CCUS Innovation Analysis

Erin Schols & Earl Goetheer

December 2017

Overview of report

- **Investigation of the innovation that has resulted from the TKI-CCUS Toeslag projects within the CATO program (CATO-2b)**
  - Interviews were conducted with each of the work package leaders plus four industrial participants
  - Results from the work packages have been analysed with respect to the current state of the art in the field and the contributions to the field from the completed work
- **Advice on the contours for the CCUS research agenda in the Netherlands**
  - An assessment of the alignment of the Dutch knowledge position with the Mission Innovation priority research directions has been completed
  - This assessment has been translated into an advice for research directions based on how CCUS and decarbonization strategies are imbedded in the Dutch industry

Approach

- Questions were put together on the topics of technical progress, partnering, broader impact, and recommendations
- Each WP leader was interviewed along with four industrial representatives (covering 8 of the 16 work packages)
- The work packages and overall program were analysed based on the interviews, review of reports, and knowledge of the reviewers
- An assessment of the position of CCUS within the Dutch context was completed based on the evaluation of results and alignment with Mission Innovation

Work package overview

No.	Title	WP Lead	Subsidy	End date	Partners
1	How to communicate and share the output from an integrated research programme? A Question & Answer Tree summarizing the CO_2 storage elements of the CATO-2 research program	TNO	40 000	2016.12.31	TNO, ECOFYS, ROAD, TAQA, UU
4	STEP-UP: SEWGS Technology Platform Upgrade	ECN	130 900	2015.12.31	ECN, KISUMA, TATA
7	Identifying challenges and barriers to CCS implementation and defining common industrial interest including drafting a common CCS position paper	ECOFYS	55 000	2015.12.31	ECOFYS, EBN, ROAD, SHELL, TAQA, UU
8	Understanding the requirements for integration of intermittent renewable electricity in low CO_2 emitting power systems with CCS	UU	89 000	2015.12.31	UU
9	Transportation and unloading of CO_2 by ship a comparative assessment	TNO	73 500	2015.12.31	TNO, ROAD
10	Unexpected swelling effects of CO_2 on clays: Good or bad news for CO_2 storage integrity and leak mitigation options?	UU	100 000	2015.12.31	UU, SHELL
11	Innovative tracer injection in K12-B	TNO	125 000	2017.09.30	TNO, ENGIE
12	Legal framework and guidance involving legal issues and regulation of CCS following from the CATO2 Program	RUG	38 400	2015.12.31	RUG, Energy- Valley, ROAD
14	AVR Duiven - CO_2 Capture	TNO	182 687	2017.11.30	TNO, AVR
15	MPP3 Aerosol Characterisation	TNO	23 306	2016.12.31	TNO, ROAD
16	Monitoring the Q16-Maas field	TNO	80 000	2017.06.30	TNO, ONE, ROAD
21	Multi-scale approach for the electrochemical conversion of carbon dioxide to value-added products	Coval	50 000	2018.03.31	Coval, TUD
25	Assessment of the role of CCS in the provision of long-term security of supply and deep CO_2 emission reduction; combining electrification trends, long term detailed weather patterns, and multiple backup options in an interconnected Europe	UU	80 000	2018.06.30	UU, GASUNIE, UNIPER, SHELL
26	Predicting the REactivity of Cement-rock-CO_2 during Annulus Leakage and remediation by Clogging (PRECALC)	TNO	50 000	2017.12.01	TNO, SHELL
27	CO_2 for 3D printing	Green-Minerals	26 130	2018.06.30	BIF, CHILL Green Minerals, TopologX, Zuyd
28	CO_2 Capture from advanced steel production processes	TNO	40 000	2017.10.01	TNO, TATA

Description of scoring for analysis

Category		Green	Yellow	Red
Technical progress	Goals reached	Goals reached within timeframe of project	Goals reached partially or reached after end of project	Goals not reached
	Valuable advances made*	Clear and useful advancement made in the SOTA or current situation	Results achieved but usefulness unclear	Little results or results not relevant for the SOTA or current situation
Partnering	Perception of results	Partners very satisfied with results	Partners neutral about results	Partners dissatisfied with results
	Involvement of partners	Partners closely involved and provided input	Partners only involved to review results	Partners involved to very limited or no extent
	Continuation of cooperation	Cooperation is already continuing or planned to continue with all partners	Cooperation would like to be continued, but no concrete plans yet or not with every partner	Cooperation unlikely to continue
Broader impact	Dissemination	Results disseminated in effective ways	Results disseminated narrowly or uneffectively	Results not disseminated beyond CATO requirements
	Follow up developments	Follow up projects already underway or confirmed	Follow up projects desired, but not yet granted	No follow ups planned
	Exploitation of results	Project results have been patented or are being actively used by the partners	Patentable results identified (but not filed) or use of results by partners in the planning	No IP has resulted from the project and no planned use of results by the partners
	Impact achieved*	A clear impact has been achieved for at least the Dutch context	Potential for impact is clear but has not yet been realized	Impact has only been minor and no greater potential expected
Lessons learned	Effectiveness of program structure	Would definitely participate in such a program again and found it effective	Would participate again, but effectiveness should be improved	Would not participate in such program again or found it not effective
	Need for changes in approach	Would not change approach in WP or no recommendations to TKI	Would change approach to WP somewhat or some recommendations for TKI	Would take different approach to WP or strong recommendations for TKI

** Opinion of reviewers based on interview responses, review of deliverables, and knowledge of the state of the art*

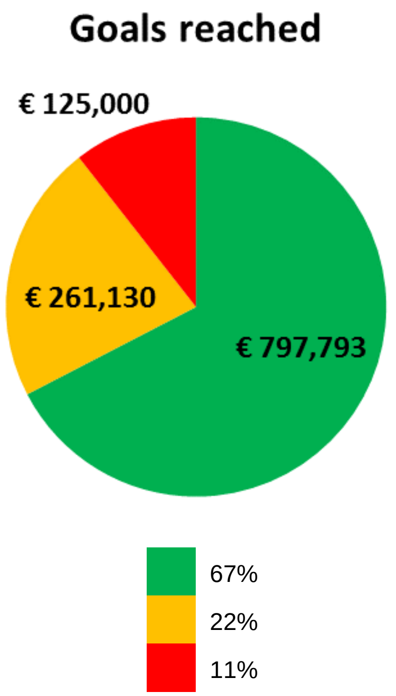
Analysis matrix

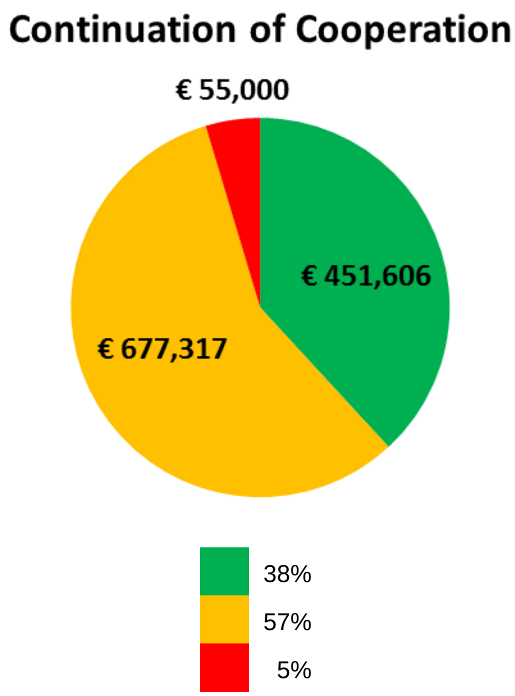
Predominantly yellow due to the fact CCS is not yet implemented

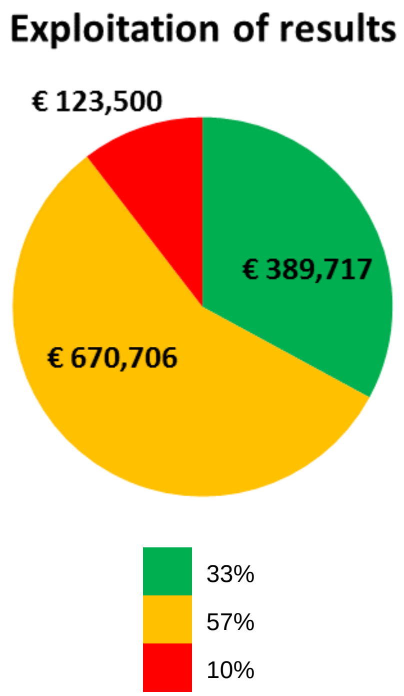
WP number and description	Status	End date	**Technical progress**	Goals reached	Valuable advances made	**Partnering**	Perception of results	Involvement of partners	Continuation of cooperation	**Broader impact**	Dissemination	Follow up developments	Exploitation of results	Impact achieved	**Lessons learned**	Effectiveness of program structure	Need for changes in approach
WP1 – Storage results	Finished	dec-16		Green	Green		Green	Green	Yellow		Yellow	Green	Yellow	Yellow		Green	Green
WP4 – STEP-UP SEWGS	Finished	dec-15		Green	Green		Green	Yellow	Green		Yellow	Green	Green	Yellow		Yellow	Yellow
WP7 – CCS position paper	Finished	nov-16		Yellow	Yellow		Green	Yellow	Red		Yellow	Red	Yellow	Yellow		Yellow	Yellow
WP8 – RES + CCS	Finished	dec-15		Green	Green		Green	Green	Green		Green	Green	Yellow	Yellow		Green	Yellow
WP9 – CCS with ships	Finished	dec-15		Green	Green		Green	Yellow	Yellow		Green	Green	Red	Yellow		Green	Yellow
WP10 – CO2 swelling in clays	Finished	dec-15		Yellow	Yellow		Green	Green	Yellow		Green	Green	Yellow	Yellow		Yellow	Yellow
WP11 – K12-B tracer injection	Finished	sep-17		Red	Yellow		Yellow	Green	Yellow		Green	Yellow	Yellow	Yellow		Green	Yellow
WP12 – Legal framework	Finished	okt-15		Green	Yellow		Yellow	Yellow	Green		Green	Green	Yellow	Yellow		Green	Yellow
WP14 – ÄVR Duiven CO2 capture	Running*	nov-17		Green	Green		Green	Green	Yellow		Yellow	Yellow	Green	Yellow		Green	Green
WP15 – MPP3 aerosols	Finished	dec-16		Green	Green		Green	Green	Green		Yellow	Green	Yellow	Yellow		Green	Yellow
WP16 – Q16-Maas monitoring	Finished	jun-17		Yellow	Yellow		Yellow	Green	Yellow		Yellow	Green	Yellow	Yellow		Green	Yellow
WP21 – Electrochemical CO2 conversion	Running*	mrt-18		Green	Yellow		Green	Green	Green		Yellow	Yellow	Green	Yellow		Yellow	Red
WP25 – CCS in deep decarbonisation	Running*	jun-18		Green	Green		Green	Green	Green		Green	Yellow	Yellow	Yellow		Green	Yellow
WP26 – PRECALC leakage clogging	Running*	dec-17		Green	Green		Green	Green	Yellow		Green	Yellow	Red	Yellow		Green	Yellow
WP27 – CO2 for 3D printing	Running*	jun-18		Yellow	Green		Yellow	Red	Yellow		Green	Yellow	Green	Yellow		Yellow	Red
WP28 – CO2 capture for steel	Finished	oct-17		Green	Green		Green	Green	Green		Yellow	Green	Yellow	Yellow		Green	Yellow

** As the work package is still in progress, scores are based on what is expected from the project given the current progress*

Results relative to subsidy







Compared to the time of assessment, more momentum is to be expected due to new plans of the Dutch Government

* Values given refer to granted subsidy

General remarks

- **Important note: at the time of the interviews, new targets regarding emissions reductions had not yet been set by the government. CCS was then perceived to be at a standstill in the Netherlands and it was not possible to see a direct impact on the Dutch context around CCS from the project results.**

- In general, the goals were achieved with valuable contributions made to the field of CCS and industrial partners satisfied with the results, further maintaining the strong position of CCS in the Netherlands.

- In almost every case, follow-up projects have already started or are planned, usually with the same partners. This has connected Dutch parties to some of the major CCS projects worldwide.

- Industrial carbon capture (from steel, cement, and waste incineration) and subsequent storage or use appears to have the most potential for industrial implementation and achievement of impact.

- <u>The Dutch knowledge base on CCS is recognized to be of worldwide importance</u>

List of key recommendations

- **An active network involving research institutes, academia, and industry is needed to maintain the knowledge base and position of NL in the field of CCS**
  - A larger program than CATO-2b would be needed to really make progress and maintain the network, but this would require a bigger budget, clearer vision and money for pieces that industry won't pay for.
- **Industry needs to be able to find results quickly and use results effectively for stakeholder management**
  - At the end of a project, there should be one document that explains all of the work that was done. This document should be easily accessible.
- **Project subsidy schemes need to be improved to better facilitate innovations being realized in practice**
  - When granting projects for first stage research, how the project will be followed up should also be considered. As it is now, piloting and pre-commercial projects do not fit into current subsidy programs.
  - More consistent rules between the various RVO subsidy schemes and decreased burden in obtaining and administering projects, at least for small subsidy amounts, are needed and will encourage more participation, especially from SMEs.
  - Increased flexibility is needed for cases when unforeseen issues arise and planning needs to be adjusted

CCS + CCU

CONTOURS RESEARCH AGENDA

CCS & CCU

- Carbon capture and storage (CCS) and carbon capture and utilization (CCU) are cornerstones for the implementation of the 2030 targets for emissions reductions and beyond

- Technology is currently available at high TRLs for application in the power sector
  - Post-combustion capture with flue gases
  - Pre-combustion capture
  - Oxyfuel processes

- Several challenges still exist related to current high TRL processes
  - Post-combustion capture: (aerosol) emissions and solvent management
  - Pre-combustion capture: availability of reformers and hydrogen-based turbines
  - Oxyfuel: burner design and NOx, SOx removal

- CCU is still at a lower TRL level and it is debatable if this could lead to a significant CO_2 reduction. However, other benefits are to be expected.

Alignment with Mission Innovation

- About MI: A global initiative of 23 signatories (22 countries, and the European Commission) to stimulate energy innovation, announced at the Paris climate summit (COP21) in November 2015.
- Challenge 3, the Carbon Capture Innovation Challenge, has the objective "to enable near-zero CO_2 emissions from power plants and carbon intensive industries".
- The challenge on carbon capture will define an R&D agenda for the next five or ten years for MI through a number of Priority Research Direction (PRDs; next slide).
- Breakthrough technologies were formulated in an invitation-only workshop held in Houston, Texas, in September 2017. Four Dutch CATO members participated in the workshop.

MISSION INNOVATION
Accelerating the Clean Energy Revolution

More information: http://mission-innovation.net/

MI Challenge 3 PRDs

Netherlands knowledge position: Strong Background | Moderate background | Under development

Main topic	Sub-topics	Priority Research Directions (PRDS)		
Capture	Solvents	Solvent management	Designing high-performance solvents	
	Sorbents	Designing tailor-made materials	Integrating materials and processes	
	Membranes	Transport phenomena in membrane materials	Architecting systems enabling cost-effective process designs	
	Combustion	High-intensity pressurized combustion	Low-cost hydrogen production with CO2 capture through combined reforming and combustion	
Utilization	Thermochemical conversion	Breakthrough transformations	New routes to functional materials	
	Electro-/photochemical conversion	Designing and controlling molecular-scale interactions	Harnessing multi-scale phenomena	
	Conversion to solid carbonates	Mineralization opportunities from complexity	Tailoring carbon mineralization	
	Biological conversion	Accelerating biological activation		
Storage	Capacity & injectivity	Multi-physics/multi-scale fluid flow	Definition of dynamic pressure limits	Control of near-well environment
	Monitoring, verification, & performance metrics	Smart conformance monitoring	Techniques to locate and evaluate anomalies	
	Induced seismicity	Characterization of fault and fracture systems	Next generation seismic risk forecasting	
	Well integrity	Locating, evaluating, and remediating existing & abandoned wells	Establishing, demonstrating, and forecasting well integrity	

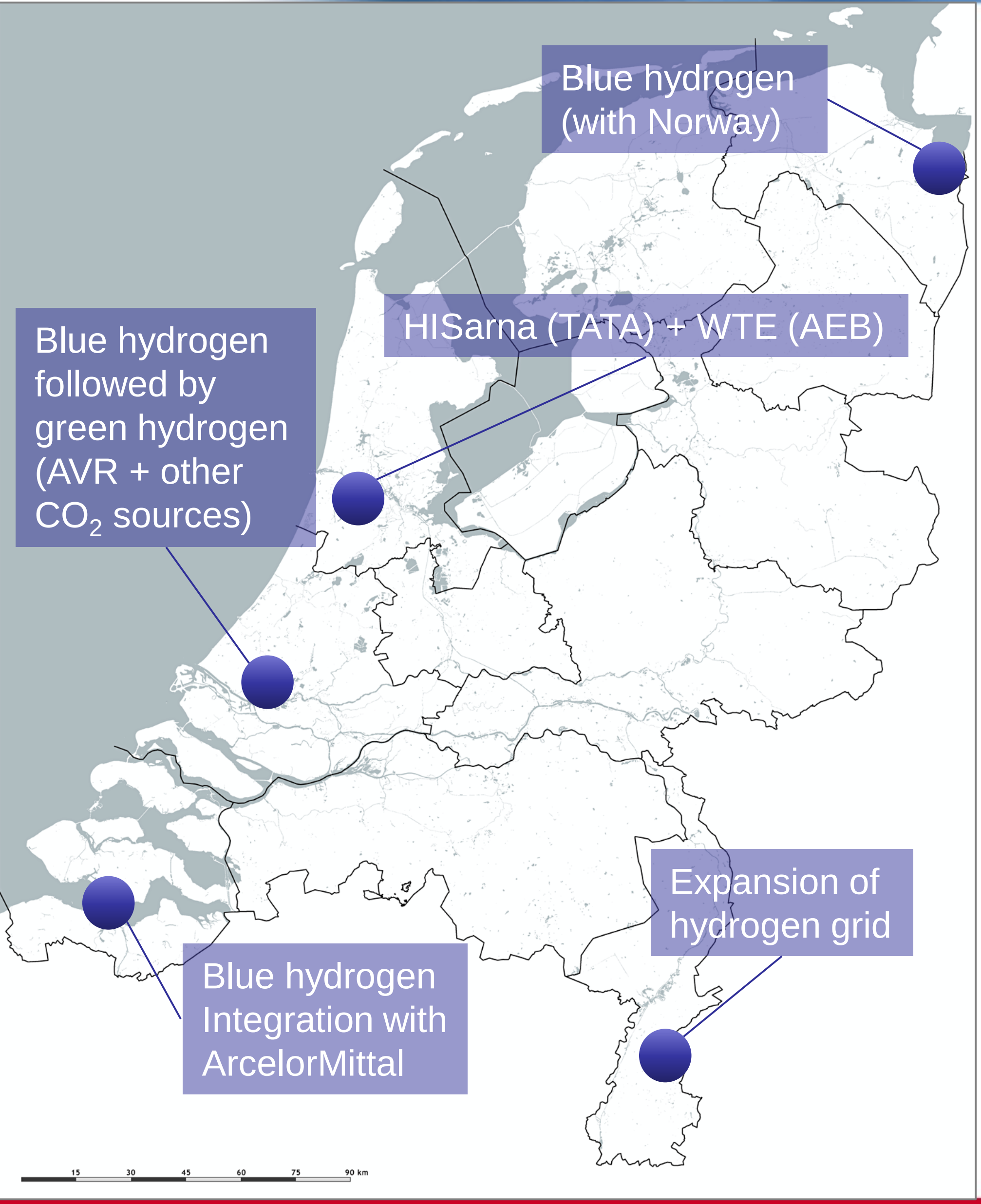
* In addition, cross-cutting issues will also be included in the overall research directions

Dutch Perspective

Sector	Sources of CO_2	Total CO_2 (Mton/yr)	Number of companies	Emissions per company (Mton/yr)
Industry	Refineries	10,8	6	**1,8**
	Steam cracker	6,4	3	**2,1**
	Production of H_2 and NH_3	6,8	7	1,0
	Others Chemical Industry	4,2	23	0,2
	Metal production	12,1	1	**12,1**
	Building materials and glass production	0,5	6	0,1
	Paper and pulp	0,9	7	0,1
	Food industry	1,4	15	0,1
	Total Industry	**43,1**		
Electricity production	Solar thermoelectric generators (STEG)	9,7	17	0,6
	Conventional units	23,5	5	**4,7**
	Total electricity production	**33,2**		

- There are only a few companies where substantial amounts of CO_2 (> 1 Mton/year) are emitted at one location. These sources should be the focus of CCUS research and demonstration efforts in order to meet emissions reductions targets in the Netherlands. Decarbonisation strategies, such as the use of blue hydrogen (conventional hydrogen production with CCUS), are applicable for all of the sources and can also have a significant impact.

Large scale opportunities for implementation in NL



Capture

- WTE (municipal waste incinerators): target of 2 Mton with only real option being post-combustion capture
- Refineries: post-combustion capture or use of hydrogen as a heating fuel; lifetime of refineries is an issue
- Steel: realization of the HISarna process
- Paper, food industry etc: hydrogen as the heating fuel
- Cement: not applicable in Netherlands
- Gas fired power plants: post-combustion capture only when operating hours are above ~60%; pre-combustion capture only when central hydrogen facility available (including hydrogen storage)

Storage

- De-risking storage: bankable storage
- Infrastructure development (including reuse of current infrastructure)

Utilization

- Integration of conversion with capture process
- Mineralisation (e.g. asbestos disposal)

Decarbonisation

- Use of green or blue hydrogen as a fuel for small to medium size point sources and some large scale combustion sources
- Residual gas utilization from steel plants
- Key criteria are expected industry lifetimes, integral costs, and impact

Research agenda contours

Post combustion capture

- Focus on derisking capture
- Non-aqueous solvent systems

Decarbonisation of methane: hydrogen

- Integration of CCS with hydrogen production
- System and landscape development, including flexible electricity production
- Hydrogen infrastructure (pipelines and storage)

Oxyfuel

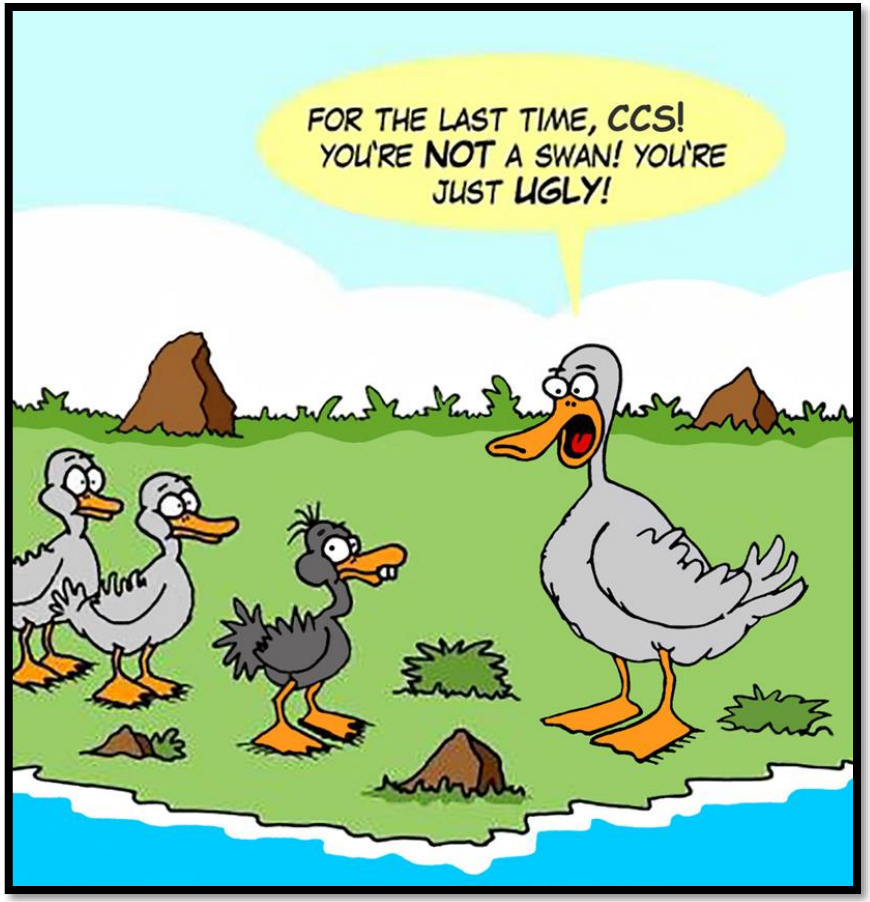
- HISarna chain development (support demonstration)

Utilisation

- Integration of capture with conversion
- Comparing direct with indirect electrochemical conversion
- Long term storage options with improved value chains (e.g. non-olevine based mineralisation)

Storage

- Bankable storage



Courtesy of Andy Read (ROAD)

A sense of urgency is needed

Current CCS Targets:

20 (18 + 2) megatons of CO_2 stored by 2030