MISSION INNOVATION

Accelerating the Clean Energy Revolution

Report of the Mission Innovation Carbon Capture, Utilization and Storage Experts' Workshop

Trondheim, Norway

June 19-20, 2019

Mission Innovation

October 2019

Appendix Section

The Research Council of Norway | CLIMIT | Department for Business, Energy & Industrial Strategy | TOTAL | equinor | GASSNOVA | NCCS Norwegian CCS Research Centre | SINTEF

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Accelerating the Clean Energy Revolution

Carbon Capture Innovation Challenge

Report of the Carbon Capture, Utilization and Storage Experts' Workshop

June 19–20, 2019
Trondheim, Norway

Carbon Capture Challenge co-leads:

Nelson Mojarro, Ministry of Energy, Mexico
Tidjani Niass, Saudi Aramco, Saudi Arabia
Brian Allison, Department for Business, Energy & Industrial Strategy (BEIS), UK

CCUS Experts Workshop:

Co-chair — Nils A. Røkke, SINTEF, Norway
Co-chair — Brain Allison, BEIS, UK

Session chairs:

Decarbonizing industry sectors
Mike Monea, CCS Knowledge Centre, Canada
The role of CCS in enabling clean hydrogen
Lars Ingolf Eide, Research Council of Norway
Storage and CO_2 networks
Isabelle Czernichowski-Lauriol, BRGM, France
Storage monitoring
Katherine Romanak, University of Texas, USA
Going climate positive
Niall MacDowell, Imperial College London, UK
CO_2 utilization
Paul Bonnetblanc, Ministry of Ecological Solidarity Transition, France

MISSION INNOVATION

Acknowledgements

We would like to acknowledge the direct financial support to the workshop from Research Council of Norway (RCN), Department for Business, Energy and Industrial Strategy (BEIS) UK, TOTAL, The CLIMIT Programme, Gassnova, and Equinor, The Norwegian CCS Research Centre (NCCS), and SINTEF Energy Research.

In planning and preparing the workshop programme we had several telephone conferences with the Steering Group of the Mission Innovation Challenge CCUS. Your guidance was instrumental and was highly appreciated!

A special thanks goes to the following:

- The *Workshop Co-Chairs*: Nils A. Røkke (SINTEF, Norway) and Brian Allison (Department for Business, Energy and Industrial Strategy, UK).
- The *Session Chairs*: Mike Monea (CCS Knowledge Centre, Canada), Lars Ingolf Eide (Research Council of Norway), Isabelle Czernichowski-Lauriol (BRGM France), Katherine Romanak (University of Texas, USA), Niall MacDowell (Imperial College London, UK), and Paul Bonnetblanc (Ministry of Ecological Solidarity Transition, France)
- The *Session Secretaries*: Stefania Osk Gardarsdottir (SINTEF, Norway), Gerdi Breembroek (Netherlands Enterprise Agency), Peter Zweigel (Equinor, Norway), Tim Dixon (IEAGHG), Nils A. Røkke (SINTEF, Norway) and Aicha El Khamlichi (ADEME, France)
- The *Introductory Speakers* at the workshop: Monica Garcia (IEAGHG), Sigmund Størset SINTEF, Norway), Phillip Ringrose (Equinor, Norway), Tip Meckel (Gulf Coast Carbon Center, USA), Niall MacDowell (Imperial College London, UK) and Jaap Vente (TNO, Netherlands)

Appendix Section

Appendix 1:

About the Workshop

The two-day workshop gathered 135 participants and had six different topics:

1. Decarbonizing industry sectors
2. The role of CCS in enabling clean hydrogen
3. Storage and CO_2 networks
4. Storage monitoring
5. Going climate positive
6. CO_2 utilization

After a welcome address by Nils A. Røkke (SINTEF) and a Mission Innovation status report by Brian Allison (BEIS), introductory presentations were given to all topics in a plenum session. The first three topics were discussed in parallel sessions in the evening of June 19 and the morning of June 20, while the last three topics were discussed in parallel sessions on June 20. Results from session discussions were presented in a plenum session as a conclusion of the workshop. The layout of the workshop program is shown below.

June 19

1700	**Welcome and introduction** Program, expectations, follow-up from Houston workshop		
1730	Introductory presentations		
1900	Dinner (buffet-style) (Briefing session for Session Chairs and Secretaries)		
2000 2100 2200	Session 1 **Decarbonizing industry sectors**	Session 2 **The role of CCS in enabling clean hydrogen**	Session 3 **Storage and CO2 networks**

June 20

0830	Session 1 **Decarbonizing industry sectors**	Session 2 **The role of CCS in enabling clean hydrogen**	Session 3 **Storage and CO2 networks**
1000	Session 4 **Storage monitoring**	Session 5 **Going climate positive**	Session 6 **CO2 utilization**
1200	Lunch		
1245	Session 4 **Storage monitoring**	Session 5 **Going climate positive**	Session 6 **CO2 utilization**
1415	Reporting session		
1530	Busses leave for airport		

The groups were asked to answer the following questions:

1. Which opportunities are identified from an industrial point of view?
2. How do we most effectively get from research to commercial product?
    a. What steps are needed?
3. What joint activities could be established to accelerate technology development and implementation?
    a. How can joint action accelerate deployment?
    b. Business models: What funding instruments are/could/would be effective?
    c. Mobilizing national efforts towards international efforts
    d. Public-private partnership, co-funding, etc.

Appendix 2:

Workshop program

JUNE 19

17:00 **Welcome and introduction** (program, expectations for the workshop)
Nils A. Røkke, SINTEF and Brian Allison, BEIS UK

17:10 **Status of Challenge #3** (recap of Houston workshop, Houston report, etc.)
Brian Allison, BEIS UK

17:30 **Introduction to topics (12 minutes each)**
Session Chair: Brian Allison, BEIS; UK

1. Topic 1: Decarbonizing industry sectors (power, cement, refineries, steel, fertilizers…)
    - Introductory speaker: Monica Garcia, IEAGHG
2. Topic 2: The role of CCS in enabling clean hydrogen
    - Introductory speaker: Sigmund Størset, SINTEF
3. Topic 3: Storage and CO_2-networks
    - Introductory speaker: Phillip Ringrose, Equinor
4. Topic 4: Storage monitoring
    - Introductory speaker: Tip Meckel, Gulf Coast Carbon Center
5. Topic 5: Going climate positive (biomass, waste to-energy, resources and technology)
    - Introductory speaker: Niall MacDowell, Imperial College London
6. Topic 6: CO_2 Utilization
    - Introductory speaker: Jaap Vente, TNO
    - "Success story" speaker: Mark Summers, Emissions Reduction Alberta (ERA)

19:00 **Dinner (buffet-style)**

Briefing session for Session Chairs and Secretaries (separate room)

20:00-22:00 **Group work over topics 1-3**

Session/Topic 1: Decarbonizing industry sectors (power, cement, refineries, steel, fertilizers…)

Chair: Mike Monea, CCS Knowledge Centre
Secretary: Stefania Osk Gardarsdottir, SINTEF

Session/Topic 2: The role of CCS in enabling clean hydrogen
Chair: Lars Ingolf Eide, Research Council of Norway
Secretary: Gerdi Breembroek, Netherlands Enterprise Agency

Session/Topic 3: Storage and CO_2-networks
Chair: Isabelle Czernichowski-Lauriol, BRGM
Secretary: Peter Zweigel, Equinor

JUNE 20

08:30-10:00 Group work over topics 1-3 (cont'd)

(Same Chairs, Secretaries and rooms)

10:00-12:00 Group work over topics 4-6

Session/Topic 4: Storage monitoring
Chair: Katherine Romanak, University of Texas
Secretary: Tim Dixon, IEAGHG

Session/Topic 5: Going climate positive
Chair: Niall MacDowell, Imperial College London
Secretary: Nils A. Røkke, SINTEF

Session/Topic 6: Utilization
Chair: Paul Bonnetblanc, Ministry of Ecological Solidarity Transition
Secretary: Aicha El Khamlichi, ADEME

12:00-12:45 Lunch

12:45-14:15 Group work over topics 4-6 (cont'd)

(Same Chairs, Secretaries and rooms)

14:15-15:25 Reporting (10 minutes each)

(To be conducted by the *Session Chair*, *Session Secretary* and *Introductory Speaker)*

- Topic 1: Monica Garcia, Mike Monea, Stefania Osk Gardarsdottir
- Topic 2: Lars Ingolf Eide, Gerdi Breembroek
- Topic 3: Phillip Ringrose, Isabelle Czernichowski-Lauriol, Peter Zweigel
- Topic 4: Tip Meckel, Katherine Romanak, Tim Dixon
- Topic 5: Niall Mac Dowell, Nils A. Røkke
- Topic 6: Jaap Vente, Paul Bonnetblanc, Aicha El Khamlichi

15:25 Summary and conclusion
Nils A. Røkke and Brian Allison

Session Topics, Chairs, Secretaries, and Introductory Speakers

Topic 1: Decarbonizing industry sectors

- Chair: Mike Monea, CCS Knowledge Centre
- Secretary: Stefania Osk Gardarsdottir, SINTEF
- Intro speaker: Monica Garcia, IEAGHG

Topic 2: The role of CCS in enabling clean hydrogen

- Chair: Lars Ingolf Eide, Research Council of Norway
- Secretary: Gerdi Breembroek, Netherlands Enterprise Agency
- Intro speaker: Sigmund Størset, SINTEF

Topic 3: Storage and CO_2 networks

- Chair: Isabelle Czernichowski-Lauriol, BRGM
- Secretary: Peter Zweigel, Equinor
- Intro speaker: Phillip Ringrose, Equinor

Topic 4: Storage monitoring

- Chair: Katherine Romanak, University of Texas
- Secretary: Tim Dixon, IEAGHG
- Intro speaker: Tip Meckel, Gulf Coast Carbon Center

Topic 5: Going climate positive

- Chair: Niall MacDowell, Imperial College London
- Secretary: Nils A. Røkke, SINTEF
- Intro speaker: Niall MacDowell, Imperial College London

Topic 6: CO_2 utilization

- Chair: Paul Bonnetblanc, Ministry of Ecological Solidarity Transition
- Secretary: Aicha El Khamlichi, ADEME
- Intro speaker: Jaap Vente, TNO
  Mark Summers, Emissions Reduction

Appendix 3:

Introductory presentations at the workshop (slides)

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Carbon Capture Innovation Challenge

Workshop #2

Dr. Nils A. Røkke
Executive Vice President Sustainability
SINTEF

Department for Business, Energy & Industrial Strategy

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المملكة العربية السعودية
Ministry of Energy, Industry, and Mineral Resources
The Kingdom of Saudi Arabia

Mission Innovation – WS- Trondheim

A full CCS week in Trondheim

TRONDHEIM CCS CONFERENCE

CO_2 CAPTURE, TRANSPORT AND STORAGE

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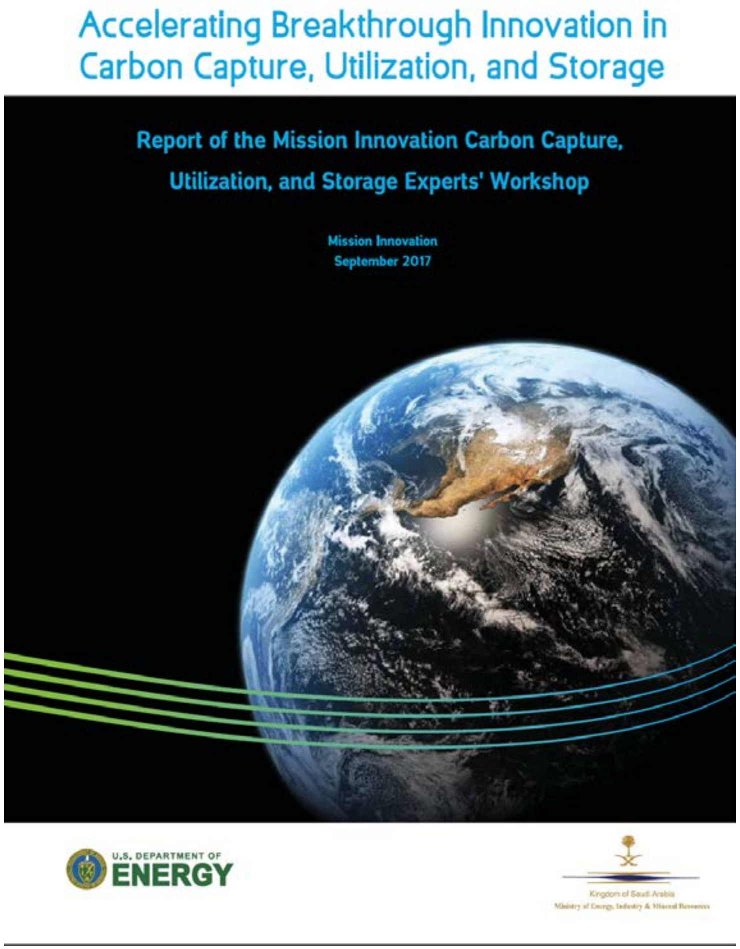
Accelerating the Clean Energy Revolution



Workshop #2 - Focus

This workshop will focus on strengthening collaboration between industry sectors and research institutions, and public and private sector:

- by identifying RD&I gaps of common interest in technologies at higher TRL

The intention is to focus on potentials and possibilities, that could yield results and full-scale implementation in the short to medium-term perspective.

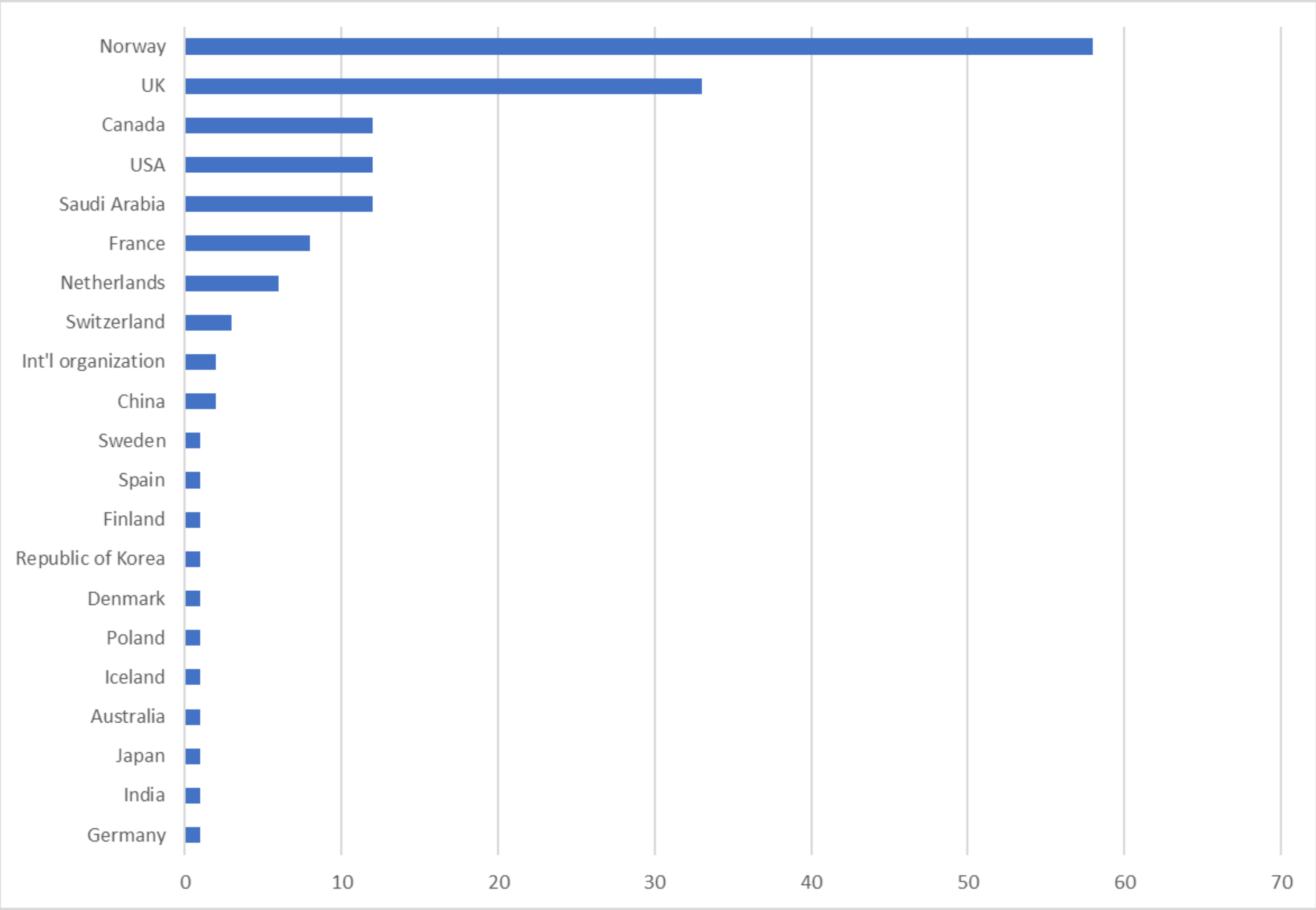
Why are we here?- Expectations

The objective of the workshop is to contribute in transferring early (low TRL) research activities to development and innovation activities (higher TRL) by developing guidance and development paths for emerging CCUS technologies, and suggestions for new and joint development activities, with the aim of accelerating the commercialization and implementation process.

The outcome will be a brief report consisting of:

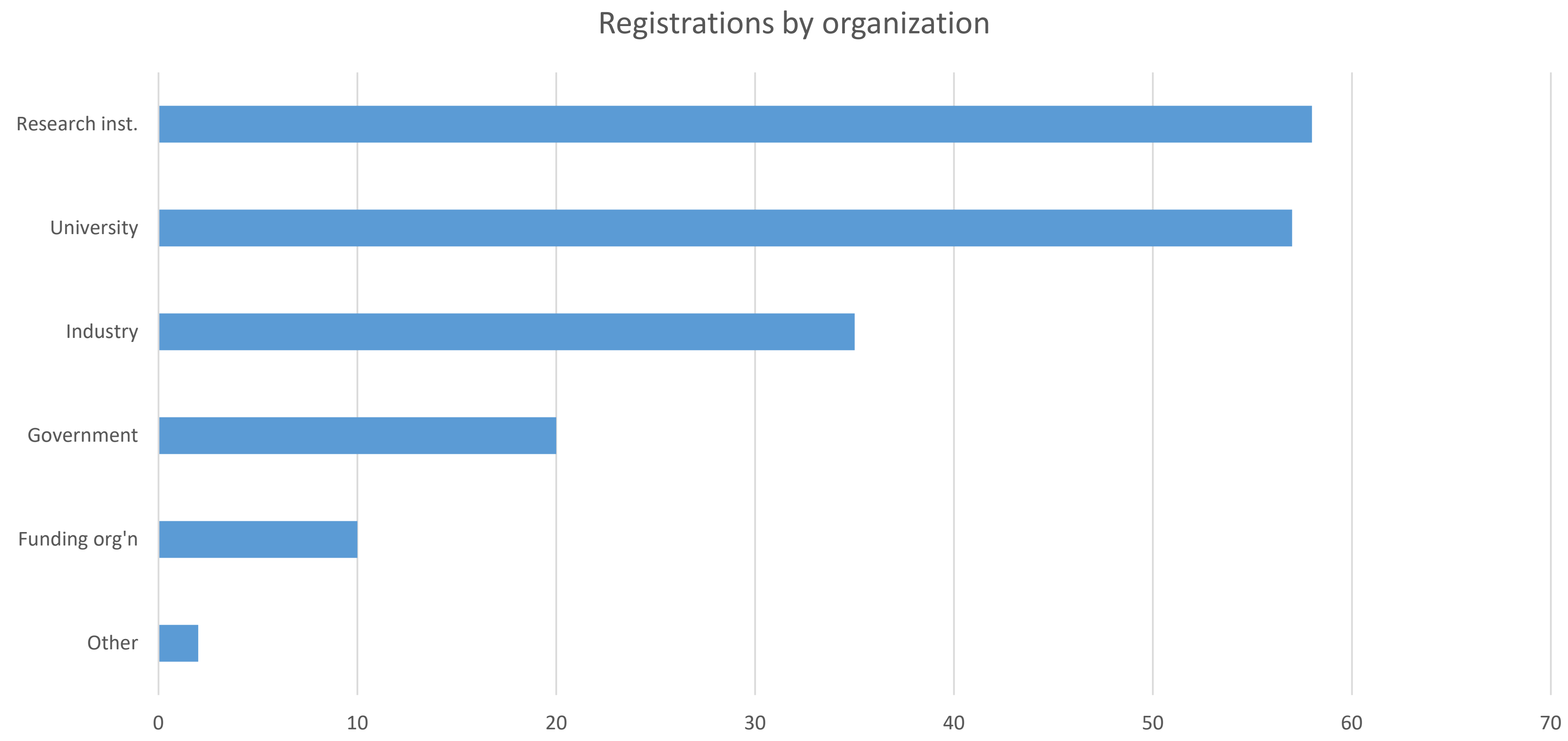
- the guidance and development path documents produced during the workshop
- proposals for new and joint development and innovation activities
- a summary of the workshop discussions

MI countries present



Germany	1
India	1
Japan	1
Australia	1
Iceland	1
Poland	1
Denmark	1
Republic of Korea	1
Finland	1
Spain	1
Sweden	1
China	2
Int'l organization	2
Switzerland	3
Netherlands	6
France	8
Saudi Arabia	12
USA	12
Canada	12
UK	33
Norway	58
Total	**159**

Network opportunities



Programme

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2200	

June 20

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Sessions

Questions to be discussed under each topic:

1. Which opportunities are identified from an industrial point of view?
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   a. What steps are needed?
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   a. How can joint action accelerate deployment?
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   c. Mobilizing national efforts towards international efforts
   d. Public-private partnership, co-funding

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Industry-driven innovation for fast-track CCS deployment

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Accelerating the Clean Energy Revolution

Carbon Capture Innovation Challenge

Brian Allison

UK Department for Business, Energy and Industrial Strategy

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المملكة العربية السعودية
Ministry of Energy, Industry, and Mineral Resources
The Kingdom of Saudi Arabia

Department for
Business, Energy
& Industrial Strategy

Mission Innovation

- A Ministerial level initiative launched in November 2015
- Mission Innovation's goal is to accelerate the pace of clean energy innovation to achieve performance breakthroughs and cost reductions to provide widely affordable and reliable clean energy solutions that will revolutionise energy systems throughout the world over the next two decades and beyond

Mission Innovation

- **A Ministerial level initiative launched in November 2015**
- **Mission Innovation's goal is to accelerate the pace of clean energy innovation to achieve performance breakthroughs and cost reductions to provide widely affordable and reliable clean energy solutions that will revolutionise energy systems throughout the world over the next two decades and beyond**
- **MI seeks to:**
  - **Double Governmental Investment in Clean Energy Innovation over 5 years (2016-2021), from $15B to $30B**
  - **Increase Private Sector Engagement in Clean Energy Innovation**
  - **Improve Information Sharing among MI countries**

Innovation Challenges

- **Global Calls for Actions in High Priority Areas of Mutual Interest**
- **Opportunities for Collaboration Between Mission Innovation Members**
- **Encourage Increased Engagement by Global Research Community, Industry, and Investors**
- **Support Mission Innovation goals of reducing GHG emissions, increasing energy security and creating new opportunities for clean economic growth**
- **Outcomes May Inform, Guide and Support MI Country Investments in R&D**

Innovation Challenges

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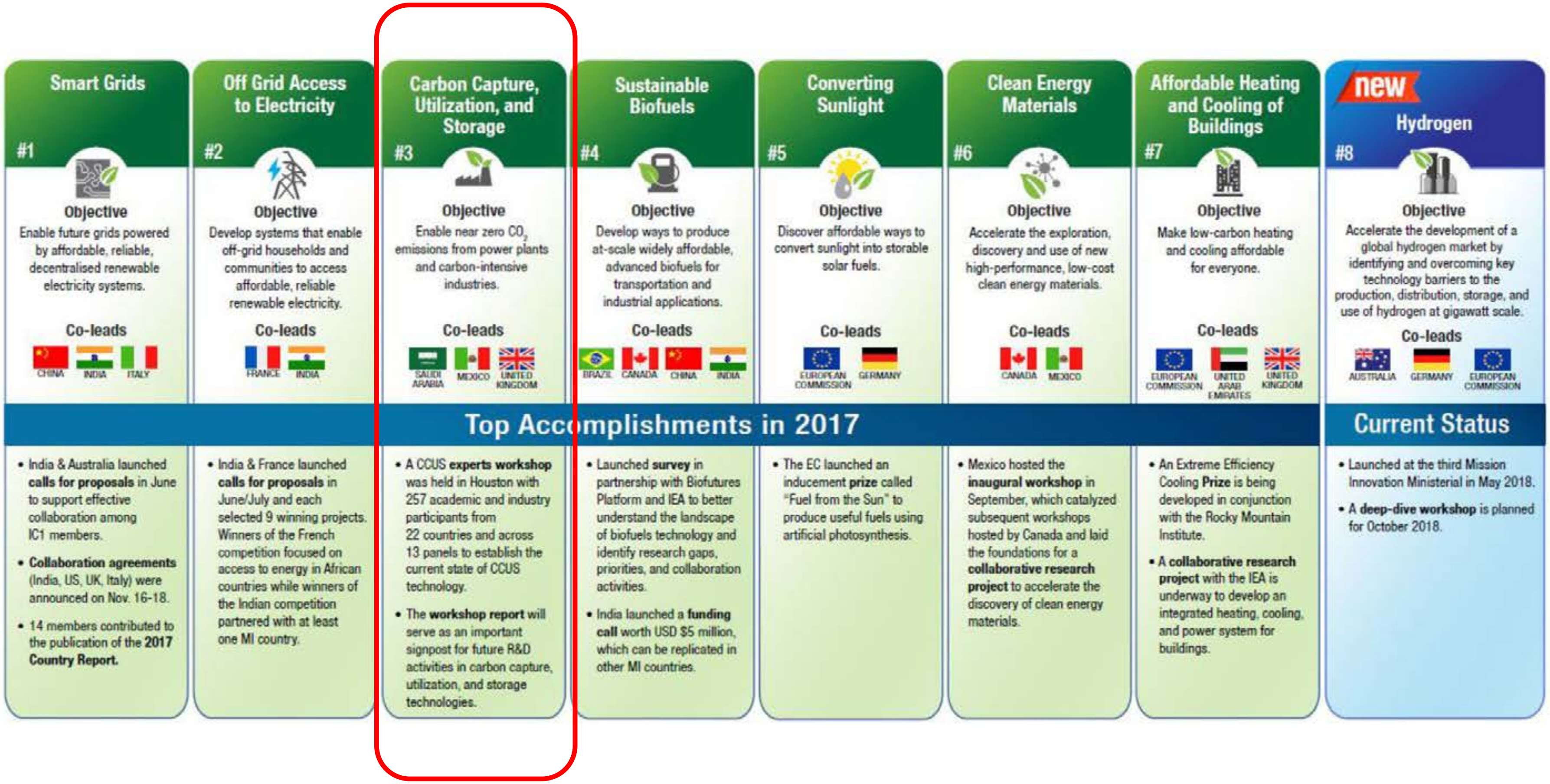
		Australia	Austria	Brazil	Canada	Chile	China	Denmark	European Union	Finland	France	Germany	India	Indonesia	Italy	Japan	Mexico	Netherlands	Norway	Republic of Korea	Saudi Arabia	Sweden	United Arab Emirat	United Kingdom	United States
1	IC1: Smart Grids Innovation Challenge	Participant	Participant	Participant	Participant		Lead	Participant	Participant	Participant	Participant	Participant	Lead	Participant	Lead		Participant		Participant	Participant	Participant	Participant		Participant	Participant
2	IC2: Off-Grid Access to Electricity Innovation Challenge	Participant		Participant	Participant		Participant		Participant	Participant	Lead		Lead	Participant	Participant		Participant	Participant	Participant	Participant	Participant	Participant		Participant	Participant
3	IC3: Carbon Capture Innovation Challenge	Participant			Participant		Participant	Participant	Participant	Participant	Participant	Participant	Participant	Participant	Participant	Participant	Lead	Participant	Participant	Participant	Lead	Participant	Participant	Lead	Participant
4	IC4: Sustainable Biofuels Innovation Challenge	Participant		Lead	Lead		Lead		Participant	Participant	Participant		Lead	Participant	Participant		Participant	Participant	Participant			Participant		Participant	Participant
5	IC5: Converting Sunlight Innovation Challenge	Participant		Participant	Participant	Participant	Participant	Participant	Lead	Participant	Participant	Lead	Participant		Participant	Participant	Participant		Participant		Participant	Participant	Participant	Participant	Participant
6	IC6: Clean Energy Materials Innovation Challenge	Participant			Lead			Participant	Participant	Participant	Participant	Participant	Participant		Participant		Lead		Participant	Participant	Participant	Participant		Participant	Participant
7	IC7: Affordable Heating and Cooling of Buildings Innovation Challenge	Participant	Participant	Participant	Participant		Participant	Participant	Lead	Participant	Participant	Participant	Participant		Participant		Participant	Participant	Participant	Participant	Participant	Participant	Lead	Lead	Participant
8	IC8: Renewable and Clean Hydrogen Innovation Challenge	Lead	Participant		Participant	Participant	Participant		Lead		Participant	Lead	Participant		Participant	Participant		Participant	Participant		Participant			Participant	Participant

Lead Participant

Carbon Capture Innovation Challenge

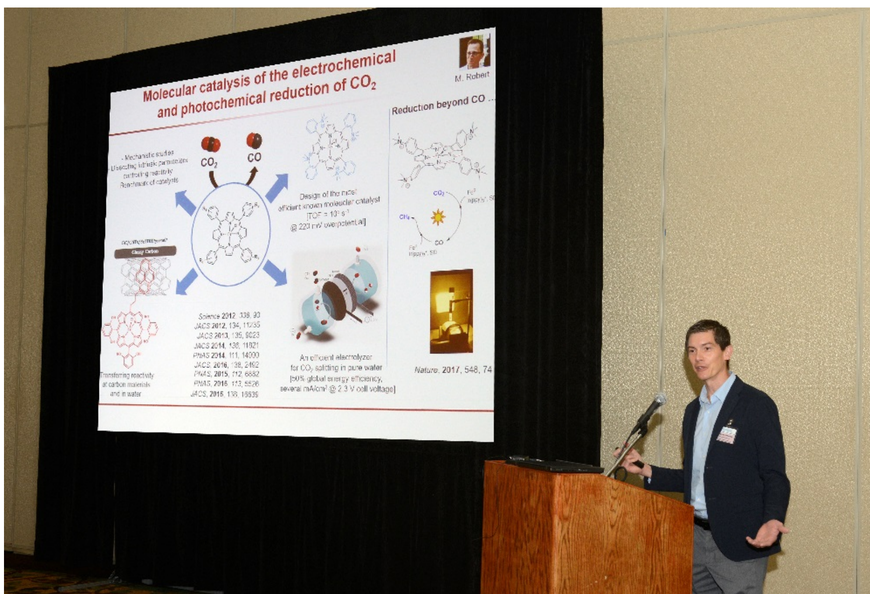
- **Co-Leads: Saudi Arabia, Mexico, United Kingdom**
- **20 Mission Innovation participating countries plus EU**
- **Objective**
  - **Enable near-zero CO2 emissions from power plants and carbon intensive industries**
- **Work-Plan**
  - **Organise a CCUS Experts Workshop and follow up (Trondheim June 2019)**
  - **Engage Stakeholders (WEF, IEA, Industry, …)**
  - **Build Multilateral Collaboration Mechanisms**

MIC#3 Mid Term Review



CCUS Experts' Workshop

- **Houston 2017**
- **257 Participants from Academy and Industry**
- **22 Countries participated**
- **13 Parallel Panel Discussions**



CCUS Experts' Workshop Structure

Focus Areas		
CO2 Capture - Panels	**CO2 Utilisation - Panels**	**CO2 Storage - Panels**
Solvents	Thermochemical Conversion and Hydrogenation of CO2	Injectivity & Capacity
Sorbents and Looping Systems	Electrochemical and Photochemical Conversion of CO2	Monitoring, Verification and Performance Metrics
Membranes	CO2 Conversion to Solid Carbonates	Forecasting and Managing Induced Seismicity
Combustion and Other Technologies	Biological Conversion of CO2	Well Diagnostics
Crosscuttings Topics (LCA,…)		

Panel Outcomes Structure

Scientific challenges

- Brief overview of the underlying science challenge

Summary of priority research direction (PRD)

- What fundamental research is needed to address the challenge?
- Why can this research be done now? (e.g. are there recently developed capabilities?)

Potential scientific impact

- What impact will this research have on the CCUS scientific field?
- What impact will it have on the general scientific community?

Potential impact on CCUS technology

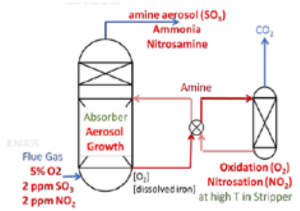
- How will this impact CCUS-relevant technologies?

CO2 Capture PRDs

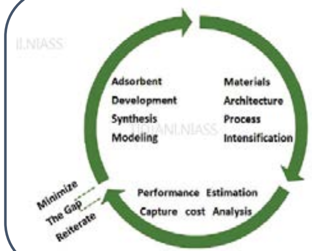
Solvents

Designing high performing solvents for CO2 capture

Creating environmentally friendly solvent processes for CO2 capture

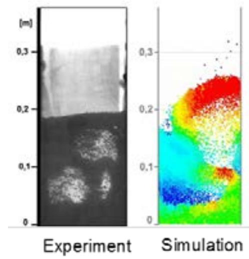


Sorbents

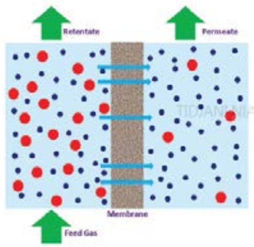


Designing tailor-made sorbent materials

Integrating sorbent materials and processes

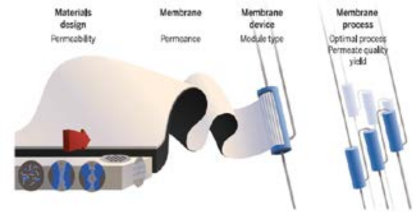


Membranes

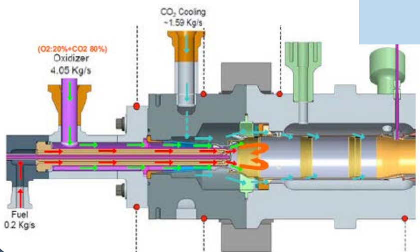


Understanding transport phenomena in membrane material

Designing membrane system architectures

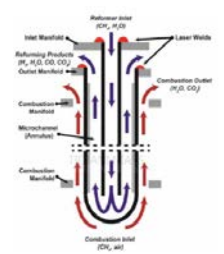


Combustion and Other Technologies



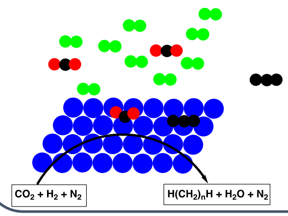
Catapulting combustion into the future

Producing hydrogen from fossil fuels with CO2 capture



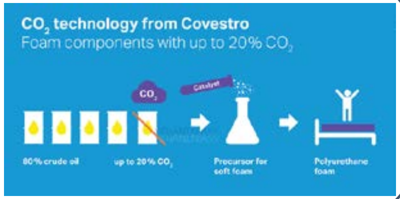
CO2 Utilization PRDs

Thermochemical Conversion and Hydrogenation of CO2

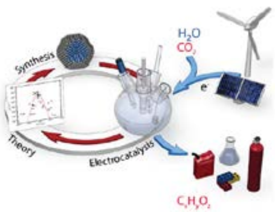


Valorizing CO2 by breakthrough catalytic transformations into fuels & chemicals

Creating new routes to carbon-based functional materials from CO2

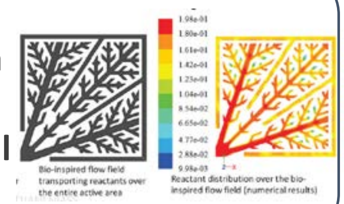


Electrochemical and Photochemical Conversion of CO2

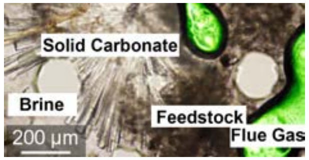


Designing and controlling molecular-scale interactions for electrochemical and photochemical conversion of CO2

Harnessing multiscale phenomena for high-performance electrochemical and photochemical transformation of CO2

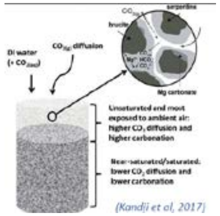


CO2 Conversion to Solid Carbonates

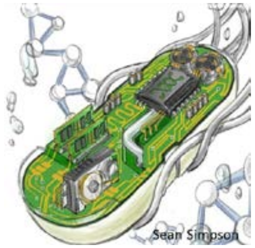


Accelerating carbon mineralization by harnessing the complexity of solid-liquid-gas interfaces

Tailoring material properties to enable carbon storage in products

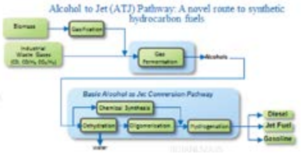


Biological Conversion of CO2



Tailoring microbial and bio-inspired approaches to CO2 conversion

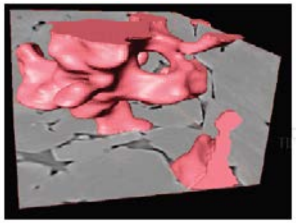
Hybridising electrochemical and biological processes for CO2 conversion to fuels, chemicals, and nutrients



Designing complex interfaces for enhancing hydrocarbon recovery with carbon storage

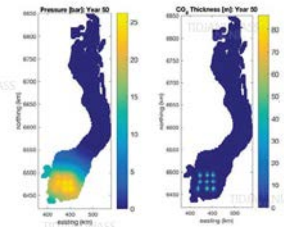
CO2 Storage PRDs

Injectivity & Capacity

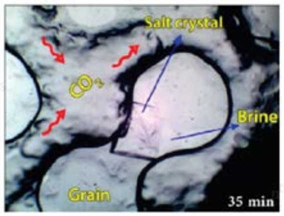


Advancing multi-physics and multi-scale fluid flow to achieve gigatonne/year capacity

Understanding dynamic pressure limits for gigatonne-scale CO2 injection

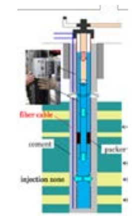


Monitoring, Verification and Performance Metrics

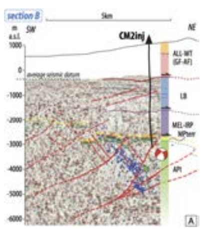


Optimizing injection of CO2 by control of the near-well environment

Developing smart convergence monitoring to demonstrate containment and enable storage site closure

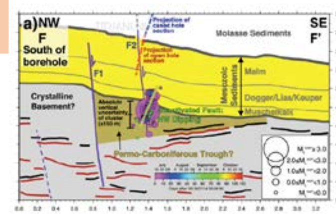


Forecasting and Managing Induced Seismicity



Realizing smart monitoring to assess anomalies and provide assurance

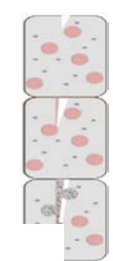
Improving characterization of fault and fracture systems



Well Diagnostics

Achieving next-generation seismic risk forecasting

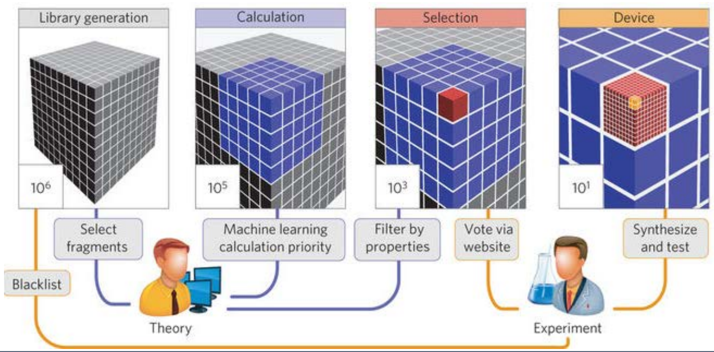
Locating, evaluating, and remediating existing and abandoned wells



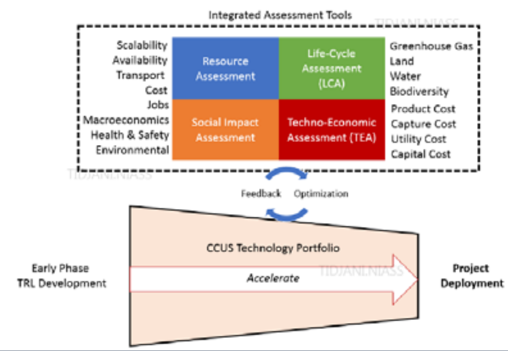
Establishing, demonstrating and forecasting well integrity

CCUS Crosscutting PRDs

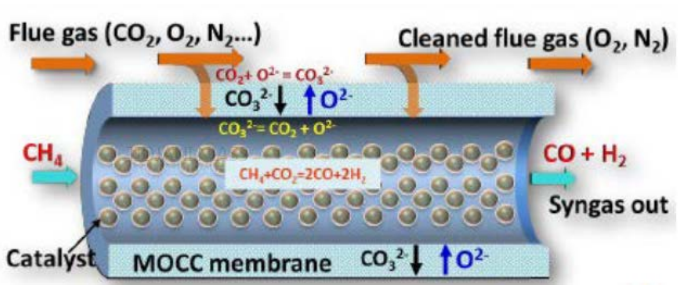
Integrating experiments, simulation, and machine learning across multiple length scales to guide materials discovery and process development in CCUS



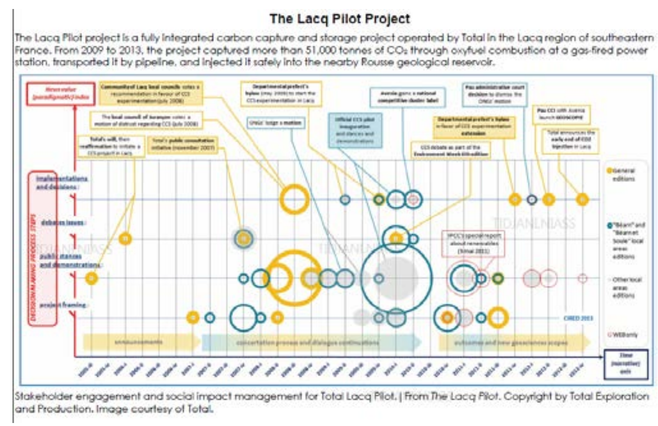
Developing tools to integrate life-cycle techno-economic, environmental and social considerations to guide technology portfolio optimisation



Coupling basic science and engineering for intensified carbon capture, purification, transport, utilisation and storage processes

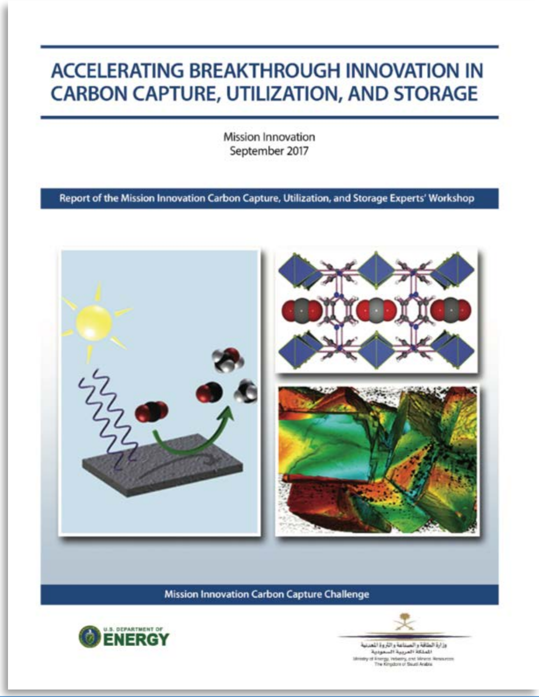


Incorporating social aspects into decision-making



CCUS Experts' Workshop Outcomes

- **Established current state of technology in CO2 Capture, CO2 Utilisation, and CO2 Storage**
- **Created an international consensus on the most critical scientific challenges on CO2 Capture, CO2 Utilisation, CO2 Storage, and Crosscutting CCUS topics**
- **Established internationally agreed Priority Research Directions (PRDs)**
- **Completed a report on CCUS Basic Research Needs**
  - **Intended to serve as a key resource for the international CCUS research community, governments, and the private sector, helping to inform national R&D policies and programs**
  - **The PRDs are not meant to be prescriptive and all-inclusive. Rather, they are designed to inspire CCUS research community to elucidate the foundational scientific phenomena that underpin CCUS**



“ACT” – An Approach to Collaboration

- **ACT (Accelerating CCUS Technologies) grant programme has 6 MI countries (France, Germany, Norway, The Netherlands, USA and UK) who have worked together to address the Workshop PRDs. Also includes non MI countries Spain, Turkey, Greece, Switzerland and Romania which gain exposure to MI**
- **Added PRDs to the call text of an existing programme**
- **Early indication that we will have some projects that will be addressing our Workshop PRDs**
- **Potential for more MI countries to join for the ACT3 call in 2020**
- **Find out at www.act-ccs.eu**

MISSION INNOVATION

Accelerating the Clean Energy Revolution

Thank You

from the MIC#3 Co-Leads

Tidjani Niass: Kingdom of Saudi Arabia

Nelson Nelson Mojarro Gonzalez: Mexico

Brian Allison: United Kingdom

Introduction to Topics

Topic 1: Decarbonizing industry sectors (power, cement, refineries, steel, fertilizers…) • Introductory speaker: Monica Garcia, IEAGHG

Topic 2: The role of CCS in enabling clean hydrogen • Introductory speaker: Sigmund Størset, SINTEF

Topic 3: Storage and CO2-networks • Introductory speaker: Phillip Ringrose, Equinor

Topic 4: Storage monitoring • Introductory speaker: Tip Meckel, Gulf Coast Carbon Center

Topic 5: Going climate positive (biomass, waste to-energy, resources and technology) • Introductory speaker: Niall MacDowell, Imperial College London

Topic 6: CO2 Utilization • Introductory speaker: Jaap Vente, TNO • "Success story" speaker: Mark Summers, Emissions Reduction Alberta (ERA)

Decarbonizing industry sectors (Power, cement, refineries, steel, fertilizers,…)

Monica Garcia Ortega
Technology Analyst, IEAGHG

Mission Innovation Challenge #3-CCUS

June 19-20th 2019, Trondheim (Norway)

Who are we?

Our internationally recognised name is the IEA Greenhouse Gas R&D Programme (IEAGHG). We are a Technology Collaboration Programme (TCP) and are a part of the International Energy Agency's (IEA's) Energy Technology Network.

Disclaimer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Evaluating technology options to mitigate greenhouse gas emissions
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جامعة خليفة
Khalifa University
JGC
RWE
The energy to lead

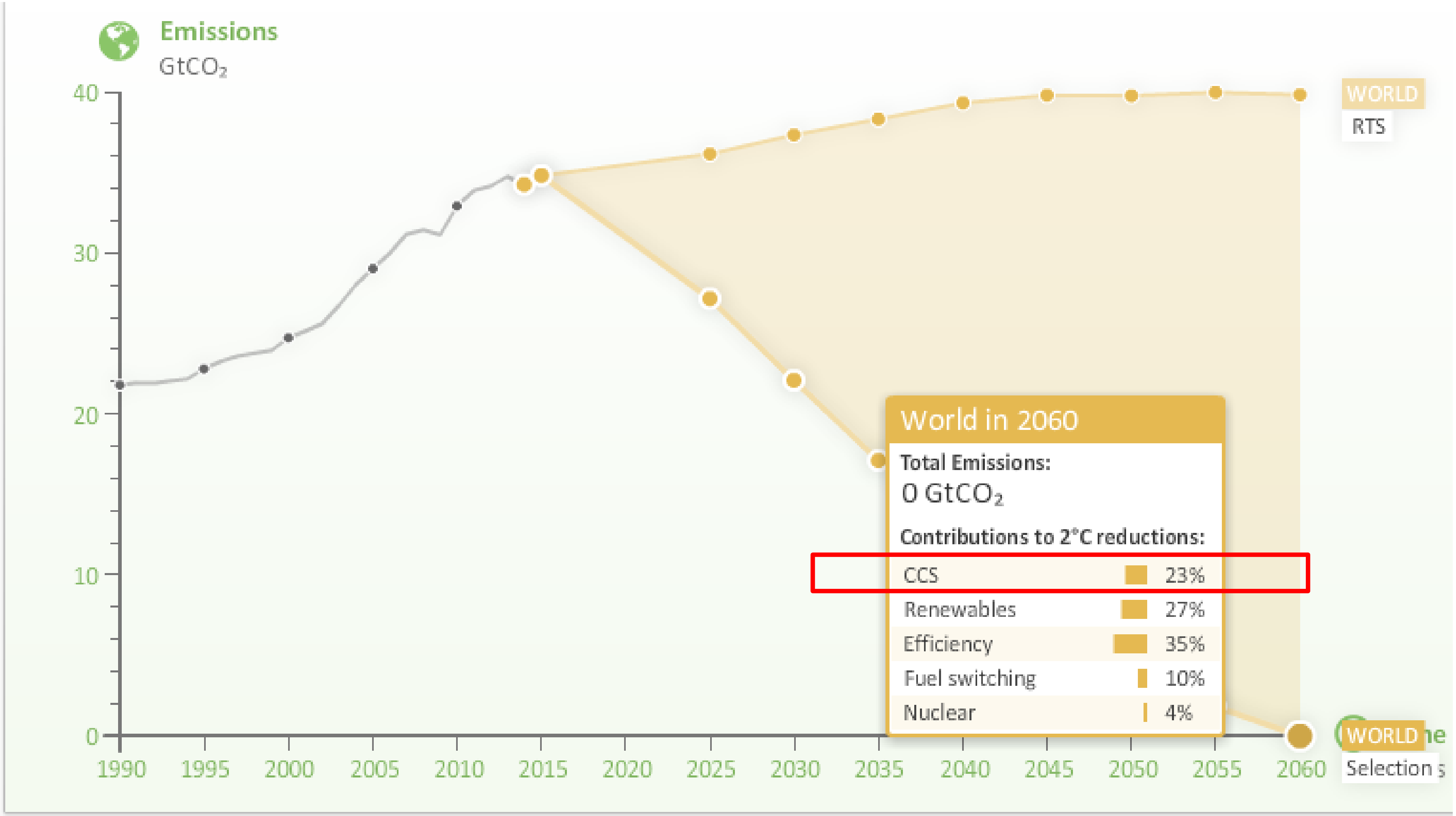
Potential Role of Industrial CCUS-power

- CCUS can bring flexibility to the electricity grid (Flexeval). Important to see the System Value (SV)
- Incorporating CCS to the power sector is a cheaper solution in the long run

Potential Role of Industrial CCUS-production industries

- Industries are essential on the economy. Expected to grow mainly in countries on development. Perhaps global market
- Industrial CO_2 emissions must be reduced by 50% in 2050 in the 2DS and more than 70% in the B2DS.
- Non-CCS options are important, perhaps will not supply the reduction fast and large enough to solve the climate change matters. Some industries CANNOT be decarbonised without CCUS (process emissions)

Potential Role of Industrial CCUS

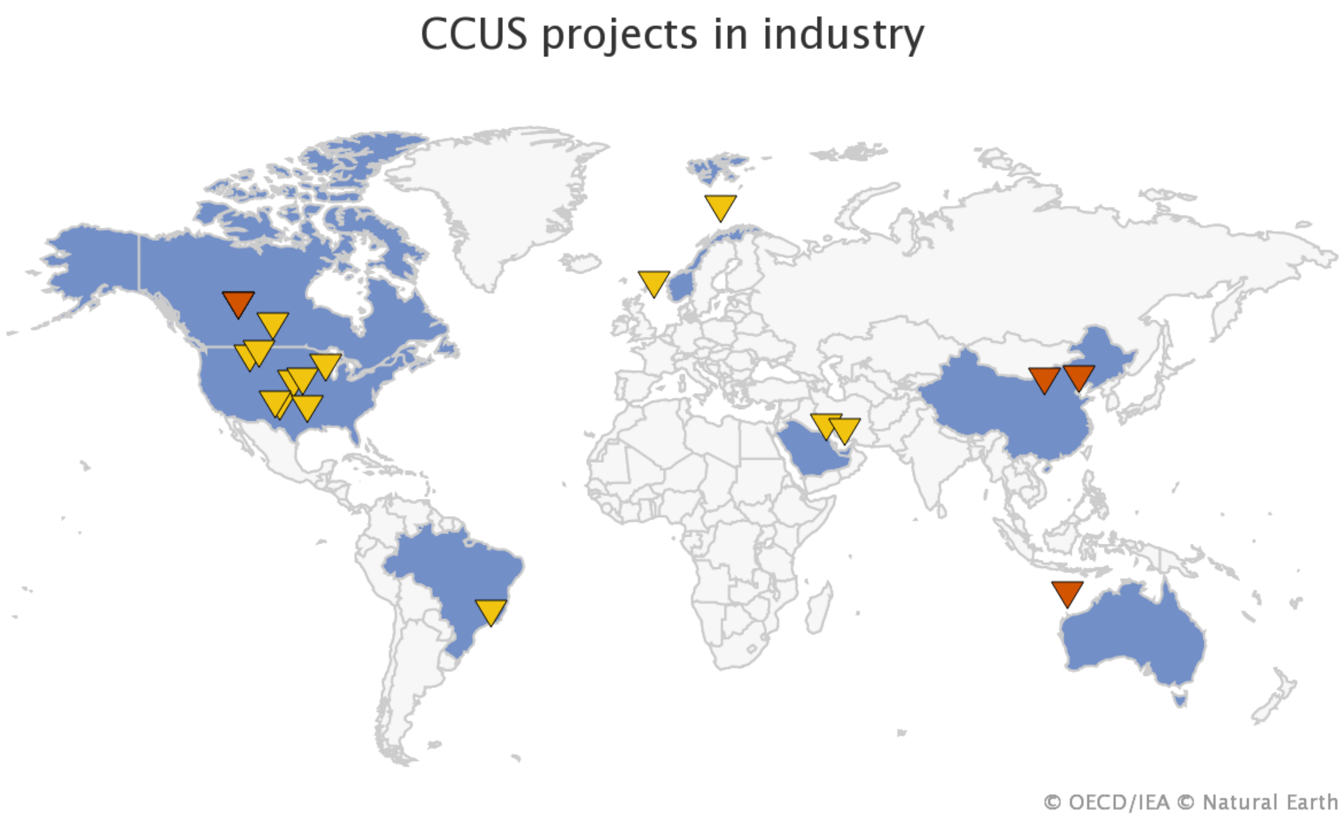


Emissions in the RTS and B2DS. Source: IEA ETP website (visited in May 2019)

Potential Role of Industrial CCUS- Power

- Large projects: Boundary Dam (Cansolv), Petranova (KM-CDR), Shand (planned, KM-CDR). It works!
- IEAGHG update on emerging technologies TRL: chemical absorption is still leading (with updated benchmark solution), 2nd generation will not wait for others. Potential for fuel cells, membranes. More research in others

Potential Role of Industrial CCUS- Production industries



Industrial CCUS projects in construction (red) and running (yellow). Source: IEA website (last update on 2018)

Potential Role of Industrial CCUS

- Industries: steel, cement, chemicals, refining, hydrogen, natural gas, heavy oil, fertilizers, waste to energy. Interaction
- Aiming to transfer the experience from the power sector (to note TRL is not the same!). Traditional chemical absorption is the "less risky", perhaps specific industries can have advantages for others and/or traces
- IEA perspective: out of track to reach decarbonisation objectives

Status- Progress

- Industries have a good potential for partial CO_2 capture. Opportunity for integration and cost reduction
- Cement
  - Several CO_2 capture technologies tested
  - Norcem, LEILAC (TRL 7ish), ECRA?
  - Others (TRL 7ish): CLEANKER, CEMCAP (TRL4)

Norcem facilities (Norway)

Status- Progress

- Steel
  - Heterogeneity in production process. Several CO_2 stacks, several technologies
  - Abu Dhabi (DRI, TRL 9ish). H_2 potential
  - STEPWISE (BF+BOF, TRL 7ish), COURSE50

Al Reyadah facilities (Abu Dhabi)

Status- Progress

- Waste-to-energy
  - Japan, Norway and Netherlands projects, all based in chemical absorption
  - Seasonal integration with district heating, heat integration with the facility
- Refining (familiar)
  - Interaction with H_2
  - Chemical absorption on stacks (Finland), oxy-firing in burners, pre-combustion on the gasifiers.
  - RECAP, suggesting non-steam technologies

Status- Progress

- Hydrogen
  - Low carbon electricity+CCS
  - Air Products' Port Arthur, Tomakomai, Air liquid (SMR)
  - Chemical/physical absorption, sorbents, PSA, membranes
- Fertilizers
  - 2 plants in USA, Yara (cancelled): opportunity of using ammonia
  - Linked to chemicals, H_2 (SMR, POX)

Yara facilities (Norway)

Status- Progress

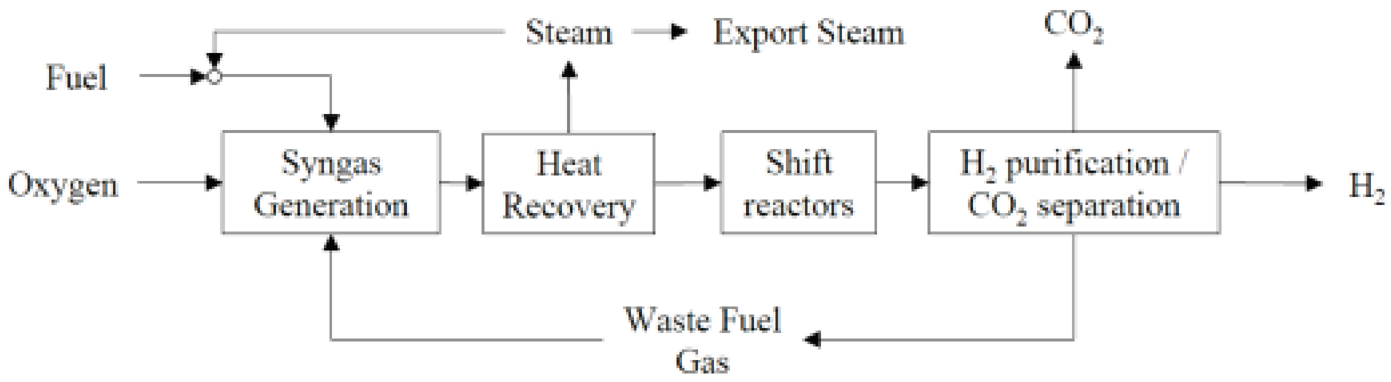
- Chemicals
  - Heterogeneous sector
- Natural Gas
  - Sleipner and Snohvit, Terrl , Shute Creek, Century Plant, Salah, Gorgon.
  - Commonly sorbents, CCUS
- Heavy oil
  - Linked to H_2
  - Diluted CO_2

Key research and innovation challenges

- Identified areas of research in the previous report :
  - C1-solvents
  - C2-sorbents
  - C3-membranes
  - Targeted application: industrial sector
  - Hydrogen

Key research and innovation challenges

- Hydrogen: PRD C-8, linked to CO_2 capture technologies challenges
  - Gasification challenges (high TRL)
  - Reforming with O_2 via high-temperature membranes and integrated with H_2 production
  - Combustion and reforming: microchannel reactors
  - Challenges related to operation , turbines, flames



Key research and innovation challenges

- Development of CO_2 capture technologies as for the power sector. Some are still at low TRL. Explore opportunities (higher CO_2 concentration, partial capture, energy/heat integration)
- To make the difference between power and industrial sectors
- Increase CCUS deployment

Steps towards, closing gaps for deployment and industrial opportunities

- Thera are many challenges for the deployment of industrial CCUS, but those can be successfully addressed to enable a decarbonised industry (BEIS, 2018)

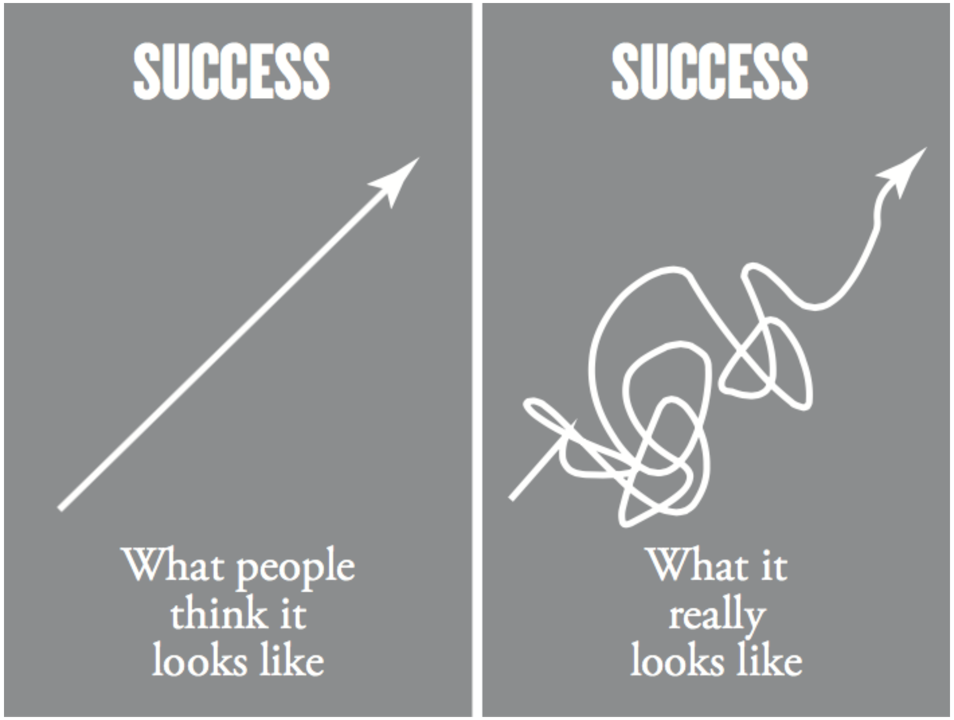


Image from:
https://leanb2bbook.com/blog/the-real-odds-of-success-for-b2b-entrepreneurs/

Relevant documents

- CSLF Task Force for Large Emitting Industries (Technical Group)
- IEAGHG studies
- *Industrial carbon capture business models*, BEIS (October, 2018)

Questions?

monica.garcia@ieaghg.org

SINTEF

THE ROLE OF CCS IN ENABLING CLEAN HYDROGEN

Sigmund Ø. Størset, SINTEF

Mission Innovation Workshop,

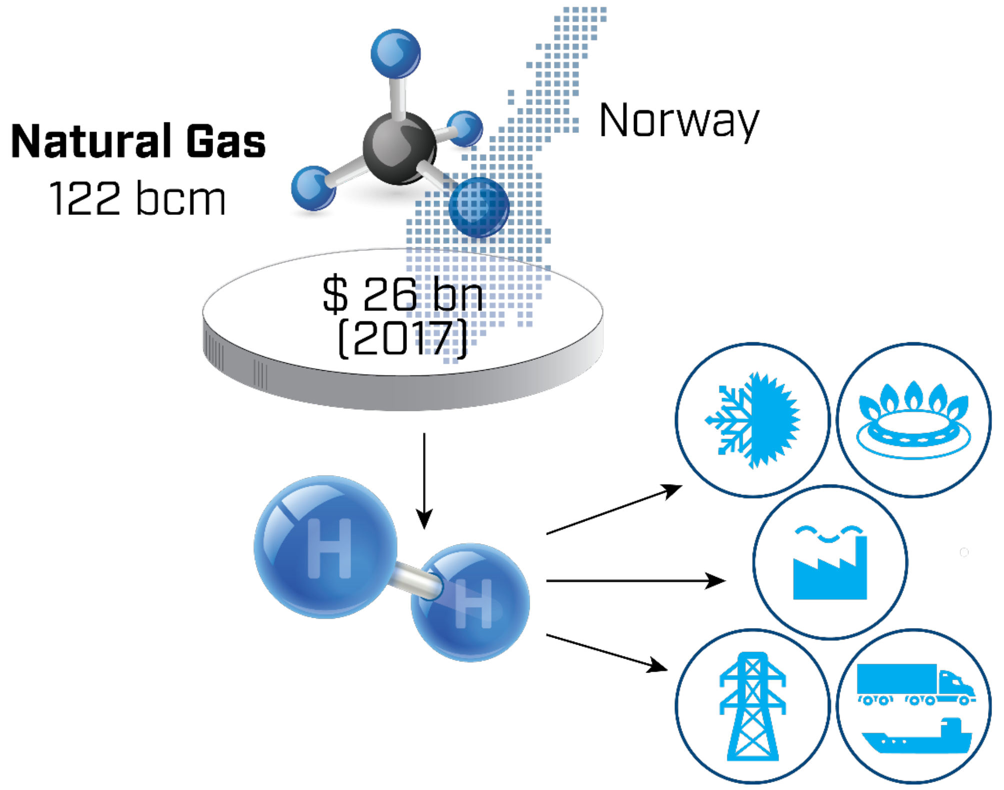
June 19th 2019


1. Security of supply
ENERGY
2. Cost
3. Environmental footprint
NTNU
SINTEF
CO_2
H_2

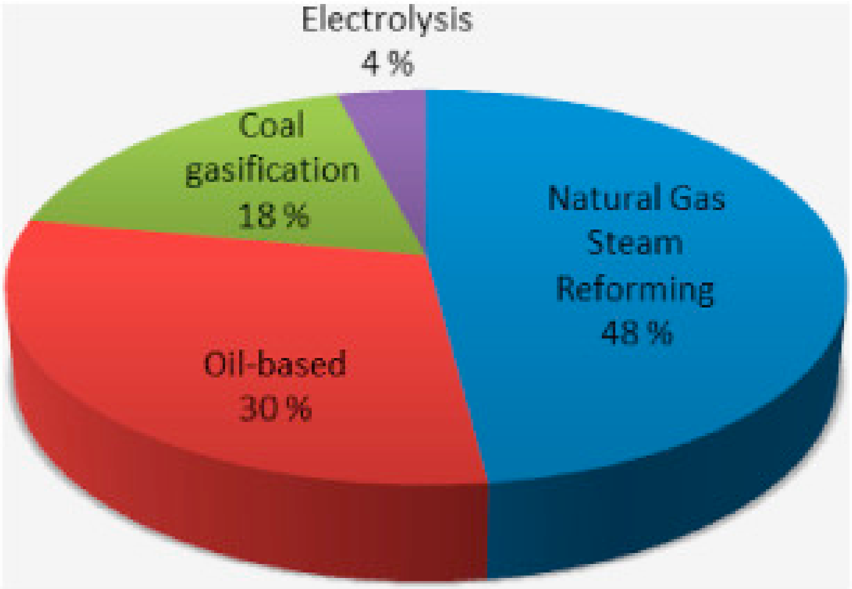
Where can we use hydrogen?

A true cross sectorial enabler – in hard to decarbonise sectors

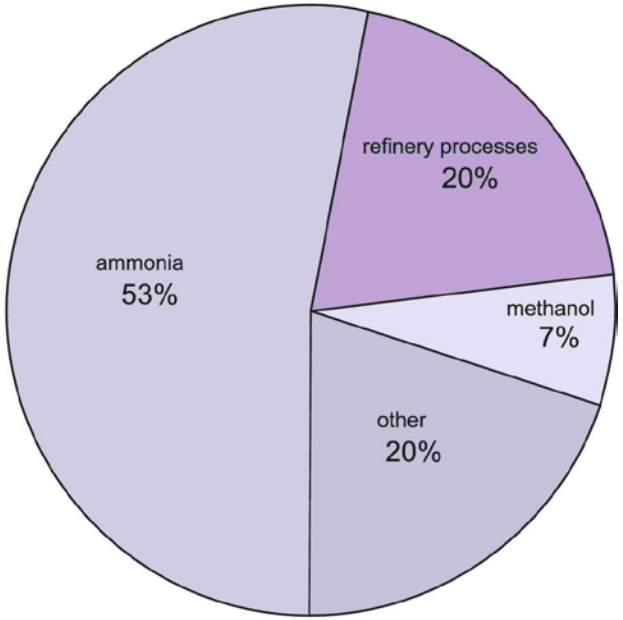
- Industry
- Heating/cooling/cooking
- Power- also zero emission backup for intermittent power
- Transportation- land, rail – possibly aviation-hybrid, marine
- Energy storage- on longer timescales



Hydrogen by source and consumption



Source: International Journal of Hydrogen Energy, Voldsund et al.



Source: The essential chamical industry - online

Global annual production: ~65M metric tons / ~2200 TWh

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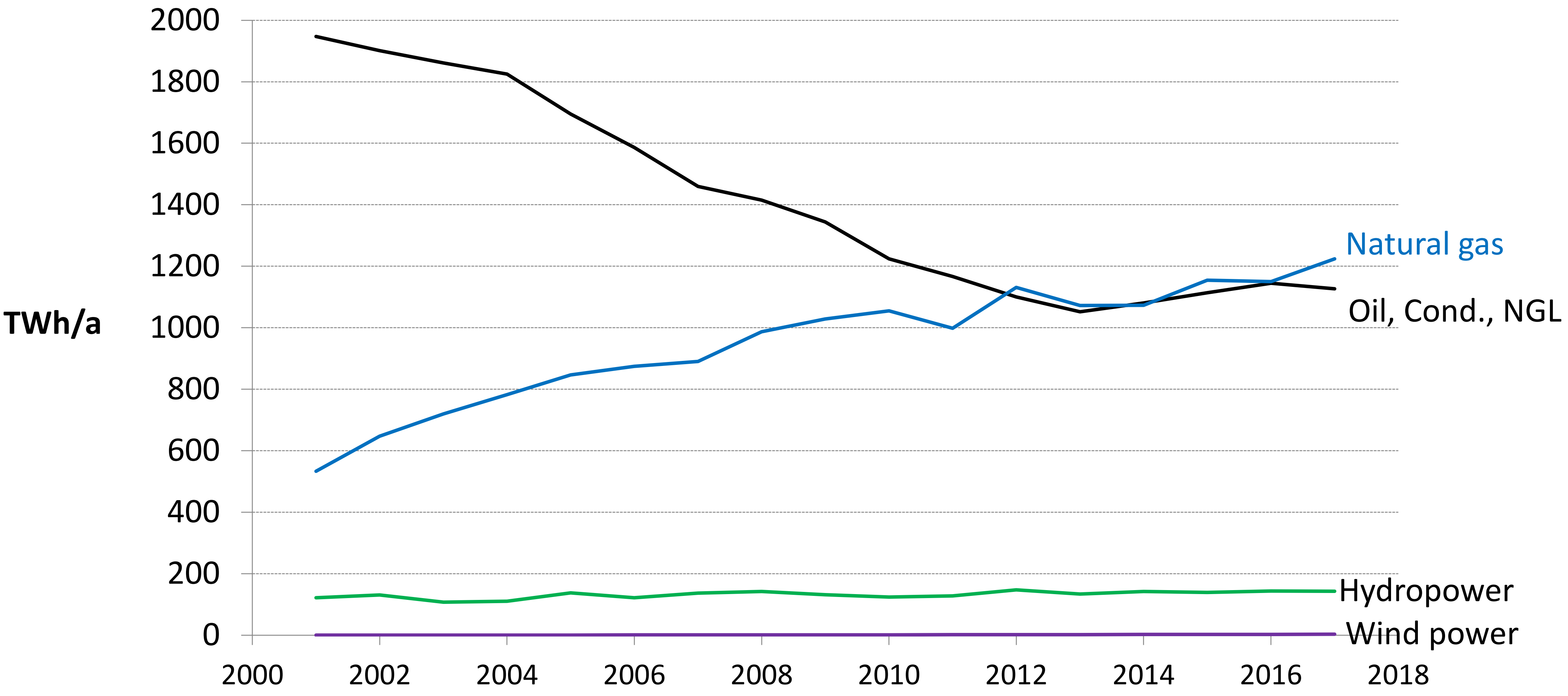
Norway: Renewable power and fossil energy



A thought example from Norway

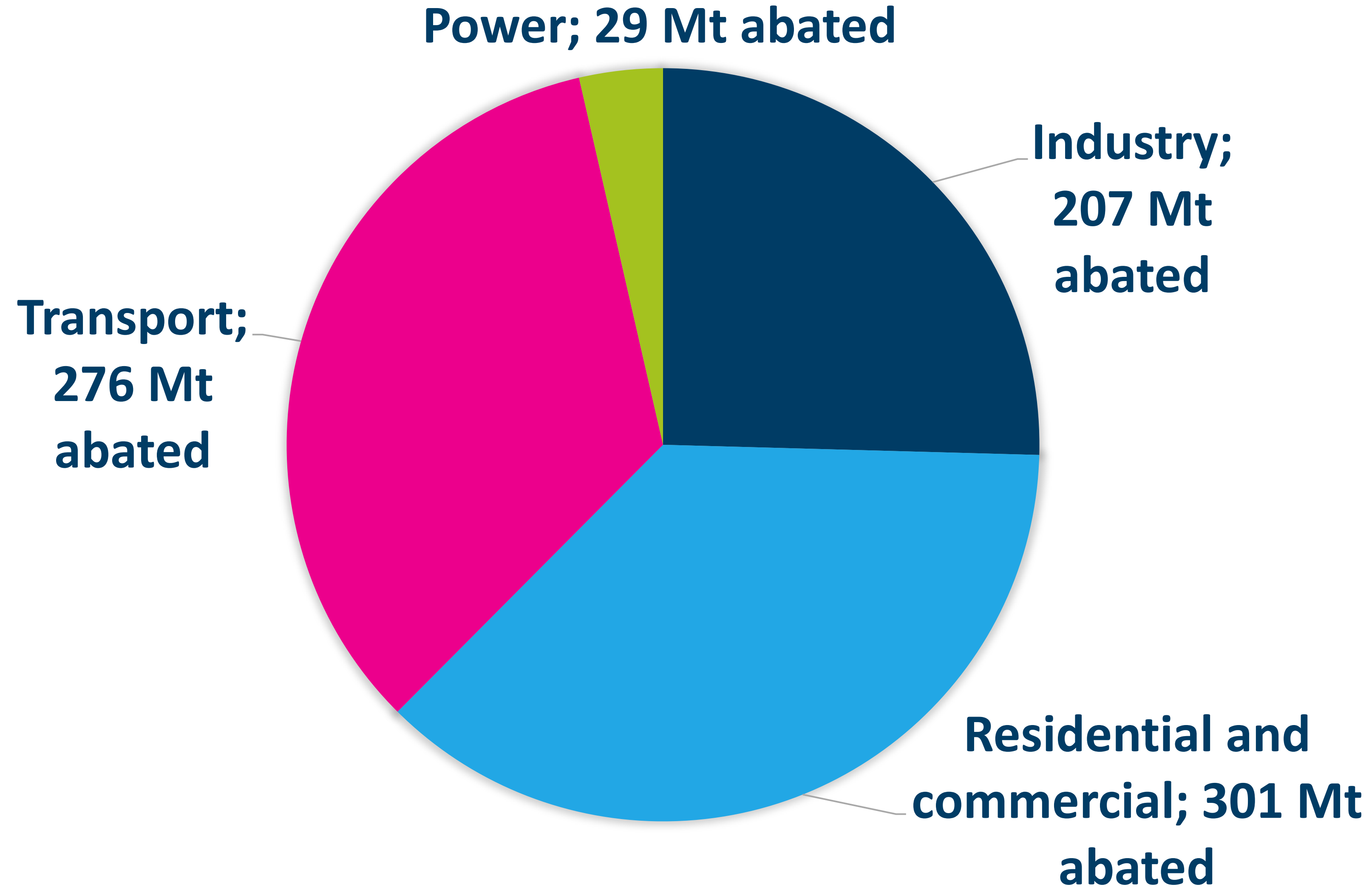
Norway's natural gas production 1400 TWh/a

→ 14% -> 200 TWh/a NG → 137 TWh/a LH_2

↓ 33,8 Mton CO_2/year storage

↓ One 160.000 m^3 ship/day

Almost 20% of current European CO_2 emissions can be abated by clean hydrogen in 2050



SINTEF
ifp Energies nouvelles

Key research challanges
- for closing the gap

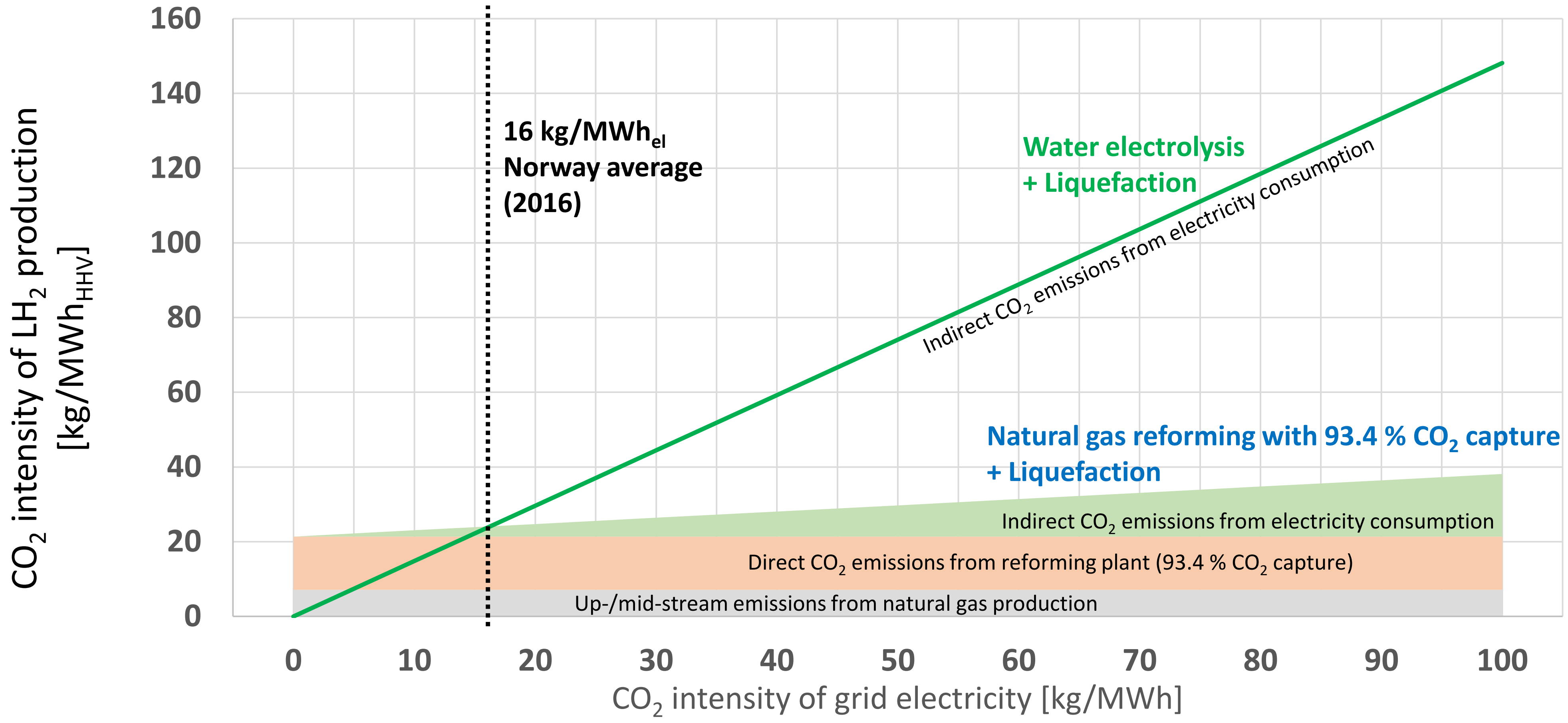
- Reforming and capture with (near) zero emissions
- Gigawatt scale transport and storage of hydrogen:
  - Compressed and liquefied
- Industrial use of hydrogen:
  - As reducing agent
  - For heating
- Whole system perspective:
  - Energy systems and value chains
  - $LH_2 – CH_2 – NH_3$

Hydrogen from natural gas with CCS is an opportunity for Europe.

Mythbusting: "Blue hydrogen" vs. "Green hydrogen"

Post-commissioning CO_2-eqivalent emissions:

CO_2-intensity of hydrogen from electrolysis vs. from autothermal reforming with 93.4 % CO_2 capture intersect at approximately 16 gCO_2/kWh_{el}



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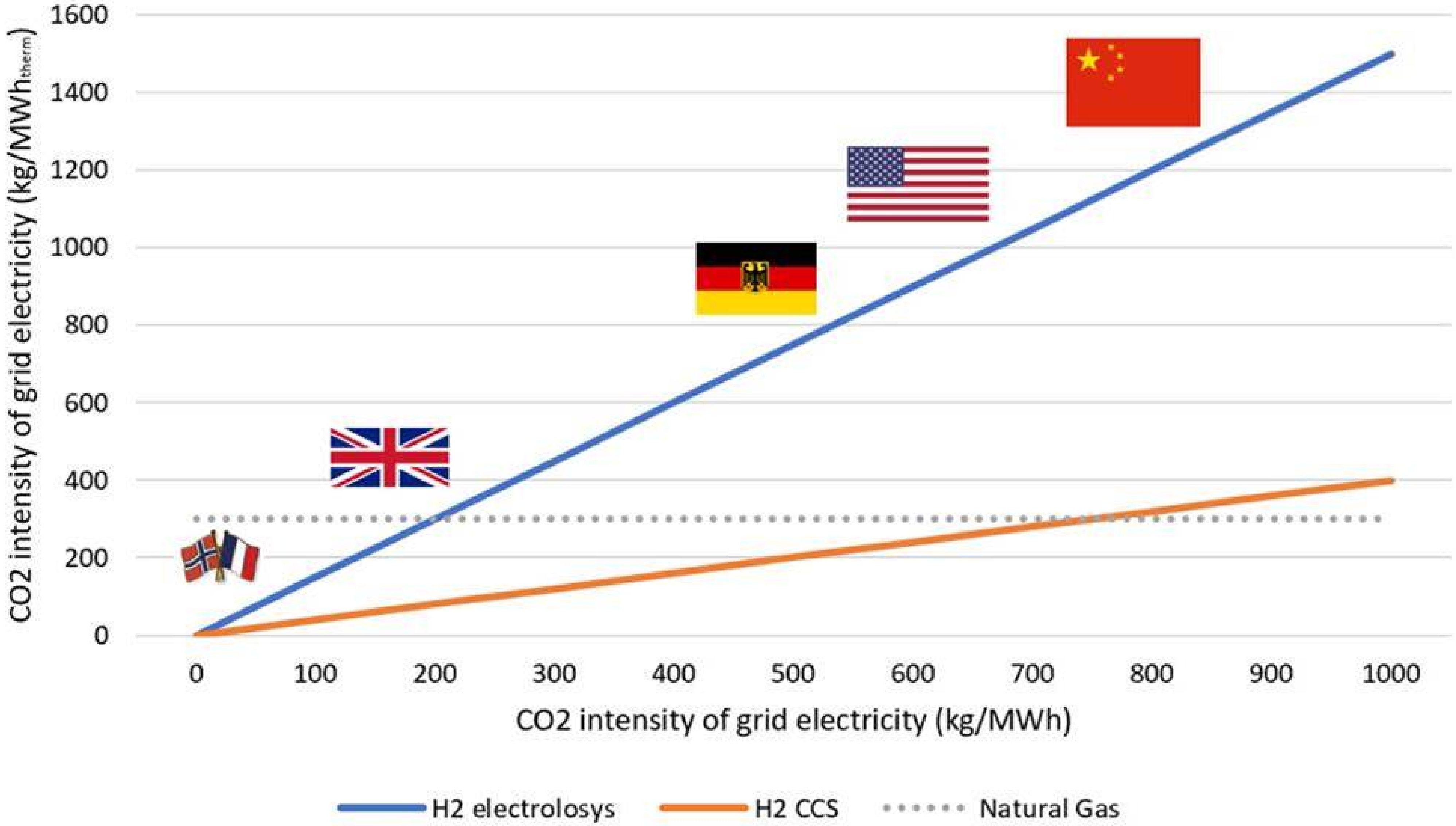
CO2 grid intensity for different countries (Bellona)



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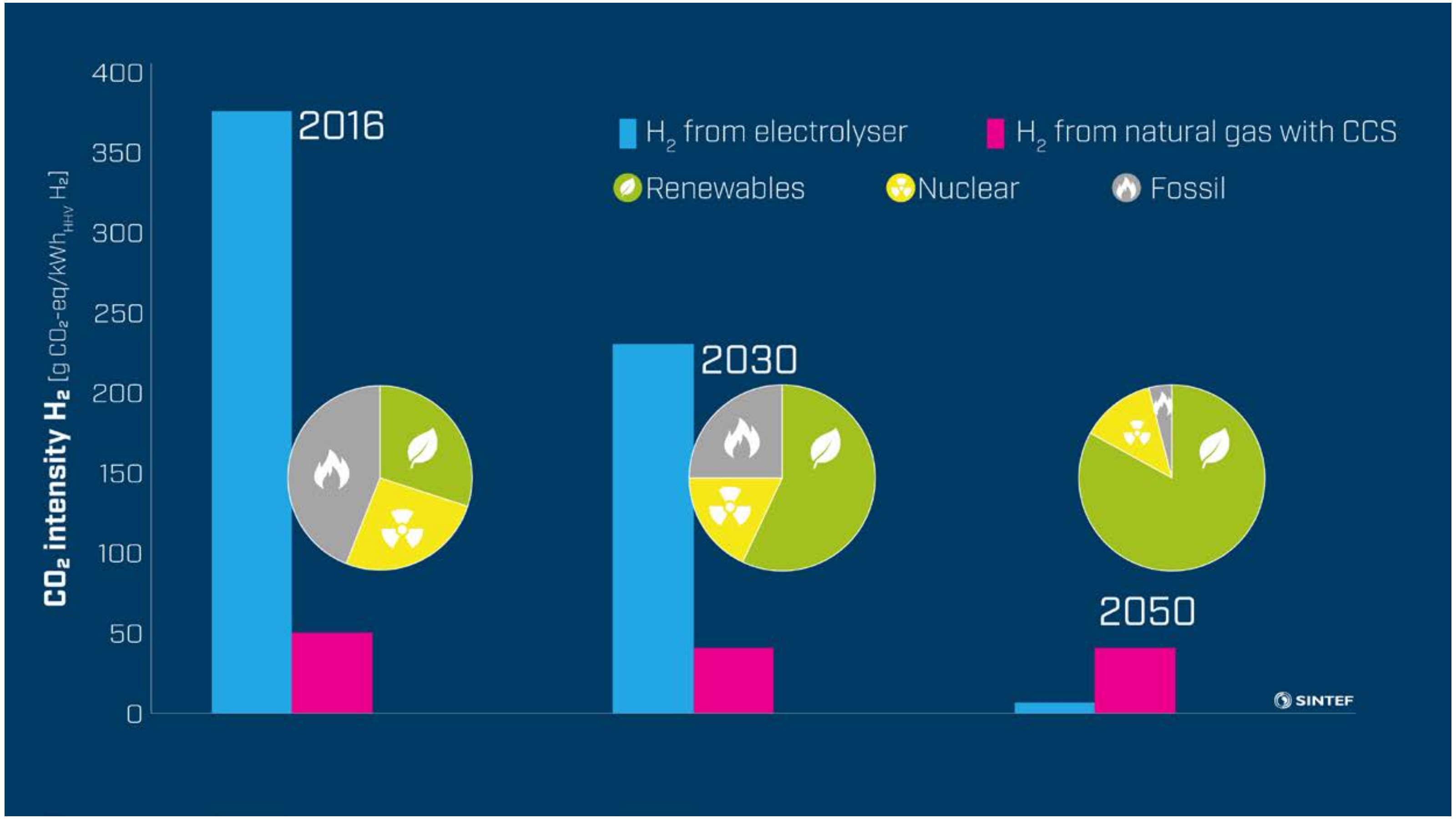
Hydrogen produced from natural gas with CCS will have lower GHG emissions than hydrogen from electricity in the EU grid for decades



- Comparison of greenhouse gas emissions related to production of hydrogen from
  - European grid electricity via electrolysers
  - Natural gas with carbon capture
- Hydrogen production from natural gas using autothermal reformers with 93 % (2016) to 96 % (2030 - 2050) CO_2 capture ratio
- European grid electricity mix shown in the pie-chart – forecasts based upon the IRENA REmap case for 2030 and the decarbonised scenarios from "A Clean Planet for All" for 2050
- Without deep decarbonization of the European power generation, emissions from production of hydrogen from dedicated renewably based electricity must account for potentially reduced emission reductions of the power sector

SINTEF

ifp Energies nouvelles

SINTEF, April 2018

Hydrogen

from natural gas with CCS could generate

NOK 220 billion annually in 2050

25,000 – 35,000 jobs

SINTEF

From the SINTEF report:
Industrielle muligheter og arbeidsplasser ved CO_2-håndtering i Norge

SINTEF

Teknologi for et bedre samfunn

Mission Innovation workshop
Trondheim, June 19-20

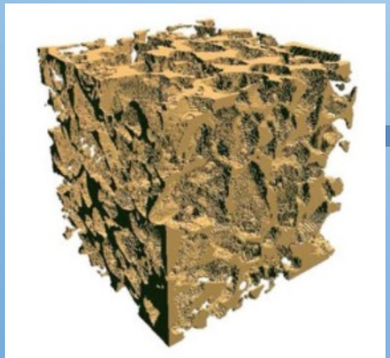
Session 3 – Storage and CO_2 networks

Introduction – Philip Ringrose, Equinor & NTNU

What we focused on in the 2017 MI Workshop

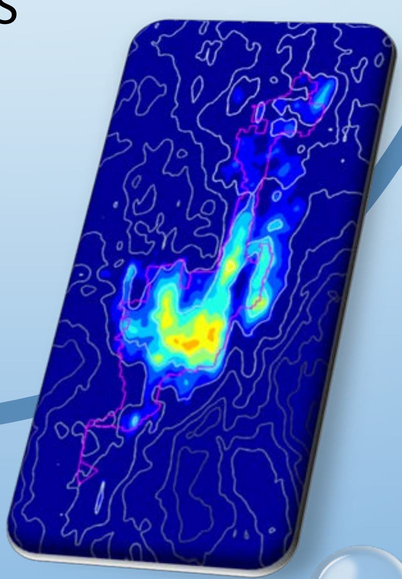
- Sequestration has to get to gigatonne (Gt) per year scale to meet global CO_2 emissions reductions targets.
- We know how to do 1Mt per year projects (e.g. Sleipner)
- We have sufficient capacity for Gt storage (in theory)
- BUT …
  - Many technical challenges need to be addressed
  - The world's nations must want to do CCS

Vison and road-map for scale-up from Mission Innovation CCUS



Pore scale:
nano to dm scale

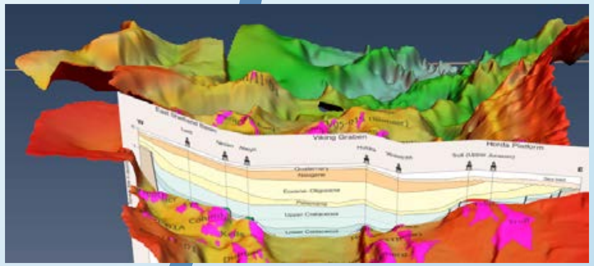
HPC:
10^{7-9} voxel models
Highly parallelized



Field scale:
dm to km scale

HPC:
10^{7-8} cell models
100's-1000's CPUs
Uncertainty handling via multiple realizations

Basin scale:
10s – 100s km

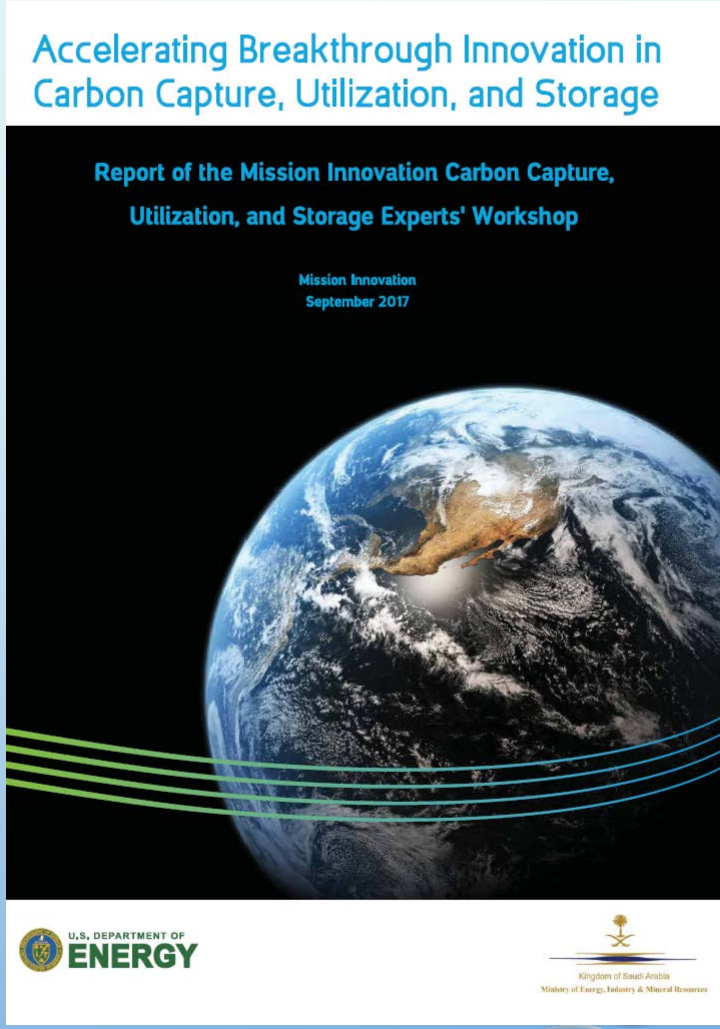


HPC:
10^{8-10} voxels
Multi-models/datasets
Parallelized

Topics covered in the 2017 MI Workshop

Focus Area 3: CO_2 storage - Co-Chair Don DePaolo (USA)

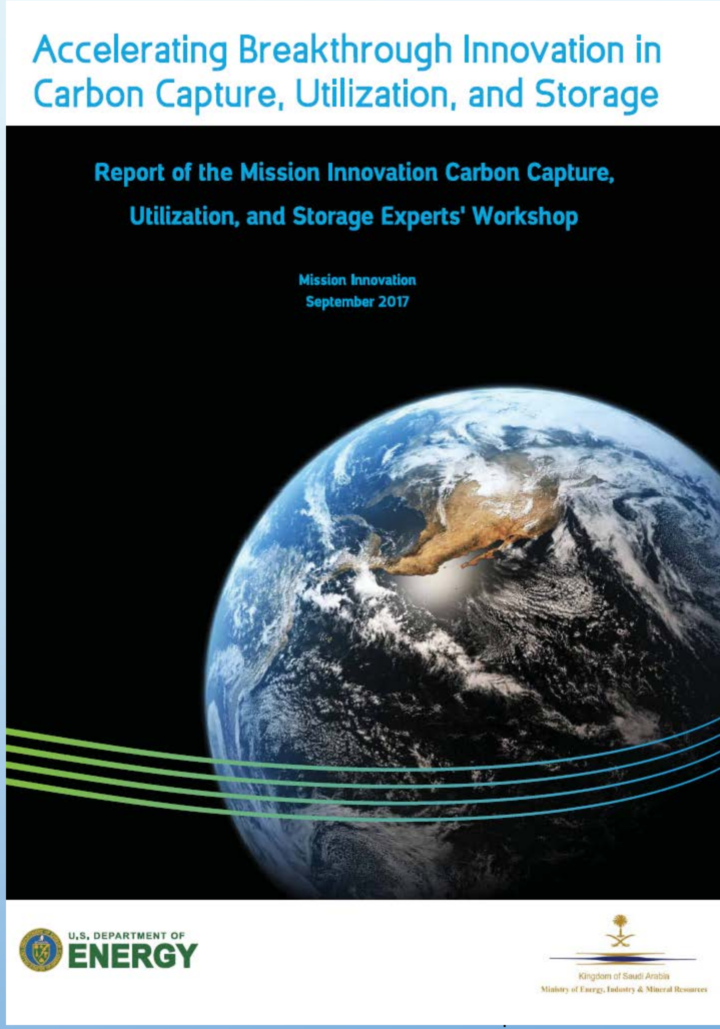
- **Panel S1: Injectivity and Capacity**
  Panel Leads: Philip Ringrose (NOR) and Curt Oldenburg (USA)
- **Panel S2: Monitoring, Verification and Performance Metrics**
  Panel Leads: Ziqiui Xue (JPN) and Jonathan Pearce (UK)
- **Panel S3: Forecasting and Managing Induced Seismicity**
  Panel Leads: Hideo Aochi (FRA) and David Eaton (CAN)
- **Panel S4: Well Diagnostics**
  Panel Leads: Franz May (GER) and Rick Chalaturnyk (CAN)



PRDs identified for CO_2 storage

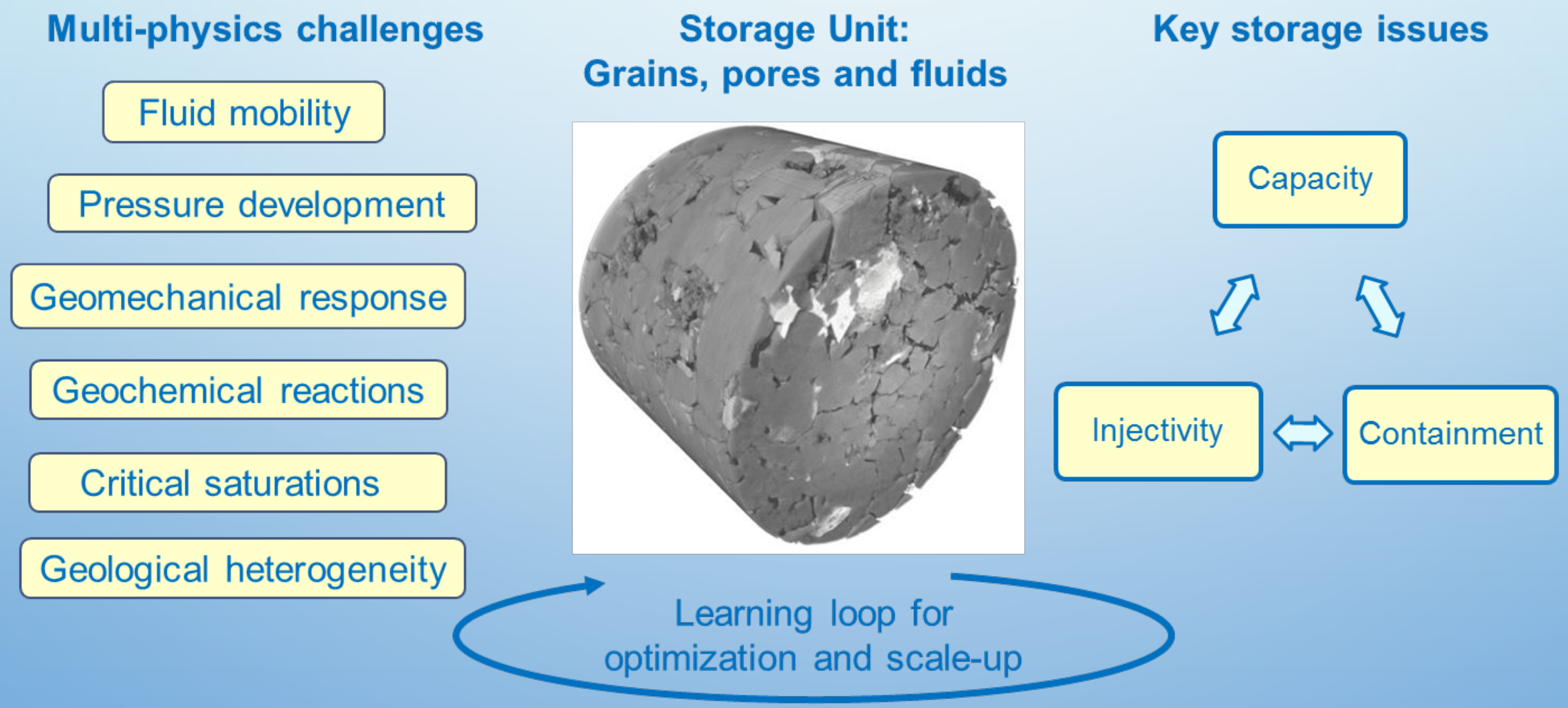
Nine ‘Principle Research Directions’ (PRDs) were identified

1. Advancing multiphysics and **multiscale fluid flow** to achieve gigatonne/year capacity
2. Understanding **dynamic pressure limits** for gigatonne-scale CO_2 injection
3. Optimizing injection of CO_2 by **control of the near-well environment**
4. Developing **smart convergence monitoring** to demonstrate containment and enable storage site closure
5. Realizing smart monitoring to **assess anomalies** and provide assurance
6. Improving characterization of **fault and fracture systems**
7. Achieving next-generation **seismic risk** forecasting
8. Locating, evaluating, and remediating existing and **abandoned wells**
9. Establishing, demonstrating and forecasting **well integrity**



Some reflections on technology for maturing Gt storage - 1

- Many ongoing R&D projects on CO2-brine flow properties, geomechanics and pressure modelling
- But **how do we transfer these learnings to emerging storage project developments**?

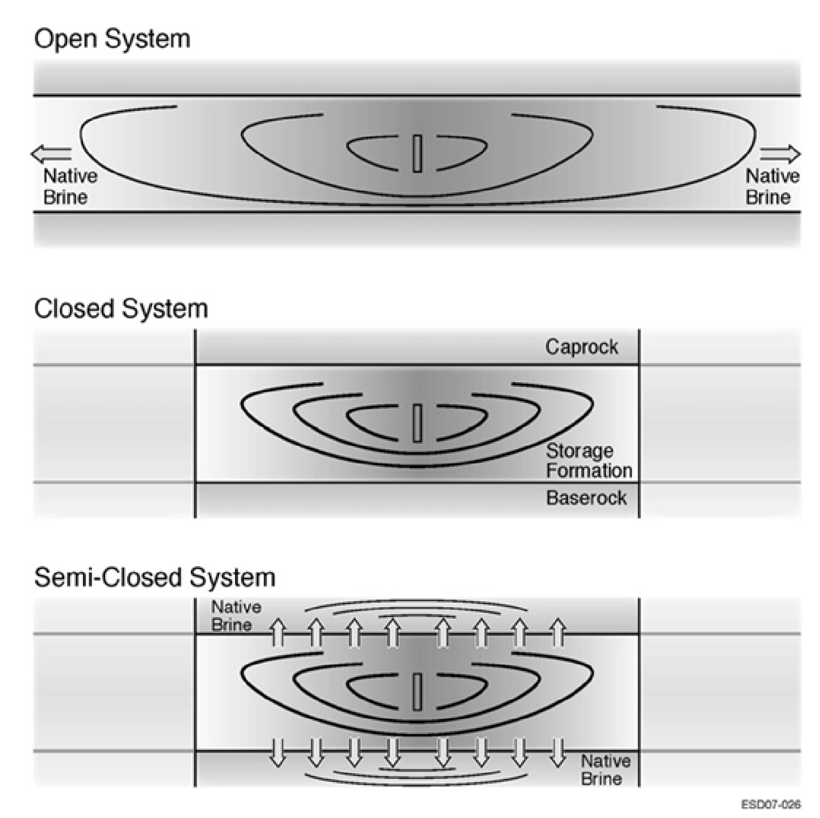


Overview of CO2 storage challenges (Core image courtesy of Sam Krevor, Imperial College London; Lai et al., 2015).

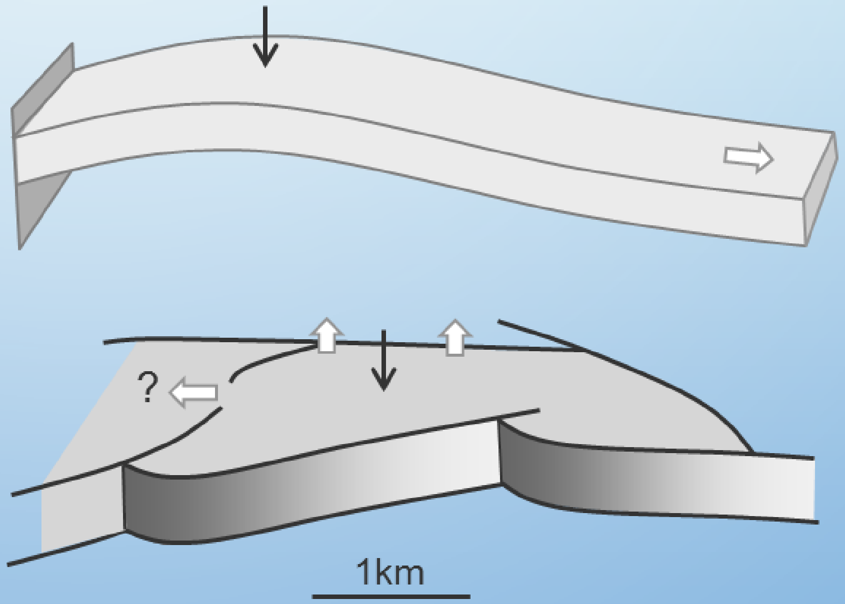
Some reflections on technology for maturing Gt storage - 2

- Much discussion and speculation on practical limits to capacity – especially pressure limits
- But **how do we turn concerns into carefully evaluated capacity estimates for projects**?

a)



b)

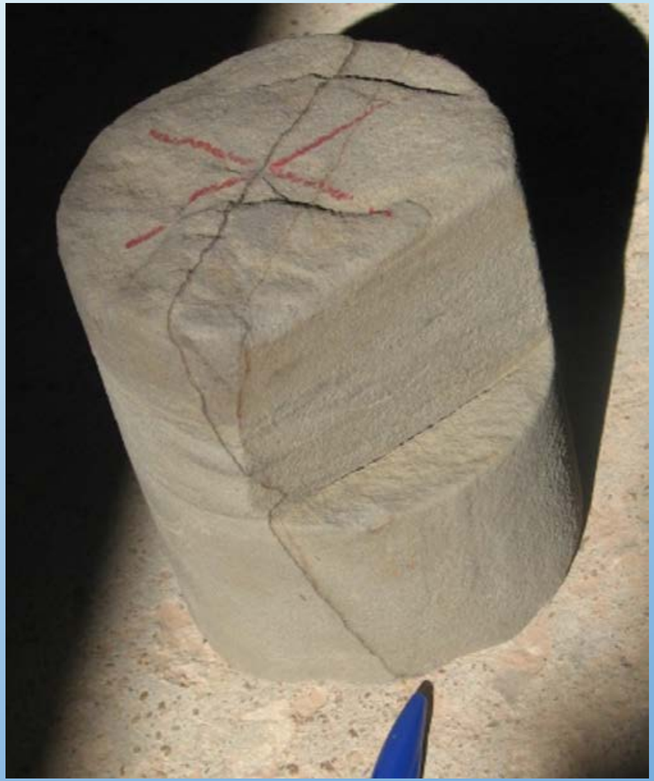


(a) Open, closed, or semi-closed systems [Image from Zhou et al. 2008]   (b) Typical 3D geometries of semi-open and semi-closed geologic storage systems.

Some reflections on technology for maturing Gt storage - 3

- Many ongoing R&D projects on monitoring systems, geomechanics/seismicity, well integrity
- But **how do we turn concerns into acceptable risks for managed projects**?

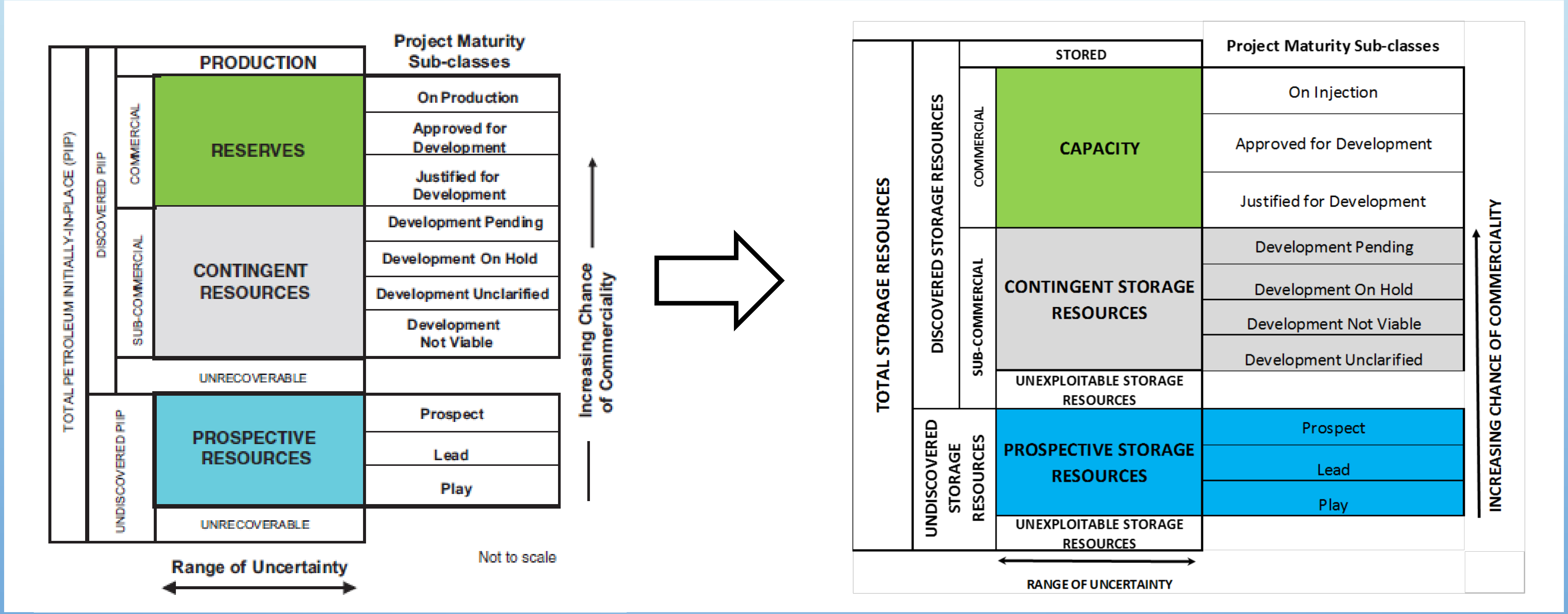
Sub-sea injection monitoring systems (Image from Equinor)



Core analysis

Finding a system for maturing storage resources

- SRMS (storage resource management system) is a framework for resource reporting derived from long established Petroleum Resources system (SPE)
- ALIGN CCUS project has proposed a practical approach to maturing CO_2 Storage Readiness Levels (SRLs)



Finding ways to manage storage project risks

1. Public perception risks
   - Needs effective communication strategy
2. Market failure risks
   - Significant and hard to handle
3. Site performance risks
   - Good track record, technically manageable

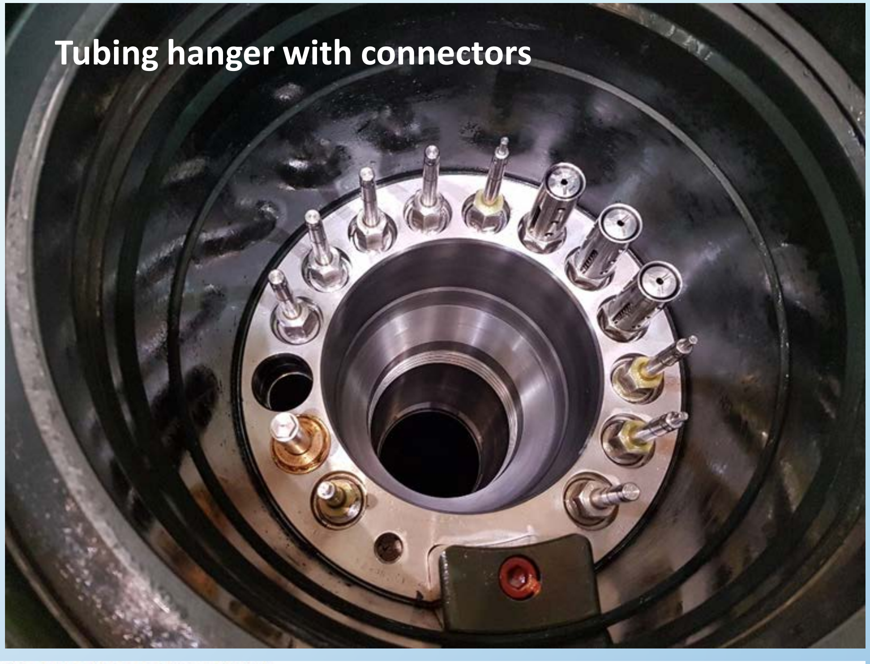
Climate and surface risks

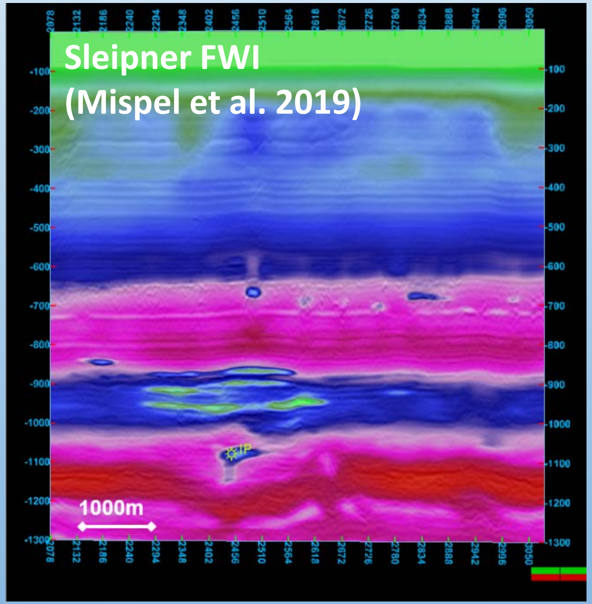
Subsurface risks

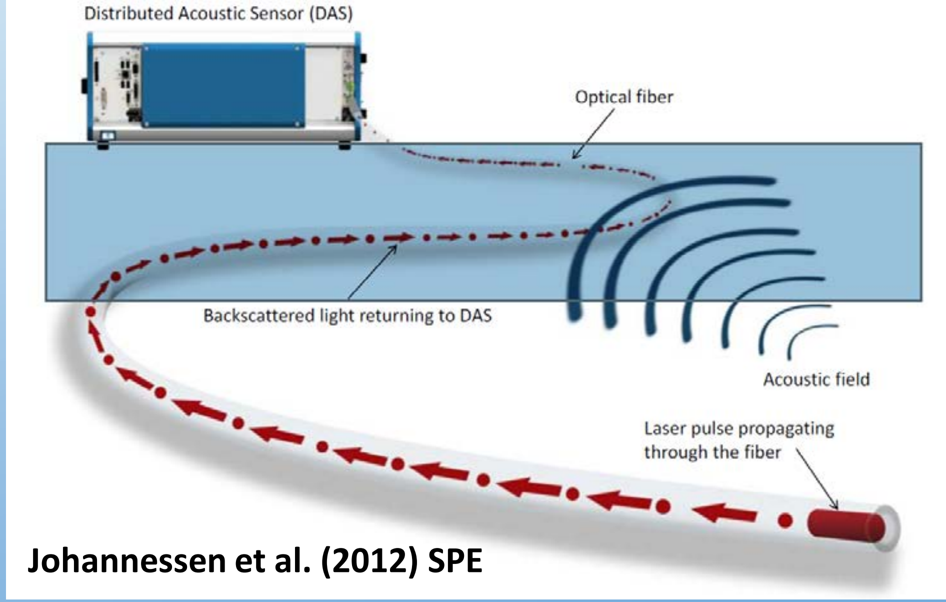
Bow-tie risk assessment methodology is applied to most projects now

Using digitization to build confidence?

1. Continuous monitoring of injection wells and injection sites using fiber-optic sensing
2. Monitoring the overburden and the reservoir using advanced seismic imaging (FWI, FO-VSP, passive sensing)
3. Cost effective environmental surveys
4. 'Can-do' attitudes
5. Using HPC power







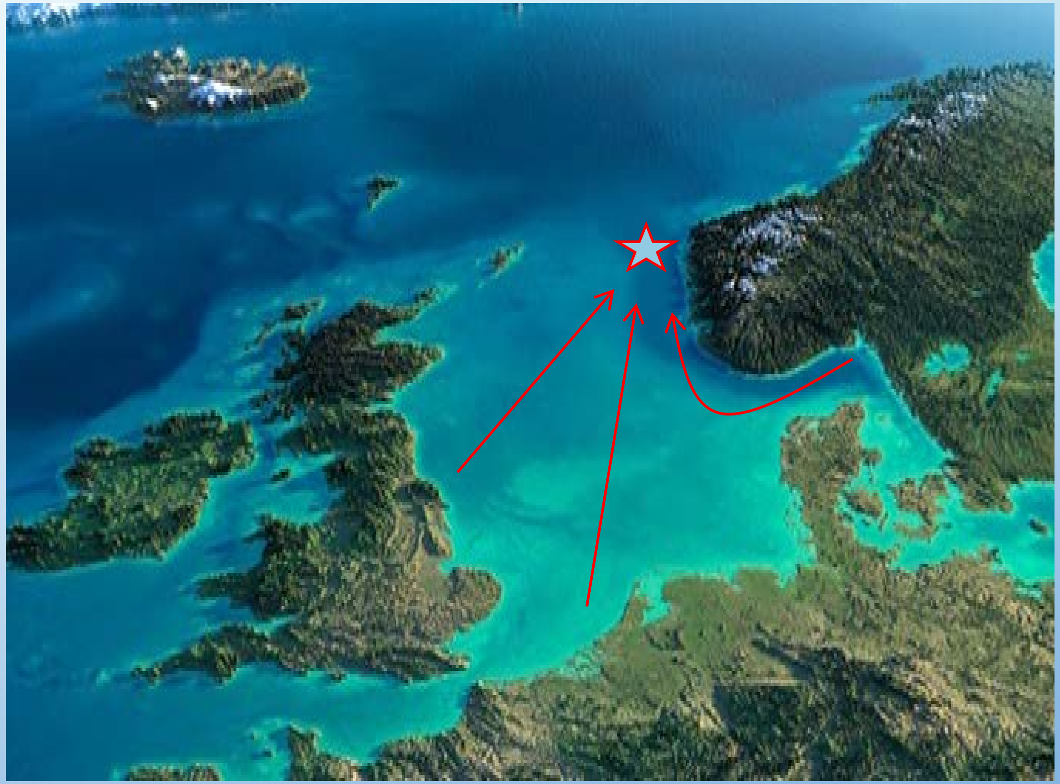
CCS hubs – strength from collaboration

- Northern Lights ‘open-source storage’ has already been an effective catalyst for CCS in Europe
- But we need more efforts on working together on integrated common solutions for CCS

CO2 storage hubs:

- Reduces risk and threshold for others
- Enables additional CO_2 storage

- Allows stepwise development of CCS from more regional hubs



- Norway CCS hub:
  Catalyst for roll-out of CCS in Europe?

Summary of challenges

1. How do we **transfer learnings** from 'R&D in the lab' to emerging storage project developments?
2. How do we turn **concerns about capacity** into carefully evaluated estimates for projects?
3. How do we turn **concerns about storage risks** into acceptable project management plans?
4. How do we **use the digital revolution** to build confidence in CO_2 storage as a public good / climate mitigation action?
5. How do we use **CCS hubs** to accelerate storage?

Topic 4: Storage Monitoring

Introduction – Tip Meckel

Mission Innovation workshop
Trondheim, Norway
June 19-20, 2019

Outline

- Review of 2017 Report: Accelerating Breakthrough Innovation in CCUS
  - Priority Research Directions
  - Scientific Challenges Identified
- Example rubrics & framing considerations

Panel S2: Monitoring, Verification, and Performance Metrics

Panel Leads: Ziqiui Xue (JPN) and Jonathan Pearce (UK)

- Advances in monitoring are needed to enable storage performance verification at a higher level of certainty, both during and following injection operations.
- Areas where basic research could lead to critical improvements include:
  - sensor and tracer technology
  - remote monitoring
  - joint inversion methods for geophysical data
  - optimized design of monitoring and information systems

Bureau of Economic Geology

PRDs identified for Monitoring, Verification and Performance Metrics

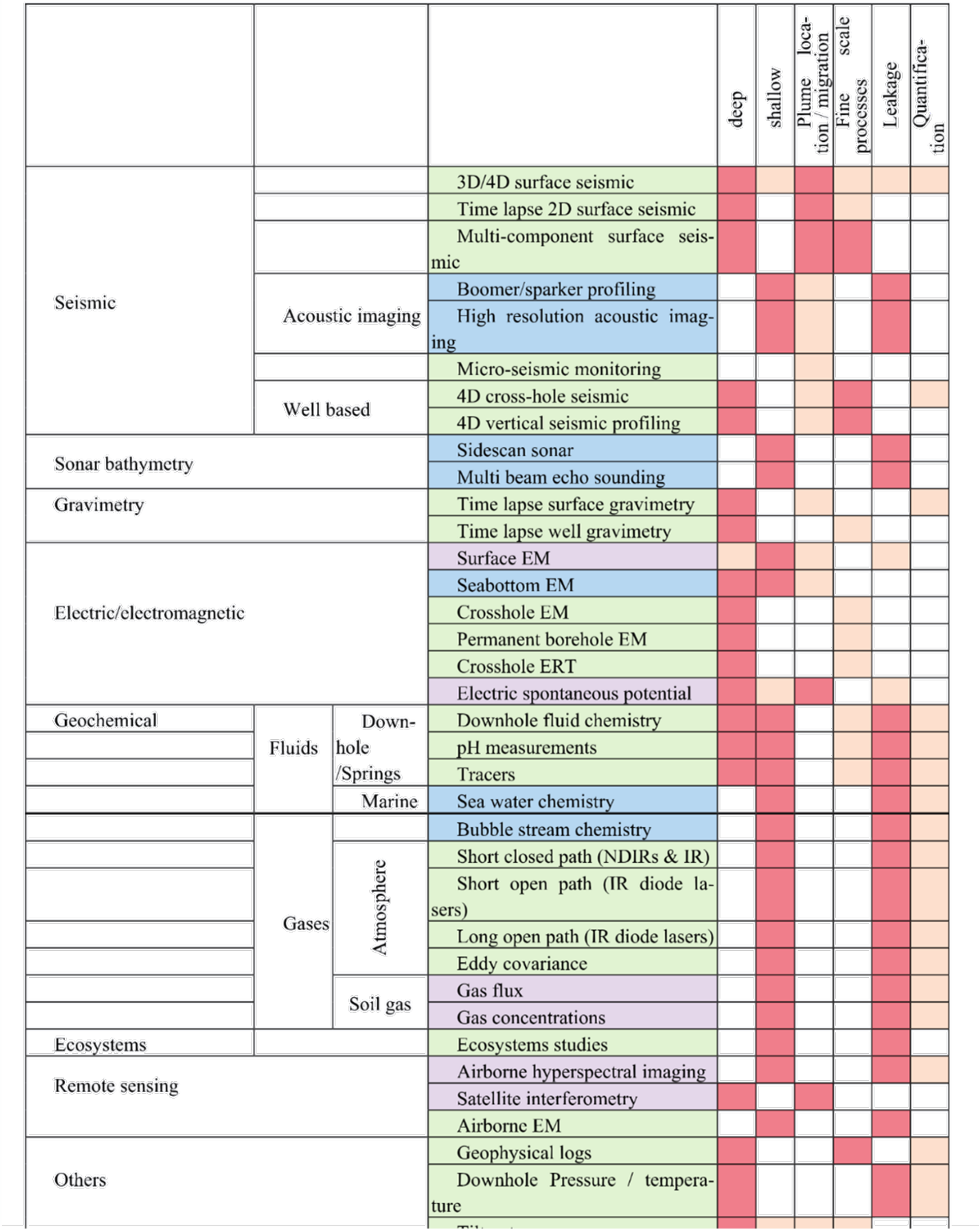
- S-4: Developing Smart Convergence Monitoring to Demonstrate Containment and Enable Storage Site Closure

- S-5: Realizing Smart Monitoring to Assess Anomalies and Provide Assurance

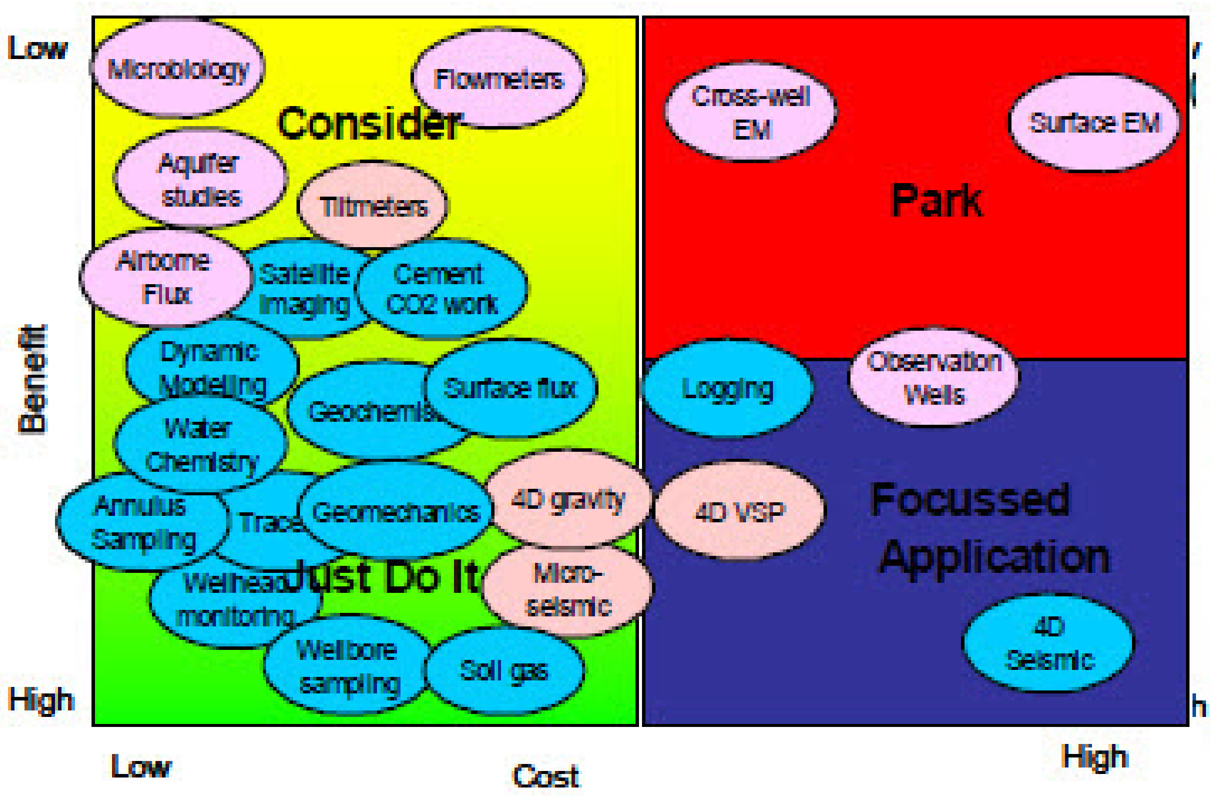
Monitoring Panel Report - Scientific Challenges Identified

- Transforming far-field monitoring with new tools to directly measure state variables
- Smart monitoring in the far-field
- Improving methodologies for monitoring plans
- Improving interpretation and use of large, complex data sets
- Assessing anomalies and providing assurance – location, attribution, quantification

IEAGHG CO_2 Monitoring Tools (2010; Online tool also) IJGGC Special Issue (2015) Lots of BPM



Mathieson et al., 2010



Monitoring

- **WHY/WHO**: Operations, Regulatory, Public
- **WHAT**: Property/State, Tools, Technology
  - Quantification precision & limitations
- **HOW:** Strategy; FOAK or routine.
- **WHERE**: Near/far field; Shallow/deep;
- **WHEN**: Risk profile, Active/passive

- Transparency
- Cost effective (not same as inexpensive)
- Integration (consistency)
- Evolution of strategies, techniques and technologies.
- Verify conformance, predict future performance (model matching) & repeat = assurance!

Closing gaps for deployment and industrial opportunities: Where should we look for innovation in monitoring?

- Two camps:
  - 'We have what we need, it just needs to be better' (high TRL)
  - 'The better/best tool is still out there, just need to find it' (low TRL)

- The brain
- The computer
- The lab
- The field

- **Other fields**: oilfield, robotics (AUV), computing, medical, materials, data management, pattern recognition
  - CCS Technology Ambassadors?

THANK YOU

EPA's Suggested Outline for MRV Plans

1. Facility Information
2. Project Description
3. Delineation of the monitoring areas
4. Evaluation of Leakage Pathways
5. Detection, Verification and Quantification of Leakage
6. Determination of Expected Baselines
7. Site Specific Modifications to the Mass Balance Equation
8. Estimated Schedule for implementation of MRV plan
9. Quality Assurance Program
10. Records Retention
11. Appendices

Multiple examples of active project compliance

Source: U.S. EPA, Office of Air and Radiation, "General Technical Support Document for Injection and Geologic Sequestration of Carbon Dioxide: Subparts RR and UU – Greenhouse Gas Reporting Program," November 2010.

Mission Innovation: Greenhouse Gas Removal

Niall Mac Dowell

Imperial College London

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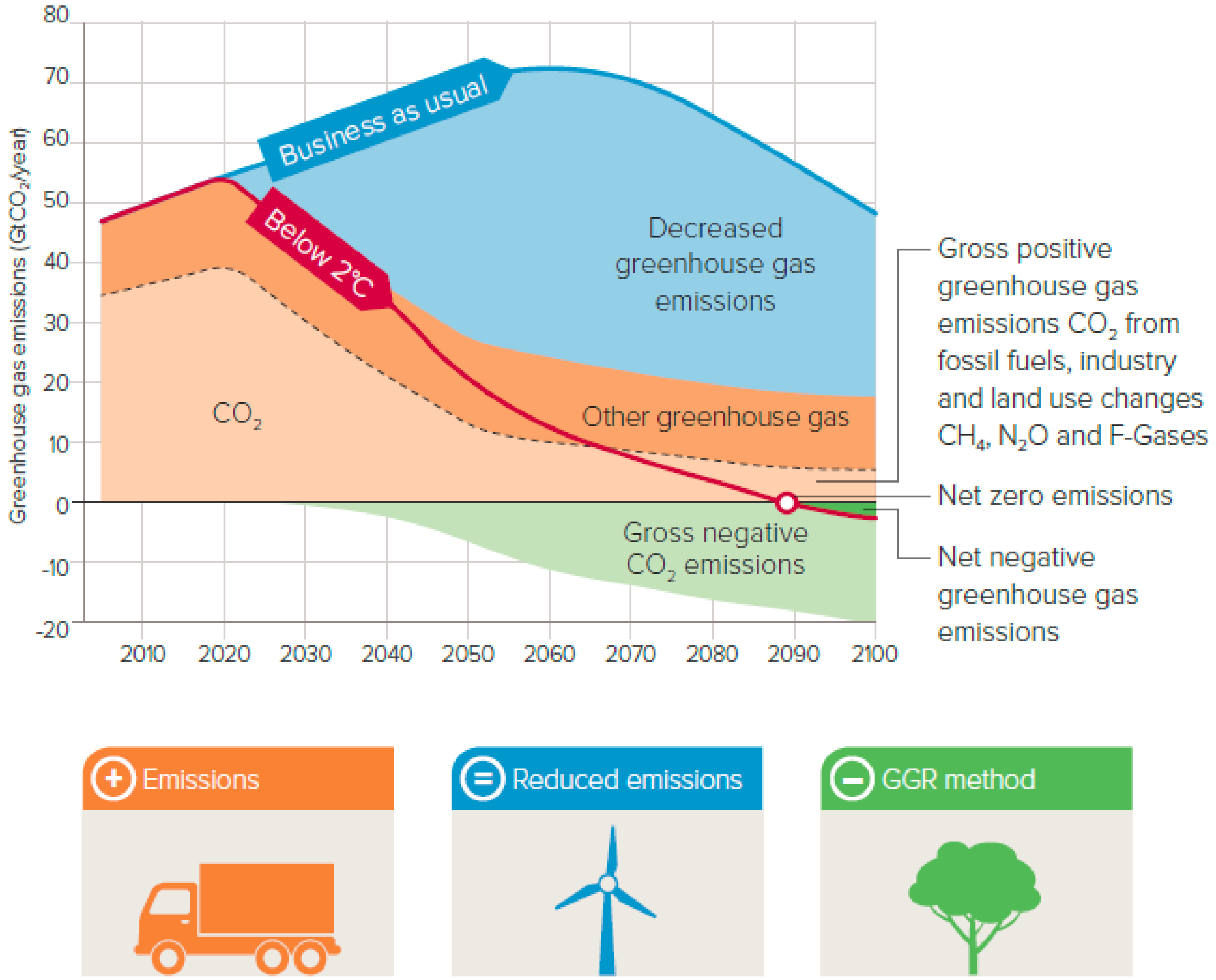
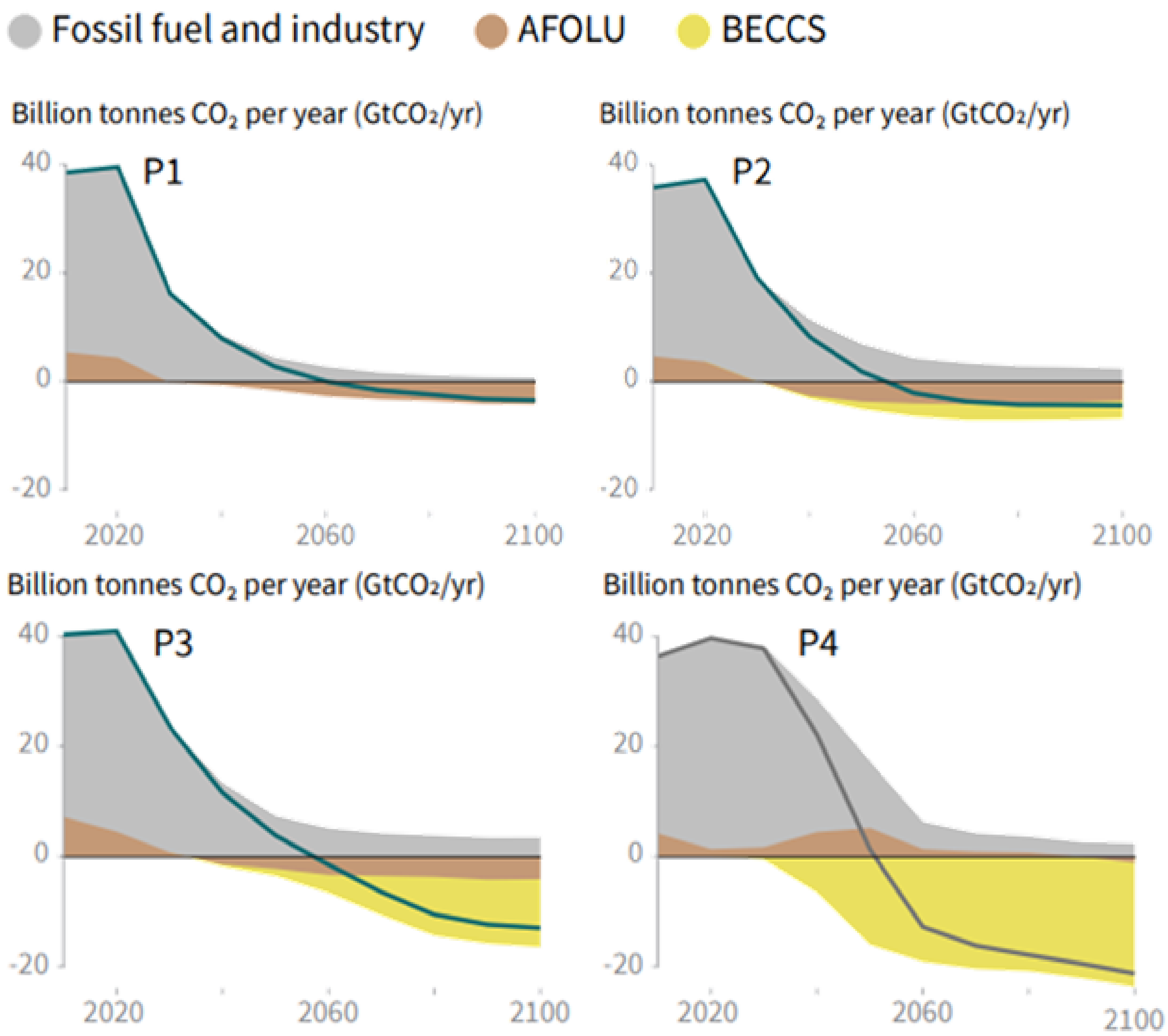
@niallmacdowell

Paris changed everything...



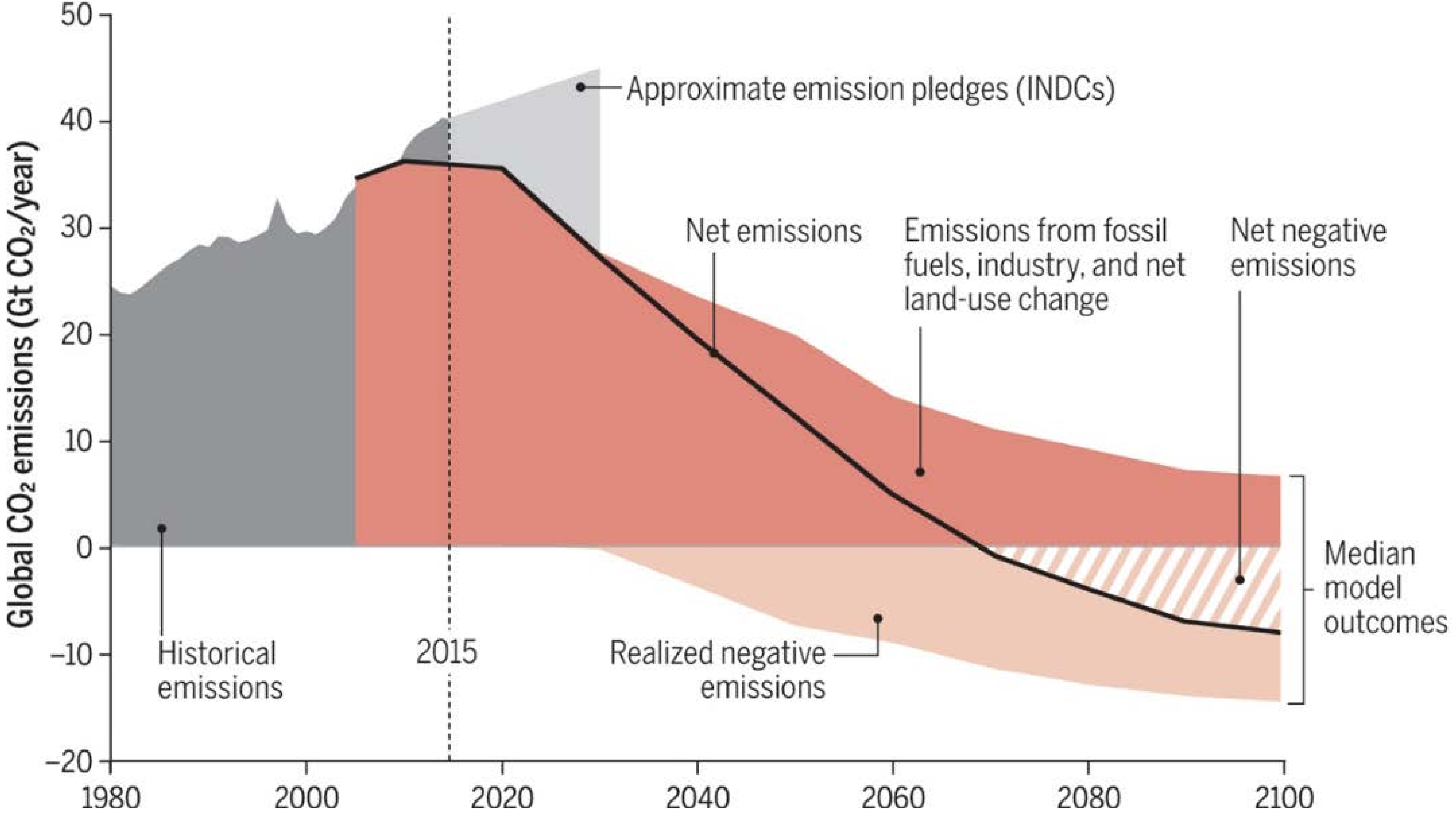
Source: RS & RAEng GGR Report, 2018

Many paths to 1.5^{o}C…



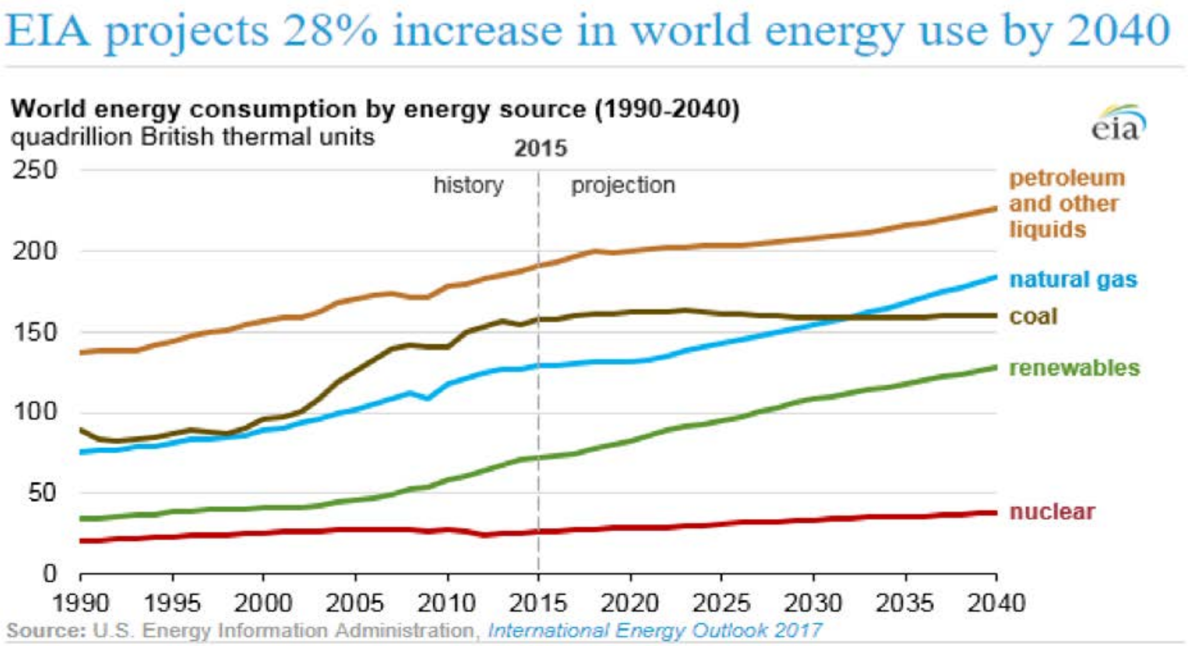
Source: IPCC, 2018, Global warming of 1.5°C

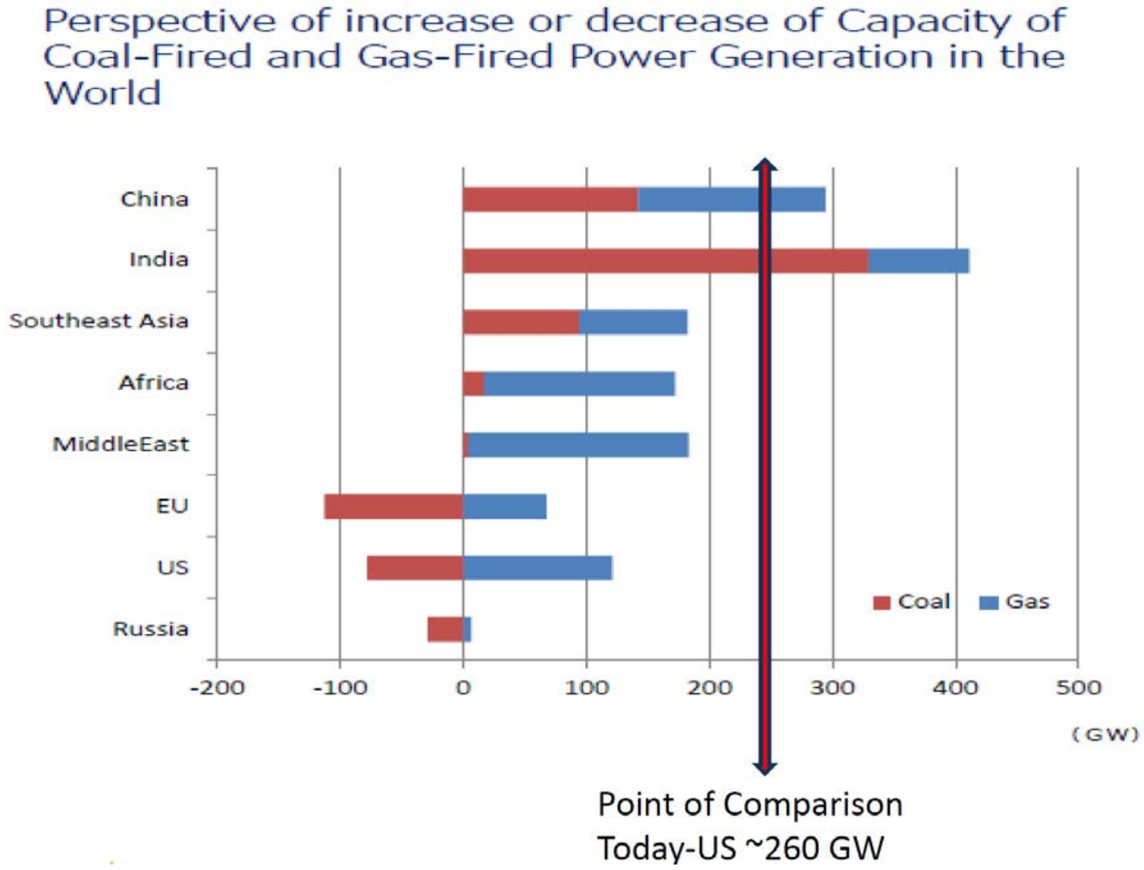
A gap between aspiration and commitment



Anderson and Peters, Science, 2016

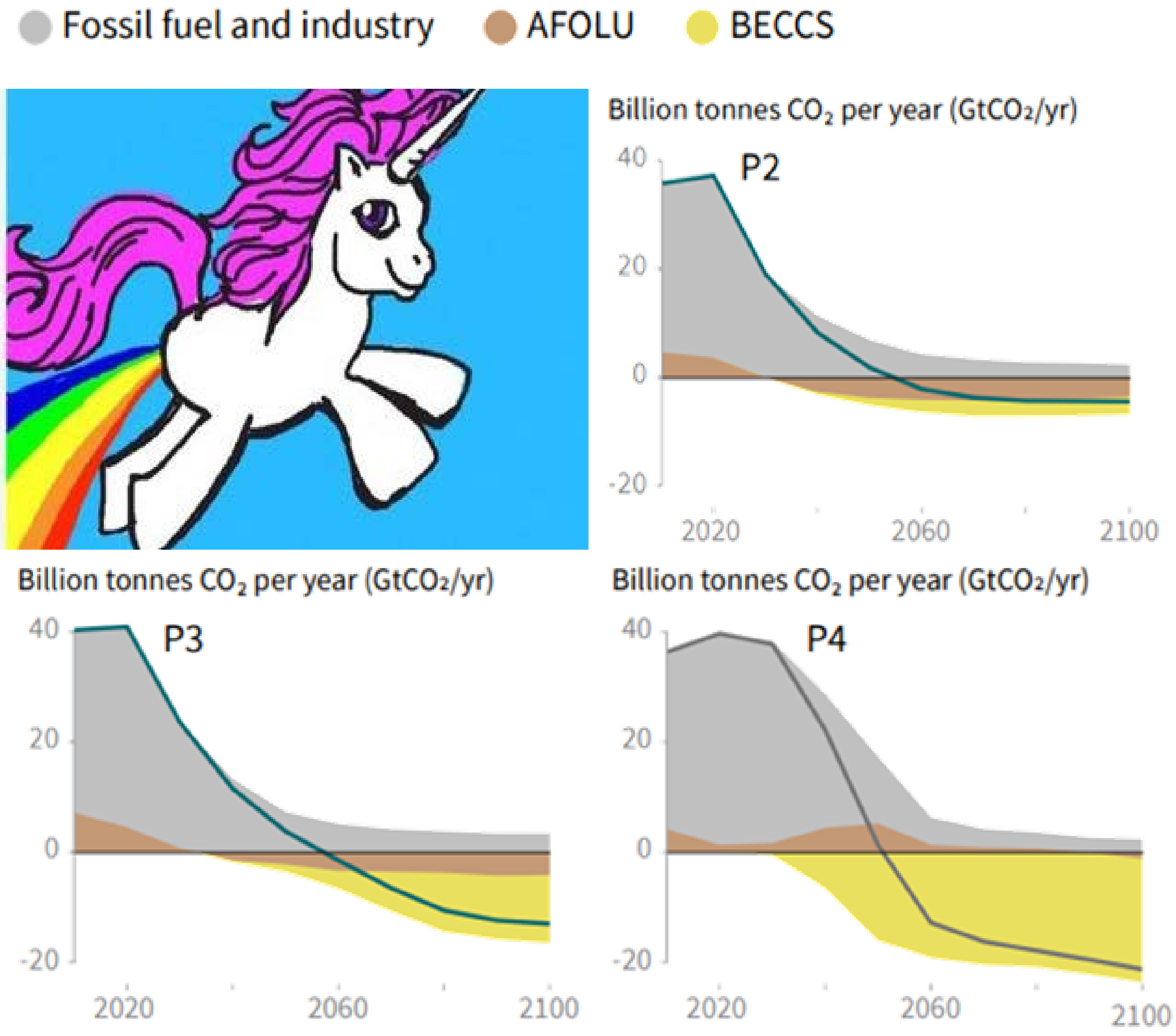
Where will we get our energy?





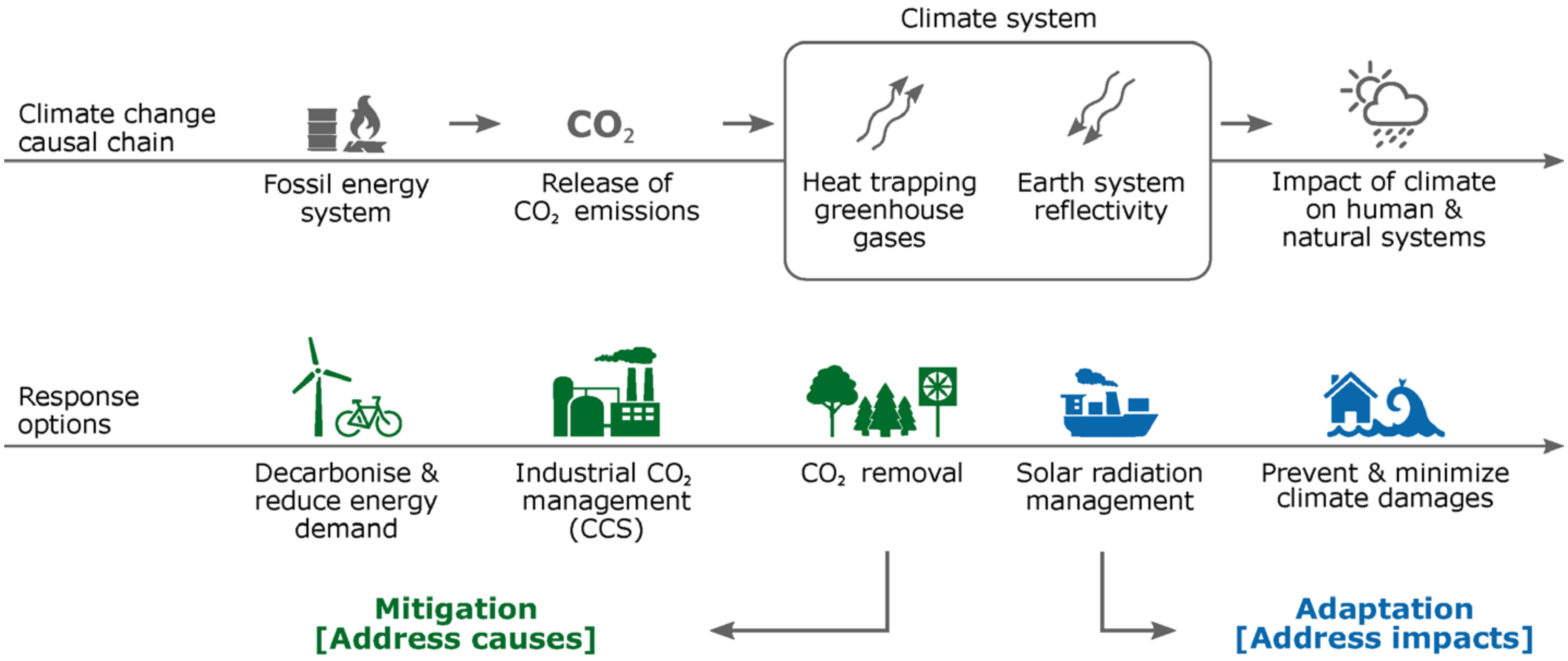
Source: US EIA, IEO, 2017, IEA, WEO, 2017, Lou Hrkman, US DOE, Update on US strategy for coal, 2019

Likely paths to 1.5°C…



Source: IPCC, 2018, Global warming of 1.5°C

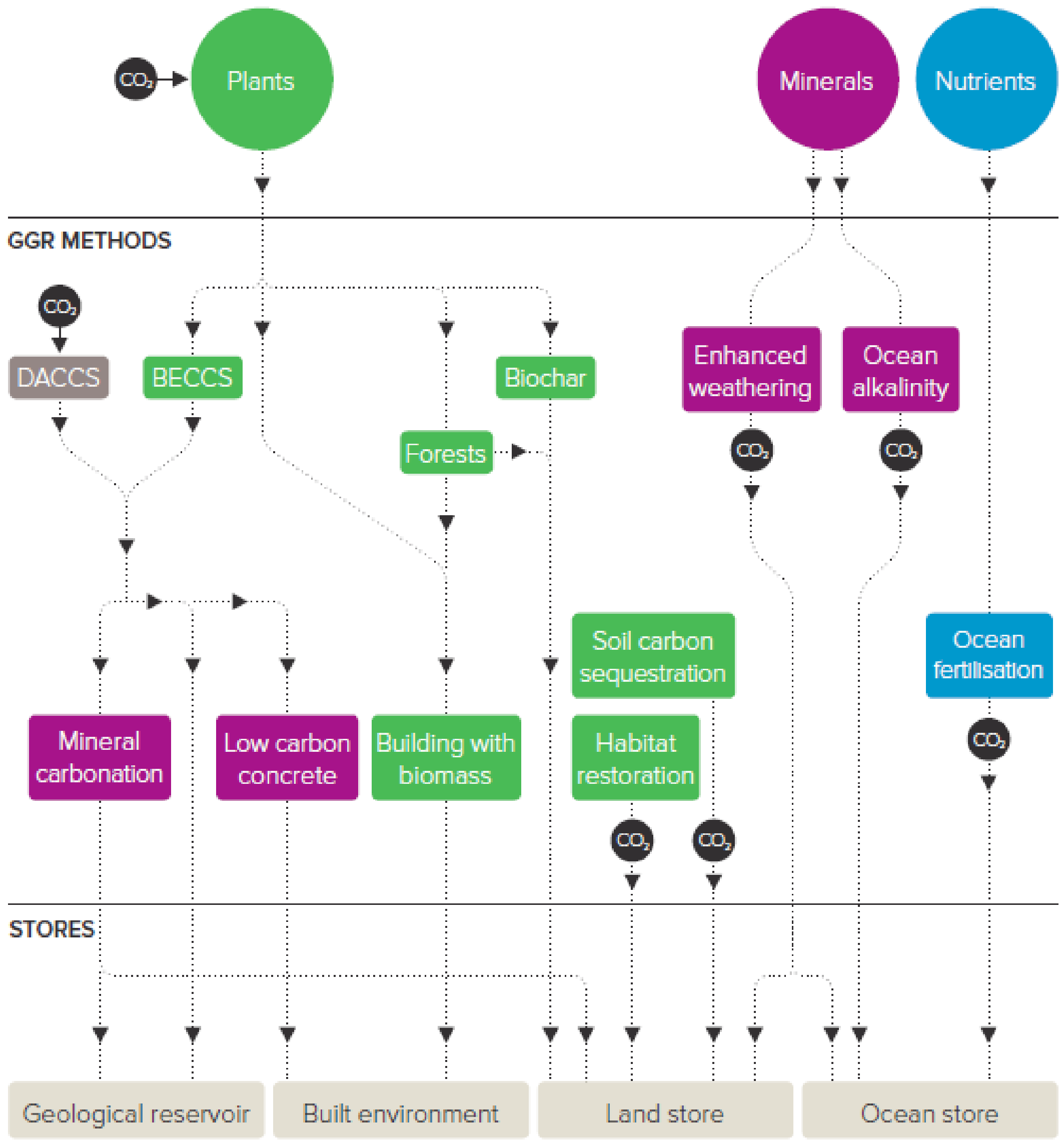
GGR as an alternative to mitigation?



- GGR is part of a portfolio of options, including mitigation and adaptation
- GGR is not an alternative to mitigation

Image from Minx *et al*, Environ. Res. Lett., 2018

A portfolio of GGR options



Source: RS & RAEng GGR Report, 2018

A portfolio of GGR options

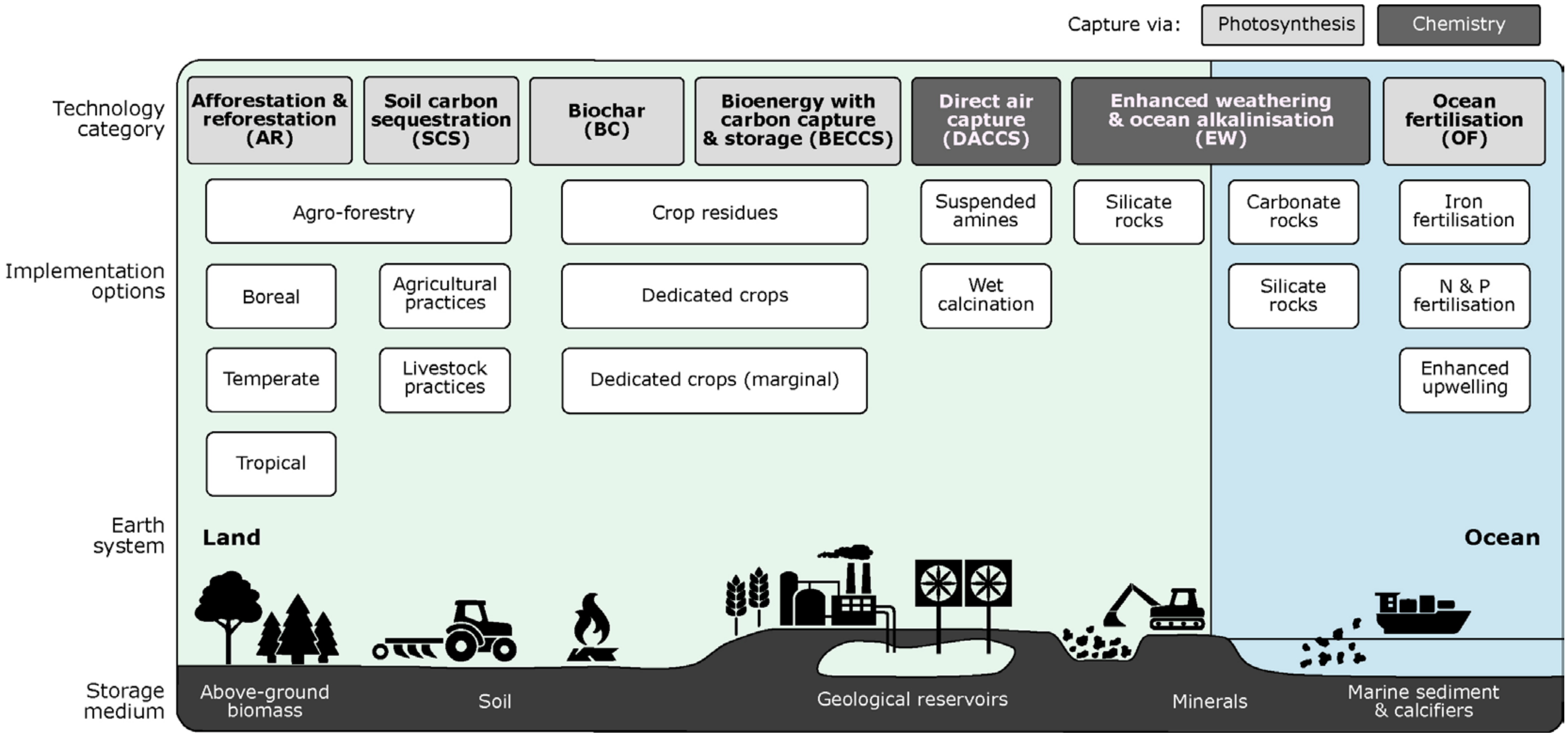
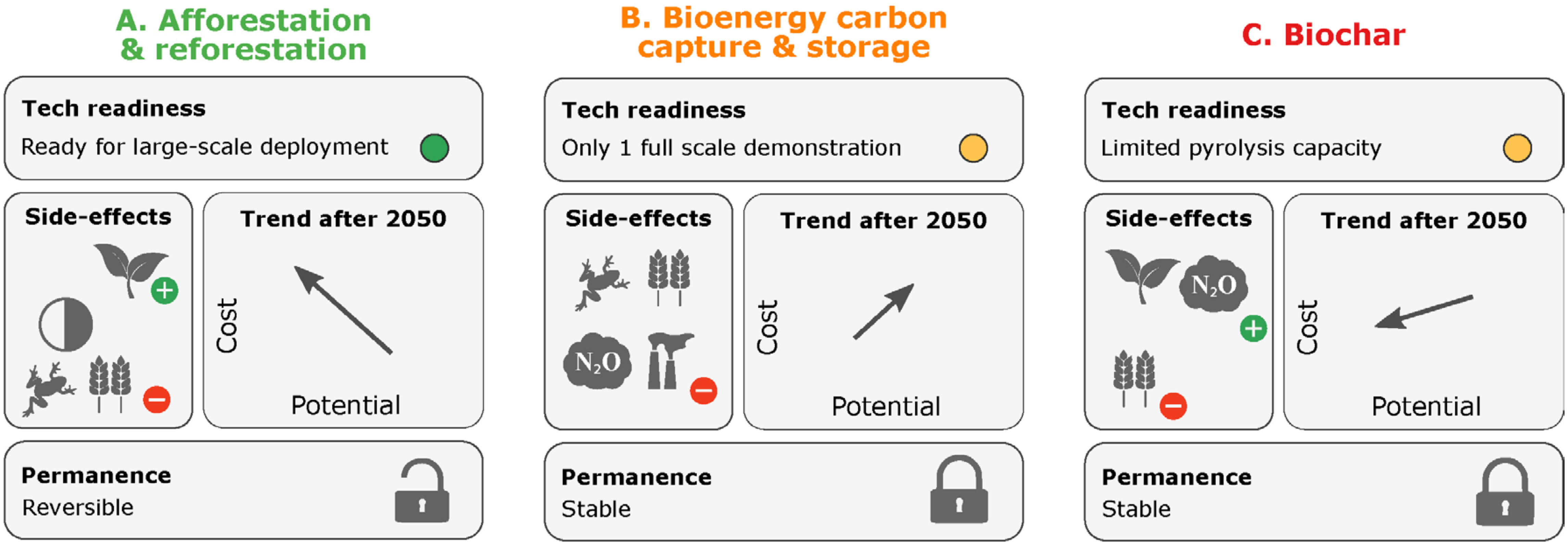


Image from Minx *et al*, Environ. Res. Lett., 2018

A portfolio of GGR options



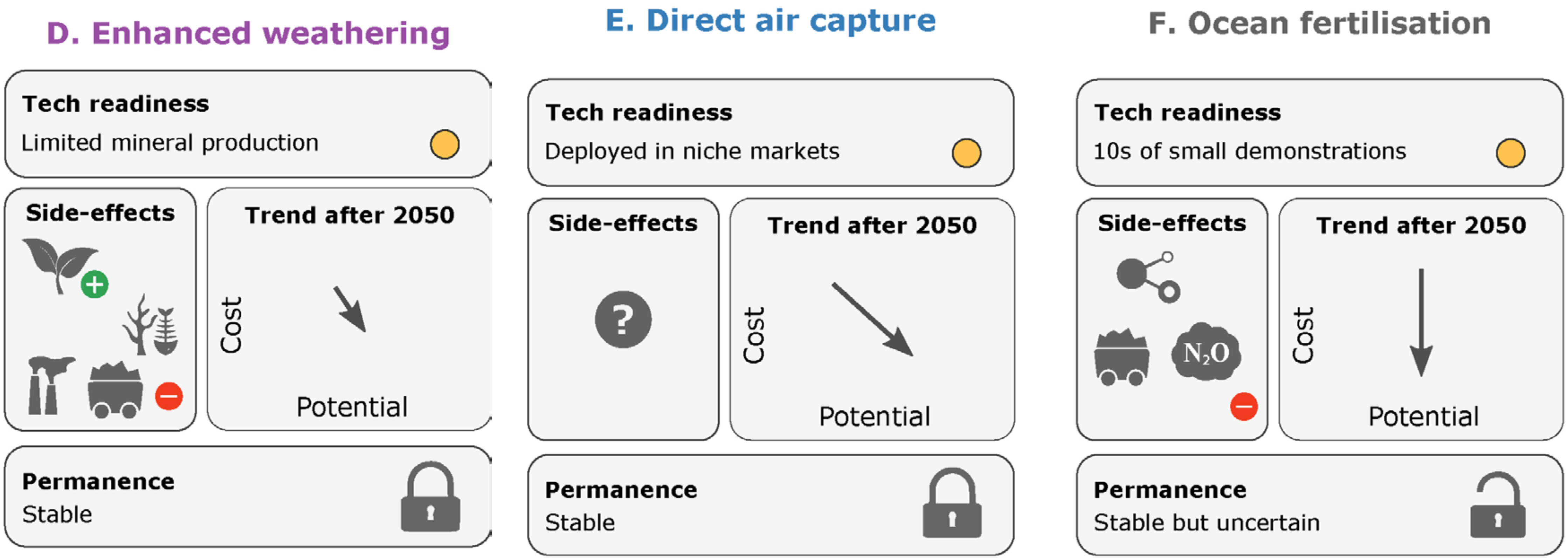
Cost: \$0 – 240/t_{CO2}

Cost: \$15 – 400/t_{CO2}

Cost: \$10 – 345/t_{CO2}

Data from Minx *et al*, Environ. Res. Lett., 2018

Portfolio of NETs



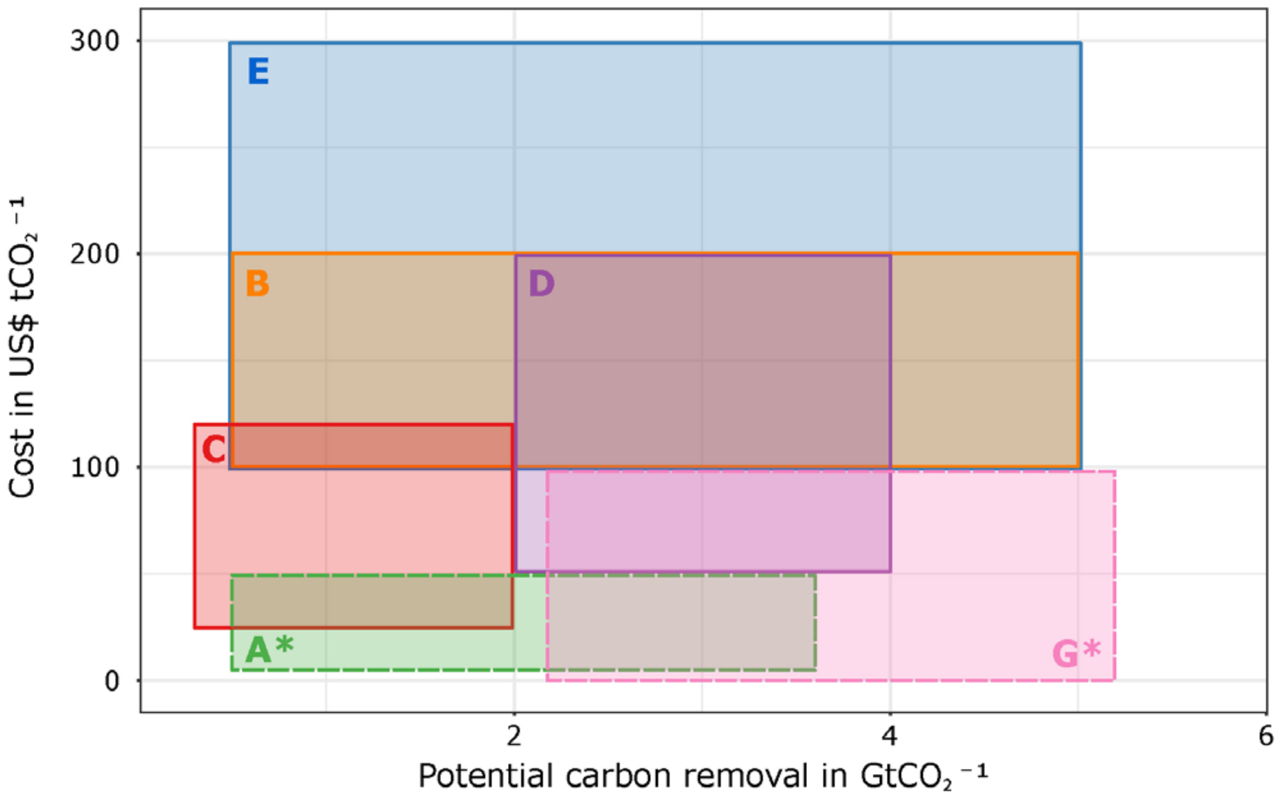
Cost: \$5 – 3460/t_{CO2}

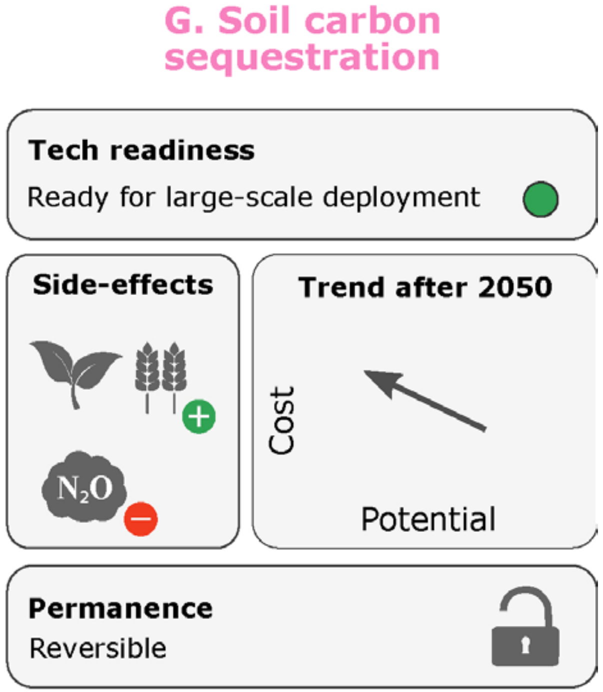
Cost: \$25 – 1,000/t_{CO2}

Cost: \$0 – 460/t_{CO2}

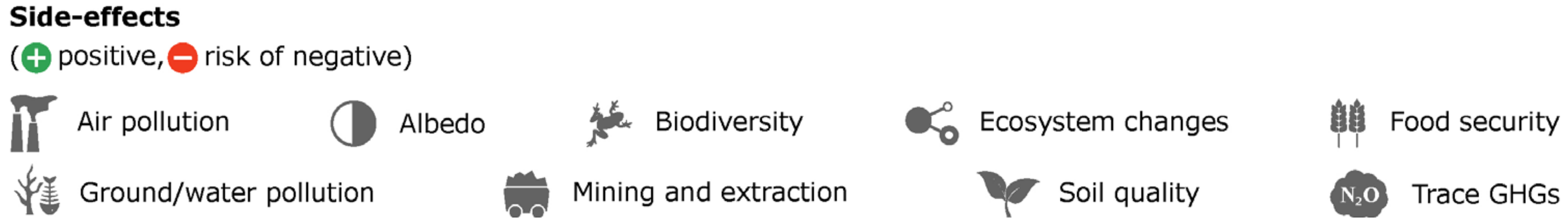
Data from Minx *et al*, Environ. Res. Lett., 2018

Portfolio of NETs



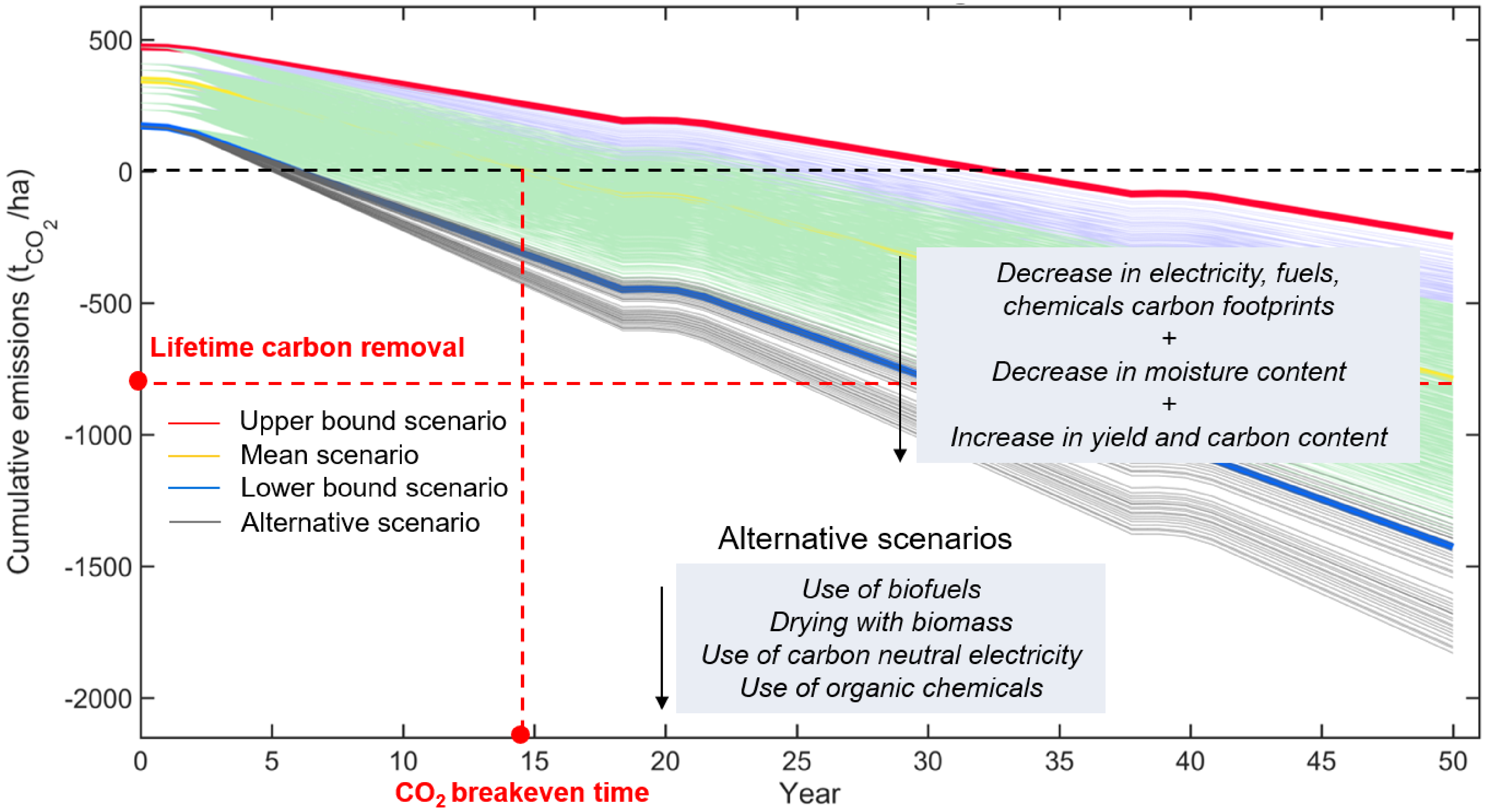


Cost: $-45 – 100/t$_{CO2}$



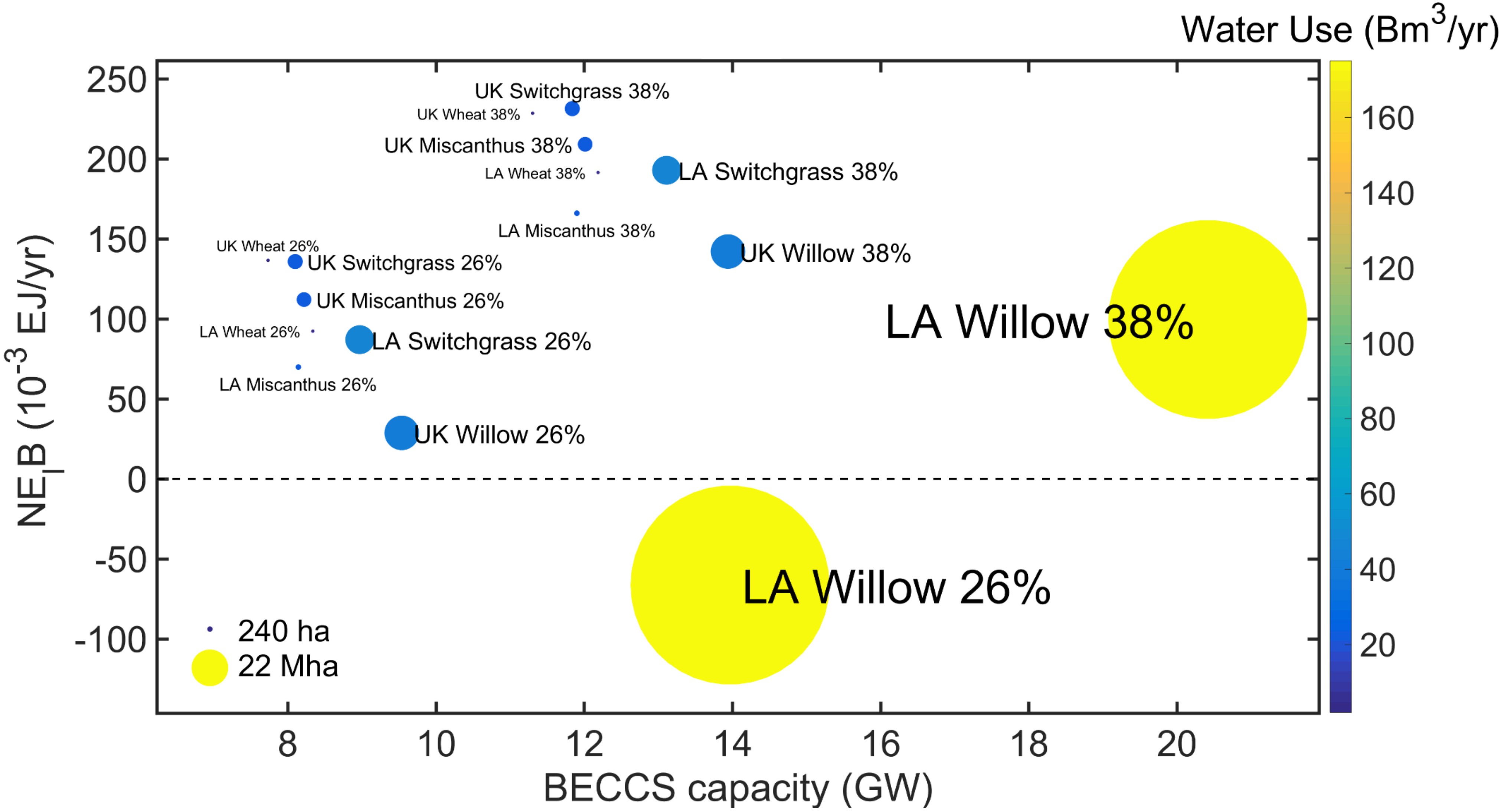
Data from Minx *et al*, Environ. Res. Lett., 2018

Does BECCS work?



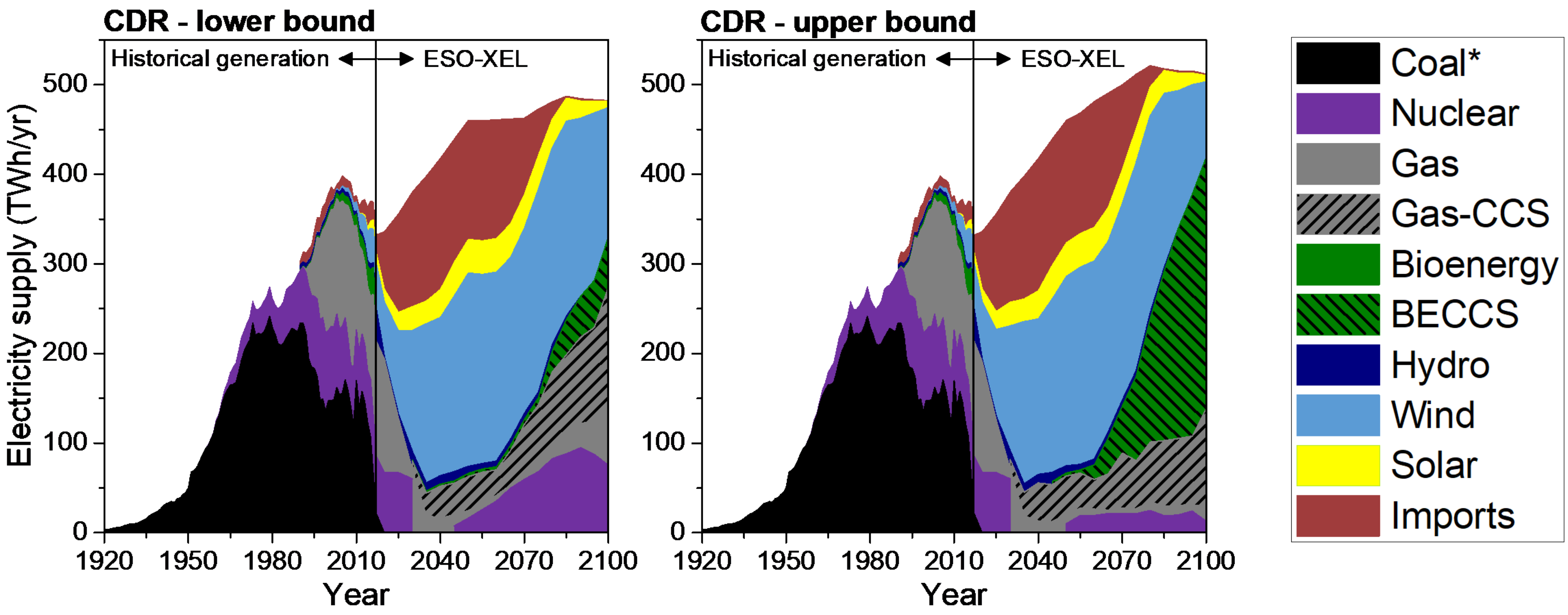
Sources: Fajardy M. and Mac Dowell N., Energy and Environmental Science (2017); Fajardy M. and Mac Dowell N., Energy and Environmental Science (2018)

Does BECCS generate power?



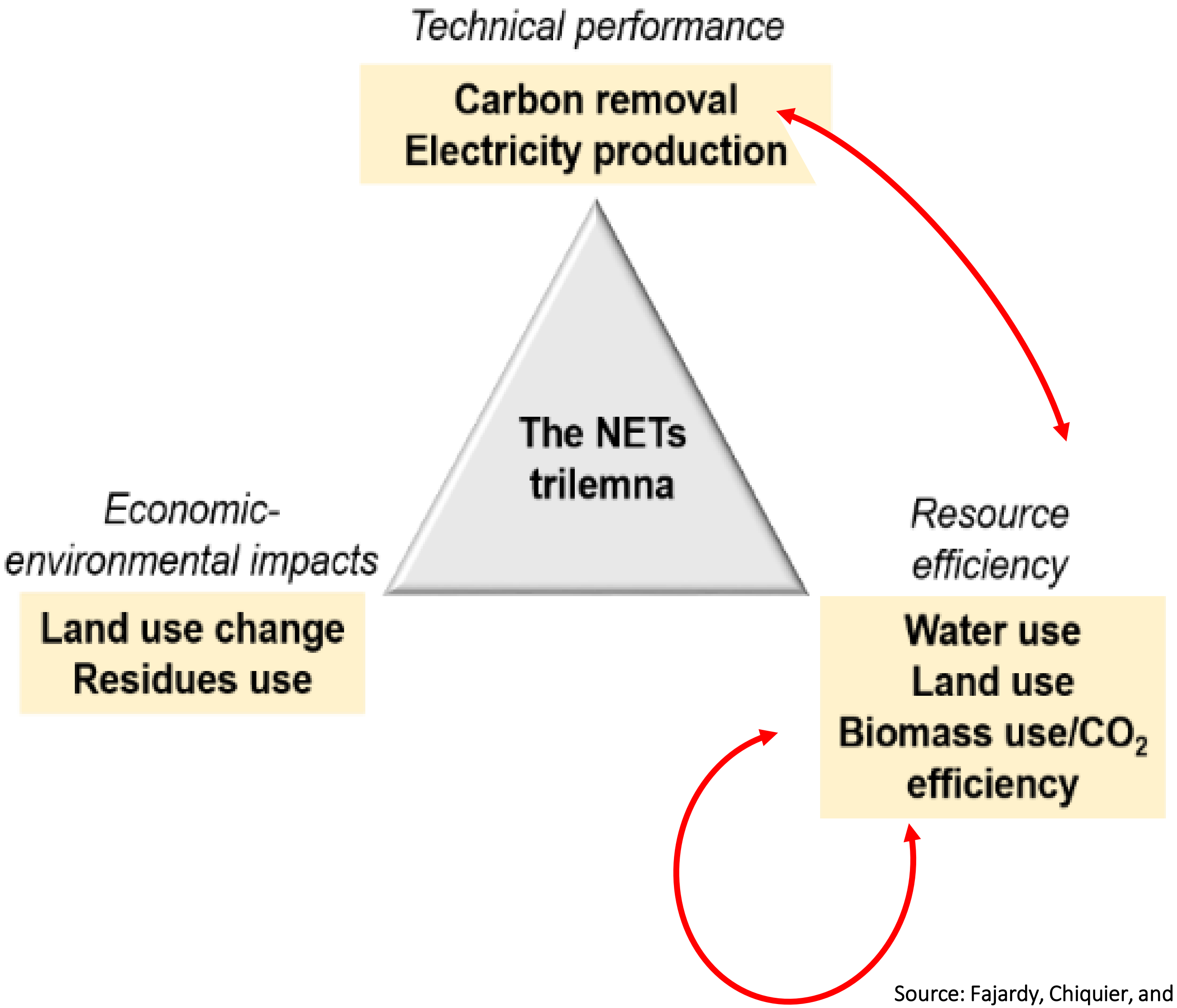
Source: Fajardy and Mac Dowell, Energy and Environmental Science, 2017

Low carbon vs. carbon negative energy systems



Source: Daggash and Mac Dowell, Joule, 2019

Trade-offs within the land-water-carbon-energy nexus

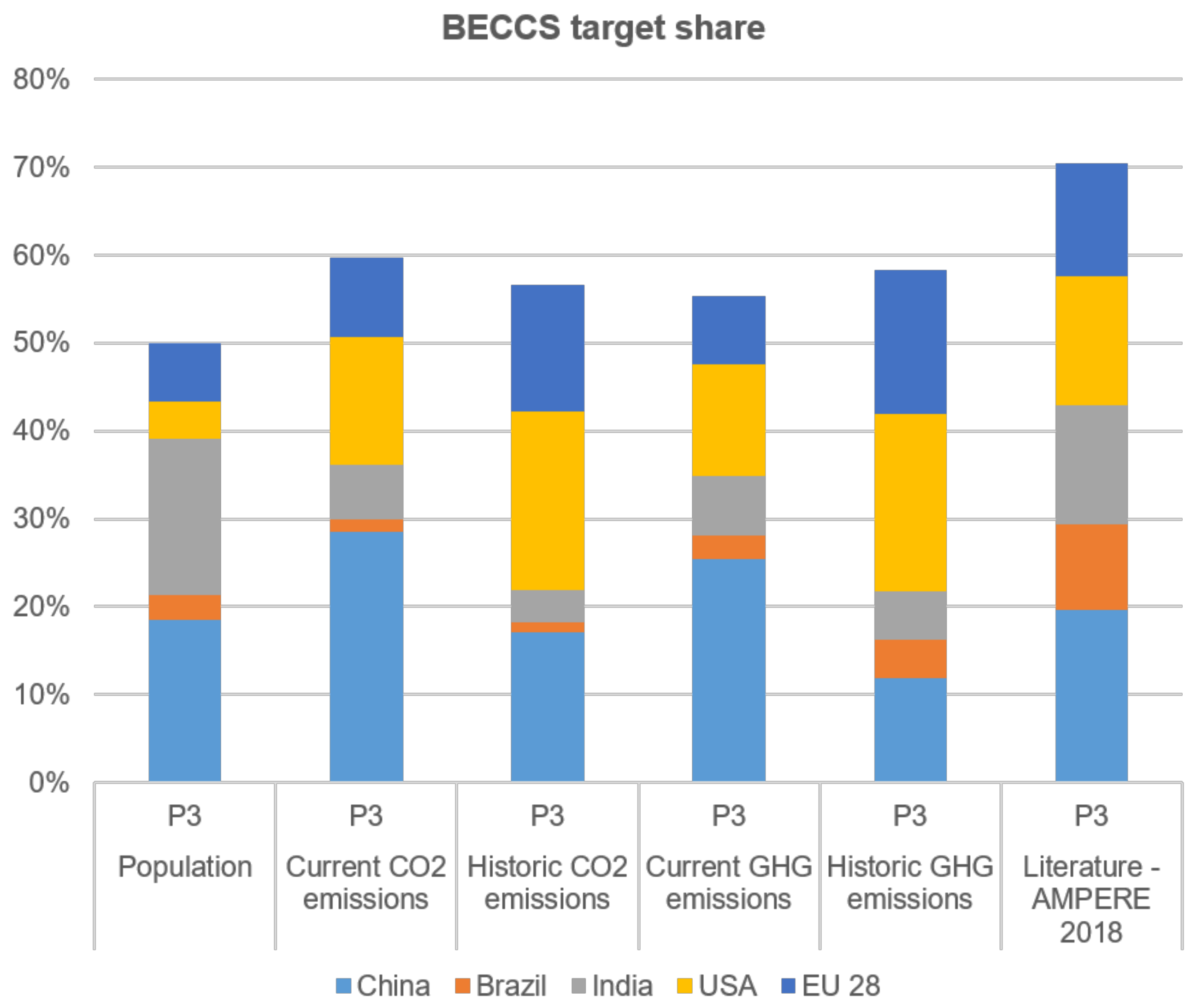


Source: Fajardy, Chiquier, and Mac Dowell, Energy and Environmental Science, 2018

Who has to do what..?

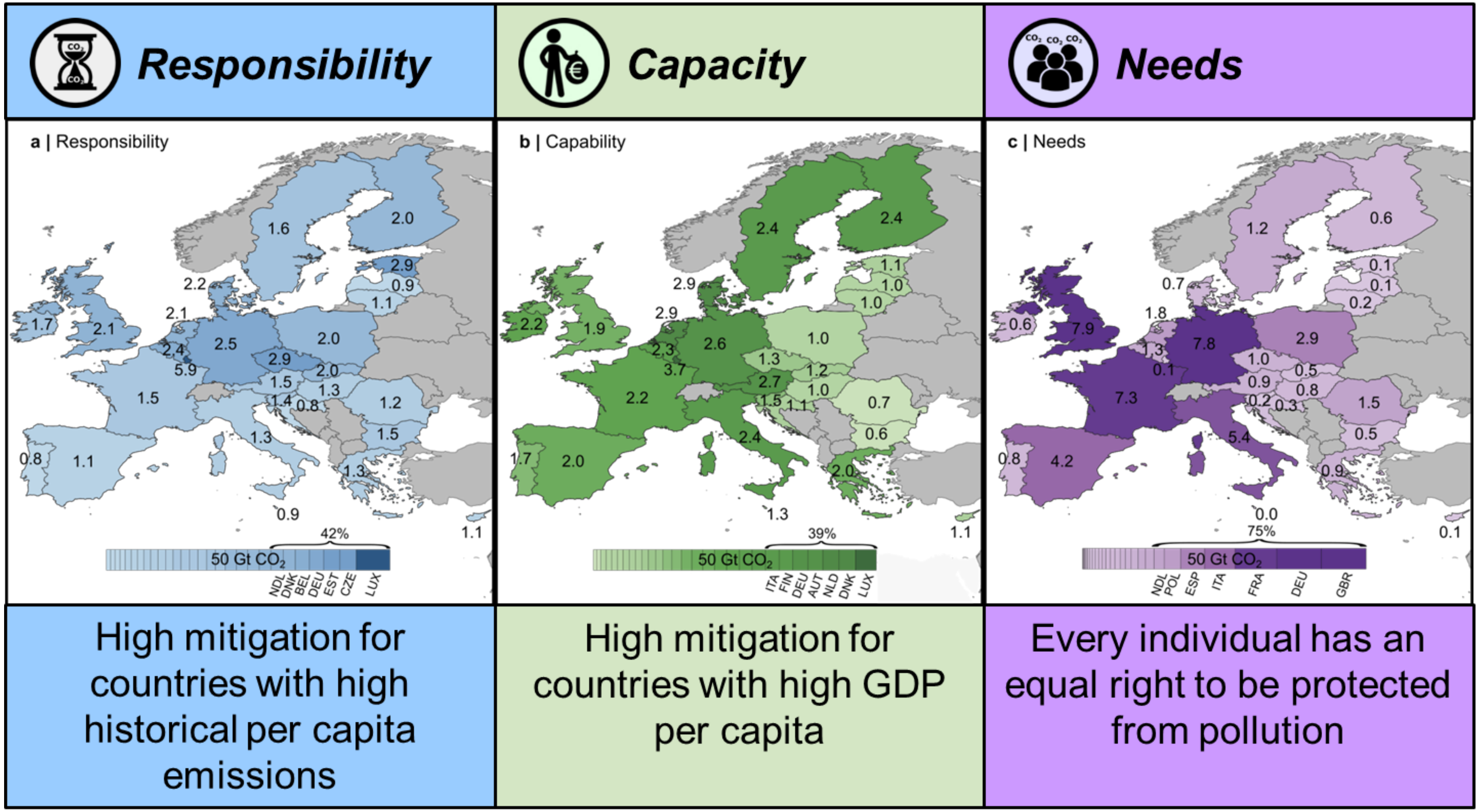
$$target(i) = Gtarget.\frac{x(i)}{\sum_{world} x(i)}$$

- **Equity**: x(i) = population in 2014
- **Responsibility** – current CO_2 emissions: x(i) = CO_2 emissions in 2014
- **Responsibility** – historical CO_2 emissions: x(i)= cumulative CO_2 emissions 1975-2014
- **Responsibility** – current GHG emissions: x(i) = GHG emissions in 2014
- **Responsibility** – historical GHG emissions: x(i) = cumulative GHG emissions 1850-2014

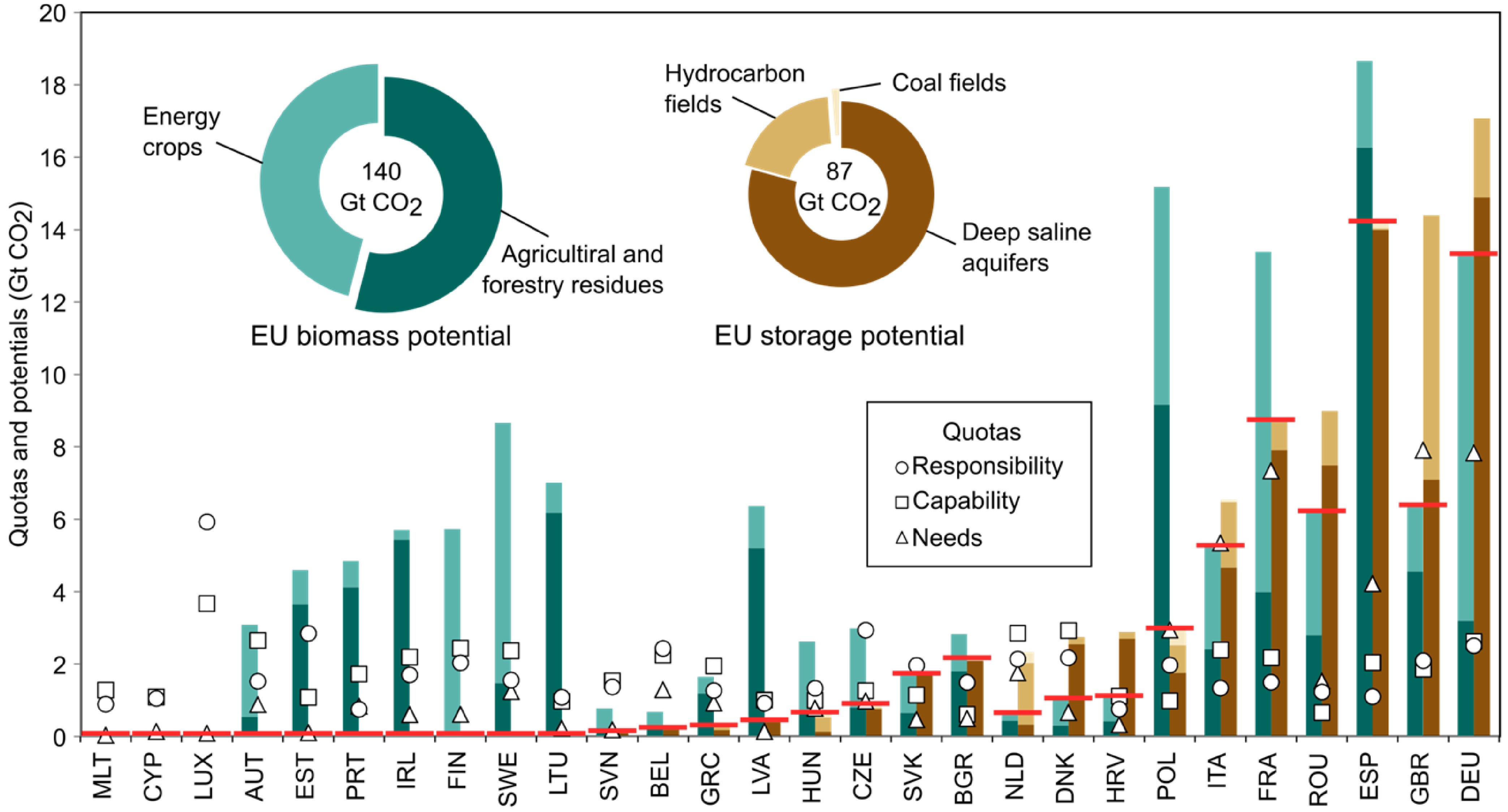


What might this look like at the national level?

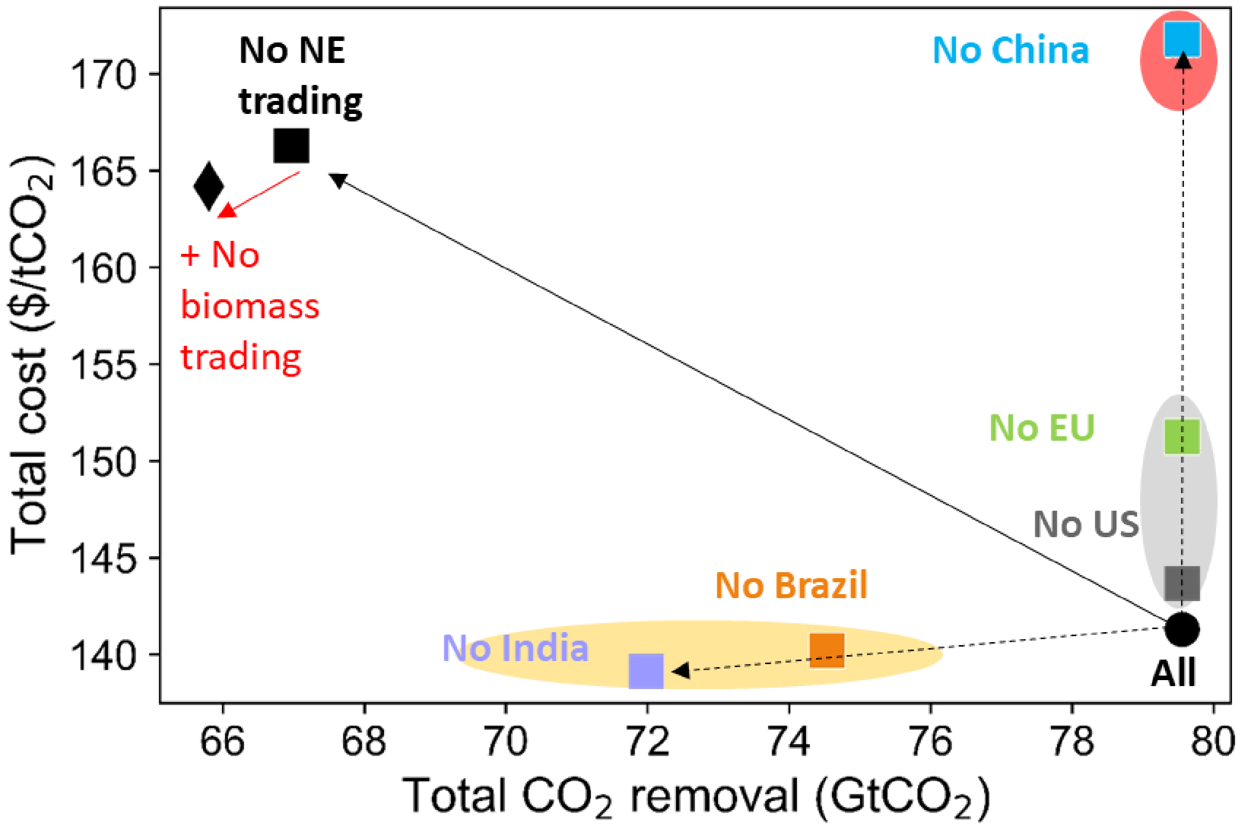
- Responsibility: per-capita historical (1960-2017) CO_2 emissions
- Capacity: per-capita GDP
- Needs: country population



Limited potential for individual action

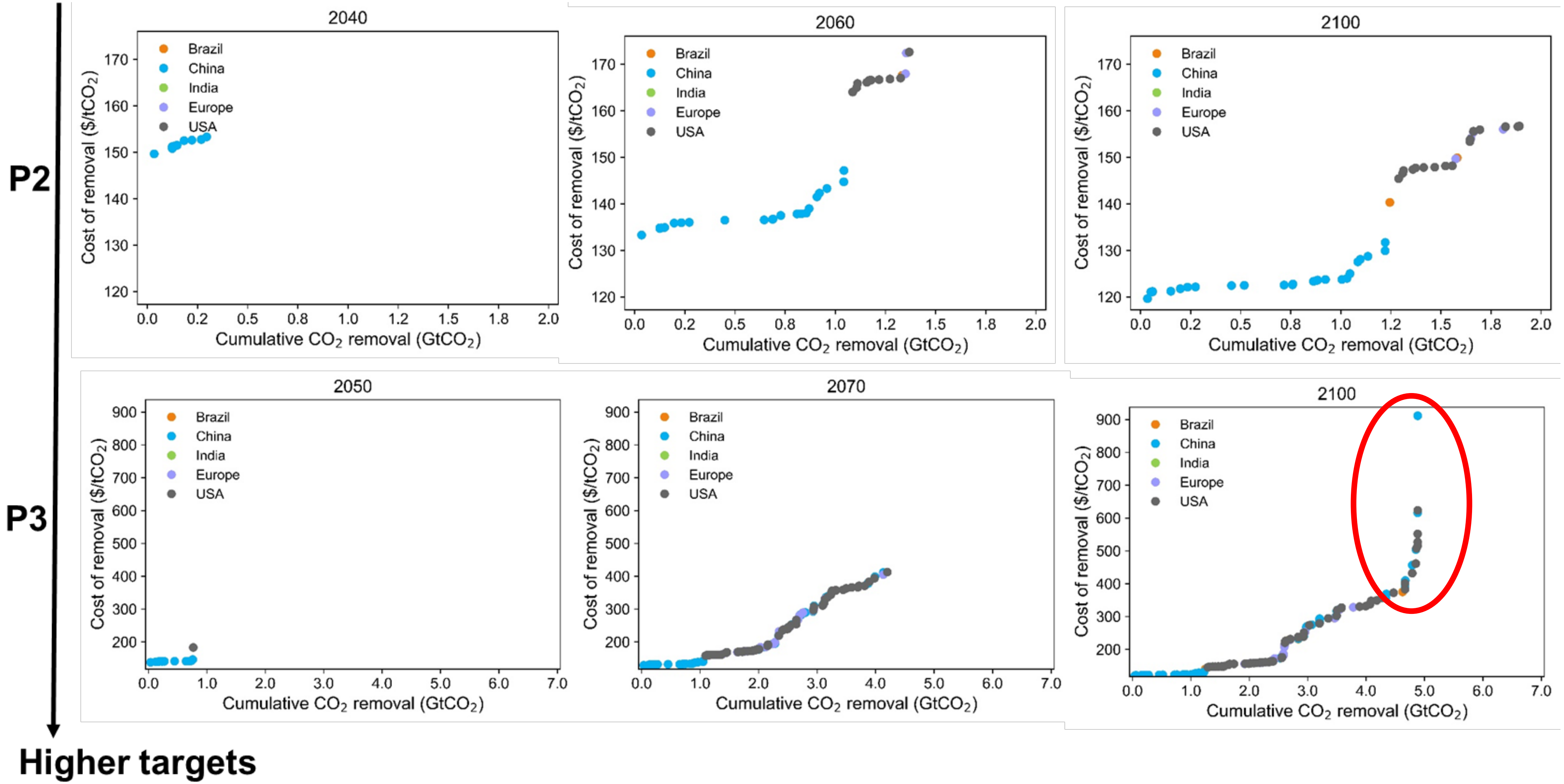


The value of cooperation

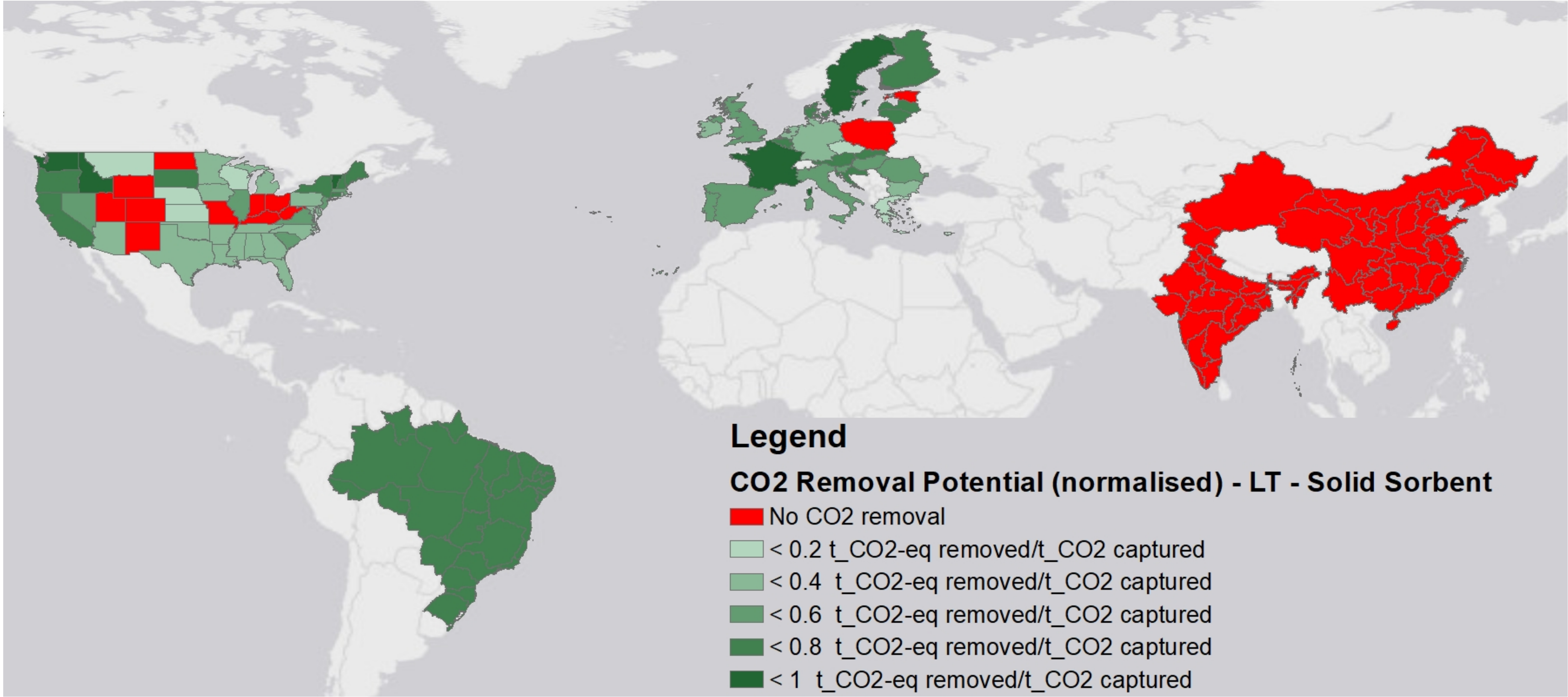


- Different players bring different values :
  - **'Independent providers'** (*e.g*. China): regions with good storage availability, low cost and low carbon biomass close to storage sites >> **much higher cost if excluded** as they can no longer provide surplus for other regions
  - **'Independent beneficiaries'** (*e.g.* EU and US): region with good storage and biomass availability but higher cost >> **higher cost if excluded** as they have to fulfil their own targets
  - **'Dependent beneficiaries'** (*e.g*. Brazil and India) : unable to meet their own targets due to lack of storage >> **unmet CO_2 removal target** if excluded

BECCS supply curve



A role for alternatives: Direct Air Capture (DAC)



Different options, different challenges

	BECCS	DACS	AR/RE	Biochar	EW
Regional constraint(s)	• CO_2 storage capacity • Biomass feedstock • Accessible and available land • Water	• CO_2 storage capacity • Low carbon energy	• Productive and available land • Water • Albedo effect	• Biomass feedstock • Accessible land (may be combined with other uses)	• Accessible land (may be combined with other uses) • Availability of minerals
CO_2 accounting and monitoring	• Cross border supply chain emissions • Delayed CO_2 removal • CO_2 stored permanently	• Immediate CO_2 removal • CO_2 stored permanently	• Immediate CO_2 removal • Permanence subject to monitoring • Sink saturation	• Delayed CO_2 removal • Permanence subject to monitoring • Sink saturation	• Immediate CO_2 removal • Sink saturation
Regional variability of performance	• Yield, water requirement, sustainable biomass availability	• Cost • Carbon footprint of energy	• Growth rate • Risk of releasing CO_2	• CO_2 uptake	

Research and innovation challenges

- NETs and GGR are still nascent
- Many remaining research challenges
  - Technology demonstration and price discovery is a work in progress
  - For BECCS,
    - We need to properly understand the value of the co-products
    - Is bioelectricity the best use of the biomass? Heat? Power? Mobility? H_2?
  - Scalability, permanence of CO_2 removal, and broader sustainability
  - Social license and political economy, in particular, remain unclear
  - How will different countries, and regions, collaborate for optimal deployment?
  - How will NETs/GGR be incentivised, monitored, and regulated?

ON CCU(S)

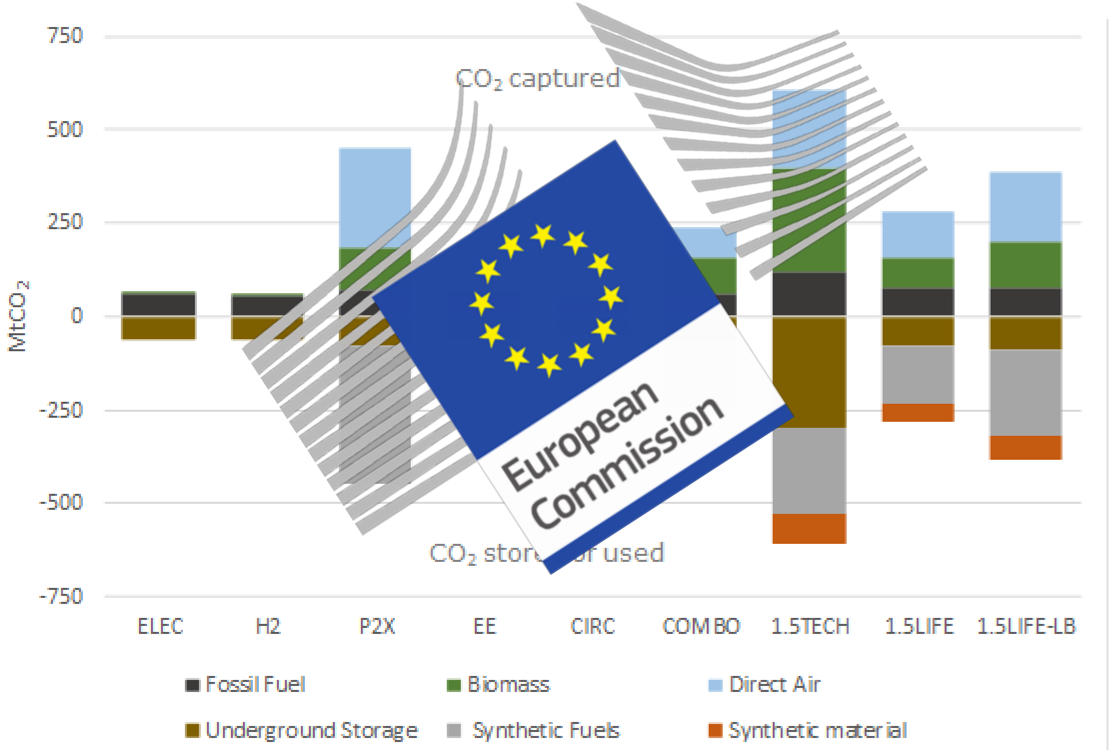
Jaap Vente

Mission Innovation Session

19 – 20 June 2019

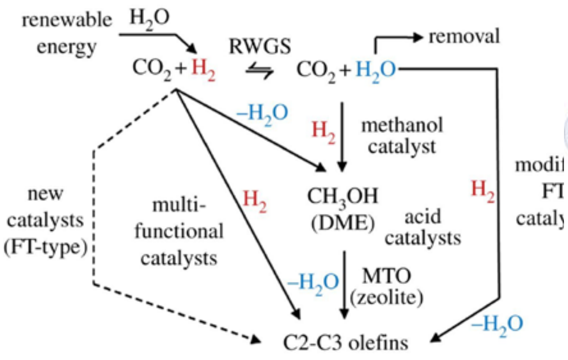
ECN › TNO innovation for life

SCENARIO ANALYSIS RESULTS FOR CCUS

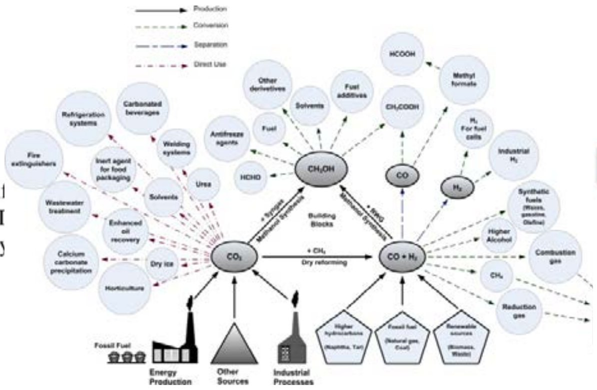


- CCS will be required to reduce emissions of any remaining fossil fuels use (power sector, industry)
- In the case of higher ambition targets, CCS combined with biomass is required to generate negative emissions
- It also seems necessary for certain hard to decarbonize industrial processes
- CCU – synthetic fuels and materials (e.g. in plastics) are also seen as options

CONVERTING CO_2



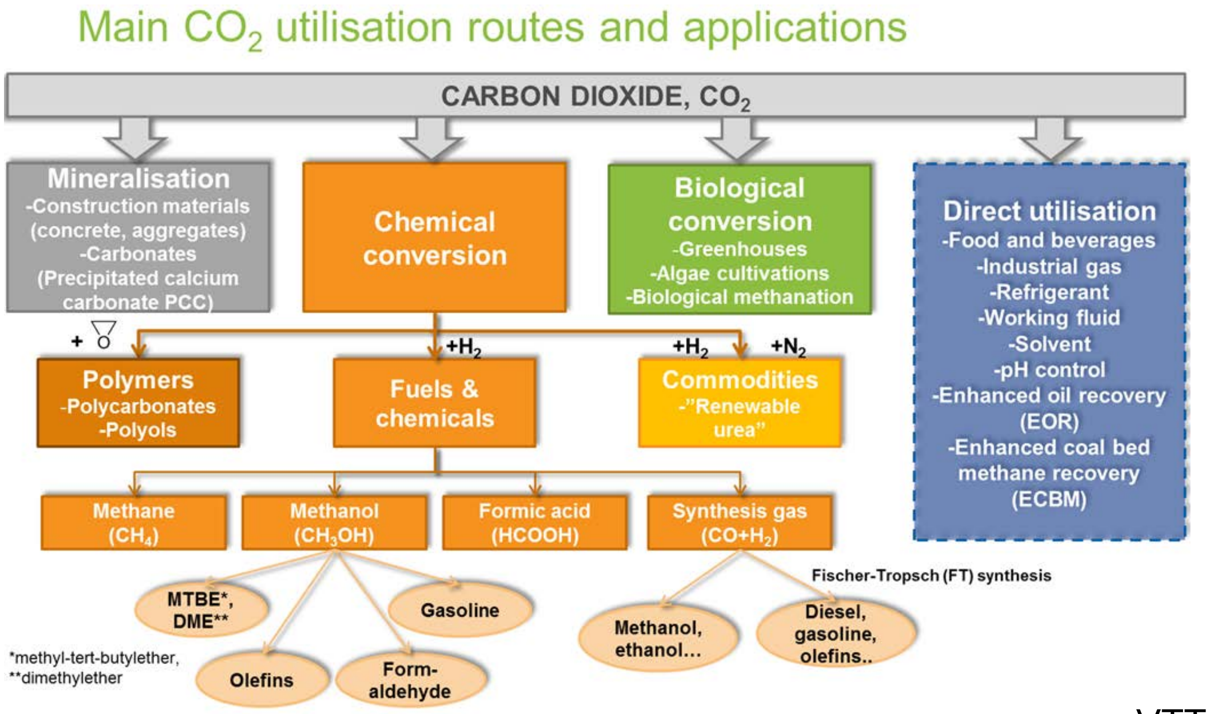
Royal Society



Science direct

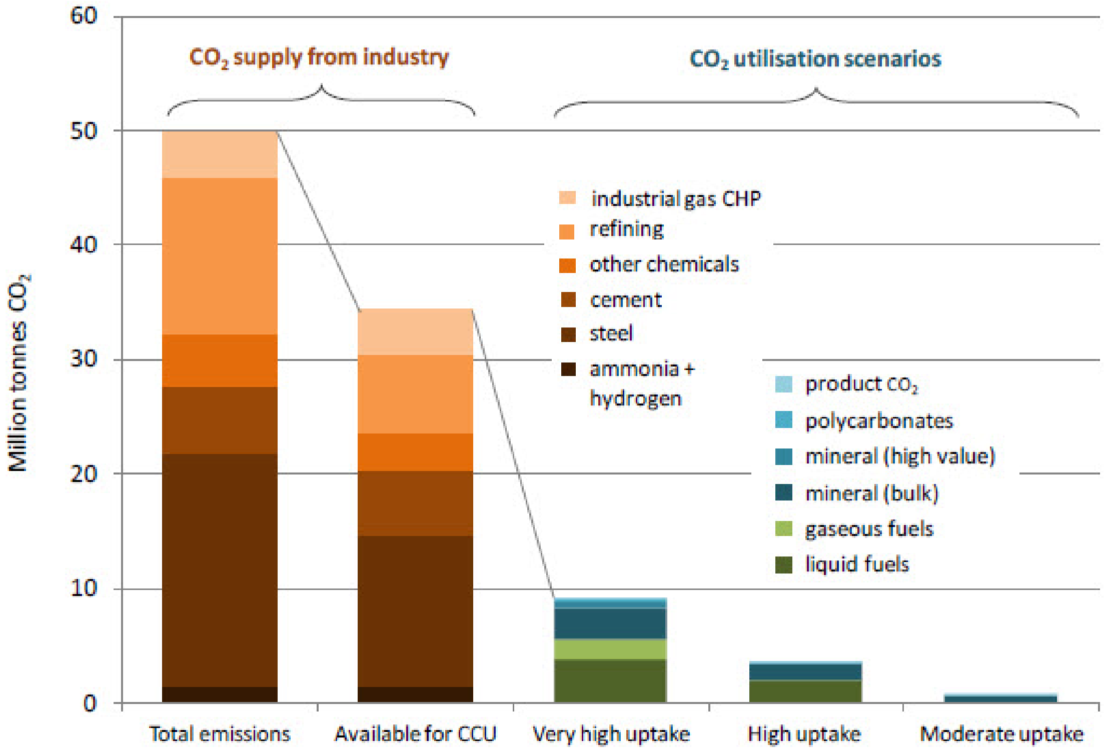
Smart spec platform

MAIN ROUTES



VTT

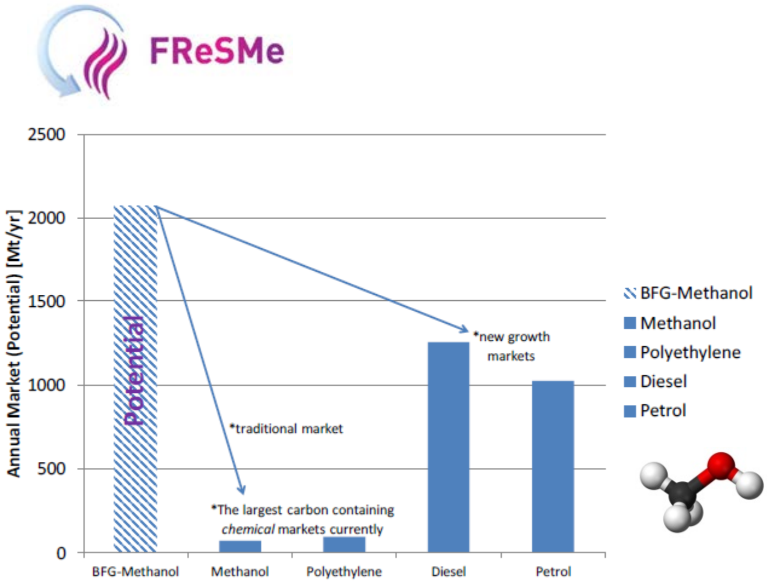
POTENTIAL

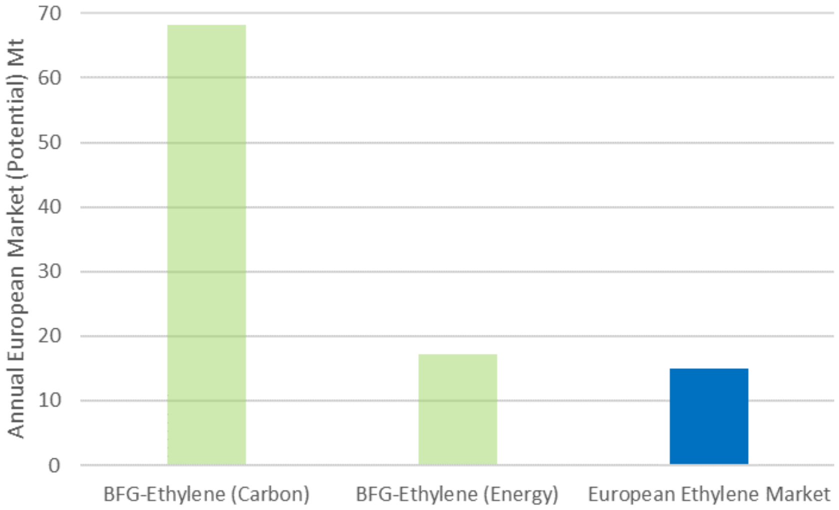


Global CCS institute

PRODUCTION POTENTIAL: CO_2-BASED

- Annual global CO_2-production in steel industry vs. current annual markets



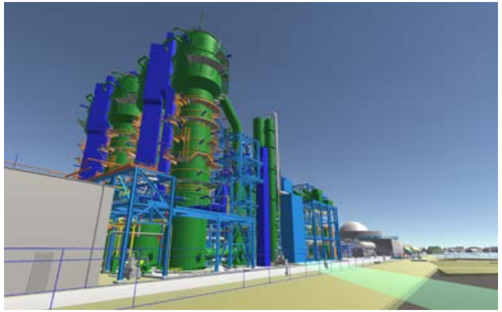


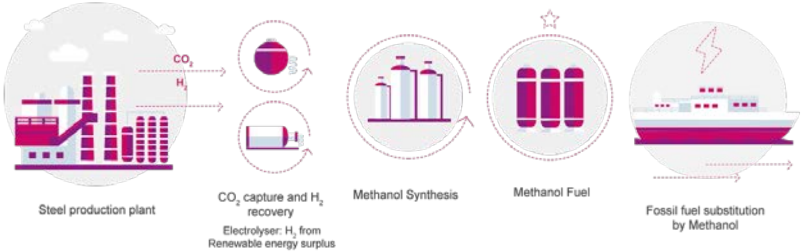
MANY INITIATIVES

Covestro Polyols

CRI Methanol

H2020 Steelanol





H2020 FReSMe project

CHALLENGES

- Often renewable H_2 required
- Most often other options are economic more favourable
- Climate benefits are questioned
- Many routes are still in infancy



A POSITIVE BUSINESS CASE

ECN › TNO innovation for life

ENERGY CONTAINING RESIDUAL STREAMS

- Unique feature of current steel making processes
- Presence of diluted energy containing streams

Gas type	CO_2	CO	N_2	H_2	CH_4	LHV (MJ/Nm^3)
BFG	22	22	49	4	--	3.2
BOFG	14	57	14	3	--	7.5
COG	2	5	7	62	24	15.3

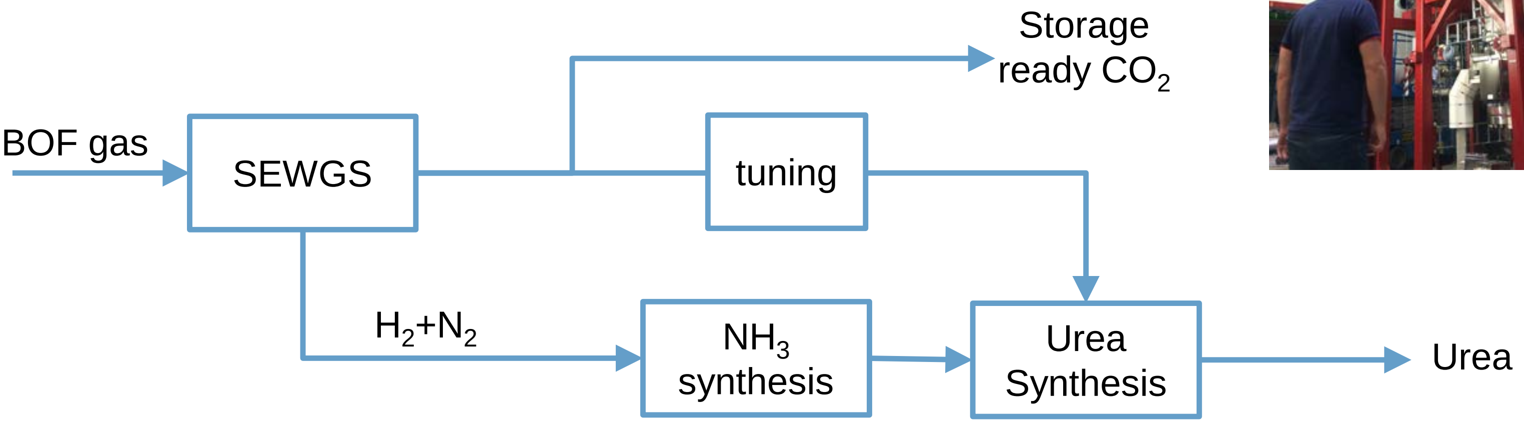
10Mt/year Iron&Steel Mill, see IEAGHG report on Iron&Steel,
http://www.ieaghg.org/docs/General_Docs/Reports/2013-04.pdf

BFG – Blast Furnace Gas
BOFG – Basic Oxygen Furnace gas
COG – Cokes Oven gas

ECN › TNO innovation for life

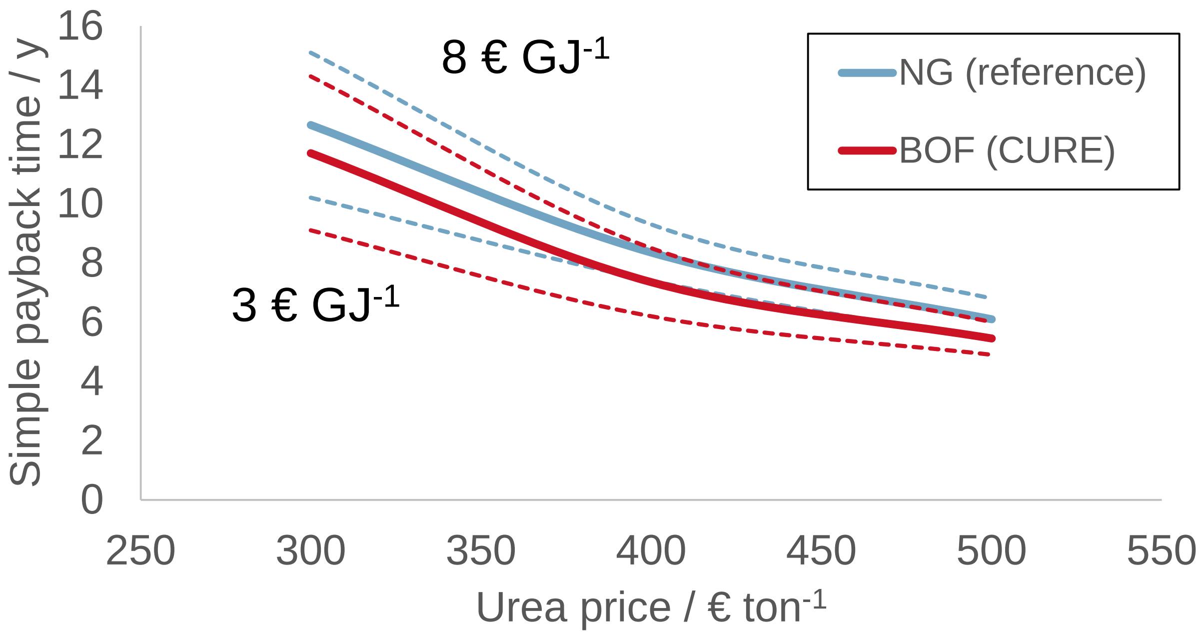
ENERGY TO VALUE ADDED CHEMICALS

- Currently energy is used for electricity production
- After STEPWISE technology
  - N_2 goes with the H_2
  - Treated BOF gas has the right H_2/N_2 ratio for ammonia synthesis

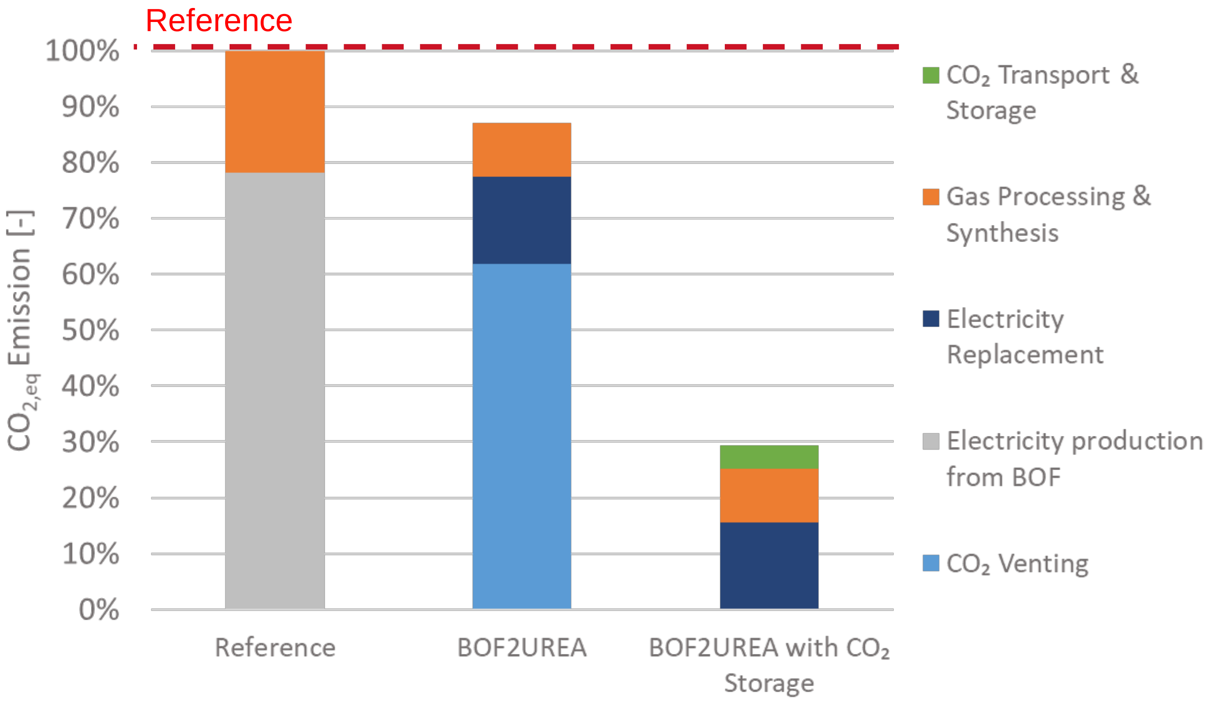


BUSINESS CASE

- Comparable economics for natural gas based and BOF-gas based urea
- Urea pays for capture technology, storage ready CO_2 as side product



LIFE CYCLE ANALYSIS



- Global Warming Potential (GWP) reduction of ~13% without CO_2 Storage.
- 70% $CO_{2,eq}$ avoided if deployed with storage and transport.
- Electricity consumption is the primary source of remaining $CO_{2,eq}$.

THANK YOU FOR YOUR ATTENTION

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TNO.NL/ECNPARTOFTNO

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ERA CCUS Investments

Mission Innovation Challenge CCUS Workshop

Mark Summers (msummers@eralberta.ca)
Emissions Reduction Alberta

June 19, 2019

EMISSIONS
REDUCTION
ALBERTA

Emissions Reduction Alberta (ERA)

MANDATE

Reduce greenhouse gas (GHG) emissions and grow Alberta's economy by accelerating the development and adoption of innovative technology solutions

VISION

Alberta has competitive industries that deliver sustainable environmental outcomes, attract investment, and are building a diversified, lower carbon economy.

STRATEGIC PRIORITIES

1. ACCELERATE TECHNOLOGY
2. DRIVE COMMERICALIZATION
3. MAXIMIZE IMPACT

EMISSIONS
REDUCTION
ALBERTA

Alberta, Canada

EMISSIONS REDUCTION ALBERTA

ERA

What We Fund

Projects that accelerate innovative solutions that secure Alberta's success in a lower-carbon economy

Scientific Discovery* TRL 1–2	Applied R&D	Technology Development	Technology Demonstration	Commercial Implementation
	TRL 3–4	TRL 5–6	TRL 7–8	TRL 9+

Cleaner Oil and Gas

Low-Emitting Electricity Supply and Demand

Food, Fibre, and Bioindustries

Low-Carbon Industrial Processes and Products

EMISSIONS
REDUCTION
ALBERTA

ERA Investments Overview

TOTAL PROJECTS:

163

FUNDS COMMITTED:

$571M

TOTAL VALUE:

>$4.5 B

CUMULATIVE GHG REDUCTIONS BY 2030:

43 Mt CO_2e

GDP IMPACT IN ALBERTA BY 2023:

>$2B

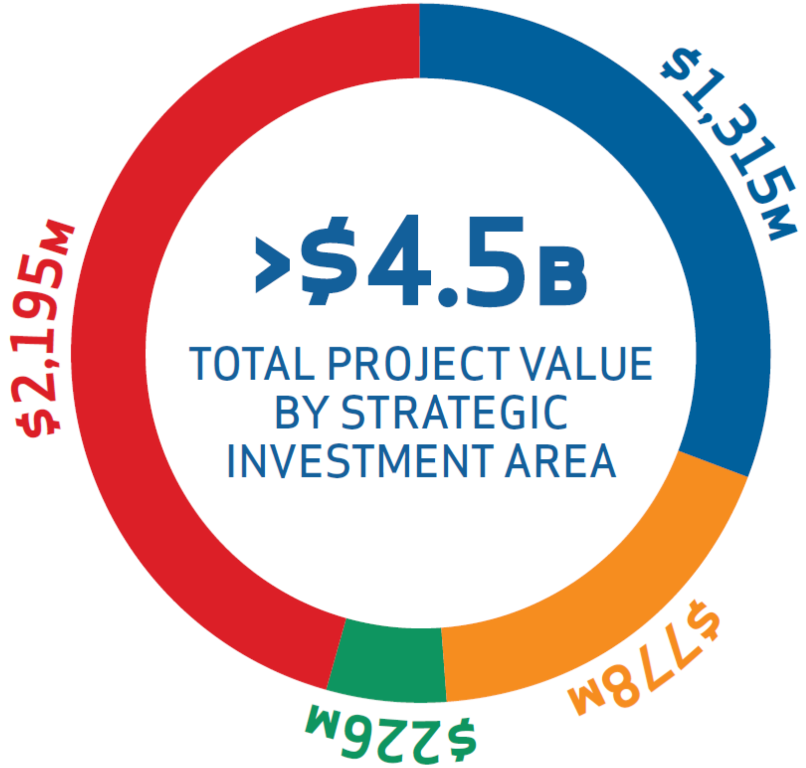
JOBS CREATED IN ALBERTA BY 2023:

>18,000

PERSON-YEAR)

EMISSIONS REDUCTION ALBERTA

Investments by Strategic Area



- Cleaner Oil & Gas (57 Projects)
- Low Emitting Electricity Supply & Demand (26 Projects)
- Low-Carbon Industrial Processes & Products (34 Projects)
- Food, Fibre & Bioindustries (46 Projects)

Carbon Capture Technologies: ERA and AI

- **Chemical solvent**: HTC Purenergy
- **Enzyme Enhanced Chemical solvent**: CO_2 Solutions
- **Oxy-fuel combustion for SAGD**
- **Solid sorbent**: Inventys
- **Solid sorbent**: UO and PNNL
- **Polymeric membrane**: MTR
- **Polymeric membrane**: NTNU
- **MCFC and SOFC**
- **Cryogenic Capture**: Sustainable Energy Solutions (SES)
- **ITM oxygen membrane**
- **Direct Air Capture**: Carbon Engineering

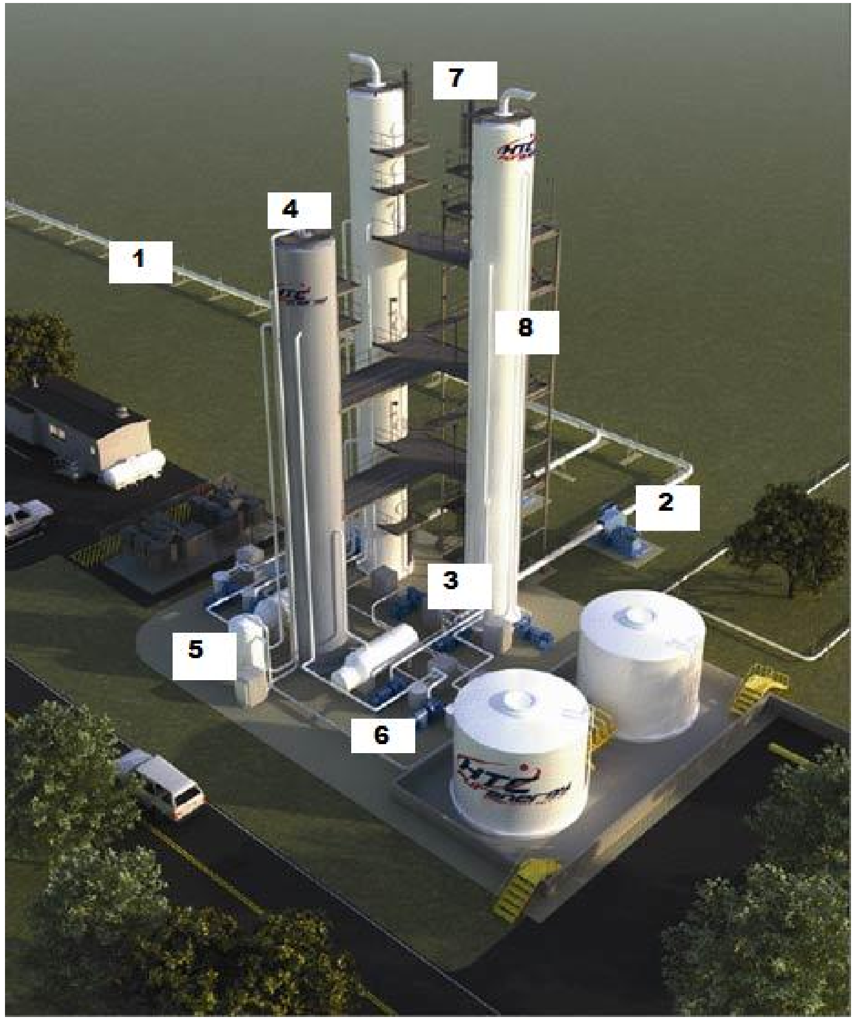
EMISSIONS REDUCTION ALBERTA

ALBERTA INNOVATES

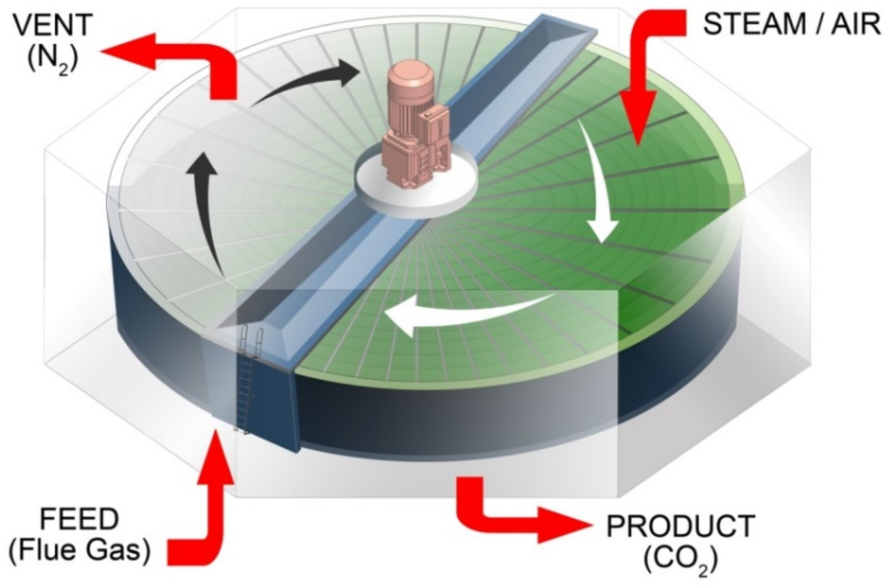
HTC-Husky: Modified Amine Process

- HTC Purenergy System
- Solvent and packing system improvement
- Modular system tailored for SAGD

- 30 TPD field demonstration
- Located at Husky Lashburn facility
- CO_2 captured from a slipstream off of a 50 MMBtu OTSG
- Captured CO_2 transported to nearby field for enhanced oil recovery



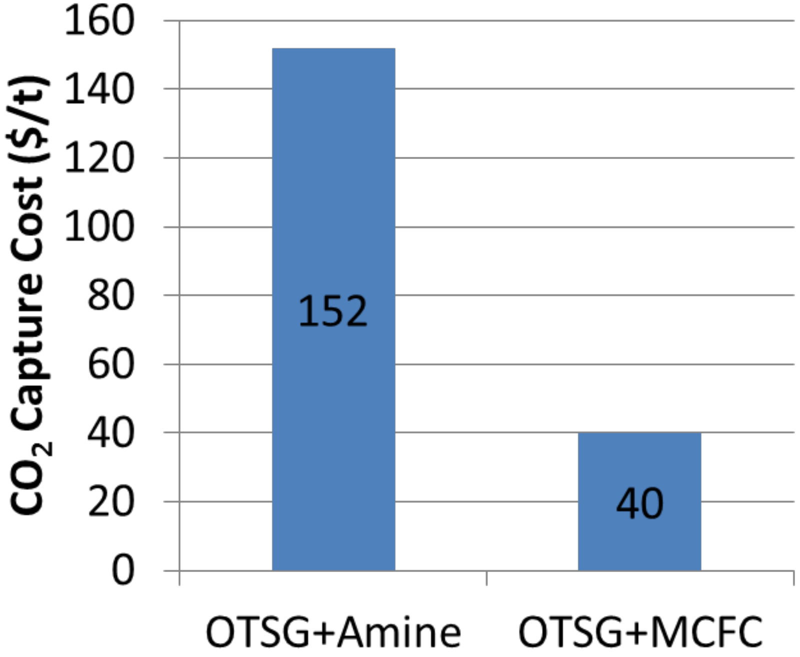
Inventys: Solid Sorbents



- Unique process design
- Lab pilot complete
- 30 TPD field pilot at Husky Lashburn under construction

Molten Carbonate Fuel Cell (MCFC) for Capture

+



- Good integration with SAGD
- 90% CO2 capture + heat + power + water

- 200 kW pre-FEED JIP
- 1.4 MW demo being developed

EMISSIONS REDUCTION ALBERTA

Commercial-Scale CCS in Alberta

- **Shell Quest**: 1 million tonnes of CO_2 each year from the Scotford Upgrade, in operation

- **Alberta Carbon Trunk Line**: under construction

ERA Grand Challenge

SCHEDULE	Phase 1	Phase 2	Phase 3	Phase 4
Round 1 2013-2016	**GLOBAL LAUNCH** 2013 Open to all applicants globally	**DETAILED PROPOSALS** By invitation only	**AWARD EVENT** April 2014 **24** Awards CAD **$500,000** **$12** MIL in Grants	**2 Year Technology Development**
Round 2 2016-2019	**GLOBAL LAUNCH** 2016 Open to all applicants globally	**DETAILED PROPOSALS** By invitation only	**AWARD EVENT** March 2017 **4** Finalists CAD **$3** MIL Grant CAD **$12** MIL in Grants	**2 Year Technology Demonstration**
Round 3 2019+	**BUSINESS PLAN** 2013 Open to all applicants globally	**EVALUATION** of Round 2 Finalists SUBMISSION DEADLINE: July 2019	**AWARD EVENT** October 2019 CAD **$10** MIL Commercialization Grant	**Technology Commercialization**

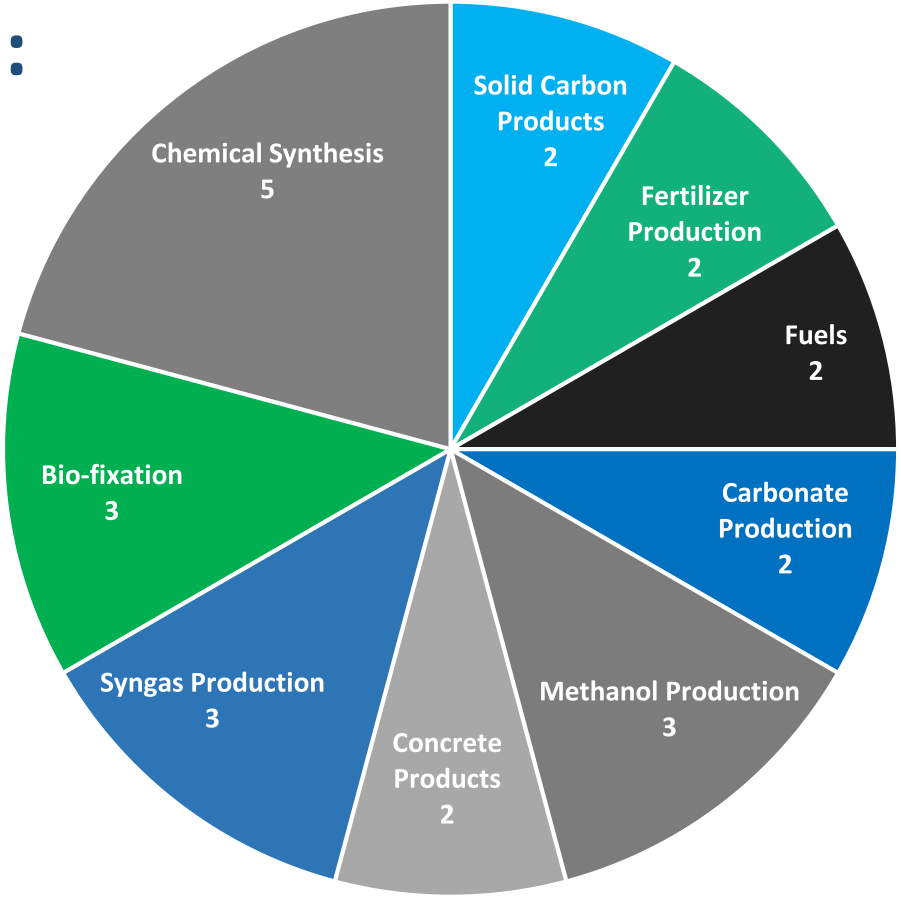
NRG COSIA Carbon XPRIZE

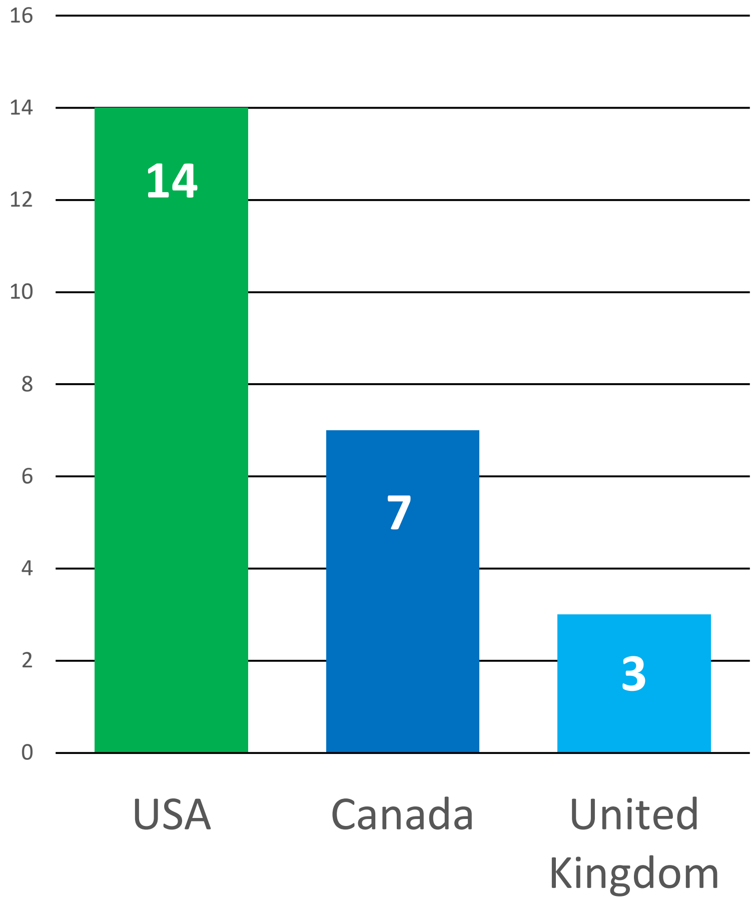
(separate, but complimentary)

ERA Grand Challenge Round 1

24 Projects Funded:

- $25M project value
- $12M ERA funding



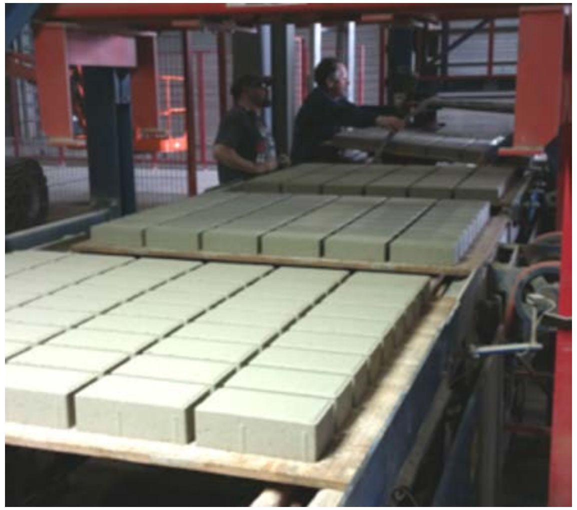


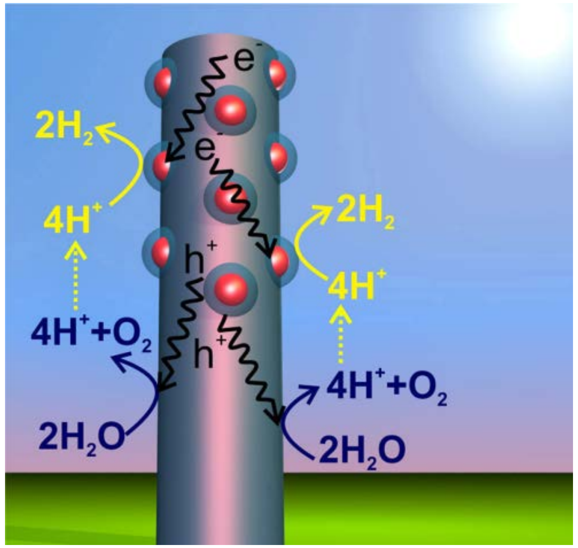
ERA Grand Challenge Round 2

Four Projects Ongoing:

- **Solidia**: A Sustainable Method for Cement Production and CO_2 Utilization
- **CarbonCure**: Carbon dioxide utilization in concrete
- **UBC/Mangrove**: Field pilot demonstration of conversion of carbon dioxide and desalination of wastewater in Alberta
- **McGill University / Lumenfab**: Carbon Dioxide Transformation System Powered by Sunlight

One finalist to be selected for $10M grant





CARBON+

Doing more with less impact on what matters most

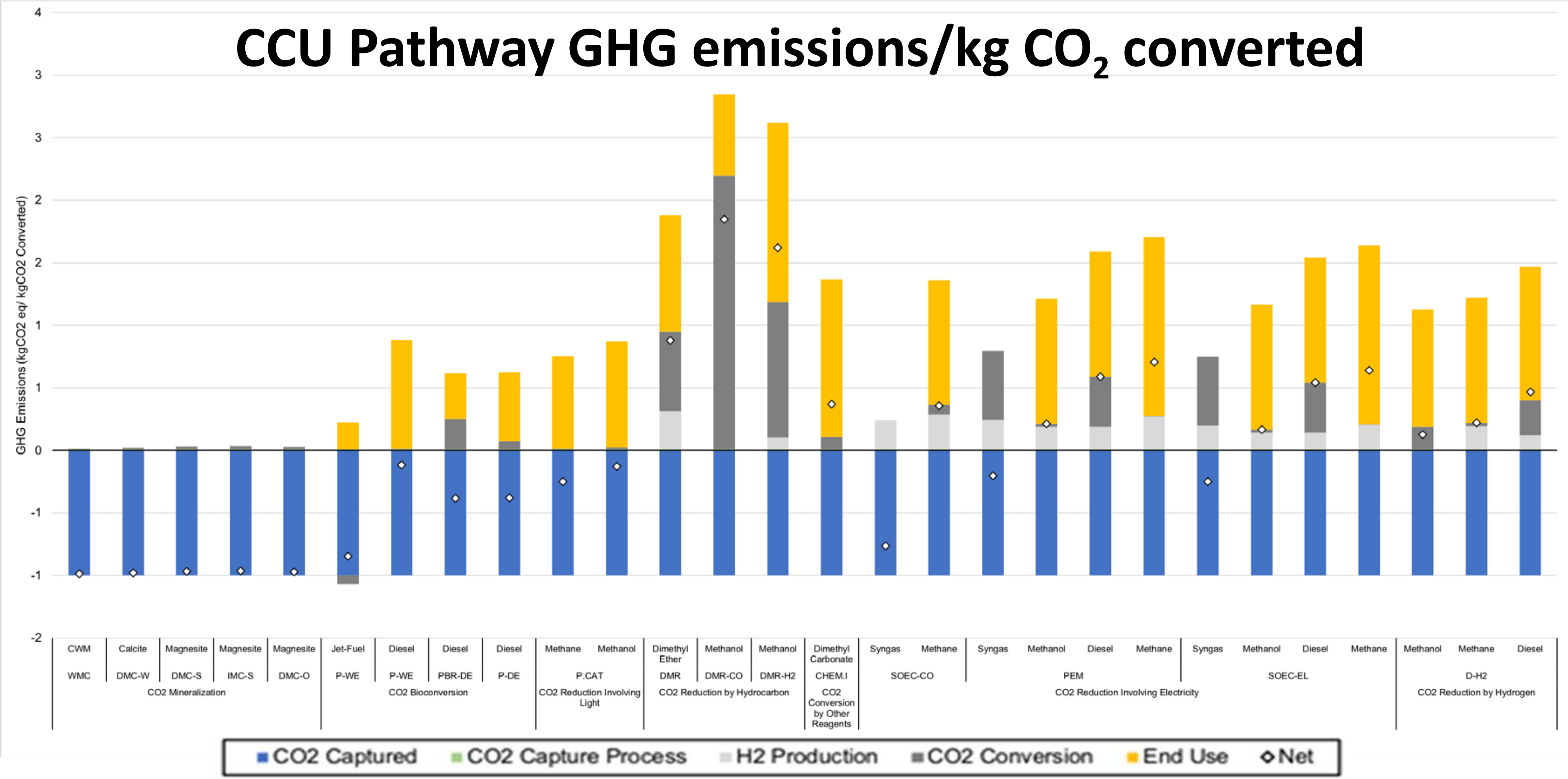
October 28-30, 2019

Edmonton Convention Centre

Register at: eralberta.ca/SPARK-2019

SPARK

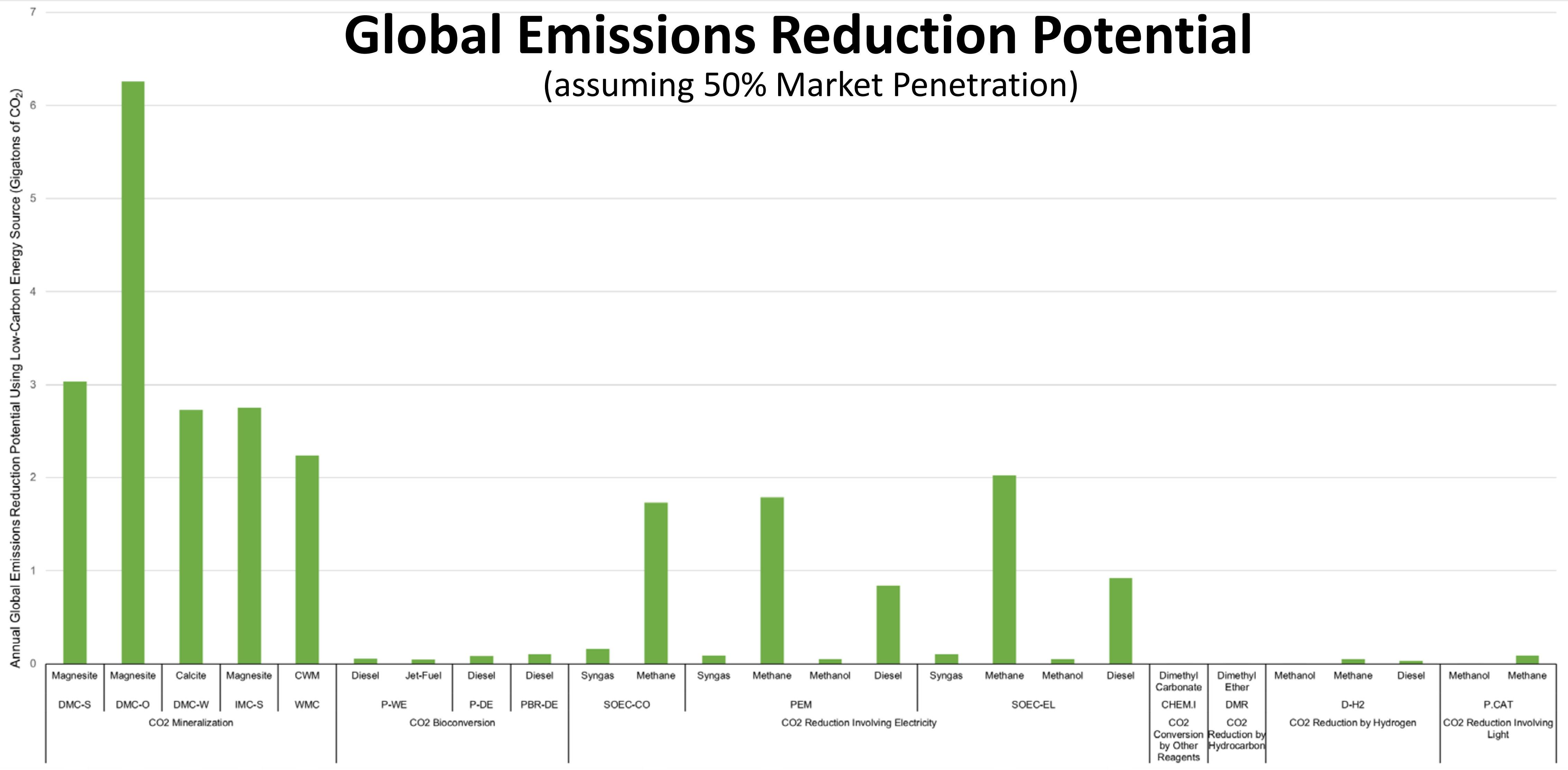
CCU Pathway GHG emissions/kg CO_2 converted



Energy and Hydrogen input from **low carbon sources**

Global Emissions Reduction Potential

(assuming 50% Market Penetration)



Energy and Hydrogen input from **low carbon sources**

EMISSIONS REDUCTION ALBERTA

Partnership Intake Program

- New program launched in 2018
- Funding for projects referred by *Trusted Partners*
- Leverage organizations with fair, rigorous processes
- Allows ERA to better respond to needs of innovators
- To date, $28.4 million for 8 projects worth $650 million
- 12 trusted partners currently, for example:

ALBERTA INNOVATES

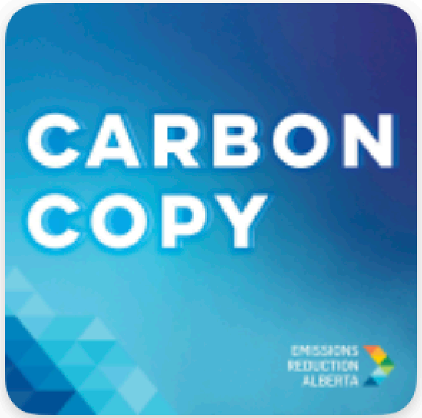
Natural Resources Canada | Ressources naturelles Canada

Canada

SUSTAINABLE DEVELOPMENT TECHNOLOGY CANADA
TECHNOLOGIES DU DÉVELOPPEMENT DURABLE CANADA

NGIF
NATURAL GAS INNOVATION FUND
GAZ NATUREL FINANCEMENT INNOVATION

EMISSIONS REDUCTION ALBERTA



EMISSIONS REDUCTION ALBERTA
ERALBERTA.CA

Carbon Copy is a show about the technology, engineering and economics of a low carbon future. Join host, Dr. Mark Summers, as he dives into the topics and technology innovations that are critical to delivering sustainable environmental outcomes, attracting investment, and building a diversified, lower carbon economy. Carbon Copy, a new podcast from ERA, takes a closer look at the technologies and people that will change our climate impact and help reshape Alberta's economy.

iTunes

STITCHER

OVERCAST

Appendix 4:

Presentations from group work sessions (slides)

Trondheim Workshop,

June 19-20

Topic no: 1

Decarbonizing industry sectors

1. Which opportunities are identified from an industrial point of view?

- CCUS is the only current mature technology able to dramatically reduce process CO_2 emissions. Opportunity for deep reduction (net zero emissions) by BECCS.
- "Waste heat" available for the CO_2 capture system: integration of the production & consumption of heat/steam/energy between the production facility and the CO_2 capture unit. Industry offers an opportunity for partial capture at moderate cost
- Flexibility on getting tailored CO_2 capture systems based on the site/region specifications
- Starting with the "low hanging fruit": capturing the "easy" CO_2 ,higher concentration emissions. Opportunity to scale-up by CO_2 will demonstrate economic benefits.
- Wide varieties of CO_2 capture technologies. Opportunity to tailor those to the flue gas/facility. Some knowledge transfer from the power sector to the production facilities, and stimulating dialog, learning from the past mistakes/success
- Solids looping technologies may play a role integrated in the cement production emissions.

2. How do we most effectively get from research to commercial product?

- Database that contains the successes and failures of projects
  - Where did the pathway fail and why? Early risk identification
  - Can we make use of existing databases and build upon those?
- Starting on the learnings from the power sector or existing plants: available space, available waste heat. Business model analysis. Flexibility on the electricity grid and/or base load following renewable energy
- Build larger demos and test centers for other industrial emissions
- Appropriately sizing pilots and demonstration – often based on available funds?
  - Evaluating the need and the success/failure metrics
  - Starting with the learnings, and tailoring the systems to the specific facility
- Incremental scale-up by CO_2 emissions sources in the production plant or by size

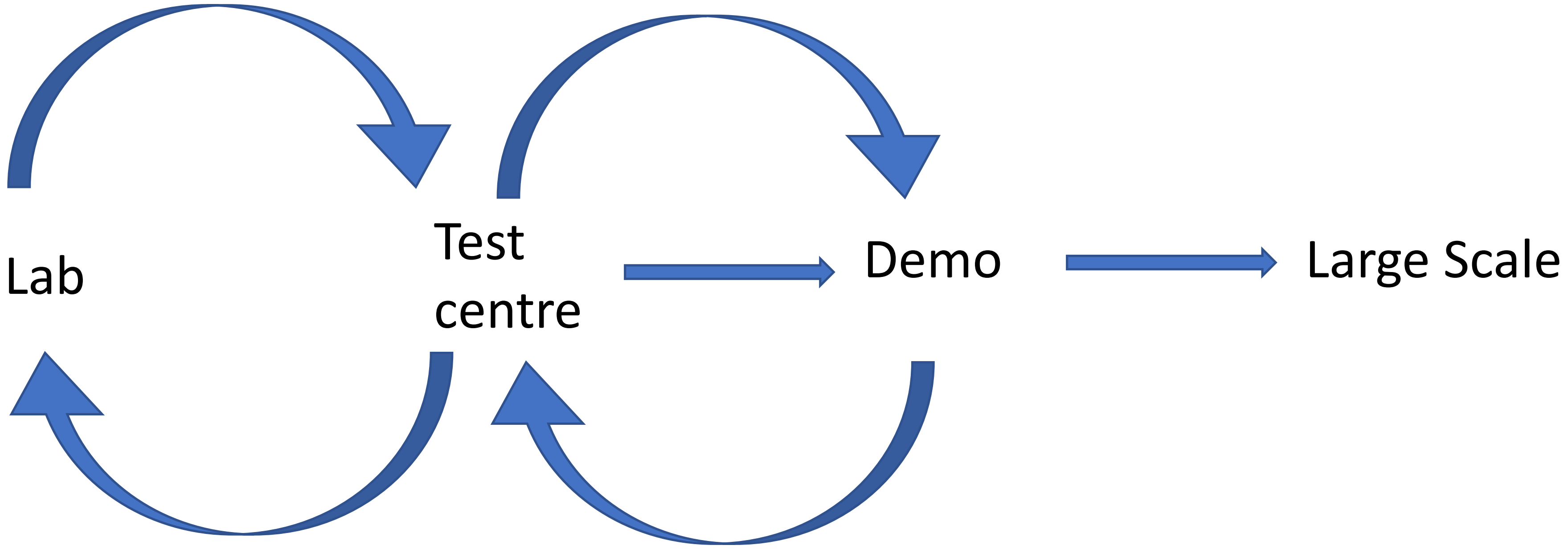
MISSION INNOVATION

2. How do we most effectively get from research to commercial product?

- Knowledge sharing and openness, from academia to private partners. Joint activities
  - Data sharing of all commercial processes, international test center network (including visiting facilities), ACT, harmonizing data, standardization and building plants for different industrial sources.
- IP-sharing: challenging task, that is the bread and butter of the vendors
- At long term: Recognize regulation/standards is important
  - Not wait for unicorn technologies, try to shorten time for construction and operational permits

MISSION INNOVATION

Iterative learning process before scaling-up



MISSION INNOVATION

3. What joint activities could be established to accelerate deployment?

- Public engagement in parallel with technology development, facilitate championing CCS plants in operation
- Educating non-conventional stakeholders
- Social engineering: encouraging people to buy low-CO_2 footprint products (consumers will drive the market price)
- Standards (in the long term), incentives or market pull
- Transfer knowledge and business models from operating plants to other industry, and from one plant to another
- Joint effort on consistent requirement for reporting on successes and failures
- Making use of development banks, linking construction opportunities with financial institutions, a gap exists between the two groups

3. What joint activities could be established to accelerate deployment?

- At early stages we have a lot of governmental support, students and universities
  - Difficult to get support at higher TRLs, when you have to test at scale (TRLs 4-8 are the valley of Death!)
- We need to learn how $DeSO_X$ and $deNO_X$ became a commercial success with lower costs through just building plants with engineering improvements.
- Global governments need to share incentives for CCS

MISSION INNOVATION

3. What joint activities could be established to accelerate deployment?

- Existing financial structures: Revenue models, risk management, funding, capital & ownership need to be shared openly
- Buisiness cases – who can offer which services? Multiple stakeholders in different industry sectors
- 45Q market pull
- Interaction between industries (e.g. H_2 production with steel or chemicals production)
- Increase on production cost assumed along the final product chain
- Joint procurement commitment, involving government procurement

MISSION INNOVATION

3. What joint activities could be established to accelerate deployment?

- International partnership, learning from projects and other industries, what works where → brings down risks, attracts investors and the public, and keeps them
  - Trying to get more partners and countries into fewer centres of excellence!!
  - Communicate our failures and and how problems were solved, highly valuable!
  - Engage with the financial industry
- Sharing liability and risks to help technology progress in capture and storage
- Creating a backbone CO_2 infrastructure, a public good! Opportunity of clusters and hubs
- Evolving roles of public-private partnerships. As the projects and infrastruture evolves, the public partnership might have a smaller role and the market will take over

MISSION INNOVATION

Trondheim Workshop,

June 19-20

Topic no: 2

The role of CCS in enabling clean hydrogen

Questions to be discussed under each topic:

1. Which opportunities are identified from an industrial point of view?
2. How do we get most effectively from research to commercial product?
   a. What steps are needed?
3. What joint activities could be established to accelerate technology development and implementation?
   a. How can joint action accelerate deployment?
   b. Business models: What funding instruments are/could/would be effective?
   c. Mobilizing national efforts towards international efforts
   d. Public-private partnership, co-funding

MISSION INNOVATION

1. Opportunities from Industrial point of view

- Overarching opportunity: Need to decarbonise!
- Specific opportunities:
  - Heavy duty transportation
  - High temperature heat – difficult to electrify
  - Reducing agent – feedstock for industry
  - Energy storage
  - Climate positive from biomass with CCS
  - Both CO2 and H2 could be a feedstock (EOR..)
- At the moment, H_2 with CCS has a lower carbon footprint and cost than H_2 from electrolysis
- Can avoid shipping CO_2 , ship H_2 instead – avoid London protocol

MISSION INNOVATION

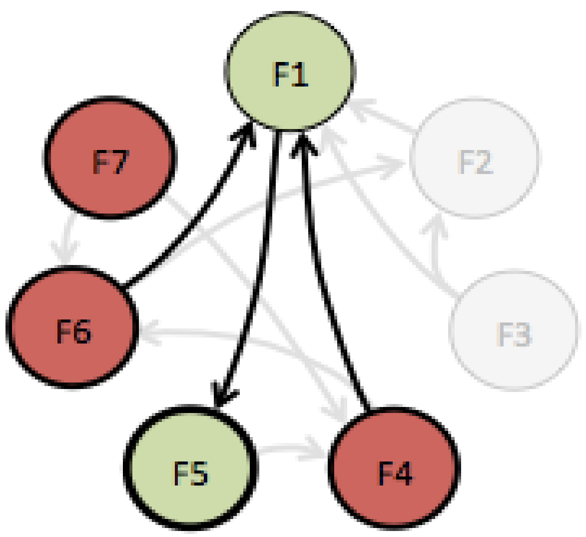
1. Opportunities from Industrial point of view

- Re-use of existing infrastructure
- Re-use existing competence
- Magnum, H21, H-Vision (Rotterdam)
- There is no ‘one size fits all’

MISSION INNOVATION

2. From research to commercial product - *effectively*

- Successful innovations need many factors for their success (M. Hekkert)
- Demonstrations will only happen when all these functions develop



Prof. Dr. Marco. Hekkert, Utrecht University, is working on innovation system analysis. There are various publications that explain the seven functions for innovation.

Seven functions, that are all needed to make the innovation successful

F1 Entrepreneurial experimentation

F2 Knowledge development

F3 Knowledge exchange

F4 Guidance of the search

F5 Market formation

F6 Resources mobilisation

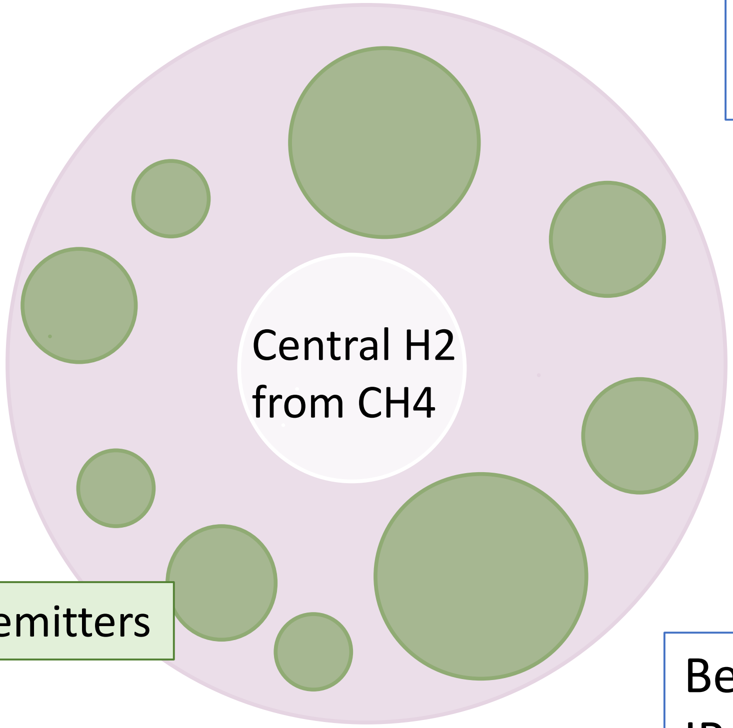
F7 Legitimacy creation

MISSION INNOVATION

2. From research to commercial product

Policy
Direction
Support
Vision
Consistent

Public perception
Support
Challenge
Want more (…or less)



Storage
National H2 grid
Use in transport/homes/etc.

Industrial cluster with CO2 emitters

Best practice
IP

Focus Research
Access knowledge

Infrastructure CO2, H2?
Public/private

2. From research to commercial product

- Thinking the whole value chain – master complexities, inform choices
- Go for large scale: impact, well-informed
- Go for small scale: room for experiments, quick decisions, niches
- Academia should inform discussions
- ‘Middlemen’ are needed to link the chain
  - Suggest opportunities
  - Industrial symbiosis

2. From research to commercial 'product' - *Effectively*

- Value chain demonstrations
- Knowledge sharing
- In absence of clear CO2 regulation or a clear price for CO2 emission - Government funding – consistent in time – and international level playing field
- International cooperation on test centre, 'TCM for hydrogen'
- Regulation to mandate low carbon content
- Encourage international collaboration and joint industry projects
- Vibrant market for technology vendors
- Encourage industry clusters

MISSION INNOVATION

2. From research to commercial ‘product’ - *Effectively*

- Supporting policies and regulations for use of H2 produced with CO2 capture
- Honest about safety
- Demonstration projects should consider
  - Capture rate
  - Energy requirement, purity of CO2, liquefaction CO2 etc.
  - Opportunity for energy storage, H2 or NH3
  - Public acceptance

MISSION INNOVATION

3. Accelerating implementation

- *Integrated in discussion of questions 1 and 2!*

Trondheim Workshop,

June 19-20

Topic no: 3

CO2 storage & networks

1. Which opportunities are identified from an industrial point of view?

- Large-scale CO_2-storage creates enormous business potential
  - Technical knowhow is there (e.g. O&G), but perception issue
  - Opportunities for new business/companies, incl. independent assessment bodies
  - Motivated young people, green topics, open (publishing)
  - Added value by/for complementary activities (water production, EOR, energy production and storage)
- Quantify project risks and benefits
  - Risk quantification; injection wells and legacy wells
- Digitalization / big data applied to CO_2 storage & transport/networks
  - Sharing of data, knowledge
  - Machine learning
- Develop cost-effective storage and transport hub systems

MISSION INNOVATION

2. How do we get most effectively from research to commercial product?

- Projects at scale beyond lab: field projects, pilots, real projects
    - Technology development/testing
    - Additional role: public perception role, local technology demonstration
- Mature R&D technologies in specific fields: *pressure management, *fault & fracture risk, *well integrity, *resource optimization/mobility control, *pipeline fracture propagation, * network & hubs planning tools
    - Many of them need pilots/demos, application in full-scale projects
- International cooperative project «International Earth Geonome project» (like Biogenome project, Space station, IODP)
    - Mapping national storage resources similarly to other resources
    - Big international test site
- «MI project» twining idea – 2 or more countries together on specific projects (technology development, pilot & demonstration)
- Transparency / openness
    - Proactive communication on risk and mitigation (NASA approach), balance with info on benefits
- Regulatory rules

MISSION INNOVATION

3. What joint activities could be established to accelerate technology development and implementation?

- Data sharing and using international digital platforms
  - Stimulate data sharing by public incentives (e.g. tax)
- MI Platform for sharing stories, knowledge and case studies
  - Better use of existing technical knowledge
  - Facilitates public communication and risk quantification
- Engage with insurance industry in building confidence in storage
- Maturation of international certification process for bankable storage resource
- Standardization of terminology and processes
- Establish internationally recognized CO2 storage software (open source)

MISSION INNOVATION

PRDs

- Advancing multiphysics and multiscale fluid flow to achieve capacity
- Understanding dynamic pressure limits for GT-scale CO2 injection
- Optimizing injection of CO2 by control of the near-well environment
- Developing smart convergence monitoring to demonstrate containment and enable storage site closure
- Realizing smart monitoring to assess anomalies and provide assurance
- Improving characterization of fault and fracture systems
- Achieving next-generation seismic risk forecasting
- Locating, evaluating, and remediating existing and abandoned wells
- Establishing, demonstrating, and forecasting well integrity

MISSION INNOVATION

Questions to be discussed under each topic:

1. Which opportunities are identified from an industrial point of view?
2. How do we get most effectively from research to commercial product?
   a. What steps are needed?
3. What joint activities could be established to accelerate technology development and implementation?
   a. How can joint action accelerate deployment?
   b. Business models: What funding instruments are/could/would be effective?
   c. Mobilizing national efforts towards international efforts
   d. Public-private partnership, co-funding

MISSION INNOVATION

Trondheim Workshop,

June 19-20

Topic no: 4
Storage Monitoring

Monitoring Verification and Performance Metrics

Agenda of Subpanel Workshop

- Context setting by the chair– 30 min
- Divide into groups to discuss topics- 1.5 hours
  - Introductions –country and expertise
  - Choose a group chair/reporter
  - Refine the topics enough to answer the questions
  - Put ideas on a PowerPoint presentation
- Lunch – 45 min
- Plenum to report/integrate ideas for reporting – 1.5 hours

Given that…

- Regulations require some form of monitoring
- Many tools and techniques have now been tested at demonstration projects
- Technological advances present new opportunities to further improve capabilities
- Challenges are within the context of upscaling, knowing that many projects may operate in close proximity creating large volumes
- Approaches will apply to either deep or shallow zones

taken from the Report of the Carbon Capture, Utilization and Storage Experts' Workshop `Storage Panel: Monitoring, Verification, and Performance Metrics, September 2017

MISSION INNOVATION

Challenges Outlined in MI 2017 Report (Groups for discussion)

1. Monitoring to demonstrate containment and enable site closure: Transforming far-field monitoring with new tools to directly measure state variables
2. Smart monitoring in the far-field
3. Improving methodologies for monitoring plans
4. Improving interpretation and use of large, complex data sets
5. Assessing anomalies and providing assurance – location, attribution, quantification

MISSION INNOVATION

Challenges Integrated into 3 Discussion Groups

1. Closure and Far-Field Monitoring to demonstrate containment and enable site closure: Transforming far-field monitoring with new tools to directly measure state variables
2. Assessing anomalies and providing assurance – location, attribution, quantification
3. Well remediation monitoring

Questions to address under each topic:

1. Which opportunities are identified from an industrial point of view?
2. How do we get most effectively from research to commercial product?
    a. What steps are needed?
3. What joint activities could be established to accelerate technology development and implementation?
    a. How can joint action accelerate deployment?
    b. Business models: What funding instruments are/could/would be effective?
    c. Mobilizing national efforts towards international efforts
    d. Public-private partnership, co-funding

MISSION INNOVATION

Closure and Far-Field Monitoring

Identified Industrial Opportunities

- Pilot closure project
  - Goals & approach: identify monitoring plan with minimum cost, evaluate the value of information and monitoring technologies, what is the monitoring system that is most efficient given a site? Highly instrumented, test out the impact of reducing information on evaluating closure; Advance monitoring techs to high TRL
- Learn from existing projects: Ketzin, Tomokomai, Aquistore
- There is an opportunity for a centralized organization to facilitate co-operative activities
- Technologies – There is an opportunity to advance monitoring technologies, both low and TRL, to contribute to site closure
- Research "What if":
  - Understanding speed limits to CO2 migration and interaction with the overburden
  - Advance lab to field characterisation technology to provide stronger predictive modelling capabilities
  - Use digital twins to explore unlikely scenarios

MISSION INNOVATION

Research to Commercial Product

- Pilot study - Learning by doing with goals to advance the TRL with the site
- Best practices and data shared from regional, national, state, company experiences
- Defining closure: Key question is how do you show that mass evolution has reached stasis; Should be able to discuss with the regulator how risks will evolve in the context of the specific project, e.g., depleted gas field – from the start of project you should also be working towards closure; Need to follow a trajectory where model uncertainty is large at the beginning of the project and narrow later, this is accommodated in Norway where they also are allowed to define their definition of closure, i.e., how will you be able to demonstrate this; There needs to be flexibility for the precise definition, e.g., of conformance, closure, to allow for knowledge gained during the course of a project; Regulatory agencies need to not be fixated on a particular outcome; Requirements for ongoing monitoring conformance and closure are very similar
- How will closure occur? – operators will keep projects going, they will look for opportunities to step out, operators like to be involved in regional development; There are major costs associated with closure; The reasons for, e.g., continuing, developing, closing, are often the result of complicated issues;

MISSION INNOVATION

Joint Activities

- Pilot closure project
- Far field - Data sharing and cooperation between neighboring fields Use existing infrastructure in neighboring areas; In the far field; Seismic in the marine environment often pick up each others' signals and operators are interested in this information; Tomography of overlapping data is useful in regional scale . Pressure interference between wells, vertical and horizontal, at scale between projects
- General – learning from experiences; There is a lot that could be learned from, e.g., the Norwegian experience; Onshore and offshore are different beasts – a lot more information onshore, fewer technology options
- Centralized organizations would help to facilitate co-operative activities

Funding Mechanisms and Business Models

- Evaluate existing models and settings: Norwegian, Canadian, and Texan models – differences in closure definition, data sharing, post-closure liability
- Mobilizing national efforts towards international efforts
- Sharing information – data sharing , benchmarking, collaboratively on same problems
- Large projects with international collaboration, e.g., CaMI
- International R&D funding mechanisms like the ACT project
- Public-private partnership, co-funding
- International R&D funding mechanisms like the ACT project

MISSION INNOVATION

Assessing anomalies and providing assurance

Identified Industrial Opportunities

- Cost effective, confidence, show compliance to regulatory, public acceptance
- Monitoring tools and techniques that can both attribute and quantify leaks – without needing baseline (ref. argument that near surface is so variant)
- Deciding what types of data to collect, to reduce costs and provide assurance
- Third party monitoring? Helps public acceptance…
- Machine learning + process/models understanding
- Utilize wells drilled checking soil conditions before installation – can you put some sensors and information?
- Risk based monitoring; faults and wells
- Deep monitoring to inform shallow monitoring, including overburden characterisation
- Combining physical measurements for locating features with geochemical assessment
- Quantification technologies and approaches

Research to Commercial

- Tools ready to go – tested.
- Need to have vendors involved in the development
- Funding pre-commercial developments

Joint Activities

- Access to data – share what is done from projects. Funding to utilize data
- A mechanism to connect researcher with the industrial data set
- Good area model – need exploration data. For example, if there is an area in the North Sea that is identified as storage hub.
- Projects learning by doing – connect funding and R&T to extract learning to broader community
- How do you use large data set and look at anomalies. Bring experts together with AI (Artificial Intelligence). (reference to medical).
- Learn from other fields, health in house treatment of data

other (messy) notes

- Moving away from baseline monitoring…
- Assessing anomalies - Combining data to look for anomalies
- Bow tie risk assessment
- We have set up the expectation very high – ten times more than O&G. Post operation monitoring…
- Need a good risk analysis and understand where the risk are for CO_2 leakage – and monitor these
- Everybody feel safe that CO_2 is stored in three – but nobody care if the three is felt…
- Hard to put properties on faults… micro seismicity
- How can we integrate the monitoring in the deep surface with what we do at the seafloor…..
- Design the seafloor monitoring? Governed by the risk
- New types of technologies that can help design risk based and cost-efficient seafloor monitoring
- Characterization of overburden
- Shearwave good for the shallow – pockets of gas.
- Instrument that can find chimneys acoustically
- Monitoring work-flow – what informs what ----
- Process-based approaches

MISSION INNOVATION

Monitoring legacy well integrity and intervention

MISSION INNOVATION

Identified Industrial Opportunities

- Leakage from **legacy wells**/faults/reservoir-containment presents a high risk
- Remediation/intervention procedures need to established for licensing, public assurance/education, and actual intervention
- Remediation need to address leakage from legacy wells and containment, and how to deal with different levels in subsurface to the surface remediation (impact on the ecosystem, social perception, impact …)
- Define thresholds (when and how to intervene (and when not))

MISSION INNOVATION

- Identifying legacy wells in the injection site (in both HC fields and aquifers) (technology gap)
  - Establishing procedures for well integrity testing for CO2 integrity (certification) for “enough” period of time. Risk assessment of legacy wells
  - Legal/regulatory/spatial planning context
  - Establishing remediation procedures (how to fix risky wells)
  - Developed technologies for the above points depends on well types (offshore (deep, shallow water), onshore, vertical, horizontal ,…)
  - Deal with sssociated uncertainty
  - How to manage the cost overhead
  - Data availability from data owners/ transparency

MISSION INNOVATION

- **Containment-leak remediation (active-passive methods)**
  - Risk from "surprise" faults. Surprise faults are small-mid size faults that could be below the imaging resolution (technology improvement opportunity).
  - How to deal will leaky faults/fractures => currently immature technology (use cement, gel, polymers, foams, …. Issues related to effectiveness and durability)

- **Social responsibility**
  - Liability (short term?, and long term?)
  - Communication to public (ownership)
  - Private-public-government commitment
  - Establish specialized governmental agencies to respond to leak emergencies (establish procedures, recommendation)
  - Lesson-learned from the failures/successes in the O&G

Joint Activities

- Partnership between stakeholders(companies, states)
- MI to establish an **A-Team**, to advise/intervene when needed
- MI to establish an advisory "peer-review" panel to help "certifying" CCS projects

Trondheim Workshop,

June 19-20

Topic: Going Climate Positive!

Going Climate Positive!

- Tech is here- resource issue
  - Biomass – renewable power – and how about sustainability
- Need a R&I agenda on a global scale- lacks on national scale
- Need to demonstrate CPS!
- Buisness models
- Rising atmospheirc CO_2 imposes a societal cost, removing is a public good, the public renumeration of that is reasonable

MISSION INNOVATION

Questions to be discussed under each topic:

1. Which opportunities are identified from an industrial point of view?
    1. Biomass and secondary biomass (convential and unconvential)
    2. Early adaptors- scaling an issue for for instance DAC(S)
    3. Maximising the value of the biomass resource
        1. Energy to CDR

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Questions to be discussed under each topic:

2 How do we get most effectively from research to commercial product?

- Global resource stocktake (terrestrial and marine)
- Algae and marine biomass important – maximizing yield and value
- Recognizing the cost of carbon- account for damages

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Questions to be discussed under each topic:

3. What joint activities could be established to accelerate technology development and implementation?

- Importance of knowledge sharing and standardization, best practices
- Leveraging R&I co-operation- global broker for climate positive solutions- accounting
- Cost of carbon consumption and scaling up
- No one fits all!- regional and even local solutions will have to play out
- Leveraging and managing consumer purchase power
- Cerification and standardization of Climate positive

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Trondheim Workshop,
June 19-20

Topic no: 6
Utilization

Questions to be discussed under each sub-topic:

1. Which opportunities are identified from an industrial point of view?
2. How do we get most effectively from research to commercial product?
    a. What steps are needed?
3. What joint activities could be established to accelerate technology development and implementation?
    a. How can joint action accelerate deployment?
    b. Business models: What funding instruments are/could/would be effective?
    c. Mobilizing national efforts towards international efforts
    d. Public-private partnership, co-funding

Utilization : sub-topics

- **Fuels/chemicals/plastics**
- **Mineralisation/ building materials**
- **CO_2-EOR**
- **Markets and thermodynamics**

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Sub-topic: Fuels/chemicals/plastics

- Source CO_2 matters: CO_2-products (as chemicals, fuels, plastics) will produce again CO_2 ending up in atmosphere so no GHG mitigation (50% max reduction regards of substitution to fossil products)
- Local potential (niche, small market): interesting for business but not mitigation tool -> will never reduce global emissions *(however no clear consensus on this point : CCU could participate in the reduction of CO2 emissions but never substitute CCS)*
- Mid-term/long-term should be considered for the selection of CCU technologies
- CO_2-fuels : could be the best case for certains sectors (aviation, marine)

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Sub-topic: carbonatation

- Advantages: it is a G-ton market and it is not disruptive (no changes of the technologies)
- Scale up issue: standardisation could help to overcome it
- Need a clear differentiation between the sequestration time of CO_2 in the product and the CO_2 quantity embedded -> set up a label
- Need incentive because cost penalties for mineralisation as tax credit
- Aggregates: flues gases could be used directly (synergy between carbonatation and industries, eg: proximity)
- Need RD: more pilots to assess/ improve the technologies of mineralisation
- Mechanism to harmonize assessment for comparison of products or sources of CO_2
- Legislation issue: waste could be used in carbonatation process but some countries as Germany/France do not allow to use it as raw materials: how to demonstrate safety of these products ?

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Sub topic: CO_2-EOR

- The main need for RD is about expanding storage capacity: switch from optimisation of oil/gas extraction to CO_2 storage
- No incentive should be given (*consensus from the whole group)* -> governments should regulate/ set up a clear framework to communicate on it as a label (?)
- Only low TRL should be considered for national support : need to improve technology at large scale for sustainability (both economic and sustainability)
- Main advantage : facilities already exist (wells, infrastructure,…) -> good opportunity to demonstrate CO_2 storage
- Main disadvantage: fossil fuels should be stopped and CO2-EOR could increase the production *however* fossil fuels are needed during the energy transition and good opportunity for Oil/Gas companies to improve image -> need to communicate why fossil fuels are still needed
- Technology already at commercial scale: proven technology/mature and acceptable in US for energy security and to substitute the use of geological CO_2 by anthropogenic CO_2
- Other opportunity: reduce impact by reusing mature field instead opening new field

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Sub topic: Market-thermodynamics

- Concern about market mismatch and thermodynamics:
  - Too much CO_2 than the need from the market
  - Thermodynamic challenges for most CCU routes: CCU technologies require more energy in than out
- CCU is one part of the solution: not a silver bullet but should not be discarded
- **Importance of LCA and TEA** for identifying the most promising CCU routes
- Market opportunities: already identified but need to be updated (market evolves)
- Different size of opportunities: all routes should be investigated even for niches
- Assessment: boundaries are very important- linking to the sources (CO_2/H_2) to focus on opportunities with high potential of GHG reduction (limited investment)
- Opportunities and benefices: existing chemicals industries could developed new processes through CCU if the market is right through CO_2 tax or regulations
- Synergy between industries (CO_2 sources) and CCU routes: same location (possibility or use directly flue gases), availability of resources (heat, waste,…)
- Better public acceptance of CCU (contrary to CCS): can be used to broaden a public acceptance for CCS if synergy between CCU and CCS.
- Common barrier for CCU and CCS: capture (even if it is not the same scale)

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