Challenges to Carbon Capture and Storage: a Portuguese case-study

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Invited lecturer on the subject '**Tópicos Avançados em Energia e Bioenergia I'** – taught by Professor Margarida Gonçalves - Master course in 'Energia e Bioenergia'
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May 28th, 2020

Fundação Ensino e Cultura "Fernando Pessoa"

CCS and CCU are integrated chains of technological processes

Capture
of CO_2 at the emission source (gas mixture)

Transport
of purified CO_2 to geological storage or utilization site

Utilization
of CO_2 in other industrial processes

Sequestration
CO_2 injection and storage in suitable geologic formations

Regulation: **Decree-Law 60/2012**
CCS Directive 2009/31/EC
on CO_2 geological storage
(amended in 24.12.2018)

1×10^5 ton CO_2/ year

International Standards - in force

ISO/TR 27912:2016 CO_2 capture - CO_2 capture systems, technologies and processes

ISO 27913:2016 CO_2 capture, transportation and geological storage - Pipeline transportation systems

ISO 27914:2017 CO_2 capture, transportation and geological storage - Geological storage

ISO/TR 27915:2017 CO_2 capture, transportation and geological storage - Quantification and verification

ISO 27916:2019 CO_2 capture, transportation and geological storage - CO_2 storage using enhanced oil recovery (**CO_2-EOR**)

ISO 27917:2017 CO_2 capture, transportation and geological storage - Vocabulary - Cross cutting terms

ISO/TR 27918:2018 Lifecycle risk management for integrated CCS projects

ISO 27919-1:2018 CO_2 capture - Part 1: Performance evaluation methods for post-combustion CO_2 capture integrated with a power plant

International Standards – under development

ISO/CD 27919-2 CO_2 capture - Part 2: Evaluation procedure to assure and maintain stable performance of post-combustion CO_2 capture plant integrated with a power plant

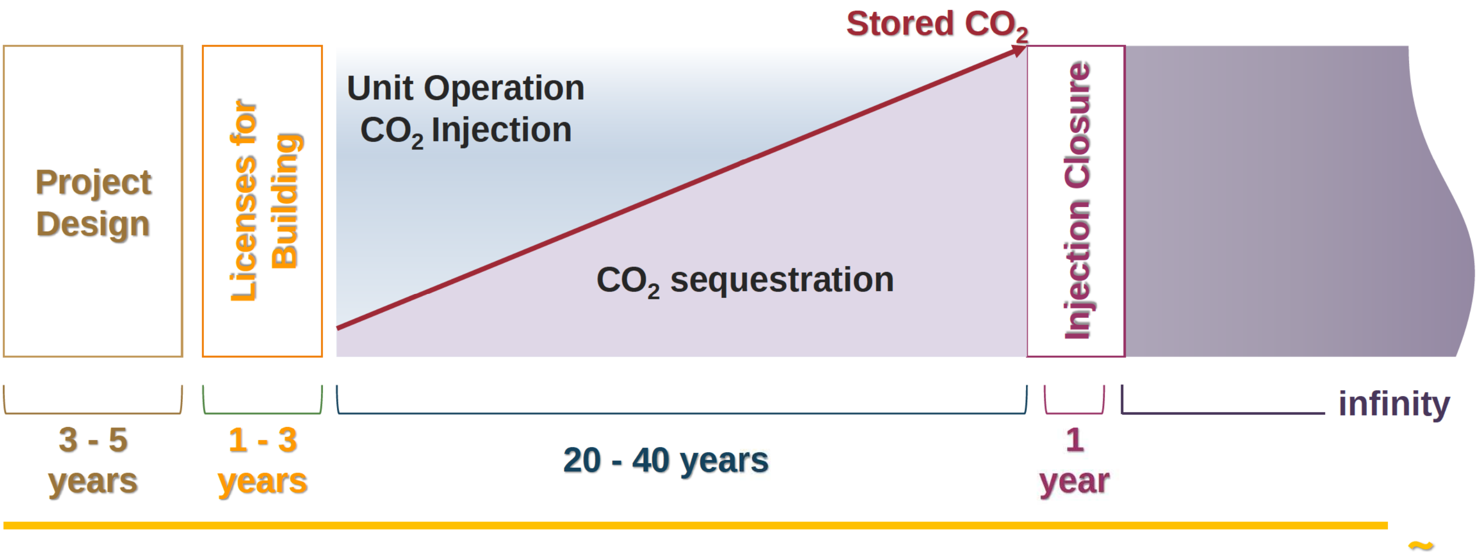
ISO/DIS 27920 CO_2 capture, transportation and geological storage (CCS) - **Quantification and Verification**

ISO/TR 27921:2020 CO_2 capture, transportation, and geological storage - Cross Cutting Issues - **CO_2 stream composition**

ISO/CD TR 27922 CO_2 capture — Overview of carbon dioxide capture technologies in the cement industry

ISO/AWI TS 27924 **Risk management** for integrated CCS projects

Life cycle of a CO_2 Storage Unit



1[st] challenge: concept of *permanent* storage → Public perception & stakeholders' reactions

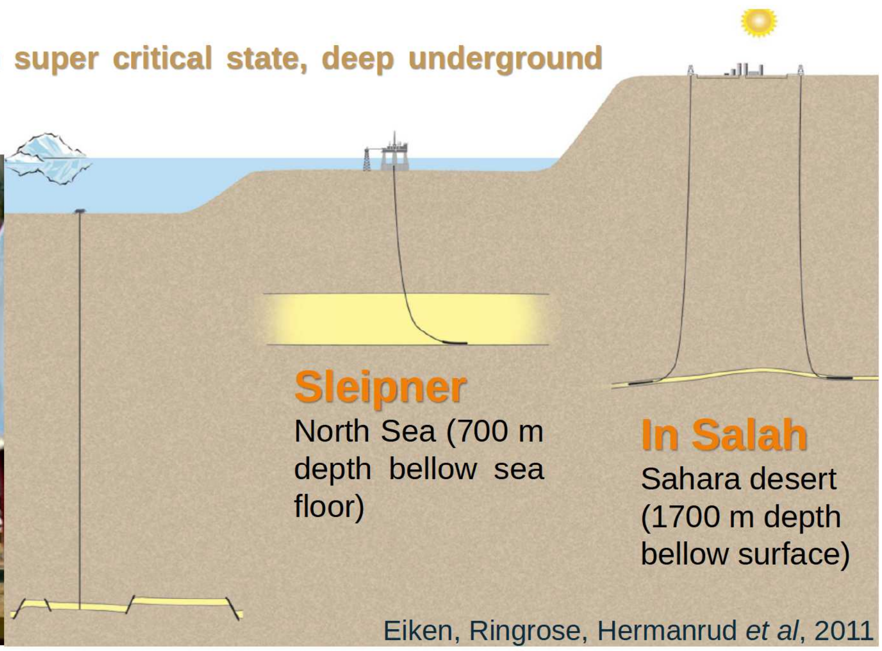
NIMBY

What is CO_2 sequestration?

Injection of a pure CO_2 stream, in super critical state, deep underground where it will remain forever

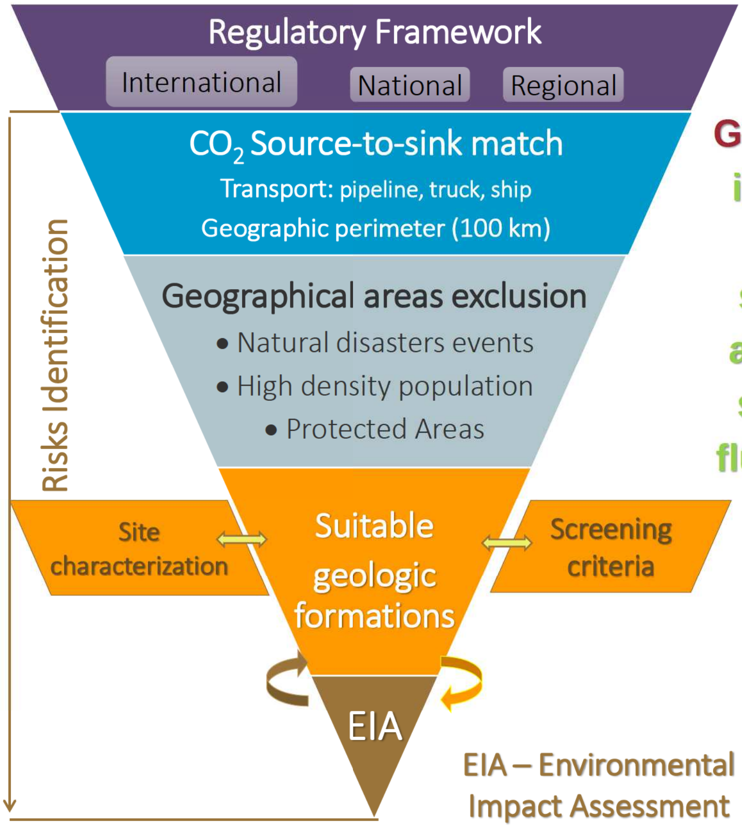
CO_2 pipeline from Dakota Gasification to Weyburn - Midale

https://ieaghg.org/2-uncategorised/59-greenhouse-issues-march-2006-number-81



Snøhvit – Barents Sea (2400 m depth bellow sea floor)

2nd challenge: Project Design



Geological Reservoir is "a subsurface of body rock with sufficient porosity and permeability to store and transmit fluids" (Kerr, T. M. 2007)

2nd challenge: Project Design

Pre-selection of geological sites

Stage 1

Exclusion of **classified**, **populated** or **hazard** geographical zones

Stage 2

Target sedimentary basins to screen and study

↓

Gather information: previous studies, surveys, samples

Use *source-to-sink* match criterion 100 km

Calculate, analyse and evaluate

3rd challenge:
Source-to-sink match

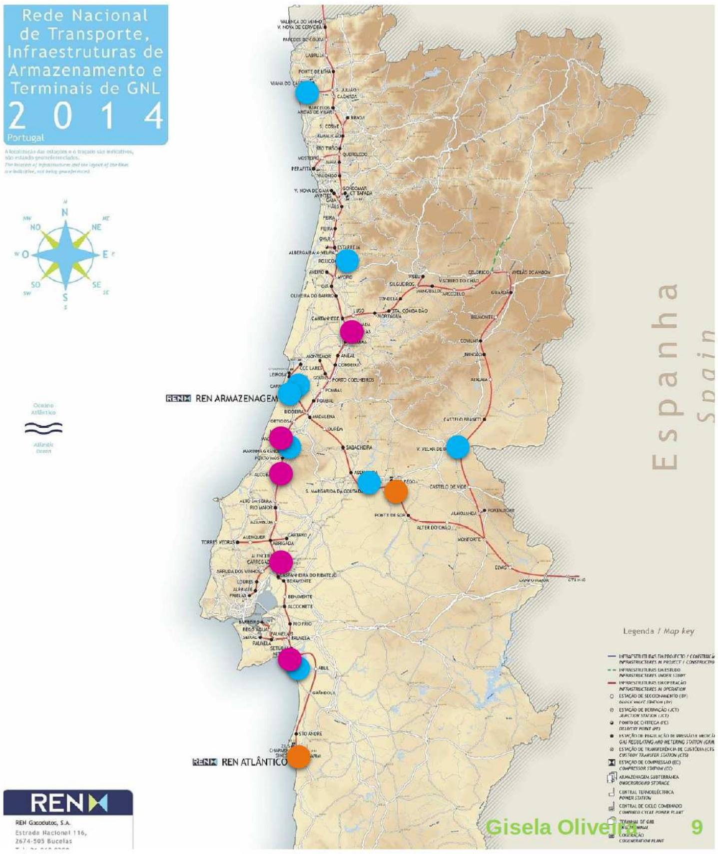
3 major emission activities identified (as LPS)

~46 % TOTAL national CO_2 emissions
20×10^6 ton CO_2

- Pulp and paper
- Coal power plant
- Clínquer and cement

— CH_4 pipeline

✓ Emission source → Transport match



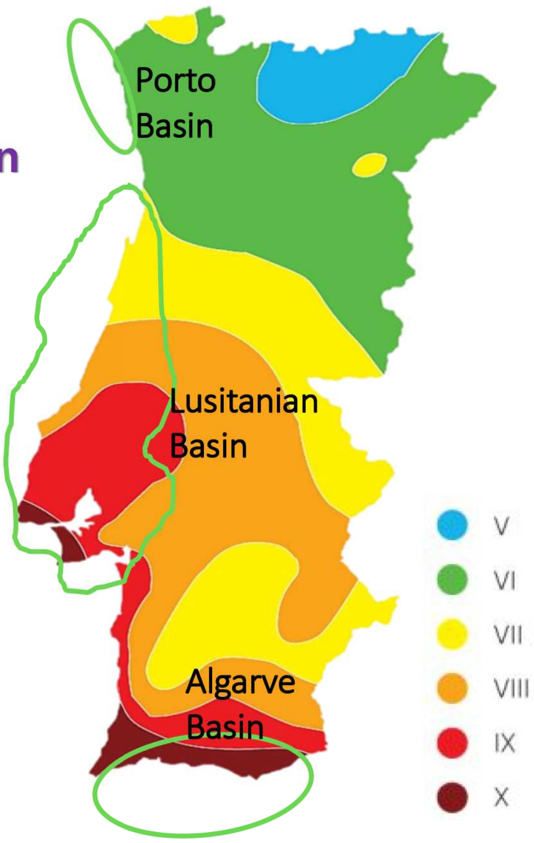
2nd challenge: Project Design

Stage 1

Porto Basin
Off-shore

North & Centre of Lusitanian Basin
Off-shore and on-shore

South of Lusitanian Basin
Algarve Basin



Exclusion criterion

Seismic risk

2nd challenge: Project Design

Stage 2

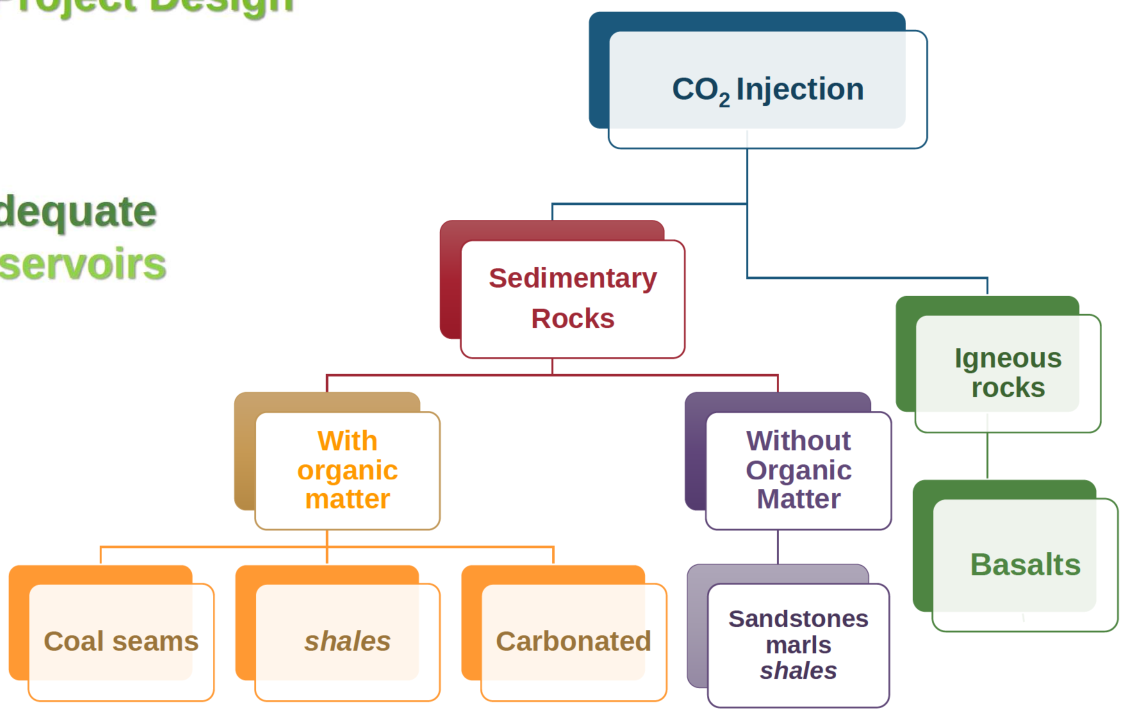
Geological formations with potential for CO_2 geological storage are normally associated with hydrocarbons or water reservoirs

- **Depleted oil and gas reservoirs**
- **Deep saline aquifers**
- **Non-explorable coal layers**
- **Shales rich in organic matter**

Collect relevant geologic information: drilling campaigns, seismic, magnetic and gravimetric surveys data, geothermal and hydrological features, stratigraphy, tectonics, including other seismic particularities of the basin

2nd challenge: Project Design

Search for adequate geological reservoirs



2^{nd} challenge: Project Design

Saline Aquifer Formations

Formation	Characteristics	Location	Drilling Well	References
Grés de Silves **(saline reservoir) – Upper Triassic cap rock Margas de Dagorda**	Clay sandstones Porosity: 15-25% Permeability very low Depth: 3000 m Thickness: 80 to 590 m	All sectors of Lusitanian Basin, Porto Basin Algarve Basin	Ca-1 SM-1 Fa – 1 Alj – 1 Alj – 2 Alc - 1	(Carneiro et al. 2011; Kullberg et al. 2006; Kullberg 2000; Machado et al. 2011; Pereira et al. 2014; Uphoff 2005)
Torres Vedras **(saline reservoir) – Lower Cretacic cap rock Cacém**	Sandstones and conglomerates **Porosity: 20-40%** **Depth: 887-1472m off-shore** **Thickness: 182 to 472 m**	Off-shore: Porto Basin Central sector of Lusitanian Basin	5A – 1 (Porto) 16A - 1 Do - 1C (Lusitanian)	(Beicip-Franlab 1996; Cardoso et al. 2012; Cavaco 2013; Kullberg 2000; Pereira et al. 2014; Susano 2015)

95% Off-shore

- **32 aquifers (Central Lusitanian Basin)**
- **Capacity 845×10⁶ ton CO_2**

2^{nd} challenge: Project Design

Organic Rich Formations

Formation - age	Lithology	Characteristics	Formation depth at specific drilling bores
Montejunto - **Oxfordian**	Limestones with sandy marl alternations	TOC: 0,7 % – 4 % Thickness: 200– 600 m Porosity: 10 - 22 % Permeability 1 D Max. depth to 2500 m (Campelos-1)	AG–2: 1200 – 1400 m; Bf-1: 1136 – 1399 m; Fx-1: 1412 – 1885 m; NM-1: 1104 – 1313 m
Cabaços - **Oxfordian**	Betuminous marls with interbedded carbonaceous shales and lignite layers	TOC: 0,7 % – 5 % Thickness: 20 - 400 m Porosity: 10 - 18 % Max. depth to 2500 m (Campelos-1)	AG–2: 1400 – 1600 m; Ab-2: 1050 – 1350 m; Bf-1: 1399 – 1585 m; Fx-1: 1885 – 2184 m
Vale das Fontes **Pliensbachian to low Torcian Brenha Group**	Marls, marl-limestone and dark laminated marls - Black shales - (MCNB)	TOC: 4 % – 15 % Thickness: 80 - 260 m Average porosity: 7 % Permeability 0,1 mD	Off-shore: 14A-1: 2185 – 2260 m; 17C-1: 900 – 1058 m (?); On-shore: Alj-2: 2555m – 2615m

2nd challenge: Project Design

Organic Rich Formations

Formation - age	Lithology	Characteristics	Formation depth at specific drilling bores
Brenha Group Pliensbachian-Calovian	Limestones (80 %) dolomites (20 %) with alternations of betuminous shales	TOC: 2,5 % – 10 % Thickness: 44-1500 m (140 – 190 m North zone) Porosity: 9 - 12 % Max. depth to 3850 m (Campelos-1)	Off-shore: 13C-1: 1082 – 1394 m; Mo-1: 1350 – 1790 m; On-shore: Ve-1: 1000 – 1400 m; Vm-1: 1550 – 2176 m; MR-W9: 1067 – 1358 m;
Água de Madeiros - Sinemurian Coimbra Group	Marl-limestone alternations with frequent and dark laminated marls Black shales - (Polvoeira Member)	TOC: 2 % – 22 % Thickness: 75-160 m	Off-shore: 14A-1: 2340 – 2380 m; 14A-2: 1200 – 1362 m (?); 17C-1: 900 – 1058 m (?) On-shore: Alj-2: 2720 – 2770 m
Coimbra Group - Sinemurian	Thick limestone beds alternations with clays	TOC: 0,2 % – 3,6 % Thickness: 250 m a 400 m Max. depth to 4000 m (Campelos-1)	Off-shore: 13E-1: 1060 – 1175 m; 14C-1A: 1145 – 1248 m; 17C-1: 1058 – 1230 m;

2nd challenge: Project Design

Search for Adequate geological reservoirs

Conclusions from Stage 2

Saline aquifers off-shore: Torres Vedras Group

Organic matter rich formations:

Montejunto > Cabaços > Vale das Fontes

Proceed to Stage 3

Collection of rock & fluid samples at adequate depths to complete geological characterization and to perform CO_2 injection tests at laboratory

2^{nd} challenge: Project Design

Characteristics of Adequate geological reservoirs

Capacity	Injectivity	Retention
Storage space • porosity Rock lithology • dimension Rock formation	CO_2 flow • permeability Rock lithology • depth Formation (P, T)	Retention of injected CO_2 • geologic sequestration mechanisms Rock formation

Concept of *geological reservoir* for CO_2 storage

2^{nd} challenge: Project Design

Storage CAPACITY evaluation

Space available to store depends on:

- Reservoir dimensions: rock layer thickness and extension
- Available void spaces (filled with rock fluids) for CO_2 storage

Rock porosity Φ: $\Phi\,(\%) = \frac{V_{void}}{V_{total}} \times 100$

Injection of CO_2 into underground formations will displace rock fluids in place

$$M_{(CO_2|s.sal)} = K_{(R|CO_2)} \times \frac{\mu_{s.sal}}{\mu_{CO_2}}$$

$M_{(CO_2|s.sal)}$ – CO_2 mobility factor relative to the saine solution in the reservoir

$K_{(R|CO_2)}$ – **Relative CO_2 permeability to saline solution in the reservoir** (0<**K**<1)

μ_{CO2} – CO_2 Viscosity at the reservoir P & T conditions (Pa.s)

$\mu_{s.sal}$ – saline solution viscosity at the reservoir P & T conditions (Pa.s)

2^{nd} challenge: Project Design

INJECTIVITY evaluation

CO_2 injection flow depends on:

Reservoir depth: local pressure (P) & temperature (T) gradients

Reservoir lithology: rock layers compaction, fracturing and permeability (K)

Darcy's Law approximation

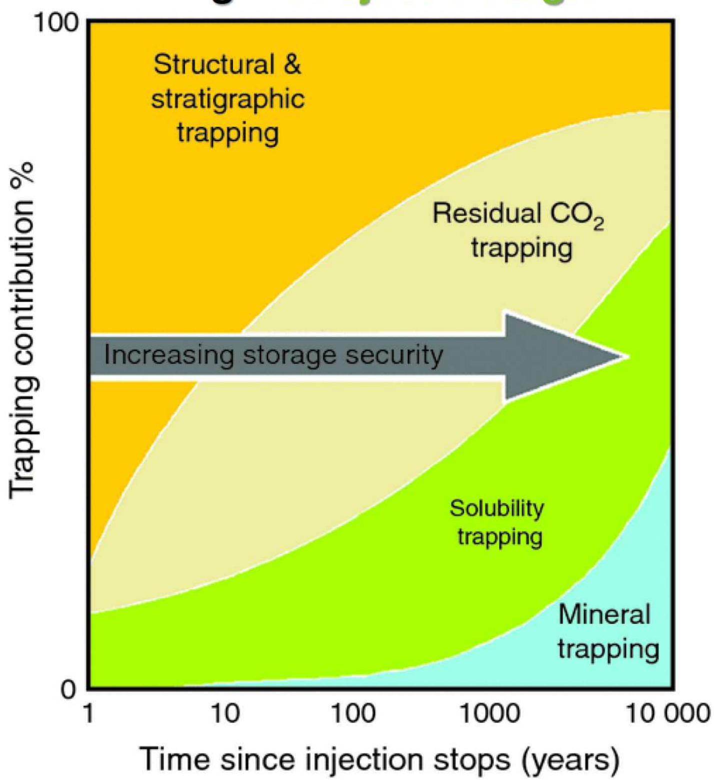
Rock permeability K

$$Q_V = -\frac{K_{CO_2}}{\mu_{CO_2}}\left(\nabla p + \rho_{CO_2} \times g \times \nabla d\right)$$

Q_V – CO_2 mass flux injected in the reservoir ($kg.m^{-2}.s^{-1}$)
K_{CO2} – Rock permeability to CO_2 (D)
μ_{CO2} – CO_2 Viscosity at the reservoir P & T conditions (Pa.s)
∇p – pressure gradient between CO_2 injection point and reservoir pressure (Pa)
ρ_{CO2} – CO_2 density at the reservoir P & T conditions ($kg.m^{-3}$)
g – Gravity ($m.s^{-2}$),
∇d – CO_2 flow gradient in vertical direction (m)

2^{nd} challenge: Project Design

RETENTION evaluation



CO_2 storage in the reservoir depends on:

Formation and reservoir complex

Retention mechanisms

Lithology and reservoir specific

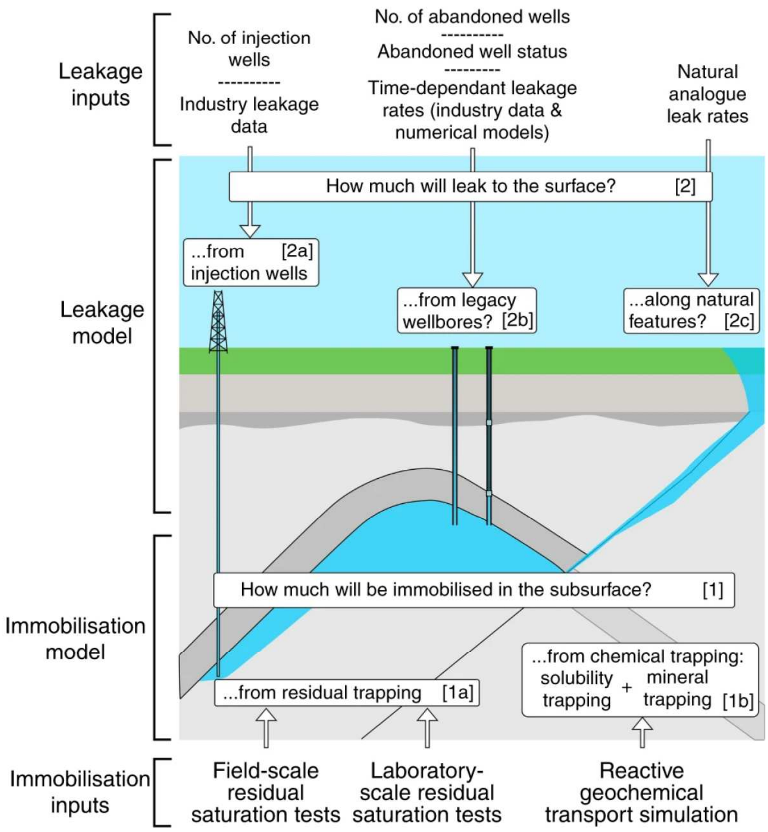
IPCC, 2005

2nd challenge: Project Design

Stage 3

Search for adequate geological reservoirs

- **Site selection**
- **Risks Identification and Evaluation**
- **Storage complex Characterization**
- **Building of a Geologic Model**
- ***in situ* data acquisition**
  - Model validation
  - Quantitative Risks Evaluation
  - Public consultation



4th challenge: Risk Assessment

Will the stored CO_2 leak from the reservoir?

How much CO_2 may rise to the surface?

What will be the leaking rate to the surface?

Many other concerns …

Alcalde, J., Flude, S., Wilkinson, M. et al. Estimating geological CO_2 storage security to deliver on climate mitigation. Nat Commun 9, 2201 (2018).https://doi.org/10.1038/s41467-018-04423-1

4th challenge: Risk Assessment

Risks assessment is site specific

Involves the Environmental Impact Assessment - EIA

ISO/TR 27918:2018 Lifecycle risk management for integrated CCS projects

Specific risks evaluation may adopt a FEP methodology

FEP – Features, Events, Processes methodology

Risk = Probability of occurring an event × Impact of the occurred event

4th challenge: Risk Assessment

Event	Probability	Consequences (direct and indirect)	Impact	Risk
Rise of the reservoir pressure above the MAXIMUM set level	Moderate - low	**Rise of the hydrostatic pressure in the reservoir** - Fluids (water, CH_4) displacement. Extinction of storage capacity – Stop injection	Minor - Moderate	Moderate - low
Rise of the reservoir pressure above the CRITICAL set level	Very Low	**Induction of local seismicity**: fracturing of the storage complex, micro fault activation by the hydrostatic pressure rise. Rupture of the sealing layer by fissures or faults Land movements	considerable - acute	Moderate
CO_2 migration to neighbour geological formations (diffusion of CO_2 at a very slow rate during thousands of years)	Very High	Lateral (or descendent) diffusion of the CO_2 plume to neighbour formations. CO_2 solubilization in rock fluids. CO_2 reaction with rock minerals - MINERALIZATION	Neglectable	Neglectable
	Very Low	**Ascendant diffusion of the CO_2 plume** to the sealing rock layer above the reservoir – very low diffusion process	Moderate - low	Neglectable

4th challenge: Risk Assessment

Event	Probability	Consequences (direct and indirect)	Impact	Risk
CO_2 migration for drinking water aquifers	Very Low	CO_2 solubilization - Acidification; water contamination	considerable	Moderate
CO_2 migration through faults	Very Low	local CO_2 accumulation in toxic concentrations if not dispersed by natural wind convection or deep ocean flows Sudden escape of CO_2 to the surface - evacuation	considerable	Moderate - low
Direct escape of CO_2 to the atmosphere at ground level during injection procedures	Low		considerable - acute	High - Moderate
CO_2 migration through old or abandoned wells	Moderate - low	CO_2 flow to the surface in very low quantities and with low rate. CO_2 migration to adjacent formations	Minor - Moderate	Moderate - low
Land movements due to drilling for monitoring wells	Very Low	Subsidence and rise of land Opening of circulation routes to underground waters Rupture of the sealing layer	considerable	Moderate - low

Very grateful to

Professor Margarida Gonçalves

and to

Professor José António de Almeida

for their kind invitation

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