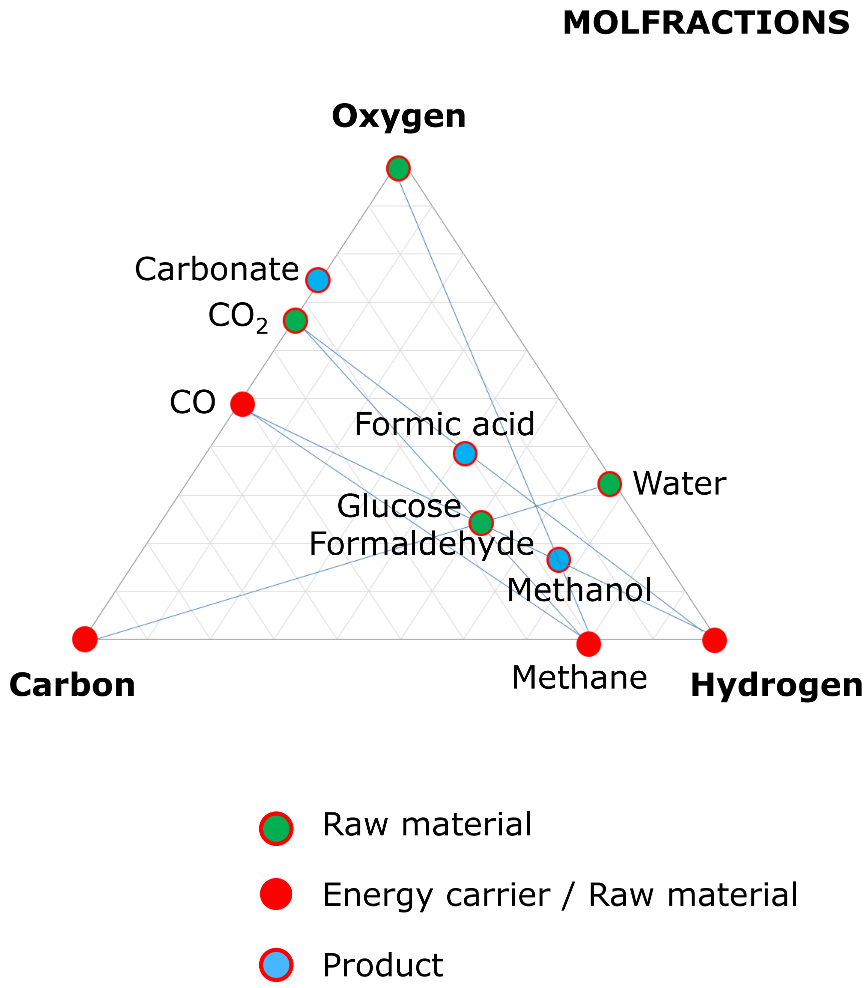

Biobased Circular Business Platform

Overview
Carbon Capture & Utilisation
Final Report

Working group C1-chemistry

January 2020

Content

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   - Opportunities for the Netherlands
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Goal and members C1 Working Group

Goal

Identify promising business opportunities in the field of utilisation of CO_2 and CO for the Netherlands

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Gert-Jan Gruter	Avantium, University of Amsterdam
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Ronnie Machielsen*, Martijn Bekker	Photanol
Peter Nossin	DSM
Marijn Rijkers	Chemelot InScite
Jan van der Stel	Tata Steel
Annita Westenbroek	Dutch Biorefinery Cluster, Platform BCB
Laura Termeer	Consultant – literature review

* member of this WG in 2018, now working for other companies and no longer member

Opportunities for the Netherlands

- Direct use in greenhouses
  (1,4 Mton CO_2 in 2030 in addition to current use of 0,6 Mton)
- Production of sodium bicarbonate by Waste to Energy Plants
  (0,02 Mton CO_2 in the Netherlands up to 0,5 Mton in EU in 2030)
- Construction materials (cement/concrete): high TRL, low margin market, limited industrial activity in the Netherlands
- Chemical building blocks:
  high potential, low/medium TRL, several demos (10 kton) expected in 2030
  - Electrochemical conversion: CO, formic acid, syngas for e.g. Fischer Tropsch
  - Catalytic conversion: e.g. methanol (shows strong dependence on cheap, renewable H_2). Countries with abundant renewable energy are better positioned
  - Photosynthetic: e.g. lactic acid, scale up of technology

CCU in relation to sustainability

CO_2-source

Atmospheric CO_2:
- Direct reduction of atmospheric CO_2-concentration
- 0,04% CO_2 in atmosphere
- sources with high CO_2-concentration are more efficient to use

Biogenic CO_2:
- Carbon neutral

Fossil based CO_2:
- no reduction of atmospheric CO_2-concentration, delay of emission
- CO_2 can substitute fossil resources
- not circular, just for transition phase
- technology development in transition phase requires easily available CO_2
- still large number of highly concentrated fossil CO_2-sources in industry
- avoid lock-ins (avoid dependence on fossil CO_2)
- Steel gasses: focus on valorization of CO and CO_2

Towards 2050 CO_2 should be biogenic or sourced via direct air capture

CCU in relation to sustainability

CCU processes

- Reductive conversion requires significant energy input (electricity/H_2/light).
- Lower overall energy efficiency and fossil based grid mix might even increase CO_2 emissions (CO_2-neutrality can then only be achieved by combination with CCS)
- Cradle to grave analysis of effects needed
  - GHG –emissions
  - material efficiency (CO_2/kg product)
  - energy efficiency of process and required installations
  - retention time
- LCA and TEA: environment & economy
- CCU from fossil CO_2 can contribute to early climate goals as long as there is fossil based industry – but it should not contribute to maintain it. Fossil CO_2 should be avoided or compensated by CCS in the coming decades

Relevance for the Netherlands: basis for selection and conditional criteria

1. Required feedstock/electricity/infrastructure and the degree in which these are or can become available in the Netherlands
2. CO_2 reduction potential compared to current reference processes (in 2030 and in 2050)
3. Probability of implementation and investments in the Netherlands
4. Knowledge position of Dutch stakeholders
5. Market size (local/international)
6. Degree to which a technology/product is a stepping stone for a sound business model in the future

Approach

Literature scan of industrial CCU initiatives worldwide

Classification:
organization, country, technology, TRL, feedstock, products, process, partners

Dropbox:
All literature available
Xls overview document

16 product clusters:
polymers (2), carbonates (2), fuels (3), chemical intermediates (9)

Technology clusters:
Electrochemical conversions, Catalytic, Photocatalytic, Photosynthetic

Evaluation criteria:
type and amount of required energy (e.g. H_2 required), costs, market size, product value, competitiveness

Challenge for the Netherlands

Industry (excluding power generation)
12 companies ➔ 62% industrial emissions (incl waste), 5 regions

Broeikasgas emissie CO_2-equivalenten in Mton	Totaal 1990	Totaal 2015	% van de industrie
Tata Steel	6,00	6,22	11,3%
Shell Nederland	6,81	5,62	10,2%
YARA	1,06	3,78	6,9%
ExxonMobil	1,82	2,86	5,2%
SABIC *		2,79	5,1%
Dow	3,08	2,64	4,8%
Air Liquide	0,00	2,43	4,4%
BP	1,52	2,34	4,3%
OCI *		1,81	3,3%
Total	0,83	1,54	2,8%
Akzo Nobel	1,52	0,98	1,8%
Air Products	0,46	0,90	1,6%
Totaal	23,08	33,74	61,5%

Bron: de emissieregistratie 2015 (RIVM e-PRTR) CO_2-eq op basis van CO_2, N_2O en CH_4

* SABIC and OCI were part of DSM in 1990

Targets for the Netherlands

Climate Agreement 2018

Industry:

➔ 49% CO2 reduction in 2030 (versus reference year 1990), climate neutral in 2050

➔ Reduction of 14,3 Mton in 2030 addition to existing policy (5,1 Mton)

Technology	Estimated avoided CO_{2eq} (Mton, 2030	Average costs €/ton CO_2 in addition to ETS	Scope 2 and 3
Process efficiency	6	0-50	±3Mton savings on natural gas due to providing residual heat
Nitrous oxide and F-gasses	2	0-30	
Electrification and green hydrogen	4	70-150	
Recycling, CCU and biobased chemicals	1	10-150	±2Mton CO_2 for greenhouses, 1-2Mton CCU and recycling that prevent foreign emissions
CCS	7	50-70	
Total (including current policy)	20		6-7Mton

CCU Pathways

CO_2 + Energy + Raw Materials → Products

Feedstock	Required	Optional	Direct use
CO_2	Electricity	Water	Beverage
• fossil based	Hydrogen	Catalyst	Greenhouses
• biobased	Sunlight	Methane	Fuel Recovery
• atmospheric	Sugar(s)	Hydrogen	Concrete
	CO	Oxygen	
	CH_4		**Conversion**
			Chem. Intermediates
			Fuels
			Carbonates
			Polymers

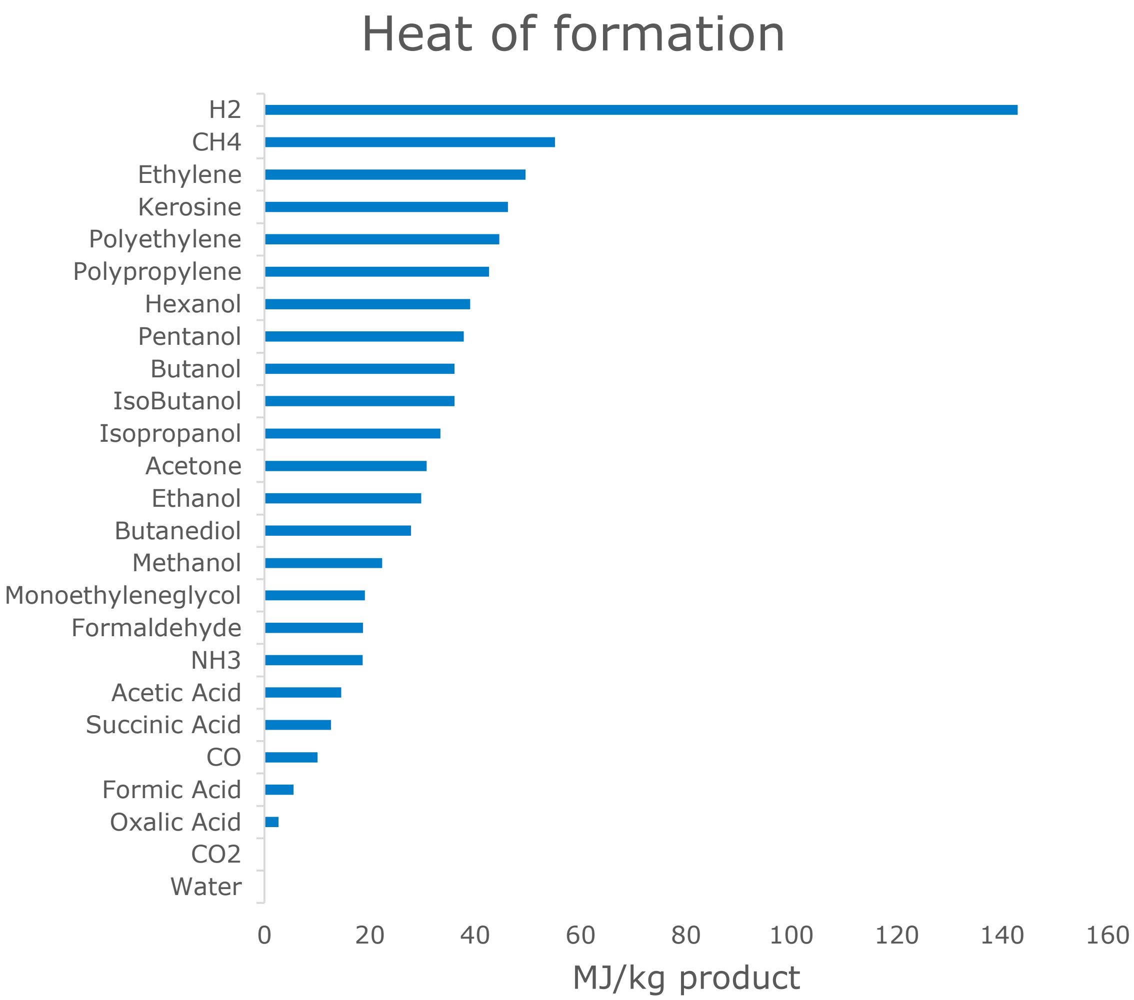
Products

Fuels
- Methane, methanol
- Ethanol, butanol
- Diesel, gasoline, other liquid fuels

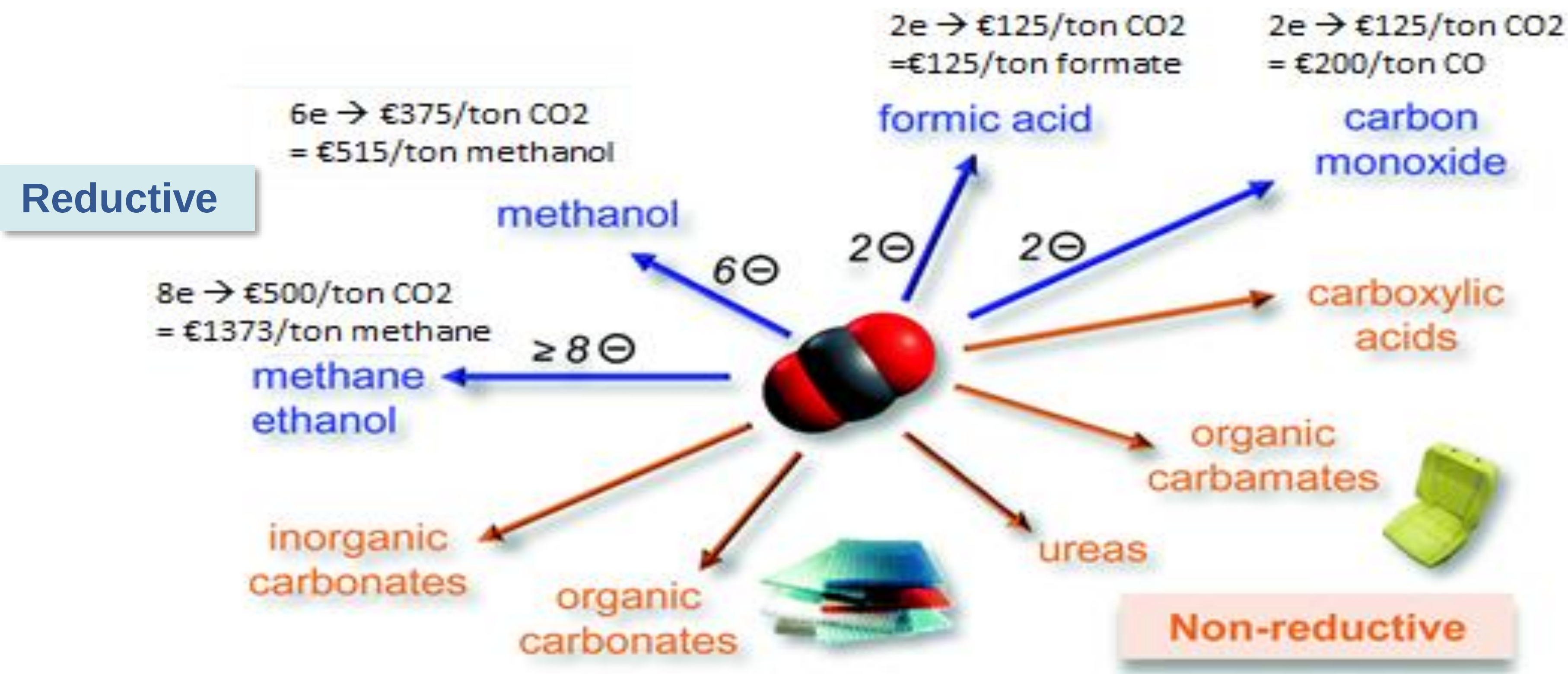
Polymers
- Polycarbonates, polyols

Chemical intermediates
- CO
- Formic acid, carboxylic acids
- Organic acids
- Methane, methanol
- Alcohols
- Ethylene

Carbonates
- Low carbon concrete, organic/inorganic carbonates
- Carbon curing

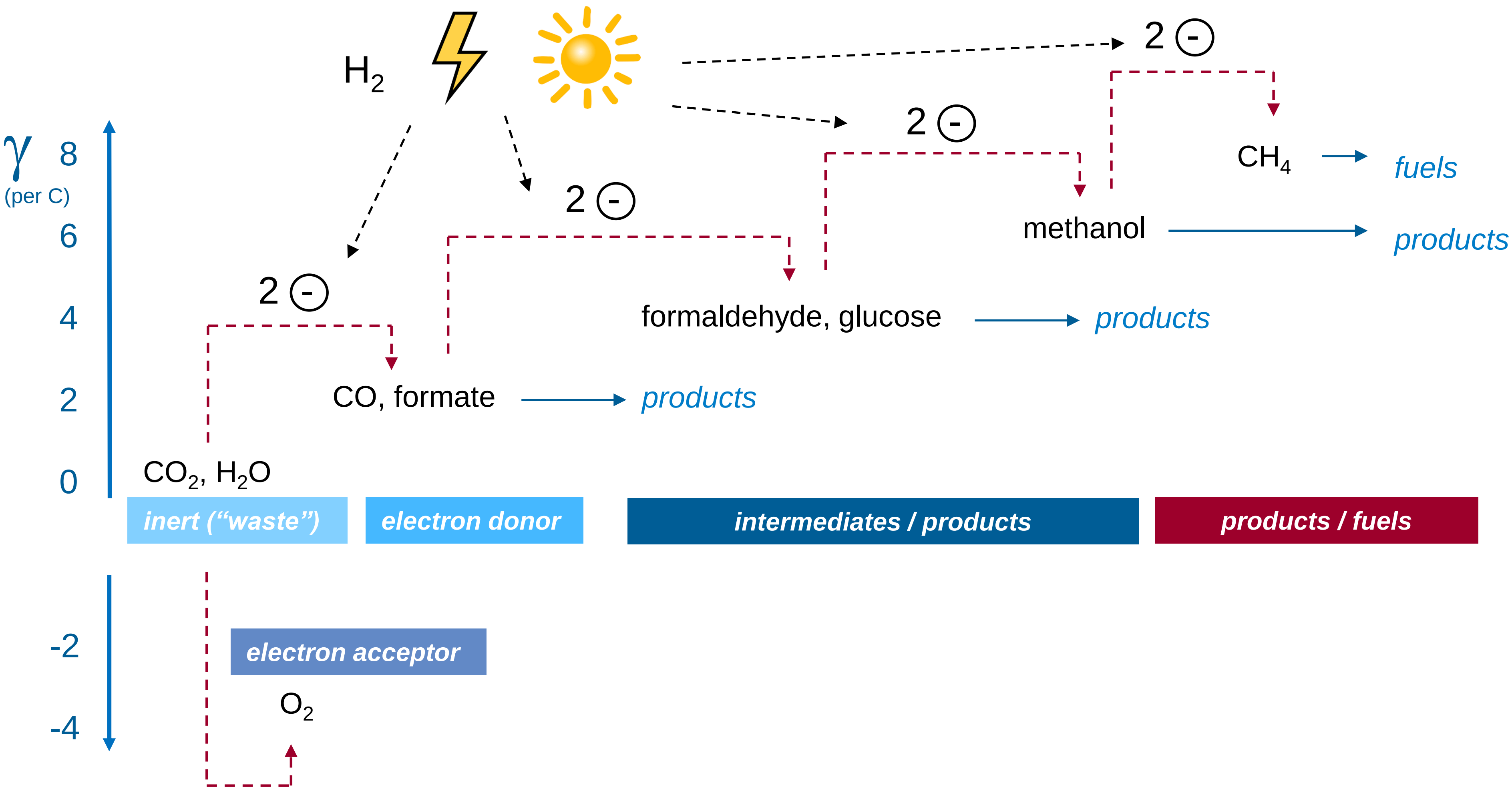


Electrochemical Reductive and Non-Electrochemical-reductive Conversion



- With 90+% FE (and low over-potential) and high Current Density
- Assume 2500 kWh electricity for a 2 electron reduction per ton CO_2
- Assume 0.05/kWh

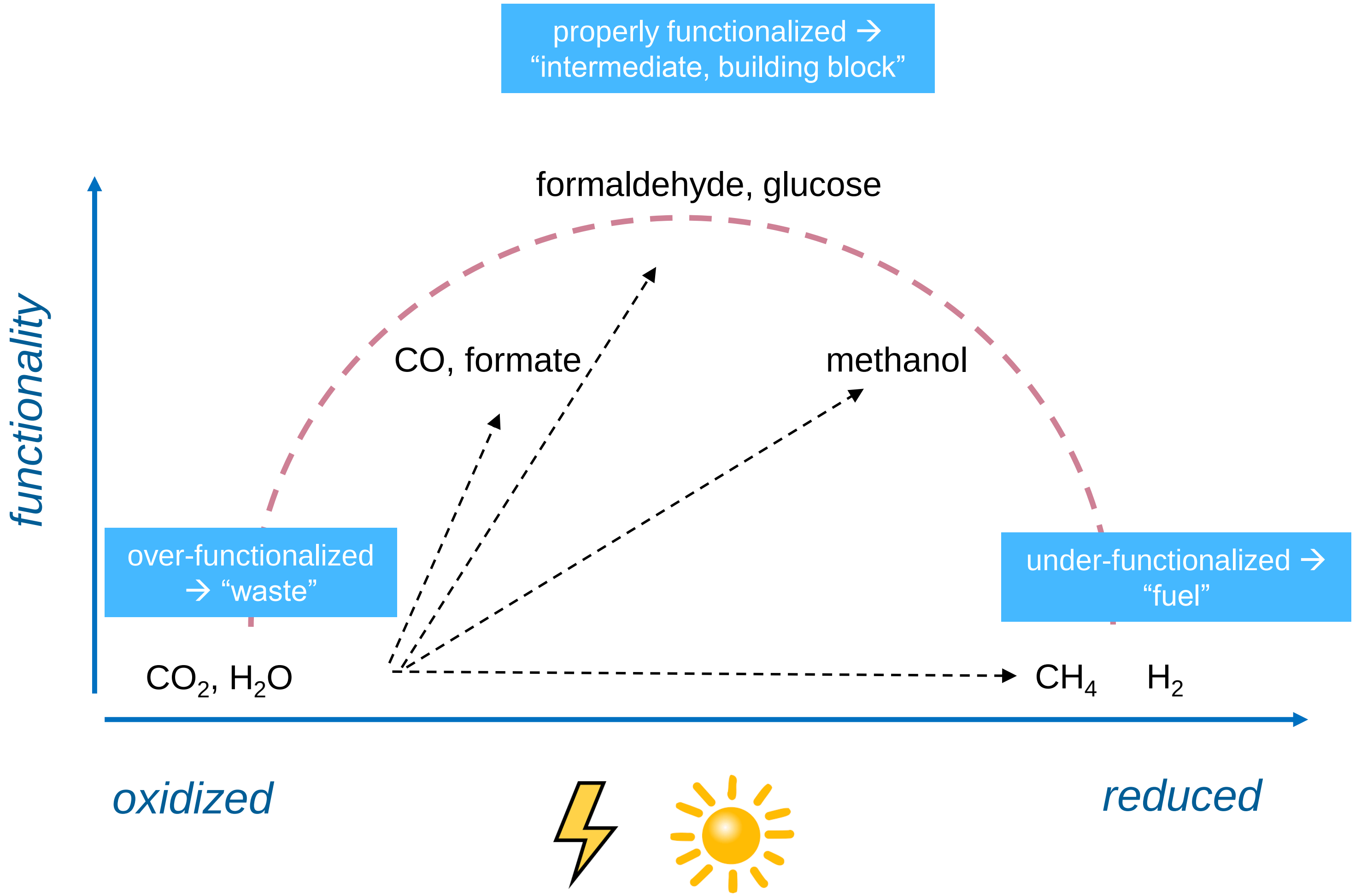
Upgrading of CO_2 – the challenge for reductive conversions



Reductive Conversions

- Energy is needed to reduce CO_2
- The more reductions needed for producing the end product, the more energy is needed
- Sources of energy:
  - Electricity (electrochemical conversion)
  - Hydrogen, or CO (catalytic conversion)
  - (Sun)light (photocatalytic and photosynthetic conversion)
- Heat of formation is also a measure for required energy: the higher, the more energy is needed to produce the end product from CO_2

Reductive conversions – degree of reduction vs value



Electrochemical Conversion of CO_2

- Electricity is used to reduce CO_2 (no H_2 required)
  Renewable electricity required for sustainable processes
- The more reductions needed for producing the end product, the more electricity is needed
- Theoretical minimum amount of energy (Faraday efficiency, current density) per electron reduction
- Theoretical productivity per electrode is higher for gases than for salts, so higher CAPEX for salts
- Electricity production costs are key factor, when electricity is cheap, CAPEX is key factor
- Target molecules: C1 (formic acid, methanol), MEG, urea
- Direct use of electricity for road transport far more efficient than synthetic fuels (electro fuels)
- Excess renewable power not enough to cover power demands synthetic fuels
- Precious metals may be required to keep electricity costs under control

ChemCat conversion of CO_2

- Basically through reduction chemistry (endothermic).
- Target molecules are typically platform chemicals upstream the value chain: syngas, methanol and urea.
- CO_2 can react with hydrogen to methanol (requires 3.0 MJ/kg CO_2 heat).
- CO_2 can react with ammonia to urea (requires 2.8 MJ/kg CO_2)
- Developments in catalysts aim at processes at lower temperatures
- Hydrogen prices are key for meeting prices of current products. Preferably in range 1 -1.5 €/kg
- Footprint of hydrogen production needs to be taken into account (energy requirement, CO_2 emissions)

Hydrogen production

Green hydrogen: H_2 produced by

- Electrolysis of water, using renewable energy
- Photocatalytic H_2O splitting
- Aqueous phase reforming
- Gasification of biomass
- Fermentation of biomass

- Yellow hydrogen = Green hydrogen, produced in countries with abundant renewable energy. Import: “Desert hydrogen”

- Turquoise hydrogen :
  Decarbonization of methane ($CH_4 \rightarrow 2\ H_2 + C$)

- Blue hydrogen:
  Steam Methane Reforming with CCS

- Grey hydrogen:
  Steam Methane Reforming

- Black hydrogen: gasification of coal

Green hydrogen production – the facts (1)

Availability of renewable electricity

- < 20% of current Dutch demand
- 30% of the time available on full capacity
- 10 times more expensive than hydrogen produced from methane (3 times due to intermittency and 3 times due to energy costs)

Investments required

- 1 M€ / MW, price might drop to about 0,5 M€ / MW
- 1 MW @ 8000 hour produces 145 tonnes of green H_2
- Dependent on availability of rare metals
- Investment related to peak capacity will only produce 30-50% of the time at this capacity

Efficiency

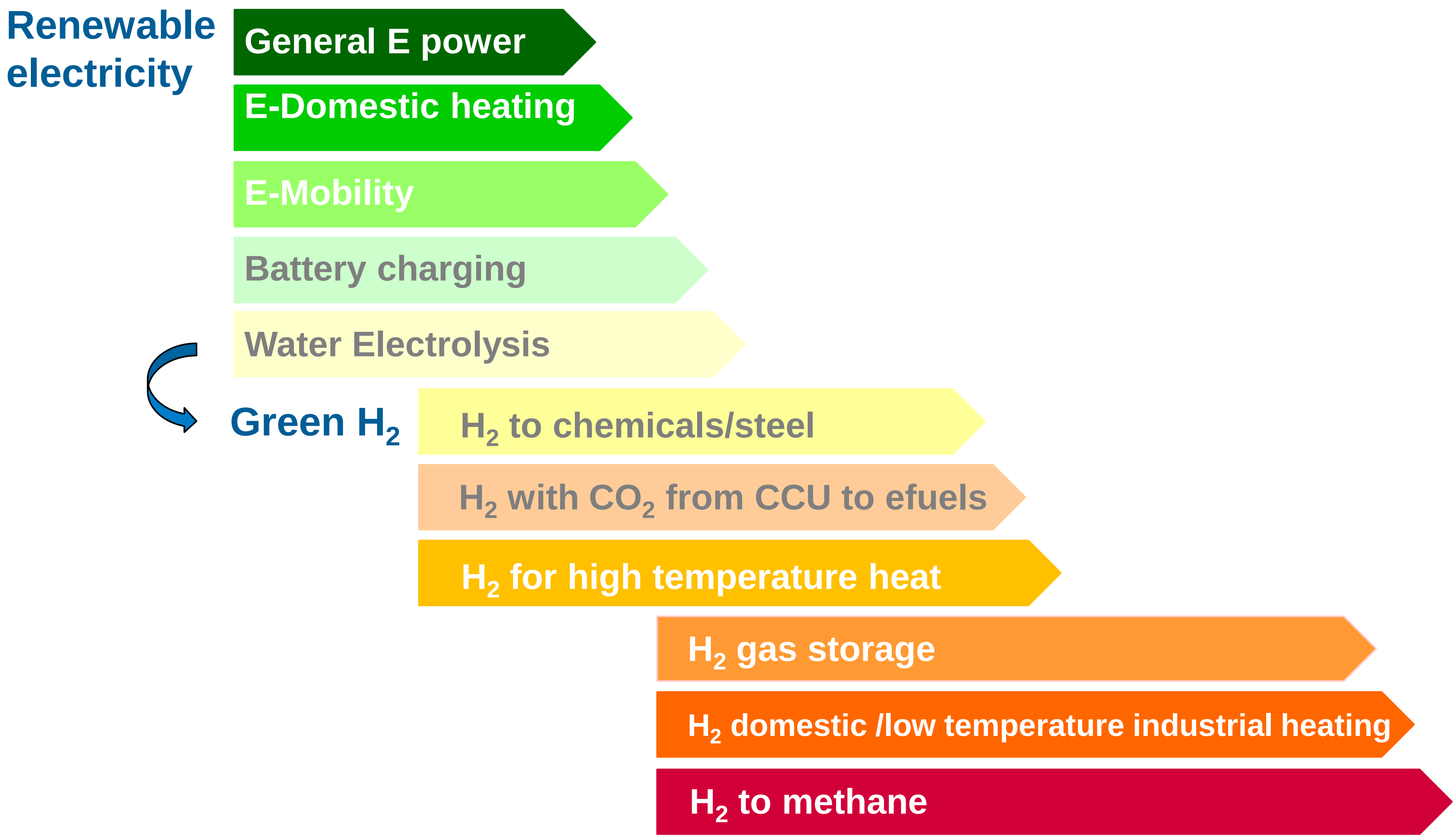
- 70% (current efficiency), limited increase in efficiency possible
- 55 MWh / ton H_2 current best practice (electrolysis only)

Green hydrogen production – the facts (2)

- H_2 produced via electrolysis of water (H_2O)
  - In near future gas price will set the price for renewable electricity
  - Price for H_2 is not expected to decrease
  - H_2 as co-product of chlorine production (limited amounts available)

- H_2 produced from CH sources (methane, biogenic sources)
  - Substantially less energy needed
  - Carbon is produced as C, CO or CO_2 , application needed, or CCS
  - Biogenic sources: ongoing debate on availability, sustainability and cascading of biomass
  - Mixed waste: combination of biogenic and fossil based

Renewable Power / Hydrogen: priorities



Fermentative conversion of CO_2

- Need of CO_2 depends on substrate and products
- Energy supplied via the substrate
- Generally, *CO_2 uptake is at best marginal*, few kiloton/year
- Mostly only applicable in anaerobic fermentations
- Redox balance must be satisfied
- Glycerol substrate offers better CCU opportunities than glucose
- Table below: kg CO_2 consumed per kg fermented product
- Ethanol can be produced (Lanzatech) from CO

Products / substrate	Glucose	Glycerol
Succinic acid	0.18	0.36
4-hydroxy butyric acid	0.00	0.06
4-amino butyric acid	-0.21	0.06
1,4-diamino butane	-1.12	0.36
ethanol	-1.91	-0.55

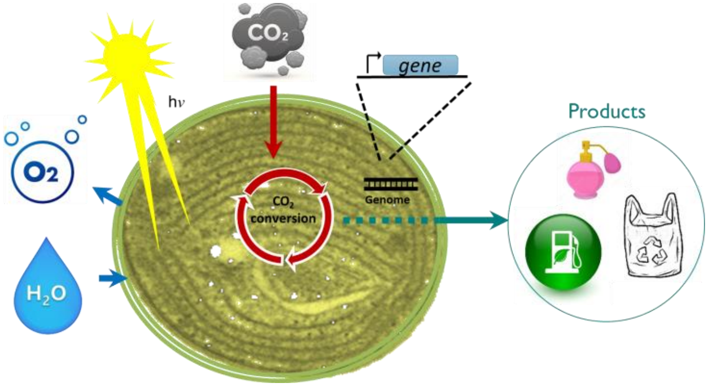
Production of CO_2 in fermentor

Source: comm. With Henk Noorman,23 March 2015 and own calculations

figures excl. growth of biomass and downstream processing

Photosynthetic conversion

- CO_2 and water are converted by photosynthetic organisms into products, for instance by algae, cyanobacteria. 2 separate pathways:
  1. Use of algae mass for extracting and refining end products. This is a proven technology (800 m$ market) [out of scope, biomass as source of product]
  2. Genetic modification of bacteria to produce dedicated chemicals that are secreted into the medium. This has high efficiency of conversion of electrical energy to chemical energy (10% using red LEDs). Technology still developing (TRL6 in outside conditions, expected TRL7 in 2020). Expected to allow for commercialization of low value bulk chemical production
- Algae mass production mainly focuses to production of high value products such as food/feed/chemicals (example: omega-3/blue food colorant) due to high production costs
- Availability of sunlight in Netherlands relatively limited compared to other regions, but moderate climate is beneficial



Visualization of pathway 2. Algae/cyanobacteria are not harvested but excrete the product into the environment

Photocatalytic conversion

- CO_2 and H_2O are converted in the presence of light and a photocatalyst
  - The best PECs using photoanodes and/or photocathodes have a solar-to-hydrogen conversion efficiency of about 2.5% and is low TRL. (State-of-the-art PV electricity, fed into a water electrolysis system, can achieve a solar-to-hydrogen conversion efficiency of more than 20%)
  - Efficiency may overtake PV by developing new materials and by understanding how energy losses can occur at the interfaces between those materials; better understanding of mechanisms of light harvesting, charge separation, charge transfer, and catalytic processes in molecules and materials
- The amount of (sun)light required depends on the oxidation state of the end molecule
- Target molecules: C1 (methanol, formaldehyde, CO, formic acid, methane), ethanol

Ref: White paper *Solar energy and photonics for a sustainable future*, 7th Chemical Sciences and Society Summit, Dalian, China, sept. 2017

Carbonates

Applications in cement and concrete

Description

Cement production is the third largest source of man-made emissions of CO_2 in the world: ± 1,5 Gton CO_2 in 2016 which is about 5% of total CO_2 emission. In cement production the CO_2 that is trapped in limestone ($CaCO_3$) is released. CO_2 emissions can be reduced by lowering the cement: clinker ratio by replacing clinkers. Different types of slag and ashes that have high levels of CaO and MgO can react with CO_2 to form carbonate material. Iron making slag is already used for this purpose. Potential to use steel making slag, which is more difficult to process.

- CarbiCrete: production of construction blocks from steel making slag
- Carbon8: production of aggregates of industrial wastes

Cement can also completely be replaced by other binders

- Solidia Tech produces calcium silicate-based cement, that has less CaO and is non-hydraulic and cures with CO_2

About 85% of cement is used for concrete

- CarbonCure reduces curing time and the amount of cement needed by treating concrete with CO_2 gas before putting it into a mold (CO_2 reacts with ions to form carbonates)

Markets

Construction market, global market is still growing

Competing processes/products

- ‘Regular’ cement and concrete. CO2 pathway could become interesting at CO2 prices of €30-40/ton
- Local markets

Strengths

- Potential of aggregates based on total global available steel slags (± 200 Mton, 2/3 BOF steel slags + 1/3 EAF steel slags) is ± 20 Mton CO_2/yr
- Steel making slag is cheap
- CO_2 potential of carbon curing per ton of product is limited but technique is easy to implement
- Solidia Tech’s technology accelerates curing time significantly
- No need for highly concentrated CO_2
- 50-150 kg CO_2/kg steel making slag

Weaknesses

- Still higher costs compared to regular cement, no incentives in the market for this type of cement
- Cement market is low margin business.
- Construction market is conservative
- Steel making slag is difficult to process
- Mineralization process is slower
- Trend in steel making industry to lower usage of CaO in carbon steel slags which decreases potential for mineralization (less active components to capture CO_2)
- Feasibility for the Netherlands low
- Environmental issues on the cement or building materials made from steel making slag and CO_2 (especially on leaching of heavy metals)

Maturity	Market size	Price	Estimated retention
Introduction/ commercial	Cement: 4,1*10^3Mton/yr	± 100 €/ton	10-50 year

(ref: Geological Survey, Mineral Commodity Summaries, 1st Jan. 2018)

Carbonates

Applications in flue gas treatment

Description

Flue gases of waste incineration plants contain CO_2, that can be scrubbed from the flue gases for mineralization. CO_2 is converted to sodium bicarbonate (SBC), which can be used directly in the waste to energy plant (WTE) to purify the flue gas stream.

Markets

Waste incineration plants

- Twence (Netherlands) produces 8,000 tons of SBC per year. For this amount 2,000 tons of CO_2 per year are captured from the flue gas

In the Netherlands 10 other WTE plants are operational, in the EU this number is 450.

Otherwise limited market potential. Could be an alternative for production of SBC from lignite.

Competing processes/products

- Conventional flue gas treatment

Strengths

- Dutch technology
- Process integration possible
- Better availability for soda than for sodium bicarbonate
- Alternative for conventional sodium bicarbonate production
- Treatment of flue gases with sodium bicarbonate is more energy efficient
- Opportunity as growth medium for algal culture

Weaknesses

- Limited market for sodium bicarbonate of 400 kton per annum
- Moderate market growth

Maturity	Market size	Market price	Estimated retention
Commercial	500,000 ton/yr* * all WtE in Europe	€230-280 €/ton	<0,5 year

Mineralization of silicate minerals

Description

Silicate minerals such as olivine, serpentine, wollastonite and basalt can react in a mineralisation process with CO_2. These silicate minerals request additional mining. The amount of rock mass that needs to be mined for binding 1 ton of CO_2 ranges from 1,6 ton of olivine to 7,1 ton of basalt[1]. In the Netherlands olivine is being studied for binding CO2 by spreading ground, sand-grade olivine along large portions of the Earth's coastlines (CATO-programme) or along roadsides and on agricultural land. Olivine could also be mixed with other materials, such as roof coverings, road salt.

Markets

As this is rather a CCS option, the products that are a result of the mineralisation processes are meant to stay on the land they were spread on, or they might flush into the sea.

[1] Ref: EC, Identification and analysis of promising carbon capture and utilisation technologies, including their regulatory aspects, 2019

Competing processes/products

- CCS

Strengths

- CO_2 retains in the carbonates, therefore this is a form of CCS
- Relatively cheap form of CCS

Weaknesses

- Spontaneously reactions at low atmospheric CO_2-pressure and ambient temperatures occur very slowly
- Formation of silica and carbonate layers on the surface during carbonation hinder further reaction and limit conversion
- Mining of silicate rocks, ore pretreatment and waste-product disposal has negative environmental side effects
- Olivine often contains Nickel which makes application on agricultural land difficult or even impossible
- Effects on the marine environment need to be assessed
- Total potential in absolute amounts of Mton CO_2 is moderate, this option is considered to be a CCS option
- No olivine available nearby the Netherlands

Maturity	Market size	Market price	Estimated retention
Pilot	not relevant	not relevant	permanent

Polymers

Polycarbonates/polyols

Description
Polycarbonates (PC) are thermoplastic polymers. Aliphatic PC is produced from copolymerisation of CO_2 and epoxides. Polycarbonate polyols are aliphatic and produced by copolymerization of CO_2 and epoxides and are used to produce polyurethanes (PUR).

- Covestro (Germany) produces polycarbonate polyols in 5kta plant
- Empower Materials (US) develops polyalkylene carbonate polymers
- Asahi Kasei (Japan) produces aromatic PC in 1000 Mt plant
- Econic Technologies (UK) develops catalysts for manufacturing polycarbonates/polyols from CO_2
- Repsol (Spain) produces polyols on pilot scale
- Norner (Norway)

Markets
Aliphatic polycarbonates are used as an intermediate for the production of polyols and as macro monomer for the production of PUR and other polymers.
PUR applications are mainly foam based products (both flexible and rigid) used for a.o. construction and consumer products.

Competing processes/products
PHA

Strengths
- Degradable

Weaknesses
- Low Tg and low strength
- Required energy for use of CO_2 as a monomer
- Costs of epoxides
- Limited performance

Maturity	Market size	Price	Estimated retention
Introduction	.. ..	± 2500-3000 €/ton	1-10 year

Polymers

PHA - Polyhydroxyalkanoates

Description

Large family of polyesters are produced by bacteria. PHAs can contain >150 different monomers and properties vary with composition. Typically PHA can be used in blends to 1) improve functionality for example of PLA, *e.g.*, in 3D printing and 2) improve biodegradability of the material.
Chemoautrophic bacteria can produce PHA from CO_2 + H_2; methanotrophs use CH_4.

Examples of published initiatives:

- [link] Newlight Technologies (US): PHA from CH_4, or CO_2
- [link] Saphium Biotechnology (Austria): PHA from CO_2 and H_2
- [link] Oakbio (US): convert CO_2 + H_2 into n-butanol and PHA
- [link] Mango Materials: PHB from CH_4
- [link] Bio-On currently produces PHA from agricultural side streams and is targeting CO_2 + H_2 as future feedstock

Markets

Packaging, bio-medical, disposables, agriculture, food services, 3D printing

Competing processes / products

- PHA produced via microbial fermentation of sugars or vegetable oil
  ➔ pure feedstock gives PHA of more controlled quality
- In development: PHA production from waste streams
  ➔ hurdle for applications in food / medical (hygiene, purity)
  ➔ difficult to produce stable, specific quality and high purity
- Competing products: other biodegradable polymers such as PLA (biodegradable under controlled conditions only)

Strengths

- Biobased plastic with demonstrated marine degradability
- Good biodegradability in both controlled and uncontrolled environments
- Blending can improve biodegradability in other plastic materials
- The product can directly be produced through gas fermentation technology

Weaknesses

- Cost position unfavorable
- Limited availability
- Complicated to produce similar PHA grades in different facilities / countries from different feedstocks
- Challenging processing behavior (*e.g.*, degradation) in relation to high production costs
- Limited market potential
- Impurities in CO_2 or CH_4 potentially toxic to production organisms

Maturity
Pilot

Market size
~30 kton in 2018
[link-European Bioplastics]

Market price
± 5000 €/ton
[link-WUR 1722, 2017, p.25]

retention time
1-10 year

Chemicals

Melamine

Description
Melamine is produced from urea (carbamide). Urea is the combination of ammonia and CO_2. Melamine is widely used for the production of resins. It is combined with urea and formaldehyde/methanol to produce in combination with wood, laminate flooring and fibre board.

Markets
Construction industry, in applications like decorative laminates, wood adhesives, paints and coatings.
Melamine market is expected to grow (2-5% in the coming years), especially in Asia/Pacific.

Competing processes/products
Melamine is combined with urea and methanol, in major volumes throughout the World. Main application is wood panel industries and laminate flooring.
Melamine, urea and methanol are good CCU options, especially if based on green hydrogen/ammonia and captured CO2. The CO2 currently used for melamine production is derived from natural gas via grey ammonia production.

Strengths
- Urea industry is the largest consumer of CO_2, *if urea is produced with non fossil based ammonia*, Melamine is an interesting mature CCU option. Combined with bio methanol the combination provides a large global CCU potential
- Netherlands among top 5 melamine producing countries in the world

Weaknesses
- Today the urea production is a net source of CO_2, as most ammonia production is based on natural gas and the urea synthesis requires a lot of energy
- Recycling of melamine is difficult, by incineration CO_2 is again released

Maturity	Market size	Market price	Estimated retention
Commercial	150.000 T production NL	± 1500 €/ton	10-20 years

Chemical intermediates

Formic acid ($2CO_2 + 2H_2O \rightarrow 2HCOOH + O_2$)

Description

Formic acid (HCOOH) has strong acidic and reducing properties. Its energy density is high. Formic acid is very corrosive. It is an important intermediate in chemical synthesis. Via electrocatalytic reduction of CO_2, formate salts are produced (drilling and de-icing applications).

New applications can be found in fuel cells – formic acid can serve as a storage medium for H_2.

- Avantium (NL): H2020 RECODE & OCEAN projects (€10M), electrochemical CO2 to formate and downstream to oxalate / oxalic acid and glycolic acid / glyoxylic acid (pilot 2020). Avantium bought Liquid Light (US) in 2017
- Twence and COVAL (NL): electrochemical conversion (pilot)
- Dioxide Materials (US): electrochemical conversion to CO and formic acid; lab scale

Competing processes/products

- Production by hydrolysis of methyl formate (starting from methanol)
- In fuel cells for road transport: competition with electric vehicles or fuel cells on H_2 or methanol
- Formic acid can also be produced directly from CO_2 and H_2.

Strengths

- Compared to H_2 formic acid is a liquid, relatively easy and safe handling
- High energy density

Weaknesses

- Formic acid is corrosive (fuel)
- Electrochemical processes require further development to reduce overpotential and increase current density
- Sustainable energy required. 2 electrons per CO_2

Markets

Formic acid and its salts are used in the feed industry, grass silage, leather tanning and anti-icing.
Other applications: dyeing and finishing of textiles, food additives, drilling fuels, natural rubber.
Formate to oxalate was commercially proven. Oxalic acid and it's reduction products glycolic acid and ethylene glycol have potential in (co)polyesters; glyoxylic acid has potential in personal care. Potential as hydrogen carrier to facilitate H_2 storage and transport

	Maturity	Market size	Market price	Estimated retention
Formic acid	Pilot (EC route)	700 kton/yr	700 €/ton	<0,5 year
Formate salts	Pilot (EC route)	?	800 €/ton	<0,5 year
Oxalic acid	Commercially proven	400 kta	450 €/ton	years
Glycolic acid	Pre-Pilot (EC route)	100- kta*	2500 €/ton	years
Glyoxylic acid	Pre-Pilot (EC Route)	400 kta*	3500 €/ton	years

*market can be much larger if costs goes down.

Chemical intermediates

CO ($CO_2 + H_2O \rightarrow CO + H_2 + O_2$)

Description

CO from CO_2 with sustainable hydrogen gives syngas that can be used as drop-in in many chemical (methanol, ethanol, etc) and fuel processes (Fischer-Tropsch fuels).

- Avantium (NL): H2020 CELBICON project, electrochemical conversion to CO. Climeworks DAC coupled to Avantium E-Chem module. (demonstration 2019/20 @ Prodock Amsterdam).
  Avantium bought Liquid Light (US) in 2017
- Dioxide Materials (US): electrochemical conversion to CO; lab scale

Competing processes/products

- Production by hydrolysis of methyl formate (starting from methanol)
- In fuel cells for road transport: competition with electric vehicles or fuel cells on H_2 or methanol

Strengths

- Drop in product for bulk chemical applications and fuels

Weaknesses

- Formic acid is corrosive
- Electrochemical processes require high overpotential
- Low solubility of CO_2 in water
- High electricity requirement

Markets

CO has huge potential with H_2 (syngas) to produce ethanol, methanol (oxygenates) and synthetic fuels via Fischer Tropsch. CO is therfore a key intermediate in CCU applications.

	Maturity	Market size	Market price	Estimated retention
CO	Pre-pilot (EC Route)	millions of tons	400-500 €/ton	<0.5 year

Chemical intermediates

Lactic acid

Description

Lactic acid ($C_3H_6O_3$) is a mild acid. Its energy density is low. It's energy density is lower than sugar. Lactic acid can be used as the substrate for chemical synthesis of PLA (Poly-Lactic-Acid), a biobased compostable and recyclable plastic. Lactic acid is currently made commercially from sugar directly. Alternative production from CO_2 is possible:

- Photanol (NL): Convert CO_2 directly into lactate using cyanobacteria as photobiocatalysts for the conversion. The energy input can be based on direct sunlight or LED light. CO_2 can be made both from biogenic and from fossil based CO_2, depending on site location and client preferences.

Markets

Lactic acid and its derivatives are used in food as a fortifier and/or as an inhibitor of contaminating bacteria. Furthermore lactid acid can be used in technical applications (cleaning agents, solvents, electronics, home and personal care, agriculture, pharma, coatings). The main growth area for lactid acid is PLA.

Competing processes/products

- Currently produced from sugars by fermentation (TRL9)
- Can also be made using 2nd generation technology (TRL6)

Strengths

- Lactic acid is a natural body owned substance and can be used to form a biobased, compostable, recyclable plastic (PLA)
- Lactic acid has a modest energy density and therefore requires only a modest amount of energy for production when starting with CO_2 as substrate
- Potentially less land is being used with systems that produce lactic acid directly from CO_2

Weaknesses

- Typical lactic acid applications have a relatively short "in-use" time, that is a short retention time of captured CO_2
- The origin of the CO_2 in the current sugar-based process already is "biogenic". The new "CO_2" based process will likely use fossil based CO_2 (end of pipe solution)

Maturity	Market size	Market price	Estimated retention
TRL6 (Pilot/Demo)	± 700-800 kton/yr	± 1000-1500 €/ton	<0,5 year

Chemical intermediates

Methanol

Description

Most processes combine production of H_2 with CO_2/CO

- Carbon Recycling International (Iceland): commercial production of methanol, catalytic process, H_2 produced by electrolysis; production capacity 4000 tons/year (~10 kton/day)
- Air Liquide (France): catalytic process based on classical syngas production, pilot 50 kg/day in 2017, aims at transport fuel under RED2
- Mitsui (Japan): catalytic process, pilot plant opened in 2009 of 33000 gallons/year (~270 kg/day), still approving commercialisation
- Opus 12 (US): electrocatalytic process using a novel membrane elektrode to favor the production of syngas, pilot 25 kg/day (2017)
- BioMCN (NL) cooperates with Nouryon and Gasunie on a feasibility study for 20 MW water electrolysis plant, investment decision expected in 2019
- H2020 project: Fresme and MEFCO2 for methanol production from CO_2 originating from blast furnace gas and powerplant
- Carbon2Chem: TKS Duisberg. Integration of using blast furance and hydrogen from electrolysis to produce methanol

Markets

- Market demand is growing and exceeds the supply (2018). Chinese market is growing due to MTO (methanol to olefins) production
- Market for green methanol growing due to renewable energy directive and targets for renewable transport fuels

Competing processes/products

- Fossil based methanol produced from natural gas or coal
- Biobased methanol produced from biogas from digestion

Strengths

- RED2
- High TRL
- High energy density
- Large market
- Easy adoption in current infrastructure
- Energy carrier

Weaknesses

- Securing H_2 supply at low costs
- Catalysts need to be highly selective and have high productivity due to high energy demand

Maturity	Market size	Market price	Estimated retention
Catalytic: Pilot/demo Electrocat: lab	± 110 Mton/yr	± 400 €/ton	<0,5 year

Chemical intermediates

Methane (SNG)

Description

- Store &Go project (Germany): methanation demo plant opened in 2018 in Falkenhagen, 1 MW, CO_2 from biogas or bio-ethanol plant – H_2 from alkaline water elecrolysis, methanation with isothermal catalytic honeycomb reactors
- Store & Go project (Switzerland): demo site in Solothurn, 700 kW, biological methanation, CO_2 from waste water treatment plant - H_2 from PEM water elecrolysis Electrochaea is technology provider for methanation
- Store&Go project (Italy): demo methanation plant in Troia, aircapture CO2, 200 kW - H_2 from alkaline water elecrolysis
- HEPP project (Switzerland): 10 KW demo plant combining SOE and catalytic methanation reactor. First production Q1 2019
- AVL (Austria): CO_2 and H_2O co-electrolysis and system integrated methanation, 10 Kwe
- Viesmann (Germany): CO_2 from biogas plant and H_2 are converted microbially (BiON process of MicrobEnergy), demoplant in Allendorf, capacity 15 Nm^3/hr

Markets

Methane is primarily used as fuel, for generation of electricity, heat and transportation. In the chemical industry, methane a.o. is used as a feedstock for the production of H_2, methanol, acetic acid and its derivatives.

Competing processes/products

- Assumed is that the benchmark should be production of natural gas (rather than methanation process). There are different economics between pipeline natural gas and SNG, dependent on policy and subsidies
- Additional competing process should be SNG production from coal, petrocoke or biomass. For example demonstration for SNG production from waste (around 20 MWth) using Haldor Topsoe technology has been done in Sweden, paid for the by the first tranche of allowance from ETS allocated originally for CCS
- Natural gas
- Biogas from digestion or gasification of biomass

Strengths

- Large market
- Easy adoption in current infrastructure

Weaknesses

- All internedate products have more value than the end product methane
- Requires H_2 supply at low costs
- Catalysts need to be highly selective and have high productivity due to high energy demand
- Only plausible at very low electricity costs (*not in the Netherlands*)
- 10 MWh/ton CO_2

Maturity	Market size	Market price	Estimated retention
Pilot/demo	± 3000. Mton/yr	± 140 €/ton (VS)	<0,5 year