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IMPACTS Recommendations for Safe and Efficient Handling of CO_2 with Impurities

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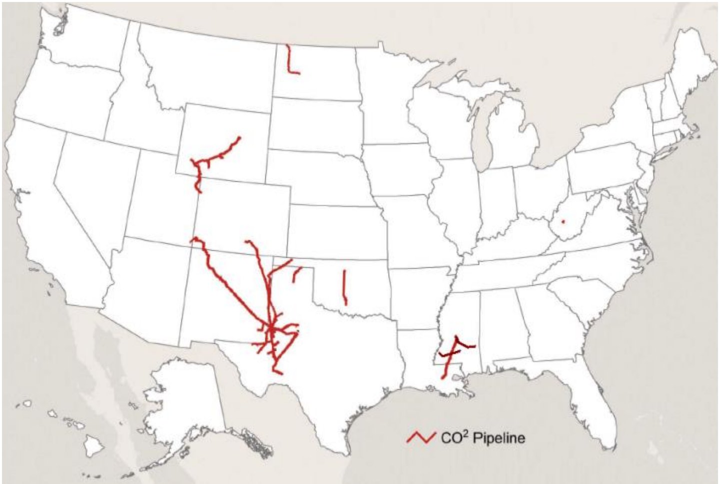
Are there CO_2 quality guidelines currently available?

- Industrial practice and recommended practices for CO_2 infrastructure exist.

- Fit-for-purpose: Direct use of CO_2 transportation experience is not always possible due to the difference in CO_2 mixtures.



DYNAMIS CO_2 quality recommendations

Table 6-1 DYNAMIS CO_2 quality recommendations

Component	Concentration	Limitation
H_2O	**500 ppm**	Technical: below solubility limit of H_2O in CO_2. No significant cross effect of H_2O and H_2S, cross effect of H_2O and CH_4 is significant but within limits for water solubility.
H_2S	**200 ppm**	Health & safety considerations
CO	**2000 ppm**	Health & safety considerations
O_2[11]	Aquifer < 4 vol%, **EOR 100 – 1000 ppm**	Technical: range for EOR, because lack of practical experiments on effects of O_2 underground.
CH_4[11]	Aquifer < 4 vol%, EOR < 2 vol%	As proposed in ENCAP project
N_2[11]	< 4 vol % (all non condensable gasses)	As proposed in ENCAP project
Ar[11]	< 4 vol % (all non condensable gasses)	As proposed in ENCAP project
H_2[11]	< 4 vol % (all non condensable gasses)	Further reduction of H_2 is recommended because of its energy content
SO_x	**100 ppm**	Health & safety considerations
NO_x	**100 ppm**	Health & safety considerations
CO_2	>95.5%	Balanced with other compounds in CO_2

So many questions regarding impurities in CCS…

In which part of the chain should impurities be removed? Should they?

Is it cheaper to purify the stream before transport?

Will CO_2 quality affect EOR?

Is "overwhelmingly" CO strong enough crit ensure safe transp storage?

How do CO_2 impuritie affect storage pH?

Is using stainless steel instead of carbon steel cheaper than adding purification processes?

How accurate do the models need to be?

Will pipelines corrodes if impurities are present?

w does CO_2 stream quality affect compression?

How will CO_2 quality affect the equipment/ operations along the chain?

What conditions are needed to avoid hydrates in the chain?

Will impurities affect depressurisation of pipelines?

Will pipeline thickness need to be adjusted to handle impurities?

What are the effects of impurities in the captured CO_2 stream on transport and storage?

Establish a method to discover the relationship between the CO_2 stream quality and the cost of safe transport and storage

Case-based approach, using reference chains

- Designed to *derive the technical and economic impacts* in a *comprehensive* way
- *Case studies* constructed to answer the *questions*

Assessment of the effects of CO_2 quality

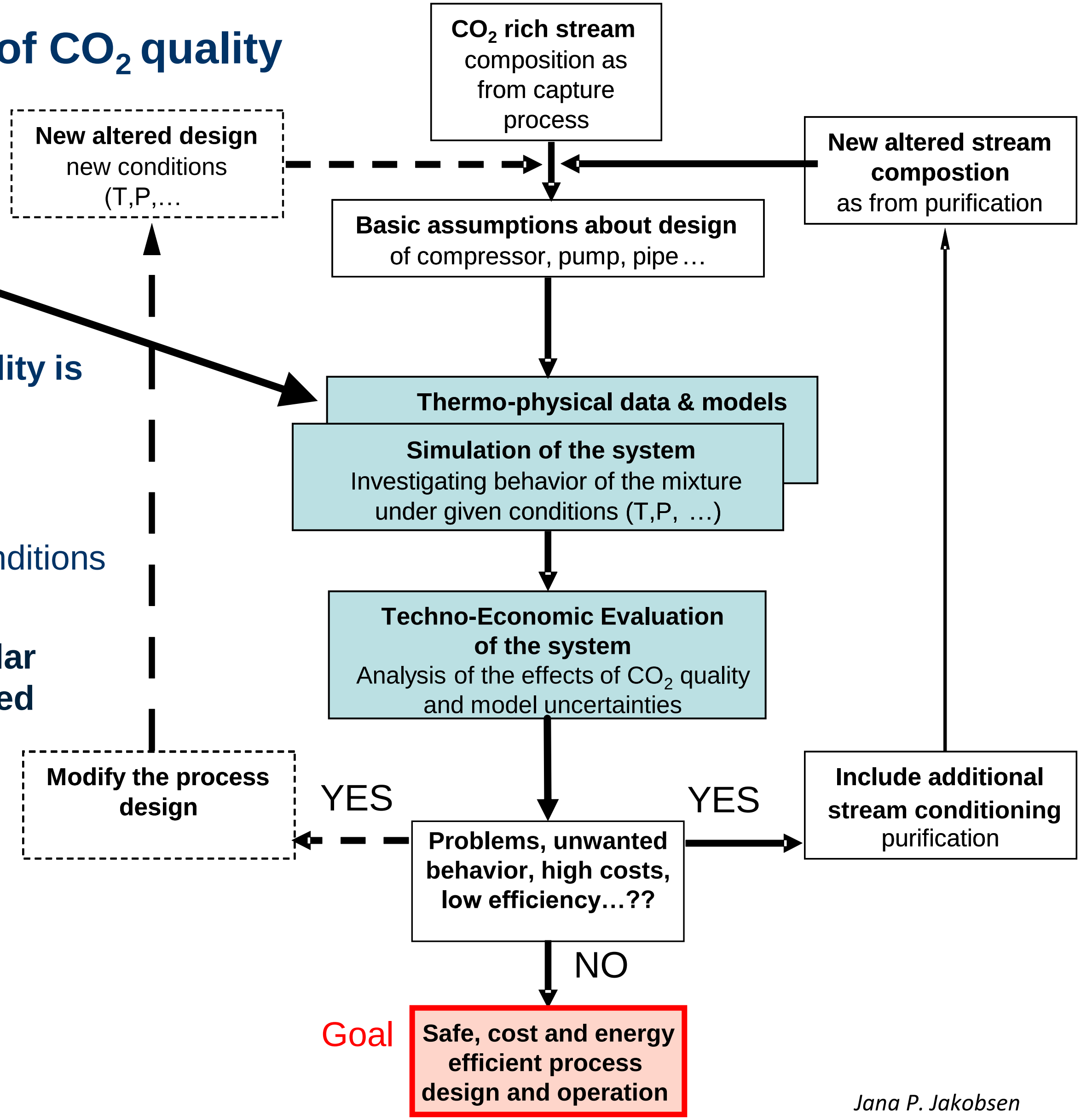
Need to evaluate the thermo-physical properties – whole range

Assessment of the effects of CO_2 quality is an iterative procedure:

- Specify the thermodynamic system (CO_2 stream quality)
- Establish the design and operating conditions

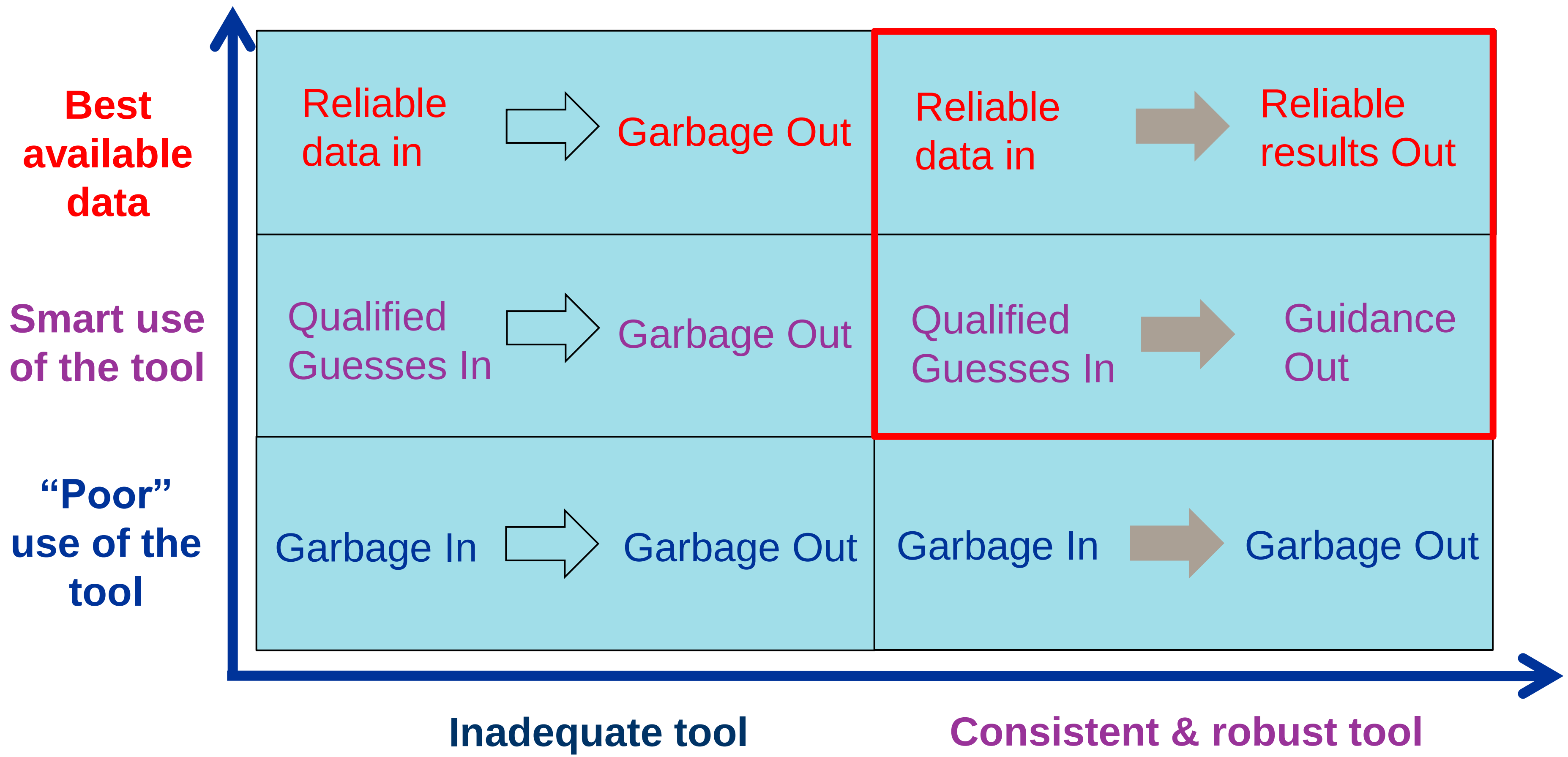
- **Investigate the behaviour of particular thermodynamic system under specified conditions**

  - Identify technical challenges
  - Evaluate costs and efficiency
  - Propose modification



Jana P. Jakobsen

Techno-economic tool and data



Jana P. Jakobsen, SINTEF ER

Summary of transport case study*: Pipeline and ship

- Two CO_2 transport chains have been investigated with respect effect of impurities

  - Pipeline transport of CO_2 over 500 km
    - Transport power consumption increases with impurities.
      - 4% impurities from N_2 and O_2 in a 24'' pipeline can increase by 100%
    - The most important thermodynamic property is the density.
    - Fracture propagation is affected by impurities

  - Ship transport of CO_2
    - Effect of impurities will impact the liquefaction process, design and equipment
    - Increased tank storage pressure/capacity affected by impurities
    - Accurate prediction of low temperature vapour-liquid – and solid – equilibrium are of vital importance in order to optimize this chain.

*see Geir Skaugen's presentation shortly

CO_2 mixtures with impurities : Examples from case studies*

Impurities affect stream properties

- Phase equilibria
- Density
- Viscosity
- Speed of sound

→

Stream properties affect the process design and costs

- Power consumption: conditioning, boosting
- Refrigeration requirements for shipping, impurity accumulation, flash tank pressure requirements

→ **Uncertainties in the thermo-physical properties = uncertainties in the process**

What is needed?

- Accurate measurements to improve models
- Simulations and techno-economic assessments needed on a **case-by-case basis**
- Sensitivity studies to reveal how uncertainties determine high risk areas

*see Geir Skaugen's presentation shortly

IMPACTS Reference CCS chains – criteria for selection

CO_2 sources considered

- Gas-fired power
- Coal-fired power
- Gas processing
- Industrial sources

CO_2 capture technologies considered

- Post-combustion capture
- Pre-combustion capture
- Oxyfuel

Transport options considered

- Pipeline
- Shipping

Storage options considered

- Aquifers
- Oil fields
- Depleted gas fields

IMPACTS' Reference CCS chains* – criteria for selection

- Needed to represent a sufficiently broad set of the CCS chains that can be envisaged as being commercially and technically plausible within 10-20 years.

- Needed to cover both standard source-to-sink simple examples and also more complicated examples covering combinations of sources and sinks and, in particular, the mixing of CO_2 streams with differing levels of impurities.

- Needed to allow for case studies to answer the specific questions.

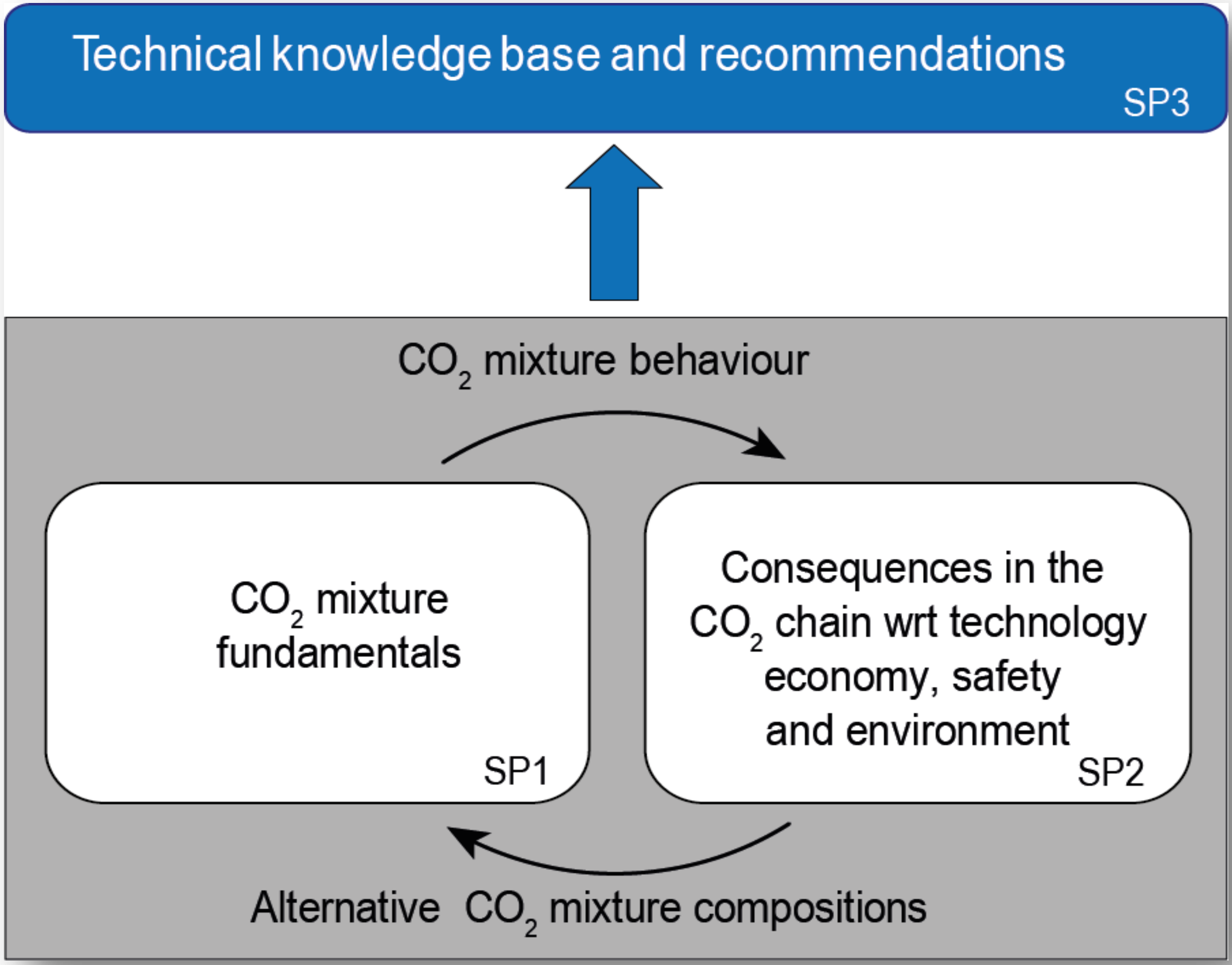
***tune into presentation by Charles Eickhoff**

IMPACTS' Reference CCS chains*

*see Charles Eickhoff's presentation at 15:10 and poster "Choice of Benchmark CCS Chains for Illustrating CO_2 Quality Issues"

Case ID	CO_2 source and capture type	Transport	Storage
A	Power Post-combustion (amine)	Pipeline off-shore	Gas Field
Case studies/variations: • The economics as a function of impurity concentrations for post-combustion capture using advanced amine absorption • The impact of corrosion and stress corrosion on an offshore pipeline • The variation in storage capacity in a gas field as a function of formation depths			
B	Power Post-combustion (chilled ammonia)	Pipeline on-shore (short, 20 km)	On-shore aquifer
Case studies/variations: • The economics of stream purity for post-combustion capture using chilled ammonia absorption • The impact of corrosion and stress corrosion on a short on-shore pipeline and the contrasts to a longer offshore one • The variation in storage capacity in aquifers at differing formation depths			
C	Power Pre-combustion	Pipeline off-shore (long, 400 km)	Oil Field
Case studies/variations: • The economics of impurity reduction / relaxation for pre-combustion capture using solexol absorption • The impact of a reducing atmosphere on transport and storage • High pressure requirements for a long pipeline • Issues relating to the injection of impurities into oil fields			
D	Power oxyfuel	Pipeline off-shore	Oil Field with EOR
Case studies/variations: • The economics of impurity reduction / relaxation for capture using the oxyfuel process • The impact of an oxidising atmosphere on transport and storage, particularly oil fields • Issues relating to the use of impure CO_2 for EOR purposes			
E	Gas processing	Shipping	Gas Field
Case studies/variations: • The economics of impurity reduction / relaxation from a gas processing capture • The impact of the use of shipping for transport in terms of economics and also reduction of subsequent impurities.			
F	Cement	Pipeline off-shore	Chalk Oil Field
Case studies/variations: • Any differences in the use of Amine absorption for cement rather than power • Issues relating to the injection of CO_2 and impurities into chalk oil fields			
G	Clusters and Mixing	Pipelines off-shore	Various Stores
Case studies/variations: • Mixing of CO_2 streams with differing contents and characteristics • Issues relating to the injection of CO_2 into multiple fields			

IMPACTS – The Concept



SINTEF

Results and Discussions from SP1 in IMPACTS

- ***Thermophysical behviour of CO_2 mixtures***
  - **09:50 Tomorrow:** Investigation of Models for Prediction of Viscosity Properties for CO2 Mixtures , Jacob Stang (SINTEF, Norway)
  - **12:10 Tomorrow:** Vapour-liquid Equilibrium Data for the Carbon Dioxide and Oxygen (CO2+O2) System at 6 Isotherms Between the Freezing Point and Critical Temperature of CO2 , Jacob Stang (SINTEF, Norway)
  - **12:30 Tomorrow**: Experimental Work at RUB and Tsinghua and a New Model Describing Thermodynamic Properties of CO2-rich Mixtures, Roland Span (Ruhr-Universität Bochum, Germany)
  - Poster: TREND – A Software Package Providing Thermophysical Properties for the CCS community, Stefan Herrig (Ruhr-Universität Bochum, Germany)
- ***Transient fluid dynamics of CO_2 mixtures***
  - **11:30 Tomorrow**: Simulation of Two-Phase Flow of CO2 Mixtures: Comparing Cubic and Reference Equations of State mHalvor Lund (SINTEF, Norway)
- ***Injection and Storage of CO2 streams with impurities***
  - **14:50 Tomorrow** : Analysing the Effect of Impurities in the CO2 Stream Injected on Fractured Carbonates Miguel Angel Delgado (CIUDEN, Spain)

Developing the IMPACT Recommendations Report

Input Requested from Sub-Project and Work Package leaders

11 work packages in 3 sub-projects

To try to address each guideline, the relevant leaders were asked to answer the following questions:

1. What are your major/key results (be concrete)?
2. Can you provide/suggest guidance for handling CCS streams (e.g. parameter regions, operational methods, safety issues, etc.)?
3. What is the IMPACT of this work? Who is the user/stakeholder and where/how can it be used?
4. What are your challenges and further work planned?

IMPACTS Recommendation on the need for upstream conditioning

It is *generally* **more economic** to clean up the CO_2 stream at **capture (upstream**) than to deal with significant downstream effects.

Justifications:

- Higher quality stainless steel pipelines are expensive
- Corrosion by-products need to be handled
- High costs of replacing storage capacity at a higher than expected rate due to reduced density of the CO_2 stream

IMPACTS Recommendations on the need for upstream conditioning

A general **cost-optimal level of nitrogen is 0.5%,** or lower if naturally so (advanced amine is below 1000 ppmm)

Justifications:

- This avoids excessive downstream effects due to e.g. density reductions.
- Reduction below this at source is not economic.

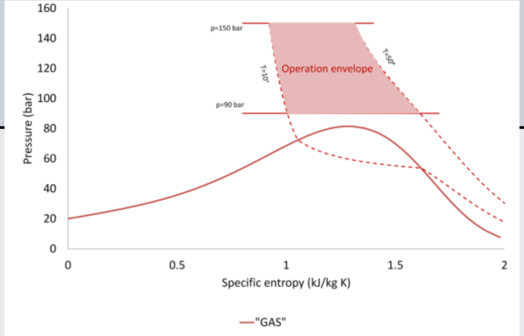
IMPACTS contributions on the design/operation of pipelines

Pressures throughout a CCS chain should be kept high enough to avoid 2-phase conditions (above 82 bar for the benchmark chains in IMPACTS)

- Safe margins to the **cricondenbar -** maximum pressure above which no gas can be formed regardless of temperature
  - Cricondenbar determined experimentally through phase equilibria studies
- TREND can be used predict two (and three) phase conditions

IMPACTS Recommendation on the design of pipelines

The **cricondenbar** should be the design criteria for avoiding running ductile fractures.



Justification:

- See Geir Skaugen's presentation for details
- Recent highly-accurate measurements from $CO_2 - N_2$ systems show that models can predict the cricondenbar with an error of 12-13 bar. This will have a direct effect on the pipeline wall thickness.

IMPACTS Guidelines on corrosion-related issues in the CCS chain

- CO_2 streams should be dried to levels below **350 ppm H_2O** to prevent significant corrosion
- **250 ppm** to ensure no hydrate formation (above 70bar and -30°C)
- **Hydrogen and H_2S levels** should each be kept to below **100 ppmm** if there is significant (>1000ppmm) moisture in the pipeline / injection systems

IMPACTS Recommendations on injection and storage of CO_2 with impurities

CO_2 for storage in chalk fields should be cleaned upstream

- Impurities are expected to cause problems with structural integrity with the formation
- Detailed tests on specific test samples would be needed before using such a field.

IMPACTS Guidelines on injection and storage of CO_2 with impurities

Storage of impure CO_2 in formations at depths of around 800 m or less are unlikely to be economic compared to the option of reducing impurities at source.

Example justification:
The depth/pressure of the storage formation has a significant influence on the capacity for storage of impure CO_2 and hence affects the trade-offs associated with it.

IMPACTS Recommendations on injection and storage of CO_2 with impurities

Generally accepted safe limit for **oxygen level** in CO_2 injected into hydrocarbon reservoirs is **10 ppm**.

Justification:

- To avoid any reaction with remaining hydrocarbons, including EOR/EGR
- When the formation temperature is below 85 °C there is a risk of the triggering of rapid growth of SRB

IMPACTS Guidelines on reaction during the mixing different of CO_2 qualities in a multi-user transportation system

Reactions between impurities in (mixed) streams are unlikely to happen

Justifications:

- IMPACTS cases have O_2 concentrations and levels of potential fuels such as H_2 that are too low for oxygenation to take place.
- Other reaction possibilities are extremely endothermic and/or below the flammable limit

Impurities limits suggested by IMPACTS

Impurity	Suggested Level	Comments
H_2O	350ppmm[1]	To limit corrosion problems
H_2O	250ppmm	To avoid hydrate formation above 70bar and -30°C
N_2	5000ppmm 250 – 1000ppmm	Pre-combustion capture; Advanced Amine capture; Optimal to avoid unnecessary reductions and storage capacity reductions
H_2	100ppmm	To avoid SOHIC if moisture >1000ppmm present
H_2S	100ppmm	To avoid SOHIC if moisture >1000ppmm present
O_2	10ppmm	If using a depleted HC field or formation temperature <85°C To avoid reaction with hydrocarbons and SRB problems

IMPACTS
Overall Summary

IMPACTS has:

- Developed a methodology for assessing the impacts of impurities on CO_2 transport and storage
- Provided high quality new data
- Developed tools (TREND and TE + others)
- Case studies on reference CCS chains to derive recommendations

Acknowledgements:

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7-ENERGY-20121-1-2STAGE) under grant agreement n° 308809 (The IMPACTS project). The authors acknowledge the project partners and the following funding partners for their contributions: Statoil Petroleum AS, Lundin Norway AS, Gas Natural Fenosa, MAN Diesel & Turbo SE and Vattenfall AB.

Funding partners:

Which aspects should IMPACTS address?

Fundamental properties of CO_2 mixtures

- What are typical CO_2 mixtures present in CCS?
- Do we have accurate thermophysical properties of CO_2 mixtures (exp. and sim.)
- What are the dynamic flow issues of CO_2 with impurities?
- Do impurities affect corrosion in CO_2 infrastructure?
- Are there effects of impurities on storage?

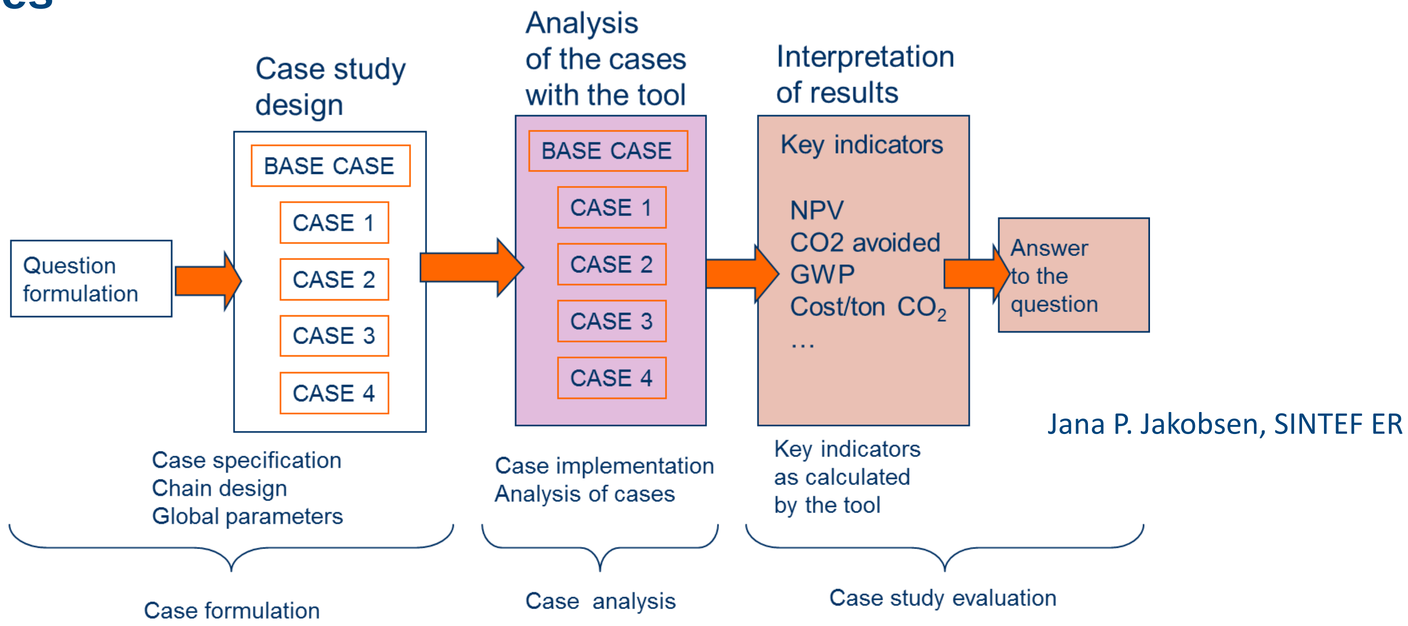
Techno-economic assessments of CCS chains with impurities

- What are the costs of impurities in the CCS chain?
- Are there economic trade-offs?
- How will impurities affect the design and operation of the whole CCS chain?

IMPACTS recommendations on CO_2 quality for safe and cost-efficient CCS

Case study research method

- Case = single instance or event – one, well-defined CCS chain
- Case study = a study based on an in-depth investigation of single or multiple cases in order to **explore causation** and to **understand governing underlying principles**



Using case studies as a research method is successful only if it is carefully planned and crafted to study a particular situation, issue or problem!!

IMPACTS technical knowledge base

The work

SP1	SP2	SP3
Fundamental properties of CO_2 mixtures	Techno-economic assessment of CO_2 chains	Synthesis and recommendations

The objectives

1. Quantifying fundamental properties
2. Revealing operational & material impacts
3. Providing guidelines & recommendations

The results

PROPERTIES	IMPACTS	RECOMMENDATIONS
Thermo-physical	Transient operation	Tolerance levels
Corrosion	Compression	Mixing protocols
Chemical reactions	Injection	Purity requirements
Geo-chemistry	Storage integrity	Trade-offs

Target

Safe and cost effective design and operation of CCS transport and storage infrastructure

IMPACTS Technical Knowledge Base