Landscape of CCUS in BSR

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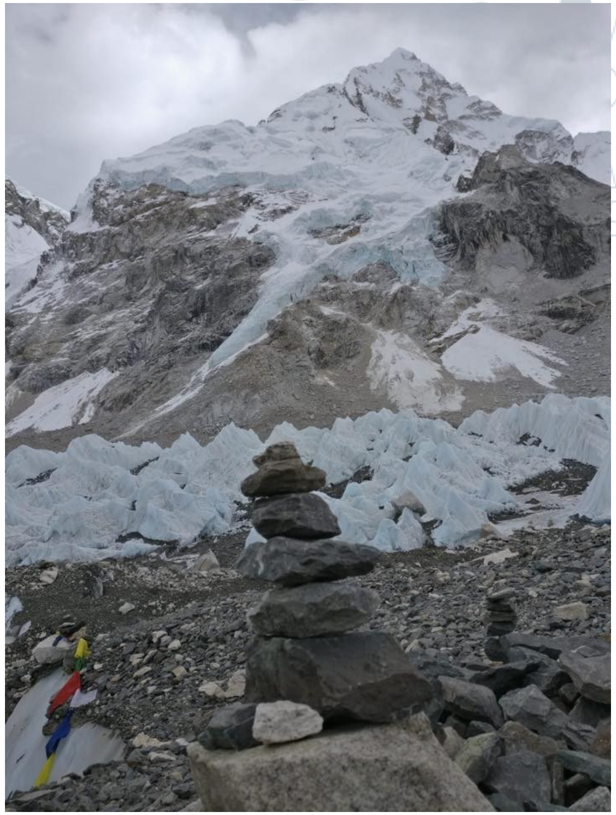
The BCF2022 conference is supported by the Nordic Council of Ministers through the Nordic Energy Research

Who is Teaching ?

- **Mayur Pal**
  - PhD Applied Mathematics Swansea University – UK
  - Masters in Scientific Computing Applied Mathematics – KTH Stockholm
  - 17+ years of professional experiments (Shell, Exxon Mobil, Maersk Oil and North Oil)
  - Grew up around Himalayan region in India
  - Everest base camp and other trekking activities
  - White water rafting and playing cricket



Content

1. Introduction
2. Role of Modelling in accomplishing Carbon Neutrality
3. Simulation needs for modelling CCUS
4. Application of AI and ML in CCUS
5. Overview Patents and New Technology in CCUS
6. Conclusions

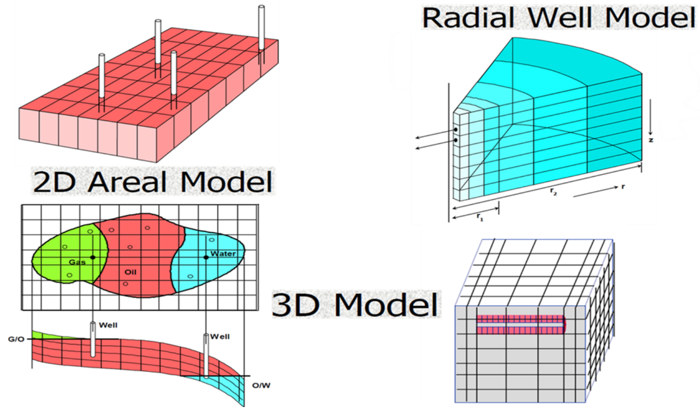
Introduction

- Carbon capture, utilisation and storage (CCUS) will play a critical role in future decarbonisation
- Important aspects of the CCUS problem
  - Sourcing and storage – infrastructure etc
  - Modelling long term fate of CO_2 storage
  - Simulation models and modelling needs
  - Use of AI and Machine learning
  - Technology landscape

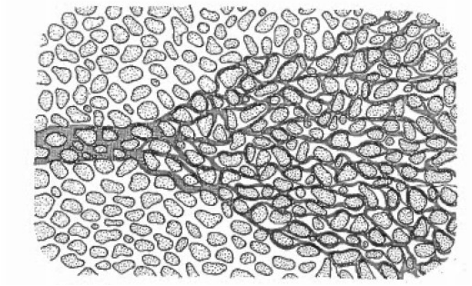
Role of Modelling in accomplishing Carbon Neutrality

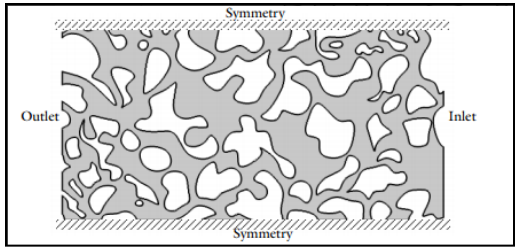
Why do we need CO2 storage models ?

- Why Modelling?
  - Screening? Feasibility Study? Quick look evaluation
- Types of Models
  - Pore network /1D / 2D/ 3D
  - Simplified or Full EOS? Chemical reactions?
- Which Tools: “Simulation Guideline” from PTE/SME network
  - It is not important which tool to use
  - It is far more important to be aware what are the processes the model(s) must capture!
  - This is project specific.
- **Today: We will not address “HOW” ?**



Subsurface view

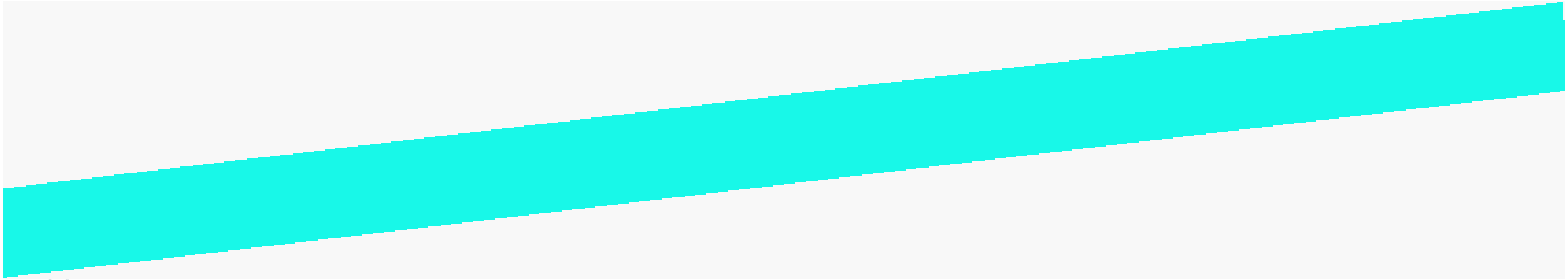




Pore scale

Why do we need CO2 storage models ?

- Storage in depleted oil fields or deep saline aquifers
- In a dipping aquifer, under gravity, the gas plume migrates upward
- The plume tip migration speed is a function of P, T, aquifer geometry (gravity force), capillary pressure (plume thickness and Sg in the plume), water chemistry and mineralogy (gas solubility), and natural convection
- Some of these processes require fine gridding, both vertically and laterally (can DLGR work? – unresolved)



Why do we need CO2 storage models ?

- CO2 Plume behavior in tilted aquifer over 100 years as function of salinity
- 3-degree slope

Why do we need CO2 storage models ?

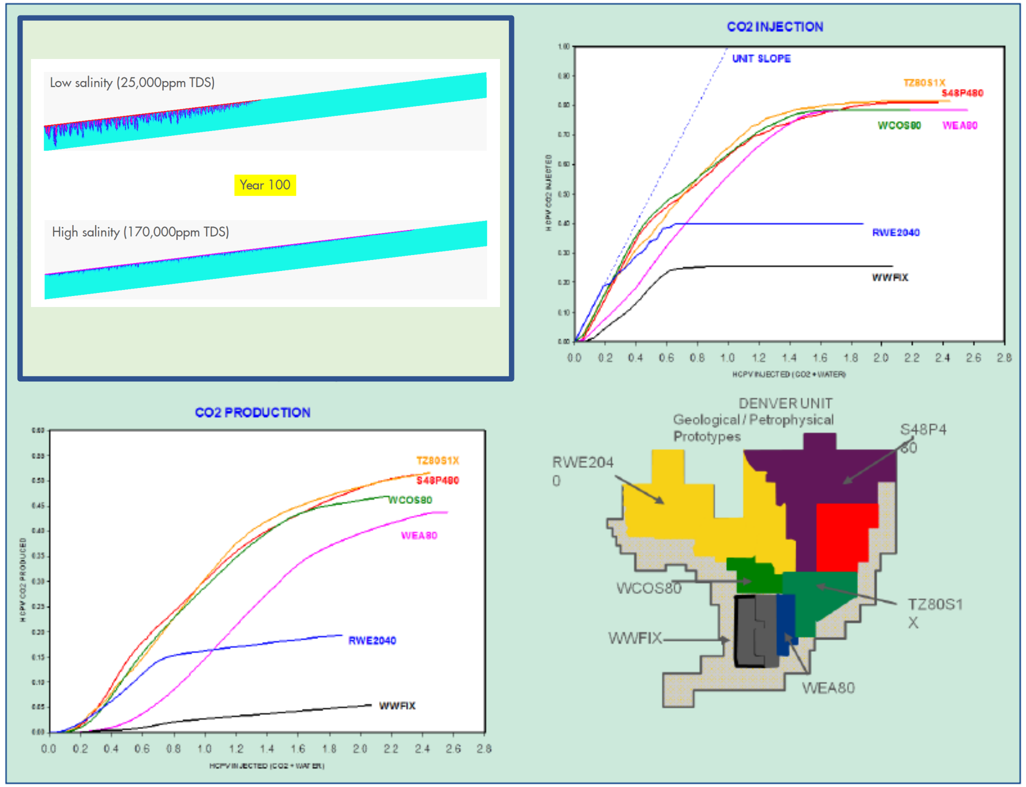
- **Key Messages:**
- There are many processes involved in gas injection, especially with CO2 and acid gases;
- There are also many details for each of the process;
- Several different modelling choices could be made to model each process;
- Key: For each project, we only have to model what is considered as “important”. Knowing what to model (“fit-for-purpose”)
- For each project, no need to measure / model everything

Simulation needs for modelling CCUS

What is a simulation model ?

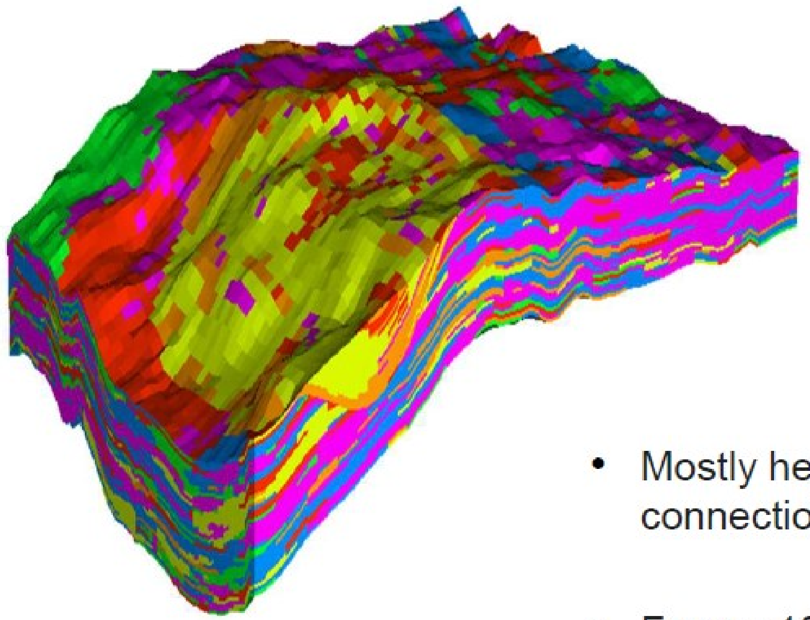
- A "reservoir model" is a mathematical representation of a specific volume of rock incorporating all the "characteristics" of the reservoir under study.

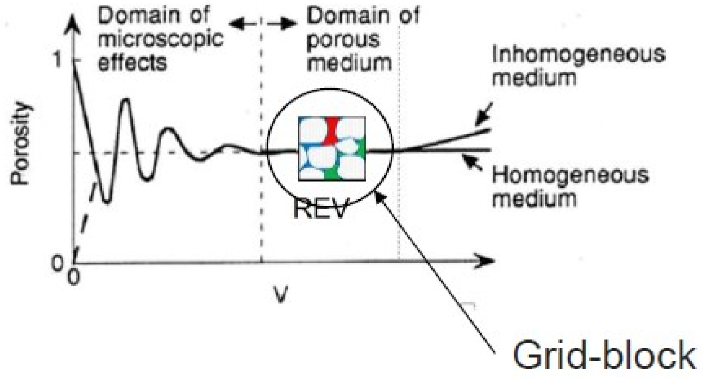
- Reservoir model consist of :
- Mathematical representation of flow processes in a geological porous medium
- Discretization of the equations and numerical solution

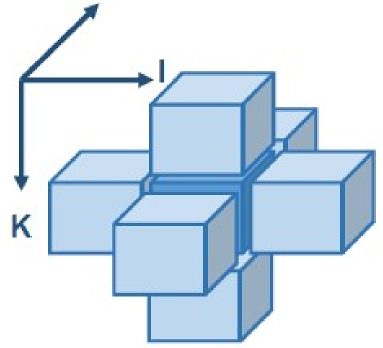


What is a simulation model ?

- PDE representing fluid flow are solved discretized using a finite-volume grid



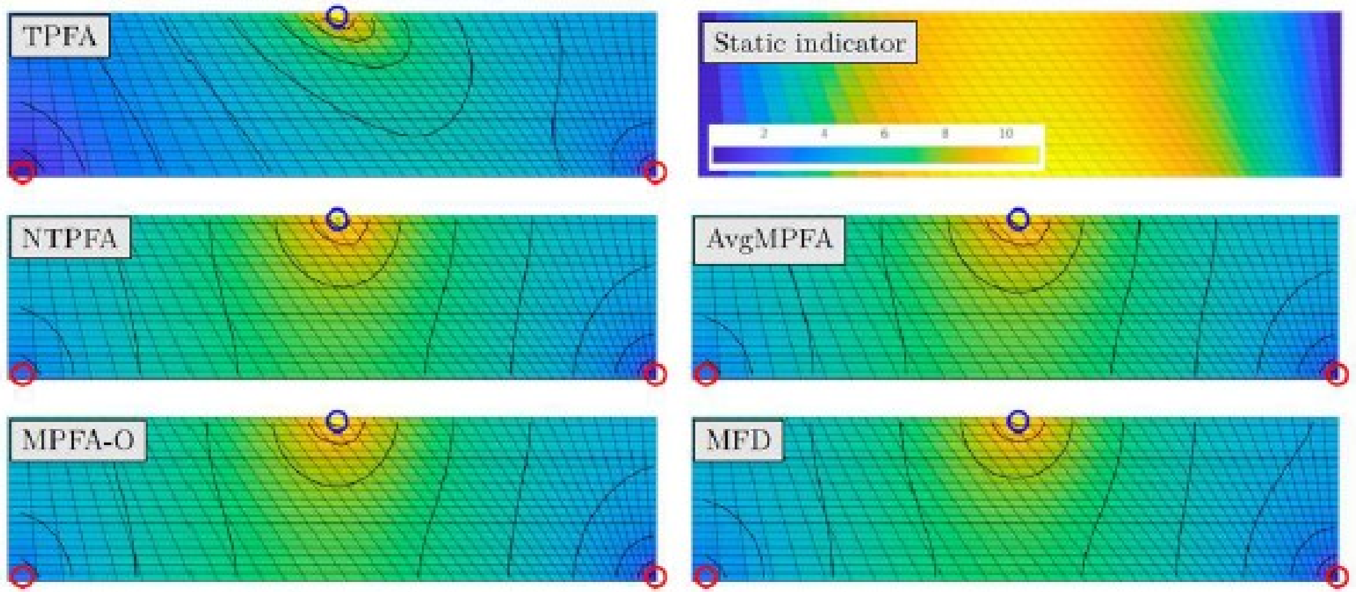




- Mostly heptadiagonal system, but possibly a large number of non-neighbor connections (e.g., pinches, non-structured grids, …).
- From ≃100k cells to tens or even hundreds of million cells

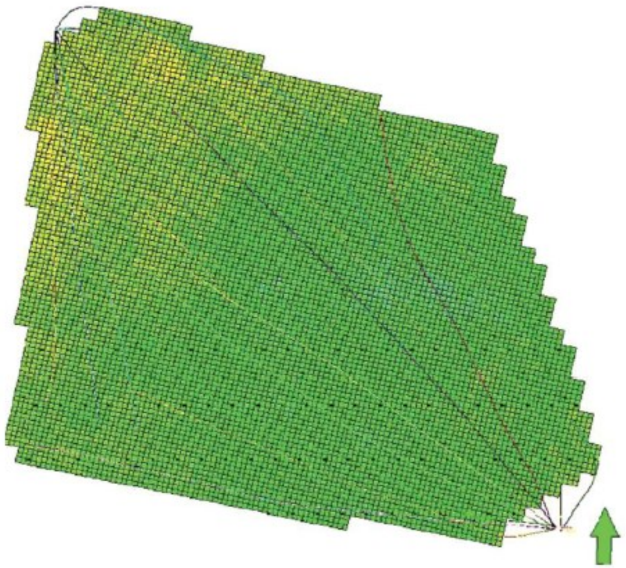
What is a simulation model ?

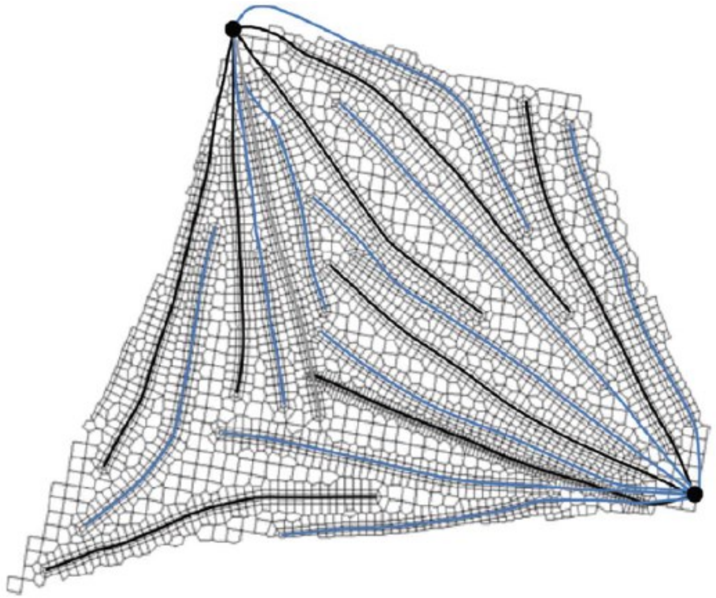
- In modelling the choice of right numerical discretization method has a big impact on results and our ultimate understanding

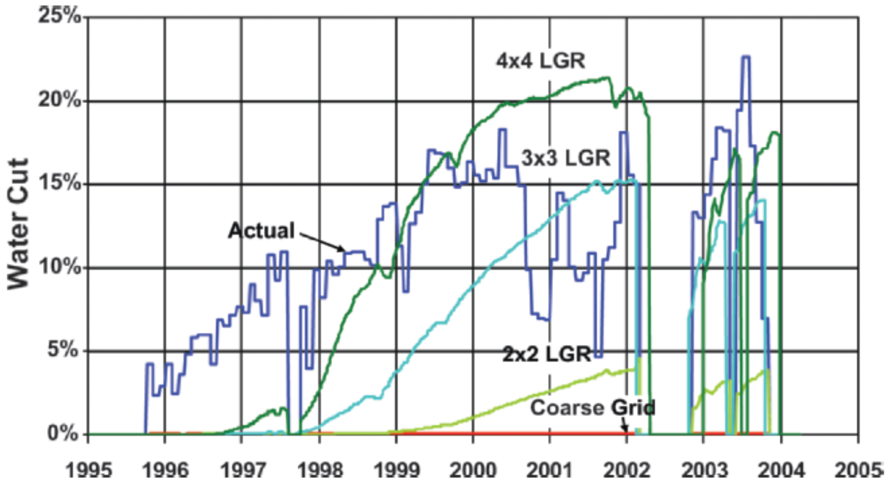


What is a simulation model ?

- Choice of discretization grids have a big impact on results too



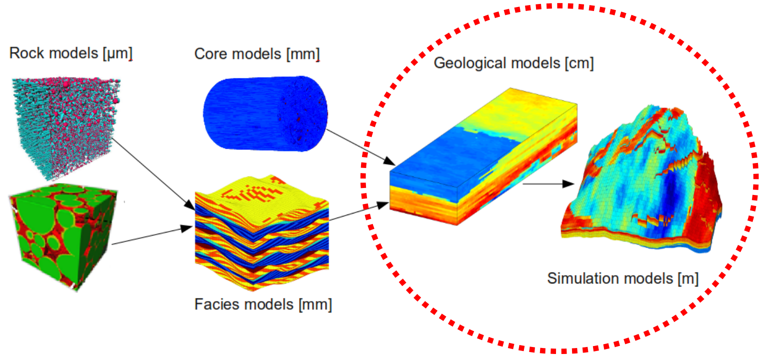




Is my reservoir model suitable?

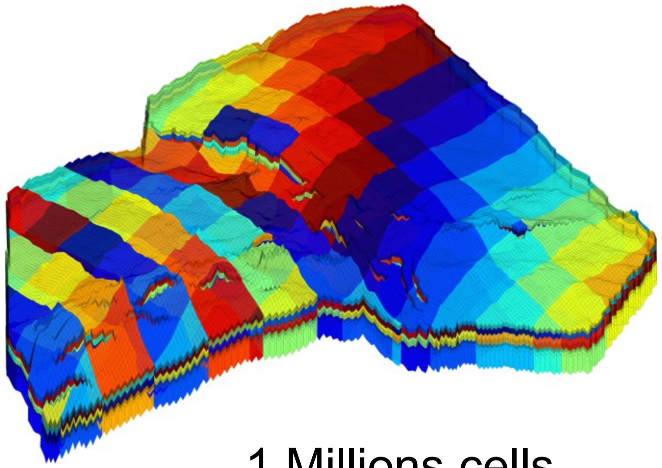
How to model reservoir heterogeneity, which has significant an impact on recovery ?

- Traditional approach for reservoir model: use the upscaled model provided by the geomodeller
  - Built from open-hole logs
  - K derived using phi/K transform
- Can this model fullfill the requirements to model water flooding?
  - MOST LIKELY NOT !
- WHY? because Heterogeneities are what define flow pattern in our reservoirs
  - Open-hole logs CAN NOT show heterogeneities below 2ft



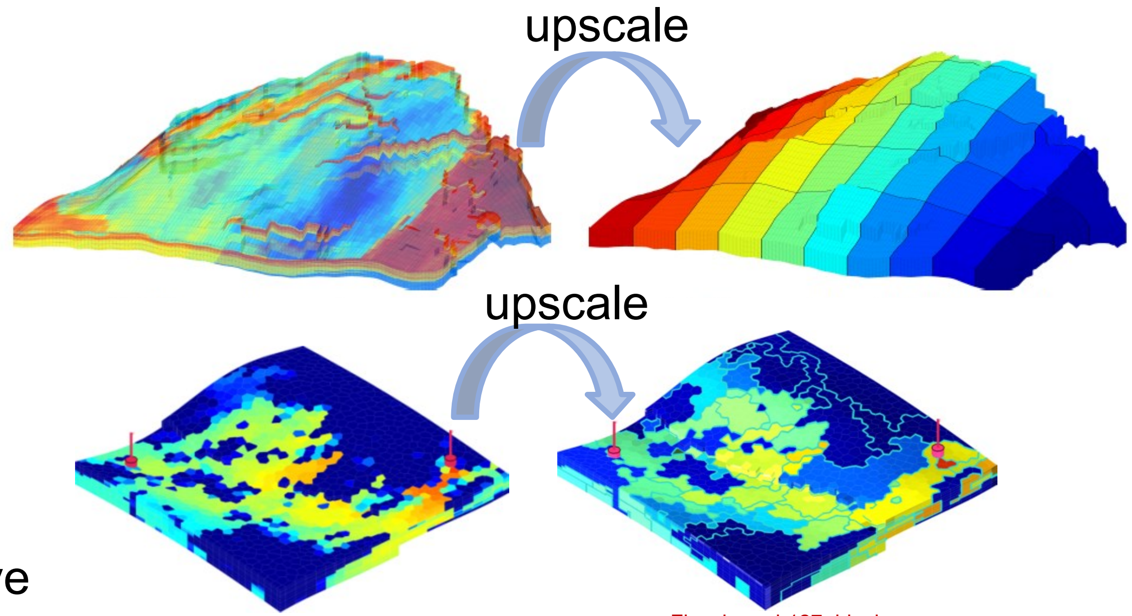
What is a simulation model ?

- Impact of upscaling/averaging parameters on results



1 Millions cells

Computationally very expensive

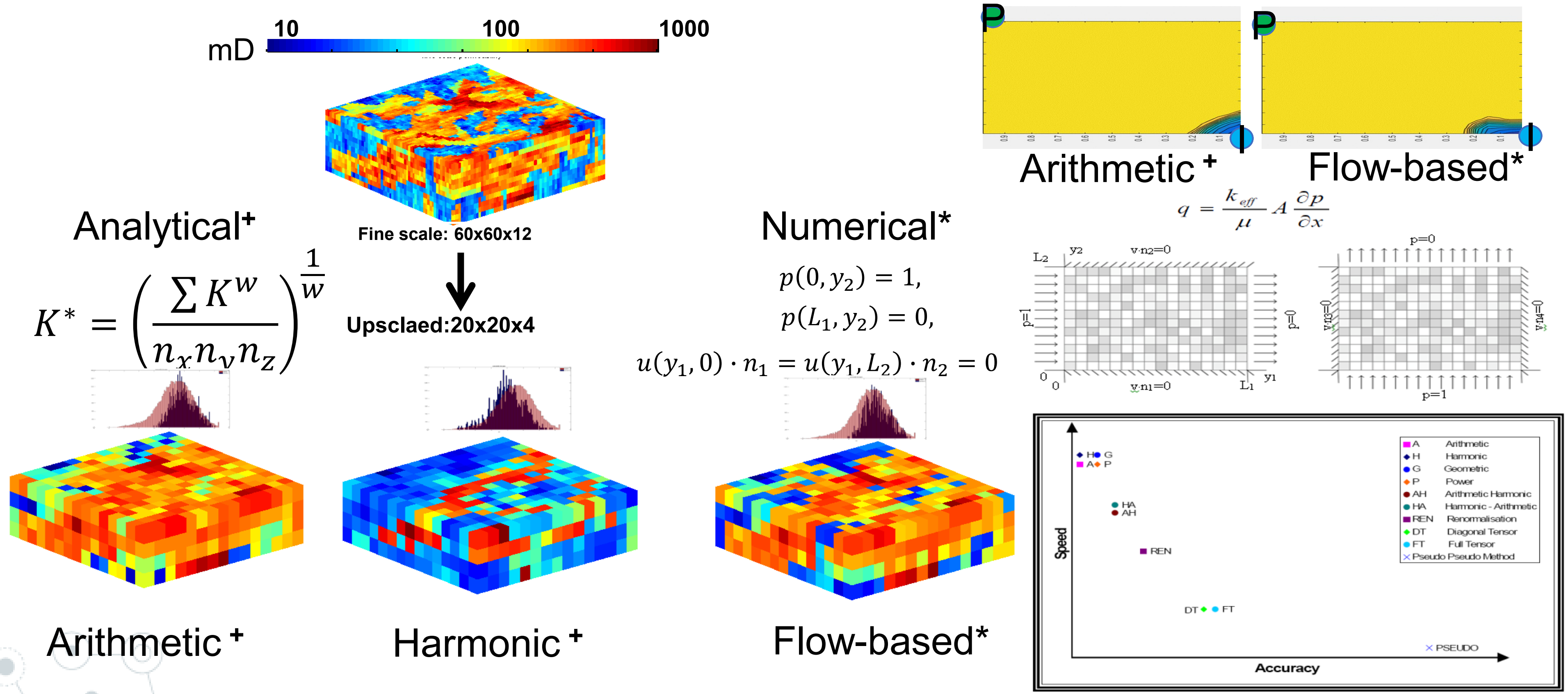


Fine grid 11864 cells

Flow-based 127 blocks

What is a simulation model ?

- Impact of upscaling/averaging parameters on results

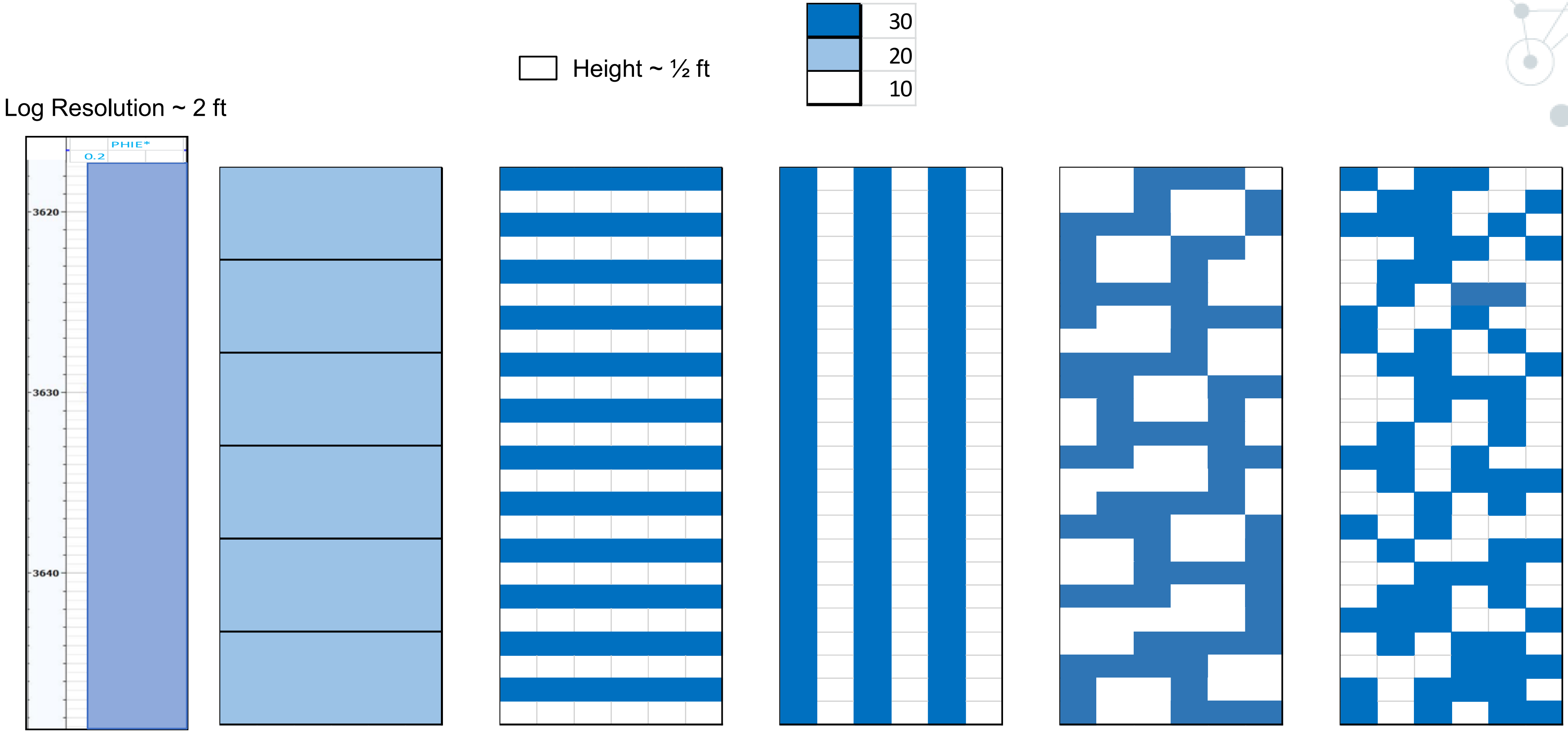


$$K^* = \left(\frac{\sum K^w}{n_x n_y n_z}\right)^{\frac{1}{w}}$$

$$p(0, y_2) = 1,$$
$$p(L_1, y_2) = 0,$$
$$u(y_1, 0)\cdot n_1 = u(y_1, L_2)\cdot n_2 = 0$$

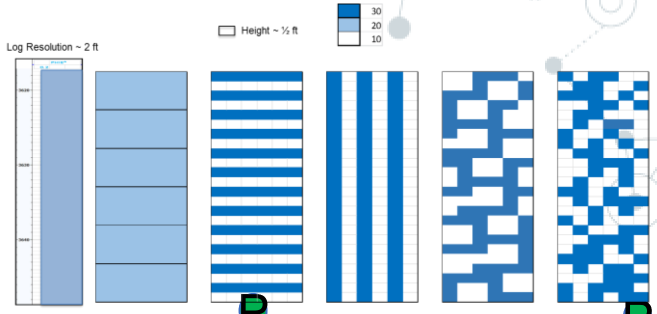
$$q = \frac{k_{eff}}{\mu} A \frac{\partial p}{\partial x}$$

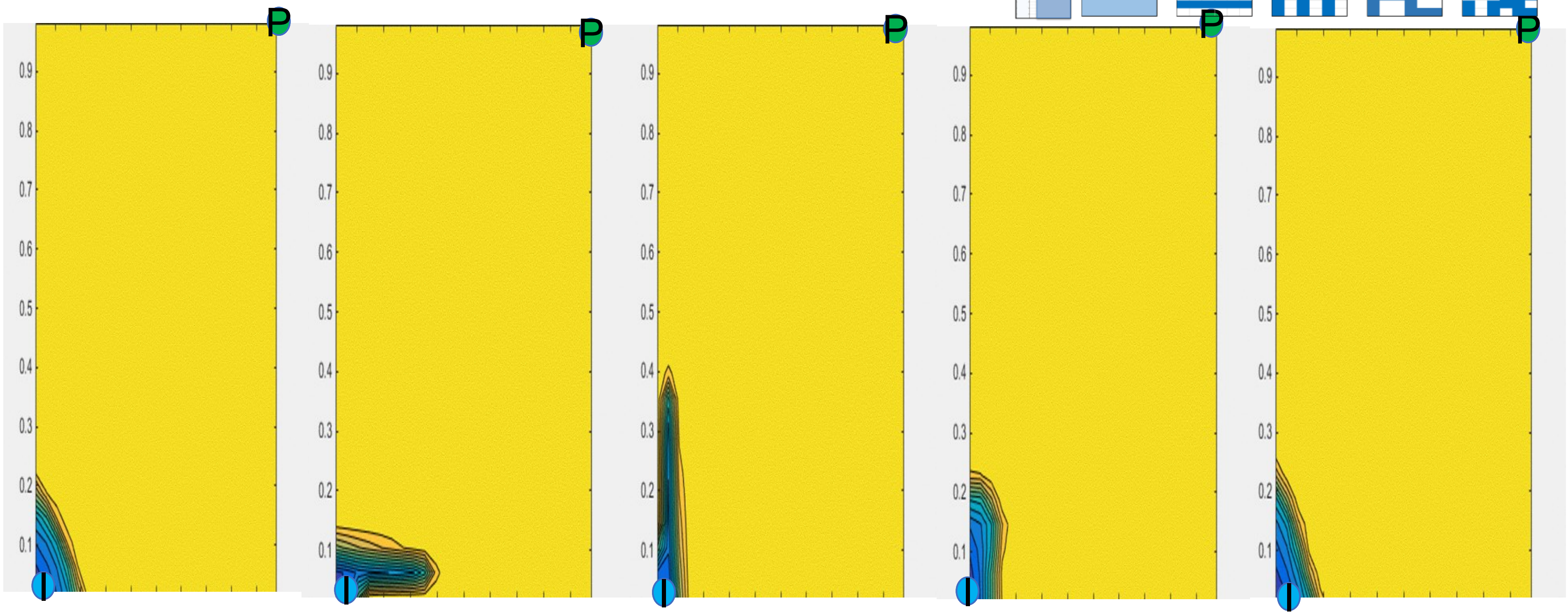
Impact of heterogeneity / distribution of porosity, on flow

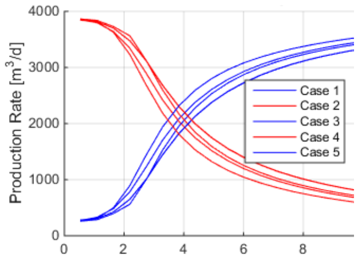


- This issue valid at any scale to evaluate reservoir flow
- It is necessary to work on a **realistic grid**, and not a gross averaged one (log derived)

Impact of heterogeneity / distribution of porosity, on flow







Application of AI and ML in CCUS

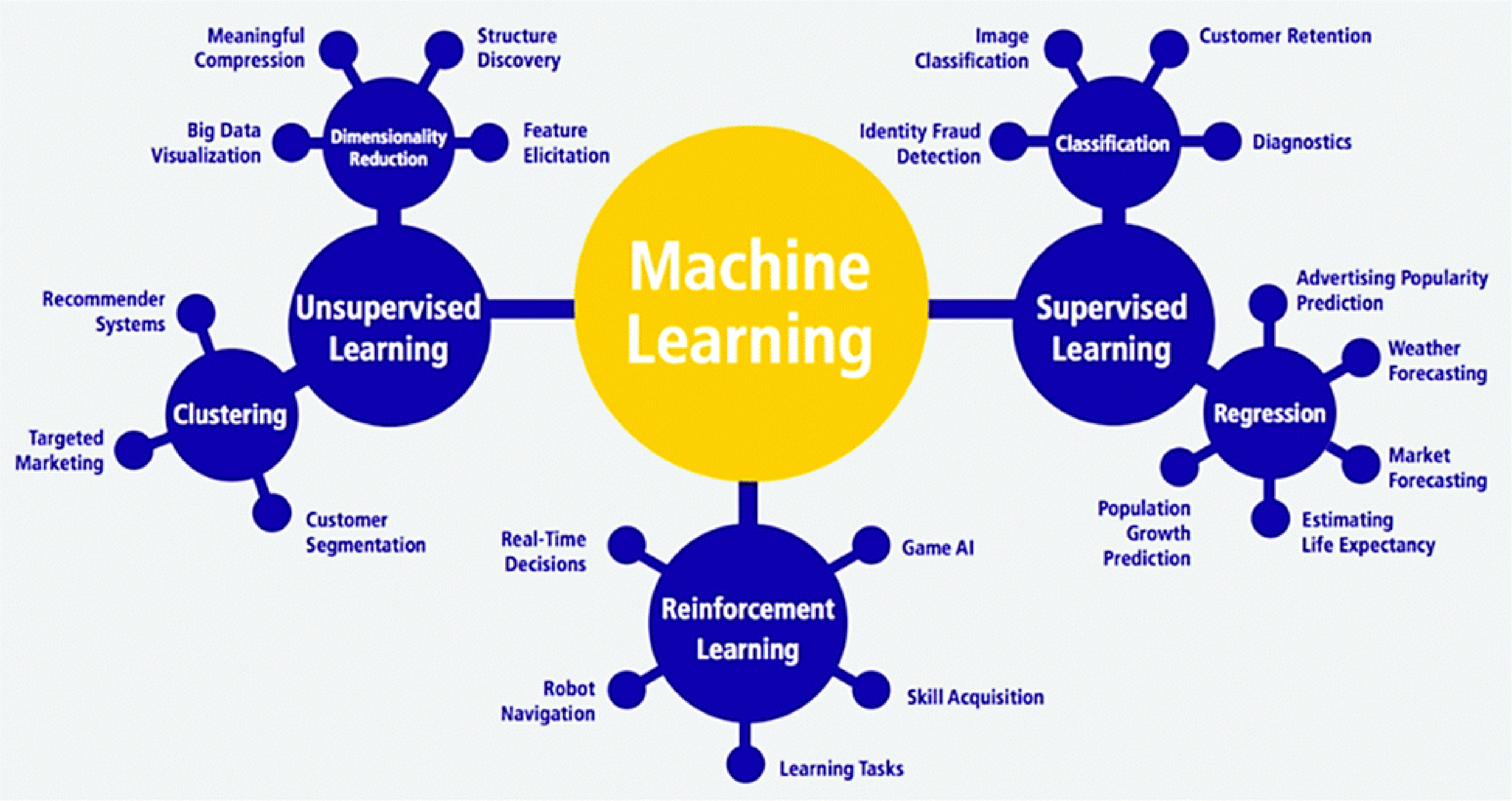
Introduction

- Carbon capture, utilisation and storage (CCUS) will play a critical role in future decarbonisation efforts to meet the Paris Agreement targets and mitigate the worst effects of climate change.
- A time and cost-efficient way of advancing CCUS is through the application of machine learning (ML).
- ML is a collective term for high-level statistical tools and algorithms that can be used to classify, predict, optimise, and cluster data.
- Within the field of CCUS, ML has begun to be utilized to evaluate new C02 sorbents and oxygen carrier materials, simulate, control and operate capture processes, simplify process economics, predict CO2 solubilities in solvents and CO2 capture capacities in adsorbents, improve the accuracy of multiphase flowmeters used for CO2 pipelines, and predict leaks from C02 wells.

Machine learning algorithms

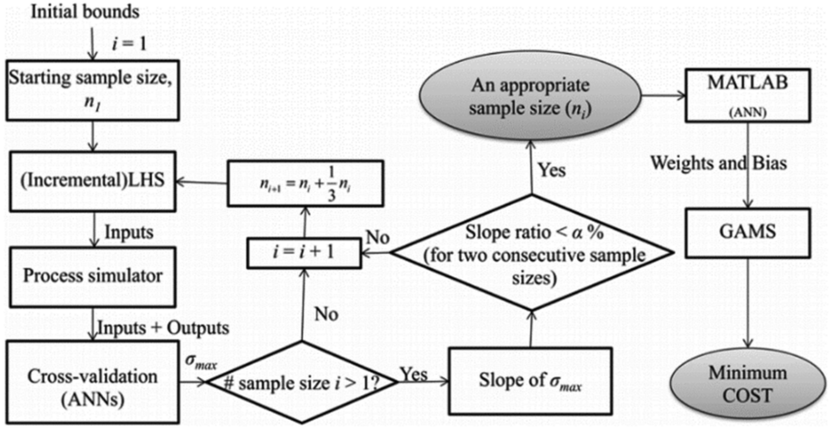
- ML is a subset of artificial intelligence (AI) that involves the study of computer algorithms that allow computer programs to automatically improve through experience.
- Its advantages include ease of trends and pattern identification, minimal human intervention (automation), ability to improve continuously, as well as high efficiency in the handling of multi-dimensional and multi-variety data.
- Figure in the next slide represents the types of ML and respective areas of application. There are three main types of ML: supervised, unsupervised and reinforcement learning.

Types of Machine Learning

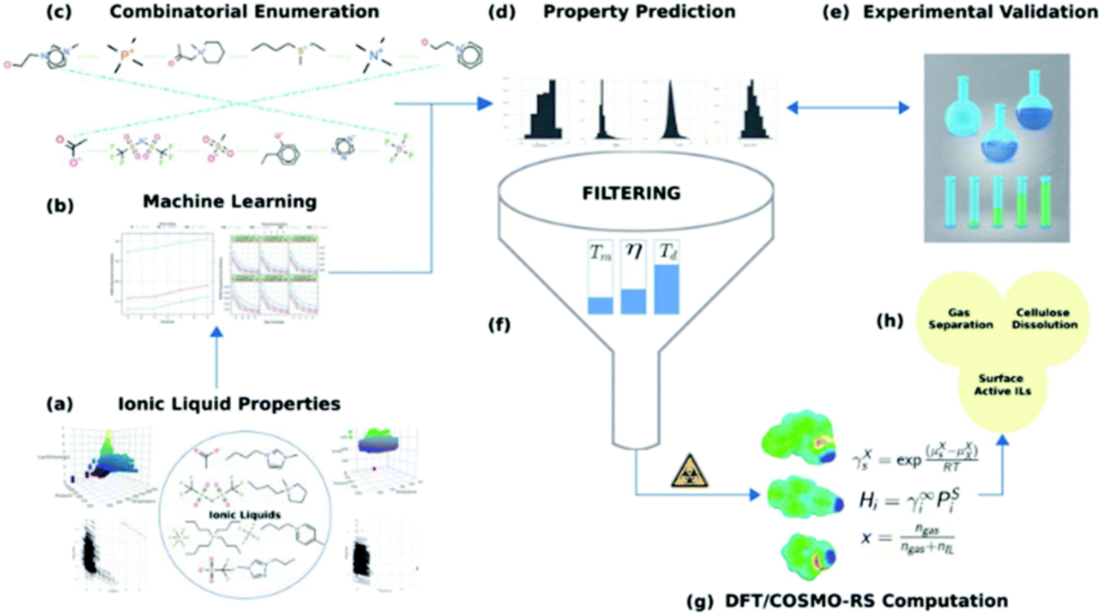


Machine learning in CO_2 absorption

- ML has wide application in modelling and analysis of different separation units such as distillation, absorption, and regeneration columns.
- Application of ML in CO_2 absorption includes process modelling, simulation, and optimisation; thermodynamic analysis; and solvents selection and design.



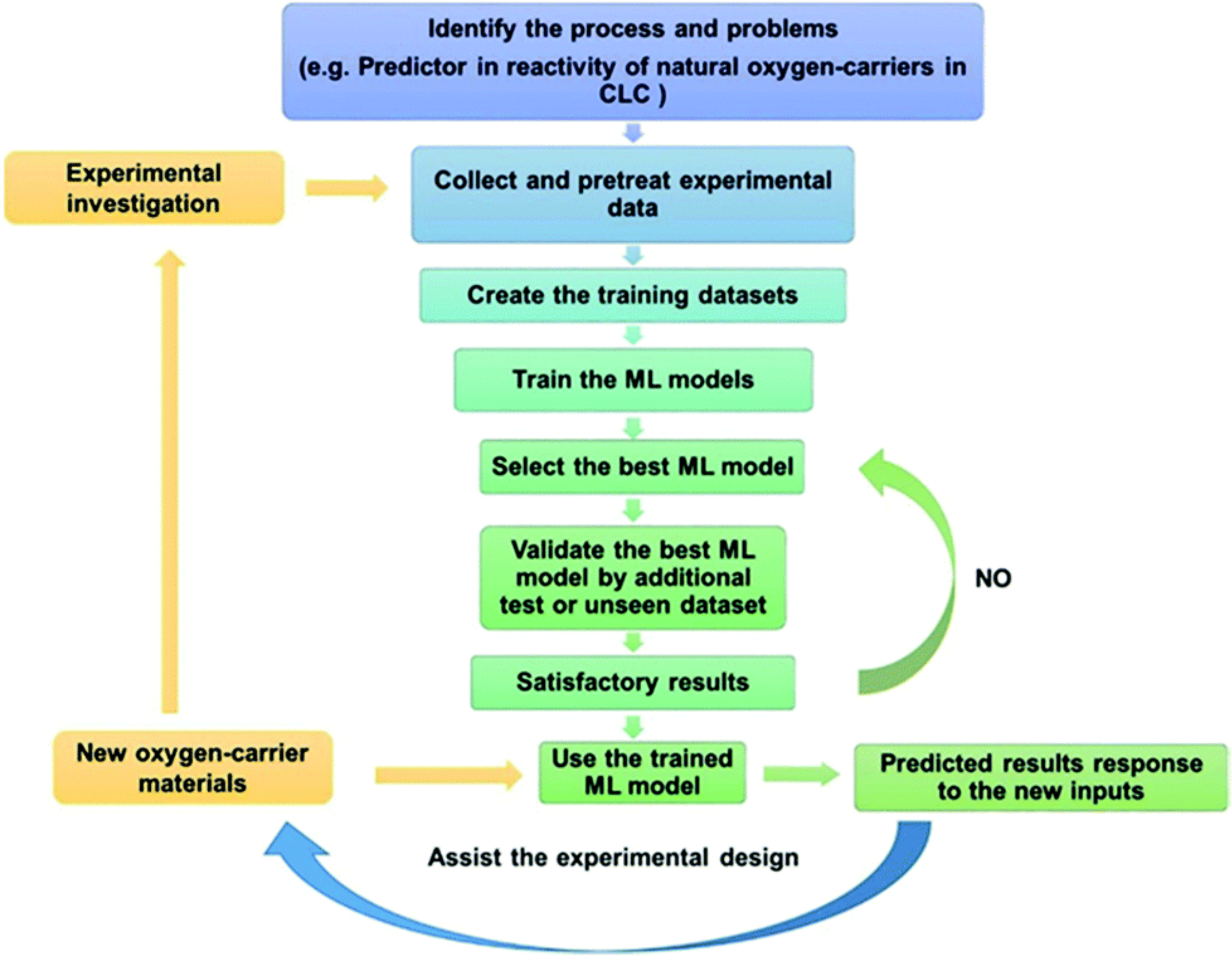
Structure of the algorithm to perform optimisation.



(a) data collection, (b) ML calibration, (c) combinatorial library design and enumeration, (d) prediction of properties by ML, (e) experimental validation of selected candidates, (f) property-based filtering, (g) theoretical evaluation, (h) potential applications.

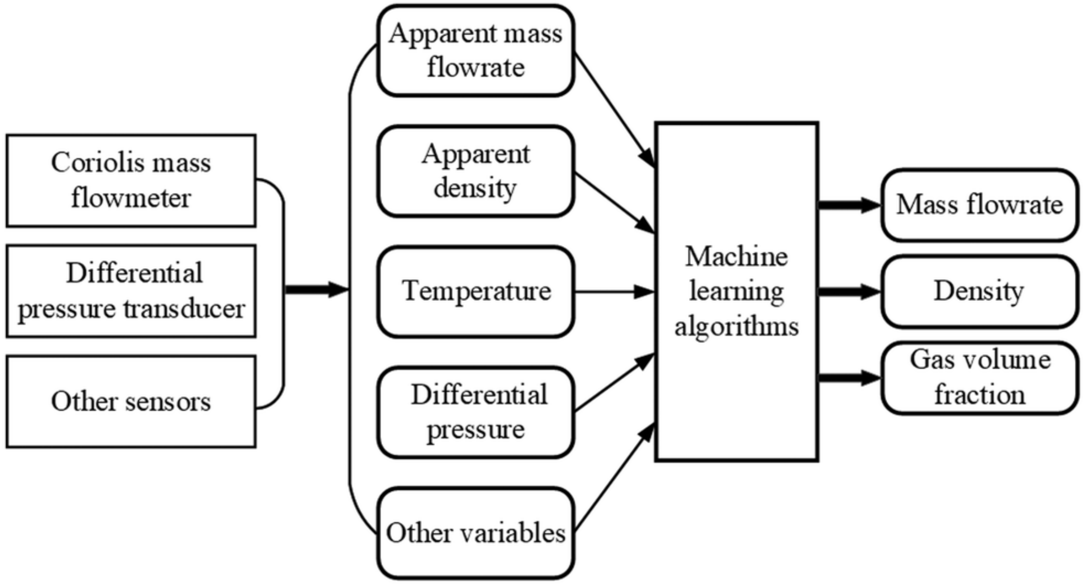
Machine learning in oxy-fuel and chemical-looping combustion for CO2 capture

- Figure below represents Workflow of developing a machine-learning model for oxygen carriers in chemical-looping processes.



Machine learning in CO2 transportation

- The captured CO2 needs to be transported from the capture points to the storage sites.
- Pipeline transportation of CO2 in the dense phase is regarded as the most cost-efficient and safest solution over a long distance.
- Mass flowrate measurement of CO2 flow is essential for the fiscal purpose in CCUS projects.
- Figure below represents a typical CO2 flow measurement system based on low-cost sensors and ML algorithms.



Machine learning in CO2 storage and utilization

- ML has been widely applied in CO2 storage and CO2 – EOR projects.
- Various ML algorithms has been employed to investigate relation between CO2 solubility and factors such as diffusivity, oil/gas–brine IFT, temperature, pressure and brine salinity.
- Studies have been performed on how to monitor and detect CO2 leakage in CCS projects using ML techniques with direct or in-direct monitoring data. The data used include seismic data, downhole monitoring information (such as pressure or TDS), porosity and permeability maps, and injection/production rate, etc.
- It is important to recognise that ML has been utilised in numerous studies regarding CO2 storage, utilisation and CO2 – EOR, however, there are still expectations that a more universal workflow will be generated to handle the whole process of a CO2 – EOR – CCS project including data interpretation, storage effect modelling, leakage detection and optimisation jobs, *etc.*

Patents and New Technology Overview

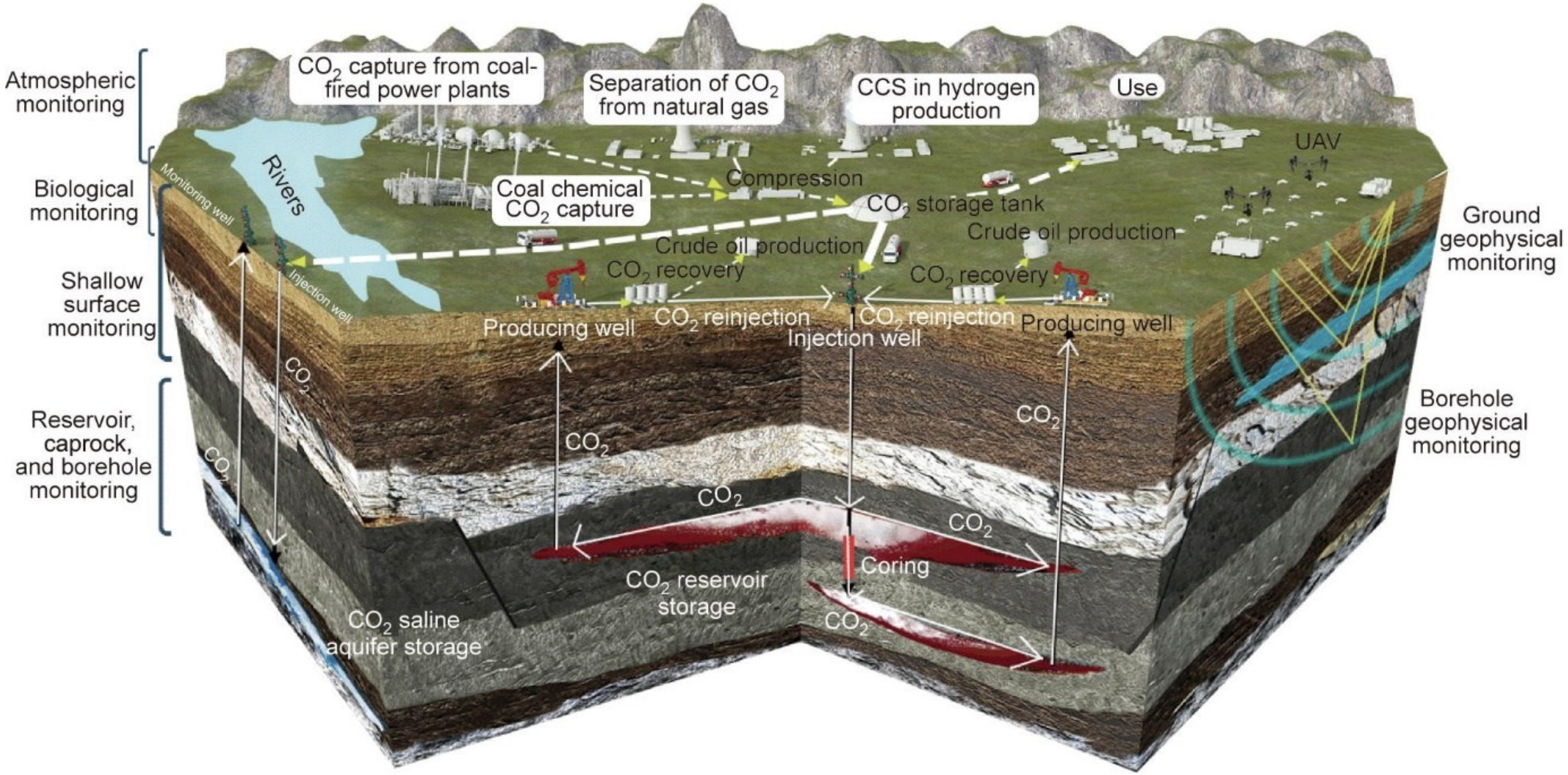
Objectives of work

- The patent landscape search has been conducted to identify patents related to Carbon capture and sequestration.
- The search has been conducted for LT OR LV OR EE OR FI OR DK OR SE OR RU OR PL OR NO OR IS OR ES and restricted with earlier Priority date from 2000-2020.
- Patents primarily focuses on CO_2 storage, monitoring, utilization, transport and further technologies.

Introduction

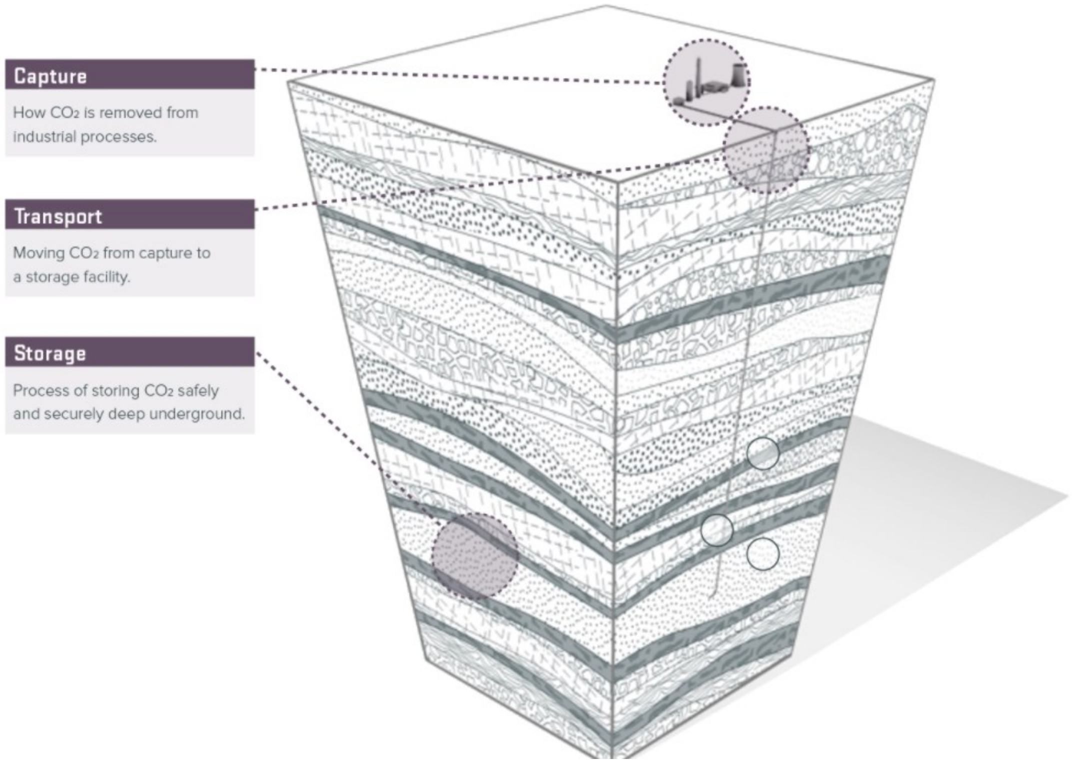
- CO_2 capture technology has been used since the 1920s for separating CO_2 sometimes found in natural gas reservoirs from the saleable methane gas.
- Just as scrubbers remove air pollutants from emissions, CCS separates carbon dioxide from other gases.
- More recently, investment in CCS is being driven by the oil and gas industries as well as cement, iron and steel, and chemical production industries in the push for decarbonization.
- Once CO_2 is separated from other gases, the carbon dioxide is then compressed, transported, and injected underground for permanent storage.
- About 90-100% of produced carbon dioxide can be captured.
- Many are betting on CCS as a key to greenhouse gas emission reductions, since leveraging CCS is expected to achieve 14-19% of the reductions needed by 2050.

The CCS industry chain



Carbon capture-steps involved

- Capturing and storing millions of tones of CO2 annually. In particular, the oil and gas industry has been operating several CCS projects for a number of years. These have helped build understanding of implementing projects in different geological environments and importantly they have demonstrated that secure storage of large quantities of CO2 is possible.
- The major steps involved in carbon capture are
  - Site selection
  - Capture
  - Transport
  - Storage
  - Monitoring and verification



Processes flow-carbon capture

Site selection

The oil and gas industry has decades of experience understanding and assessing sites kilometers deep underground. The latest technology to map oil and gas fields is now being used to assess sites suitable for CO_2 storage. The most effective way to ensure permanent safe storage is to choose sites of sufficient depth (typically deeper than 800 meters) with adequate capacity and an overlying sealing system to ensure containment of fluids.

Capture

CO_2 has been captured from emitting sources and sold for use by other industries. Existing capture technologies can be applied to large-scale industrial processes, such as power generation, oil and gas production and cement manufacture. Capturing CO_2 requires extra energy, but even taking this into account, the cost efficiency of CCS is still better than most forms of low-carbon energy generation. Three main technologies exist: post-combustion, pre-combustion and oxy-firing.

Transport

Captured CO_2 has to be compressed and transported, most likely by pipeline, to a site suitable for storage. Ships may be viable for CO_2 transportation over long distances. Even if a suitable storage site lies directly beneath the source of capture, the captured CO_2 will have to be compressed and pumped underground. Pipelining of gases and liquids is widespread throughout the world, and includes millions of tonnes of CO_2 that are transported each year for use in Enhanced Oil Recovery (EOR) operations and in emerging CCS projects. Pipeline infrastructure can be costly, but heavy industries are often 'clustered' together which allow CO_2 pipeline networks to be shared.

Storage

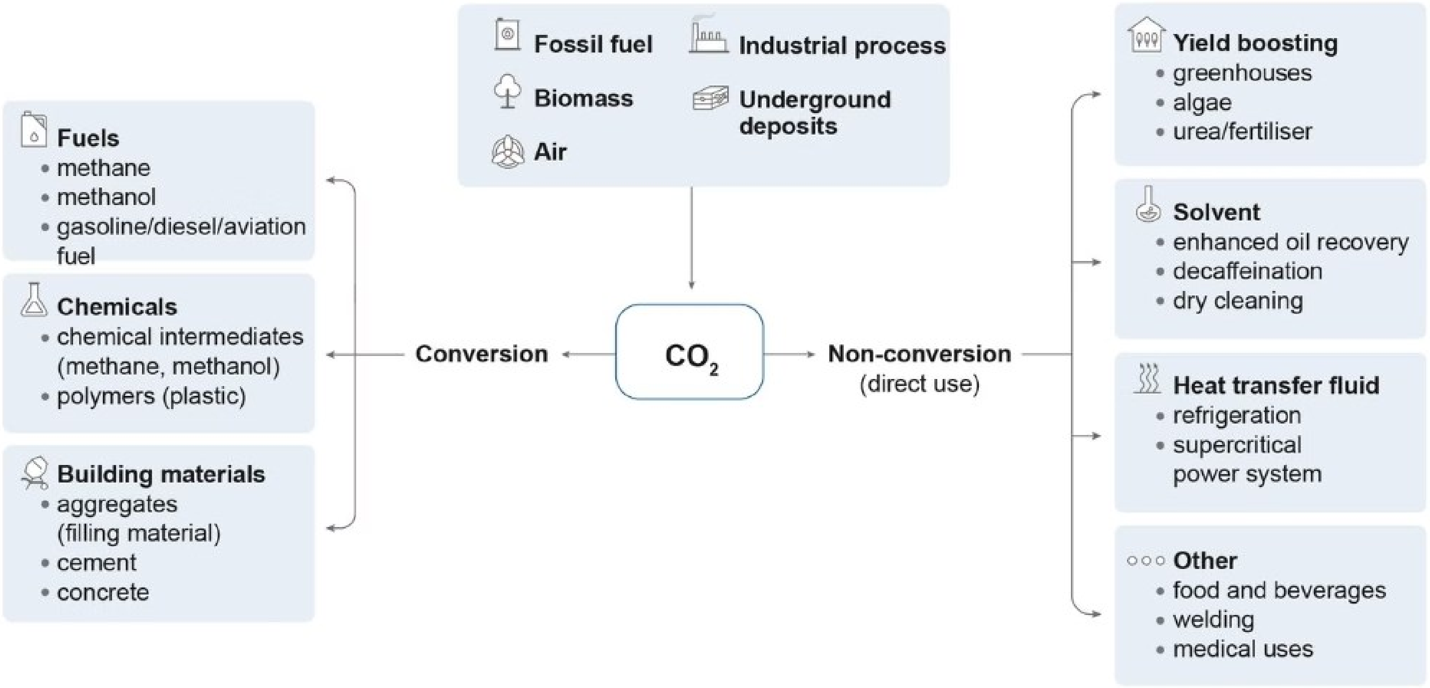
The oil and gas industry has years of experience injecting CO_2 underground into geological formations in a process used to enhance oil recovery (EOR). Millions of tonnes of CO_2 are injected annually under regulations which protect local communities and the environment. As oil and gas has become more difficult to access, the industry has rapidly developed precise drilling practices to meet the challenge. This technology is being deployed to ensure CO_2 storage takes place safely and securely.

Monitoring and verification

A wide array of monitoring technologies has been used by the oil and gas industry to track fluid movement in the subsurface. These techniques are readily adaptable to CO_2 storage to monitor the behavior of CO_2 underground. For example, seismic surveying provides an image of the subsurface, often allowing the behavior of stored CO_2 to be mapped and predicted. Other monitoring technologies include down-hole and surface CO_2 sensors. New technologies such as satellite imaging, which can detect movements of less than 1mm in the Earth's surface are also being developed.

CO2 usage technologies

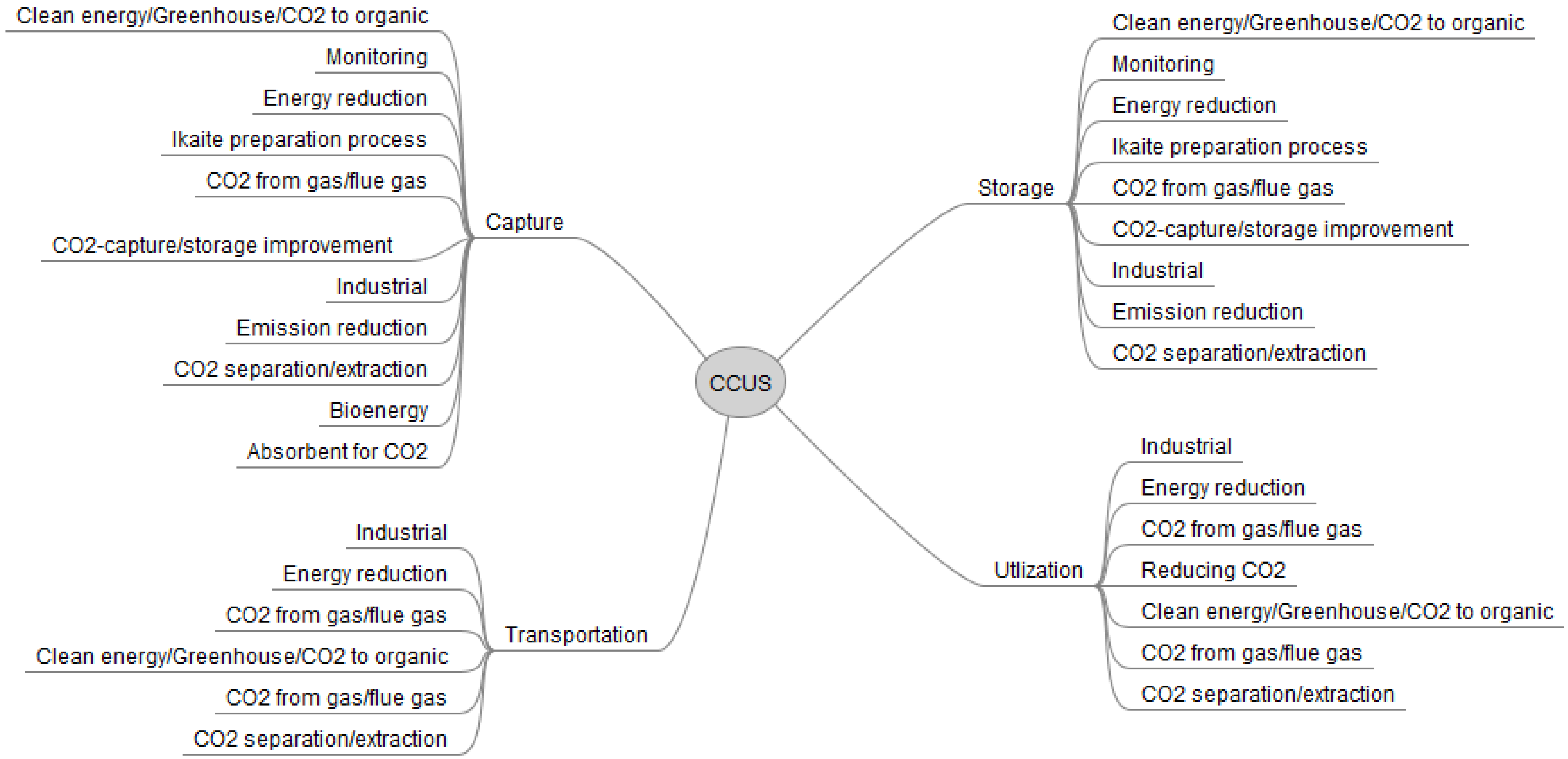
- The potential applications for CO2 use include direct use, where the CO2 is not chemically altered (non-conversion), and the transformation of CO2 to a useful product through chemical and biological processes (conversion).
- CO2 can be used as an input to a range of products and services – fuels, chemicals, building materials, yield boosting, solvent, heat transfer fluid and others.



Search methodology

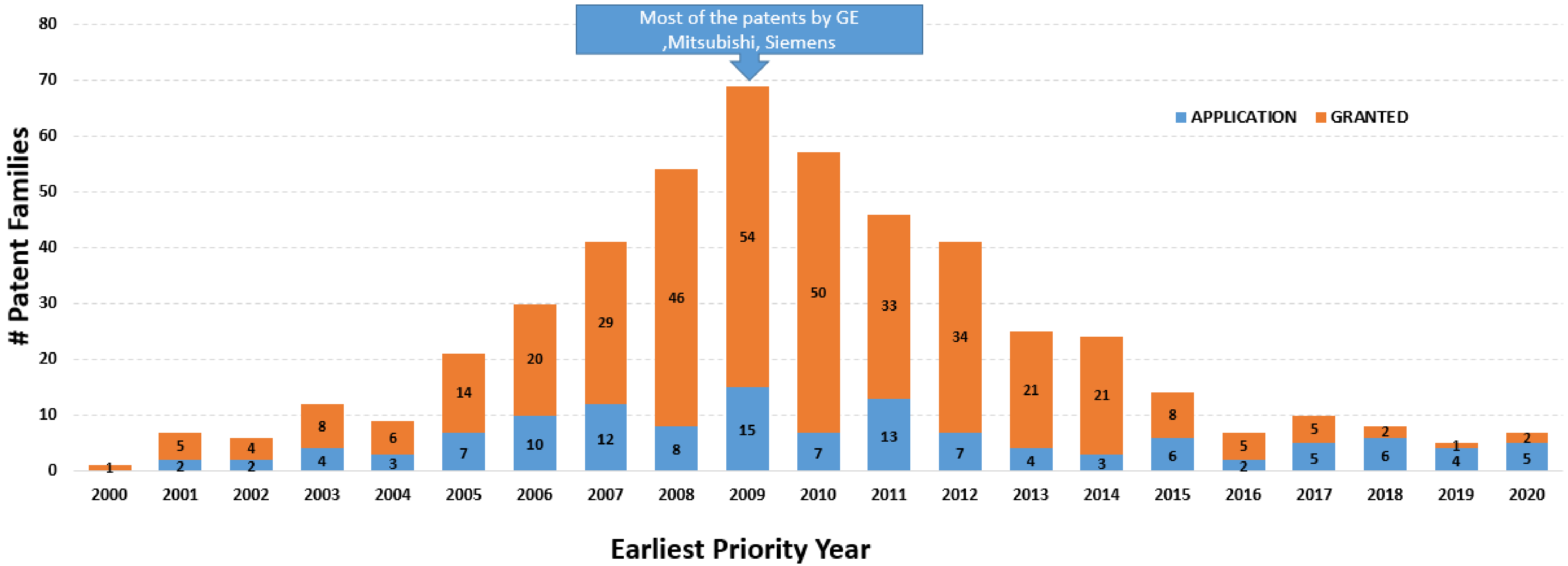
- The patent search is conducted to identify patents related to CCUS technology. Patent search was conducted on Orbit database.
- The search resulted in 3299 patent families.
- A relevancy analysis was done to identify patents which are related to CCUS & resulted in 497 patent families.
- Identified relevant patents have been categorized in a classification scheme described in the next slide.
- The search was conducted in June 2022 and results include patent/patent applications.

Patent classification scheme



Patent Filing – 1st Application year

- A total of 497 patent families are found relevant in the analysis related to CCUS technology.
- Below is a chart representing earliest priority filing (first patent application date) trend.

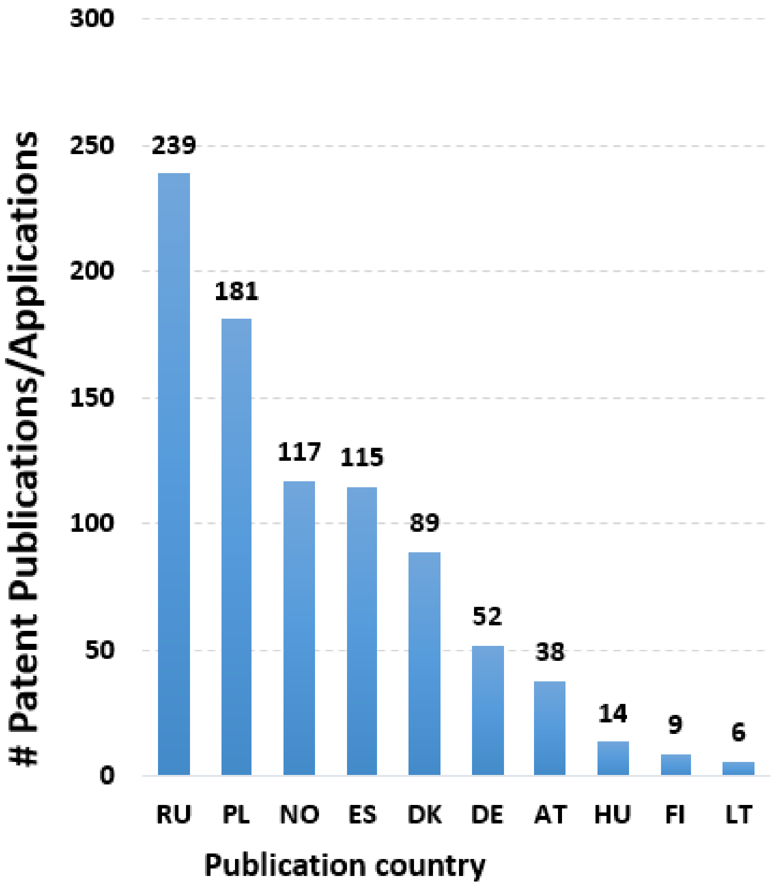


- Observed 2009 has most number of IP activity for CCUS for both applications and grants
- Observed 2005-2009 has an increasing trend for CCUS activities
- Observed 2010-2015 has a decreasing trend for CCUS activities

Patent Filing - Countries

- CCUS technology has found attention all over norther and eastern European countries.
- The charts below show geographical representation of patent filing across LT OR LV OR EE OR FI OR DK OR SE OR RU OR PL OR NO OR IS OR ES and the assignees.

Assignees	Russia	Poland	Norway	Spain	Denmark	Germany	Austria	Hungary	Italy
GE	42	12	3	5	5	2			
MITSUBISHI	23		10		10	3			
SIEMENS	14	9	1	4	1	4			
IFP	6	7	5	4	3	4	5	1	1
KANSAI ELECTRIC POWER	10		5		4	1			
AIR PRODUCTS & CHEMICALS	2	12	1	5	1	2	2		
AKER CARBON CAPTURE	2	8	10	3	1				
IHI		11	1	9					
AIR LIQUIDE	3	9		4		2	3		



- RU has the highest number of publications followed by PL and NO
- GE has more filings in RU and PL
- IFP has consistent filing in the north-Eastern European countries

Patent Filing – Countries vs Application year

- Chart below represents all the north-eastern European countries.

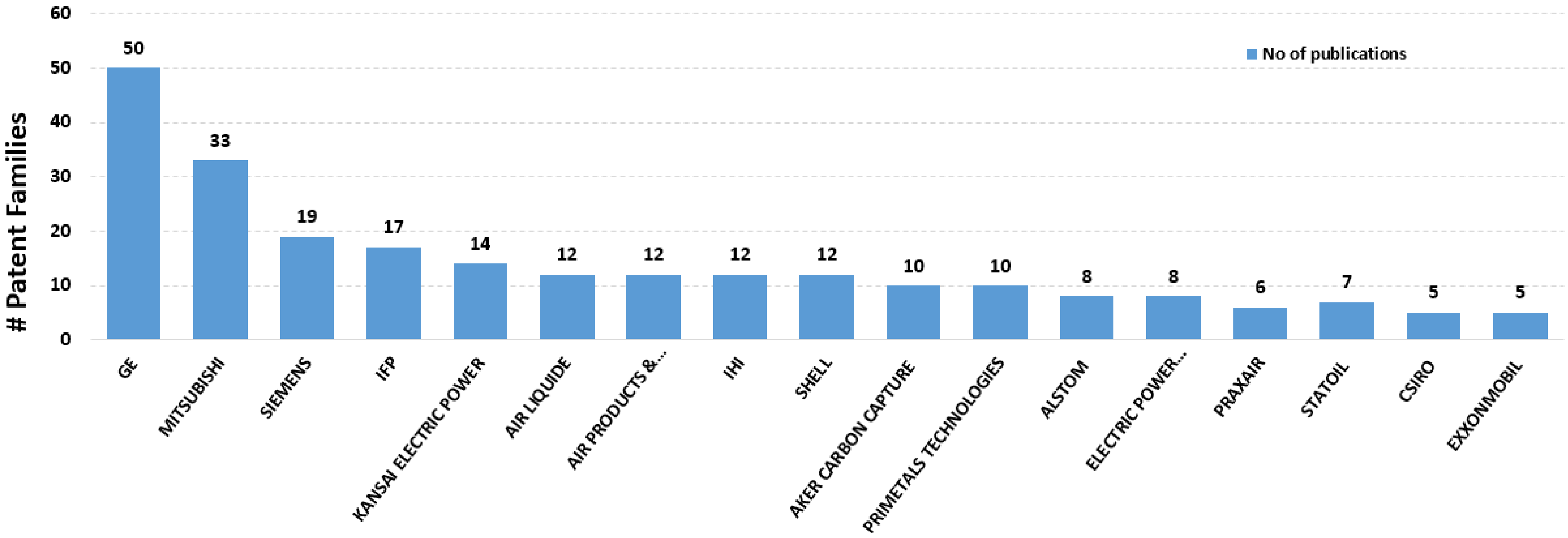
1st Application year

PUBLICATION COUNTRIES

Country	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Russia		1	5	7	8	18	21	26	46	25	23	19	13	12	6	4	5	2	2		
Poland	1	1	5	2	6	8	27	17	17	25	19	14	12	10	4	3	4				
Norway	2	3	5	7	8	11	8	18	11	7	10	5	5	3	1	1	2	3	3		
Spain	2	1	5	1	5	8	16	13	12	17	11	8	7	2	3	1	2				
Denmark	3		4	4	2	4	7	12	10	10	8	8	6		3	1	1	1	3		
Germany	3	3	6	2	6	5	7	8	3	4	1	2	1		1						
Austria	1	3	6	2	5	2	6	7	1	3											
Hungary						1	1	2		2	3	1	1		2						
Finland		1				1	1	2	2		2										
Lithuania						1	1			2	1						1				
Iceland					1																

- **RU has most filings in 2010**
- **PL, NO, ES and DK has more filings from 2006-2014**

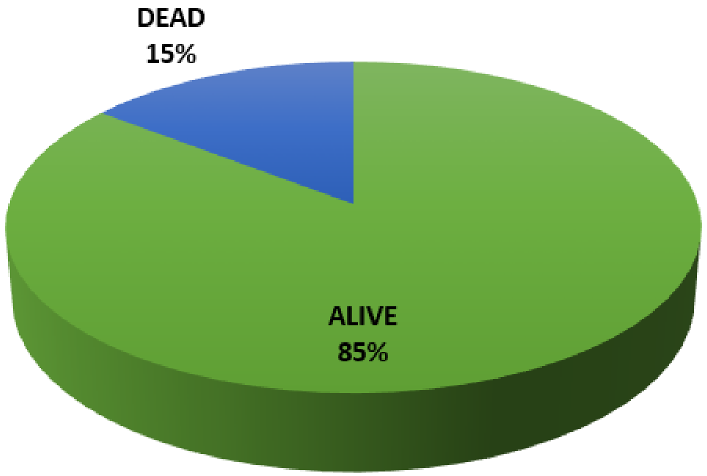
Top assignees



- GE has the highest number of publications followed by Mitsubishi and Siemens

Legal Status of INPADOC families

- Charts below represents legal status of all the patents.



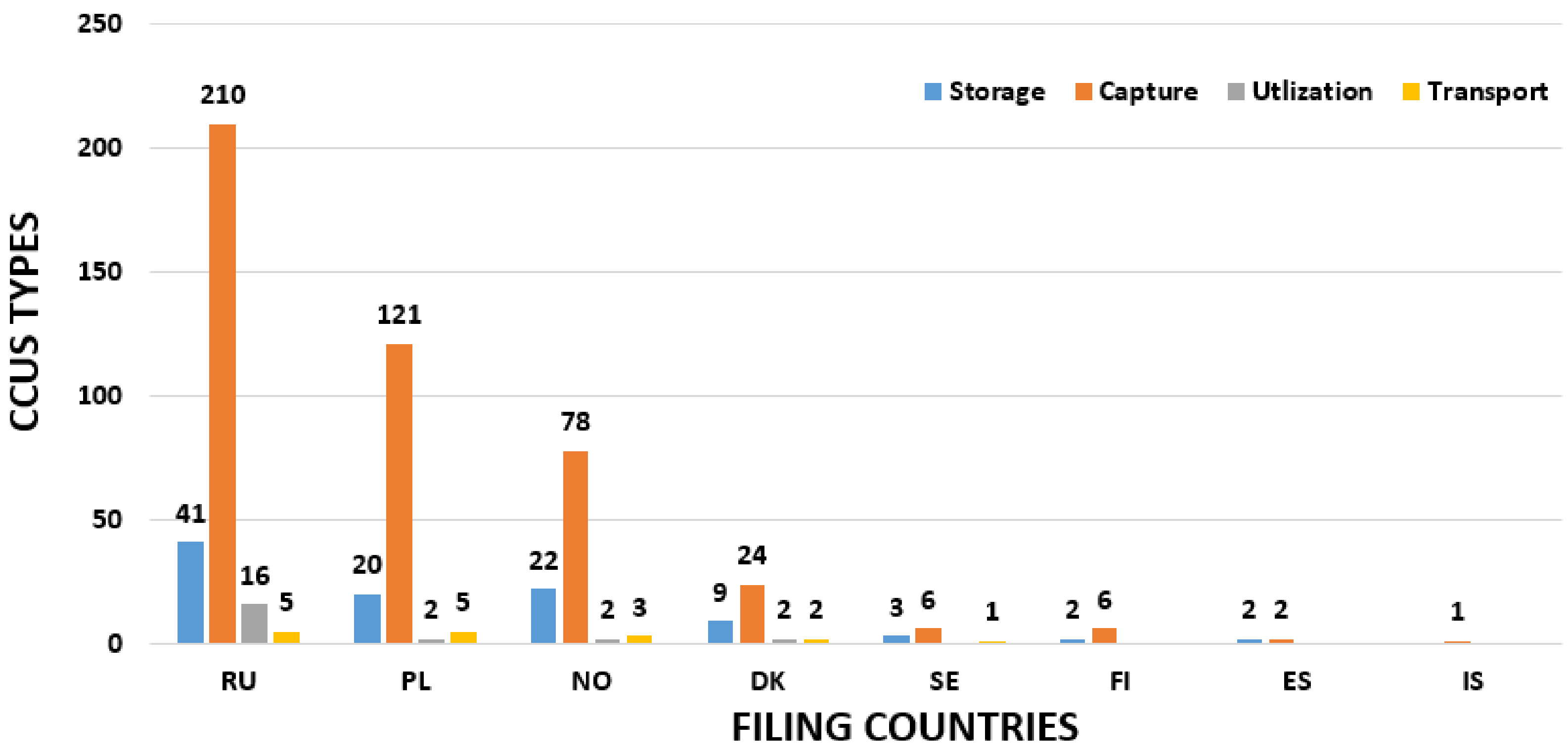
Country wise- Legal Status

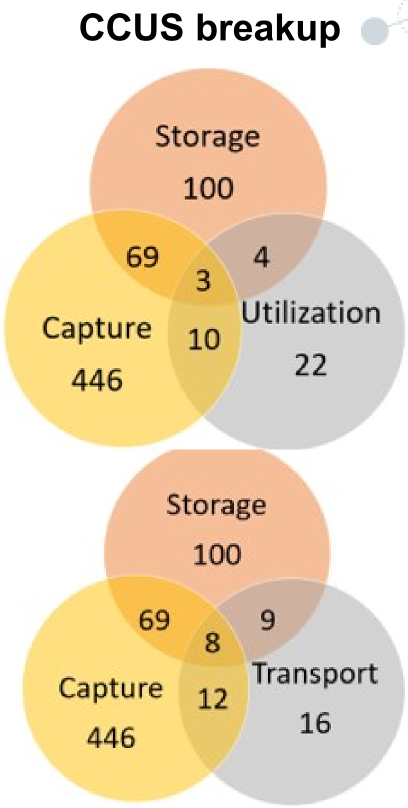
Assignees	Alive	Dead
GE	41	9
MITSUBISHI	29	4
KANSAI ELECTRIC POWER	11	3
SIEMENS	16	3
AIR LIQUIDE	11	1
AIR PRODUCTS & CHEMICALS	11	1
IHI	12	
IFP	9	8
AKER CARBON CAPTURE	10	
PRIMETALS TECHNOLOGIES	10	
ALSTOM TECHNOLOGY	6	2
ELECTRIC POWER DEVELOPMENT	8	

- 85% of 497 relevant Patent families are Alive.

Primary category-CCUS types

- Charts below represents categorization for the relevant patents.

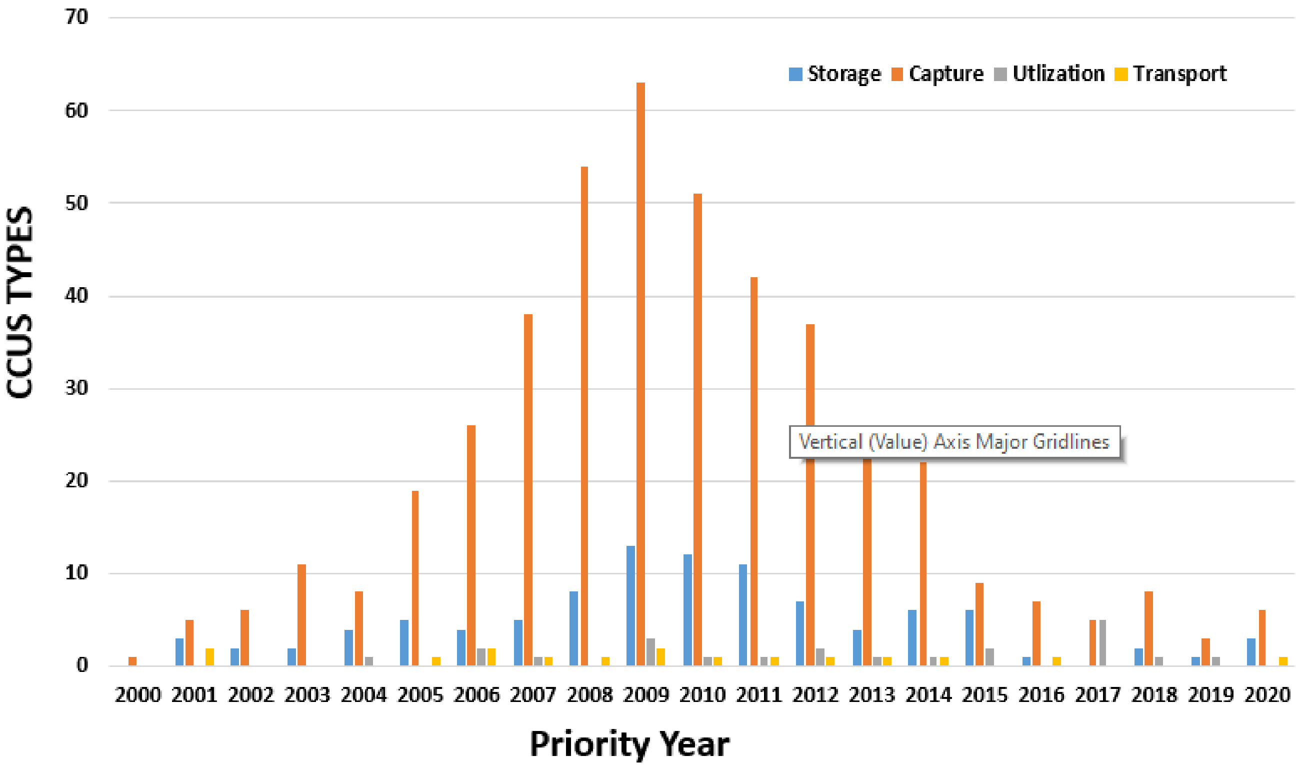




- RU has the most number of patents/publications in CO2 capture, Storage, Utilization and transport followed by PL and NO
- CO2 capture is the most explored technology/CCUS type.
- Capture technology along with storage is the most common.

CCUS types- EPR

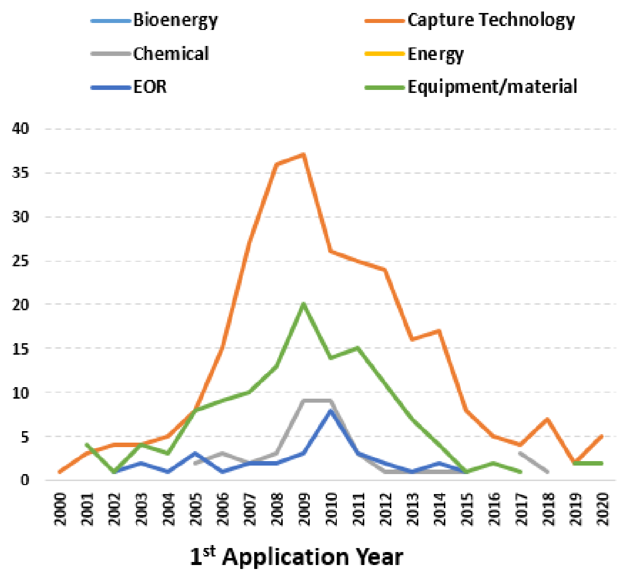
- Charts below represents, CCUS types with the priority year.



EPR	Storage	Capture	Utlization	Transport
2000		1		
2001	3	5		2
2002	2	6		
2003	2	11		
2004	4	8	1	
2005	5	19		1
2006	4	26	2	2
2007	5	38	1	1
2008	8	54		1
2009	13	63	3	2
2010	12	51	1	1
2011	11	42	1	1
2012	7	37	2	1
2013	4	23	1	1
2014	6	22	1	1
2015	6	9	2	
2016	1	7		1
2017		5	5	
2018	2	8	1	
2019	1	3	1	
2020	3	6		1

- **2009 has the most number of filing for capture**
- **Capture technology has been prominent from 2003-2013**
- **2009 has the most number filing in all CCUS types**

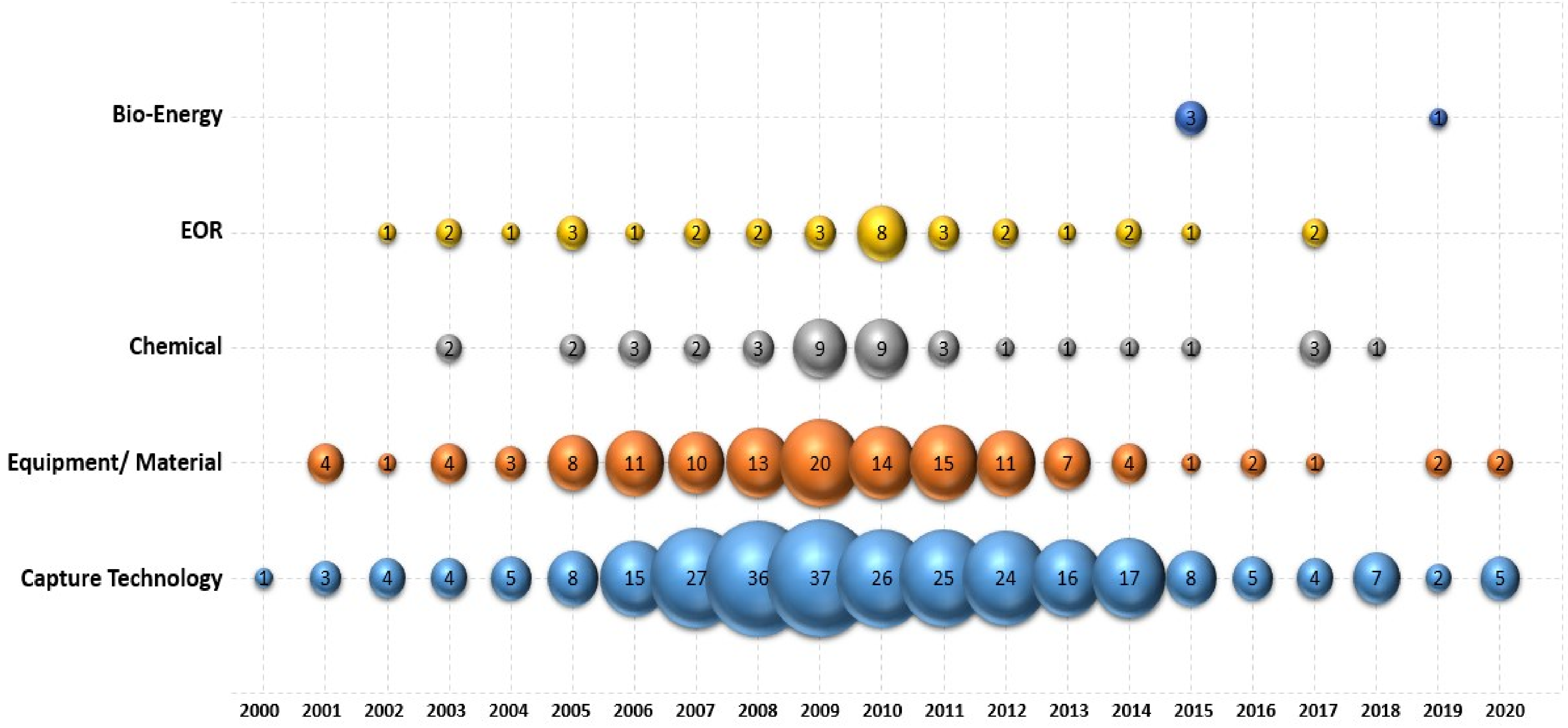
Technology focus (primary)-Countries and 1st Application Year



CCUS TYPE	Storage							Capture								Utlization				Transport				
Countries	DK	ES	FI	NO	PL	RU	SE	DK	ES	FI	IS	NO	PL	RU	SE	DK	NO	PL	RU	DK	NO	PL	RU	SE
Bioenergy		1			1	1			1					1		1								
Others		1			1	1			1					1		1								
Capture Technology	5		2	6	11	20	2	12	1	3	1	48	80	126	3			2	7	1	2	3	2	
Absorption								1				8	2	15										
Calcium looping	1				1		1	1	1			1	3	1	1									
Chemical absorption								2				1	4	7					2					
General	4		2	4	5	10	1	6		2	1	22	33	57	1				4	1	1	2		
Membrane Separation												3	2	7	1									
Others					1								3	1				1						
Oxyfuel				1	2	6				1		3	19	13					1		1		1	
Post Combustion/Physical separation				1	2	2		2				9	12	23				1				1	1	
Pre combustion						2						1	2	2										
Chemical				1	4	4		2				4	11	13	1				5			1	1	
Absorption														2										
Chemical absorption								1				3	8	8					1					
General				1	4	4							2	1	1							1		
Membrane Separation												1												
Others								1						1					4				1	
Post Combustion/Physical separation													1	1										
EOR				12	2	4		2				12	3	7		1	2		1	1				
Chemical absorption					1							1												
General				9	1	3		1				6	2	6		1								
Membrane Separation				2								2												
Others				1				1				2					2		1	1				
Oxyfuel						1						1		1										
Post Combustion/Physical separation													1											
Equipment/material	4	1		4	2	11	1	8		3		15	27	60	2				3		1	1	2	1
Absorption								1				2	1	6										
Chemical absorption												1		1										
General	3			1	1	5	1	2		1		3	5	21					1		1		1	
Membrane Separation						2						1	1	3										
Others	1	1						4		1		4	10	20	2				1				1	1
Oxyfuel						2						1	2	5					1					
Post Combustion/Physical separation				3	1	3		1		1		3	5	4								1		
Pre combustion													3											
Total	9	2	2	23	20	41	3	24	2	6	1	79	121	207	6	2	2	2	16	2	3	5	5	1
Total CCUS	100							446								22				16				

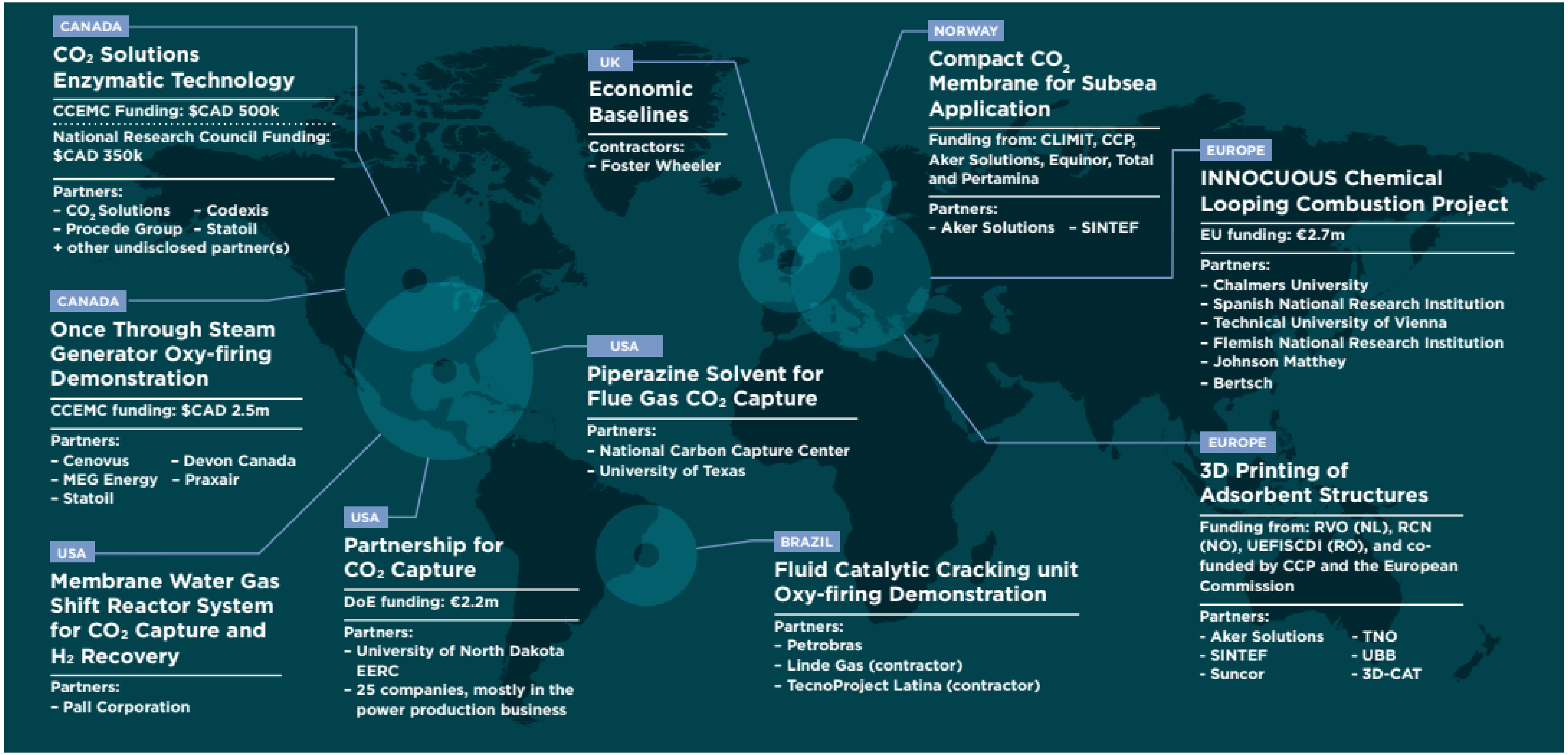
- **Observed capture technology has the most number patents/publications, General, Post combustion being the top categories followed by oxyfuel**
- **RU is the top country in storage, capture, utilization and transport**
- **Spike in 2009 and 2018 for capture technology**

Primary category vs 1st Application Year



- 2009 has the most number of filing for capture
- Capture technology has been prominent from 2000-2020
- 2009 has the most number filing in all CCUS types

CCUS partnerships and collaborations worldwide



Conclusions

- Identified 497 patents as relevant to CCUS (capture, storage, utilization and transport).
- In 2009 we have the greatest number of IP activity for CCUS for both applications and grants.
- In northern and eastern Europe, Russia & Poland are leading the research & patent filing in the CCUS domain.
- GE has the highest number of publications followed by Mitsubishi and Siemens.
- 85% of 497 relevant Patent families are Alive. GE has around 78% of its families alive.
- The top patents are related to capture, storage, sequestration or disposal of greenhouse gases and followed by patents related to Separation.
- CO2 capture is the most explored technology/CCUS type along with storage.
- 2009 has the most number filing in all CCUS types. Unfortunately, there is a decreasing trend in patent filings since 2016.

Challenges ahead in CCUS

- The carbon sequestration beneath the ocean and saline aquifers has great potential and can save millions of tons of CO_2 emission to the atmospheres.
- Over the period, the stored carbon again may convert into fuel, which may be explored in future. On the contrary, there are challenges and problems related to the stored carbon.
- Injection of CO_2 into saline aquifers will give rise to a variety of coupled physical and chemical processes.
- After storage of CO_2 into different formations, there is risk of leakage.
- The CCUS technologies are striving to gain traction in the set of options for dealing with climate change, but growth is very slow due to absence or low intervention of government action on climate change, public scepticism, increasing costs, and advances in other options including renewables and shale gas.

The future of CCUS

- Cementing in CO_2 for the ages, New processes could lock up CO_2 permanently in concrete, “storing” CO_2 in buildings, pavements, or anywhere else concrete is used.
- CO_2 could be used to create virtually any type of fuel.
- CO_2-neutral or even carbon-negative, Bioenergy with carbon capture and storage (BECCS) relies on nature to remove CO_2 from the atmosphere for use elsewhere.
- Carbon fiber, Superstrong, superlight carbon fiber is used to make products from airplane wings to wind-turbine blades, and its market is booming.
- Alternative cement with low carbon footprint, Carbon dioxide (CO_2) emissions can be reduced during production by up to two thirds when a previously unused overburden from bauxite mining is used as a raw material.
- Direct Air Capture, Direct air capture (DAC) technologies extract CO_2 directly from the atmosphere.