INTEGRATED LIFE CYCLE APPROACHES FOR UNDERSTANDING CARBON DIOXIDE UTILISATION AND SEQUESTRATION PATHWAYS

4 MARCH 2015

PAM LIVERSIDGE BUILDING, UNIVERSITY OF SHEFFIELD, MAPPIN STREET, SHEFFIELD S1 3JD

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UKCCS
RESEARCH CENTRE

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AGENDA

10:00 - 10:05	**Peter Styring** (Sheffield University) - *Introduction to CO_2Chem*
10:05 - 10:10	**Jon Gibbins** (University of Edinburgh) - *Introduction to the UKCCSRC*
10:10 - 10:40	*Short updates from attendees about their research*
10:40 - 11:00	**Niall Mac Dowell** (Imperial College London) *Multi-Scale Modelling of BECCS in the UK*
11:00 - 11:20	Coffee
11:20 - 11:40	**Rosa Cuellar-Franca** (University of Manchester) *Carbon Capture, Storage and Utilisation Technologies: A Critical Analysis and Comparison of their Life Cycle Environmental Impacts*
11:40 - 12:00	**Peter Styring** (University of Sheffield) *Carbon Dioxide Utilisation: Myths and Magic!*
12:00 - 12:20	**Campbell Skinner** (University of Bangor) *Energy Evaluation in Supercritical CO_2 Extraction*
12:20 - 13:20	Lunch
13:20 - 14:00	**Niklas von der Assen** (Aachen University) *Current, Best and Future Practice of LCA for CO_2 Utilization*
14:00 - 16:00	Workshop

SPEAKER BIOGRAPHIES

Jon Gibbins, UKCCSRC

Jon has worked on coal and biomass gasification and combustion for over 25 years, at Foster Wheeler, Imperial College and University of Edinburgh and on carbon capture and storage (CCS) since 2002. He is currently the Principal Investigator of the UK Carbon Capture and Storage Research Centre supported by the Engineering and Physical Sciences Research Council (EPSRC) as part of the Research Councils UK Energy Programme. He is also the Professor of Power Plant Engineering and Carbon Capture at the Institute for Materials and Processes based at the University of Edinburgh. He is involved in a number of other academic, industrial and government initiatives on CCS in the UK and overseas, including the DECC Advisory Committee on Carbon Abatement Technology, and has also contributed to a number of media pieces and other outreach activities on CCS.

Peter Styring, UK Centre for Carbon Dioxide Utilization (The University of Sheffield)

Peter Styring is Professor of Chemical Engineering & Chemistry at The University of Sheffield. He is a Chartered Engineer and Chemist and Fellow of the RSC and IChemE. He is also an Associate Fellow at the Crick Centre for Political Engagement. Peter's expertise lies in carbon dioxide capture and utilisation, especially the formation of fuels and polymers. His research embraces a whole systems approach in which LCA plays a pivotal role. He is Editor of the Elsevier book "Carbon Dioxide Utilisation: Closing the carbon cycle" and co-author of the book "Carbon Capture and Utilisation in the Green Economy. Peter is Director of the CO2Chem Network and the UK Centre for Carbon Dioxide Utilisation. Peter is also Chair of the 2015 Faraday Discussion on CDU and a member of the International Scientific Board of ICCDU. He is principal investigator on a number of grants including two to define funding policy for CDU in the European Union.

Niall Mac Dowell, Imperial College London

Dr Niall Mac Dowell is a lecturer at Imperial College London and is a Chartered Engineer with the Institution of Chemical Engineers. He has a Bachelor's degree (UCD/UCLA) and a PhD (Imperial College) in Chemical Engineering and in 2010 he was awarded the Qatar Petroleum Prize for his doctoral research. His research interests are in the area of multi-scale modelling of decarbonised energy systems. He conducts consultancy work for companies involved in power generation and has given expert advice to DECC, the ETI, the JRC and the IEA in a number of paid consultancy roles, and has travelled on behalf of the Foreign Office to travel to the Far East to promote low carbon power generation. He has been invited to provide written evidence to members of the Select Committee on Energy and Climate Change. He is currently acting as the Chief Technologist on the CO_2 Utilisation project ACUTEC for the JRC and also for the IEA GHG R&D Programme on flexible low carbon power generation.

Rosa Cuellar-Franca, University of Manchester

Rosa holds an M.Eng. in Chemical Engineering from the Technology Institute of Tijuana and an M.Sc. in Environmental Technology from The University of Manchester. During her M.Sc. Rosa collaborated with a major international construction company to estimate the carbon footprint of construction materials. This experience led her to pursue a Ph.D. in Sustainable Construction at The University of Manchester, which she completed in early 2013. Rosa is now a Post-Doctoral Research Associate in the Sustainable Industrial Systems group based in the School of Chemical Engineering and Analytical Science at The University of Manchester. She is currently working on the 4CU project in partnership with The University of Sheffield, University College London and Queen's University Belfast. The project, which is funded by the EPSRC, is developing a comprehensive approach to understand and analyse schemes for converting CO2 to fuels (carbon capture and utilisation).

Campbell Skinner (University of Bangor)

Campbell is the life cycle assessment analyst at the Bio Composites Centre in Bangor University, working under the BEACON project. He has a Masters with distinction in environmental sciences and has provided environmental accounting expertise on a number of funded university research projects. His previous work has focused on greenhouse gas emissions and

carbon foot printing, initially in the context of Welsh livestock farming. This broadened out to cover food production supply chains when he joined the university's commercial carbon foot printing consultancy as their carbon footprint manager. Since moving to the BioComposites Centre, his work has focused on lifecycle analysis (in line with the ISO 140040/44 framework) and bio-based products.

Niklas von der Assen (Aachen University)

Niklas von der Assen studied at RWTH Aachen University, University of California in Davis, USA and Universitat Rovira i Virgili in Tarragona, Spain and received a diploma degree in Mechanical Engineering in 2010 and a diploma degree in Business Administration in 2011 both from RWTH Aachen University. Since 2010, he is a PhD student at the Institute of Technical Thermodynamics at RWTH Aachen University. Here, he is leading the research group "energy systems engineering" since 2015. His research focus is on environmental assessment of CO2 capture and utilization using life cycle assessment.

ABSTRACTS FOR PRESENTATIONS

Peter Styring University of Sheffield

Carbon Dioxide Utilisation: Myths and Magic!

What role can carbon dioxide utilisation (CDU) take in CO_2 mitigation? Is there capacity to employ CDU? To be able to answer these questions we need to set CDU in context with other mitigation approaches. There are a number of myths surrounding CDU, due mainly to a lack of appreciation of what can and cannot be achieved. For example, it is often stated that CDU cannot cope with the quantities of CO_2 emitted and that CCS is the only solution. It is also stated that the leading CDU technology is CO_2-enhanced recovery (EHR). The problem is that common boundary conditions are not applied. How does CO_2 conversion to synthetic oil compare with EHR of previously inaccessible oil? The talk will look at a common framework for LCA in these systems and present preliminary comparative results from a number of systems.

Niall Mac Dowell Imperial College London

Multi-Scale Modelling of BECCS in the UK

It is becoming increasingly clear that, in order to meet our emission reduction targets, it will be necessary to remove carbon dioxide directly from the atmosphere in addition to preventing its emission in the first place. There are many ways to achieve this, but the generation of carbon negative electricity via the co-firing of fossil fuels and biomass in conjunction with CCS (sometimes referred to as Biomass Enhanced CCS - BECCS) is a promising option. BECCS also allows the offsetting of hard-to-reach emissions such as those from transport or certain industrial sources. However, the generation of carbon negative electricity via BECCS is likely to be significantly more expensive than simply generating low carbon electricity [1] and moreover, owing to additional process water in addition to the embodied water in the biomass, the water

footprint of a BECCS facility is also likely to be significantly higher [2].In this presentation, these factors are quantified and the implications for policy makers are considered.
[1] Akgul, A. et al., Int. J. GHG. Con., 2014 [2] Feng, T. MSc Imperial College, 2014

Rosa Cuellar-Franca University of Manchester

Carbon Capture, Storage and Utilisation Technologies: A Critical Analysis and Comparison of their Life Cycle Environmental Impacts

A comprehensive comparison of environmental impacts of carbon capture and storage (CCS) and carbon capture and utilisation (CCU) technologies are presented. Life cycle assessment studies found in the literature have been reviewed for these purposes. In total, 27 studies have been found of which 11 focus on CCS and 16 on CCU. The CCS studies suggest that the global warming potential (GWP) from power plants can be reduced by 63-82%, with the greatest reductions achieved by oxy-fuel combustion in pulverised coal and integrated gasification combined cycle plants and the lowest by post-combustion capture in combined cycle gas turbine plants. However, other environmental impacts such as acidification and human toxicity are higher with than without CCS. For CCU, the GWP varies widely depending on the utilisation option. Mineral carbonation can reduce the GWP by 4-48% compared to no CCU. Utilising CO_2 for production of chemicals, specifically, dimethylcarbonate (DMC) reduces the GWP by 4.3 times and ozone layer depletion by 13 times compared to the conventional DMC process. Enhanced oil recovery has the GWP 2.3 times lower compared to discharging CO_2 to the atmosphere but acidification is three times higher. Capturing CO_2 by microalgae to produce biodiesel has 2.5 times higher GWP than fossil diesel with other environmental impacts also significantly higher. On average, the GWP of CCS is significantly lower than of the CCU options. However, its other environmental impacts are higher compared to CCU except for DMC production which is the worst CCU option overall.

ATTENDEES

Name	Institution
Ana Villa	
Andrew Cox	Energy Intelligence & Marketing Research
Arturo Castillo	Imperial College
Athanasios Angelis-Dimakis	Imperial College London
Camille Petit	Imperial College London
Campbell Skinner	Bangor University
Chris Hodrien	Ti mins CCS Ltd
Chris Jones	University of Sheffield
Ebuwa Osagie	Cranfield University
Eileen Yu	Newcastle University
Emilie Brady	UKCCSRC
Enrico Andreoli	Swansea University
Evgenia Mechleri	Imperial College London
George Dowson	University of Sheffield
Grant Wilson	The University of Sheffield
Jasmin Kemper	IEAGHG
John Broderick	Tyndall Centre
Jon Gibbins	UKCCSRC
Kamal Miah	University of Sheffield
Katy Armstrong	CO2Chem
Killian Gleeson	
Matthew Billson	University of Sheffield
Michael Joyes	University of Bath
Muhammad Akram	University of Sheffield
Niall Mac Dowell	Imperial College London
Niklas von der Essen	RWTH Aachen University
Peter Styring	The University of Sheffield
Pier Sazio	University of Southampton
Rhodri Owen	University of Sheffield
Romain Viguier	SCCS
Rosa Cuellar-Franca	University of Manchester
Shanwen Tao	University of Strathclyde
Stephen Florence	Carbon Cycle Ltd
Taofeeq Ibn-Mohammed	University of Sheffield
Yang Zhang	Mechanical Engineering Department, The University of Sheffield
Yanna Dimitriou	University of Sheffield

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4th March 2015

Integrated life cycle approaches for understanding CCU/S pathways

Jon Gibbins
Director, UK CCS Research Centre
Professor of Power Plant Engineering and Carbon Capture
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The UKCCSRC is supported by the Engineering and Physical Sciences Research Council as part of the Research Councils UK Energy Programme

Pioneering research and skills

About the UKCCSRC

The UK Carbon Capture and Storage Research Centre (UKCCSRC) **leads and coordinates a programme of underpinning research on all aspects of carbon capture and storage** (CCS) in support of basic science and UK government efforts on energy and climate change.

The Centre brings together around 250 of the UK's world-class CCS **Academics** and 220 **Early Career Researchers** to provide a **national focal point for CCS research and development** and **capacity building**.

There is also an **Associate Membership** programme and a **Network**.

Initial core funding for the UKCCSRC is provided by £10M from the Engineering and Physical Sciences Research Council (EPSRC) as part of the RCUK Energy Programme. This is complemented by £3M in additional funding from the Department of Energy and Climate Change (DECC) to help establish new open-access national pilot-scale facilities (www.pact.ac.uk). Partner institutions have contributed £2.5M.

www.ukccsrc.ac.uk

The future of LCA in a carbon-balanced world?

In order to keep within a fixed carbon budget:
Carbon out of the ground = Carbon back into the ground

Permanent carbon storage certificates required for all fossil fuels, limestone etc. to be legally bought and sold

Carbon storage certificates from any source of CO_2 , e.g.:

- Power plants with CO_2 capture
- Industry with CO_2 capture
- Direct air capture of CO_2

Does LCA for Carbon become unnecessary?

Carbon capture, storage and utilisation technologies: A critical analysis and comparison of their life cycle environmental impacts

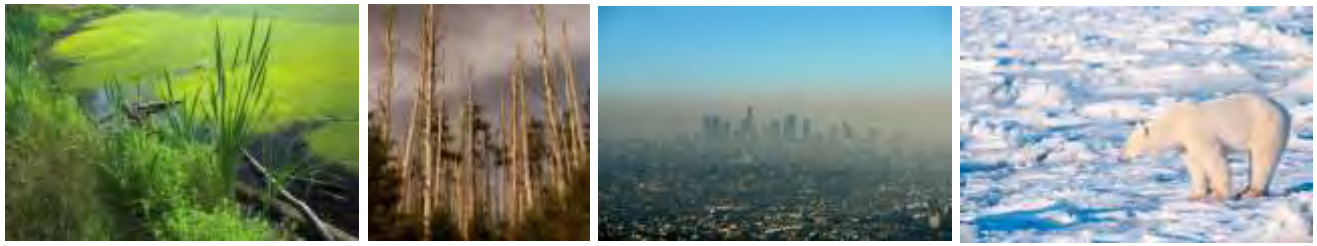
Rosa Cuéllar-Franca
and
Adisa Azapagic

School of Chemical Engineering and Analytical Science
The University of Manchester

LCA in CO_2 Utilisation
4th March 2015
Sheffield, UK

The importance of LCA in CCS and CCU systems

- To avoid mitigating climate change at the expense of other environmental issues
- To avoid shifting the environmental burdens from one life cycle stage to another



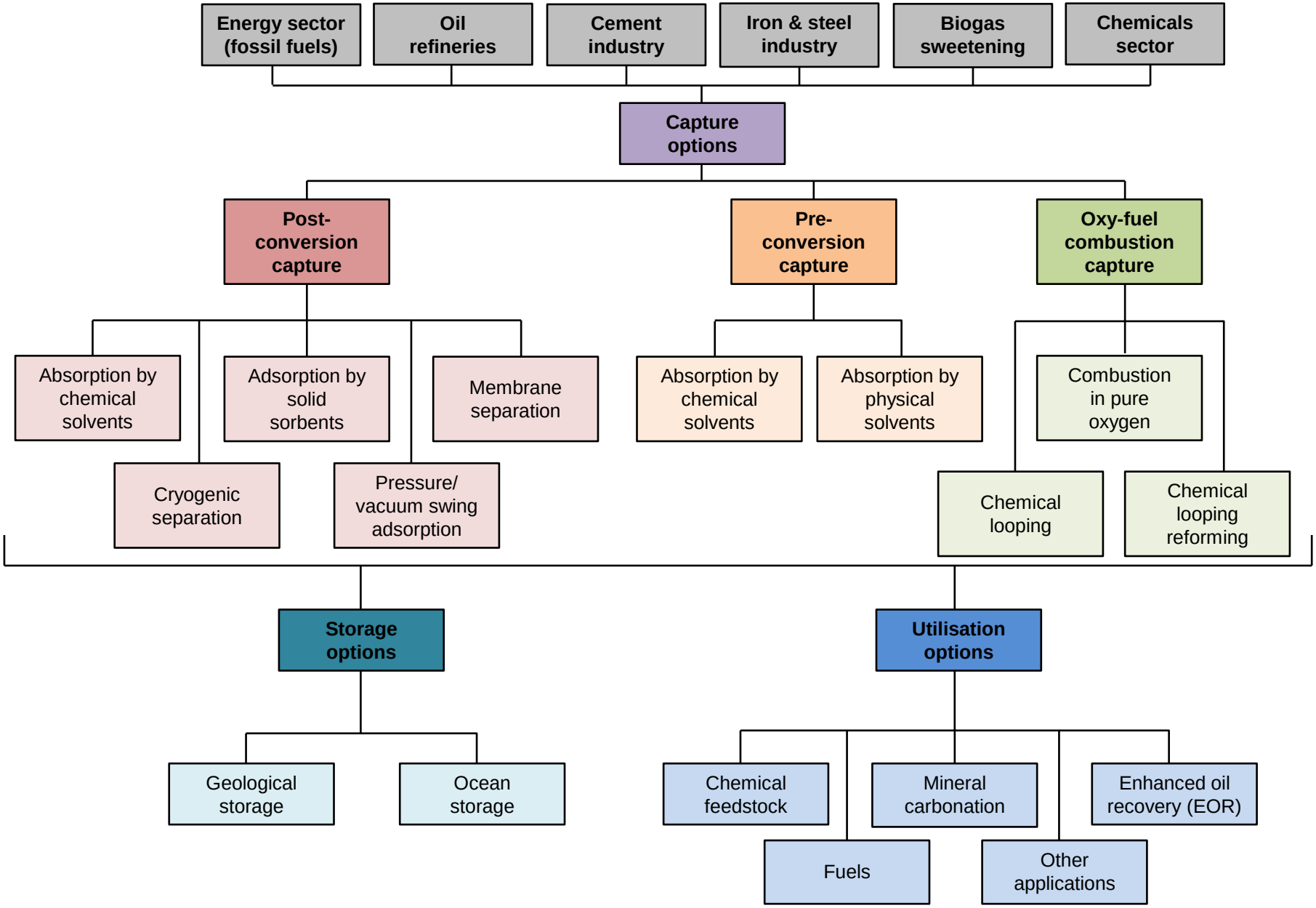
Foreseeing a future using CO_2

Overview

- Life cycle environmental impacts of
  - CCS and
  - CCU
- Comparison of environmental impacts of CCS and CCU technologies
- Presentation based on:

Cuellar-Franca, R and A. Azapagic (2015). Carbon capture, storage and utilisation technologies: A critical analysis and comparison of their life cycle environmental impacts. *Journal of CO_2 Utilization,* 9, 82–102.

Different carbon capture, storage and utilisation options

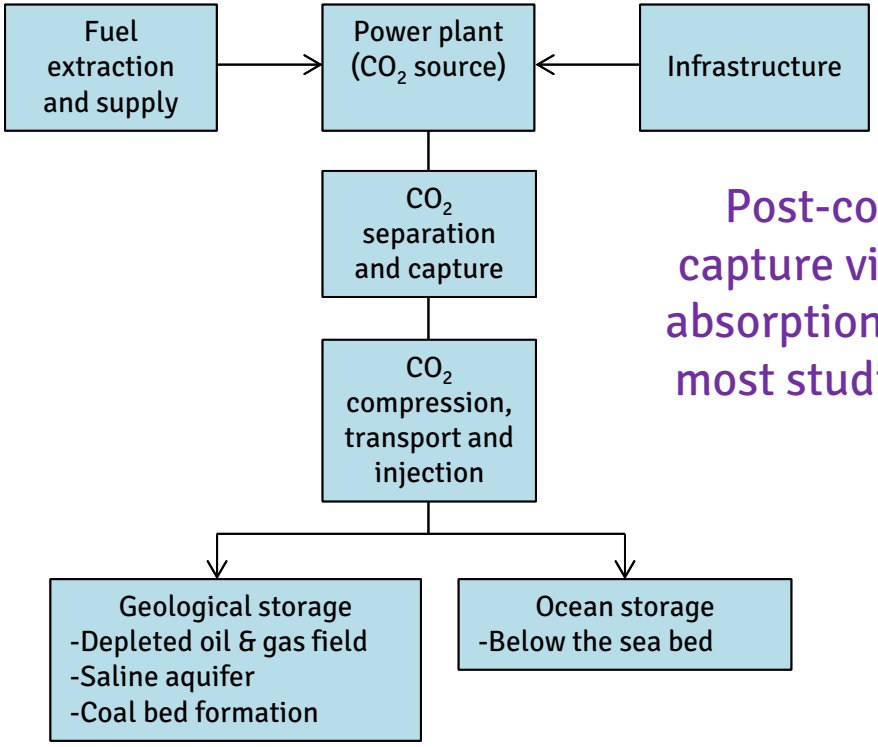


LCA studies on CCS

- LCA studies are mainly focused on CCS technologies for power plants
  - Pulverised coal
  - Integrated coal gasification combined cycle
  - Combined cycle gas turbine
- Variation in goal and scope
  - Comparison of different CCS technologies
  - Power plants with and without CCS
  - CCS vs renewable energy technologies

LCA studies on CCS

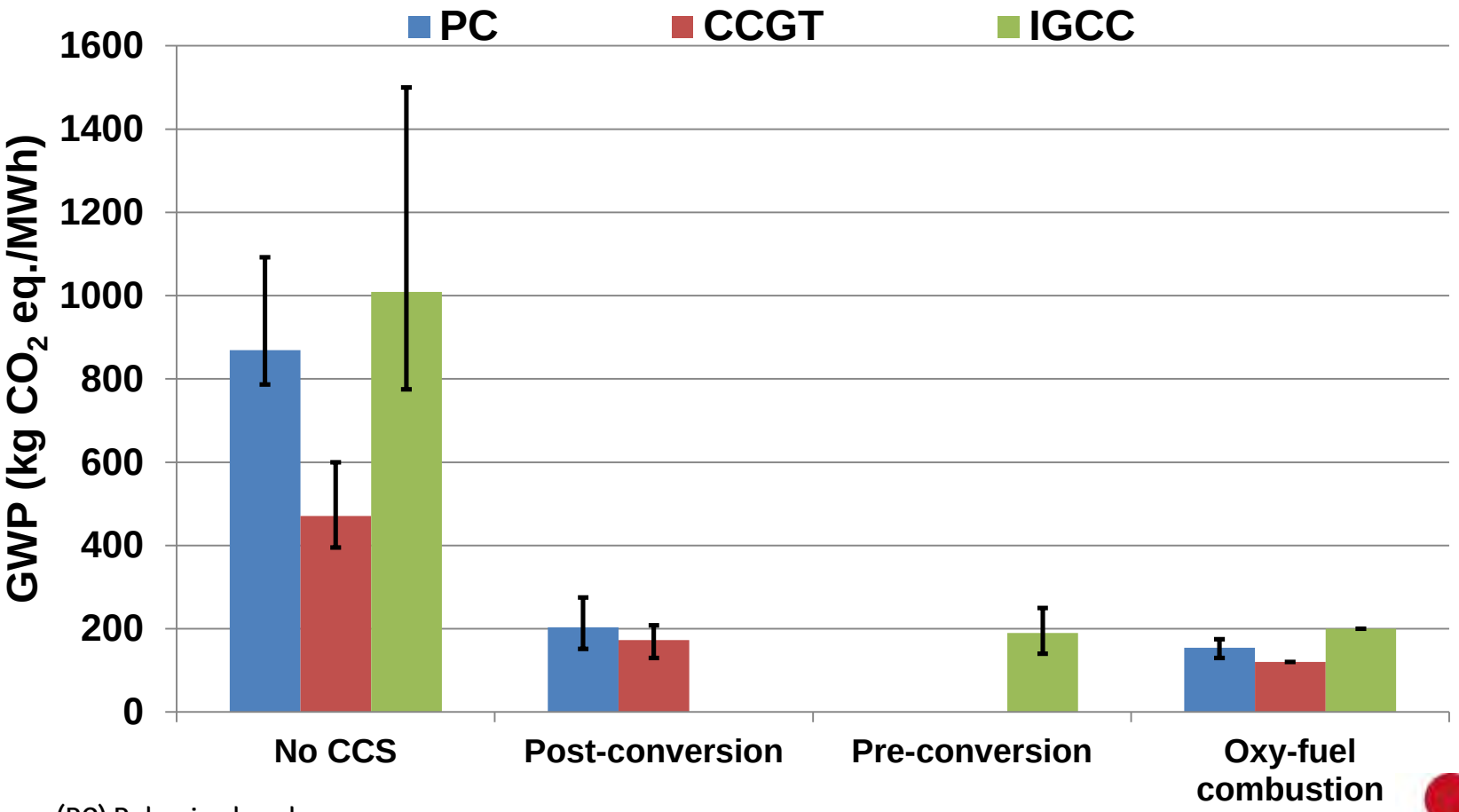
- Functional unit (unit of analysis) related to a unit of electricity generated
- System boundaries consistent across all studies



Post-conversion capture via chemical absorption using MEA most studied method

Most studies considered geological storage

Global warming potential of PC, CCGT and IGCC plants with CCS



(PC) Pulverised coal
(CCGT) Combined cycle gas turbine
(IGCC) Integrated coal gasification combined cycle

R.M. Cuéllar-Franca, A. Azapagic/ Journal of CO_2 Utilization 9 (2015) 82-102

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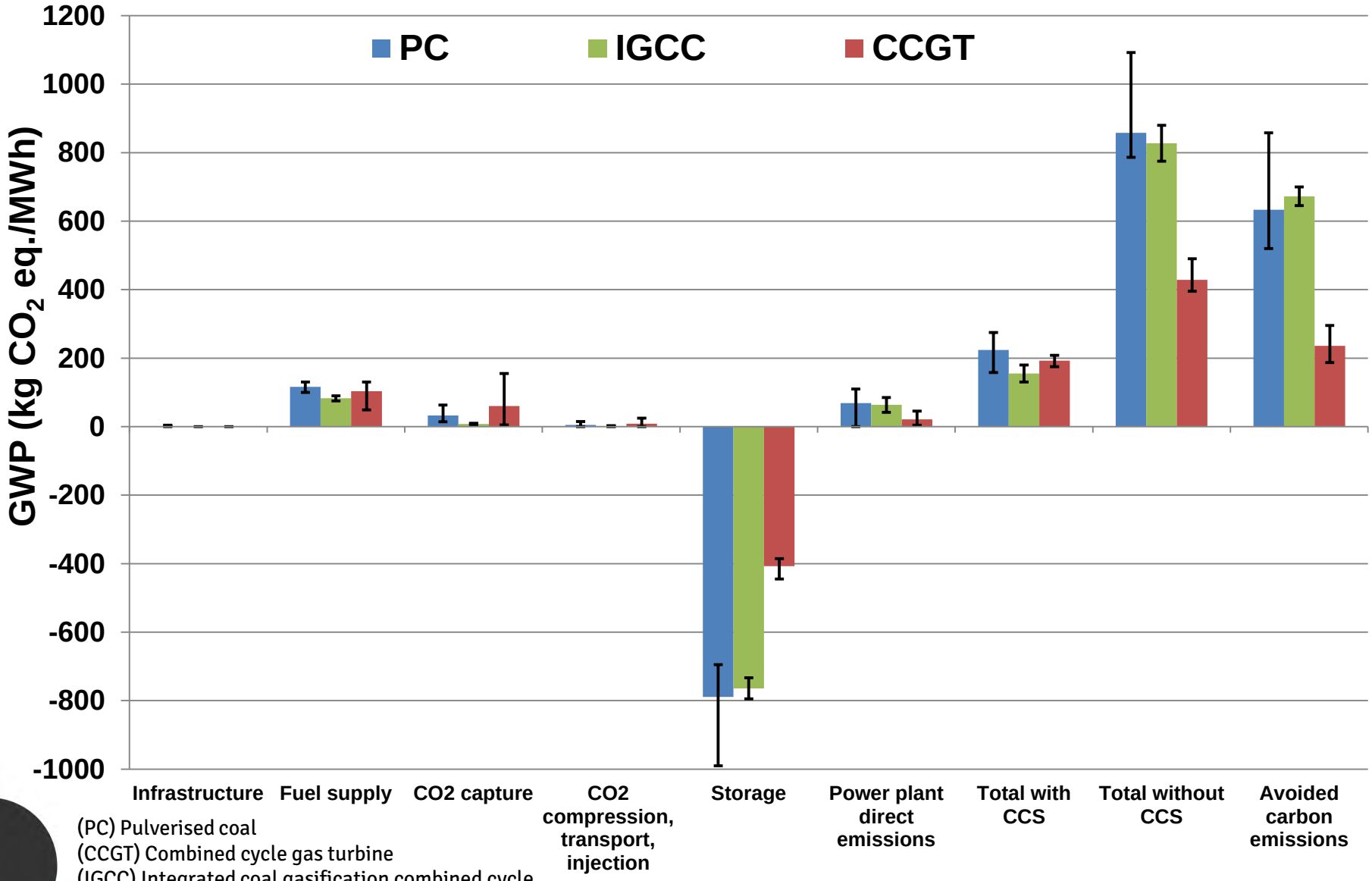
GWP of PC, IGCC and CCGT plants with CCS



(PC) Pulverised coal
(CCGT) Combined cycle gas turbine
(IGCC) Integrated coal gasification combined cycle

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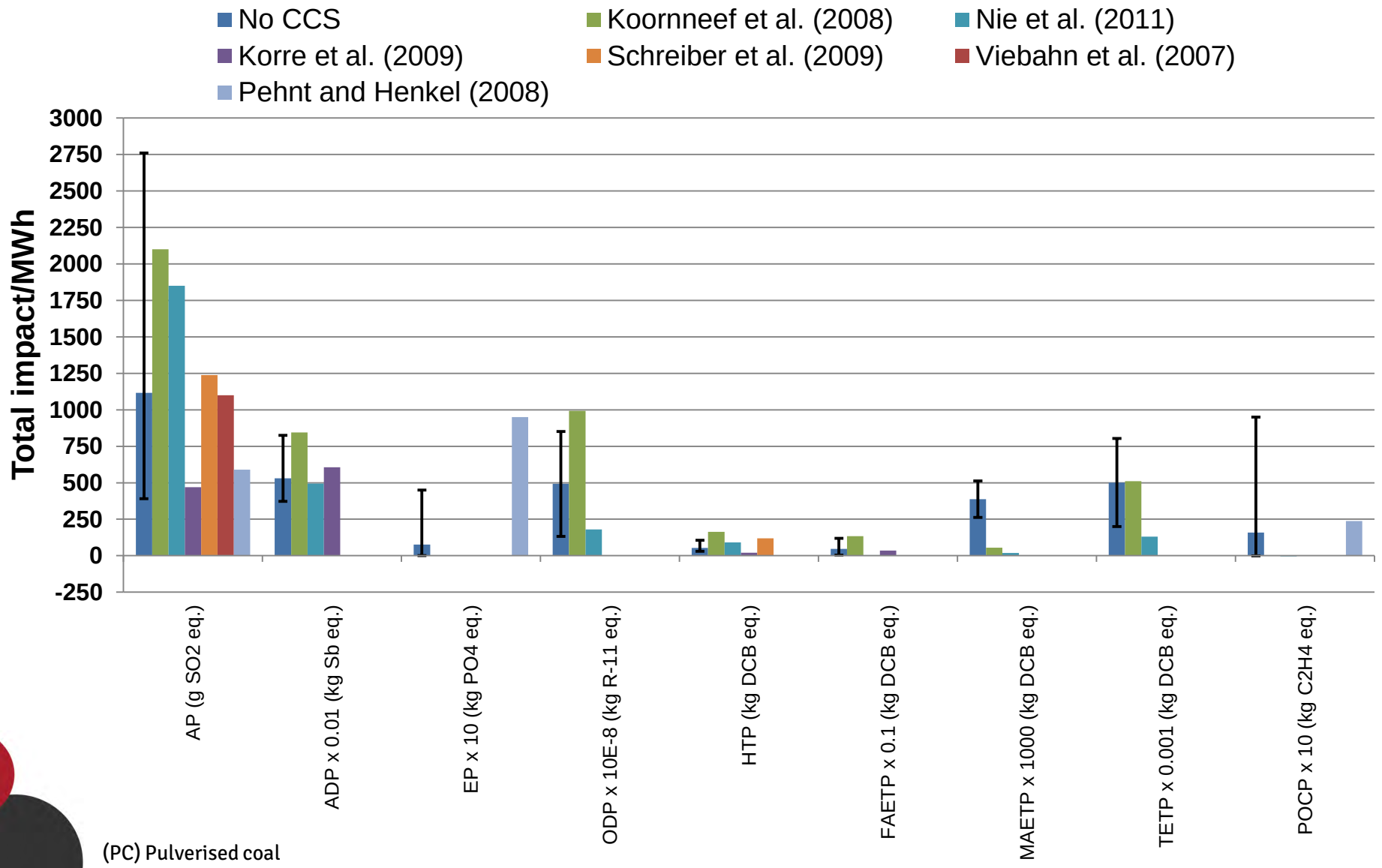
Other environmental impacts of PC plants with and without post-conversion CCS



(PC) Pulverised coal

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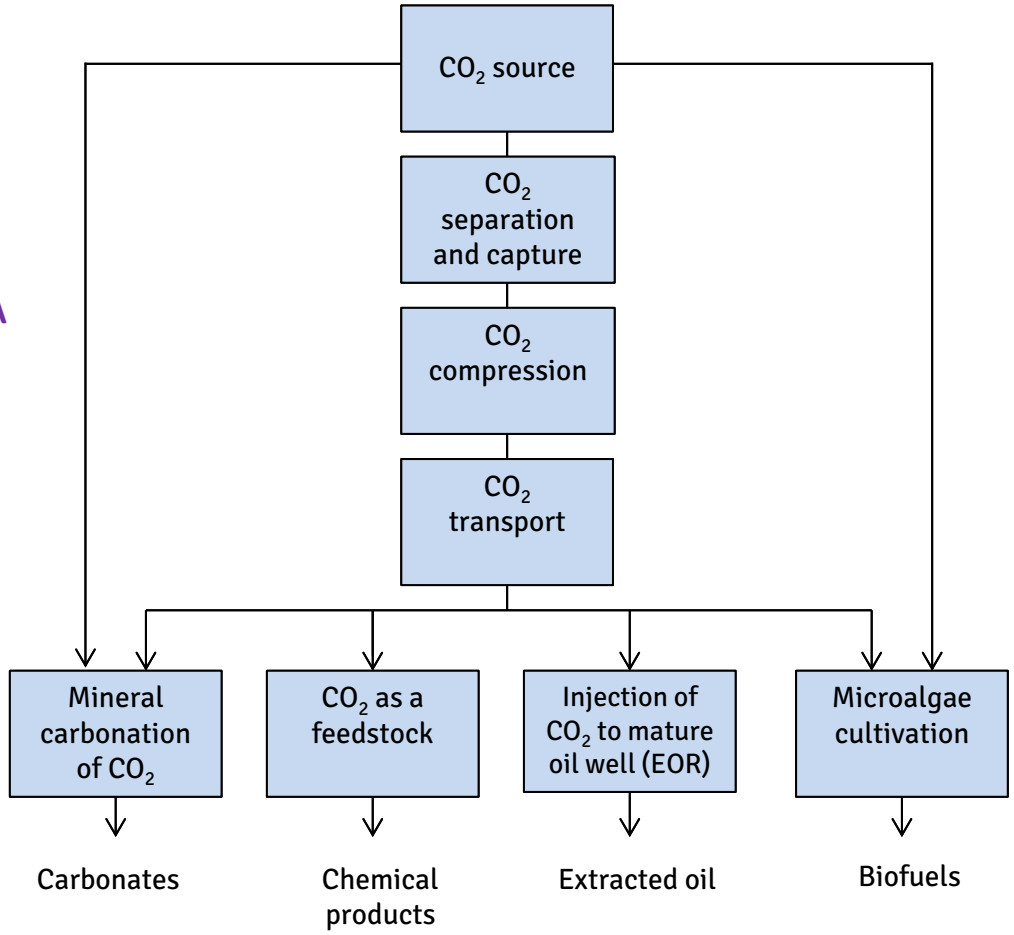
LCA studies on CCU

- LCA studies on CCU technologies for
  - Power plants
  - Chemical plants
- CO_2 utilisation options studied
  - Enhanced oil recovery (EOR)
  - Production of mineral carbonates
  - Chemicals
  - Biodiesel from microalgae

LCA studies on CCU

- System boundaries more or less consistent across all studies

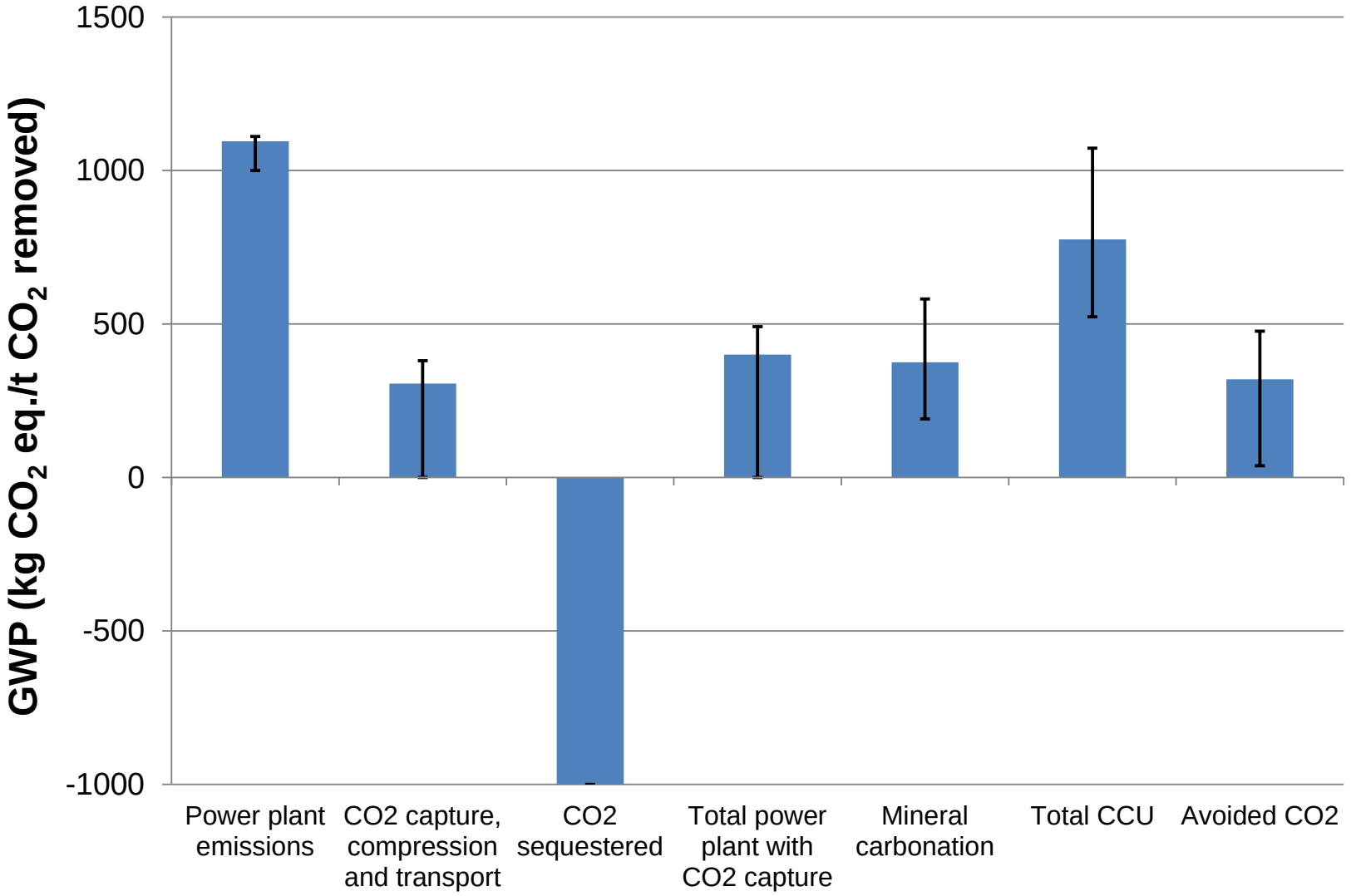
Post-conversion capture via chemical absorption using MEA most studied method



LCA studies on CCU

- Functional unit varied across the studies
  - Related to the main product
    - Electricity generated
    - Chemicals produced
    - Biodiesel produced
    - Extracted oil
  - Amount of CO_2 removed
  - Energy content in biodiesel
  - Distance travelled

GWP of mineral carbonation



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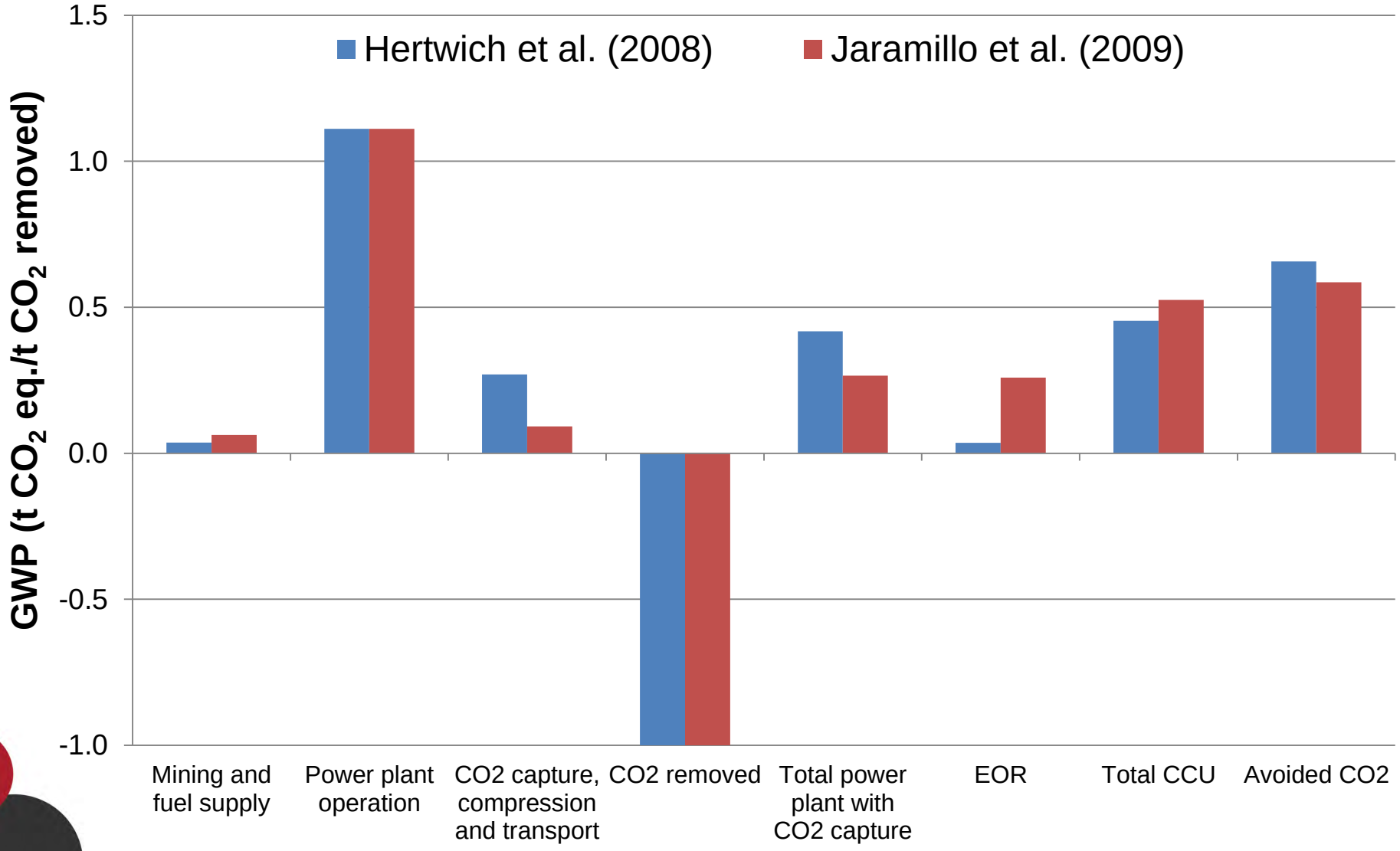
GWP of enhanced oil recovery



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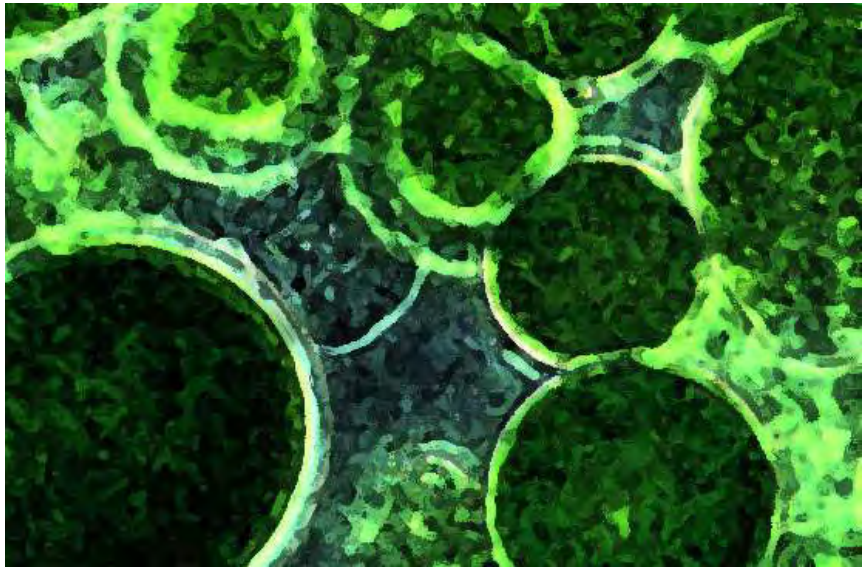
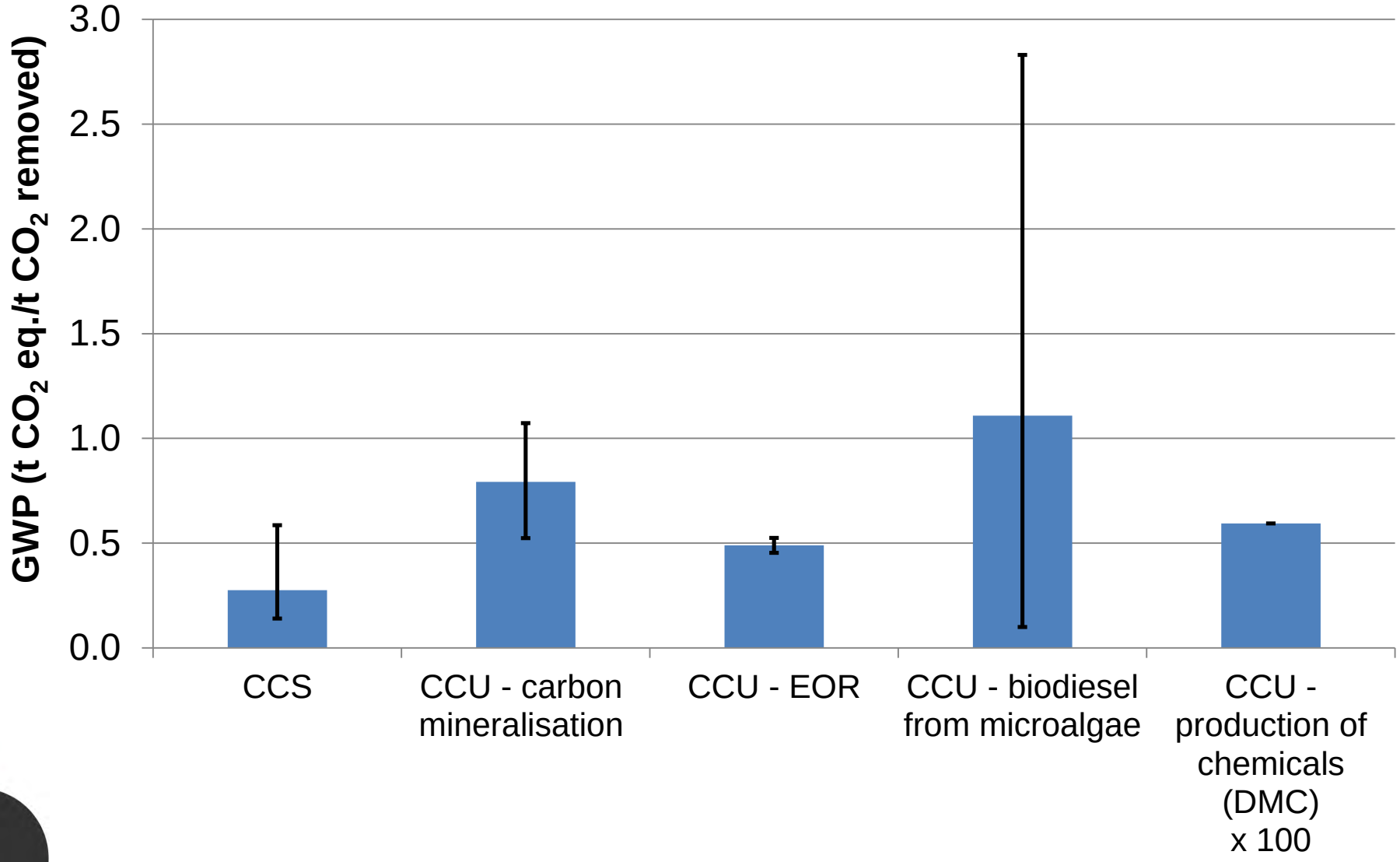
GWP of other CCU options

- Utilising CO_2 for production of dimethyl carbonate reduces GWP by 4.3 times compared to the conventional DMC process
- Capturing CO_2 by microalgae to produce biodiesel has 2.5 times higher GWP than fossil diesel



GWP of CCS and CCU options



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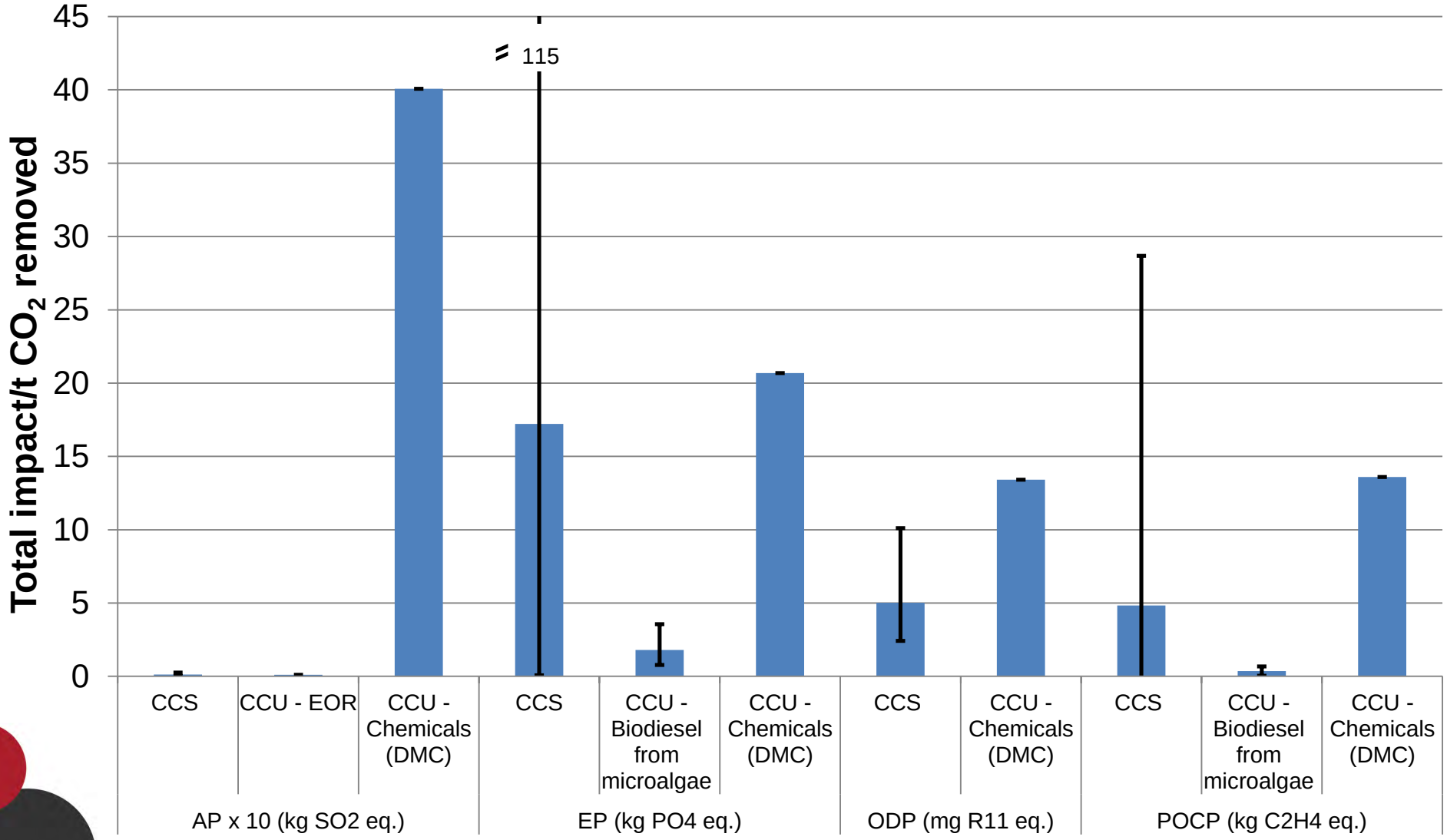
Other environmental impacts of CCS and CCU



R.M. Cuéllar-Franca, A. Azapagic/ Journal of CO_2 Utilization 9 (2015) 82-102

Conclusions

- CCS studies suggest that the GWP from power plants can be reduced by 63-82%
- Other environmental impacts are higher with than without CCS
- For CCU, CO_2 savings depend largely on the utilisation option
- The average GWP of all CCS options is significantly lower than the GWP of any CCU options considered

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Recommendations

- Specific guidelines for application of the LCA methodology to CCS and CCU technologies
  - Definition of system boundaries
  - Establishment of a standard functional unit
- Consideration of wider range of environmental impacts from CCS and CCU
- Consideration of different allocation methods
- Assessment of the uncertainty in the data and results
- Studies of different sources of CO_2

4CU
Foreseeing a future using CO_2

Further information

Cuellar-Franca, R and A. Azapagic (2015). Carbon capture, storage and utilisation technologies: A critical analysis and comparison of their life cycle environmental impacts. *Journal of CO_2 Utilization,* 9, 82–102.

Acknowledgement

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UCL

Queen's University Belfast

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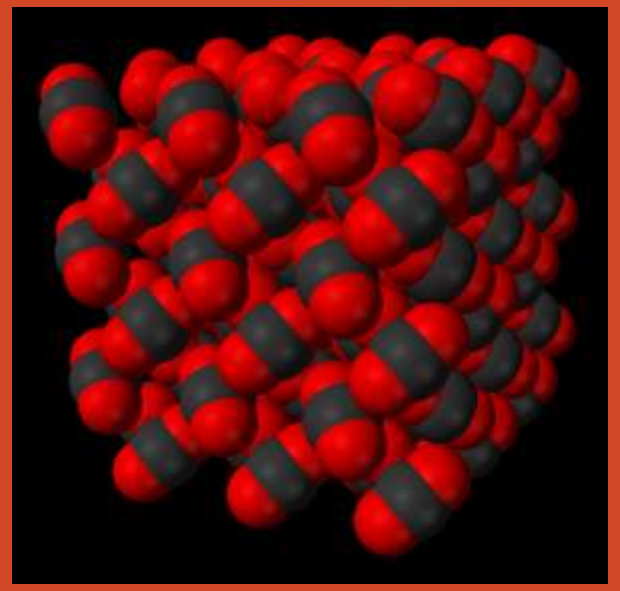
Carbon Dioxide: Myths and Magic?

Professor Peter Styring

UK Centre for Carbon Dioxide Utilisation

The University of Sheffield, United Kingdom



CDUK

UK Centre for Carbon Dioxide Utilisation

CO2Chem

An EPSRC Grand Challenge Network

The University Of Sheffield.

Summary

1. What is CDU/CCU?
2. Setting the Boundaries
3. The Functional Unit
4. Global Capacity
5. Conclusions: Separating Myth and Magic

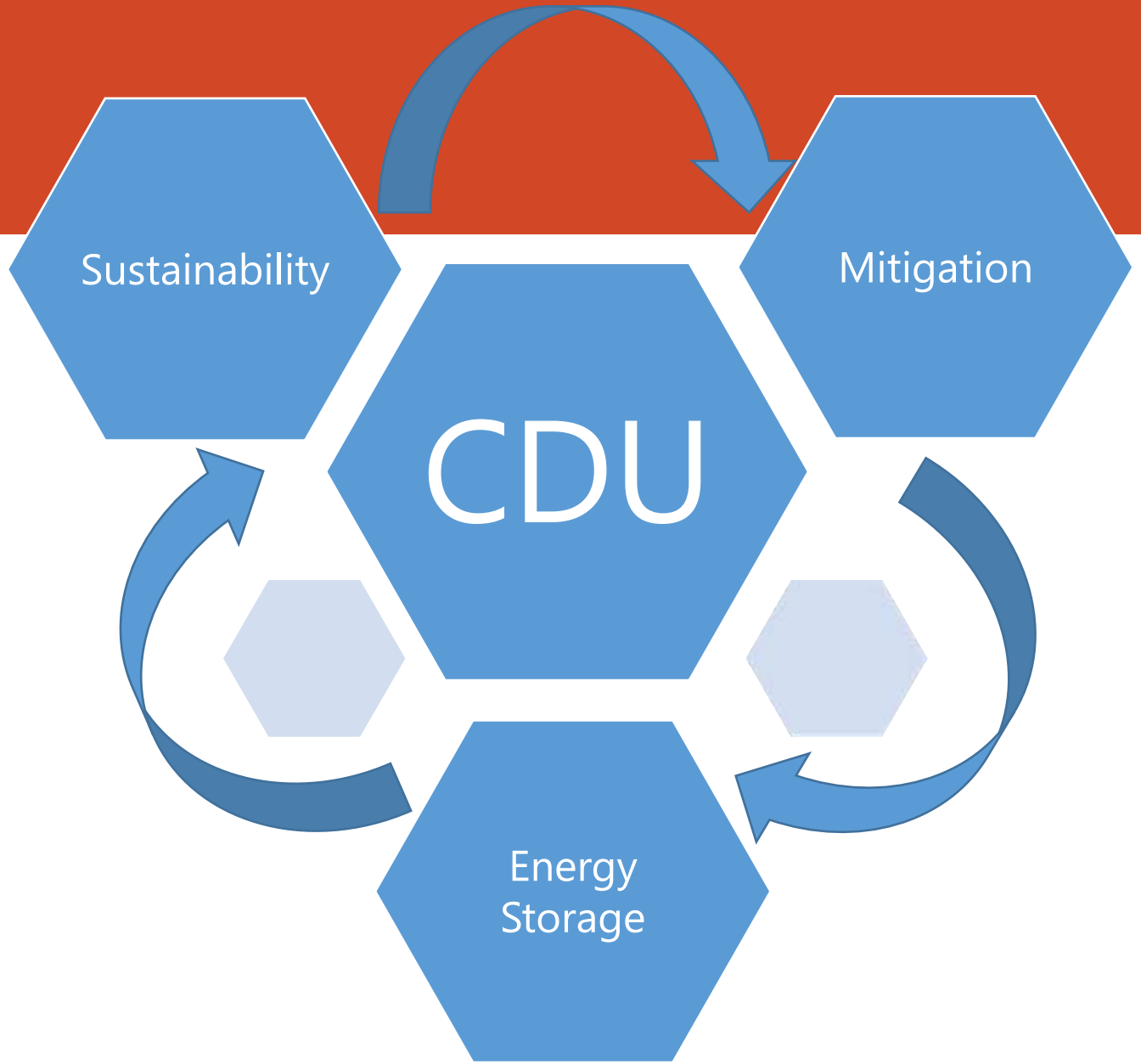
The CO_2 Trilemma

Mitigation: long-term and short-term carbon dioxide sequestration

Sustainability: carbon avoided, fossil product avoidance

Energy Storage: renewable electrical energy to chemical fuels and materials for long-term seasonal storage

Carbon Cycle: to manage emissions from synthetic fuels emissions (although remembering carbon avoided)



What is CDU/CCU? Setting the boundaries

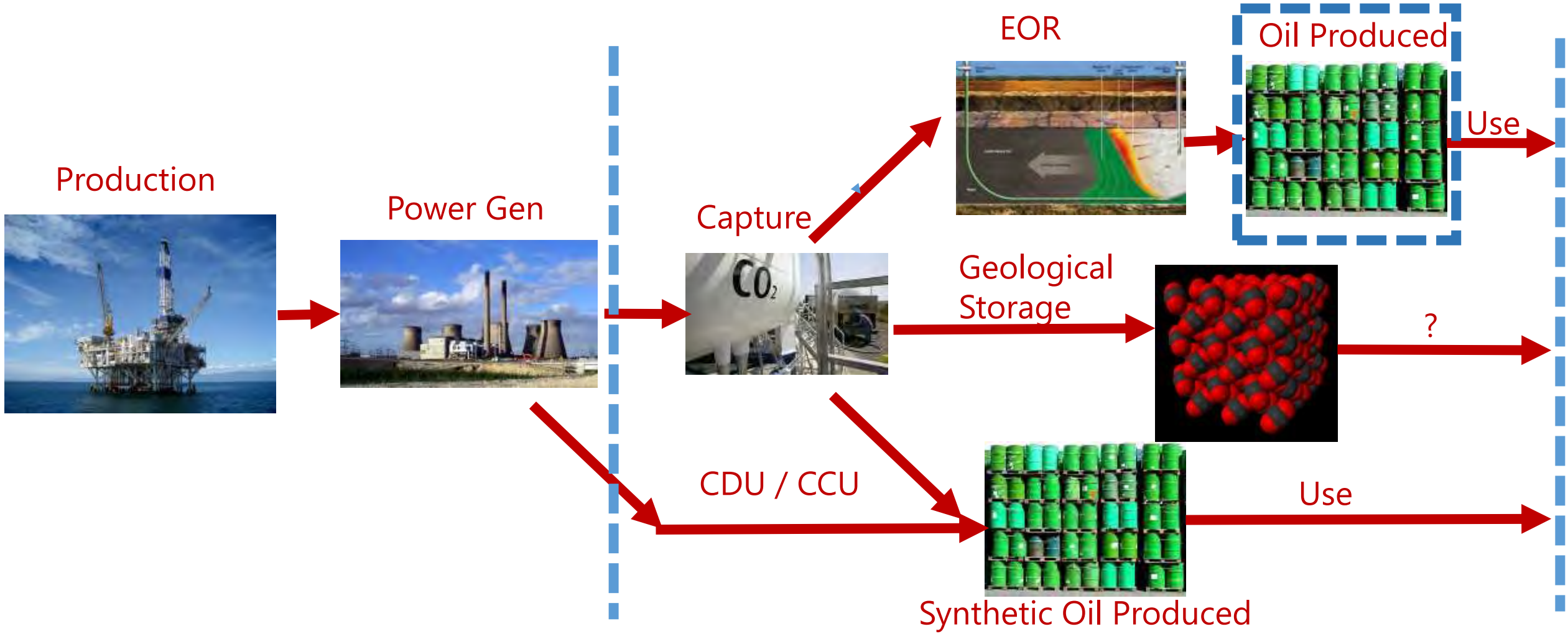
- **Carbon Dioxide Utilisation**: No separate capture step required
- **Carbon Capture & Utilisation**: Concentration and purification of CO_2 is required before reaction
- **Bonds** are broken and made: CO_2 goes in to a process, something else emerges
- Likely to provide a **net** CO_2 emissions reduction potential: carbon sequestration and avoidance
- There is an attractive **financial return** over the process
- The following are **not CDU/CCU**: CCS, EHR/EOR, technical use (e.g. decafination, solvent, *etc.* where there is no chemical change)

Styring's modification of Nyholm's Law

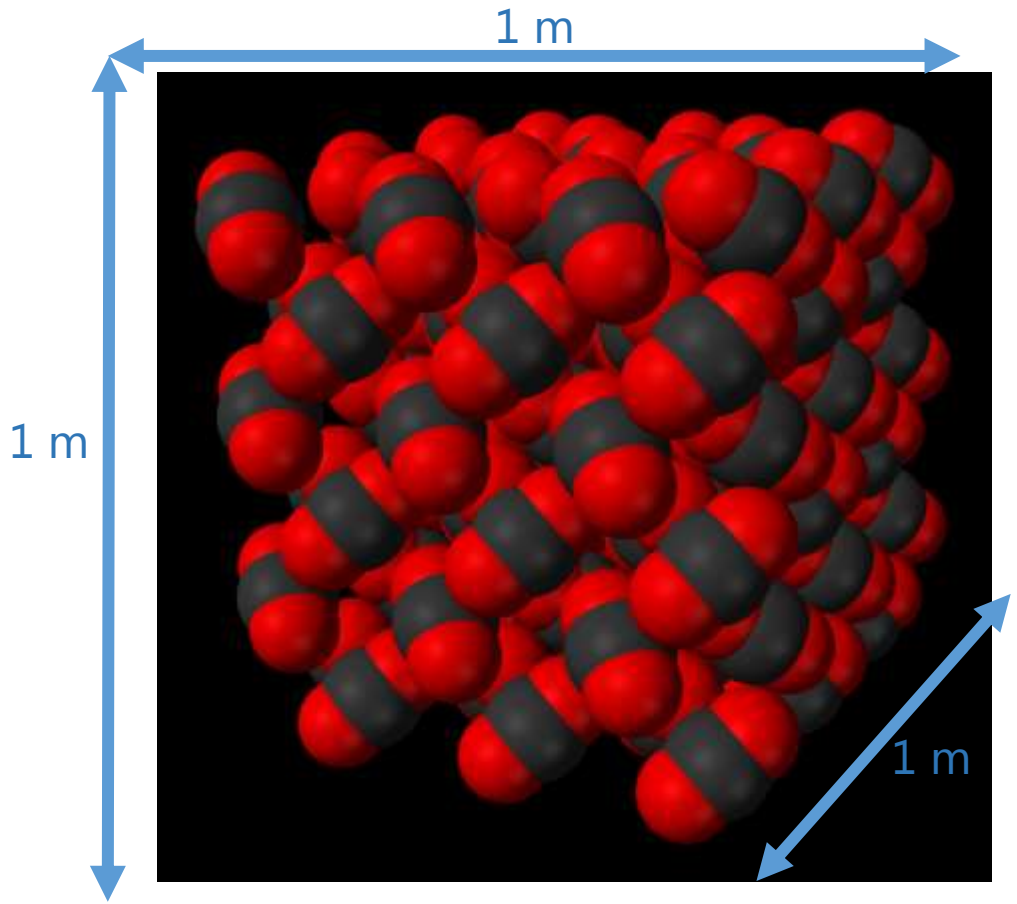
$$\frac{\text{Data}}{\text{Model}} = \frac{\text{Fact}}{\text{Fiction}}$$

MYTH - CO2 is unreactive…….

Boundaries


EOR
Oil Produced
Use
Production
Power Gen
Capture
CO_2
Geological Storage
?
CDU / CCU
Use
Synthetic Oil Produced

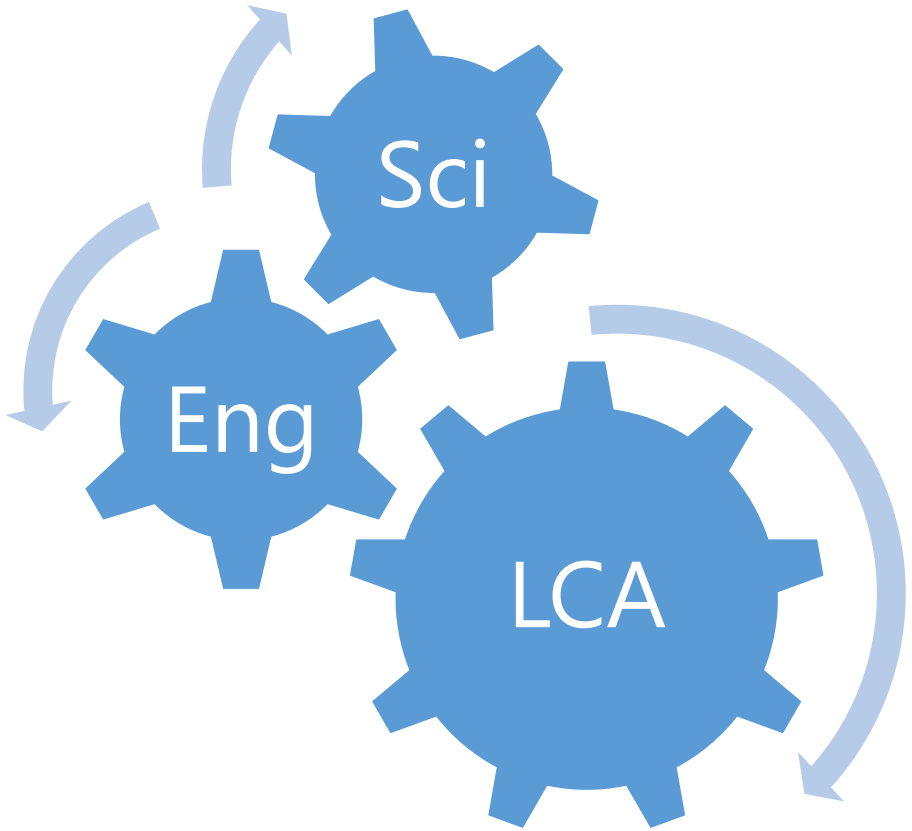
MYTH: CO_2 to Fuels will just cause more emissions
Functional Units are important

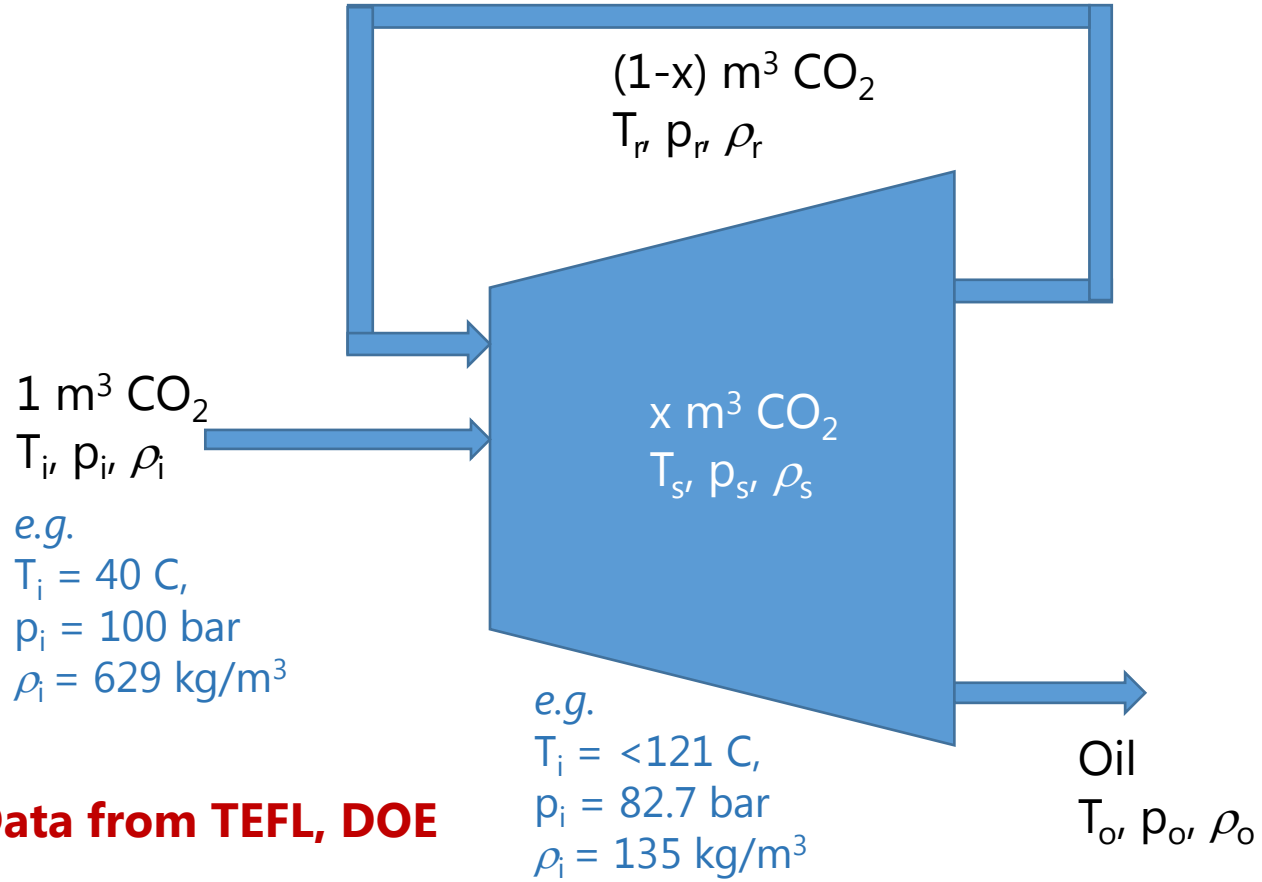


Armstrong & Styring, *Frontiers in Energy Research*, 2015, **3**, 8

- **CCS** sequesters 1 m^3 $scCO_2$ (469 kg)
  Net emissions - 469 kg CO_2
- **EOR (immiscible)** sequesters 1 m^3 $scCO_2$ (469 kg) and produces 1 m^3 (900 kg) crude oil.
  Product combustion emissions 3,051 kg CO_2
  Net emissions +2,582 kg CO_2
- **EOR (miscible)** sequesters 0.5 m^3 $scCO_2$ (234.5 kg) and produces 0.5 m^3 (450 kg) crude oil.
  Product combustion emissions 1,526 kg CO_2
  Net emissions +1,526 kg CO_2
- **CDU** sequesters 1 m^3 $scCO_2$ (469 kg) and produces 139 kg of synthetic oil.
  Product combustion emissions 469 kg CO_2
  Net emissions 0 kg CO_2

MAGIC: Can only work with knowledge of whole system





Data from TEFL, DOE

MYTH

CDU will never be able to operate at a capacity large enough to deal with CO_2 emissions

Global CCS Capacity

www.globalccsinstitute.com/projects/large-scale-ccs-projects

- **22** global projects in Operation (13) or Execute (9) phases in 2014.
- Total **42 Mt/yr** (up to 2016)
- Total to 2020 is **102 Mt/yr**
- DECC Scenario for UK by 2030 is **13 GWe/yr** or in terms of CO_2 **95 Mt/yr**

Type of plant	Number of projects	Type of capture	Storage method	Total CO2 Mt/annum	
Chemical Production	5	2 Industrial Separation 3 Pre-combustion	3 EOR	4.96	8-9
			2 Geological	3-4	
Coal to liquids	3	Pre-combustion	1 EOR	2.5	5.5
			1 Geological	1	
			1 Unspecified	2	
Fertiliser	4	Industrial Separation	3 EOR	2-2.6	4.5-5.1
			1 Geological	2.5	
H_2 Production	2	Industrial Separation	1 EOR	1	2
			1 Geological	1	
Iron and Steel	1	Industrial Separation	EOR		0.8
Natural gas processing	13	Pre-combustion	8 EOR	22.4	29.6-30.1
			5 Geological Storage	7.2 - 7.7	
Oil Refining	1	Pre-combustion	EOR		1.2
Power Generation	23	9 Post-combustion 10 Pre-combustion 4 Oxy	10 EOR	17.7	41.2
			11 Geological	19	
			2 unknown	4.5	
Synthetic Natural Gas	2	2 Pre-combustion	2 EOR		8.5
Unknown	1	Unknown	Geological		1
TOTAL	**55**				**102.3**

Current CDU Processes

Current CCS 27 Mt/yr
Current CDU 180 Mt/yr

2016 CCS 56 Mt/yr
2016 CDU 256 Mt/yr

2020 CCS 102 Mt/yr

Compound	Actual production /Mt	CO_2 used/Mt	2016 Forecast/Mt	CO_2 needed/Mt
Urea	155	114	180	132
Methanol	50	8	60	10
DME	11.4	3	>20	>5
TMBE	30	1.5	40	3
Formaldehyde	21	3.5	25	5
Polycarbonates	4	0.01	5	1
Carbamates	5.3	0	>6	1
Polyurethanes	>8	0	10	0.5
Acrylates	2.5	0	3.0	1.5
Inorganic carbonates	200	ca.50	250	70
TOTAL		**180**	Aresta, *et al.* 2013	**256**

Carbon Dioxide Utilisation Potential

Armstrong & Styring, Frontiers in Energy Research, 2015, **3**, 8

Global CCS Capacity 2020

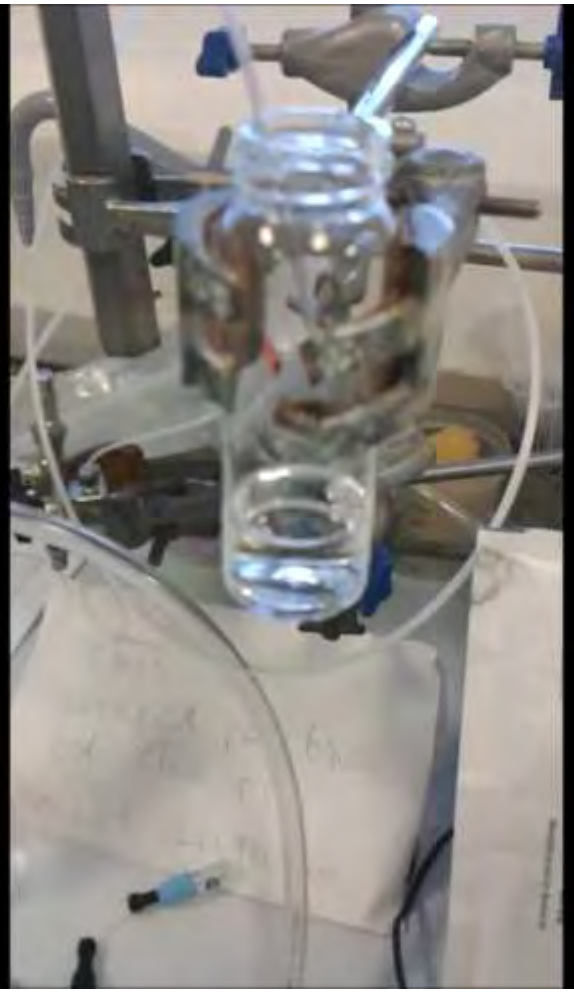
MYTH

- We should concentrate **only** on CCS as CDU/CCU as it can never match the capacity of CCS in dealing with global emissions
- Current global emissions are *ca.* 40 Gt/yr
- Current CCS capacity is *ca.* 27 Mt/yr (6.75×10^{-5} %)
- Current CDU capacity is *ca.* 180 Mt/yr (4.5×10^{-4} %) almost x7 more

In reality we need to be both

MAGIC

- Energy
- Process
- Hydrogen
- Reagents



- Profit
- Public Acceptance
- Scale
- The Carbon Cycle
- Direct Air Capture

Conclusions

- CDU / CCU has many associated myths: we need to be able to see through these
- LCA data are only as valid as the input data
- Many LCA studies are based on secondary data
- Studies need to be carried out with knowledge of scientific and engineering principles
- Conclusions must be made that are evidence based, even if it is through the collation of secondary data
- More real-life valedictory studies need to be carried out

Acknowledgements

Katy Armstrong

Dr Grant Wilson

Ana Villa Zaragoza

Dr George Dowson

Current, Best and Future Practice of LCA for CO_2 Utilization

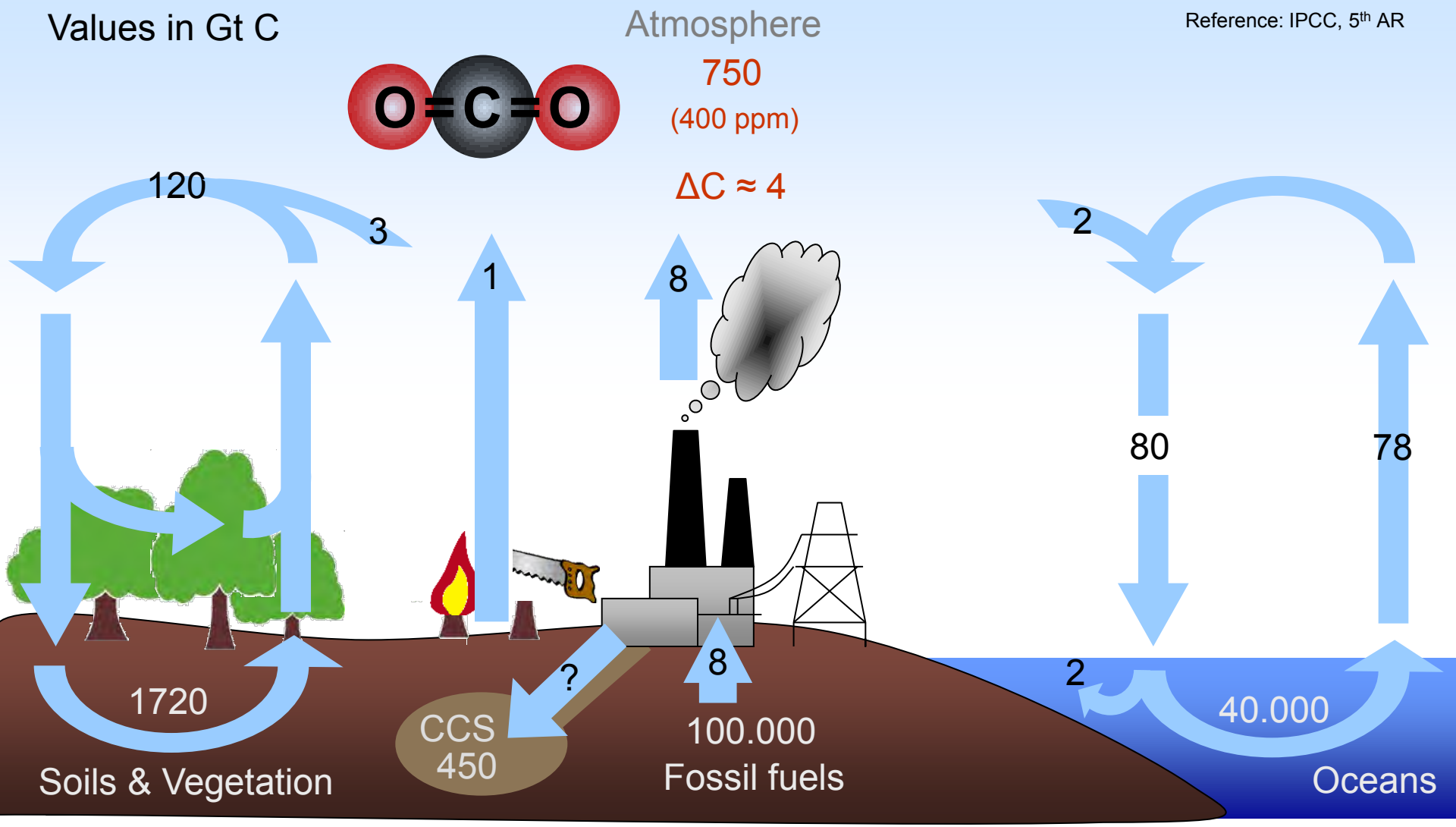
Niklas von der Assen

Workshop: Integrated life cycle approaches for understanding carbon dioxide utilization and sequestration pathways

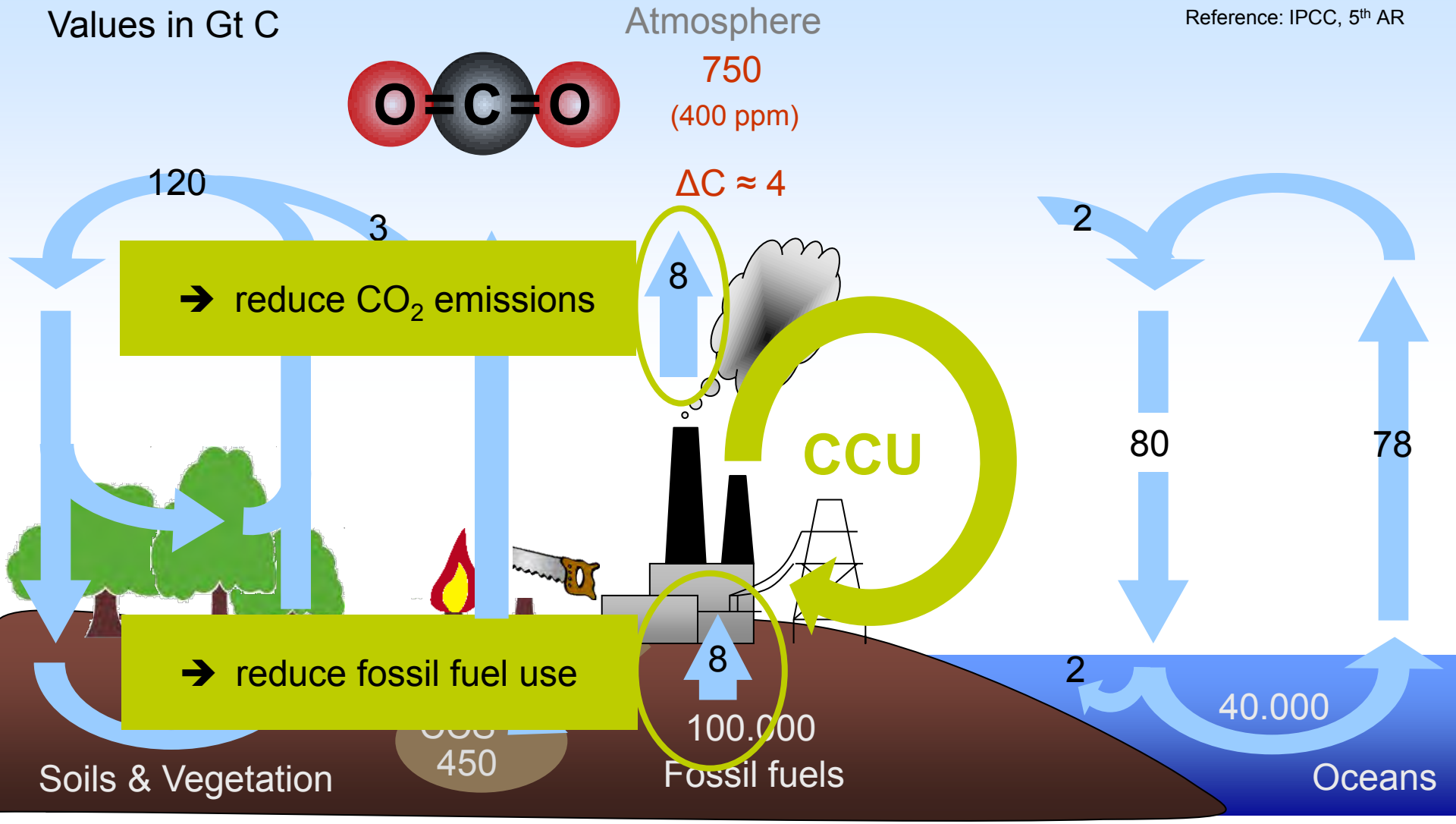
4 March 2015, Sheffield

LTT Lehrstuhl für Technische Thermodynamik | RWTH AACHEN UNIVERSITY

The Carbon Cycle – and CO_2 Capture and Utilization (CCU)

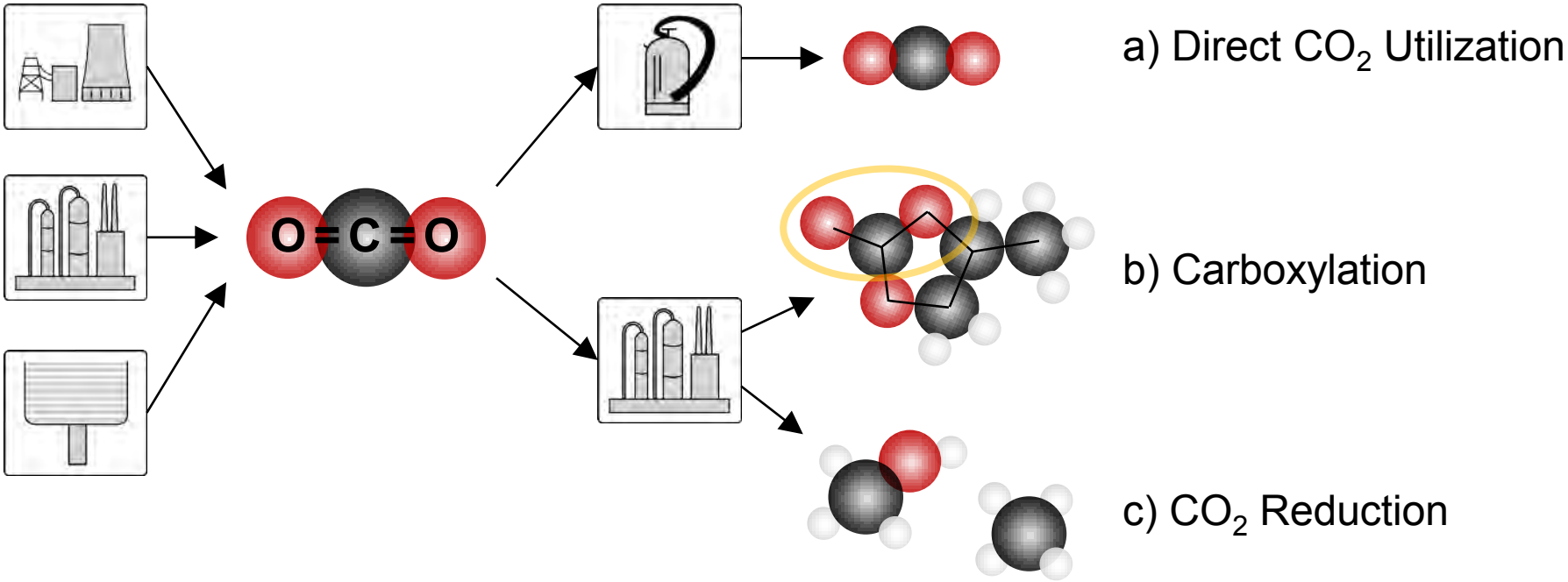


The Carbon Cycle – and CO_2 Capture and Utilization (CCU)



CO_2 Capture and Utilization (CCU) – Our Definition

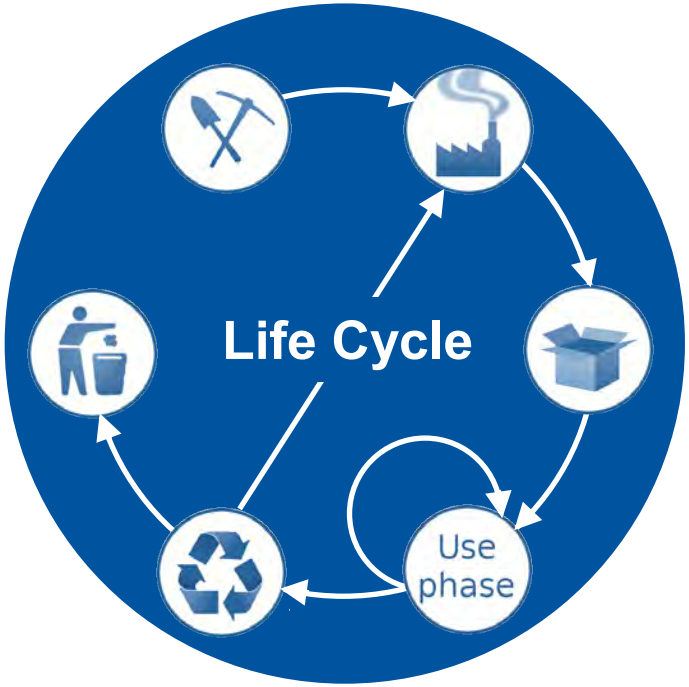
Industrial CO_2 capture & separate, **functional** utilization of CO_2



Reference: von der Assen et al., Energy Environ. Sci., 2013, 6, 2721

What is Life Cycle Assessment (LCA)?

Goal & scope definition



Inventory (LCI)

Flows from / to the environment

Inputs: resources
- … kg crude oil
- … kg coal
- …

Outputs: emissions
- … kg CO_2
- … kg NO_x
- …

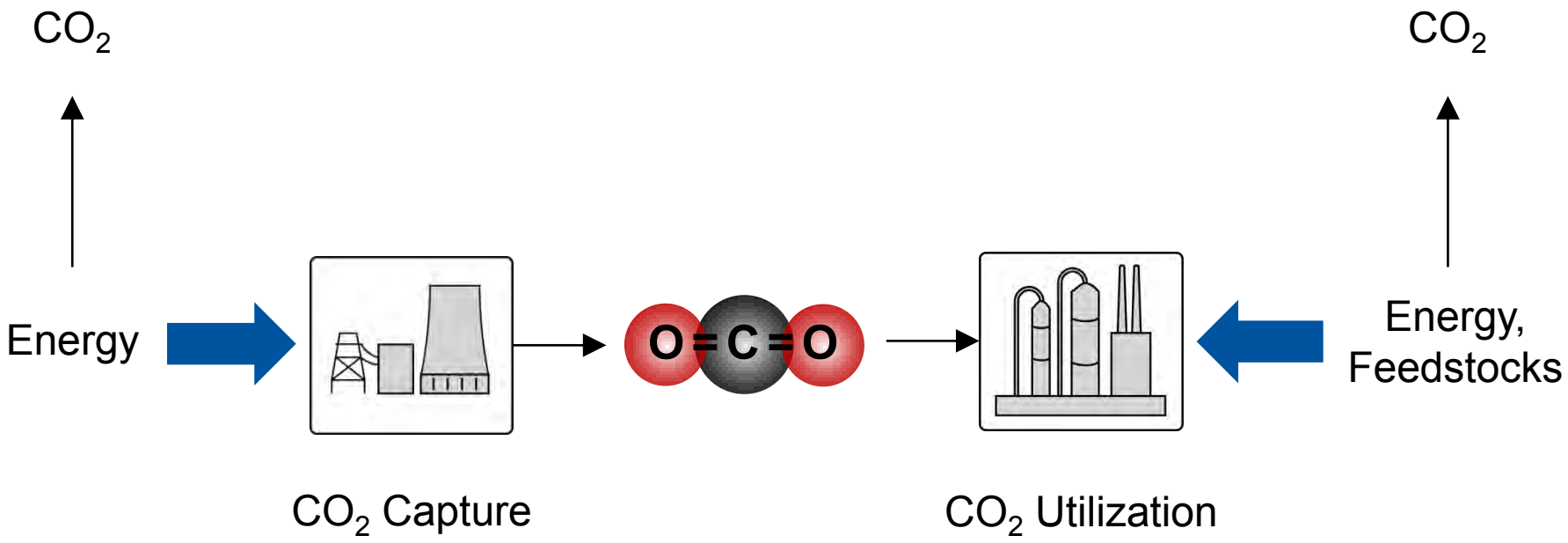
Impact Assessment (LCIA)

Environmental impacts

- fossil resource depletion
- water use
- global warming
- acidification
- others

Reference: von der Assen et al., Chem. Soc. Rev., 2014, 6, 2721

Why do we need LCA for CCU? (1/2)



➔ Environmental Benefits **not** guaranteed !

➔ Environmental Assessment / LCA required

Why do we need LCA for CCU? (2/2)

Current short-cut metrics in early development stages of CCU:

- Atom Economy
- E-factor
- Yield
- Amount CO_2 used [1]
- Share of CO_2 in reactants [2]
- Amount CO_2 fixed [1]
- CO_2 storage duration [1]

Environmental impacts of non-CO_2 reactants not considered ! (e.g. H_2, epoxides)

CO_2 source often neglected !

Separate, overrated metric ! (more later)

[1] Peters et al., ChemSusChem., 2011, 4(9), 1216
[2] Müller et al., Chem. Eng. Tech., 2014, 37(9), 1612

➔ Current short-cut metrics **not** reliable !

➔ Simplified LCA **is accessible** & **more reliable**

Research field *«CO_2 Utilization and Life Cycle Assessment»*

Our Team

Our Project Partners

BAYER

cat® Catalytic Center

IASS POTSDAM

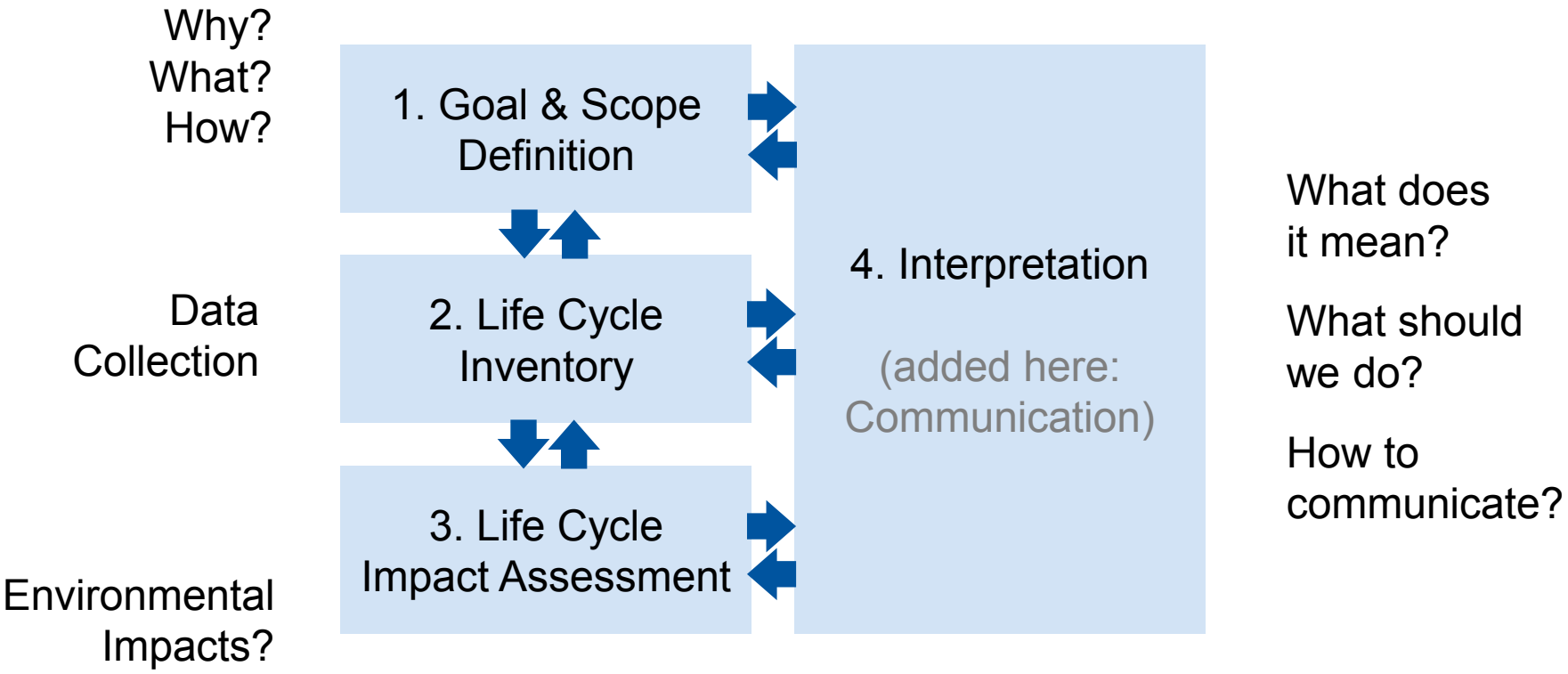
ITMC RWTH

RWE The energy to lead

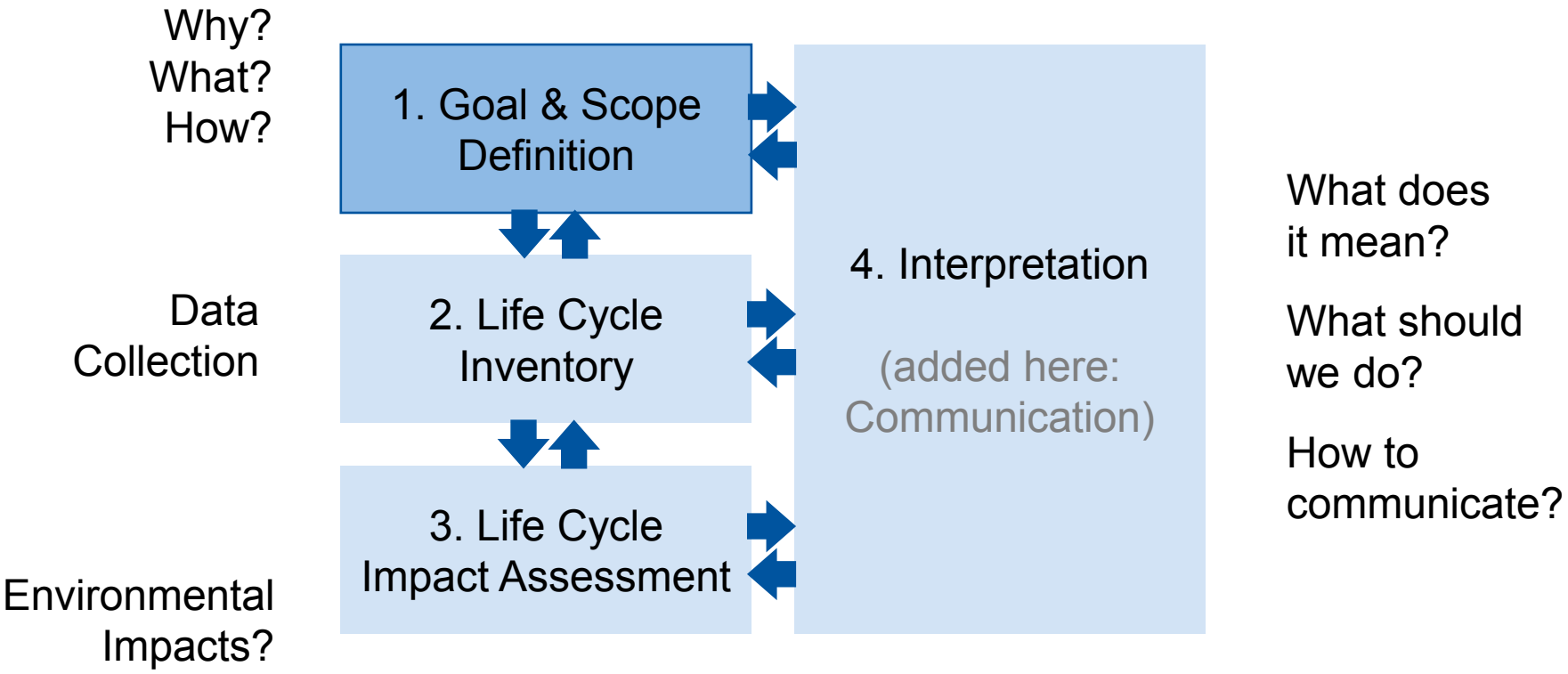
Our LCA+CCU Topics

- CO_2-based polyurethanes
- CO_2-based supply chains
- Power-to-Gas (CH_4)
- Power-to-Fuels (CH_3OH)
- Power-to-Chemicals (CO)
- Formic Acid
- Renewable H_2 production
- Alternative CO_2 sources

Agenda – LCA Structure by ISO 14040/14044



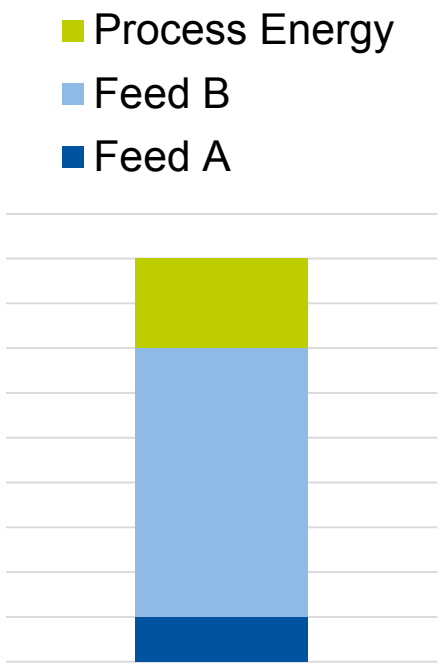
1. Goal & Scope Definition



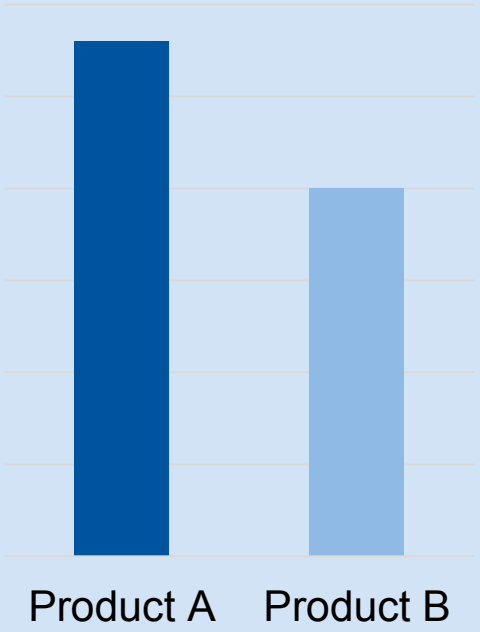
1. Goal & Scope Definition

Why? – Typical Goals in LCA

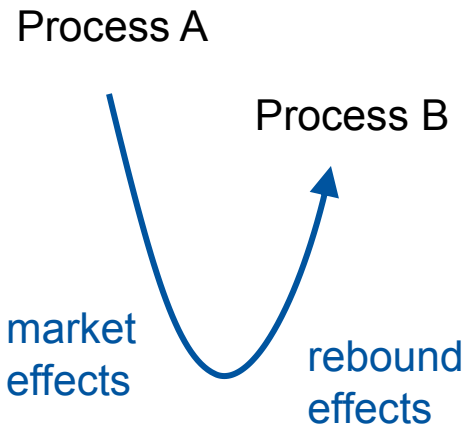
1. Hot-Spots



2. Comparisons



3. Consequences

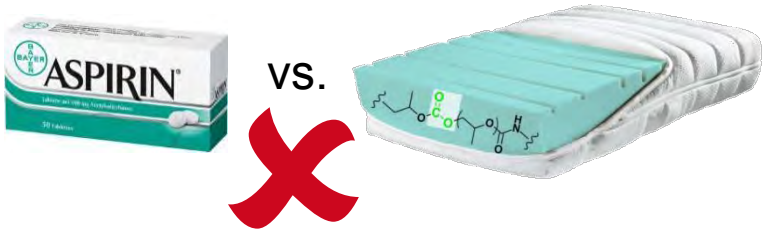


- 100 t CO_2-eq

1. Goal & Scope Definition

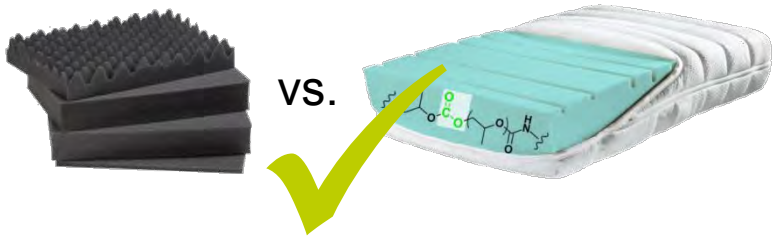
What? – Functional Unit Definition for Fair Comparisons

- Consider *function* and *performance/quality*!



CO_2-based aspirin

CO_2-based polyurethane



fossil-based polyurethane

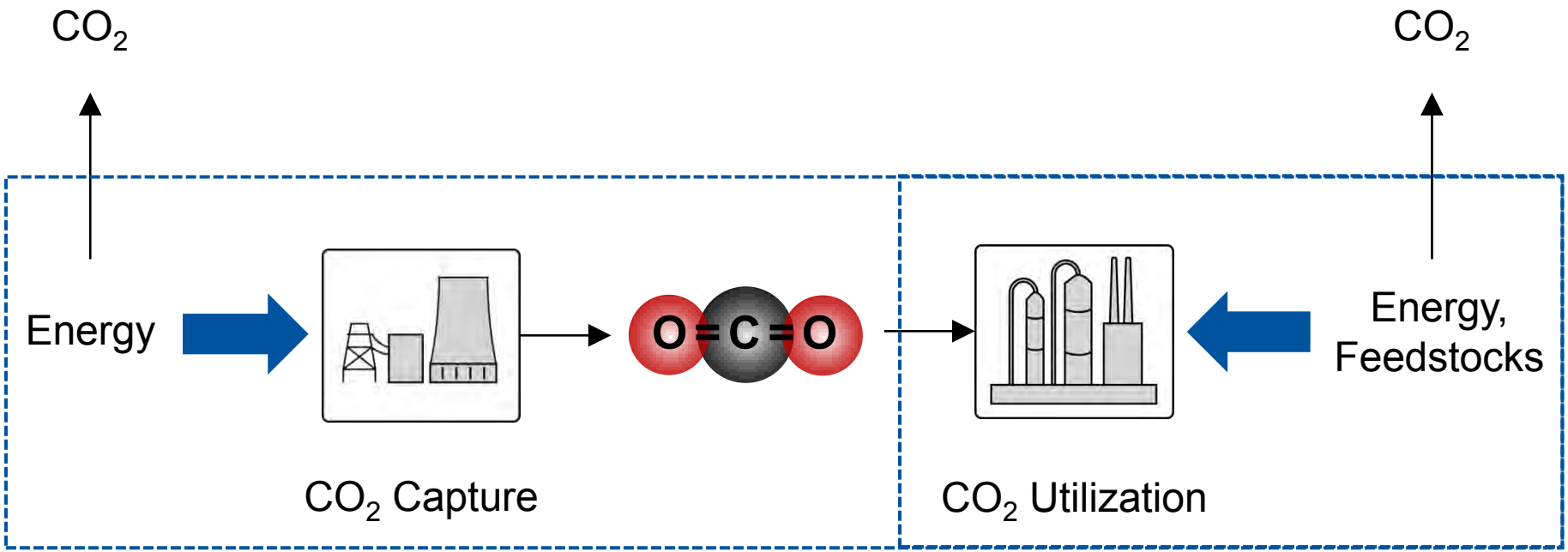
CO_2-based polyurethane

➔ Do not compare apples and oranges !

Reference: von der Assen et al., Chem. Soc. Rev., 2014, 6, 2721

1. Goal & Scope Definition

What? – System Boundaries

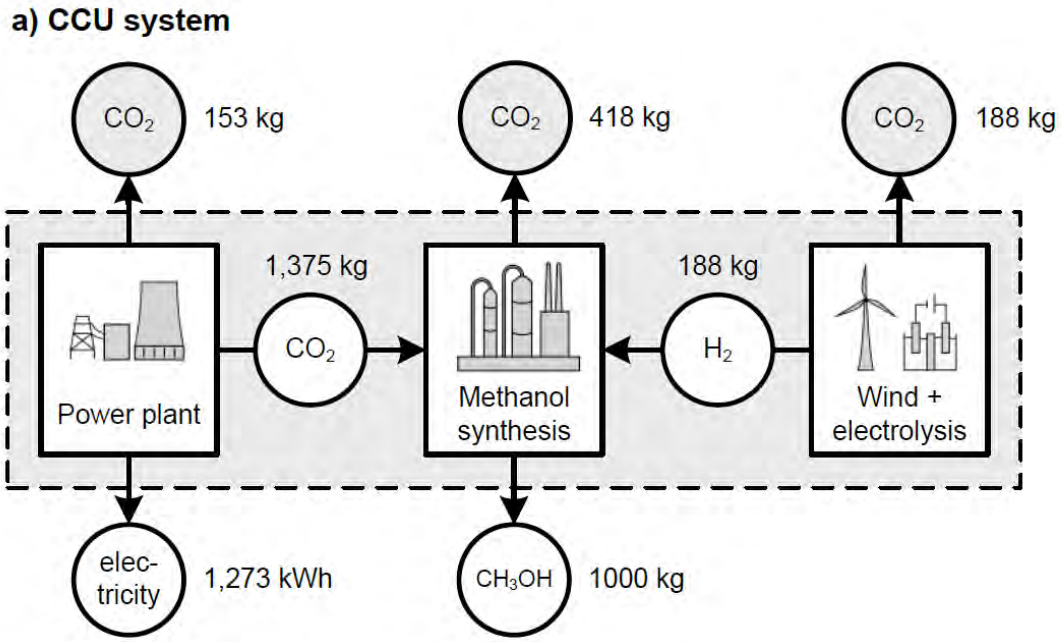


➔ Include the CO_2 source !

Reference: von der Assen et al., Energy Environ. Sci., 2013, 6, 2721

1. Goal & Scope Definition

What? – System Boundaries for a Fair Comparison

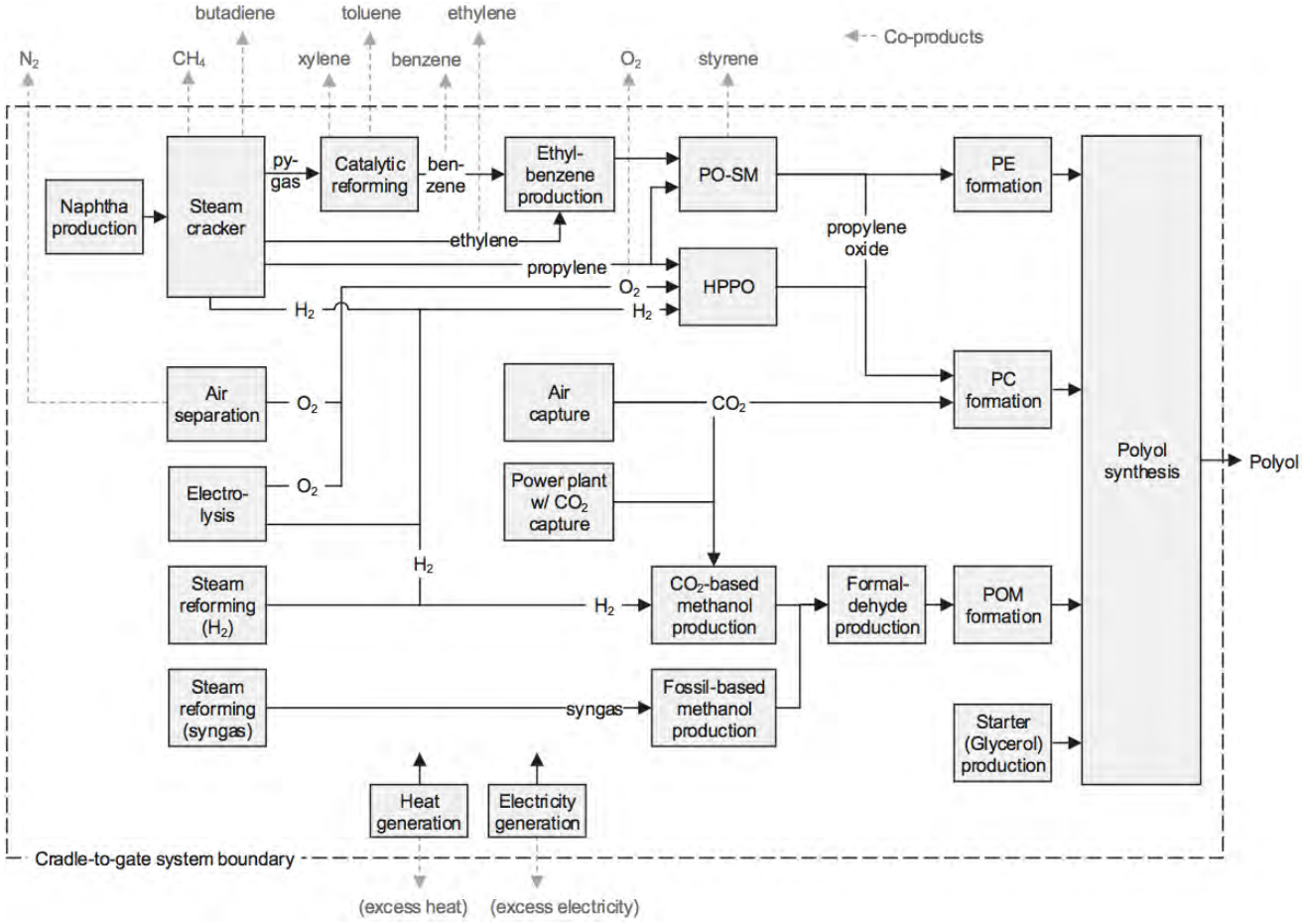


➔ Compare against equivalent system with same products !

Reference: von der Assen et al., Energy Environ. Sci., 2013, 6, 2721
Bernet et al., Energy Procedia, 2014, 63, 7976

1. Goal & Scope Definition

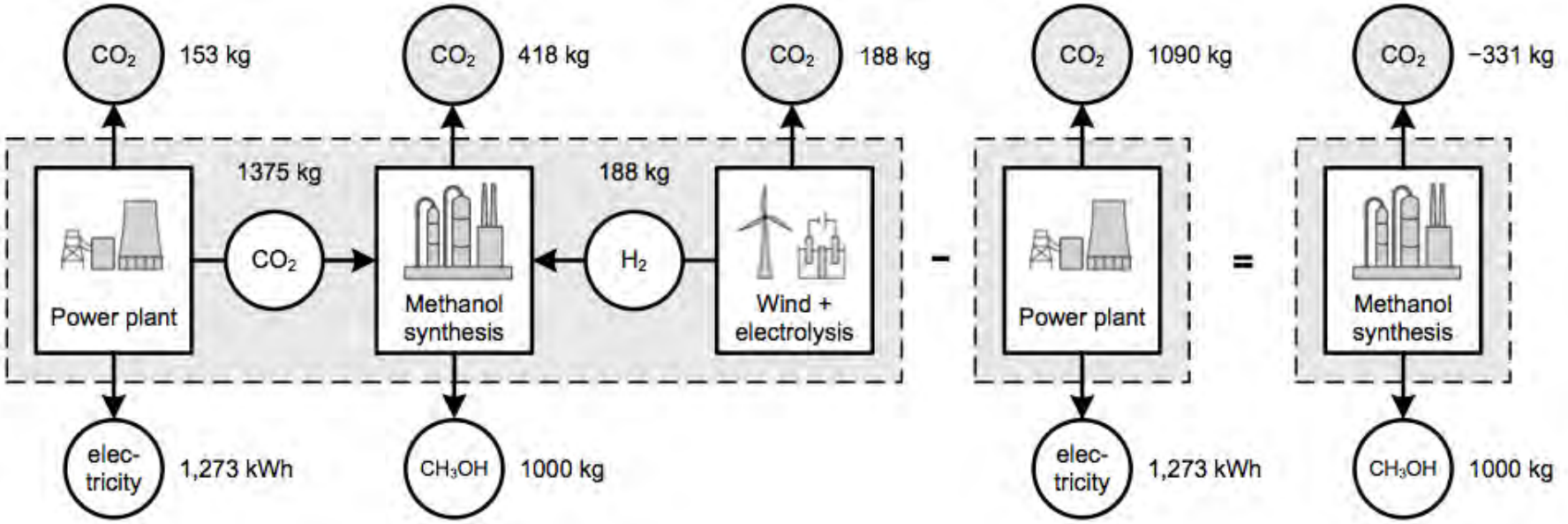
What? – System Boundaries



Reference: von der Assen et al., PSE, 2015, accepted

2. Life Cycle Inventory

Account for all co-products! Here: Avoided Burden

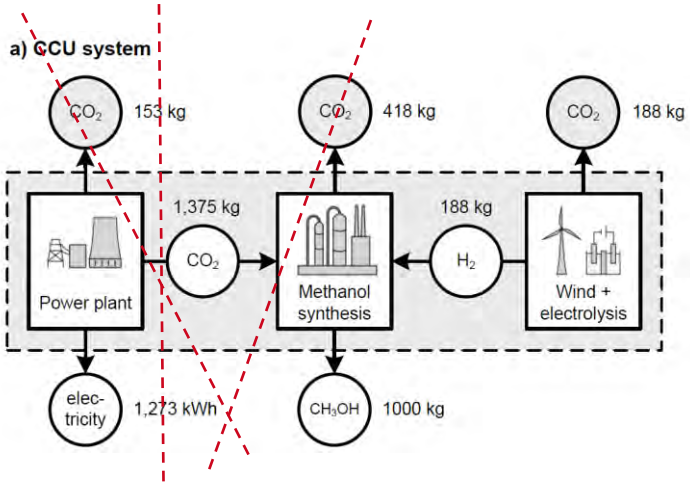


➔ Avoided Burden Implies a Comparison !

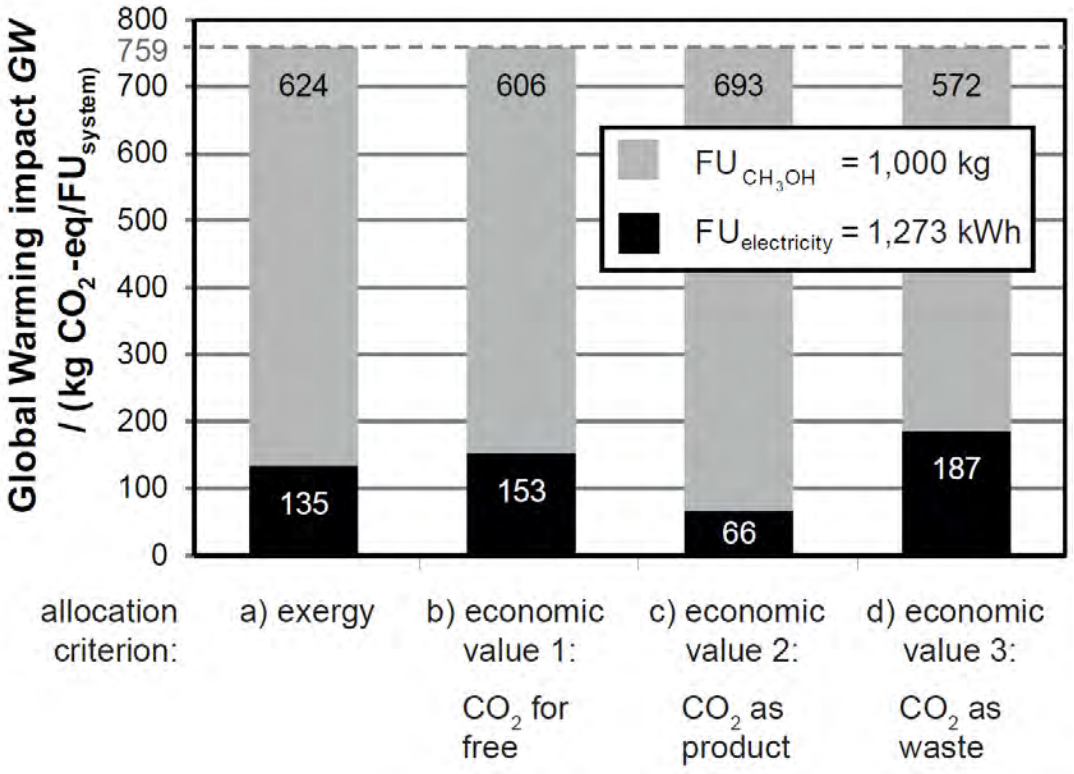
Reference: von der Assen et al., Energy Environ. Sci., 2013, 6, 2721

2. Life Cycle Inventory

Account for all co-products! Here: Allocation



where to „cut“ the integrated system?



Reference: von der Assen et al., Energy Environ. Sci., 2013, 6, 2721

2. Life Cycle Inventory

Account for all co-products! Best practice for CCU?

Attributional LCA

- System expansion favorable:
  - Unambiguous
  - Overall reductions clearly determined
- Avoided Burden:
  - Implies comparison!
- Allocation:
  - Where?
  - Which criterion?

Consequential LCA

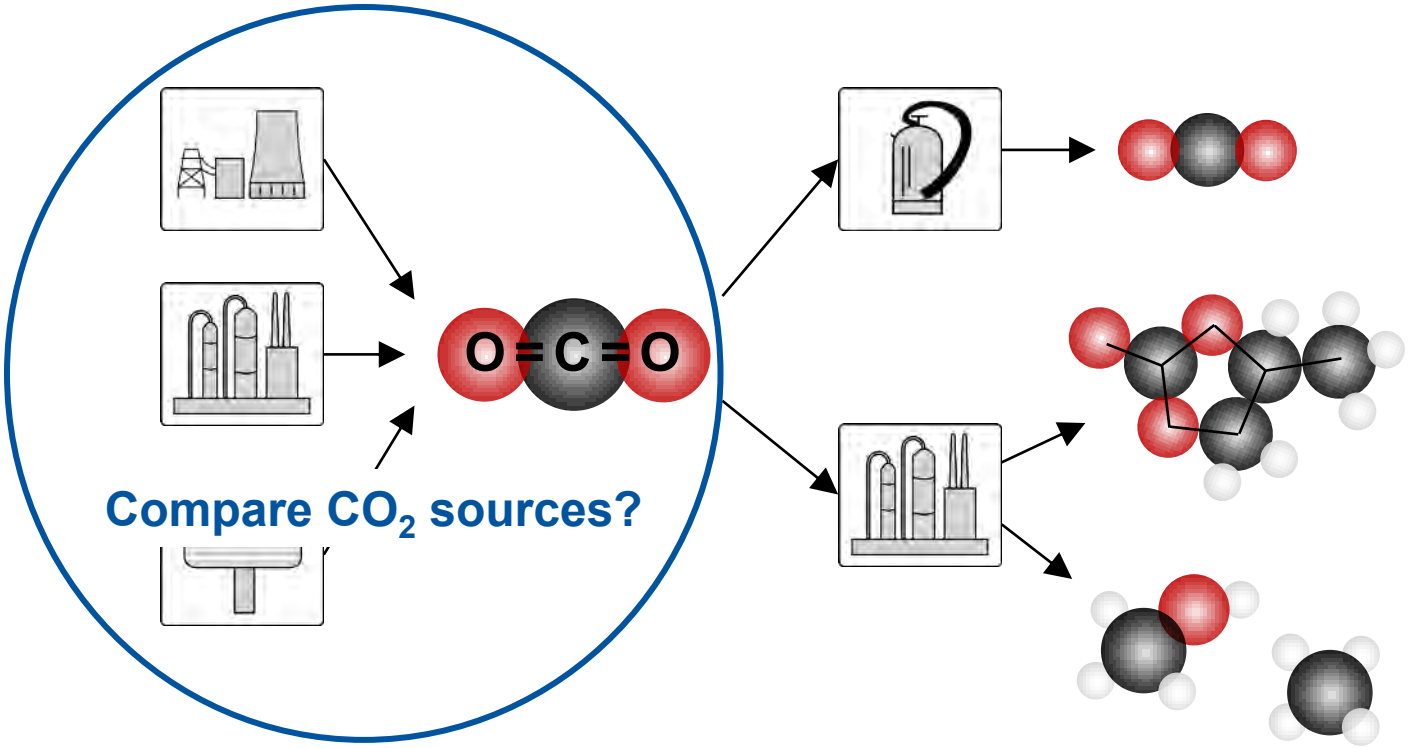
- Avoided Burden

➔ Guidelines / Product Category Rules desired !

References: von der Assen et al., Energy Environ. Sci., 2013, 6, 2721
Pelletier et al., Int J. Life Cycle Assess., 2015, 20(1), 74

1. Goal & Scope Definition

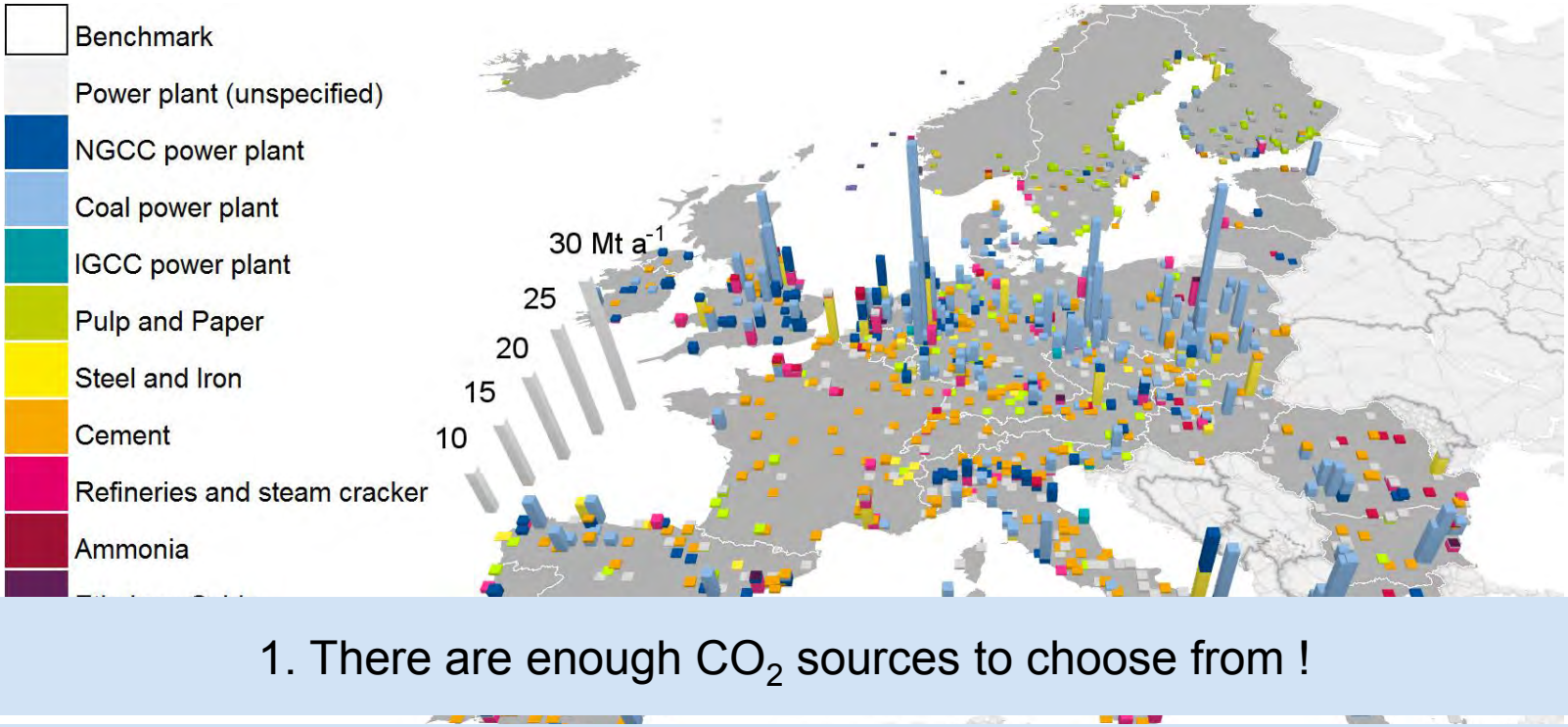
What to compare? – Real choices and limiting factors!



1. Goal & Scope Definition – What to compare?

Selecting CO_2 sources for CO_2 utilization

Total: 1700 Mt CO_2



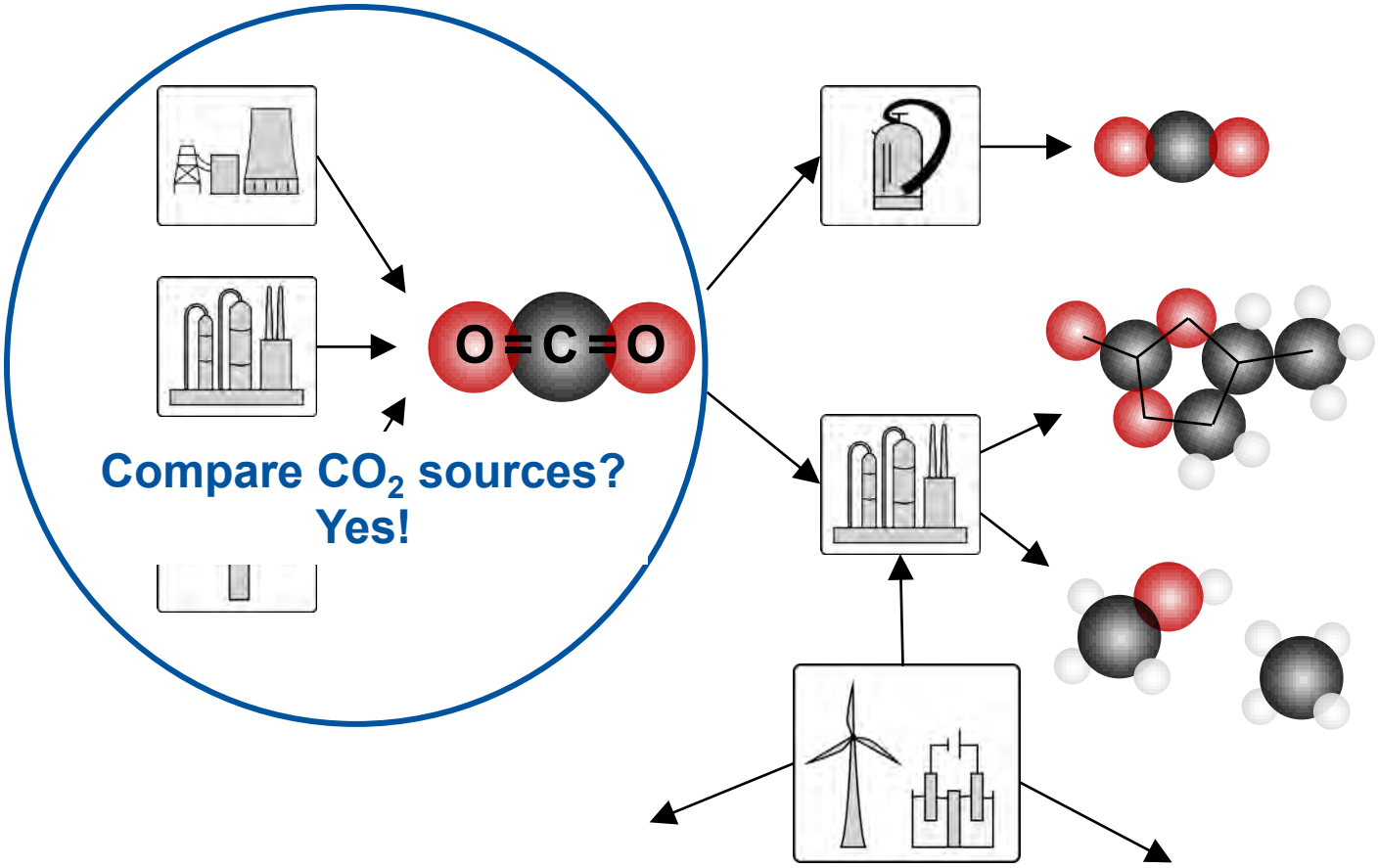
1. There are enough CO_2 sources to choose from !

2. There is enough CO_2 for **all** CO_2 utilization options !

Reference: von der Assen et al., 2015, submitted

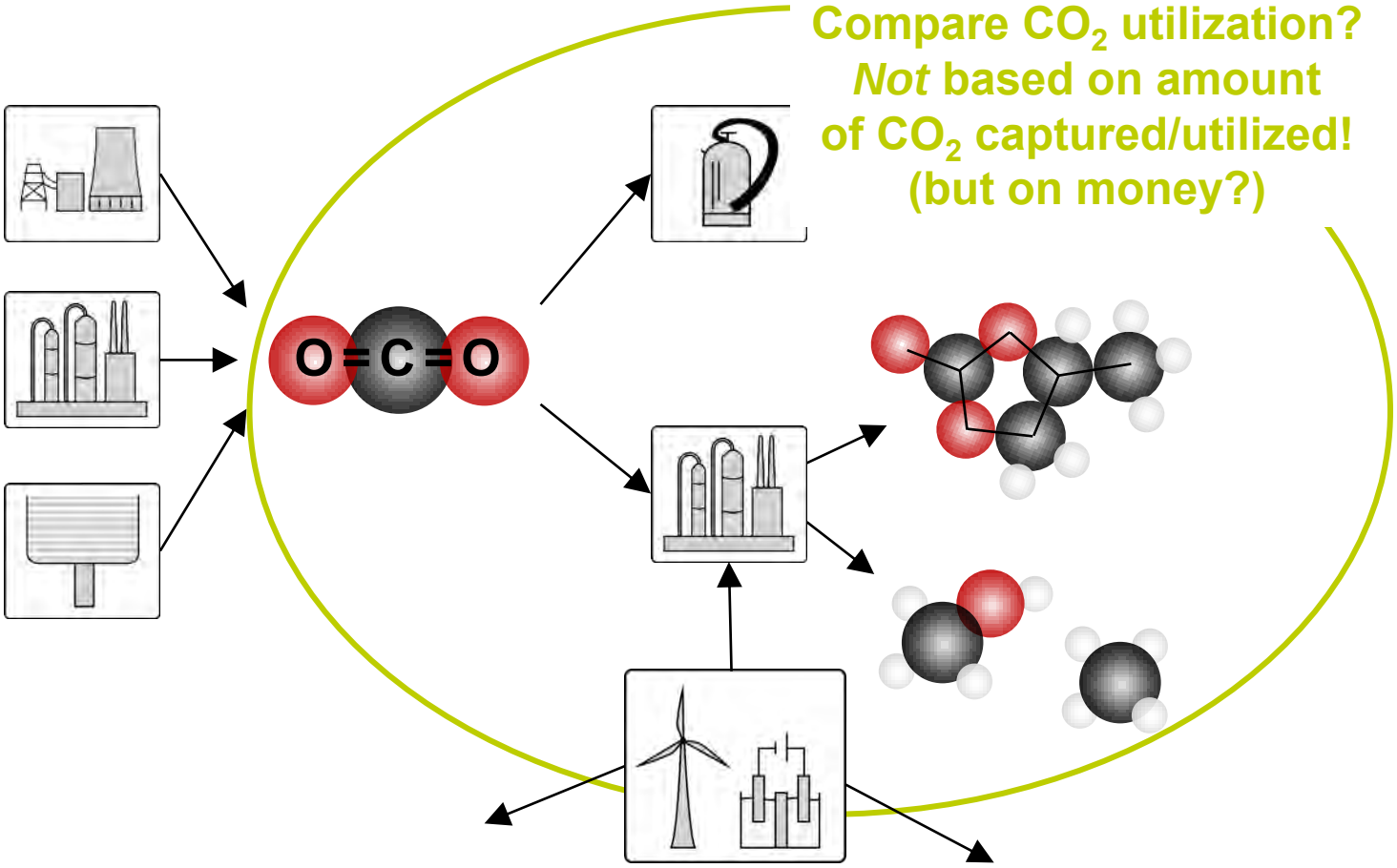
1. Goal & Scope Definition

What to compare? – Real choices and limiting factors!



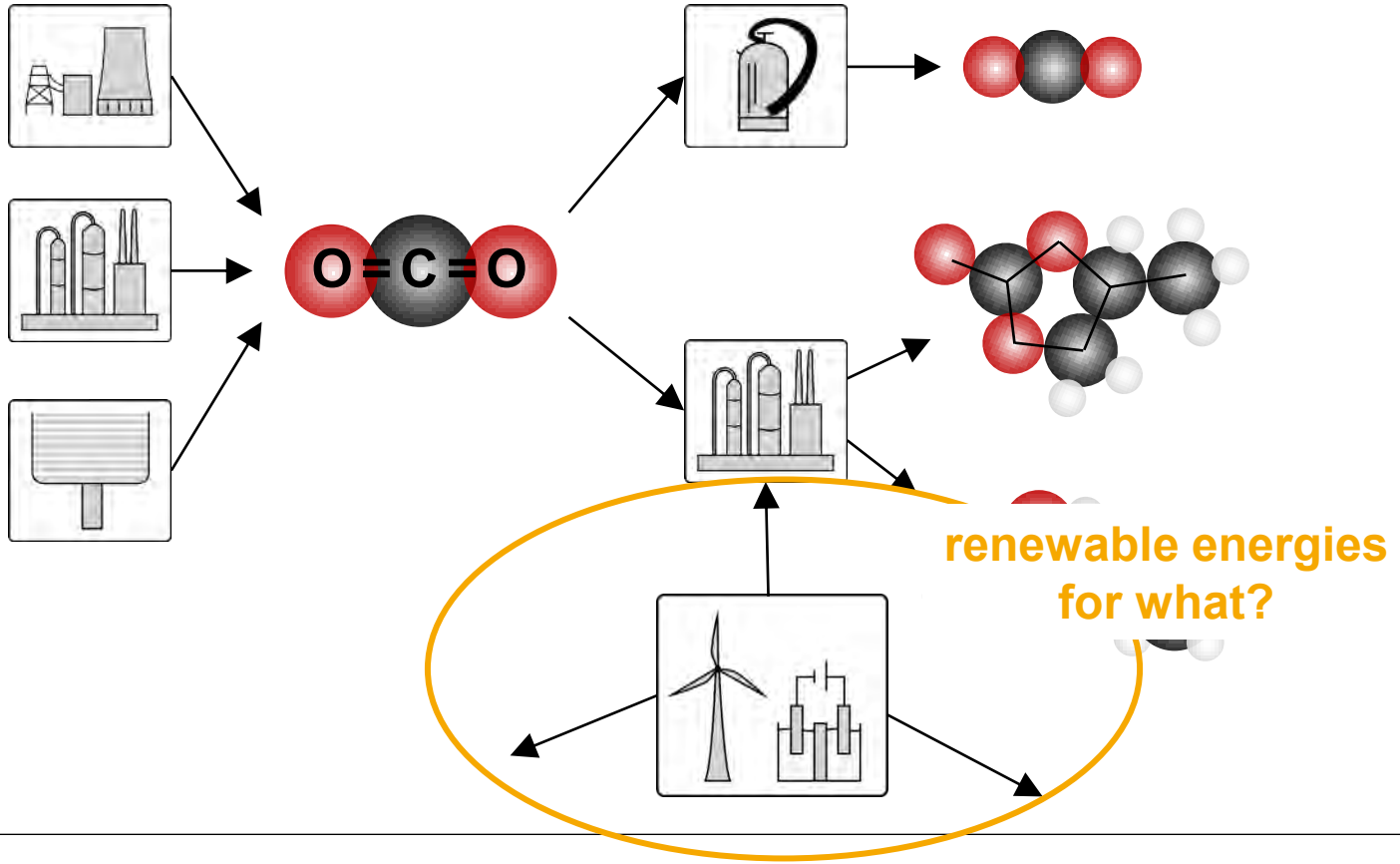
1. Goal & Scope Definition

What to compare? – Real choices and limiting factors!



1. Goal & Scope Definition

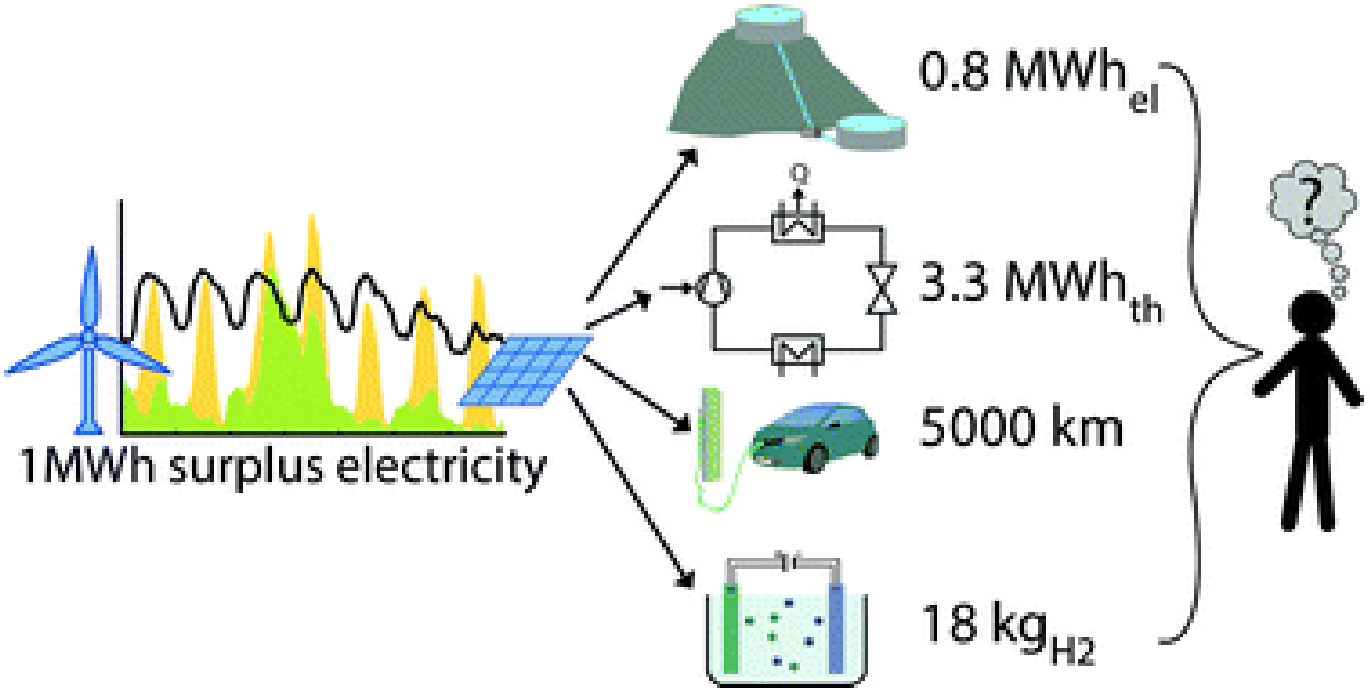
What to compare? – Real choices and limiting factors!



1. Goal & Scope Definition – What to compare?

Power-to-What?

What should the limited renewable energy / surplus power be used for?



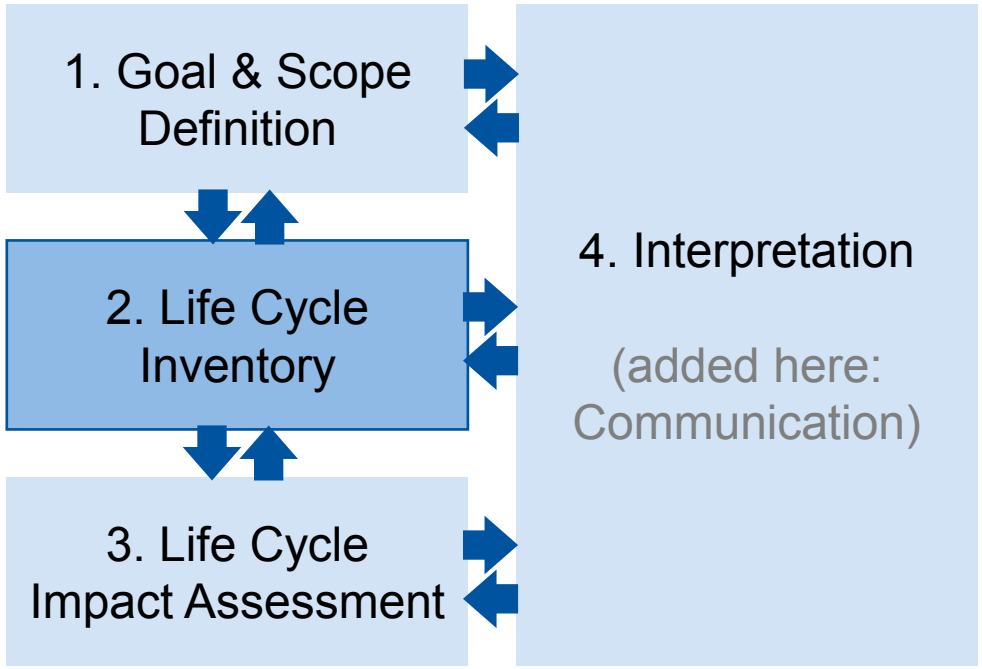
Reference: Sternberg et al., Energy Environ. Sci., 2015, 8, 389

2. Life Cycle Inventory

Why?
What?
How?

Data Collection

Environmental Impacts?



What does it mean?

What should we do?

How to communicate?

2. Life Cycle Inventory

Simplified LCA for screening

Methanol production from CO_2:

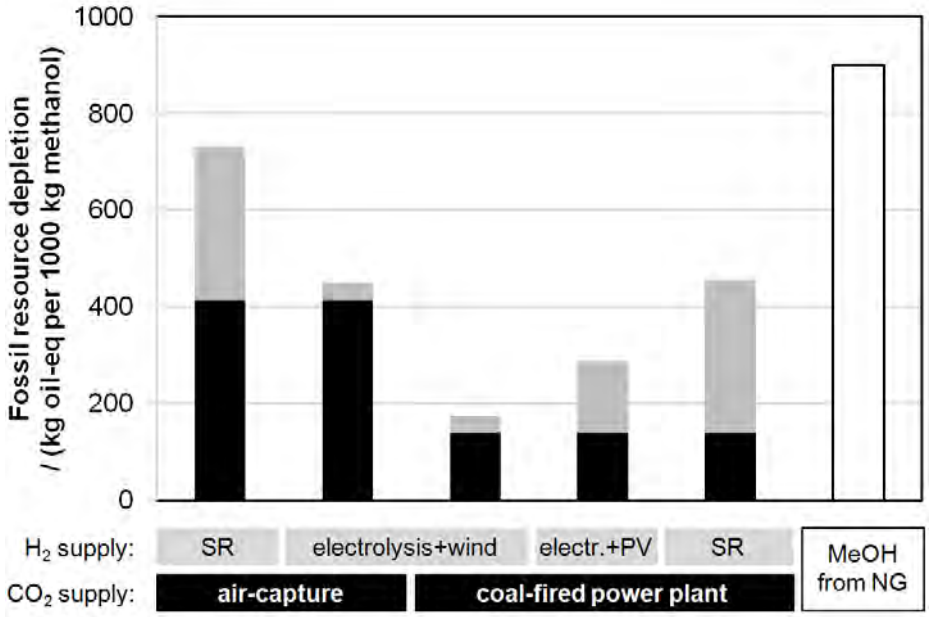
- $CO_2 + 3\ H_2 \rightarrow CH_3OH + H_2O$

Stoichiometry:

- 1375 kg CO_2 + 187.5 kg H_2

  → 1000 kg CH_3OH + 562.5 kg H_2O

Feedstock Impacts from Databases➔



➔ Lower-bounds for Environmental Impacts !

Reference: von der Assen et al., Chem. Soc. Rev., 2014, 6, 2721

Bridging Data Gaps

- Thermodynamics / Engineering Principles (e.g. Energy and Exergy balance)
- Process estimation tools (e.g. based on presence of water, product concentration etc.) [2]
- Estimation tools for chemicals based on molecular structure [1]

➔ Integrate with Chemical Process Design !

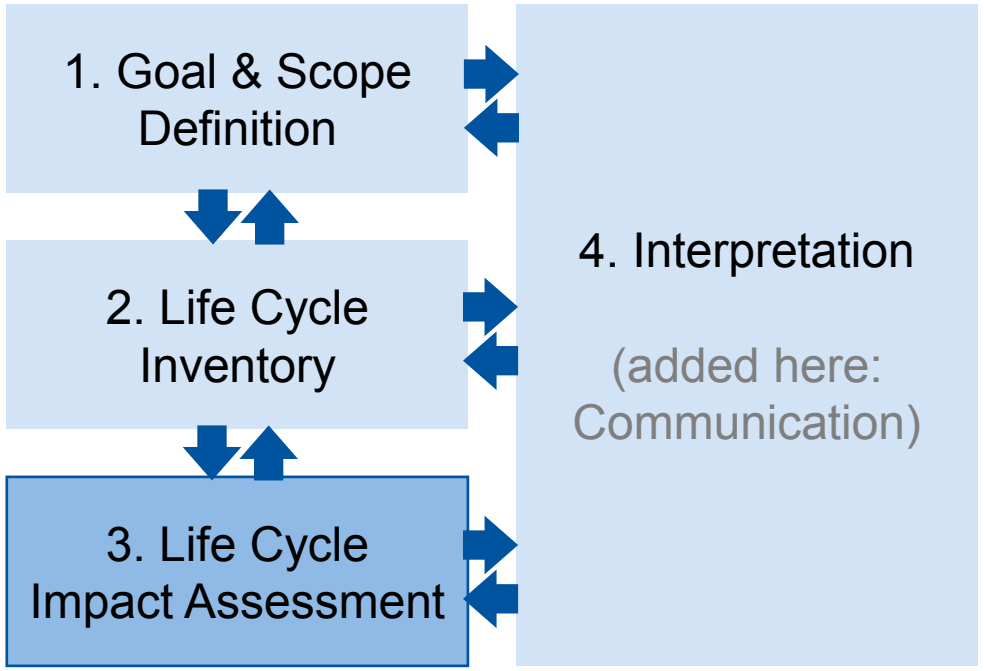
References: [1] Wernet et al., Green Chem., 2009, 11, 1826
[2] Patel et al., Energy Environ. Sci., 2012, 5(9), 8430

3. Life Cycle Impact Assessment

Why?
What?
How?

Data Collection

Environmental Impacts?



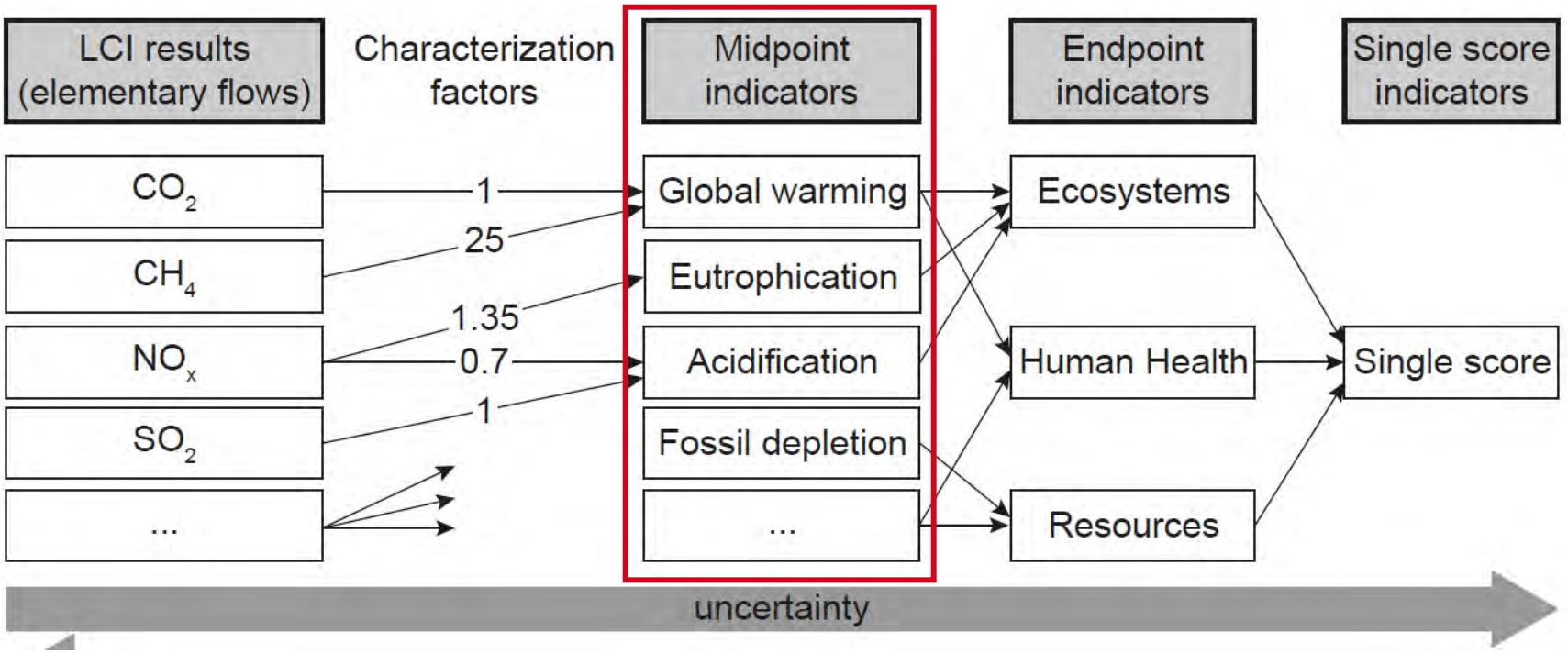
What does it mean?

What should we do?

How to communicate?

3. Life Cycle Impact Assessment

Midpoint, Endpoint or Single Score?



3. Life Cycle Impact Assessment

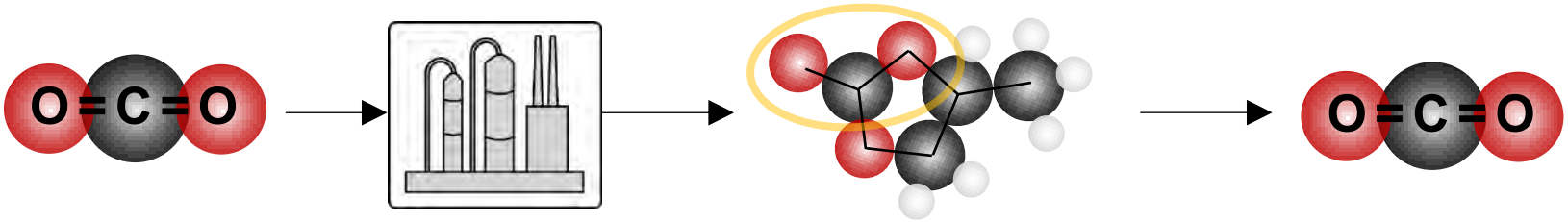
Which environmental impacts should be considered?

Quality level I	Quality level II	Quality level III
- Global warming	- Ionizing radiation, human health	- Land use
- Ozone depletion	- Photochemical ozone formation	- Water use
- Particulate matter I/II	- Acidification	
	- Eutrophication, terrestrial and aquatic	
	- **Resource depletion, mineral and fossil**	
	- Human toxicity	
	- Ecotoxicity, freshwater II/III	

Reference: Hauschild et al., Int. J. Life Cycle Assess., 2013, 18, 683

3. Life Cycle Impact Assessment

Effect of CO_2 storage duration on climate?



Temporary CO_2 storage

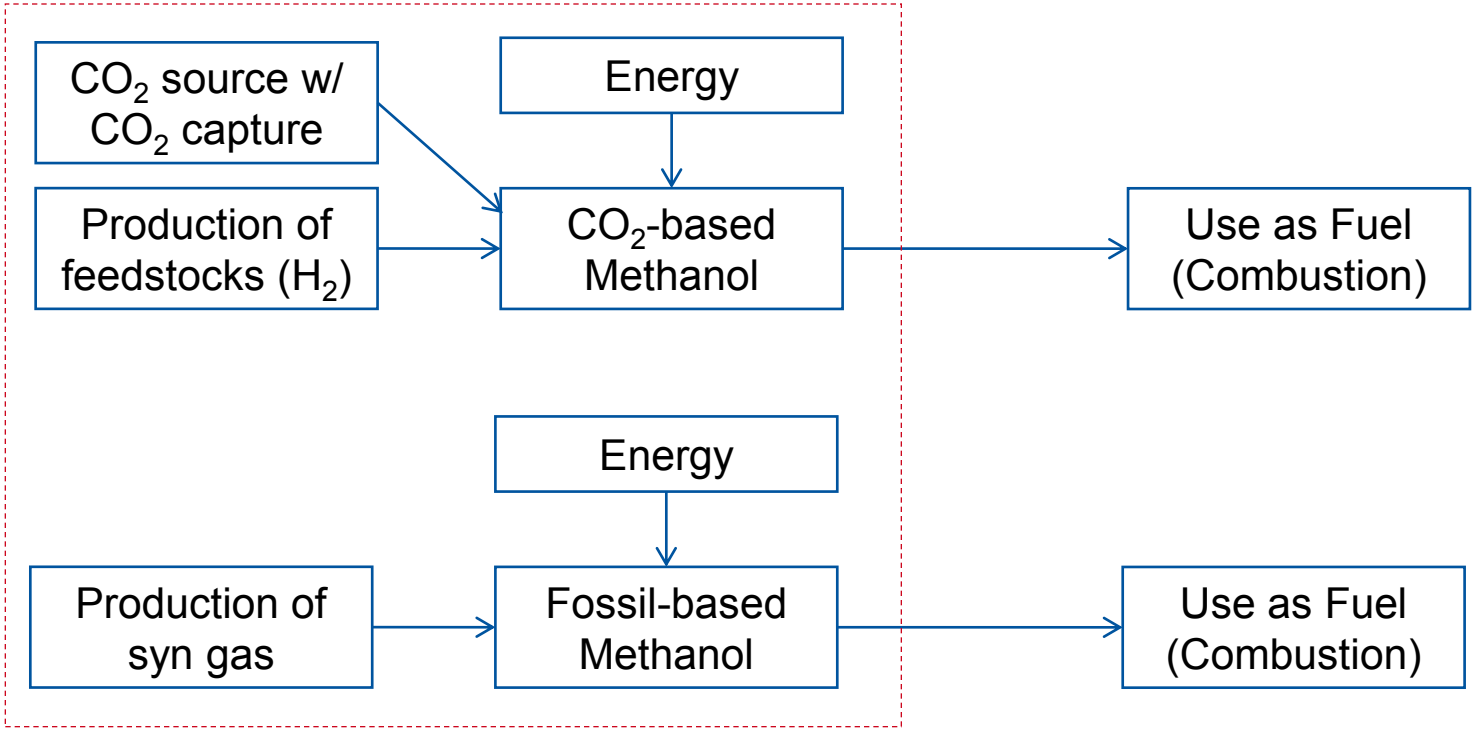
Frequent claim:

options with **short CO_2 storage duration** have **no climate benefit!**

Really?

3. Life Cycle Impact Assessment

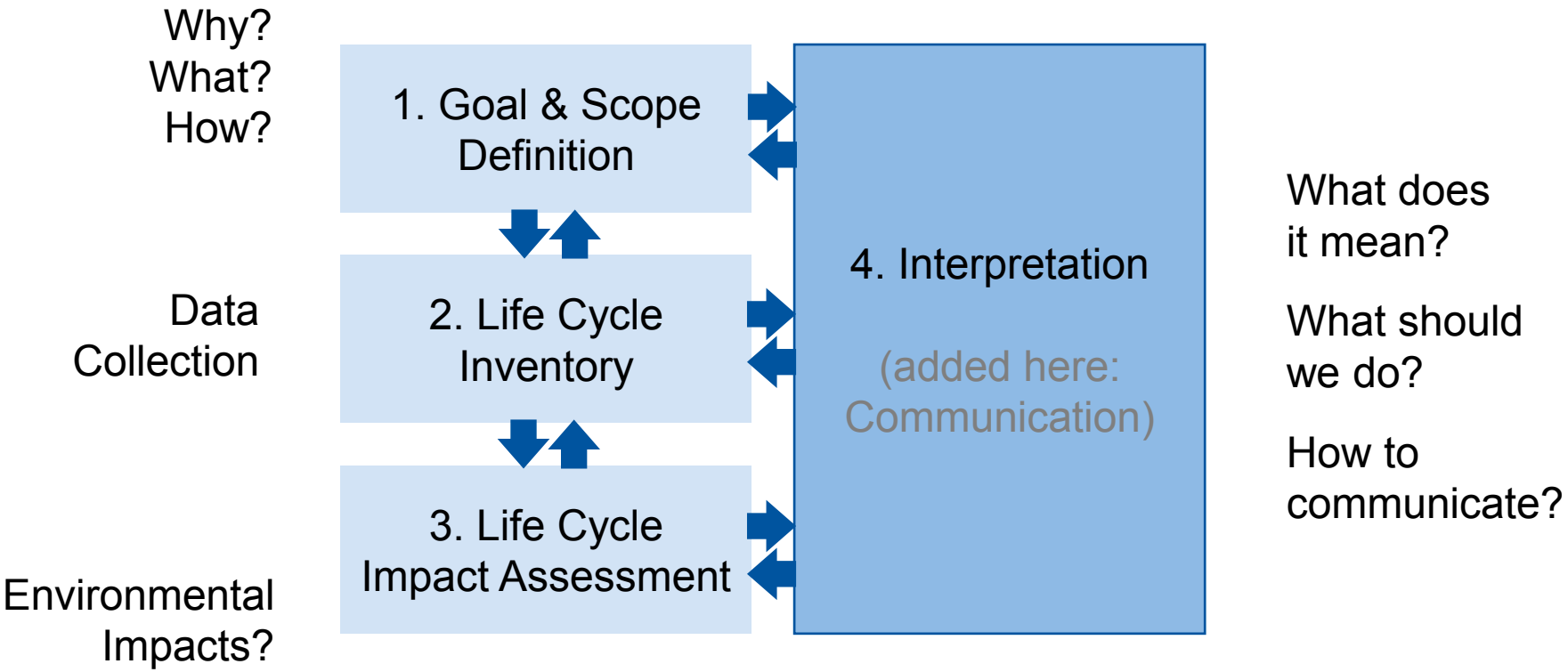
Incorporate CO_2 storage duration in global warming metric



➔ Effect of CO_2 storage duration is typically overrated !

Reference: von der Assen et al., Energy Environ. Sci., 2013, 6, 2721

4. Interpretation and Communication



4. Interpretation and Communication – “Dream Production“

SPONSORED BY THE Federal Ministry of Education and Research

Reference: von der Assen et al., Green Chem., 2014, 16, 3272

Scrubbing and supply of CO_2

VORWEG GEHEN

Process development and conversion of CO_2

Bayer Technology Services

Production and testing of polyurethanes with CO_2

Bayer MaterialScience

Fundamental research

CAT® Catalytic Center

RWTH AACHEN UNIVERSITY

Life Cycle Assessment

4. Interpretation and Communication – “Dream Production“

Reference: von der Assen et al., Green Chem., 2014, 16, 3272

Power

CO_2

CO_2

Scrubbing and supply of CO_2

VORWEG GEHEN

Process development and conversion of CO_2

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Production and testing of polyurethanes with CO_2

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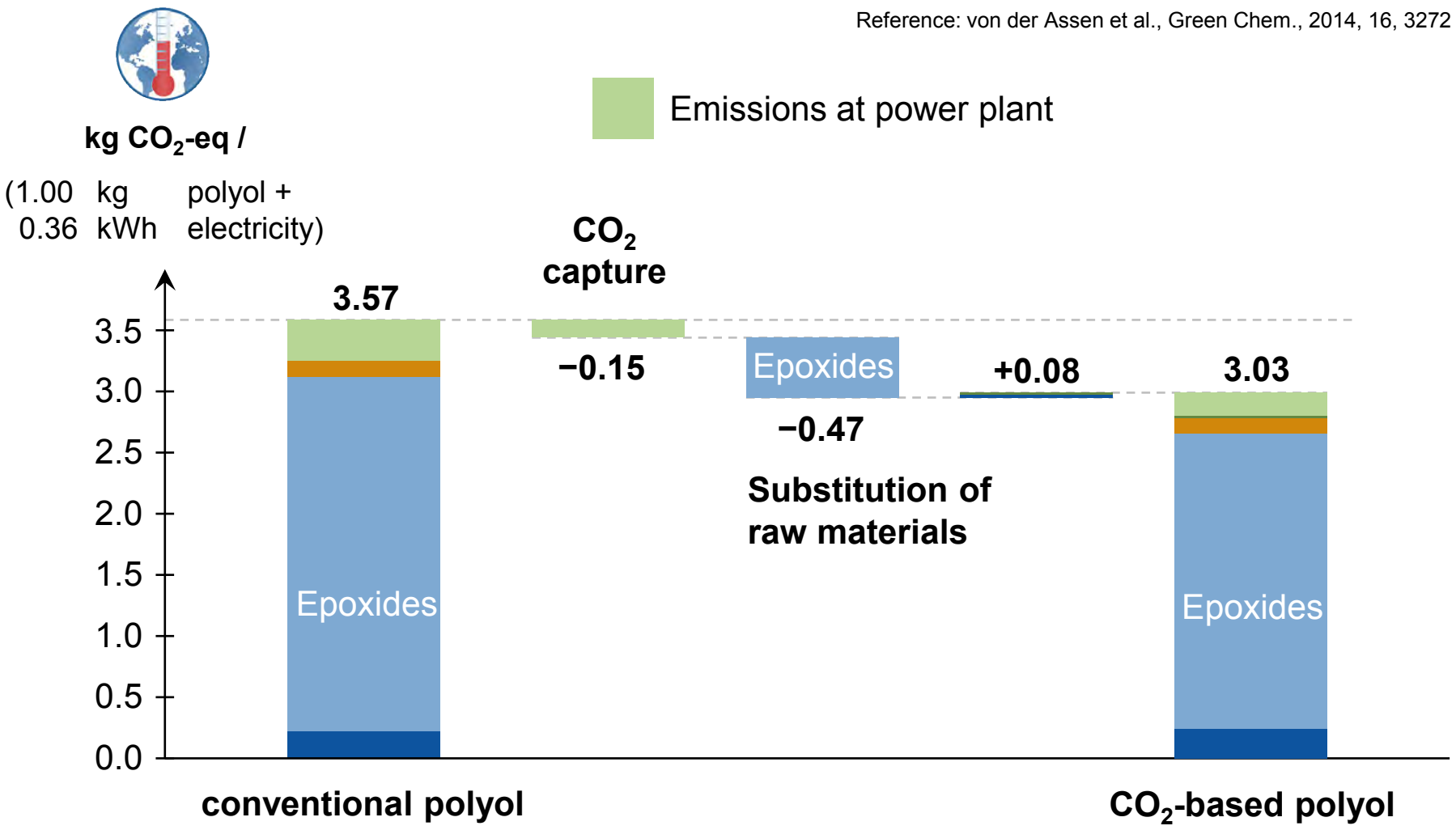
Life Cycle Assessment

4. Interpretation and Communication – “Dream Production“

Reference: von der Assen et al., Green Chem., 2014, 16, 3272



Experience and Advise

- Don‘t get tired! – Data collection from/with industry is possible!
- Give explicit values only if results are final/robust (semi-internal and external)!
- Clear communication to media: “no mattress is best for climate”
- (Dis)Advantage of LCA: everyone wants to/can join the discussion!

Thank you for your attention!

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