UOULU), Tero Joronen (TAU) and Saija Rasi (LUKE)

WP3: Targets

- Analysis of alternative products to enter the Bio-CCU markets
- New (circular) catalyst materials and conversion routes for green fuels and chemicals production
- Increasing the value of end products in biogas plants (in-situ methanation)
- Direct conversion of CO_2 to solid carbon in large quantities and elevated value (earth construction and agricultural context)



CO_2 from biogas and biomass conversion and waste to energy plants

WP1 Applications, technology, quality requirements and sustainability of CO_2 capture

WP2 Cost optimized hydrogen production and storage systems

WP4 Evaluation, Optimisation and Integration of concepts

Dynamic generic ecosystem model for Bio-CO_2 utilization

WP5 Regulation Sustainability, Market drivers and Value mining

Optimised sustainable value chains

WP3 Conversion technologies and product applications

WP 6 Common activities in knowledge sharing, dissemination, and exploitation of results

WP3: Tasks and Results

TASK 3.1

New knowledge on utilizing CO_2 as a feedstock to alternative products (Responsible leader: UOULU)

TASK 3.2

Development of new circular catalyst materials and conversion routes for P2G and P2C (Responsible leader: UOULU)

TASK 3.3

Development of biogas plants as a biorefinery (Responsible leader: LUKE)

TASK 3.4

Development of continuous disc-shaped electrolysis (Responsible leader: TAU)

TASK 3.5

INTEGRATION TO WP4 AND WP5 VALUE CHAINS

(Responsible leader: UOULU)

- **Task 3.1:** The TRLs for the catalytic conversion of CO_2 into various products are at very different stages. The most interesting routes from the research point of view are the ones towards high value products.

- **Task 3.2:** The designed and prepared novel 10w-% NiAl xerogel catalyst is found to be active in the reverse water gas shift reaction (RWGS), and in addition it shows activity in CO_2 methanation.

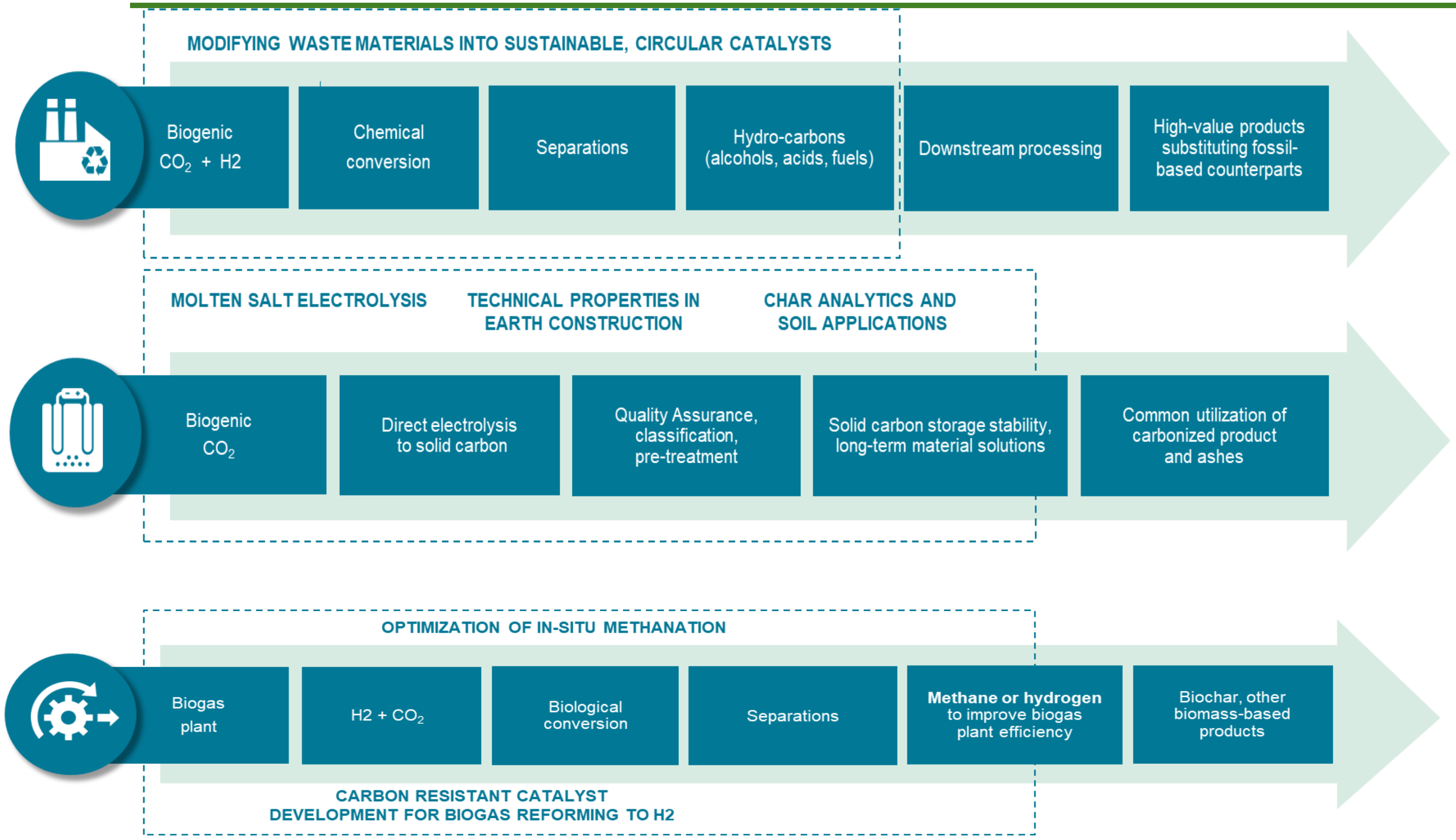
- **Task 3.3:** The amount of CO_2 in biogas can be reduced by feeding hydrogen into the biogas reactor. The efficient methanation of hydrogen and CO_2 can be influenced for example by the amount of hydrogen and the periodicity of the feed.

- **Task 3.4:** Technical carbon production by electrolysis in molten salt was made in a continuous mode for the first time in the world. Production in the bench-scale was stable, and the morphology and quality of the product constant. Stable material for the electrodes and the equipment was found. Carbon was not contaminated by impurities. Utilization of carbon was studied in land construction and was found suitable as being light weight and stable material. The stability of carbon in soil was studied, and the first results showed that stability for 100 years is probable.

- **Task 3.5:** New information was received for the value chains studied in the BioCCU project (Chemical and Biological conversion routes as well as Solid carbon route) and in the ForestCUMP project (Chemical conversion route via RWGS and Fischer-Tropsch processes to polymers).

WP3: Overview of Technological Development in the Project's Production Chains

BioCCU



MODIFYING WASTE MATERIALS INTO SUSTAINABLE, CIRCULAR CATALYSTS

Biogenic CO_2 + H2

Chemical conversion

Separations

Hydro-carbons (alcohols, acids, fuels)

Downstream processing

High-value products substituting fossil-based counterparts

MOLTEN SALT ELECTROLYSIS

TECHNICAL PROPERTIES IN EARTH CONSTRUCTION

CHAR ANALYTICS AND SOIL APPLICATIONS

Biogenic CO_2

Direct electrolysis to solid carbon

Quality Assurance, classification, pre-treatment

Solid carbon storage stability, long-term material solutions

Common utilization of carbonized product and ashes

OPTIMIZATION OF IN-SITU METHANATION

Biogas plant

H2 + CO_2

Biological conversion

Separations

Methane or hydrogen to improve biogas plant efficiency

Biochar, other biomass-based products

CARBON RESISTANT CATALYST DEVELOPMENT FOR BIOGAS REFORMING TO H2

Biological conversion route (BioCCU)

TASK 3.5

INTEGRATION TO WP4 AND WP5 VALUE CHAINS

(Responsible leader: UOULU)

Solid carbon conversion (BioCCU)

Chemical conversion routes

- **Catalytic conversion (BioCCU)**
- **Fischer-Tropsch synthesis (ForestCUMP)**

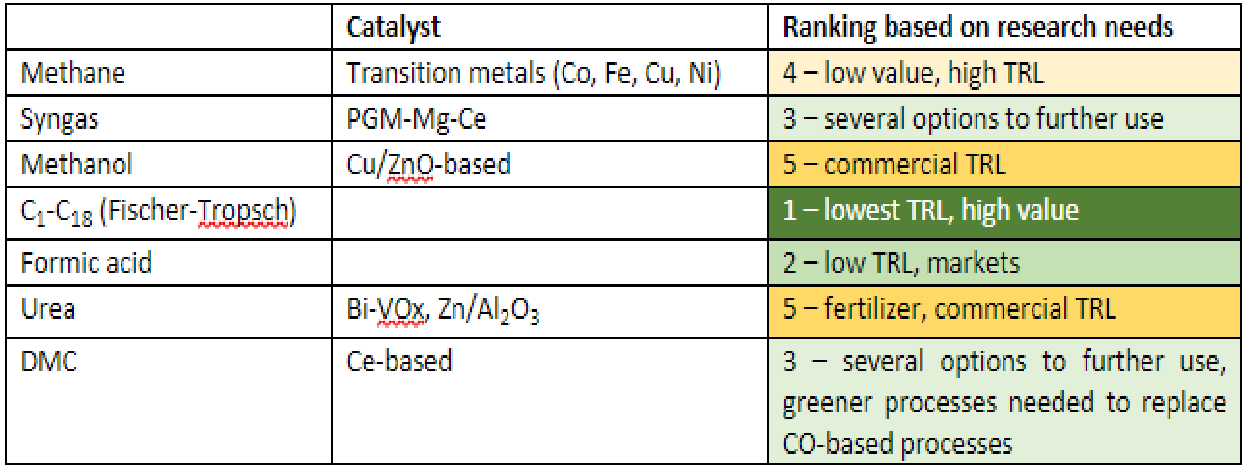
BUSINESS FINLAND

WP3: New Knowledge on CO_2 Utilization

- **Literature survey** on conversion (catalytic and biological) of CO_2 to valuable products
- Based on the survey, selected products/processes via the catalytic conversion route to be further studied are:
    1. Methanation of CO_2 (CH_4)
    2. Fischer-Tropsch (C1-C5 products)
    3. Methanol and further DMC production
- The information collected in the Task 3.1 is used as catalysts and reactions selection in the Task 3.2

TASK 3.1

New knowledge on utilizing CO_2 as a feedstock to alternative products (Responsible leader: UOULU)



	Catalyst	Ranking based on research needs
Methane	Transition metals (Co, Fe, Cu, Ni)	4 – low value, high TRL
Syngas	PGM-Mg-Ce	3 – several options to further use
Methanol	Cu/ZnO-based	5 – commercial TRL
C_1-C_{18} (Fischer-Tropsch)		1 – lowest TRL, high value
Formic acid		2 – low TRL, markets
Urea	Bi-VOx, Zn/Al_2O_3	5 – fertilizer, commercial TRL
DMC	Ce-based	3 – several options to further use, greener processes needed to replace CO-based processes

WP3: Literature Survey (Chemical & Biological)

- The literature survey of production of various P2X compounds (fuels, chemicals, and other products)
- The information gained from the literature is used to design and prepare the catalysts for methane production

TASK 3.1

New knowledge on utilizing CO_2 as a feedstock to alternative products (Responsible leader: UOULU)

Product	Catalyst	Ranking based on research needs
Methane	Transition metals (Co, Fe, Cu, Ni)	Low value, TRL 9
Methanol	Cu/ZnO-based	Several options to further use, commercial TRL 9
Urea	Bi-VOx, Zn/Al_2O_3	Fertilizer, commercial TRL 9
DMC	Ce-based	Several options to further use, greener processes needed to replace CO-based processes, TRL 8
Syngas	PGM-Mg-Ce	Several options to further use, TRL 6
Formic acid	PGM (Pd, Ru)	Markets, TRL 6
C_3-C_{18} (F-T)	Fe-based	High value, TRL 5

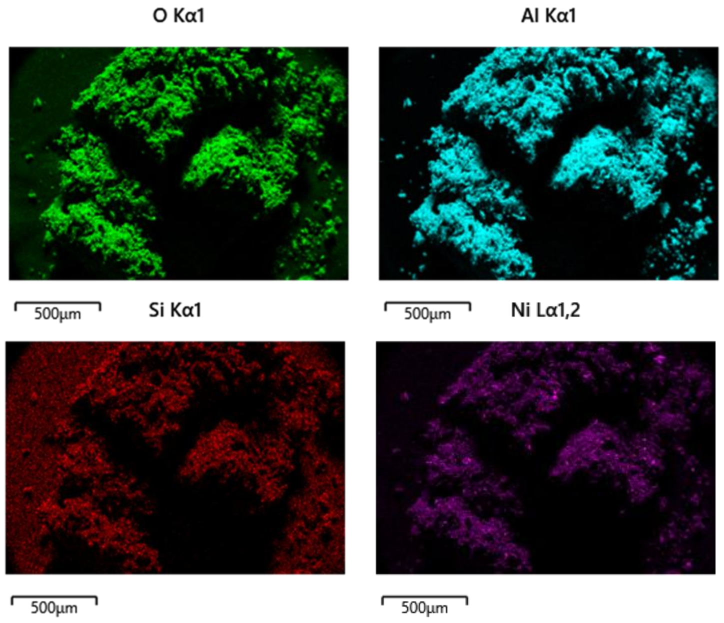
Product	Technology	Ranking based on research needs
Methane	Ex-situ methanation	Low value, TRL 9
Methane	In-situ methanation	Low value, TRL 6-7
Methanol	Aerobic fermentation	Wide variation in production yield
Ethanol	Anaerobic fermentation	Usually mixture of compounds are produced, wide variation in TRL (based on literature)
Lipids	Microalgae	TRL 4-5
Organic acids	Aerobic OR anaerobc fermentation	TRL 3-5, wide possibilities for end products

WP3: Catalysts for P2X applications

TASK 3.2

Development of new circular catalyst materials and conversion routes for P2G and P2C (Responsible leader: UOULU)

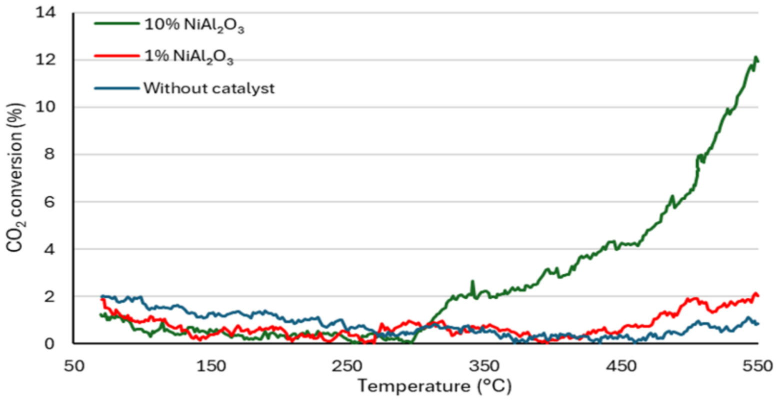
- Two catalysts, 1 wt-% and 10 wt-% $NiAl_2O_3$, were prepared by sol-gel synthesis and a subcritical drying method for aerogels.
- Physisorption measurements, FE-SEM, DRIFT and XRD.
- Small amounts of catalysts were tested in an activity test for methanation reaction.
  - Total gas flow 400 ml/min, consisting of 1% CO_2, 4% H_2, and the rest being inert gases.

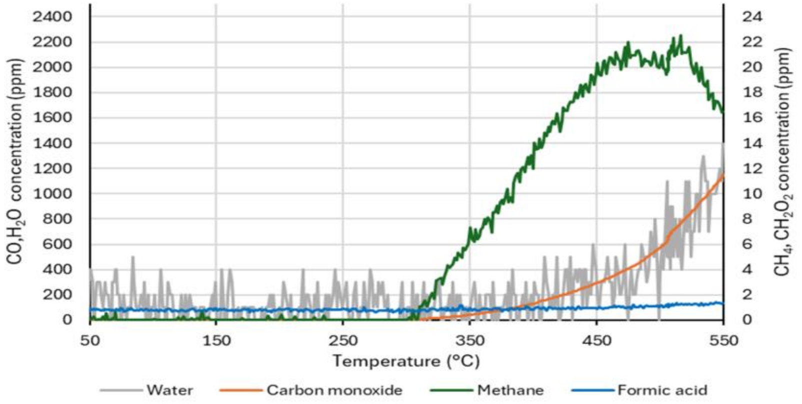


- Annunen L. (2024) Catalysts for P2X applications. Master’s thesis, University of Oulu, 85 p.

WP3: Catalysts for RWGSR and CO_2 methanation

- 10 wt-% $NiAl_2O_3$ catalysts showed the most promising results.
- Conversion was ~12% at 548 °C.
- 23 ppm of CH_4 at 515 °C.
- 1149 ppm of CO and 1400 ppm of H_2O were formed indicating a possible RWGS-reaction.
- 1 wt-% $NiAl_2O_3$ catalyst showed no activity in methana reaction.





TASK 3.2

Development of new circular catalyst materials and conversion routes for P2G and P2C (Responsible leader: UOULU)

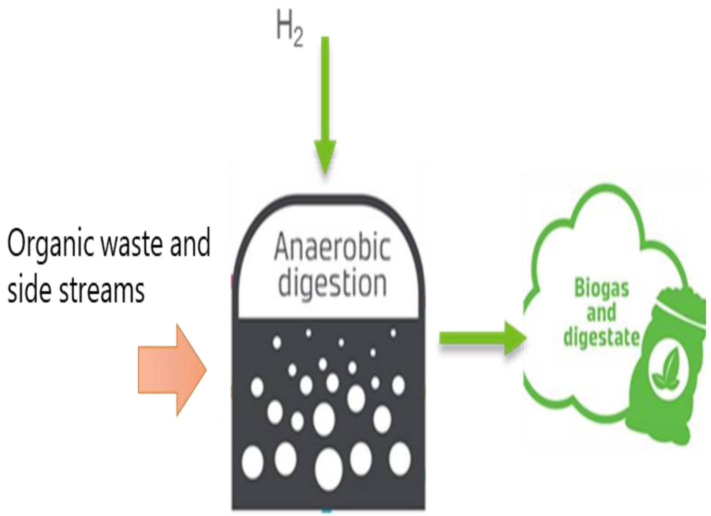
- Annunen L, Huuhtanen M, Tiainen M, Catalysts for P2X applications. Poster.

WP3: Biological Production of Methane

TASK 3.3

Development of biogas plants
as a biorefinery (Responsible leader: LUKE)

- Poster: CO_2 utilization with in-situ methanation (Luke)



WP3: Continuous Electrolysis in Biochar Production

TASK 3.4

Development of continuous disc-shaped electrolysis (Responsible leader: TAU)

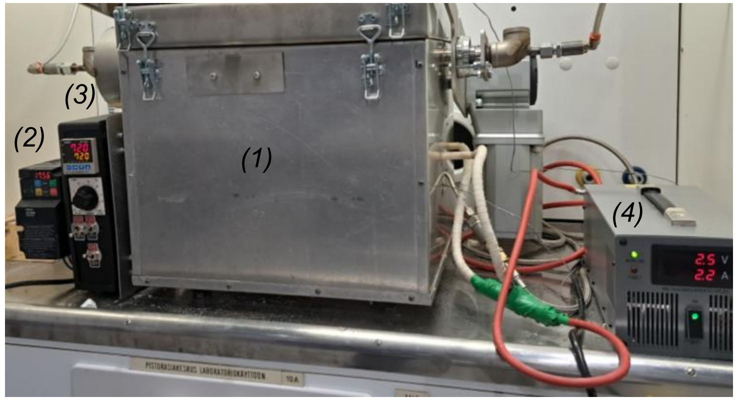
Next slides indicate the subtasks

1. Develop a scalable continuous molten salt electrolysis process, TAU
2. Molten salt electrolysis chemistry and carbon product properties, TAU Aerosol physics
3. Technical properties of solid carbon products will be investigated in earth construction, applications (e.g. light-weight embankment fill, frost insulation material in traffic infrastructures), TAU TERRA Research Center
4. Stability in soil application, Luke

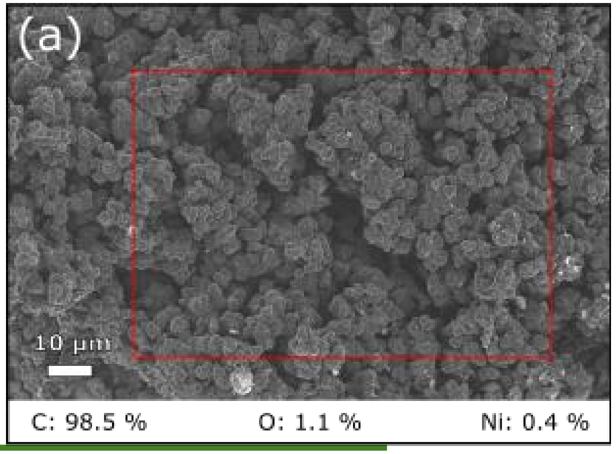
- Poster: Valuable Solid Carbon with Molten Salt Electrolysis
- Poster: CO_2capture in form of solid carbonmaterials–Soil applications (Luke)

WP3: Scalable Continuous System

- Molten salt electrolysis occurs at high temperatures, 750 °C
- Lithium carbonate being the most extensively studied
- In Hygcel, the nickel cathode and tin dioxide anode were stable
- A continuous system featuring a rotary cathode was designed and constructed at Tampere University
- Ultimately, after several rebuilds, the system operated for 30 hours without any issues
- Product is homogeneous and pure carbon



Continous system equipments (1) oven, (2) VSD, (3) Temperature control, and (4) Power supply



TASK 3.4

Development of continuous disc-shaped electrolysis (Responsible leader: TAU)

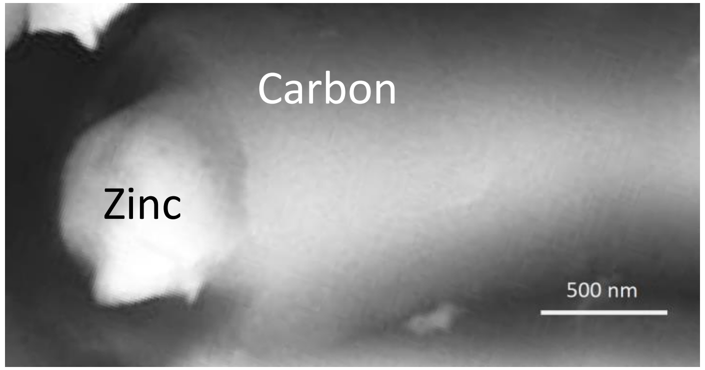
Bio-CCU / WP3 / TAU Aerosol Physis

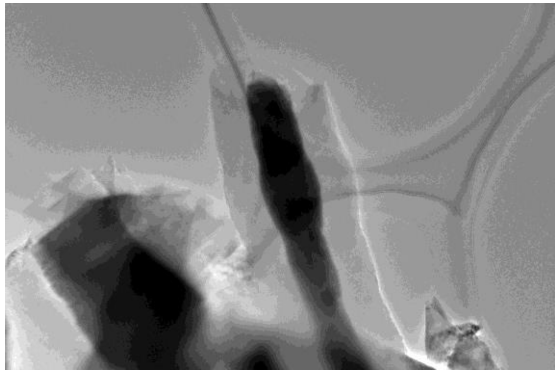
Researchers: J.M. Mäkelä (Prof.), M. Sorvali (PhD), A. Charmforoushan (MSc), I. Suontausta (BSc/MSc)

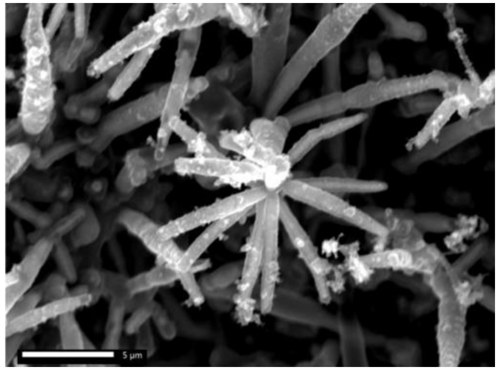
Focus: Theoretical and experimental analysis on solid carbon products in molten salt carbon capture

Activities: Specific interest on transition metal nucleated catalysis & formation of carbon allotropies

- Literature study on solid carbon products in molten salt carbon capture process
- Transition metal nucleated catalysis -- Survey of carbon structure analysis
- Research exchange visit to Lund University, Division of Solid State Physics, in March-April 2024; → Microscopy studies and collaboration on structure analysis (Profs. K. Deppert & M.E. Messing)
- Two journal article manuscripts, to be submitted during 2024:
    - ”Continuous production of carbon nanostructures from captured CO_2 in molten salt electrolysis ” (Sorvali, M. et al.)
      → Carbon nano onions → potential application in supercapacitors etc.
    - ”Palm-shaped Zinc-Carbon nanocomposites fabricated by molten salt electrolysis” (Mäkelä, J.M. et al.) → nanoelectronics







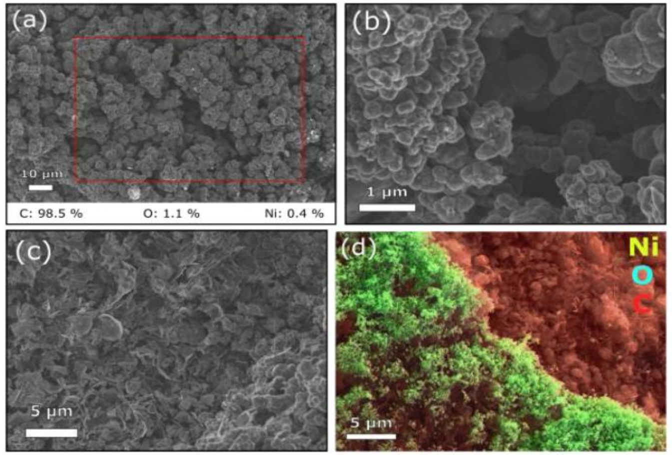


Figure 3: Typical SEM images showing mostly carbon nano-onions (a-b), an SEM image showing plate-like carbon particles (c), and an EDS map depicting nickel oxide impurity particles and a mixture of nano-onions and plate-like carbon particles (d). Image (a) also shows EDS results of a map scan performed on the area marked with a red rectangle.

TASK 3.4

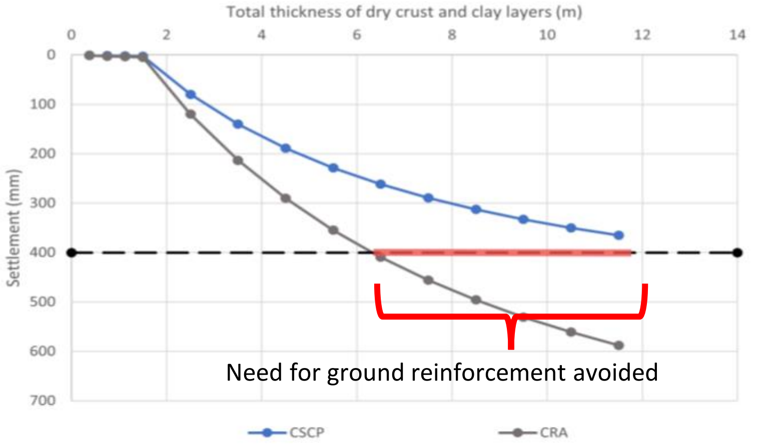
Development of continuous disc-shaped electrolysis (Responsible leader: TAU)

WP3: Use of Solid Carbon in Infrastructure Construction

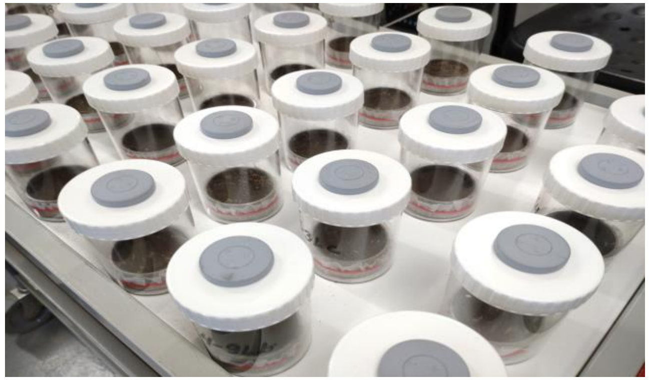
TASK 3.4

Development of continuous disc-shaped electrolysis (Responsible leader: TAU)

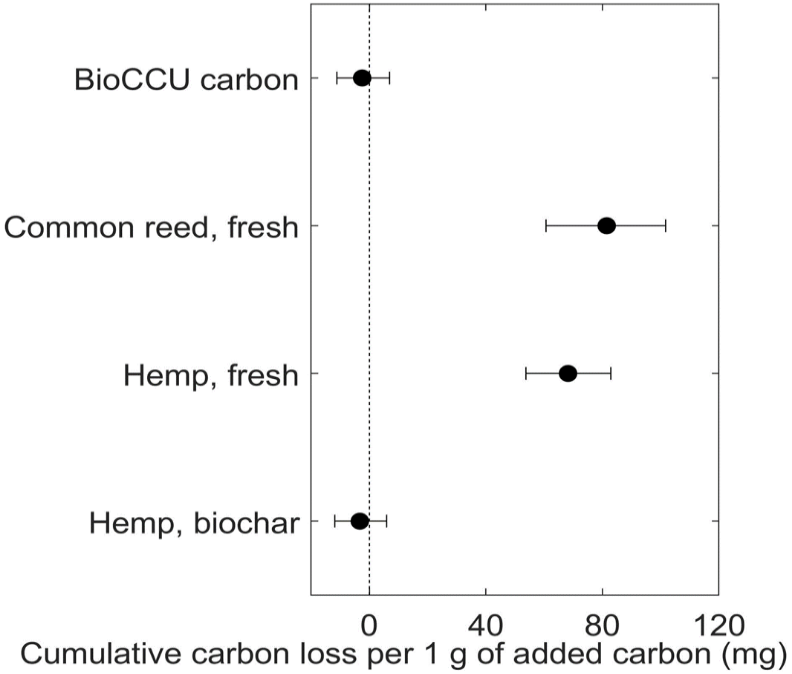
- Construction industry is using annually huge amounts of virgin natural aggregates; in Finland alone > 100 Mtons (up to 60 Mm^3)
- Technically even several Mm^3 of natural aggregates could be replaced by solid carbon in Finland every year; on the other Northernly located countries the technical potential is manyfold
- The most high-value large-volume application is to use solid carbon as light-weight fill and/or frost insulation material - thereby even the need for expensive and CO$_2$-intensive ground reinforcements (stabilization, piling) on soft subsoil areas could be avoided
- Smaller volume applications include the utilization of solid carbon as an additive in concrete and asphalt production, or as a soil stabilizing agent
- The most important challenges remaining to be solved include: price/economy, matching together supply and demand both in
  time and spatially, workability, impacts on health and environment



WP3: CO_2 Captured in Form of Solid Carbon Materials – Soil Applications



- Captured solid carbon can be applied in agricultural soil and stored potentially for centennial-scale.
- The stability of solid carbon in soil was studied using a 90-day incubation experiment and compared to that of biochar and fresh plant material.
- Cumulative carbon loss per one gram of added carbon (3 mg) did not statistically differ from that of the control soil or hemp biochar
  - For comparison, the cumulative carbon loss of fresh plant materials was 81 mg for common reed and 68 mg for hemp.
- A short-term incubation experiment suggests that the stability of Bio-CCU carbon in soil is comparable to that of biochar.
  - Biochars are considered as one of the potential carbon sequestration measures capable to store carbon in soil over 100-year.
  - As analogy to biochars, possible benefits for crop production need to be studied.



TASK 3.4

Development of continuous disc-shaped electrolysis (Responsible leader: TAU)

WP3: Researchers

- UOULU: firstname.lastname(at)oulu.fi
  - Riitta Keiski, PI until 31.3.2024; Esa Muurinen, PI from 1.4.2024
  - Mika Huuhtanen, Laura Annunen, Ahmed Rufai Dahiru, Minna Tiainen
- TAU: firstname.lastname(at)tuni.fi
  - Tero Joronen
  - Jyrki Mäkelä, Miika Sorvali, Ida Suontausta, Pauli Kolisoja, Ville Orkola, Nuutti Vuorimies
- LUKE: firstname.lastname(at)luke.fi
  - Saija Rasi
  - Markku Vainio, Ilmari Laaksonen, Kimmo Rasa, Jaakko Heikkinen, Mari Räty, Satu Ervasti

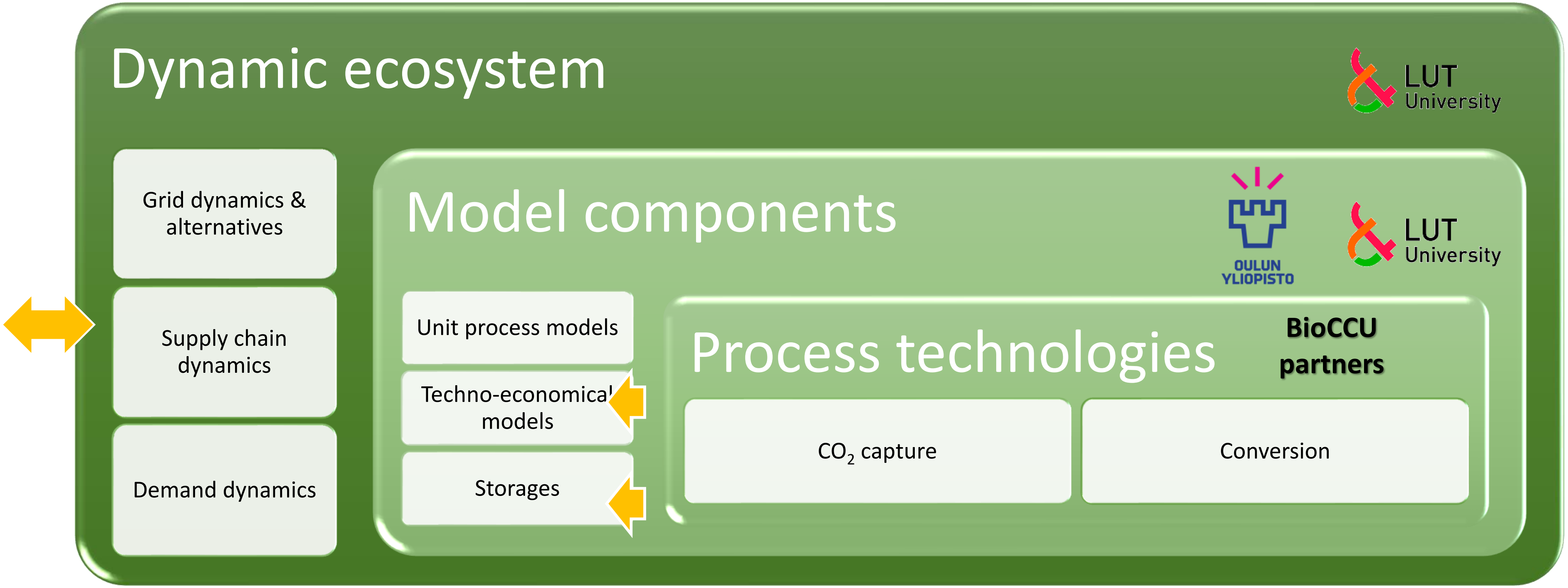
WP4: Simulation of Biogenic Carbon Capture and Utilization Process Chain

Conference paper presented in SIMS EUROSIMS 2024, 11.-12.9.2024 in Oulu

Kristian Tiiro, Markku Ohenoja, Outi Ruusunen, Riitta L. Keiski and Mika Ruusunen

Environmental and Chemical Engineering, University of Oulu

WP4: Towards BioCCU hub model



BioCCU partners

Regulation
Sustainability
Markets

Dynamic ecosystem

Grid dynamics & alternatives

Supply chain dynamics

Demand dynamics

Model components

Unit process models

Techno-economical models

Storages

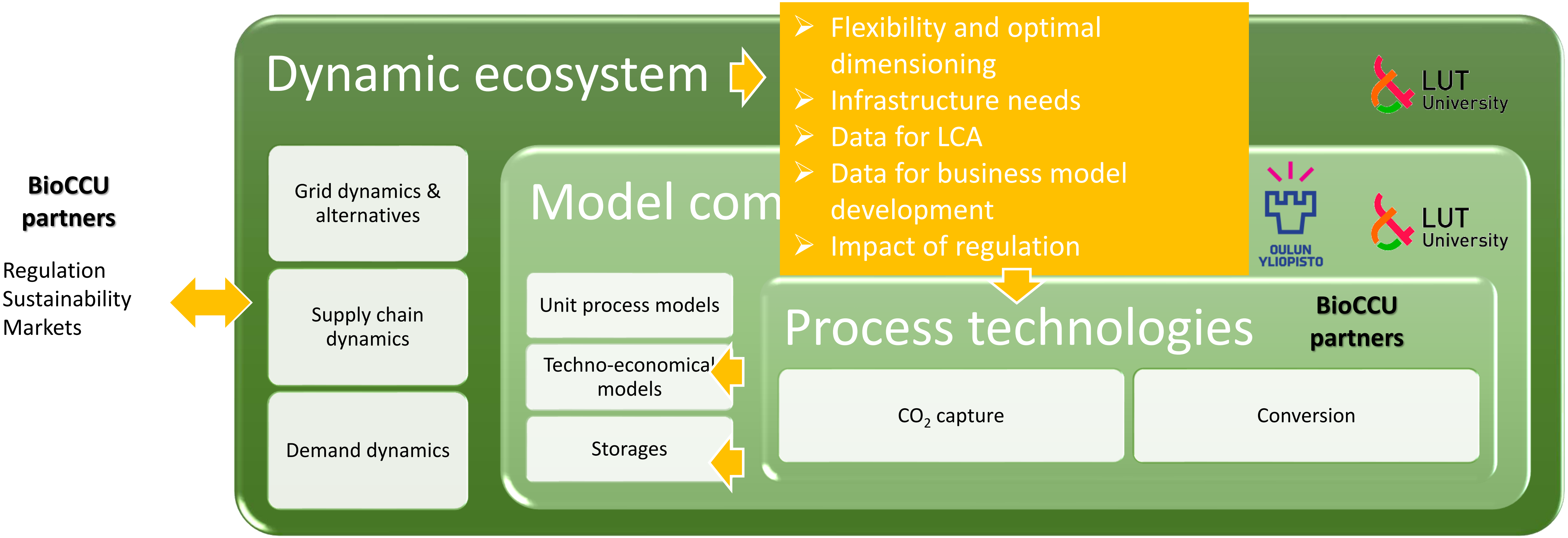
Process technologies

BioCCU partners

CO_2 capture

Conversion

WP4: Towards BioCCU hub model



BioCCU partners

Regulation
Sustainability
Markets

Dynamic ecosystem

- Flexibility and optimal dimensioning
- Infrastructure needs
- Data for LCA
- Data for business model development
- Impact of regulation

Grid dynamics & alternatives

Supply chain dynamics

Demand dynamics

Model com

Unit process models

Techno-economical models

Storages

Process technologies

BioCCU partners

CO_2 capture

Conversion

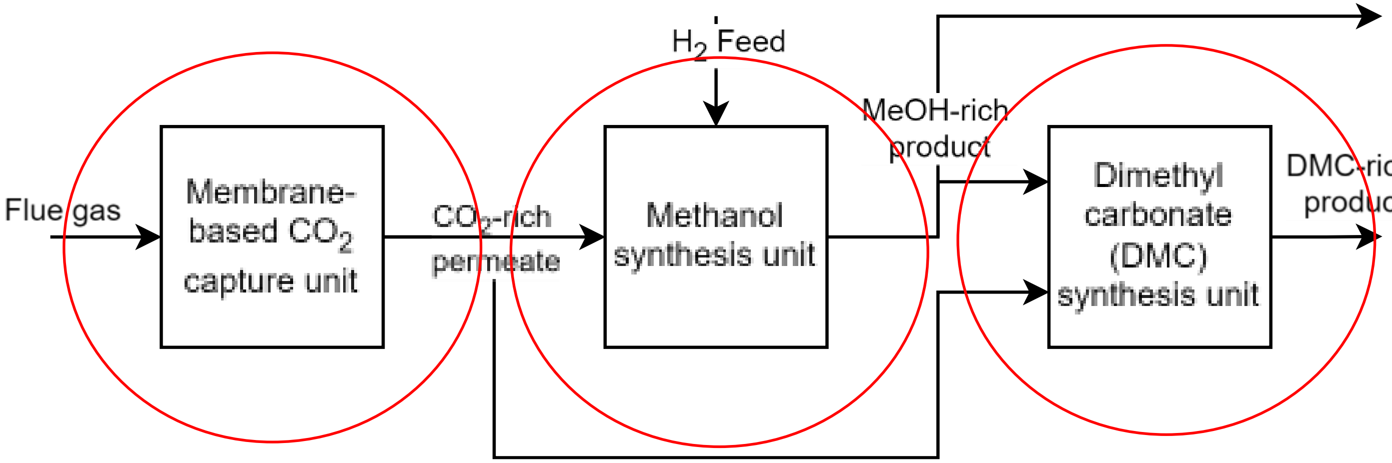
Motivation

- Evaluate Key Performance Indicators (KPIs) of CCU process chain:
  - Yields
  - Specific electricity consumptions (SEC)

→Increase understanding how different circumstances affect KPIs

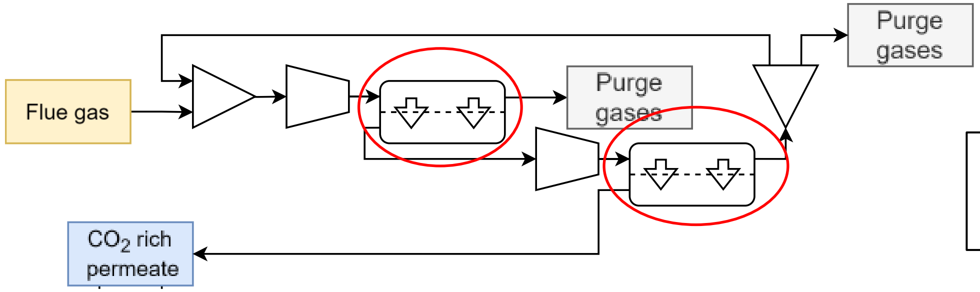
Simulated process chain

- Membrane separation instead of prevailing monoethanolamine (MEA) absorption
- Methanol synthesis according to prevailing industry practices
- For DMC, an emerging eco-friendly synthesis route with low technological readiness level



Model structure

- 2-stage CO_2 separation with recycle stream
  - Hollow fibre membranes[1,2]
- Methanol synthesis in Lurgi-type tube-end-shell reactor modeled in steady state
  - $Cu/ZnO/Al_2O_3$ catalyst
- DMC synthesis modeled as batch reactor with kinetics fitted to literature data[3] using differential evolution[4]
  - Assuming perfect separation in outlet stream
- Electricity consumptions for membrane unit and MeOH due to compressors
- MATLAB models, methanol synthesis model publicly available on Github[5]

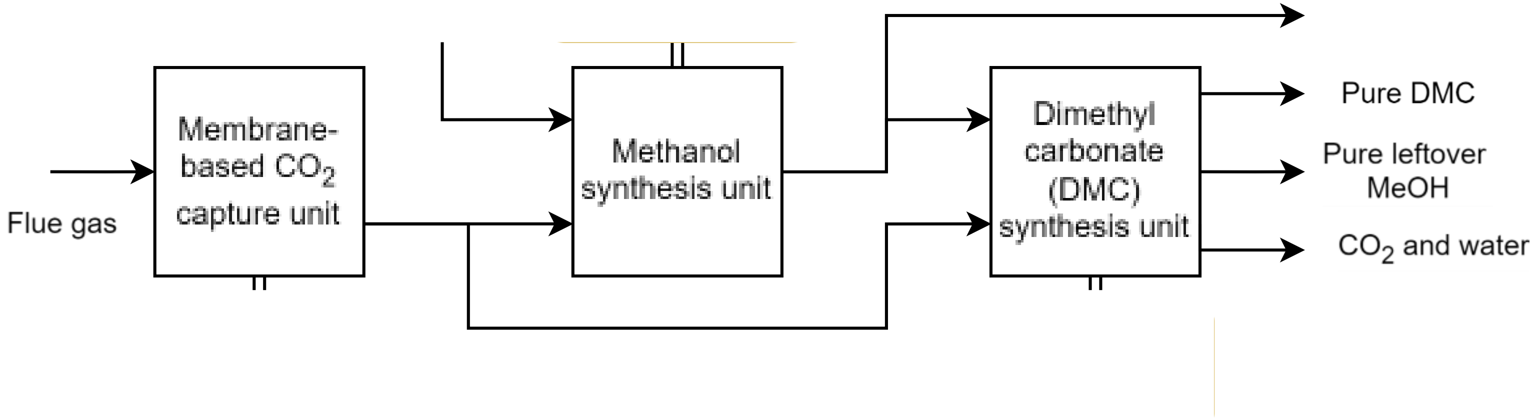


$$CO_2 + 3H_2 \rightleftarrows CH_3OH + H_2O$$
$$CO_2 + H_2 \rightleftarrows CO + H_2O$$

1. (Asadi & Kazempoor, 2021); 2. (Khalilpour et al., 2012)
3. (Camy et al., 2003); 4. (Storn and Price, 1997);
5. (Tiiro, 2024)

Simulation settings

- Flue gas from pulp mill recovery boiler[6]
  - Cooled to 50 °C and dried
  - CO_2, N_2, O_2
- CO_2-rich permeate division
  - 125 mol/s permeate → DMC synthesis
  - Rest → MeOH synthesis
- MeOH requires H_2 feed
  - Assumed available and 100 % pure
  - Always 3:1 molar ratio of H_2:CO_2
- MeOH division
  - 45 mol/s MeOH → sold directly
  - Rest → DMC synthesis



6. (Gardarsdoţr et al., 2014)

Simulation scenarios

A. Sensitivity to feed conditions

- Case I, II , III

  ± 10% Flue gas flow

  ± 5 % CO_2 concentration

B. Process chain flexibility to compensate for low feed flow (Case III)

- Temperatures, pressures, recycle ratios optimized

C. Sensitivity to modeling uncertainties

1. Reaction kinetic parameters
2. Equipment sizing
3. Long-term stability of the process

A. Sensitivity to feed fluctuations

	Case I	Case II	Case III
Captured CO_2 flow (mol_{CO2} / s)	430	470	388
Captured CO_2 quality (mol-%)	97.8	98.2	97.4

	Case I	Case II	Case III
Flue gas flow (mol/s)	3734	4107	3361

- CO2 capture rate ± 4 %-units
- MeOH yield and both SECs, small changes (≈±1%)
- DMC yield changes ±5 %-units mainly due to feed ratio changes

B. Process chain flexibility

	Case I	Case III
Flue gas flow (mol/s)	3734	3361
CO_2 content (mol-%)	16.4	15.6

- Increasing CO_2 capture rate, worsens permeate purity
- SEC better for CO_2 capture, worse for MeOH synthesis

→ Overall, 12 % increase in kW

- Is it possible to achieve equal output with Case III as with Case I by changing operational variables?

→ Yes

- Manipulated variables from a solver
  - Membrane:
    - 2nd stage pressure: 5 → 11.5 bar
  - MeOH synthesis:
    - Reactor inlet temperature: 237 → 232 ℃
    - Reactor shell side temperature: 260 → 261 ℃
    - Recycle ratio: 5.0 → 11.2

	Base Case III	Flexible Case III
Captured CO_2 quality (mol-%)	97.4	91.3
CO_2 capture rate (mol-%)	74.0	82.0

C. Sensitivity to model uncertainties

- Comparisons made to Case I
- C1. Reaction kinetics parameters
  - MeOH synthesis two kinetic parameter values adjusted from original source[7] to updated[8]
- C2. Equipment sizing
  - 2.5 % decrement in membrane fiber radius[9]
- C3. Long-term stability of the process
  - $Cu/ZnO/Al_2O_3$ catalyst activity 100 → 50 %, simulating 1 year age in the 3-to-4-year lifespan[10,11]

→ C1. Results to MeOH production

- MeOH yield 94.1→ 96.7 %
- SEC 33.9 → 33.0 kJ_{el} / mol_{MeOH}

→ C2. Results to membrane CO_2 capture

- CO_2 purity 97.8 → 97.6 %
- CO_2 capture rate 70.1 → 69.2 %
- SEC 78.4 → 82.0 kJ_{el} / mol_{CO2}

→ C3. Results to MeOH production

- MeOH yield 94.1→ 74.2 %
- SEC 33.9 → 42.6 kJ_{el} / mol_{MeOH}

7. (Bussche & Froment, 1996); 8. (Mignard & Pritchard, 2008);
9. (Bocciardo, 2015); 10. (Bozzano & Manenti, 2016);
11. (Parvasi et al., 2008);

Conclusions

- KPIs insensitive to flue gas variations
- Flexible operation → same production with 10 % less flue gas and 5 % less CO_2 content
- Large impact from model parameters and assumptions
  - Industrial data required for realistic models
  - Long-term effects should be considered in techno-economic analyses, especially catalyst aging
  - Carbon capture and green H_2 expensive → Process design, such as reactor sizing needs to optimized along operational costs

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WP4: BioCCU hub

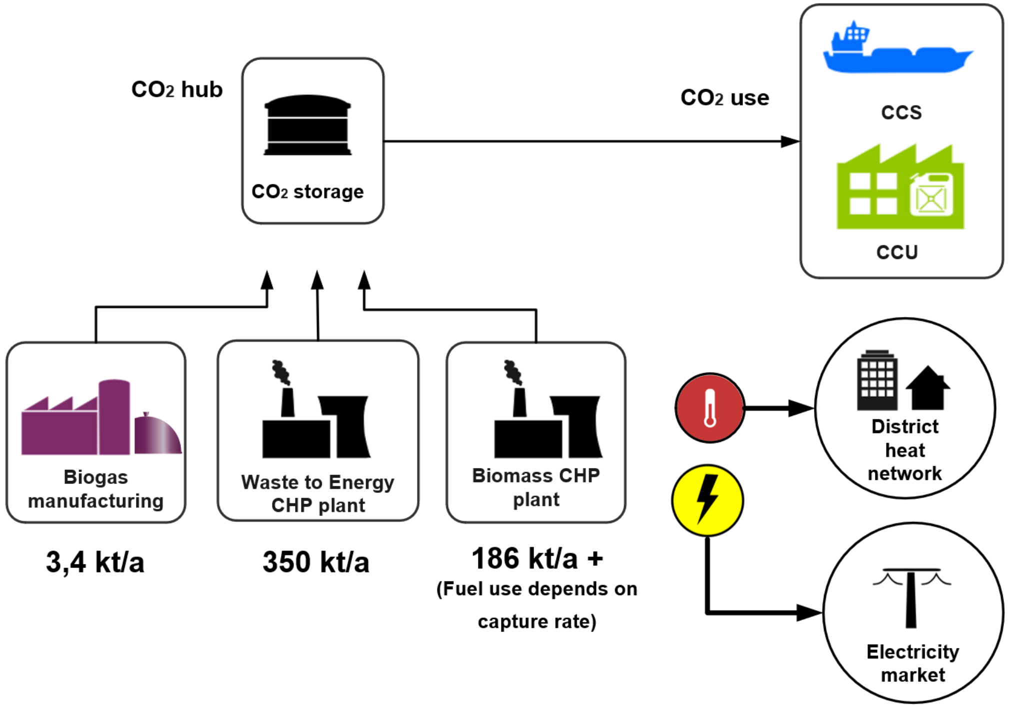
Optimizing CO_2 hub with multible operators

Jaakko Hyypiä, Hannu Karjunen, Tero Tynjälä
LUT University

Presented as poster in BioCCU final seminar

Introduction

- A biogenic CO2 hub including multiple CO2 sources was modelled
- The electricity price and heat demand were set to be variable, therefore making the capture cost time dependent
- System was optimized for minimum costs with energy system modelling framework

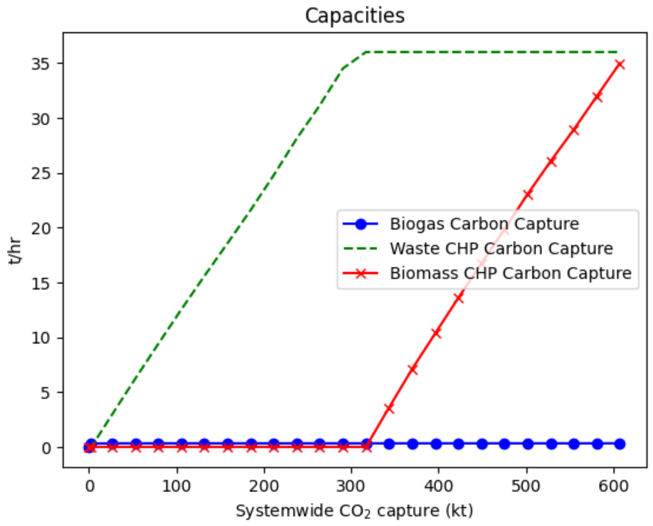


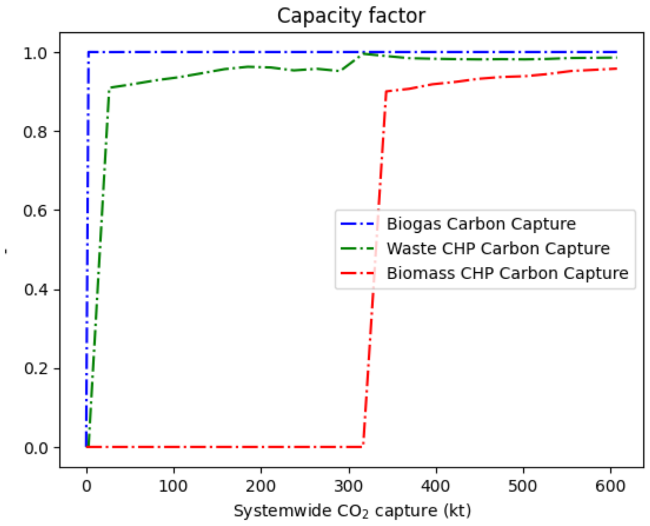
Methodology

- A Mixed-Integer Linear Programming (MILP) optimization problem was constructed
- The capacities and operation of the carbon capture processes were set as decision variables
- Electricity price and heat demand was based on spot-price and outdoor temperature
- Amine carbon capture cost and technical parameters were used
- The investment cost in carbon capture was estimated as an integer decision – consisting of purchase cost and capacity cost
- The two 100 MW_{fuel} CHP plants have different operation and fuel cost – Waste CHP constant power, biomass CHP based on heat demand

Results

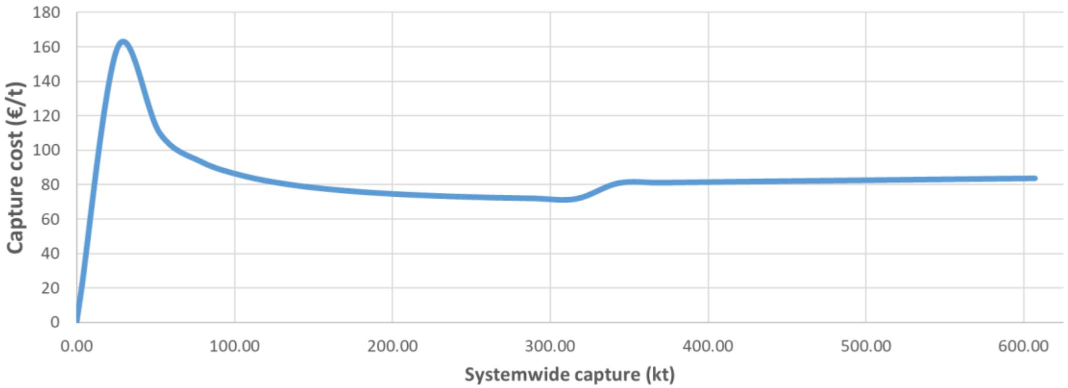
- The carbon capture investments are done in the order biogas, waste CHP, biomass CHP
- Capacity factor remains high indicating very little part load operation of the carbon capture.



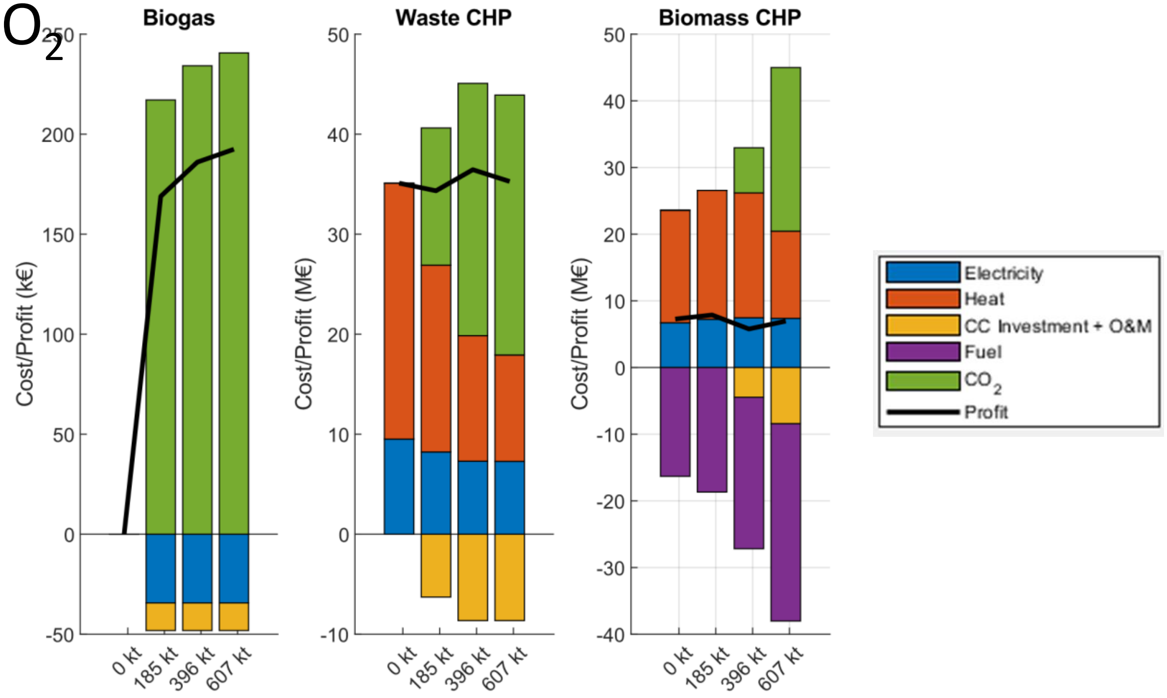


Results

- In example system, the systemwide capture cost decreases after initial peak for small CO_2 requirement
- Operator specific profits for common CO_2 market price can vary greatly



Systemwide capture cost on different total capture rates. 2023 data, 825 GWh DH network



Operator specific profits/costs when systemwide CO_2 capture cost is used as the value of CO_2 for individual operators

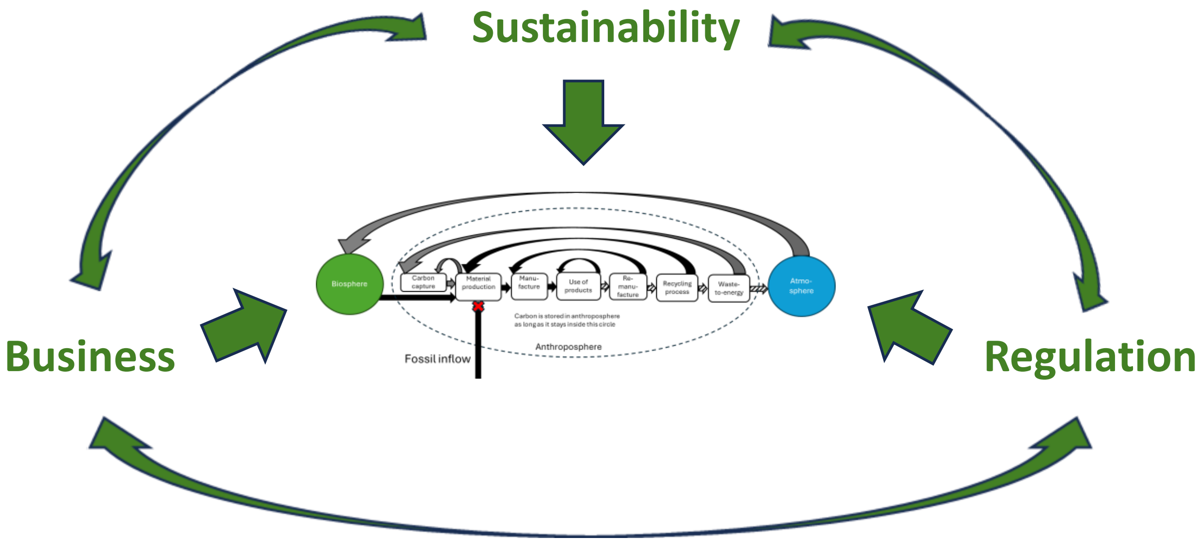
Conclusions

- Due to the limited heat demand in DH network, heat sales can be shifted from CHP plant to another
- System level capture cost is lowered due to heat sale optimization
- Part loading carbon capture plants was observed only in limited quantities (Capacity factor > 90%)
- Questions about the CO_2 pricing mechanism arises
  - How investment costs of CO_2 hub will be funded and shared?
  - How market price for CO_2 will be determined?
  - How profits from CO_2 sales and possible CO_2 sinks will be valued and shared?

WP5: Regulation, Sustainability, Market Drivers and Value mining

University of Helsinki, LUT University, Tampere University

Bio-CCU WP5 research agenda

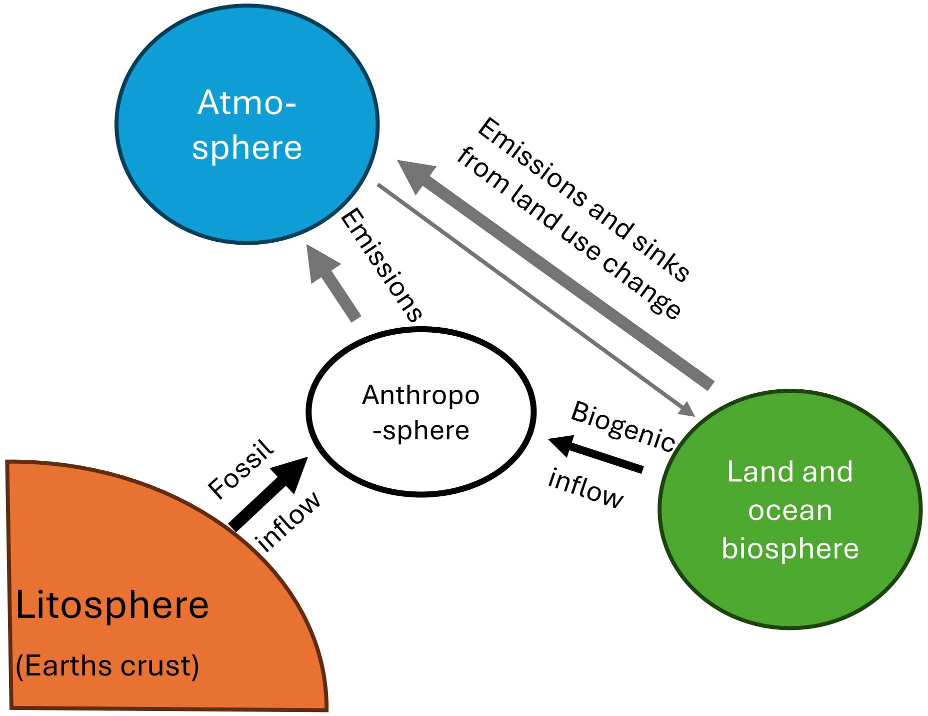


- Interdisciplinary research team
- Approaching two Bio-CCU value chains through three lenses:
  - Sustainability
  - Regulation
  - Business
- Identifying key issues for value chain optimization
- Redefining agenda for future research

Bio-CCU sustainability: Climate change mitigation

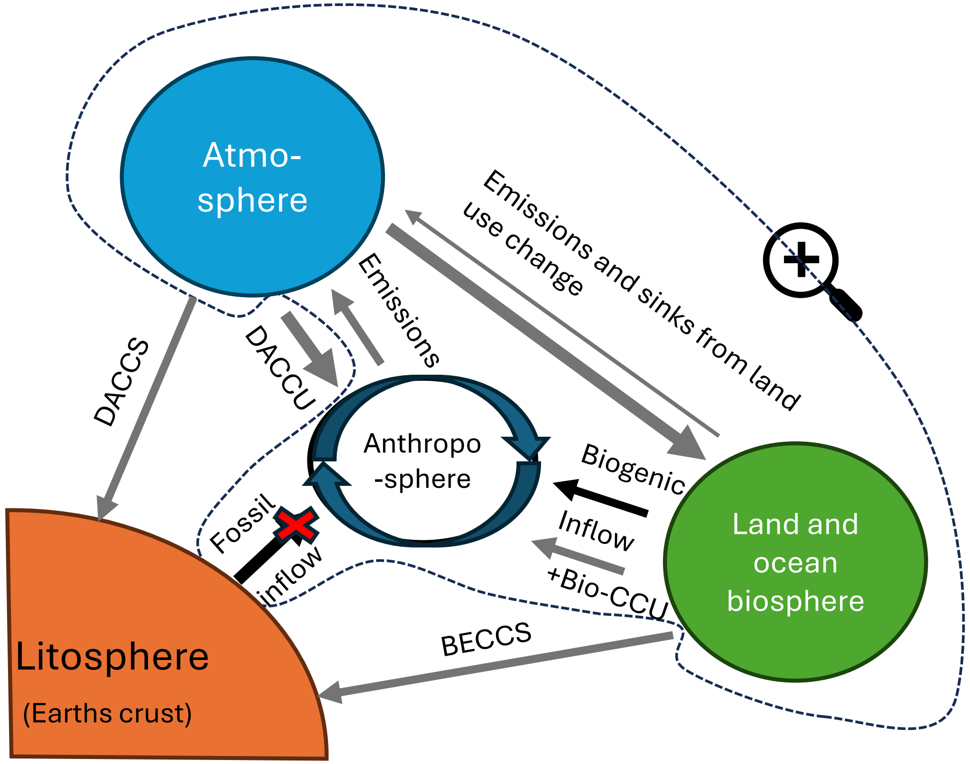
LUT University, Life Cycle Management
Risto Soukka
Mikko Ropo
Olli Helppi
Mariia Zhaurova

Linear carbon flows



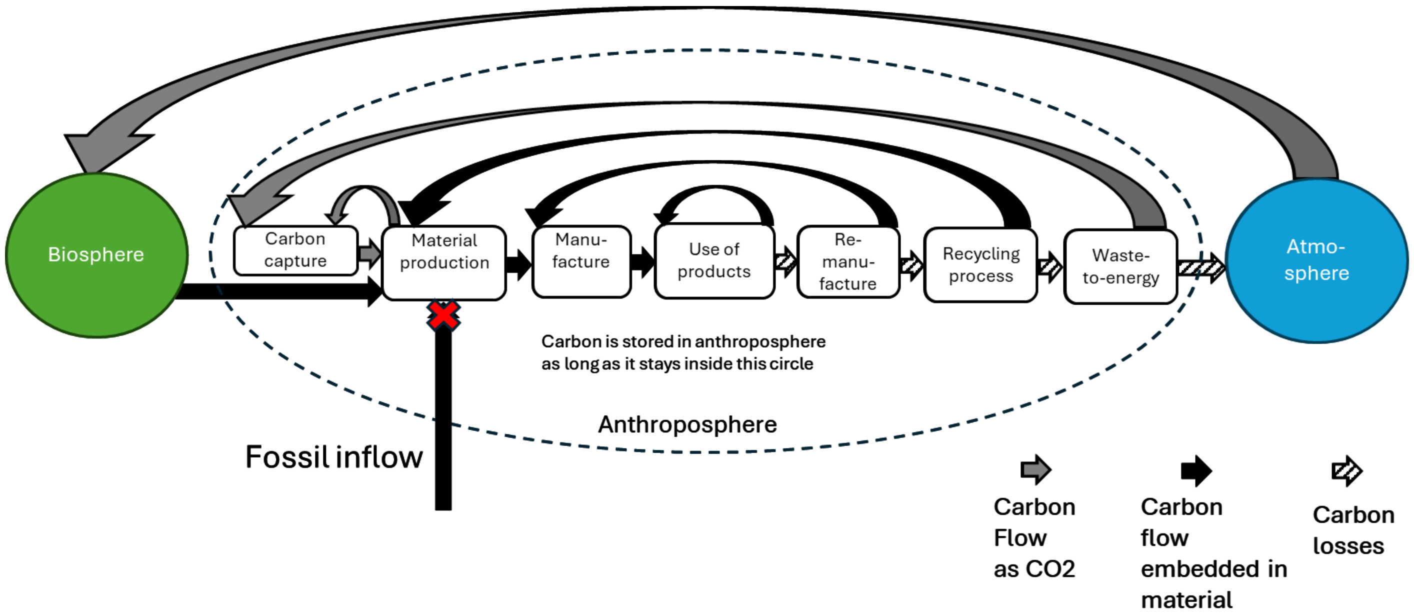
- Natural carbon cycle in balanced state
- Humans interact in nature
- All human controlled systems that use fossil resources emit CO2 into the atmosphere
- CO2 emissions are the main driver of climate change
- How do we balance the CO2 flows to mitigate climate change?

Managed carbon flows



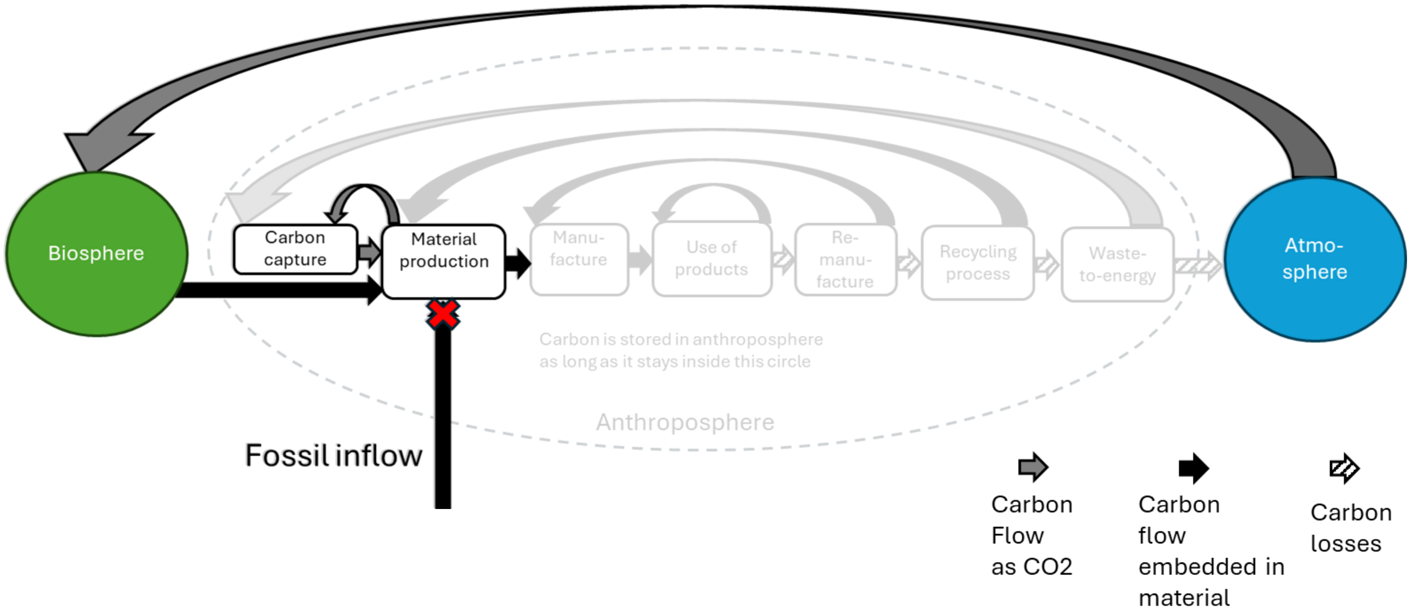
- Reduce emissions and sequestrate CO2 to biomass
- With CCS technologies CO2 can be stored back into ground (DACCS/BECCS)
- We should also produce products with CCU to replace the fossil inflow (Bio-CCU/DACCU)
- Carbon circulation can be further improved with circular economy
- This project focused on Bio-CCU

Carbon circulation in CCU value chain



- CCU can be used in both ends of a circular value chain to improve the circulation of carbon in the economic system
- This adds a new human controlled carbon cycle into the circular economy
- Replacing a fossil product with a CCU product can create climate benefits

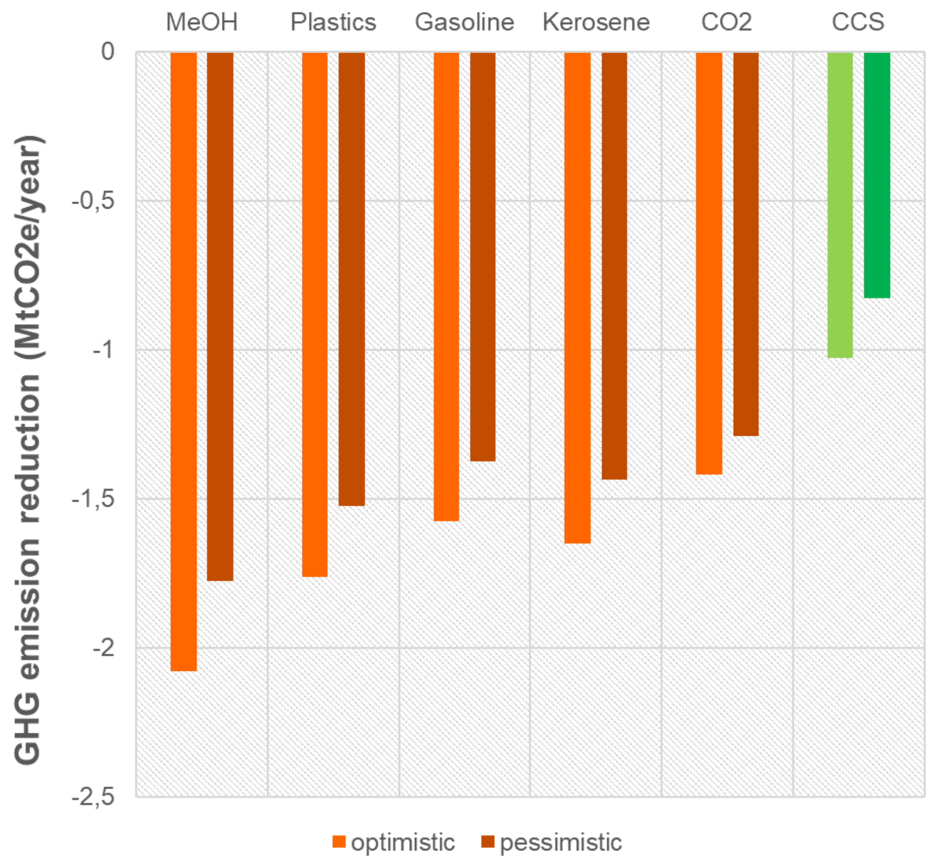
Value chain 1: Pulp Mill



- A pulp mill in Oulu produces annually 1,4 Mt of CO2 emissions
- 90% is biogenic CO2
- What is the climate impact of producing methanol-based products from that CO2?
    - Methanol
    - Plastics
    - Fuels
    - CO2 utilization

LUT University HELSINGIN YLIOPISTO Tampere University

Results for pulp mill case

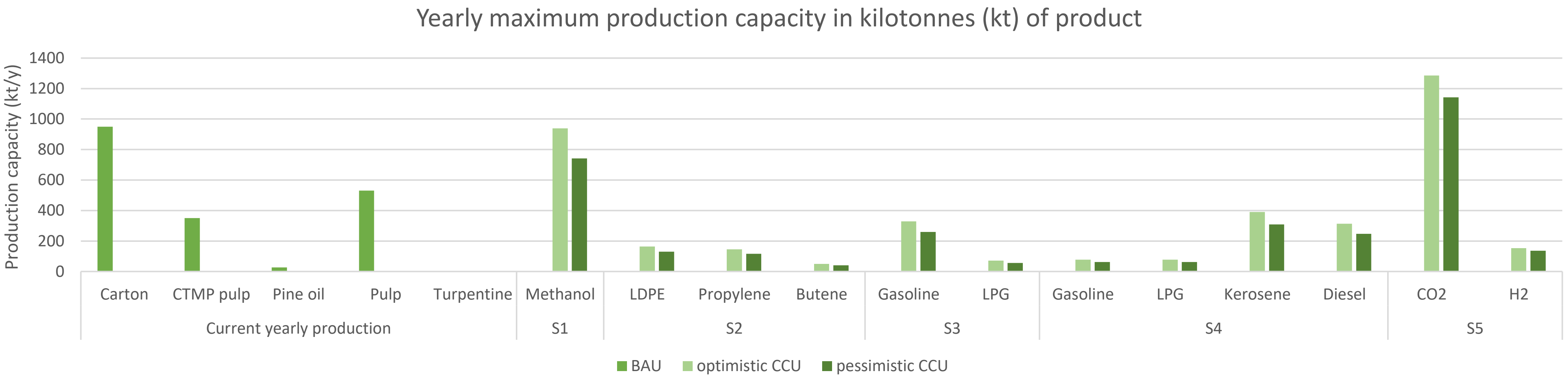


- Only the CCS scenario results in negative CO2 emissions
- However, the relative emission reduction of CCU can be greater than in the case of CCS, when:
  1. The CCU product permanently replaces a fossil conventional product
  2. The replaced fossil flow does not enter the economic system elsewhere

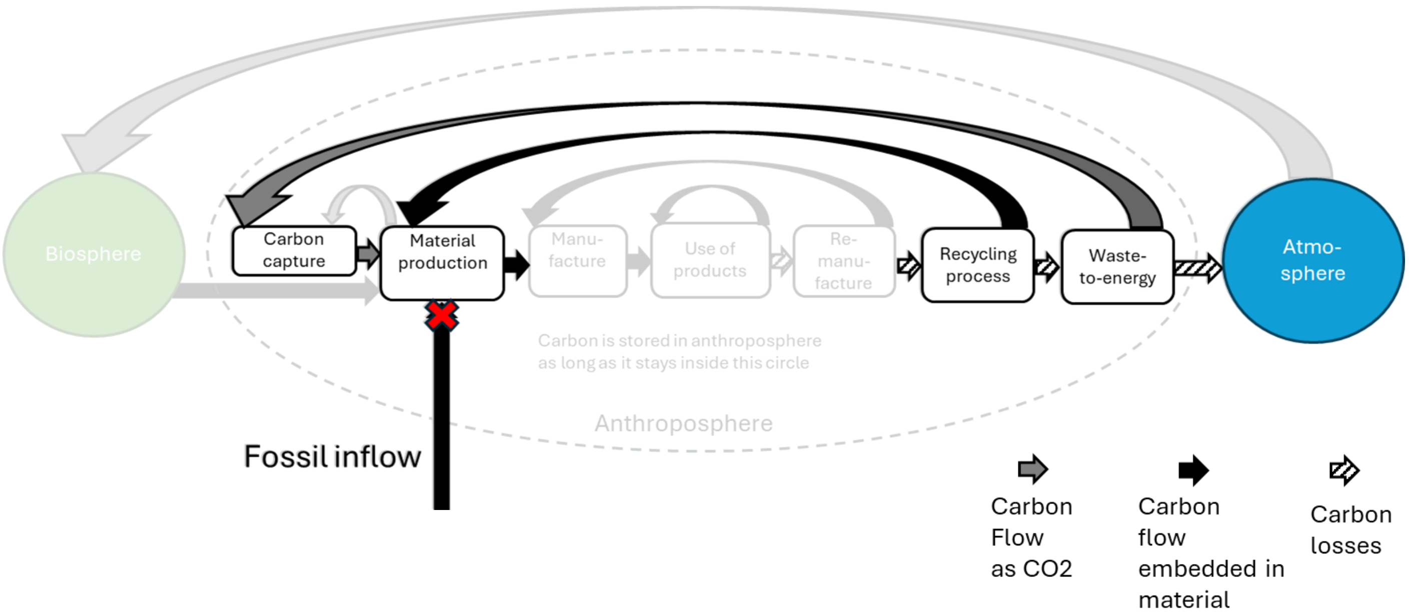
  → CCU can be more effective in climate change mitigation during the transition phase away from fossil-based products
- More information on poster

CCU production capacities

- CCU provides new production functions and therefore new business opportunities
- In the case of full implementation of CCU, the yearly CCU production capacities can be significant
- Combinations of different CCUS routes give possibility to adapt to different developments in markets and regulation

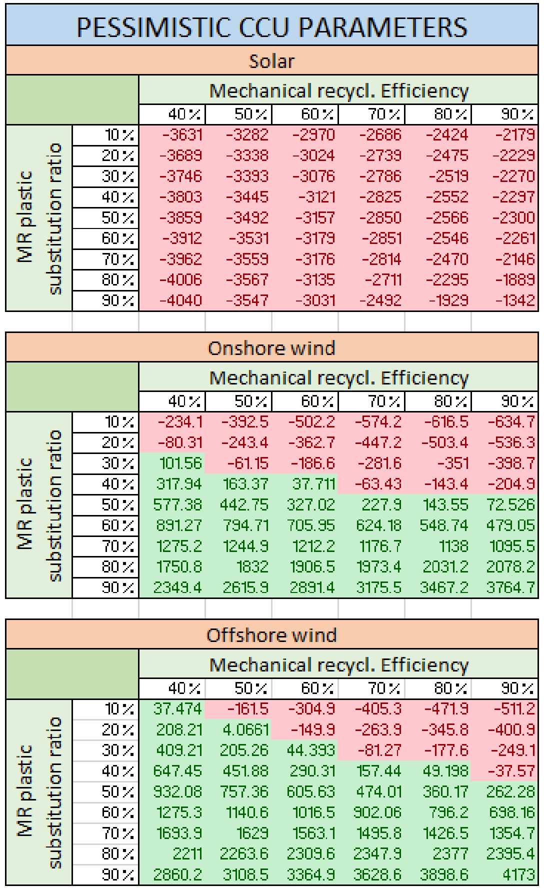


Value chain 2: Waste-to-Energy



- A Waste-to-Energy plant produces 50% biogenic CO2 emissions
- What is the climate impact of using CCU to improve the recycling of plastics against using CCS?

Results for Waste-to-Energy



PESSIMISTIC CCU PARAMETERS

Solar

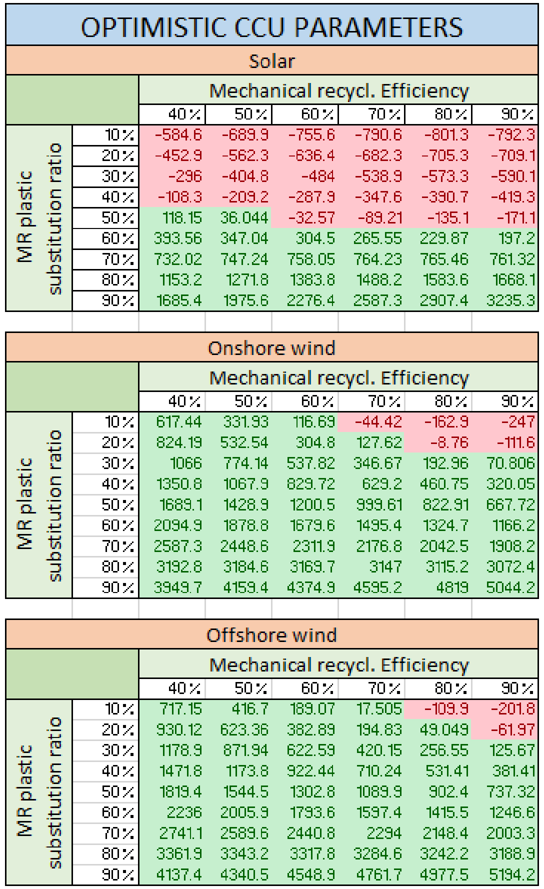
	Mechanical recycl. Efficiency					
MR plastic substitution ratio	40%	50%	60%	70%	80%	90%
10%	-3631	-3282	-2970	-2686	-2424	-2179
20%	-3689	-3338	-3024	-2739	-2475	-2229
30%	-3746	-3393	-3076	-2786	-2519	-2270
40%	-3803	-3445	-3121	-2825	-2552	-2297
50%	-3859	-3492	-3157	-2850	-2566	-2300
60%	-3912	-3531	-3179	-2851	-2546	-2261
70%	-3962	-3559	-3176	-2814	-2470	-2146
80%	-4006	-3567	-3135	-2711	-2295	-1889
90%	-4040	-3547	-3031	-2492	-1929	-1342

Onshore wind

	Mechanical recycl. Efficiency					
MR plastic substitution ratio	40%	50%	60%	70%	80%	90%
10%	-234.1	-392.5	-502.2	-574.2	-616.5	-634.7
20%	-80.31	-243.4	-362.7	-447.2	-503.4	-536.3
30%	101.56	-61.15	-186.6	-281.6	-351	-398.7
40%	317.94	163.37	37.711	-63.43	-143.4	-204.9
50%	577.38	442.75	327.02	227.9	143.55	72.526
60%	891.27	794.71	705.95	624.18	548.74	479.05
70%	1275.2	1244.9	1212.2	1176.7	1138	1095.5
80%	1750.8	1832	1906.5	1973.4	2031.2	2078.2
90%	2349.4	2615.9	2891.4	3175.5	3467.2	3764.7

Offshore wind

	Mechanical recycl. Efficiency					
MR plastic substitution ratio	40%	50%	60%	70%	80%	90%
10%	37.474	-161.5	-304.9	-405.3	-471.9	-511.2
20%	208.21	4.0661	-149.9	-263.9	-345.8	-400.9
30%	409.21	205.26	44.393	-81.27	-177.6	-249.1
40%	647.45	451.88	290.31	157.44	49.198	-37.57
50%	932.08	757.36	605.63	474.01	360.17	262.28
60%	1275.3	1140.6	1016.5	902.06	796.2	698.16
70%	1693.9	1629	1563.1	1495.8	1426.5	1354.7
80%	2211	2263.6	2309.6	2347.9	2377	2395.4
90%	2860.2	3108.5	3364.9	3628.6	3898.6	4173



OPTIMISTIC CCU PARAMETERS

Solar

	Mechanical recycl. Efficiency					
MR plastic substitution ratio	40%	50%	60%	70%	80%	90%
10%	-584.6	-689.9	-755.6	-790.6	-801.3	-792.3
20%	-452.9	-562.3	-636.4	-682.3	-705.3	-709.1
30%	-296	-404.8	-484	-538.9	-573.3	-590.1
40%	-108.3	-209.2	-287.9	-347.6	-390.7	-419.3
50%	118.15	36.044	-32.57	-89.21	-135.1	-171.1
60%	393.56	347.04	304.5	265.55	229.87	197.2
70%	732.02	747.24	758.05	764.23	765.46	761.32
80%	1153.2	1271.8	1383.8	1488.2	1583.6	1668.1
90%	1685.4	1975.6	2276.4	2587.3	2907.4	3235.3

Onshore wind

	Mechanical recycl. Efficiency					
MR plastic substitution ratio	40%	50%	60%	70%	80%	90%
10%	617.44	331.93	116.69	-44.42	-162.9	-247
20%	824.19	532.54	304.8	127.62	-8.76	-111.6
30%	1066	774.14	537.82	346.67	192.96	70.806
40%	1350.8	1067.9	829.72	629.2	460.75	320.05
50%	1689.1	1428.9	1200.5	999.61	822.91	667.72
60%	2094.9	1878.8	1679.6	1495.4	1324.7	1166.2
70%	2587.3	2448.6	2311.9	2176.8	2042.5	1908.2
80%	3192.8	3184.6	3169.7	3147	3115.2	3072.4
90%	3949.7	4159.4	4374.9	4595.2	4819	5044.2

Offshore wind

	Mechanical recycl. Efficiency					
MR plastic substitution ratio	40%	50%	60%	70%	80%	90%
10%	717.15	416.7	189.07	17.505	-109.9	-201.8
20%	930.12	623.36	382.89	194.83	49.049	-61.97
30%	1178.9	871.94	622.59	420.15	256.55	125.67
40%	1471.8	1173.8	922.44	710.24	531.41	381.41
50%	1819.4	1544.5	1302.8	1089.9	902.4	737.32
60%	2236	2005.9	1793.6	1597.4	1415.5	1246.6
70%	2741.1	2589.6	2440.8	2294	2148.4	2003.3
80%	3361.9	3343.2	3317.8	3284.6	3242.2	3188.9
90%	4137.4	4340.5	4548.9	4761.7	4977.5	5194.2

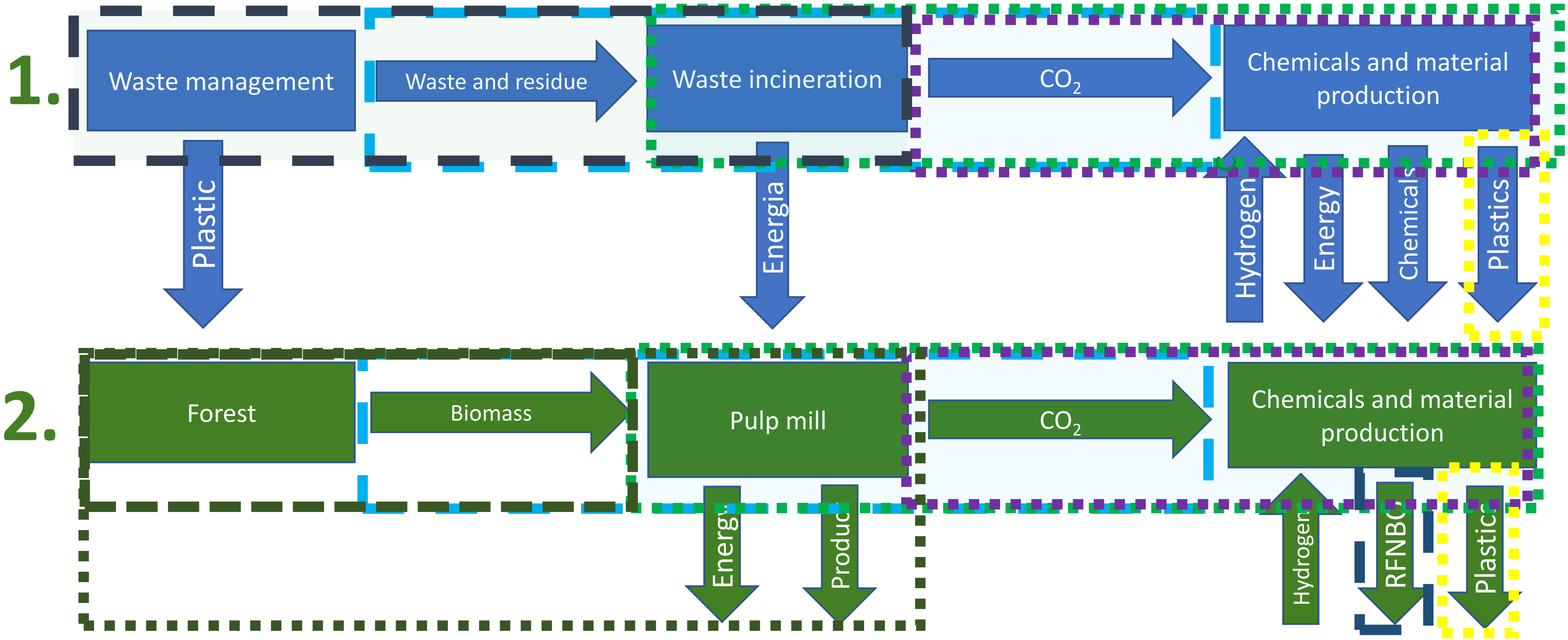
- In the right conditions waste-to-energy integrated CCU can yield more climate benefits compared to CCS from the same context
- CCU can reduce emissions by enhancing material recovery and replacing fossil production
- Details available in the poster by Olli Helppi, LUT

Regulation:
CCU value chains and lawscapes

University of Helsinki, Faculty of Law
Kai Kokko
Emilie Yliheljo
Tiina Paloniitty
Susanna Kaavi

Regulation: CCU value chains and lawscapes

BioCCU



1.

Waste management

Waste and residue

Waste incineration

CO_2

Chemicals and material production

Plastic

Energia

Hydrogen

Energy

Chemicals

Plastics

2.

Forest

Biomass

Pulp mill

CO_2

Chemicals and material production

Energ

Produc

Hydrogen

RFNBC

Plastic

Regulation: CCU value chains and lawscapes

1. **RED III:** biomass definition and sustainability criteria define which part of CO_2 is biogenic

2. **ETS Directive:** incentives to capture fossil CO_2 – not applicable to waste incineration (yet) , biogenic CO_2, or sources of predominantly biogenic CO_2.

3. **CRCF Regulation:** incentive to store biogenic CO_2 in products if storage at least 35 years

4. **Waste Framework Directive:** Waste hierarchy regulates source and availability of CO_2 . Whether CO_2 captured from waste incineration for utilization is classified as waste is uncertain.

5. **Plastics regulation:** does not recognize CCU-plastic – though recognizes many other types of plastics, e.g biogenic, compostable.

6. **GHG savings criteria and incentives** for synthetic fuels (RED III, ReFuel Aviation, FuelEU Maritime and ETS,

7. **Forest regulation** on carbon sink (LULUCF) and biodiversity (e.g. Nature Restoration Law) regulates the availability of sustainable biogenic CO_2.

Business approach to CCU

Tampere University, Industrial Engineering and Management
Leena Aarikka-Stenroos
Mikko Sairanen
Olga Dziubaniuk

Business-related dilemmas in Bio-CCU and two analysis levels

1. How companies can make business from decarbonization and carbon management (and Bio-CCU):

- ➢ *Key results: A mapping of CCU business model innovations and value capture drivers; a typology and conceptual model of low-carbon business models*
- ➢ Company level analysis

2. What determines economic value creation in Bio-CCU value chains:

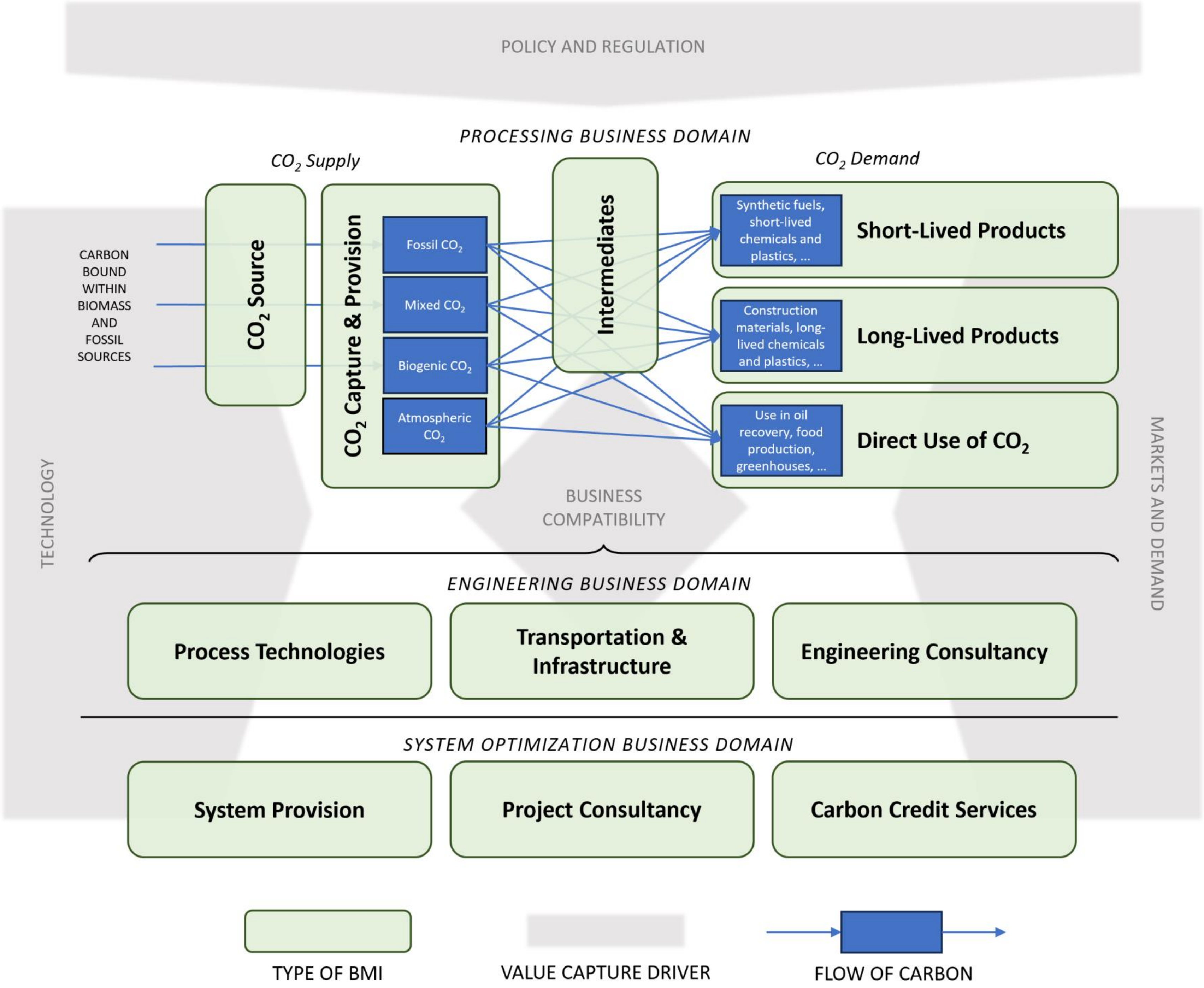
- ➢ *Key results: Value determinants adding (or reducing) business feasibility and economic value creation*
- ➢ Value chain level analysis

In both dilemmas, business is strongly shaped by regulation and with differing sustainability impacts

1. Business model approach: How a company can harness Bio-CCU and decarbonization in its business model

CCU business models and drivers of value capture

BioCCU



POLICY AND REGULATION

PROCESSING BUSINESS DOMAIN

CO_2 Supply

CO_2 Demand

CARBON BOUND WITHIN BIOMASS AND FOSSIL SOURCES

CO_2 Source

CO_2 Capture & Provision

Fossil CO_2

Mixed CO_2

Biogenic CO_2

Atmospheric CO_2

Intermediates

Synthetic fuels, short-lived chemicals and plastics, …

Short-Lived Products

Construction materials, long-lived chemicals and plastics, …

Long-Lived Products

Use in oil recovery, food production, greenhouses, …

Direct Use of CO_2

TECHNOLOGY

MARKETS AND DEMAND

BUSINESS COMPATIBILITY

ENGINEERING BUSINESS DOMAIN

Process Technologies

Transportation & Infrastructure

Engineering Consultancy

SYSTEM OPTIMIZATION BUSINESS DOMAIN

System Provision

Project Consultancy

Carbon Credit Services

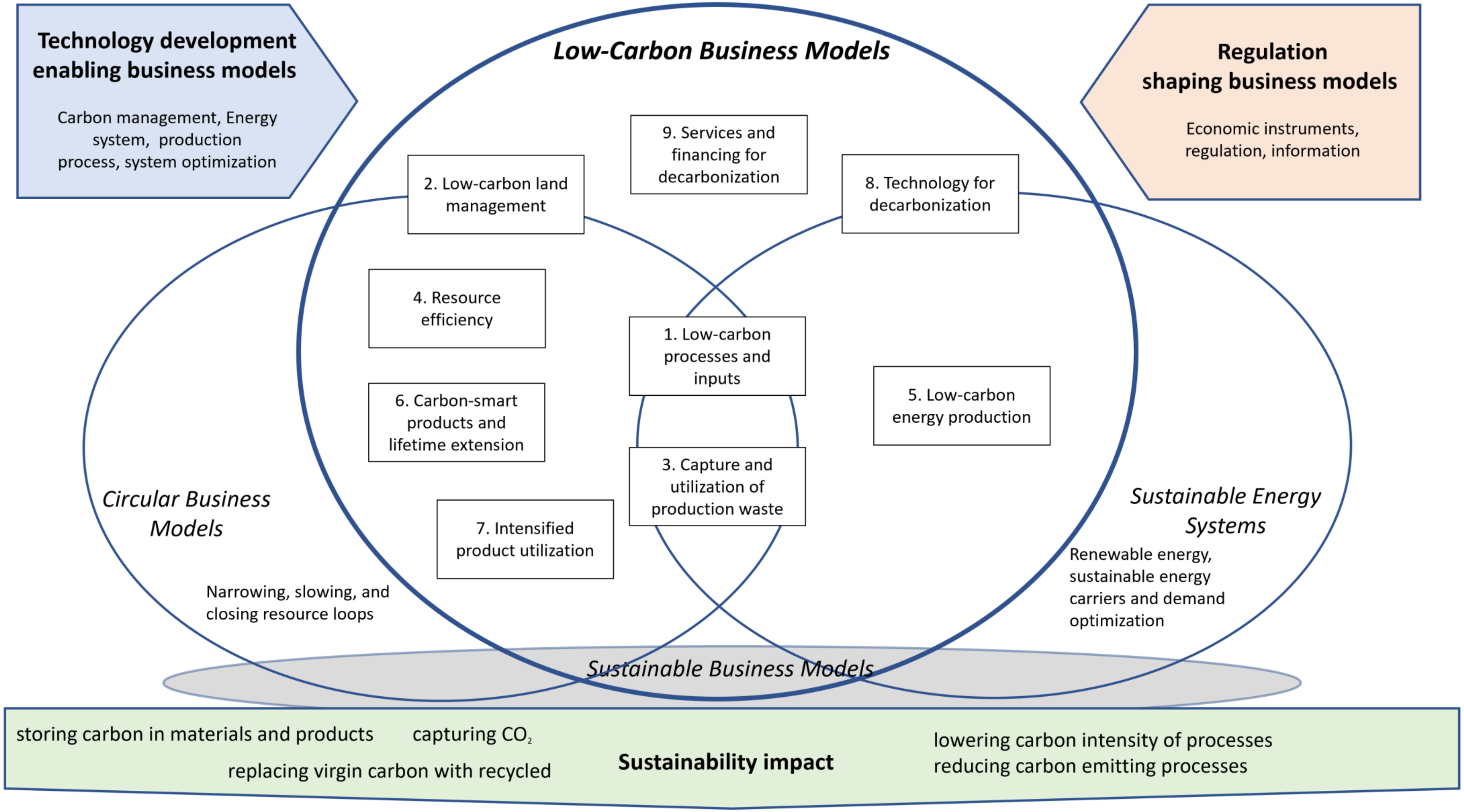
🟩 TYPE OF BMI

▨ VALUE CAPTURE DRIVER

→■→ FLOW OF CARBON

Low-carbon business models

BioCCU



Technology development enabling business models

Carbon management, Energy system, production process, system optimization

Low-Carbon Business Models

9. Services and financing for decarbonization

2. Low-carbon land management

8. Technology for decarbonization

4. Resource efficiency

1. Low-carbon processes and inputs

5. Low-carbon energy production

6. Carbon-smart products and lifetime extension

3. Capture and utilization of production waste

7. Intensified product utilization

Regulation shaping business models

Economic instruments, regulation, information

Circular Business Models

Narrowing, slowing, and closing resource loops

Sustainable Energy Systems

Renewable energy, sustainable energy carriers and demand optimization

Sustainable Business Models

storing carbon in materials and products

capturing CO_2

replacing virgin carbon with recycled

Sustainability impact

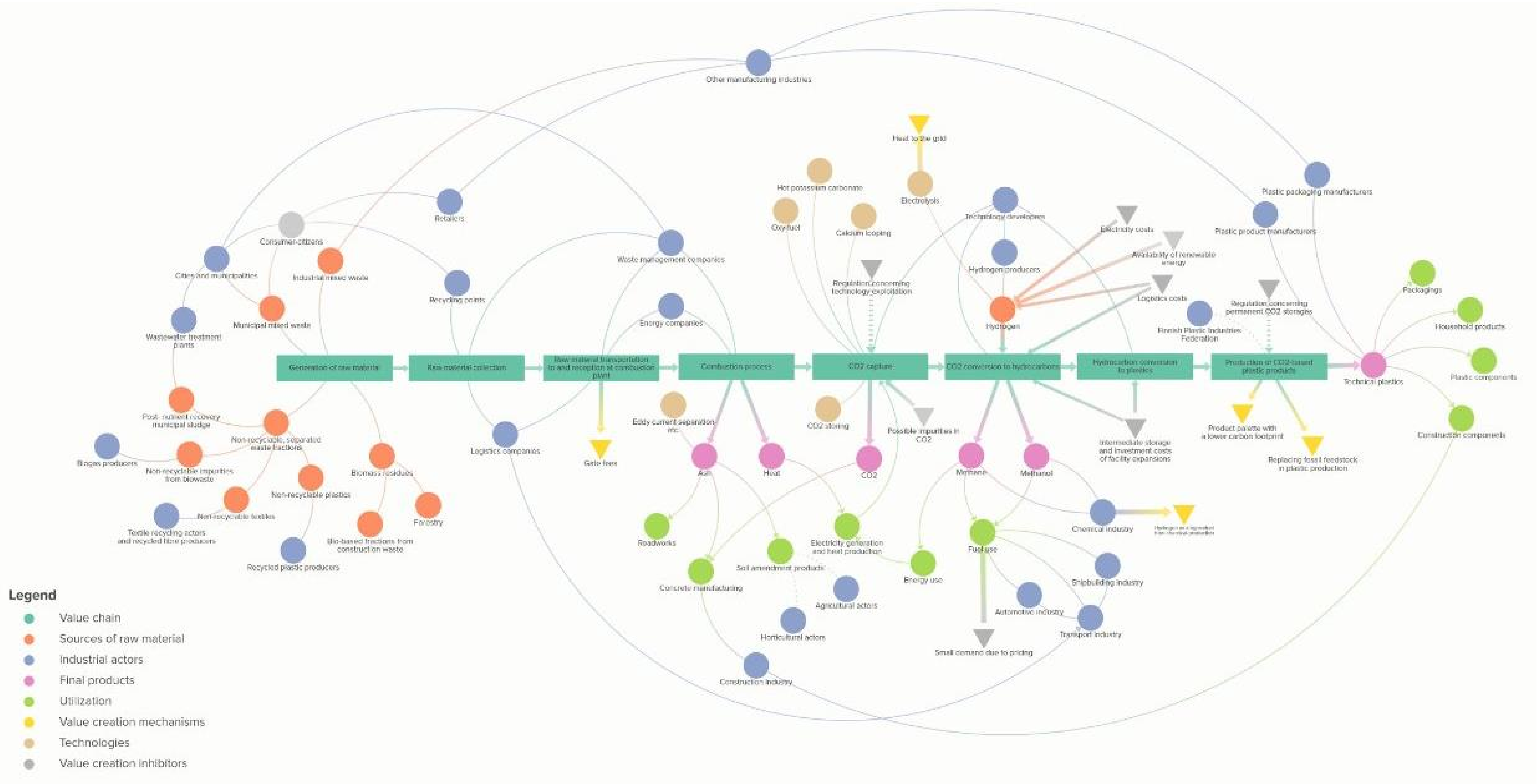
lowering carbon intensity of processes

reducing carbon emitting processes

2. Value chain approach:
How value chains look like?
What are the factors that shape critically economic value creation in Bio-CCU value chains

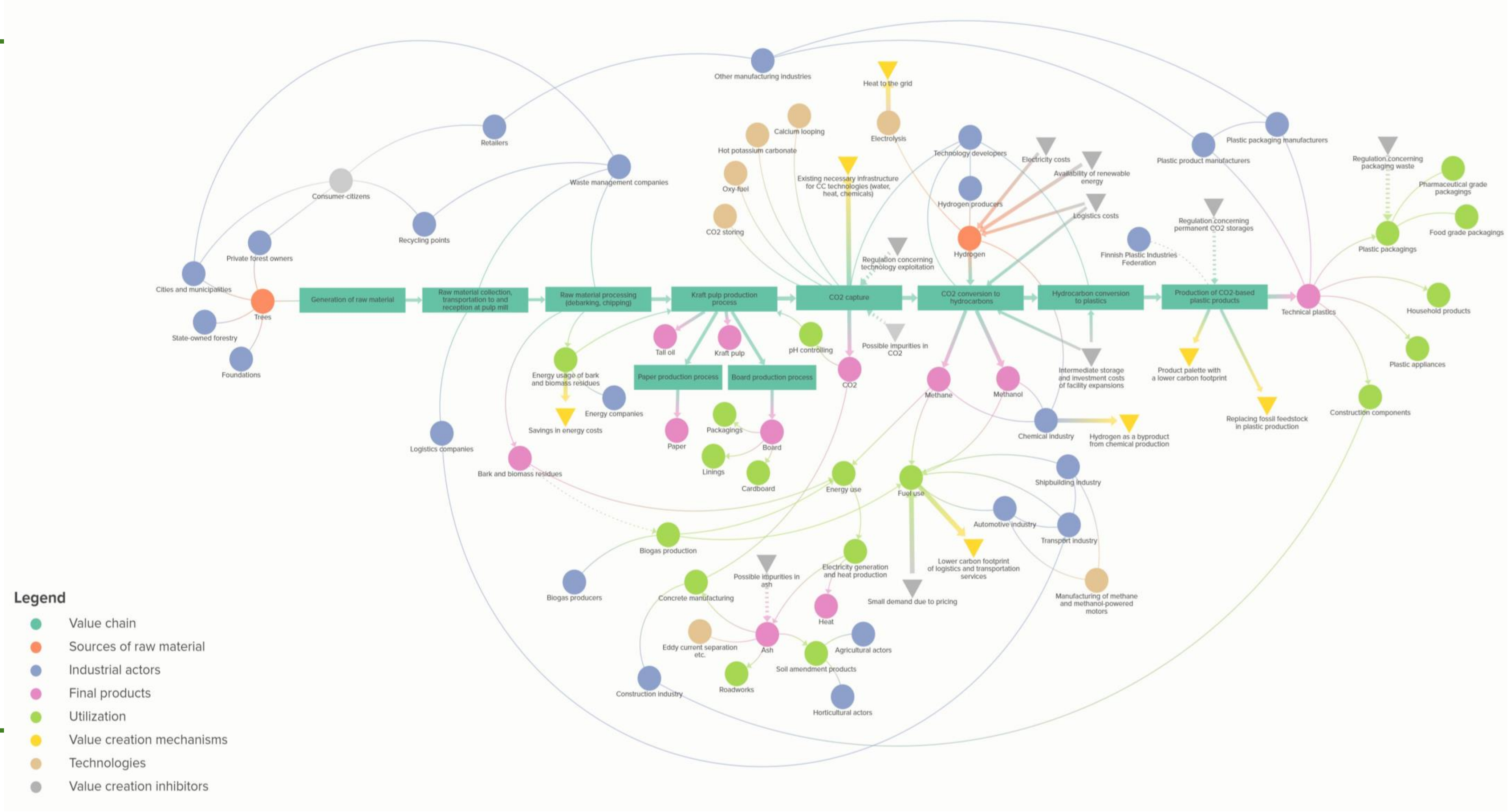
Value chain mappings –
Sensemaking the complexity of value chains

Example:
Waste combustion
value chain



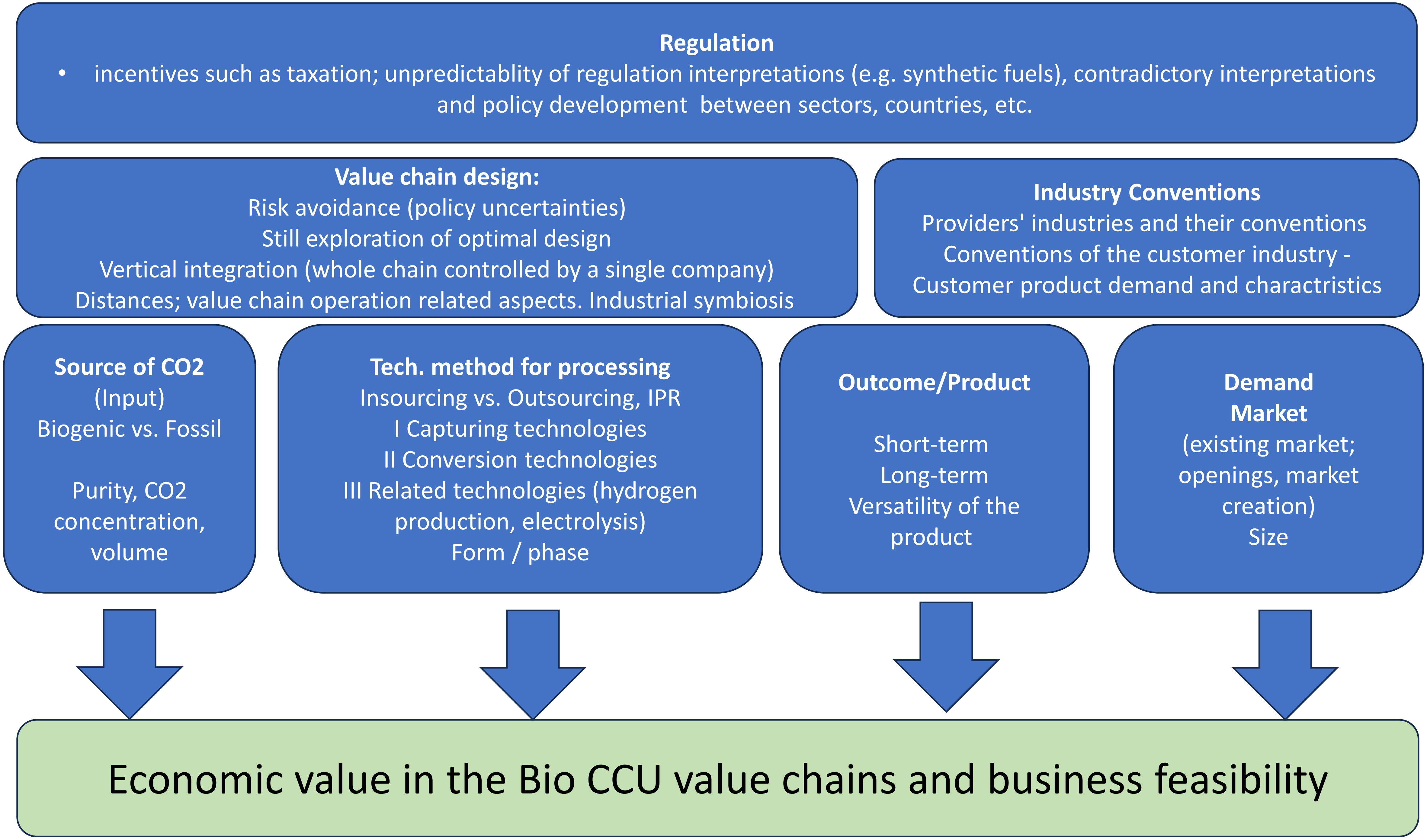
Value chain mappings

Example: forest biomass to plastic value chain



Legend

- ● Value chain
- ● Sources of raw material
- ● Industrial actors
- ● Final products
- ● Utilization
- ● Value creation mechanisms
- ● Technologies
- ● Value creation inhibitors



Regulation

- incentives such as taxation; unpredictablity of regulation interpretations (e.g. synthetic fuels), contradictory interpretations and policy development between sectors, countries, etc.

Value chain design:
Risk avoidance (policy uncertainties)
Still exploration of optimal design
Vertical integration (whole chain controlled by a single company)
Distances; value chain operation related aspects. Industrial symbiosis

Industry Conventions
Providers' industries and their conventions
Conventions of the customer industry -
Customer product demand and charactristics

Source of CO2
(Input)
Biogenic vs. Fossil

Purity, CO2 concentration, volume

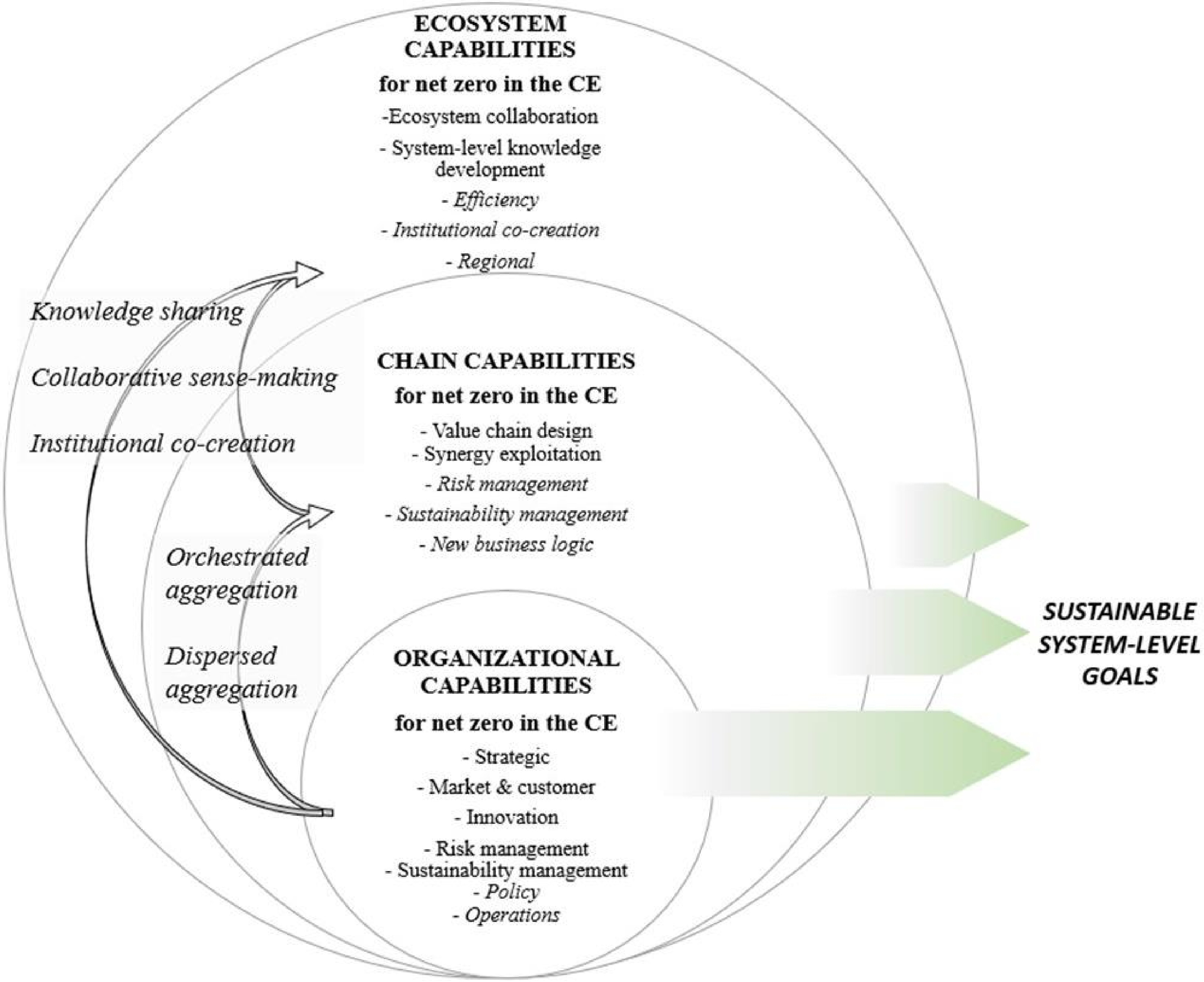
Tech. method for processing
Insourcing vs. Outsourcing, IPR
I Capturing technologies
II Conversion technologies
III Related technologies (hydrogen production, electrolysis)
Form / phase

Outcome/Product

Short-term
Long-term
Versatility of the product

Demand
Market
(existing market; openings, market creation)
Size

Economic value in the Bio CCU value chains and business feasibility



ECOSYSTEM CAPABILITIES

for net zero in the CE

-Ecosystem collaboration

- System-level knowledge development
- *Efficiency*
- *Institutional co-creation*
- *Regional*

Knowledge sharing

Collaborative sense-making

Institutional co-creation

CHAIN CAPABILITIES

for net zero in the CE

- Value chain design
- Synergy exploitation
- *Risk management*
- *Sustainability management*
- *New business logic*

Orchestrated aggregation

Dispersed aggregation

ORGANIZATIONAL CAPABILITIES

for net zero in the CE

- Strategic
- Market & customer
- Innovation
- Risk management
- Sustainability management
- *Policy*
- *Operations*

SUSTAINABLE SYSTEM-LEVEL GOALS

BioCCU

Environmental sustainability

CCU was found to have significant climate change mitigation possibilities with certain requirements:

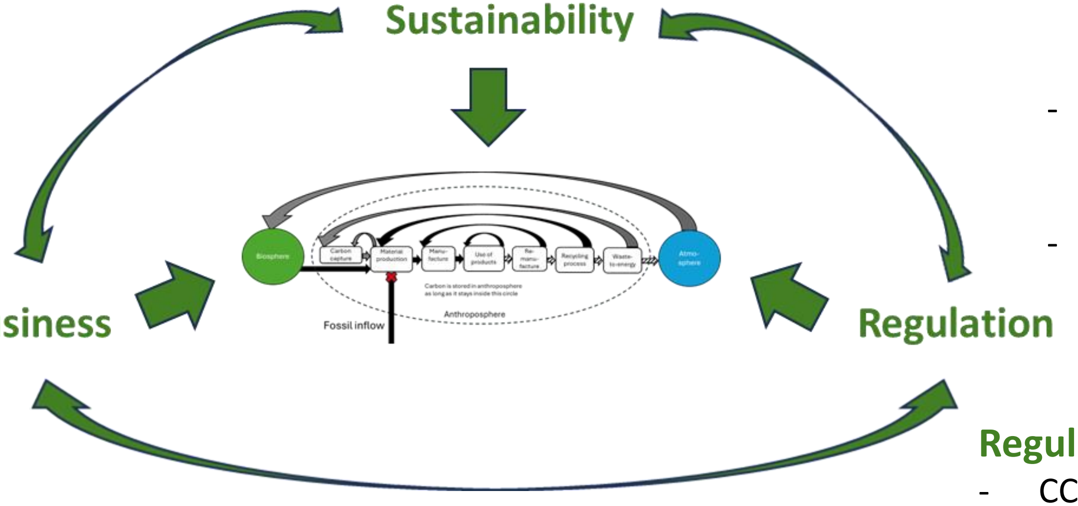
- Permanent fossil product replacement
- Renewable energy
- Sustainable biogenic or circular carbon source

Sustainability ←→ Business

- CCU business models and value chains should be directed to replacing fossil-based products and be promoted by, for example, envir. policies affecting market prices
- Combined cost and sustainability assessments are required in value chain design

Sustainability ←→ Regulation

- Policies and regulation should promote success of Bio-CCU value chains in fossil intensive markets
- Demand for CCU intermediates could be increased by a minimum input requirement of circulated carbon in products
- CCU should fill sustainability criteria with certain strict requirements



Sustainability

Business

Regulation

Business & economic value creation

- Companies need updated and completely new business models to exploit diverse emerging CCU business opportunities
- In feasible CCU value chains, all business models need to be profitable and participating companies need to possess sufficient capabilities to collaborate
- Value capture of companies and value chains is driven by technology, market demand for sustainability, and business compatibility

Business ←→ Regulation

- Uncertainties in regulation translate into regulatory risks for companies
- Legal complexity of CCU value chains significantly increase the regulatory risks (compared to e.g. CCS)
- Regulation drives business feasibility by creating demand for CCU-based products, lowering their costs, and shaping the market through carbon pricing

Regulation

- CCU value chains are varied. Different parts of the value chain are governed by different legal instruments all of which do not recognise CCU
- Different expectations towards CCU stemming from both regulation and policy. Policy expectations not always supported by regulation.
- System level sustainability of the CO2 is not only dependent on CCU regulation but also on the functioning of e.g. biodiversity regulation and waste regulation.

BioCCU - Arvonluontia biopohjaisesta hiilidioksidista

Julkinen loppuraportti