TECHNOLOGIE CCS
aneb
S OXIDEM UHLIČITÝM
POD ZEM

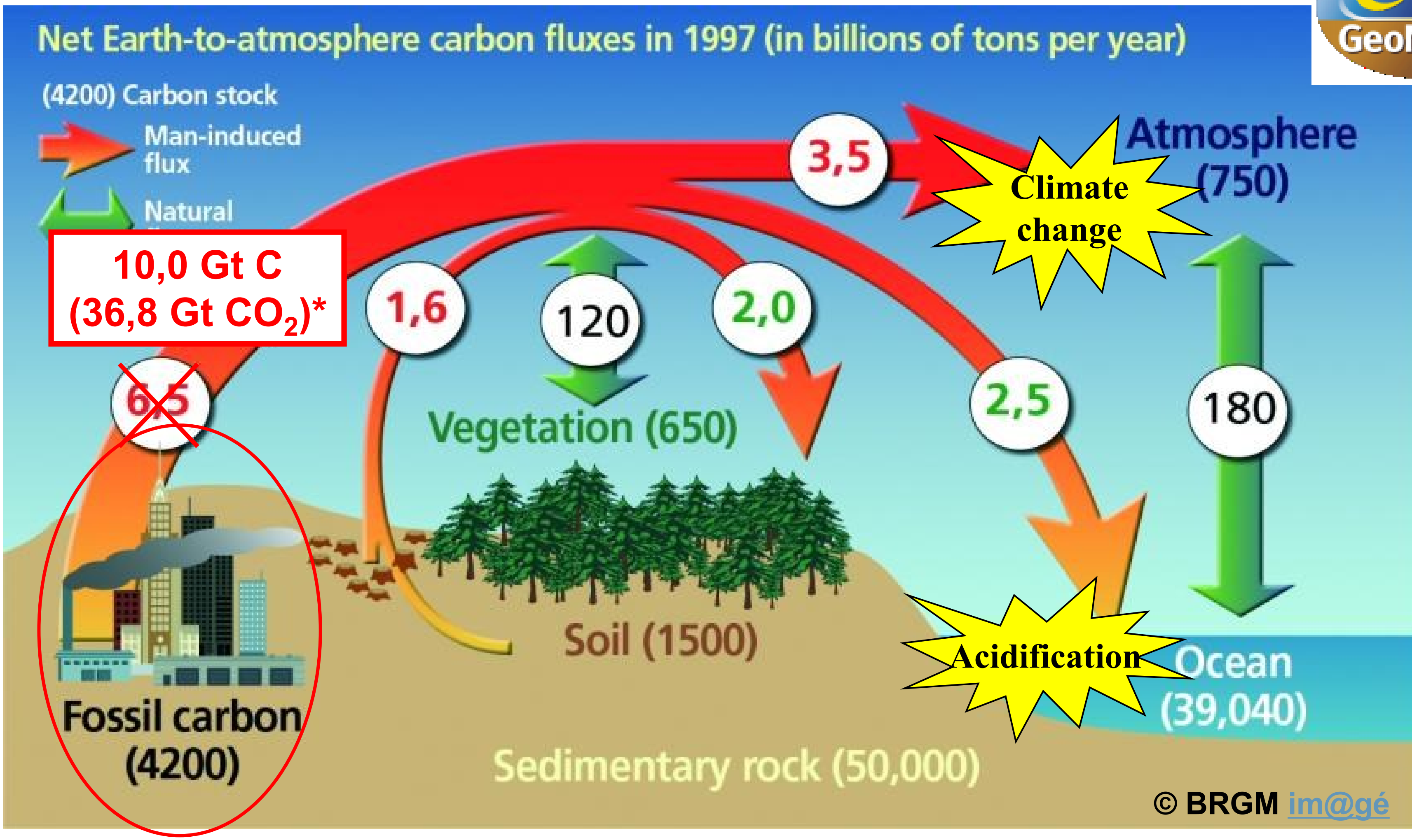
Vít Hladík (Česká geologická služba)

Obsah přednášky

- Role CO_2 ve změně klimatu
- CCS jako mitigační technologie
- Princip technologie CCS – zachytávání, doprava, ukládání
- CCS ve světě
- Situace v ČR
- Ekonomické faktory
- Shrnutí

Koloběh uhlíku mezi Zemí a atmosférou

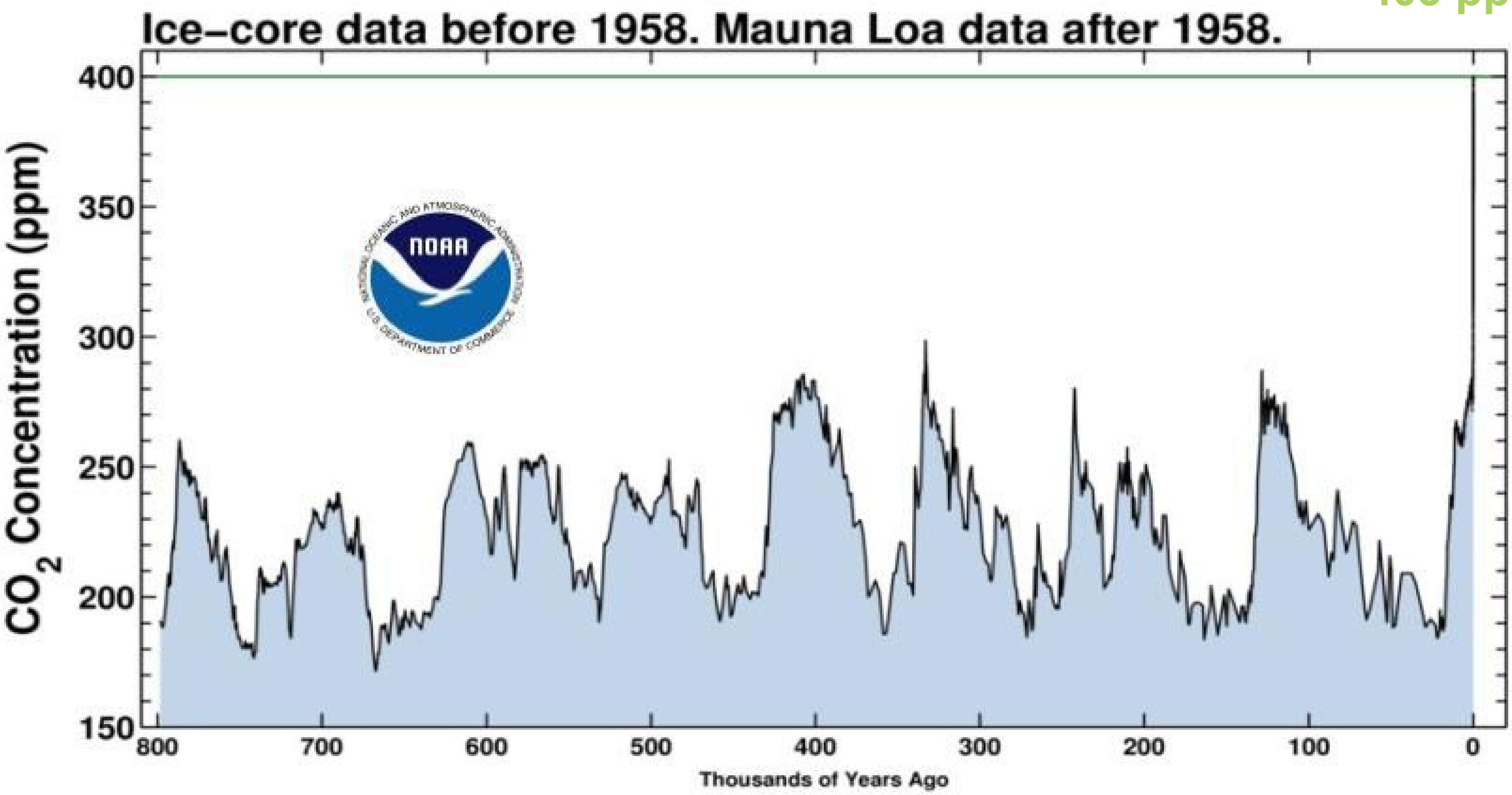
(v miliardách tun za rok)



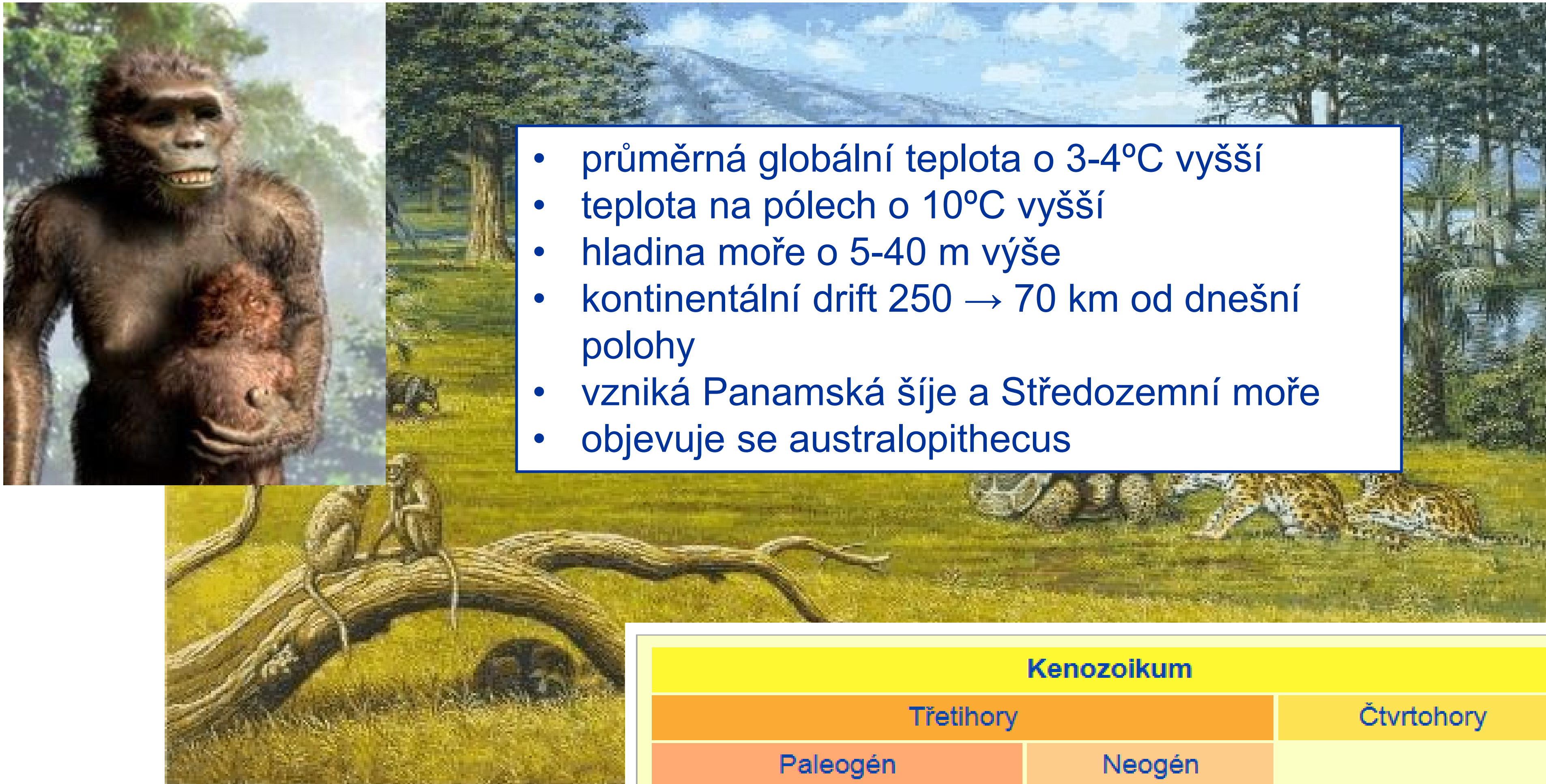
*odhad na rok 2017 podle Global Carbon Budget 2017

Obsah CO_2 v atmosféře (ppm_v)

403 ppm (2016)



Pliocén (před 5.3 – 2.6 mil. lety)



- průměrná globální teplota o 3-4°C vyšší
- teplota na pólech o 10°C vyšší
- hladina moře o 5-40 m výše
- kontinentální drift 250 → 70 km od dnešní polohy
- vzniká Panamská šíje a Středozemní moře
- objevuje se australopithecus

Kenozoikum						
Třetihory					Čtvrtohory	
Paleogén			Neogén			
Paleocén	Eocén	Oligocén	Miocén	**Pliocén**	Pleistocén	Holocén

Global carbon budget

The cumulative contributions to the global carbon budget from 1870

The carbon imbalance represents the gap in our current understanding of sources and sinks

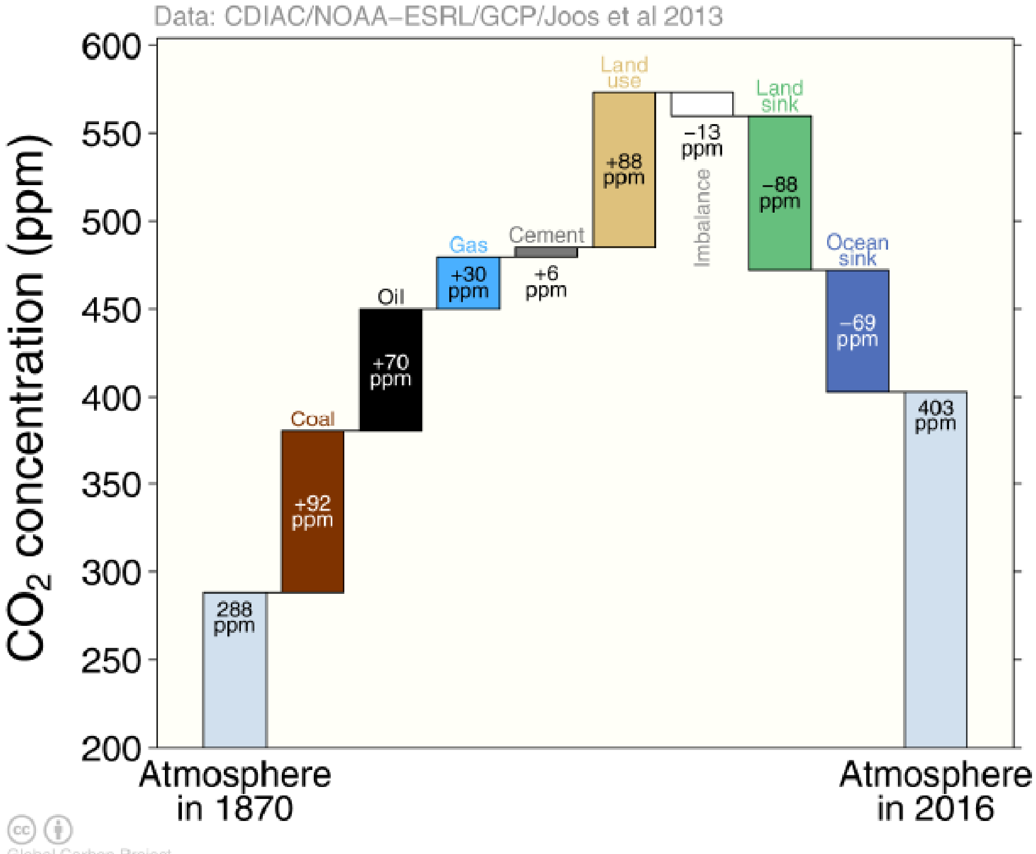
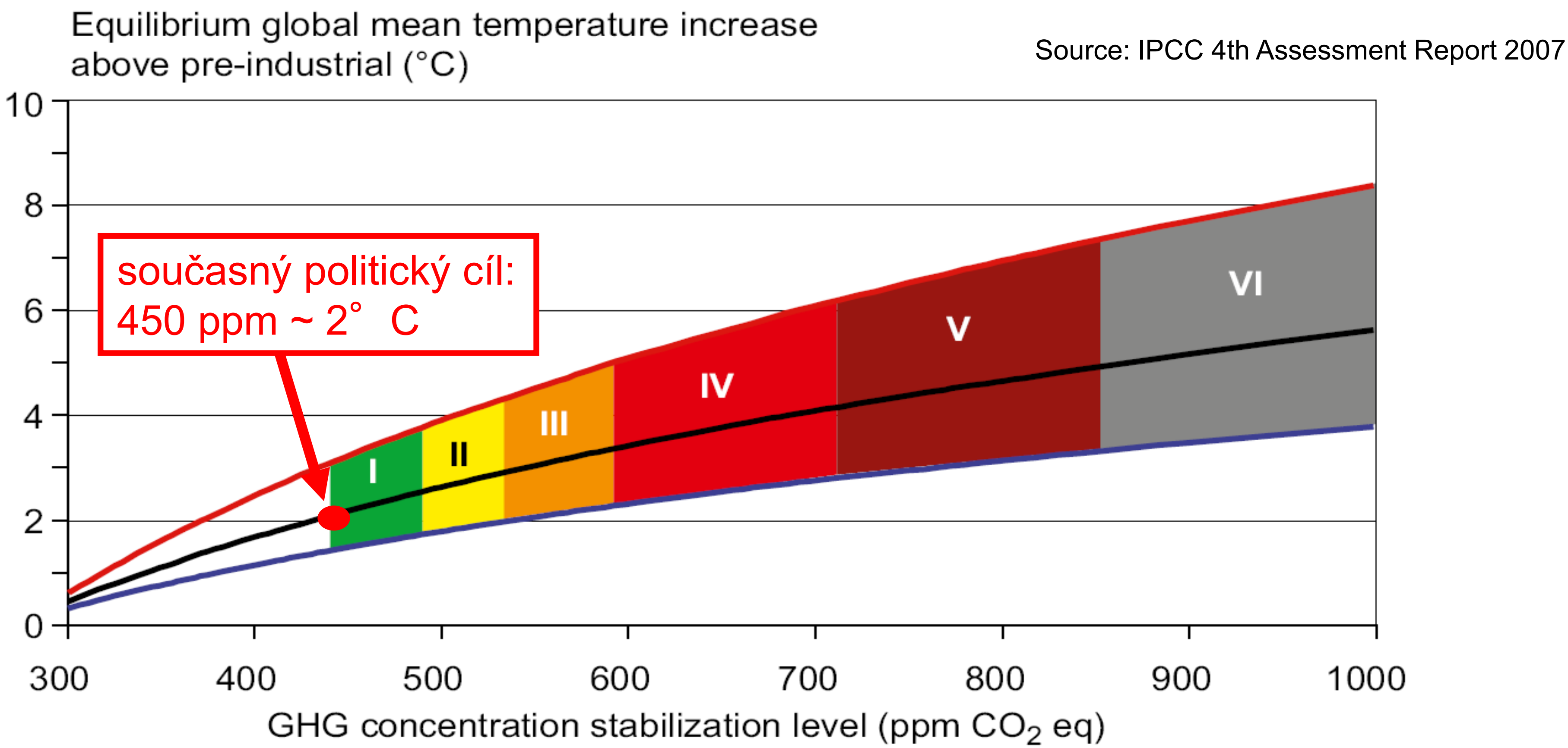


Figure concept from Shrink That Footprint

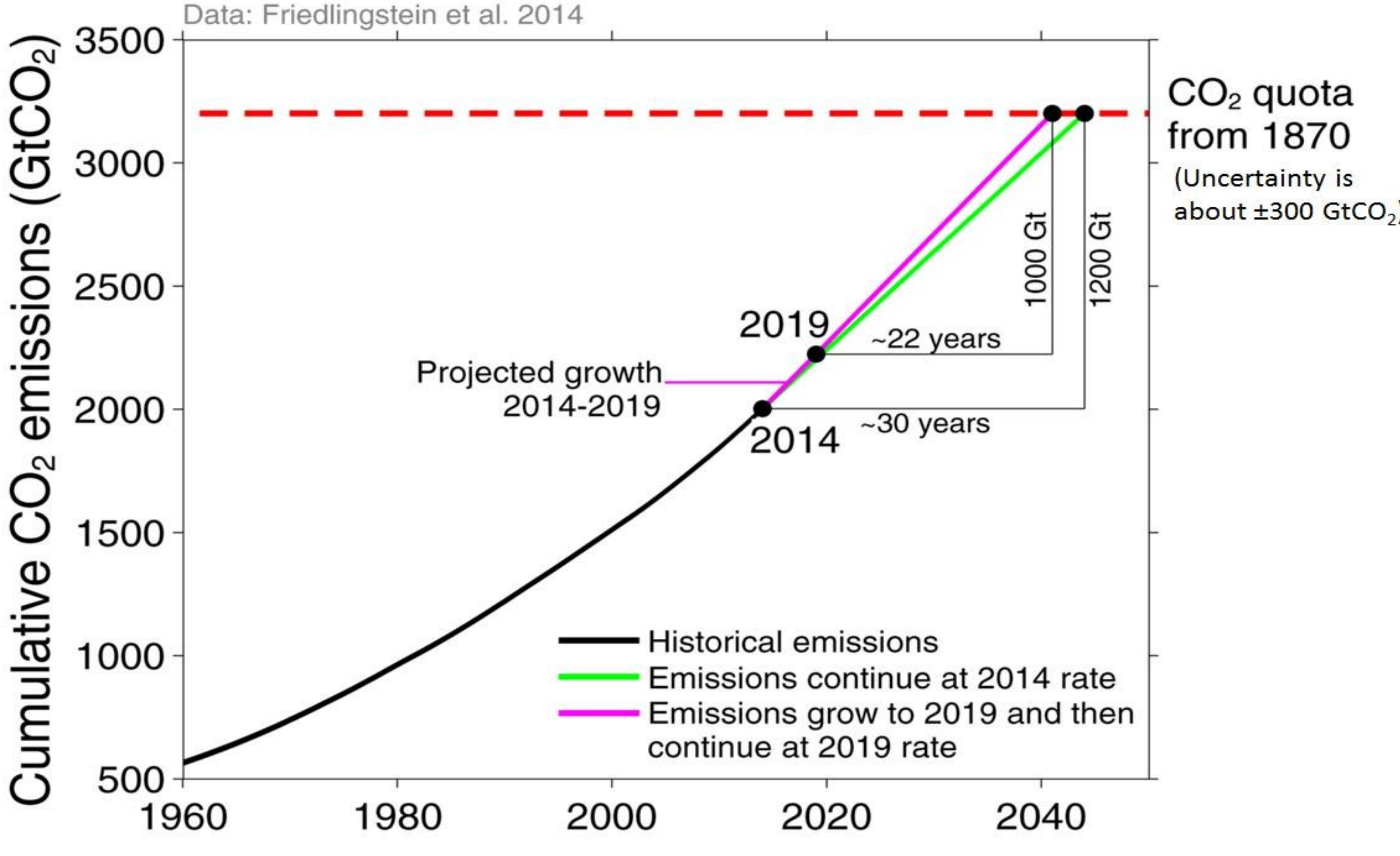
Source: CDIAC; NOAA-ESRL; Houghton and Nassikas 2017; Hansis et al 2015; Joos et al 2013; Khatiwala et al. 2013; DeVries 2014; Le Quéré et al 2017; Global Carbon Budget 2016

Klimatické modelování – vztah mezi teplotou a obsahem CO_2 v atmosféře



Remaining emissions quota

Cumulative CO_2 emissions should remain below about 3200 Gt for a 66% chance of staying below 2°C
At present emissions rates the remaining budget would be used up in about 30 years

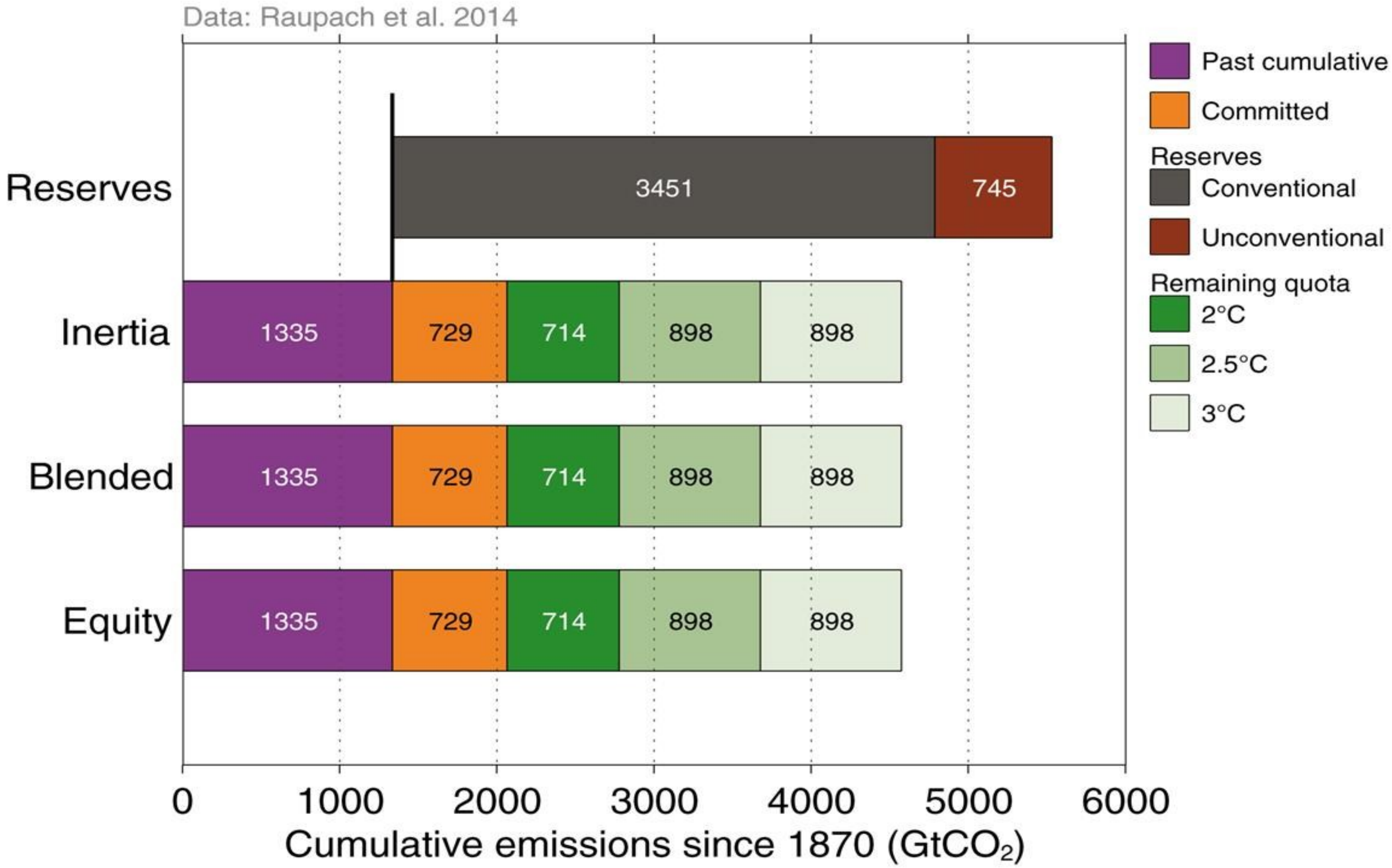


If emissions continue to grow as projected to 2019 and then continue at the 2019 rate, the remaining budget would be used up about 22 years from 2019

Source: Friedlingstein et al 2014

Global Quotas, Committed Emissions, Fossil-Fuel Reserves

To keep temperatures below 2°C requires two-thirds of fossil fuels to remain in the ground*
Committed emissions in existing infrastructure represents 50% of the remaining quota*



*Assuming a 50% chance to stay below 2°C and no carbon-capture and storage

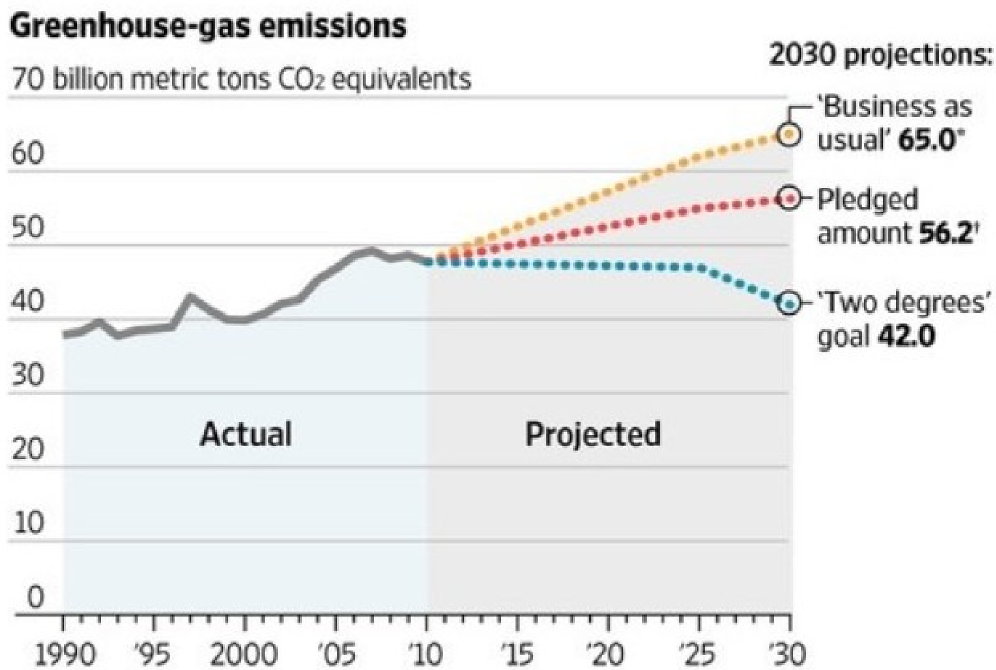
Source: Raupach et al 2014

Pařížská dohoda 2015

Pařížská dohoda 2015

Promising Start

Pledges made at the summit may not be enough to limit global warming to less than 2 degrees Celsius above pre-industrial levels but could spur a significant cut in emissions compared with existing policies.

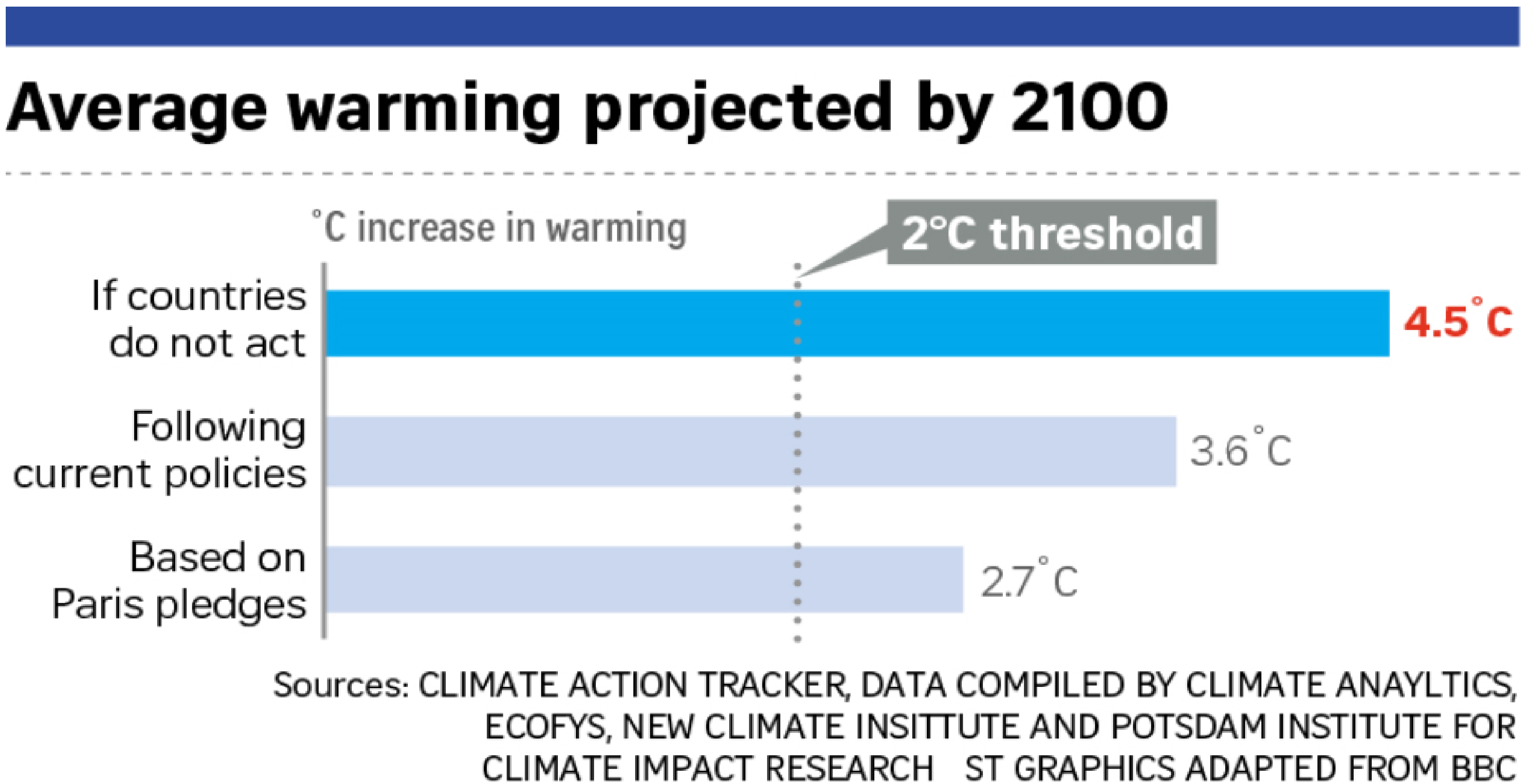


*Assumes no new national energy polices from 2010 onwards
†Based on unconditional INDCs of 102 countries Source: Michel den Elzen, PBL Netherlands Environmental Assessment Agency

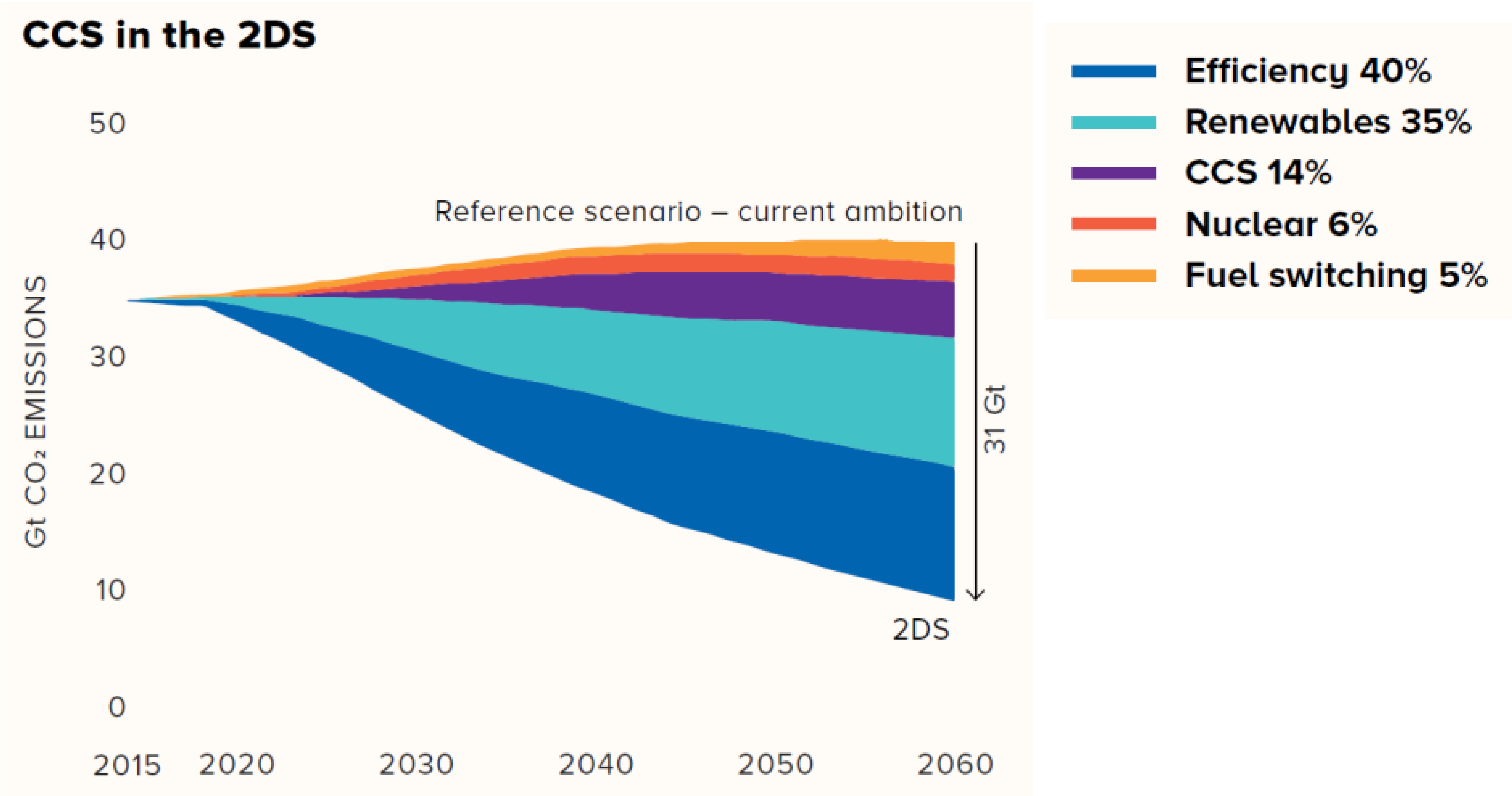
Key points of the agreement

- Aims to bring growth of greenhouse gases in the atmosphere to zero by the second half of this century
- Requires for first time that all countries curb emissions, not just developed ones
- Targets no more than 2° C (3.6° F) rise in temperature, but aspires to go further
- Richer countries take lead in mobilizing more than $100 billion annually to help developing countries meet agreement
- Establishes a process to review, assess and update emissions-reduction plans

Scénáře globálního oteplování



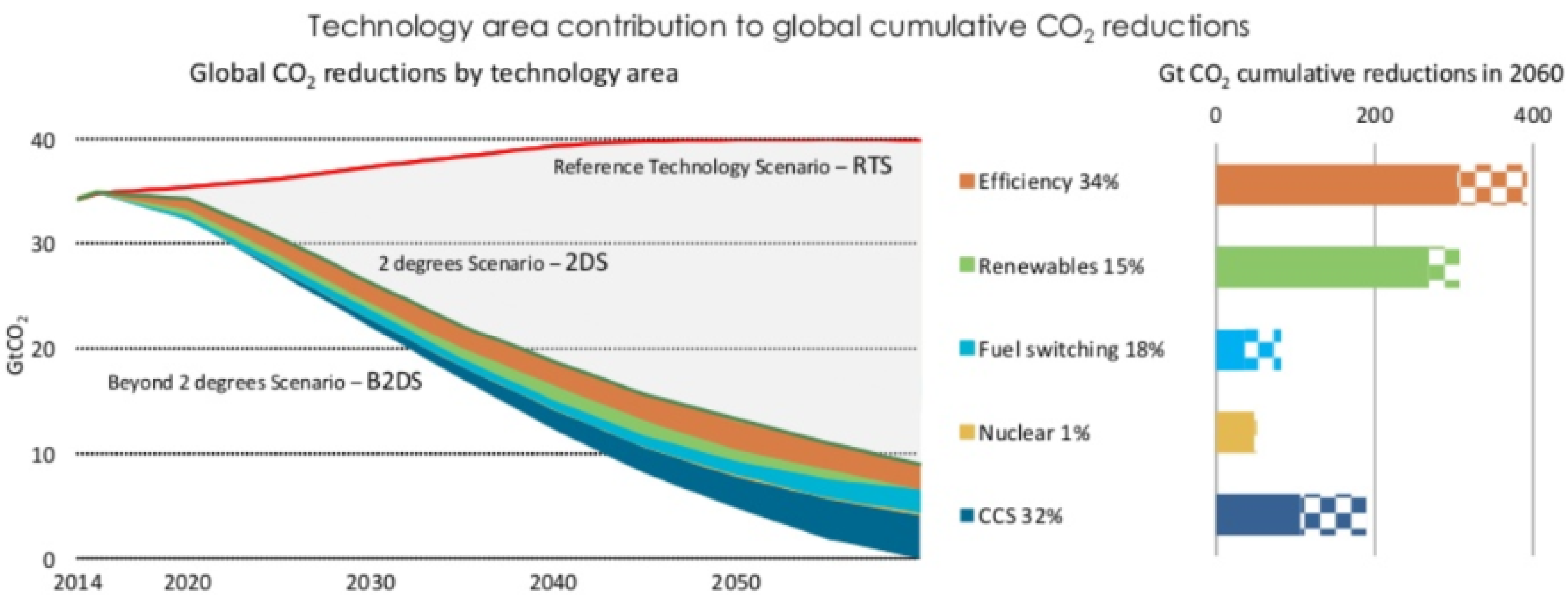
Technologie pro redukci emisí CO_2



Source: IEA Energy Technology Perspectives 2017

Technologie pro redukci emisí CO_2

How far can technology take us?

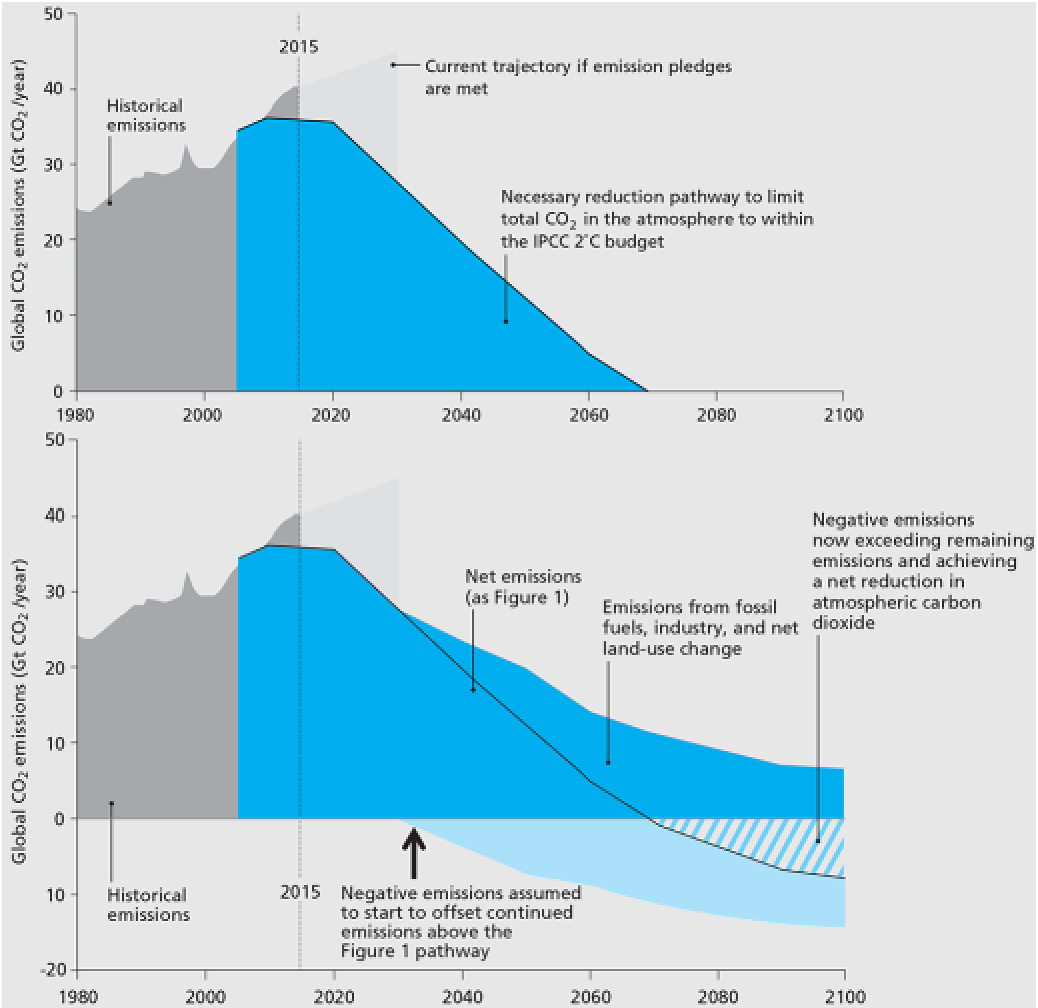


Pushing energy technology to achieve carbon neutrality by 2060 could meet the mid-point of the range of ambitions expressed in Paris.

Source: IEA Energy Technology Perspectives 2017

ENOS

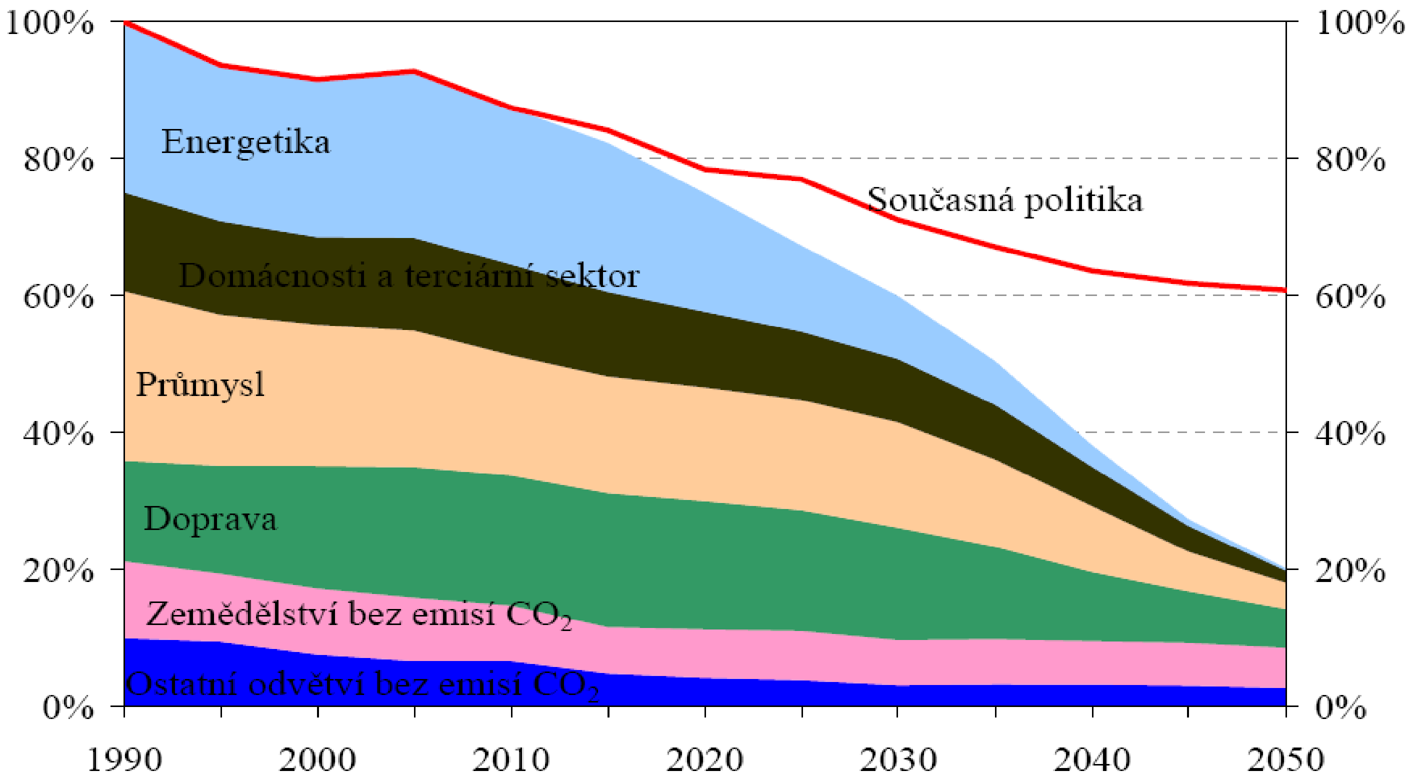
Technologie pro redukci emisí CO_2



Source: European Academies Science Advisory Council (EASAC) report 2018

EU - Plán přechodu na konkurenceschopné nízkouhlíkové hospodářství do roku 2050 (Sdělení EK z 8.3.2011)

Obrázek 1: Projekce 80% snížení domácích emisí skleníkových plynů v EU (100 % = 1990)



ENOS

EU - Plán přechodu na konkurenceschopné nízkouhlíkové hospodářství do roku 2050 (Sdělení EK z 8.3.2011)

Tabulka č. 1: Snížení emisí podle odvětví

Snížení emisí skleníkových plynů oproti roku 1990	2005	2030	2050
Celkem	–7 %	–40 až –44 %	–79 až –82 %
Odvětví			
Energetika (CO_2)	–7 %	–54 až –68 %	–93 až –99 %
Průmysl (CO_2)	–20 %	–34 až –40 %	–83 až –87 %
Doprava (včetně emisí CO_2 z letecké dopravy; vyjma námořní)	+30 %	+20 až –9 %	–54 až –67 %
Domácnosti a služby (CO_2)	–12 %	–37 až –53 %	–88 až –91 %
Zemědělství (bez CO_2)	–20 %	–36 až –37 %	–42 až –49 %
Ostatní emise bez CO_2	–30 %	–72 až –73 %	–70 až –78 %

Technologie CCS = zachytávání a ukládání CO_2

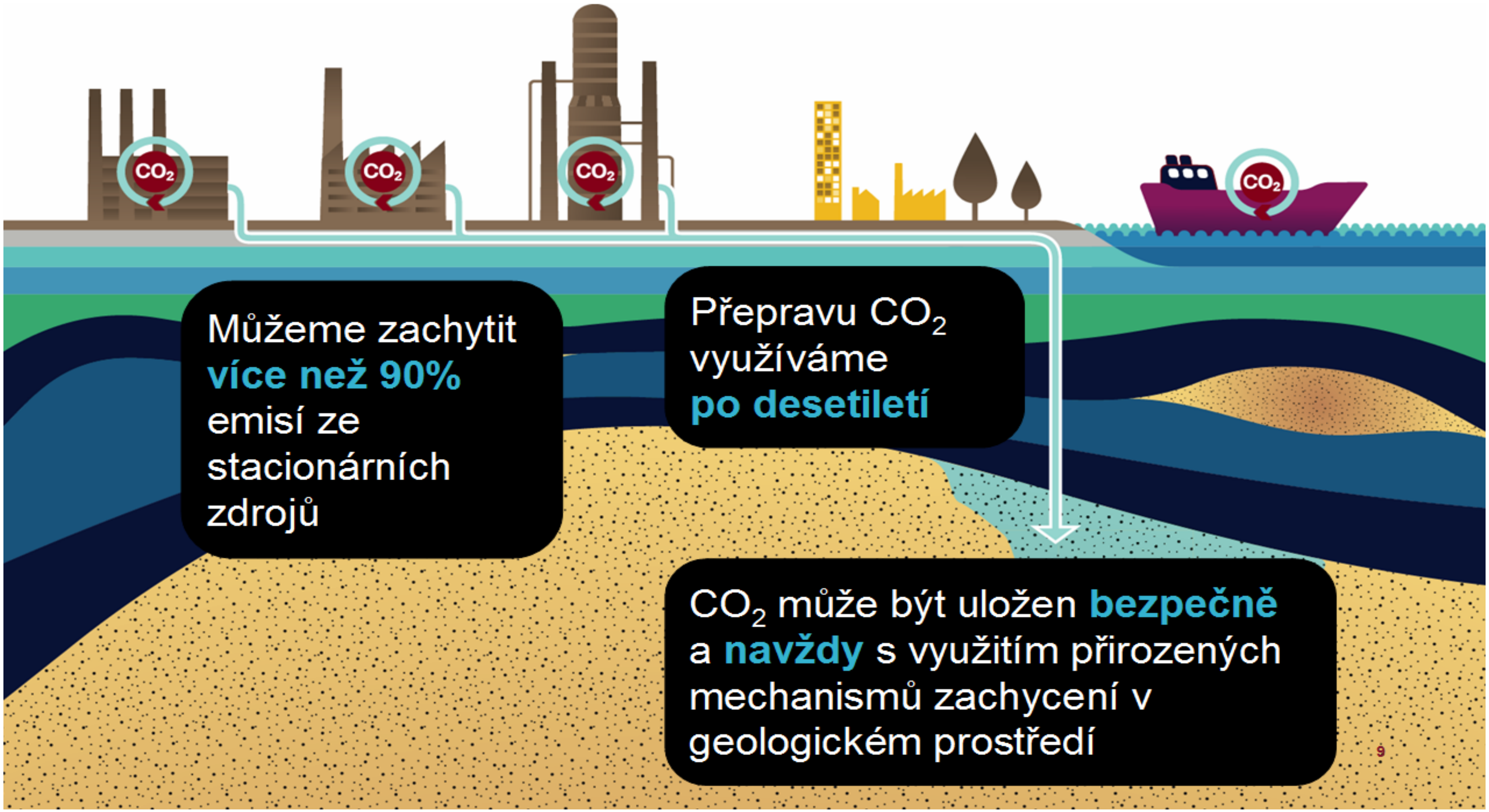
CCS (Carbon /Dioxide/ Capture and Storage) je tzv. mitigační opatření - cílem je snížení emisí CO_2 jako skleníkového plynu

Princip: zachycení emisí přímo u velkého stacionárního zdroje (elektrárna, ocelárna, cementárna, chemický provoz, úpravna plynu aj.), jeho přeprava a bezpečné uložení do vhodné geologické struktury

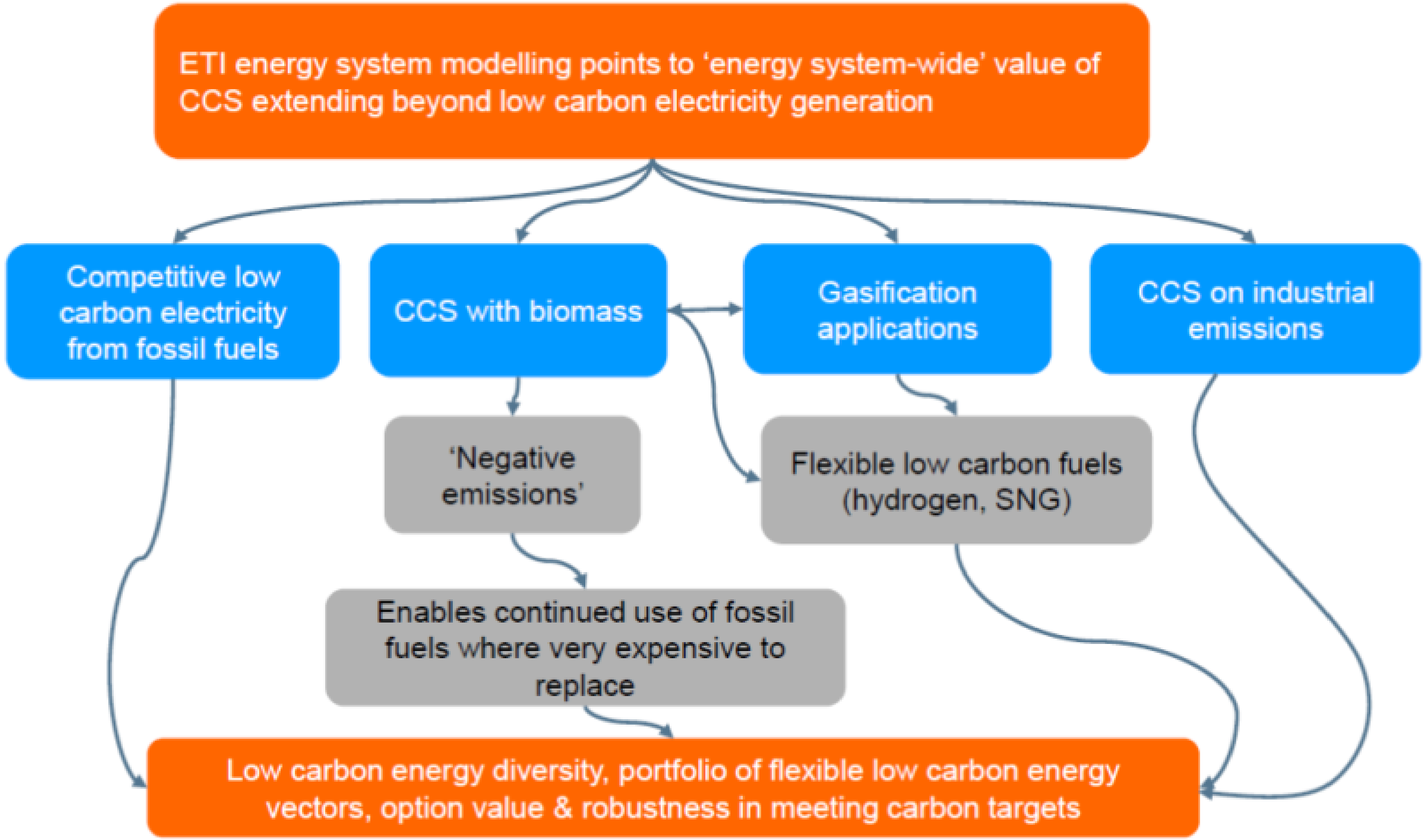
Výchozí předpoklady:

- dochází ke změně klimatu
- antropogenní emise CO_2 jsou významným hybatelem klimatické změny
- chceme s tím něco dělat

Princip CCS


CO_2
CO_2
CO_2
CO_2
Můžeme zachytit **více než 90%** emisí ze stacionárních zdrojů
Přepravu CO_2 využíváme **po desetiletí**
CO_2 může být uložen **bezpečně** a **navždy** s využitím přirozených mechanismů zachycení v geologickém prostředí

CCS maintains multiple options and delivers significant value at a whole-system level



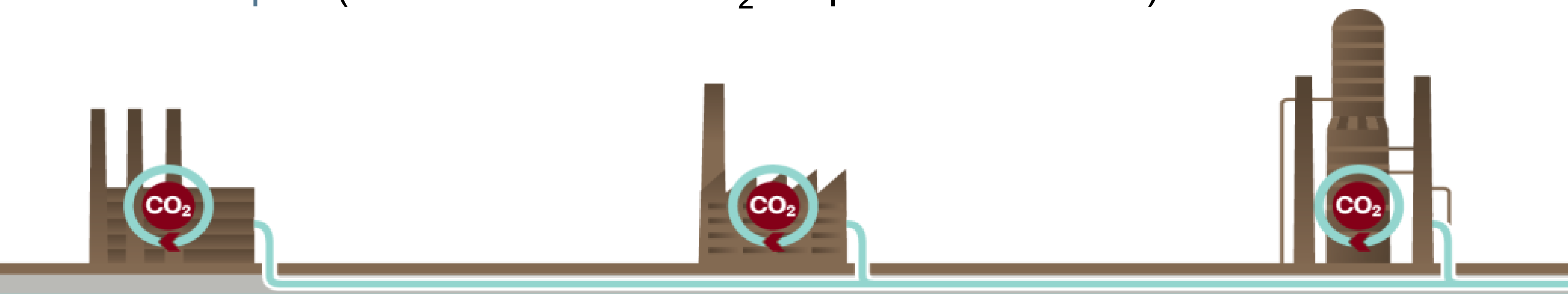
Zachytávání CO_2

Primární cíle = velké stacionární zdroje emisí produkující statisíce až milióny tun CO_2 ročně (menší zdroje mohou být seskupeny do klastrů):

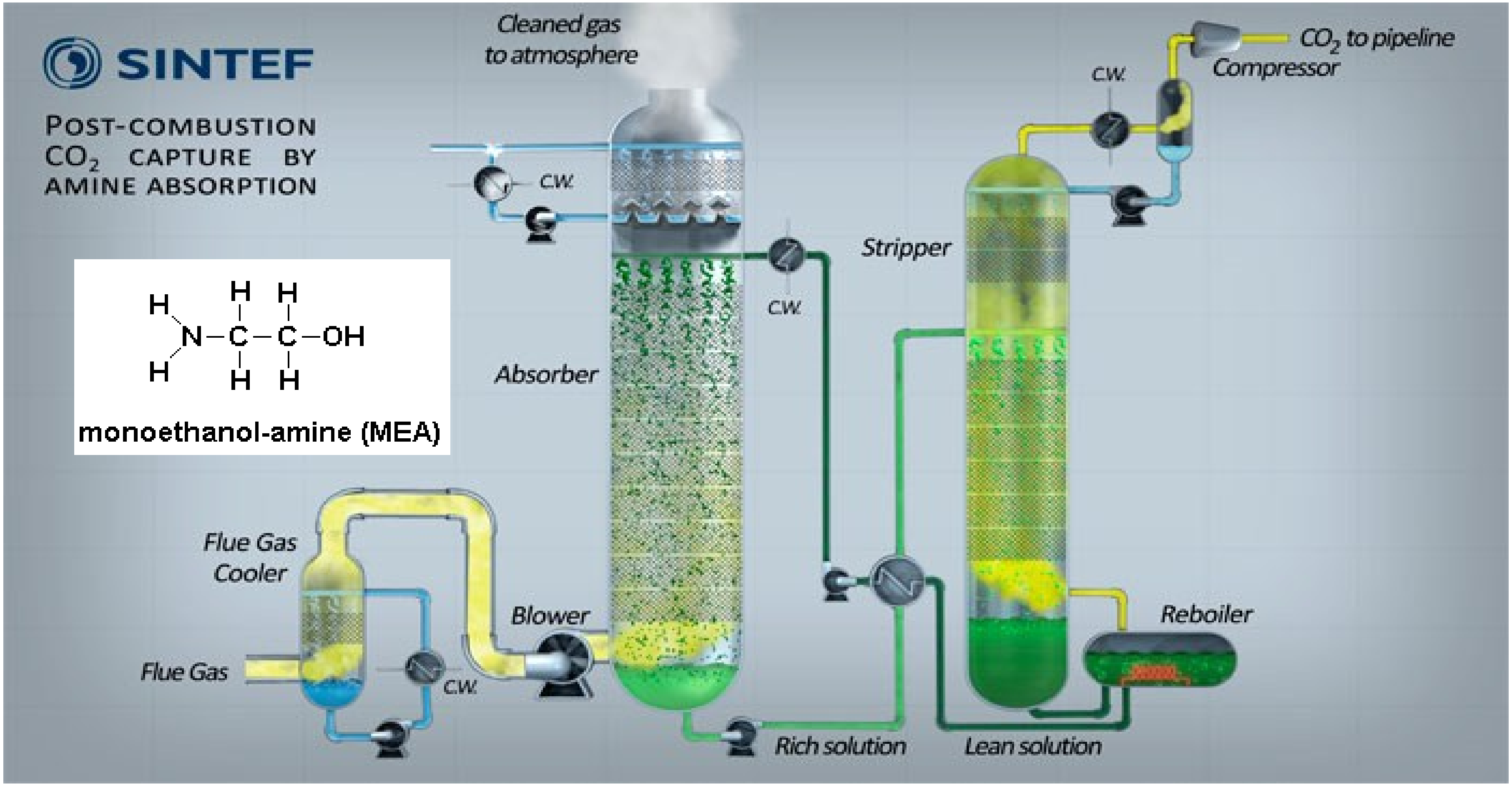
- elektrárny spalující fosilní paliva nebo biomasu
- zařízení na úpravu ropy a zemního plynu
- průmyslové provozy (výroba cementu, železa a oceli, papíru a celulózy)
- rafinerie a petrochemické provozy

V současnosti jsou komerčně dostupné technologie 1. generace:

- chemická absorpce (chemická vazba)
- fyzikální absorpce (rozpuštění v rozpouštědle – Selexol, Rectisol)
- adsorpce (adheze molekul CO_2 na povrch sorbentu)



Princip chemické absorpce



Princip adsorpce

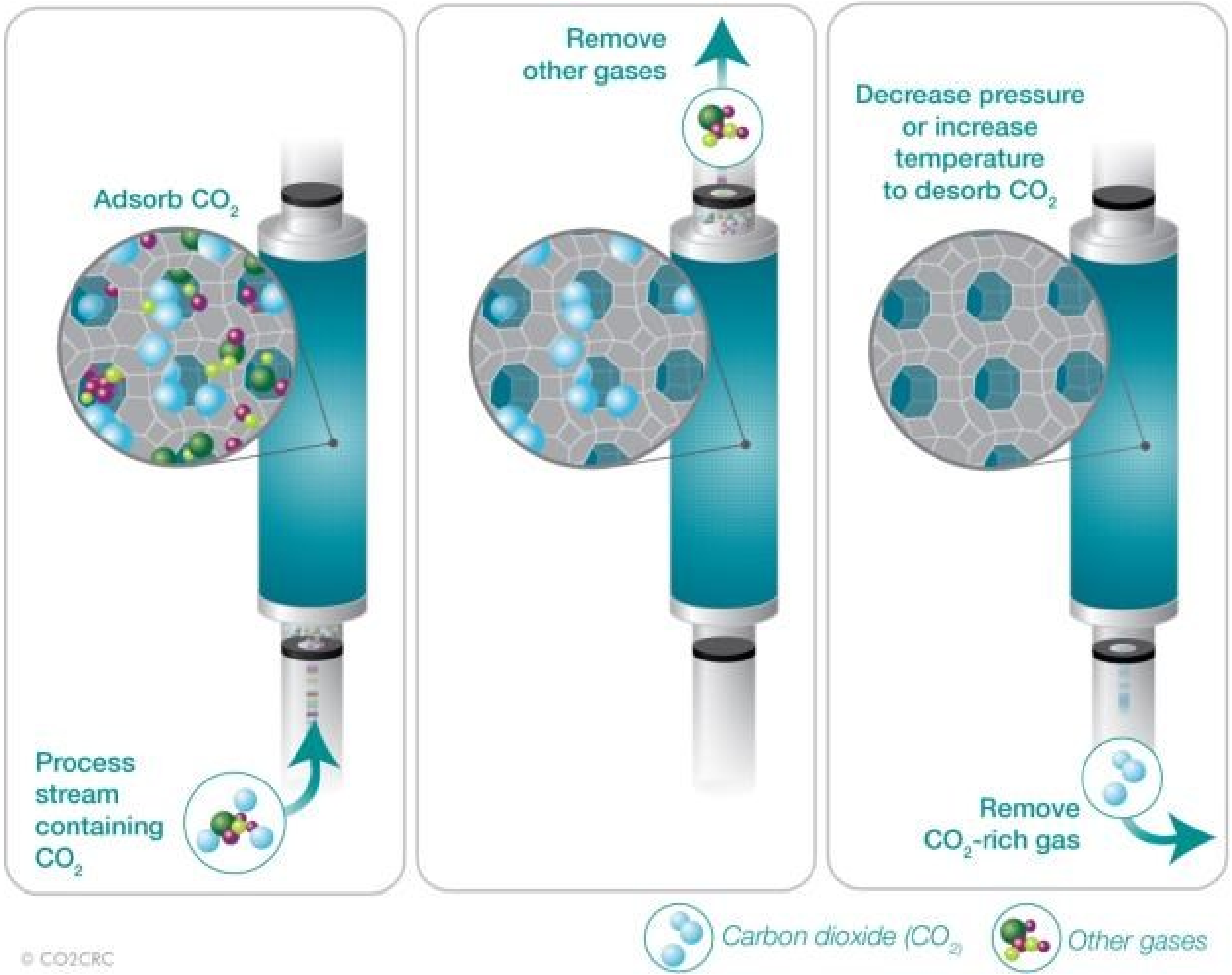


image courtesy CO2CRC

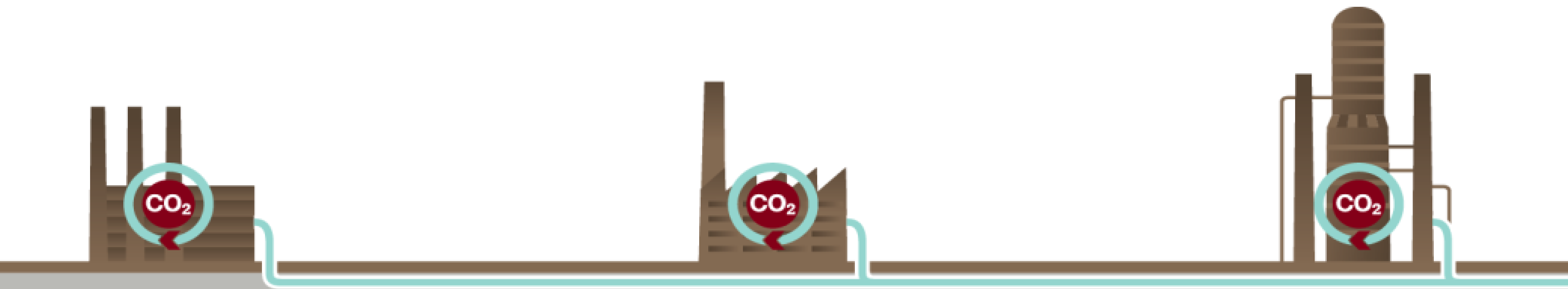
Technologie dalších generací

2. generace – v současnosti v pilotním měřítku

3. generace – v současnosti v laboratorním měřítku

Rozvíjené a zkoumané technologie

- nové absorbenty pro chemickou absorpci
- nové adsorbenty a adsorpční procesy
- membrány
- kryogenní destilace
- biogenní zachytávání (mikrobi, řasy)



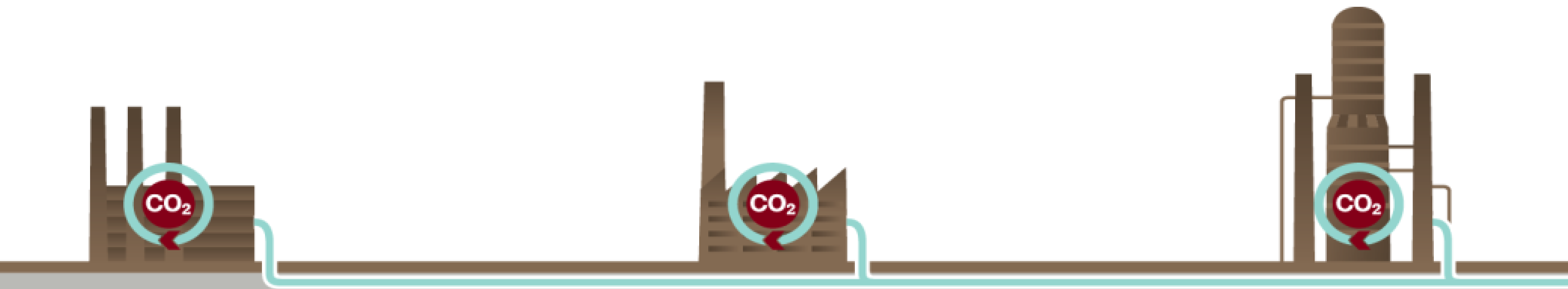
Zachytávání CO_2 u spalovacích procesů

Stávající technologie:

- Pre-combustion (před spalováním):
  CO_2 je zachytáván ještě před spálením paliva
- Oxy-fuel (spalování v kyslíkové atmosféře):
  CO_2 je separován během spalování
- Post-combustion (po spalování):
  CO_2 je zachytáván po spálení paliva
  (Tato technologie může být použita i pro stávající zařízení jako retrofit)

Nově vyvíjené technologie:

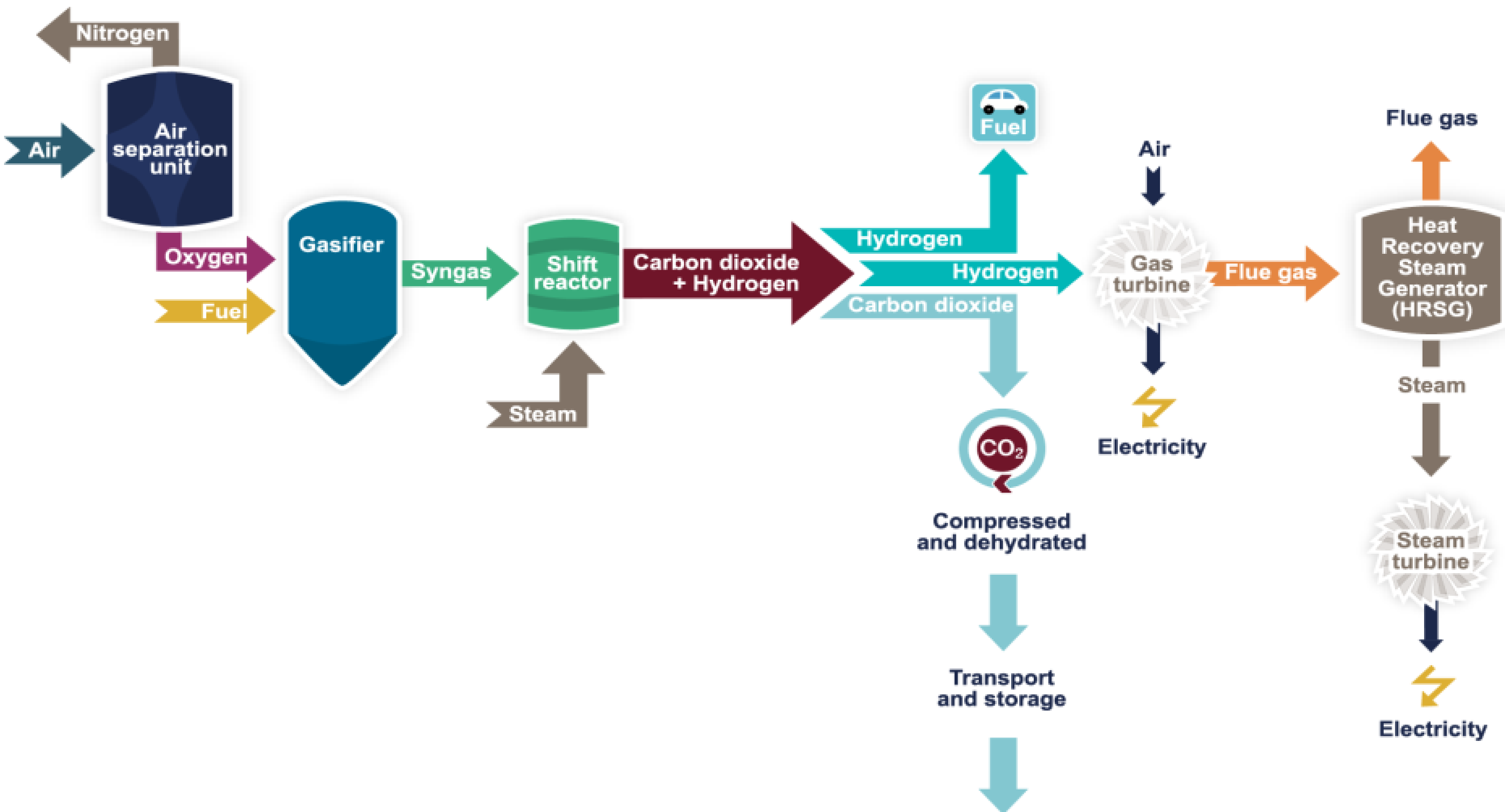
- High temperature solid looping cycles (karbonátová a chemická smyčka)



Zachytávání po spalování

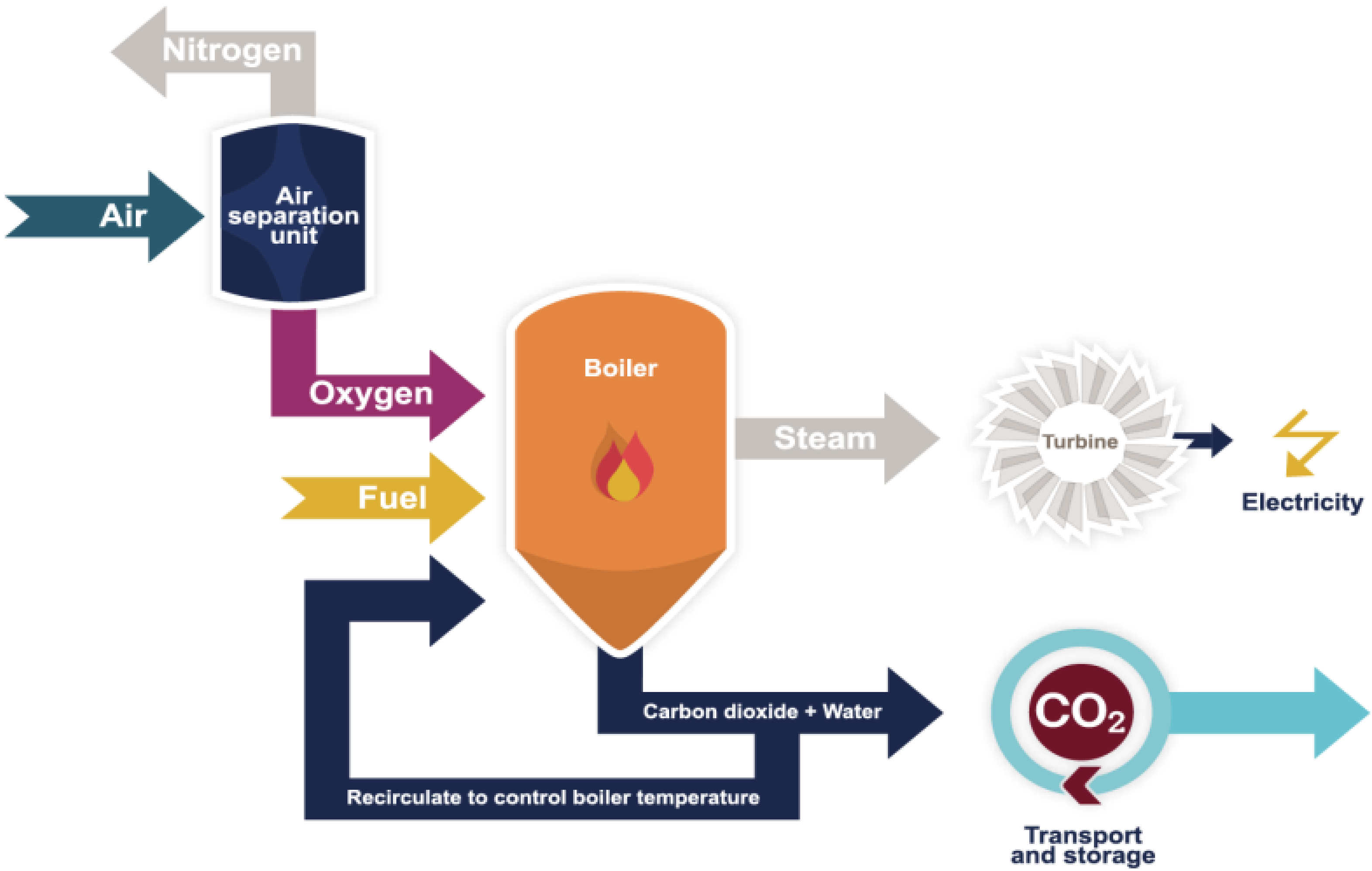
CO_2 je zachytáván po spálení paliva

Pre-combustion



CO_2 je zachytáván před spálením paliva

Technologie oxy-fuel

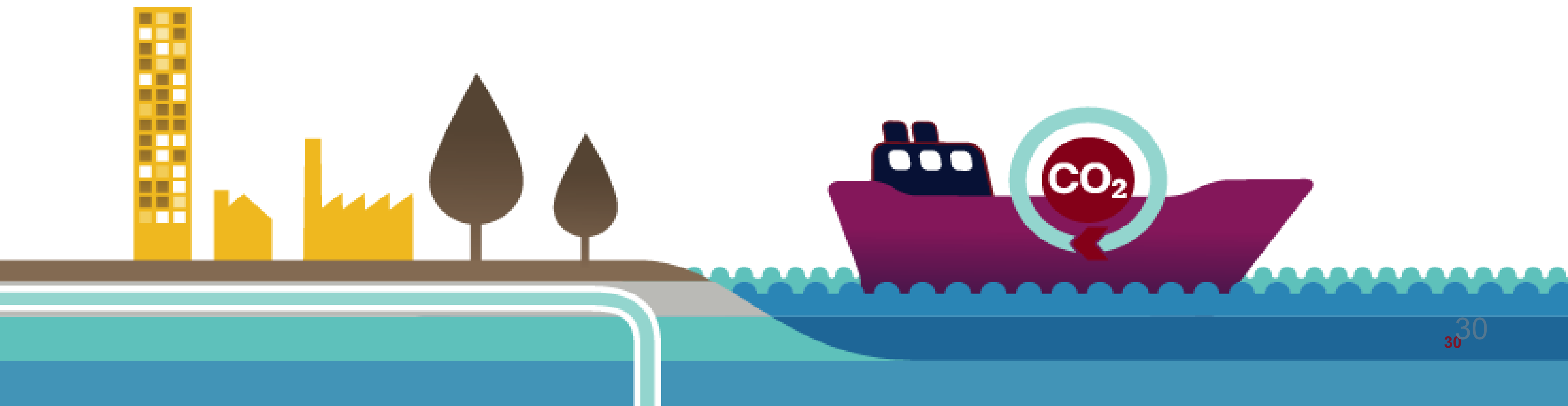


Průmyslové procesy

- Úprava zemního plynu (absorpce / Sleipner, Snøhvit NOR)
- Zplynování uhlí / bitumenu (fyzikální absorpce)
  - výroba syngasu (Great Plains Synfuels Plant USA)
  - výroba vodíku (North West Sturgeon Refinery CAN)
- Výroba vodíku pomocí parního reformingu (absorpce n. adsorpce / Port Arthur Project USA, Shell Quest Project CAN)
- Chemická výroba:
  - výroba čpavku (CO_2 je vedlejší produkt ve vysoké koncentraci)
  - výroba etanolu (ADM Illinois Industrial CCS Project USA – první aplikace BioCCS)
- Výroba oceli (chemická absorpce / ASI CCS Project UEA)
- Výroba cementu (zachytávání CO_2 zatím v pilotním měřítku)

Transport CO_2

- Po zachycení je CO_2 stlačen do kapalného, popř. superkritického stavu, zbaven vody a dopravován na místo uložení.
- Pro větší množství CO_2 je nejvýhodnějším způsobem dopravy produktovod (v Sev. Americe provozováno téměř 5000 km) – typické podmínky 10-15 MPa, 15-30°C.
- Pro menší množství a velké vzdálenosti na moři lze využít tankery – dnes do 1800 t CO2, ~ -30 °C, ~ 1,6 Mpa; připravují se větší.



Ukládání CO_2

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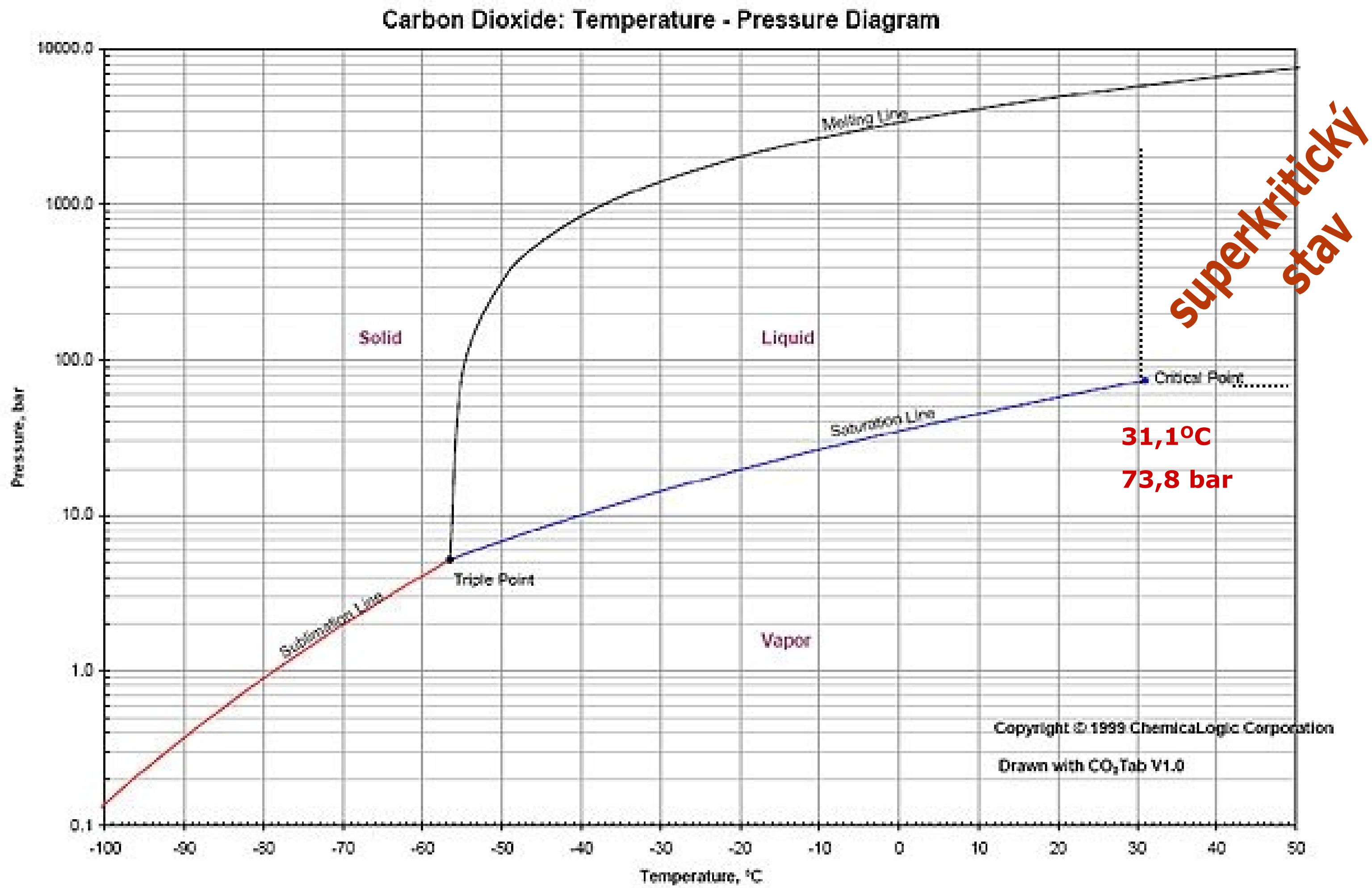
Bezpečné ukládání CO_2

- Využívá se **přirozených mechanismů** které v přírodě zadržují CO_2, zemní plyn a ropu po milióny let
- Tekutý CO_2 se vtláčí hluboko do podloží do některého ze dvou základních typů úložišť:
  - hlubinné slané akvifery (hloubka 700 – 3000 m)
  - vytěžená ložiska ropy a plynu (hloubka až 5000 m)
- Oba typy úložišť mají vrstvu **porézní horniny,** která pohltí CO_2 a v nadloží nepropustnou vrstvu **těsnící horniny (cap rock)**, která úložiště utěsňuje

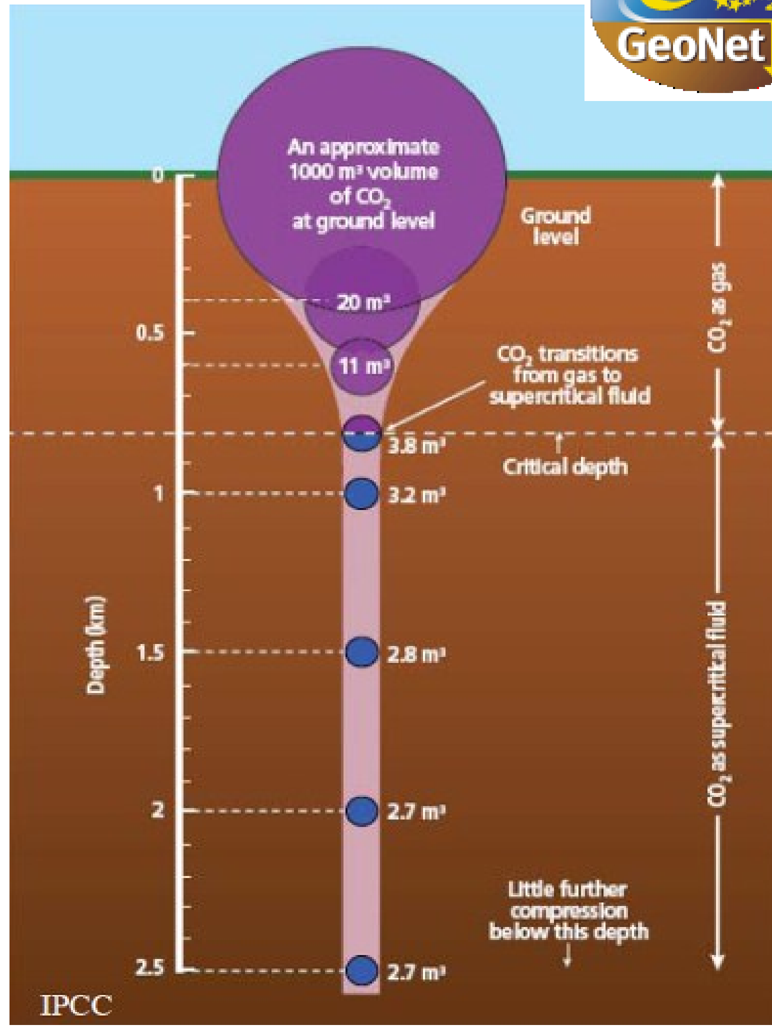
Fázový diagram CO_2



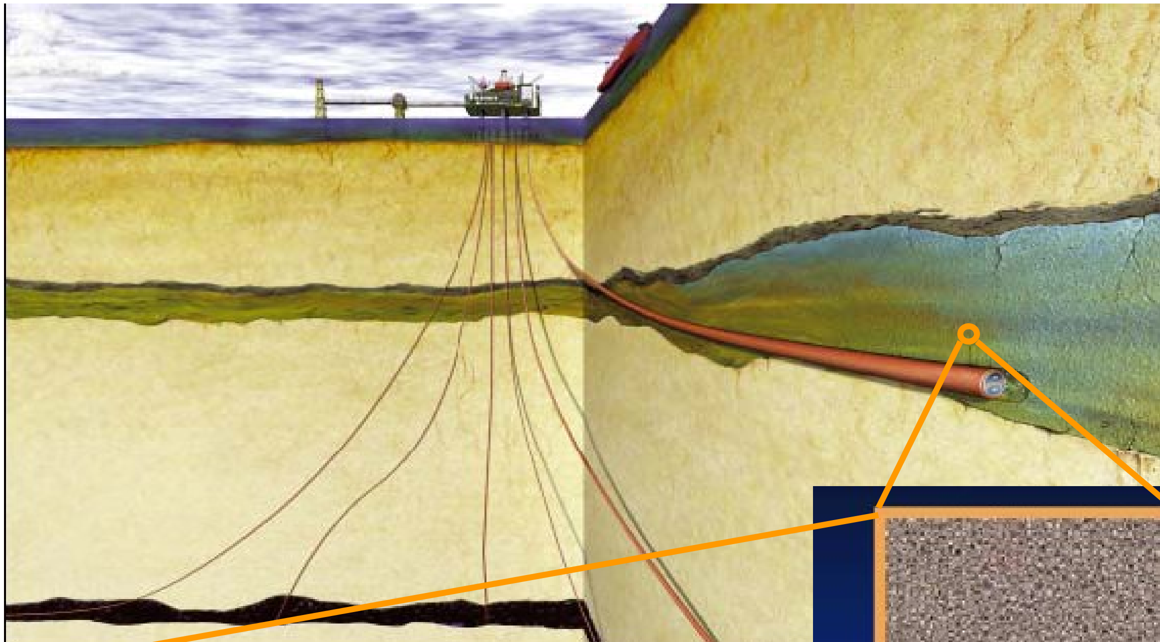
Superkritický CO_2 – vlastnosti

- plyn z hlediska viskozity
- kapalina z hlediska hustoty

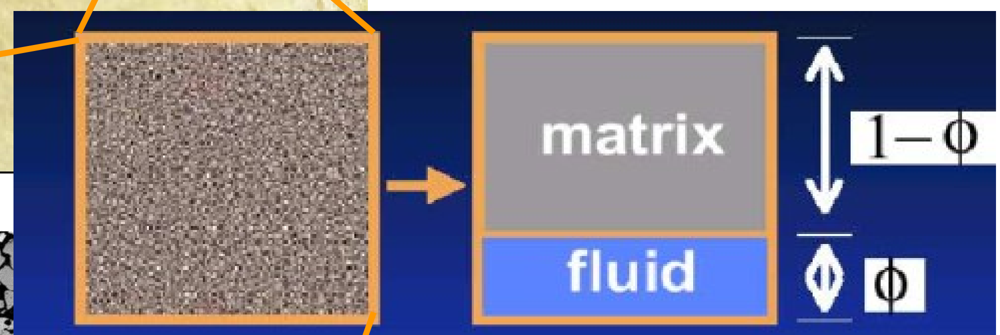
T=100° C, P=280bar (2800m)	hustota (kg/m3)	viskozita (cP)
superkritický CO_2	615	0.05
voda	804	0.16
plyn (metan)	150	0.02

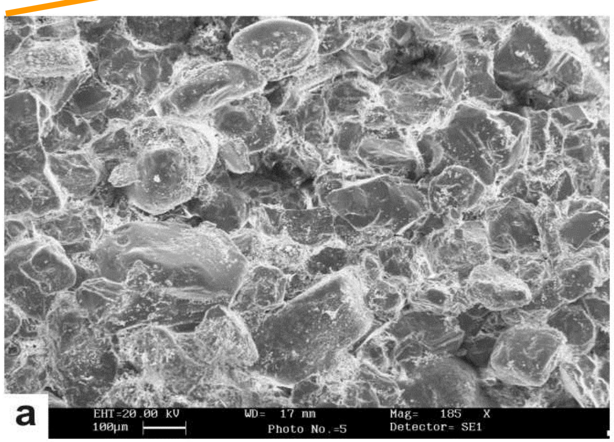


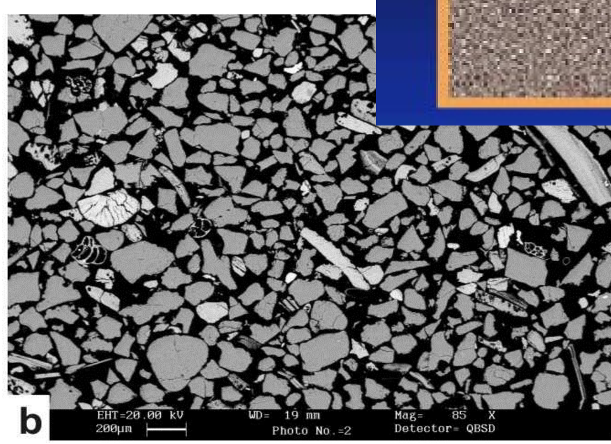
Koncept vtláčení CO_2 do porézních hornin (akvifery, ložiska ropy a plynu)



Courtesy CO2STORE

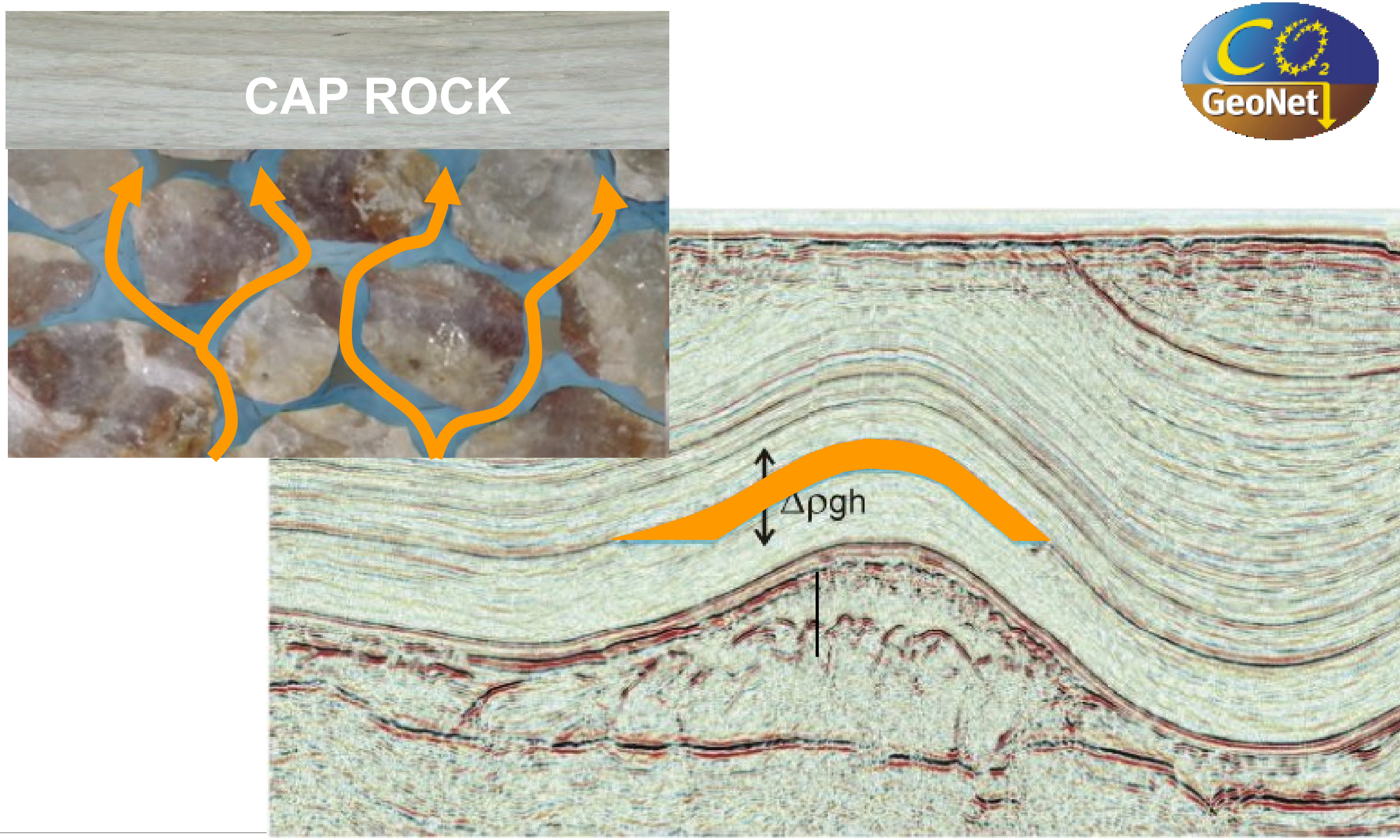




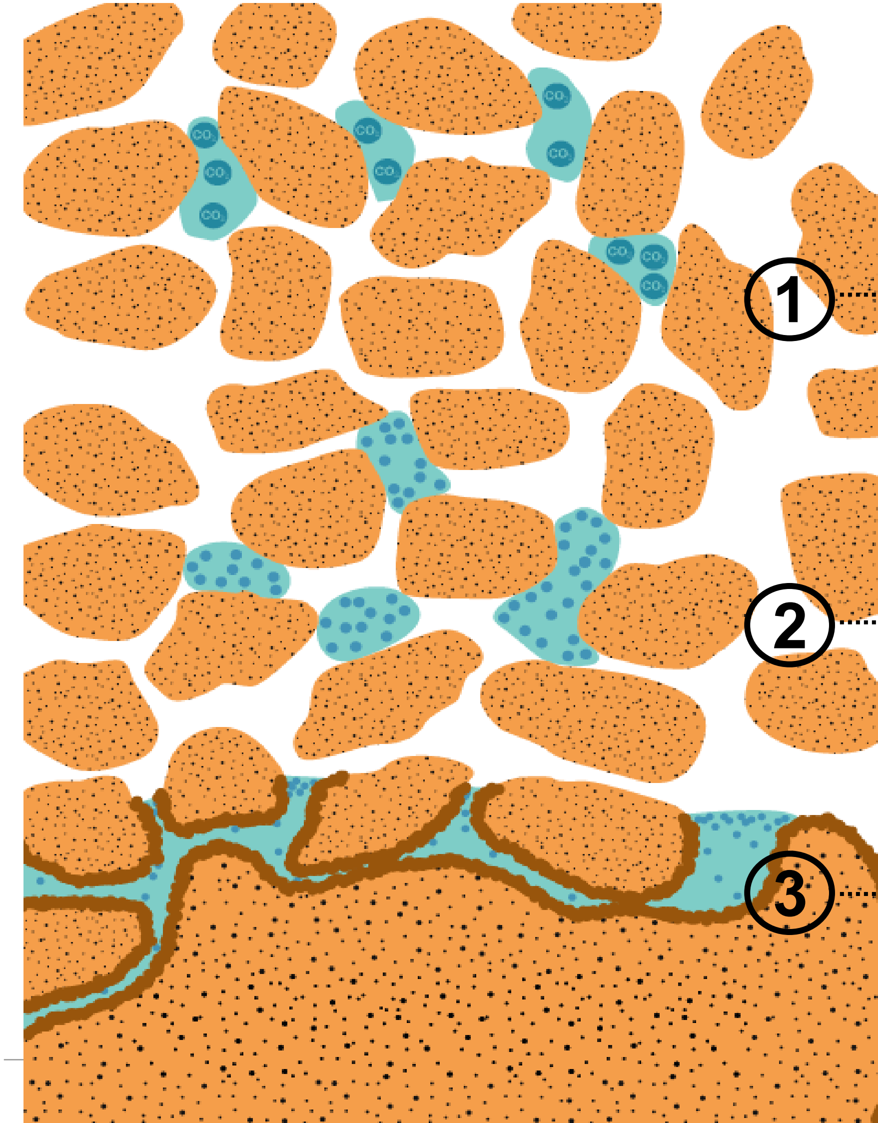


SEM images of the Utsira Sand
a) Reflected light
b) Transmitted light (pore-spaces are black)

Strukturní trapping CO_2



Bezpečnost uložení CO_2 roste s časem



... díky 3 přirozeným mechanismům

Reziduální trapping

CO_2 je nevratně zachycen v mikropórech a nemůže se dále pohybovat

Rozpouštění

CO_2 se rozpustí v okolní solance; ta pak klesá ke dnu rezervoáru

Minerální trapping

CO_2 geochemicky reaguje s minerály a vytváří chemické vazby

Požadované vlastnosti úložiště

Geologické

- Kapacita umožňující uložit uvažované množství CO_2 (objem pórů, p-T podmínky)
- Injektivita zaručující dostatečnou rychlost vtláčení CO_2 do struktury (permeabilita, bariéry toku)
- Dostatečné těsnící vlastnosti nadloží, bránící úniku CO_2 z úložiště (zejména dostatečná mocnost a neporušenost těsnících hornin v nadloží)

Ekonomické

- Vzdálenost od zdroje emisí
- Existující infrastruktura
- Dostupnost geologických a dalších údajů

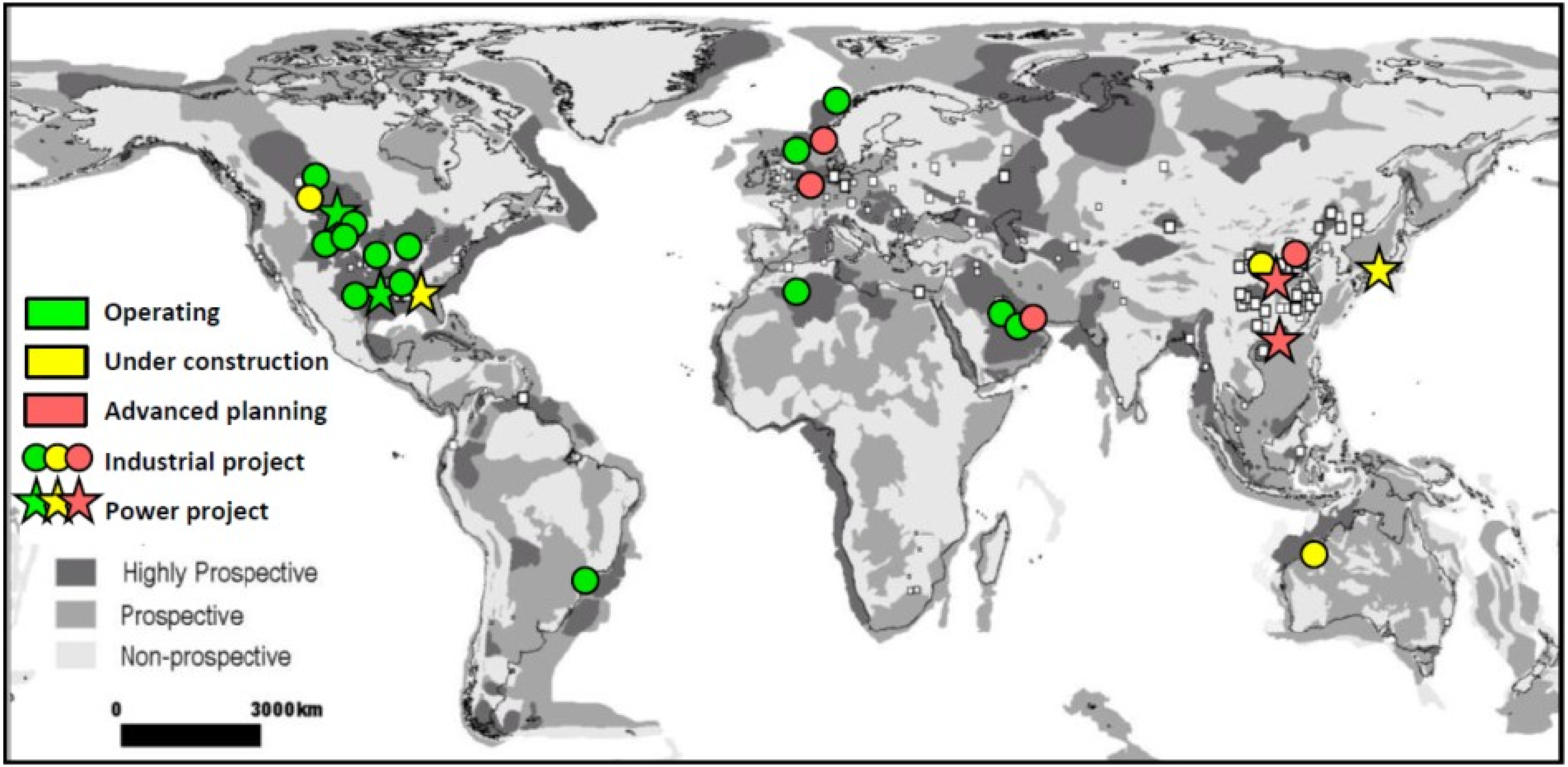
Ostatní

- Konflikty zájmů
- Přijatelnost pro veřejnost

CCS ve světě

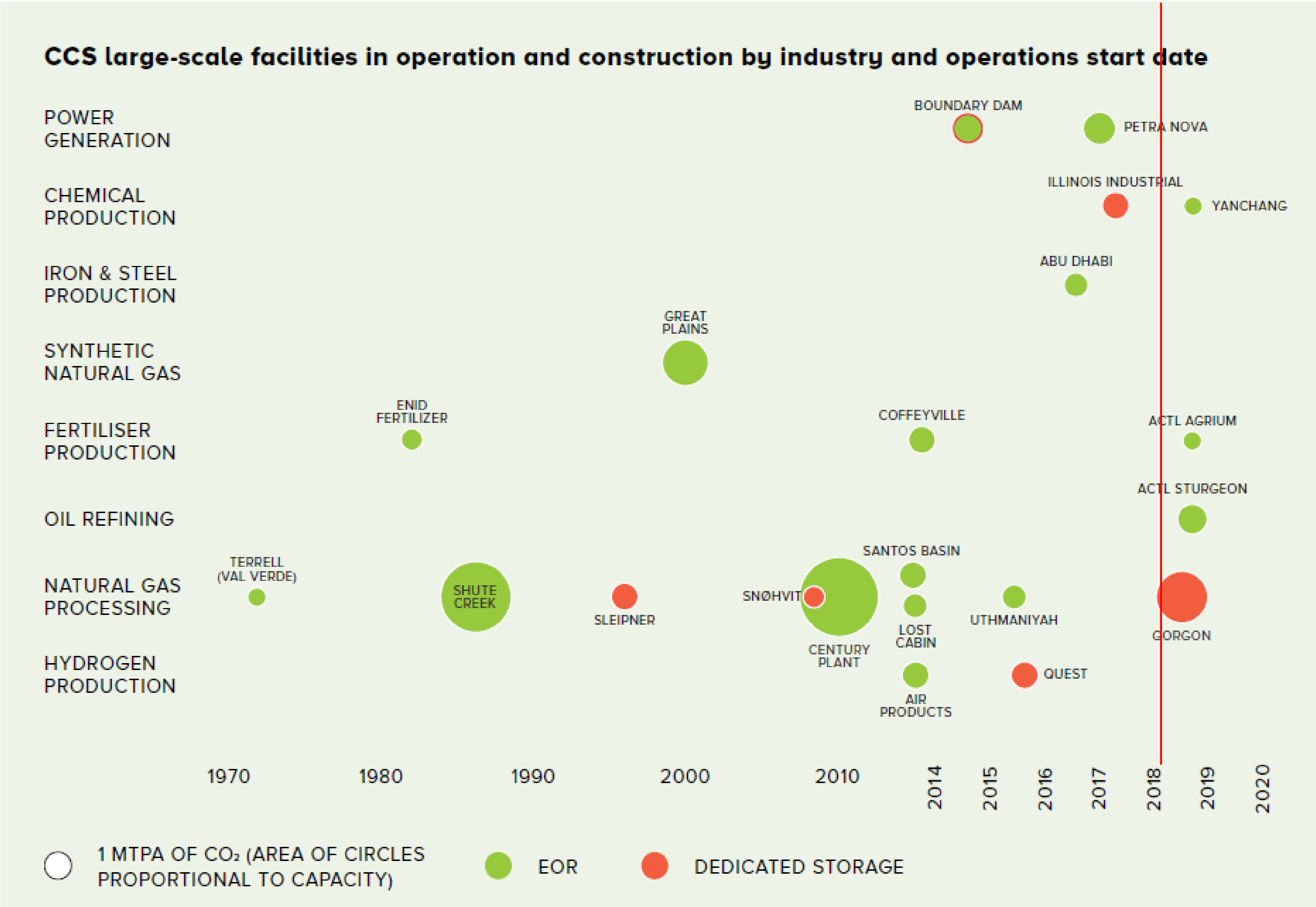
Mapa
Satelitní
SCCS
Google
Obrázky ©2015 NASA, TerraMetrics
Podmínky použití

CCS ve světě



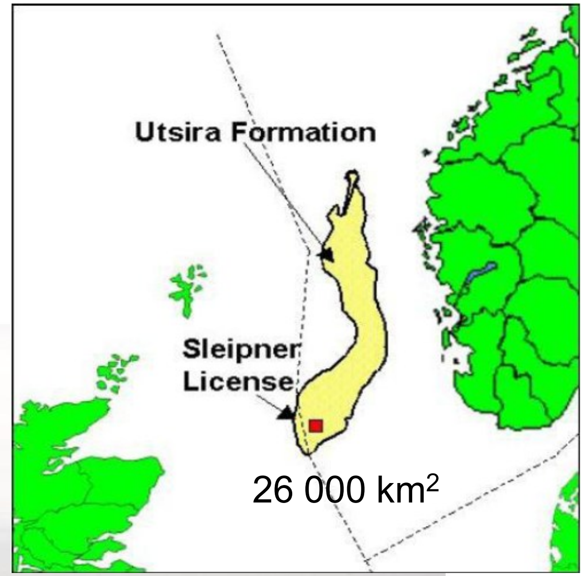
17 operating plants, storing >22 Mtons CO2 each year

CCS ve světě

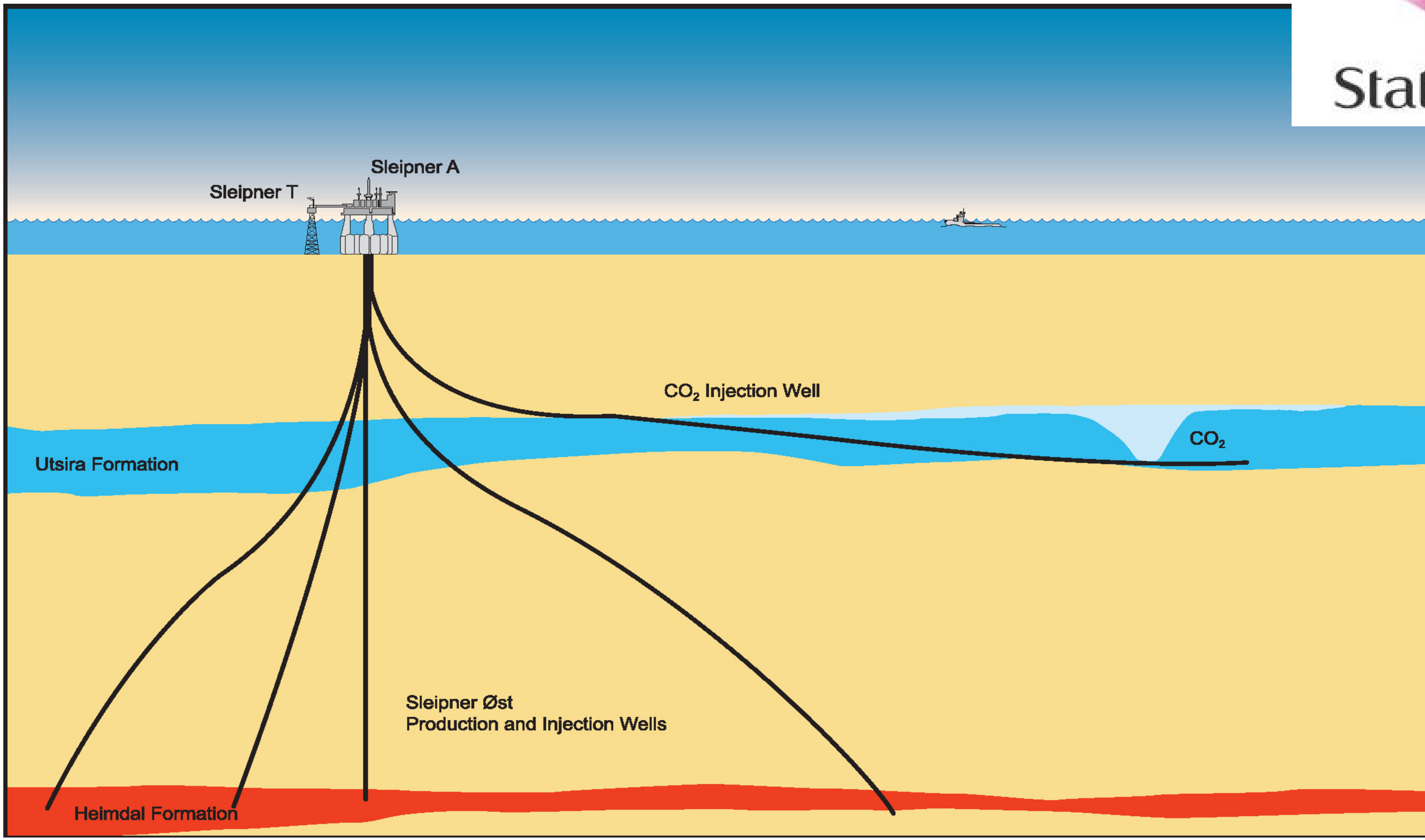


CCS large-scale facilities in operation and construction by industry and operations start date
POWER GENERATION
CHEMICAL PRODUCTION
IRON & STEEL PRODUCTION
SYNTHETIC NATURAL GAS
FERTILISER PRODUCTION
OIL REFINING
NATURAL GAS PROCESSING
HYDROGEN PRODUCTION
BOUNDARY DAM
PETRA NOVA
ILLINOIS INDUSTRIAL
YANCHANG
ABU DHABI
GREAT PLAINS
ENID FERTILIZER
COFFEYVILLE
ACTL AGRIUM
ACTL STURGEON
TERRELL (VAL VERDE)
SHUTE CREEK
SLEIPNER
SNØHVIT
CENTURY PLANT
SANTOS BASIN
LOST CABIN
UTHMANIYAH
GORGON
AIR PRODUCTS
QUEST
1970
1980
1990
2000
2010
2014
2015
2016
2017
2018
2019
2020
1 MTPA OF CO₂ (AREA OF CIRCLES PROPORTIONAL TO CAPACITY)
EOR
DEDICATED STORAGE

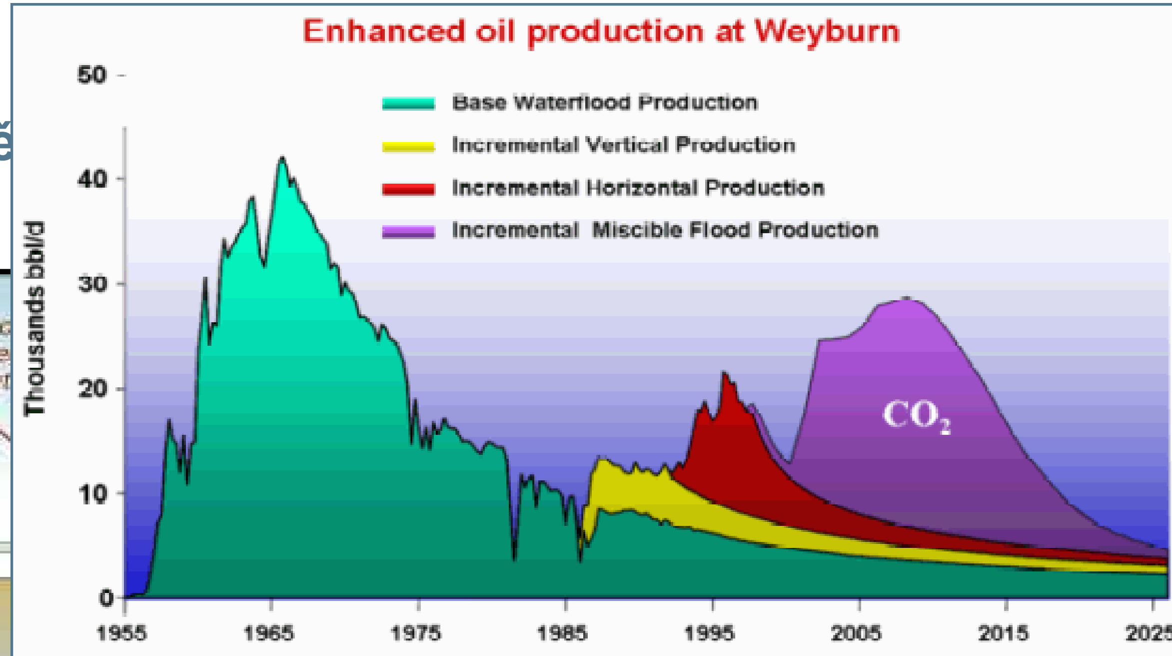
Projekt Sleipner – 22 let ukládání CO_2 (od 1996)

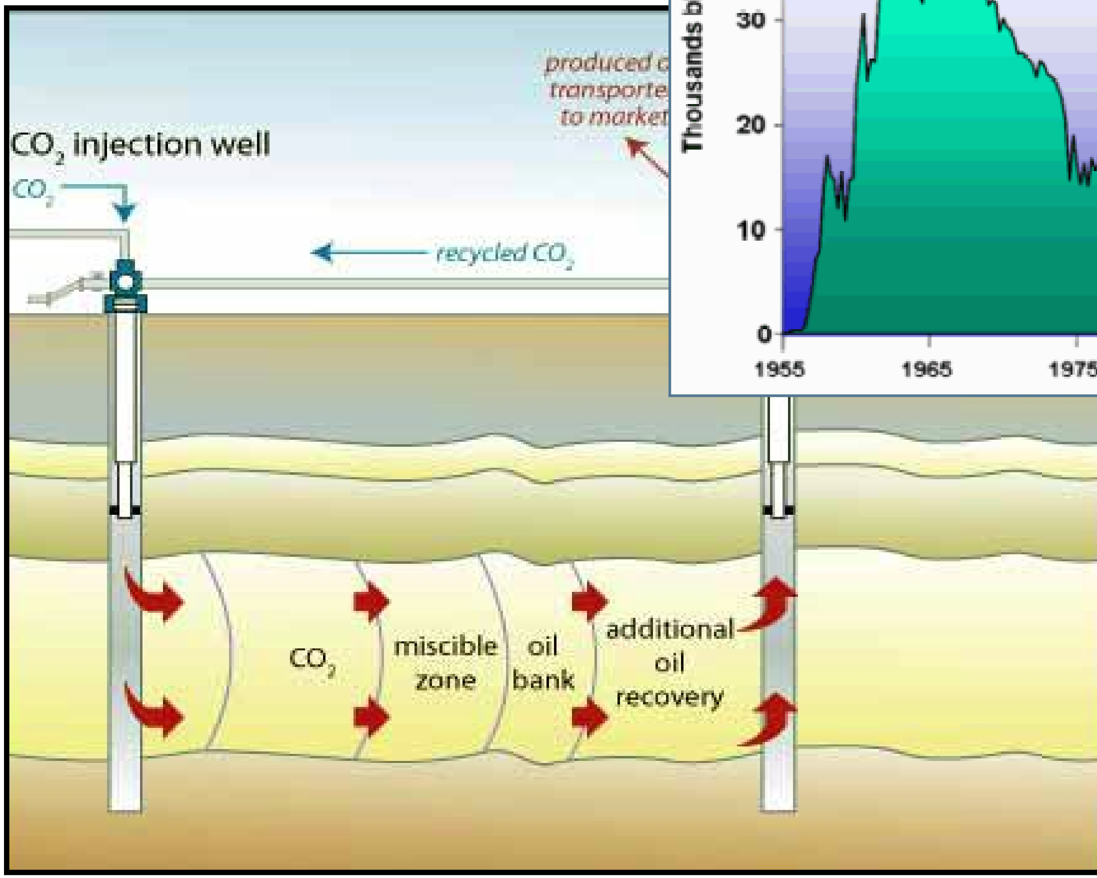


Sleipner - schéma



Weyburn – EOR
(druhotná intenzifikace tě



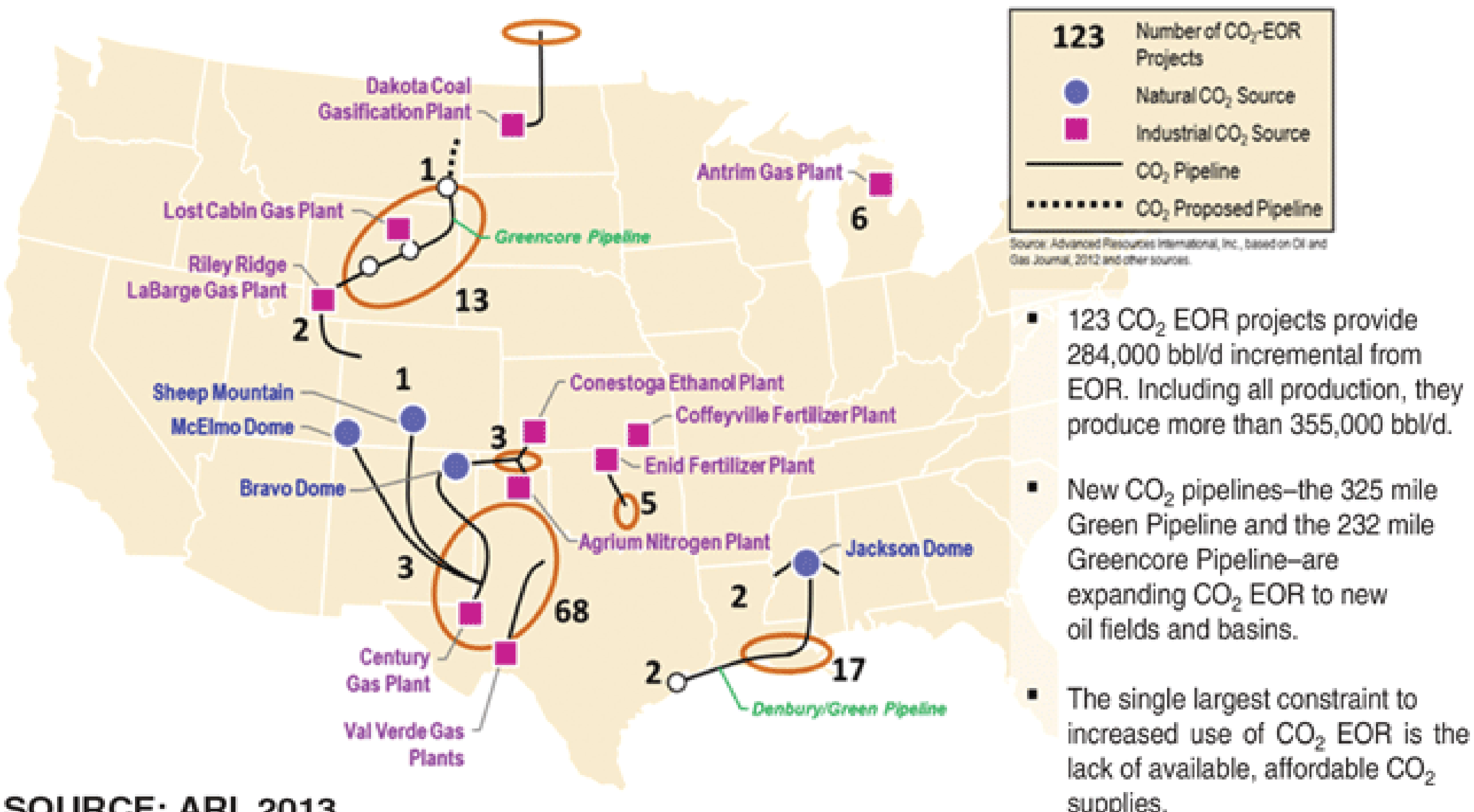


North Dakota coal gasification plant – 3,3 Mt CO_2 za rok

ENOS

CO_2-EOR v USA

- projekty na komerční bázi od r. 1972
- v r. 2014 bylo v běhu 136 projektů EOR, 300 tis. barelů dodatečné ropy denně
- vybudováno přes 5 800 km produktovodů
- celkem injektováno přes 700 Mt CO_2, 62 mil. tun v r. 2013 (z toho cca 20 % antropogenní)



SOURCE: ARI, 2013

První elektrárny s CCS

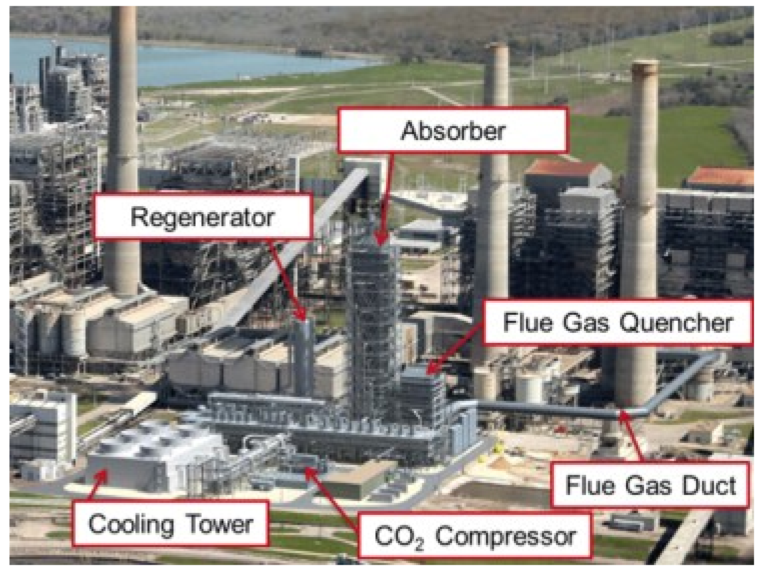
Boundary Dam

(Kanada, Saskatchewan)

- retrofit - blok 130 MW (HU)
- cca 1 mil. t CO_2 ročně
- post-combustion (Cansolv)
- EOR (66 km produktovod)
- zahájení 10/2014

Petra Nova (USA, Texas)

- retrofit - blok 250 MW (HU)
- cca 1,5 mil. t CO_2 ročně
- post-combustion (MHI)
- EOR (130 km produktovod)
- zahájení 1/2017



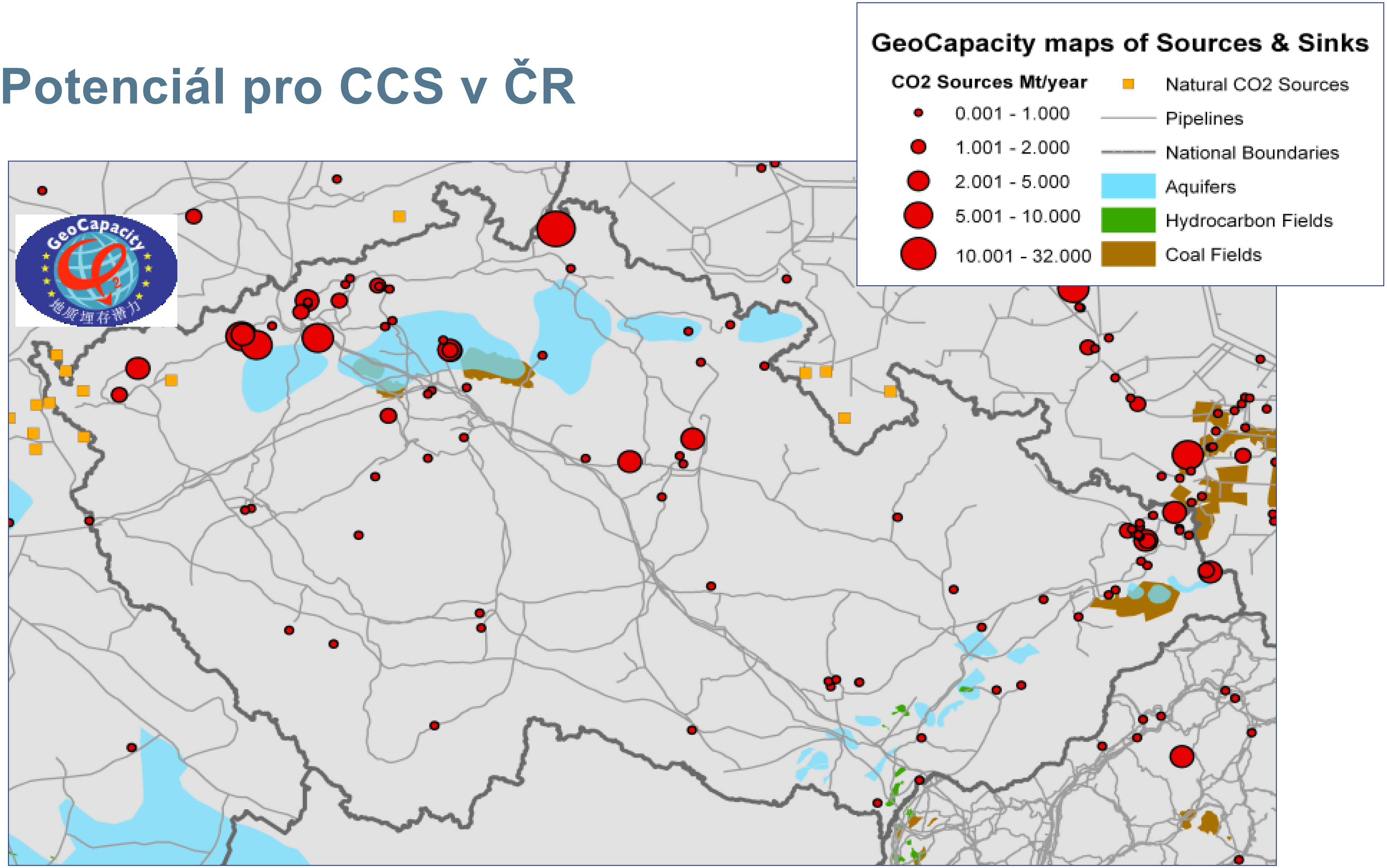
Situace v ČR

- CCS nepatří mezi priority energetické a klimatické politiky
- Aktualizace Státní energetické koncepce připouští možnou roli CCS po r. 2040 a doporučuje věnovat se výzkumu geologického ukládání CO2
- Politika ochrany klimatu 2017 – jeden ze scénářů založen na významném podílu CCS
- Zákon 85/2012 neumožňuje průmyslové využití CCS do r. 2020 a klade další překážky (max. 1 Mt na úložiště, finanční záruka)
- Podpora V&V – program MPO TIP, TAČR
- Nový impuls – Norské fondy 2009-2014 – Program CZ08 (CCS)

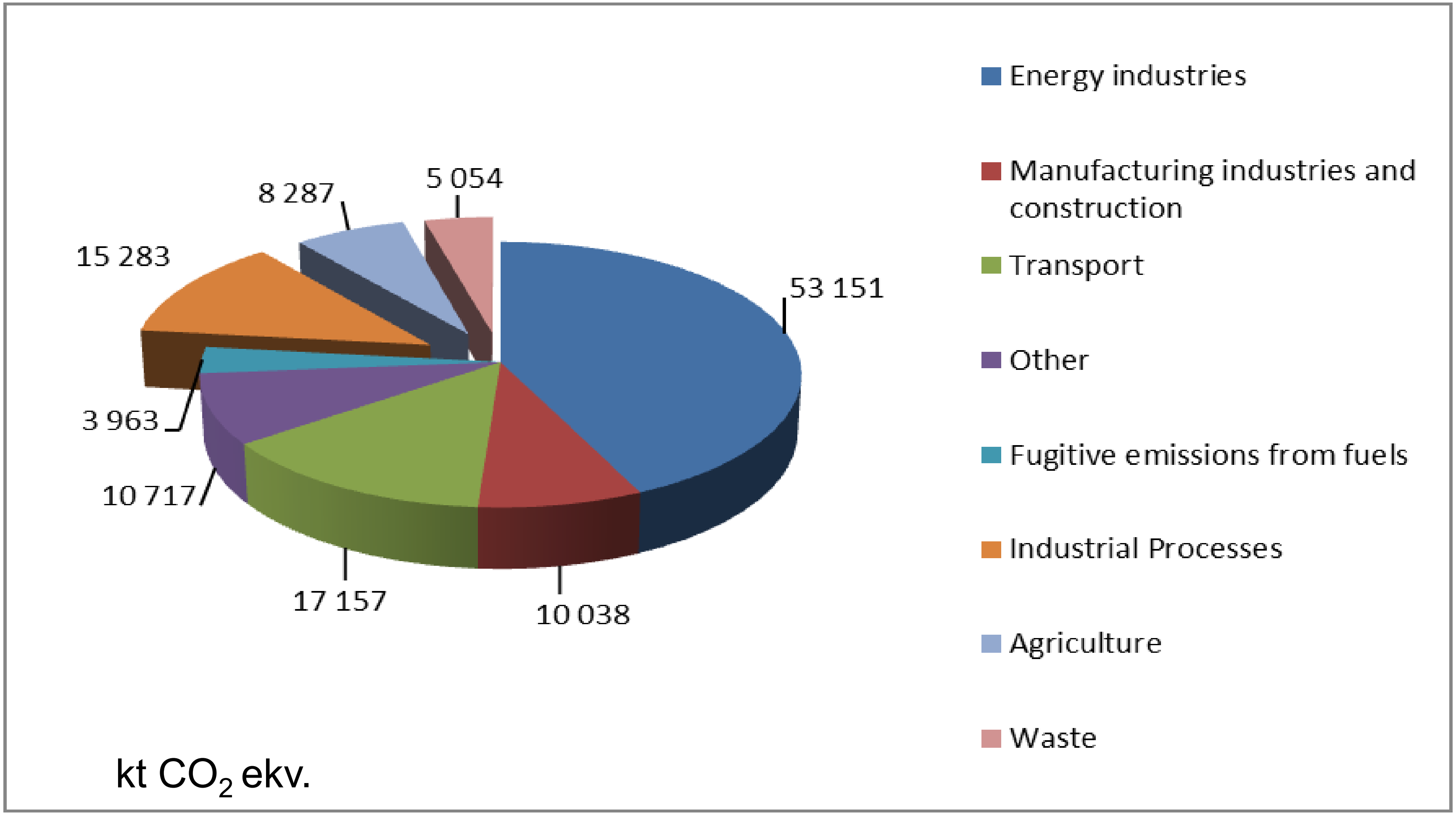
Proč může být technologie CCS v budoucnu pro ČR důležitá?

- Je to jediná metoda, která umožňuje snížit emise CO_2 ze spalování fosilních paliv až o 90 % (význam např. při zavedení EPS nebo pro udržení životnosti nových bloků)
- Pro některé průmyslové výroby (ocelárny, cementárny, některé chemické výroby) představuje jedinou alternativu snížení emisí
- Bez CCS bude dosažení cíle 80% snížení emisí v r. 2050 obtížné a drahé
- CCS může být v budoucnu levnější než nákup povolenek (nové technologie 2. generace)
- Kombinace spalování biomasy a CCS je uhlíkově negativní (zlepšení uhlíkové bilance)

Potenciál pro CCS v ČR

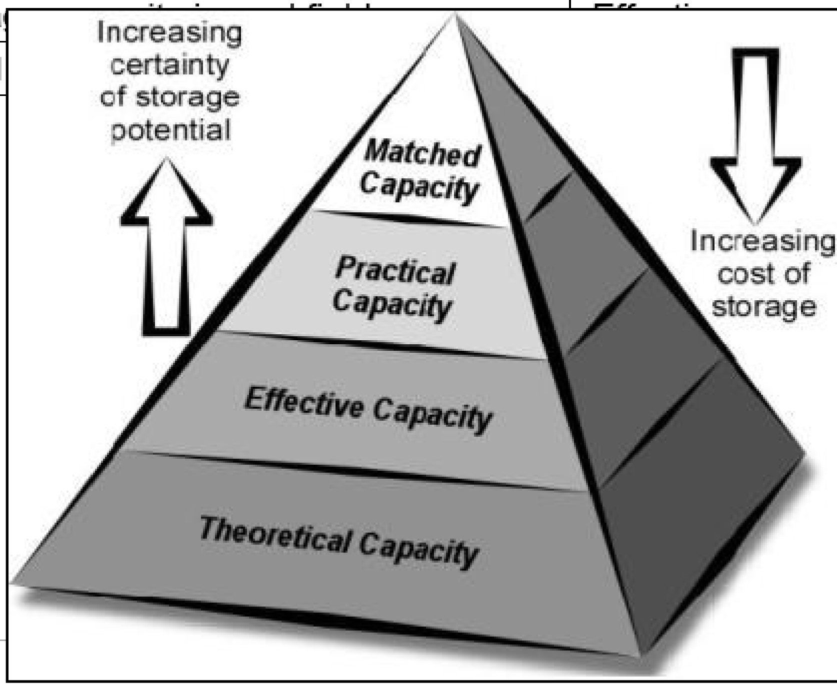


Emise skleníkových plynů v ČR v r. 2014 podle sektorů



Potenciál ukládání CO_2 v ČR

CO_2 emissions		Year(s)	Average CO_2 emissions (Mt)
CO_2 emissions from large point sources in database		2005	78
Total CO_2 emissions		2006	128
CO_2 storage capacity	**Pyramid class**	**Conservative estimate (Mt)**	**Estimate in database (Mt)**
Storage capacity in aquifers	Effective	766	2863
Storage capacity in hydrocarbon fields	N/A	33	33
Stora[...]	Effecti[...]	54	54
Total		**853**	**2950**

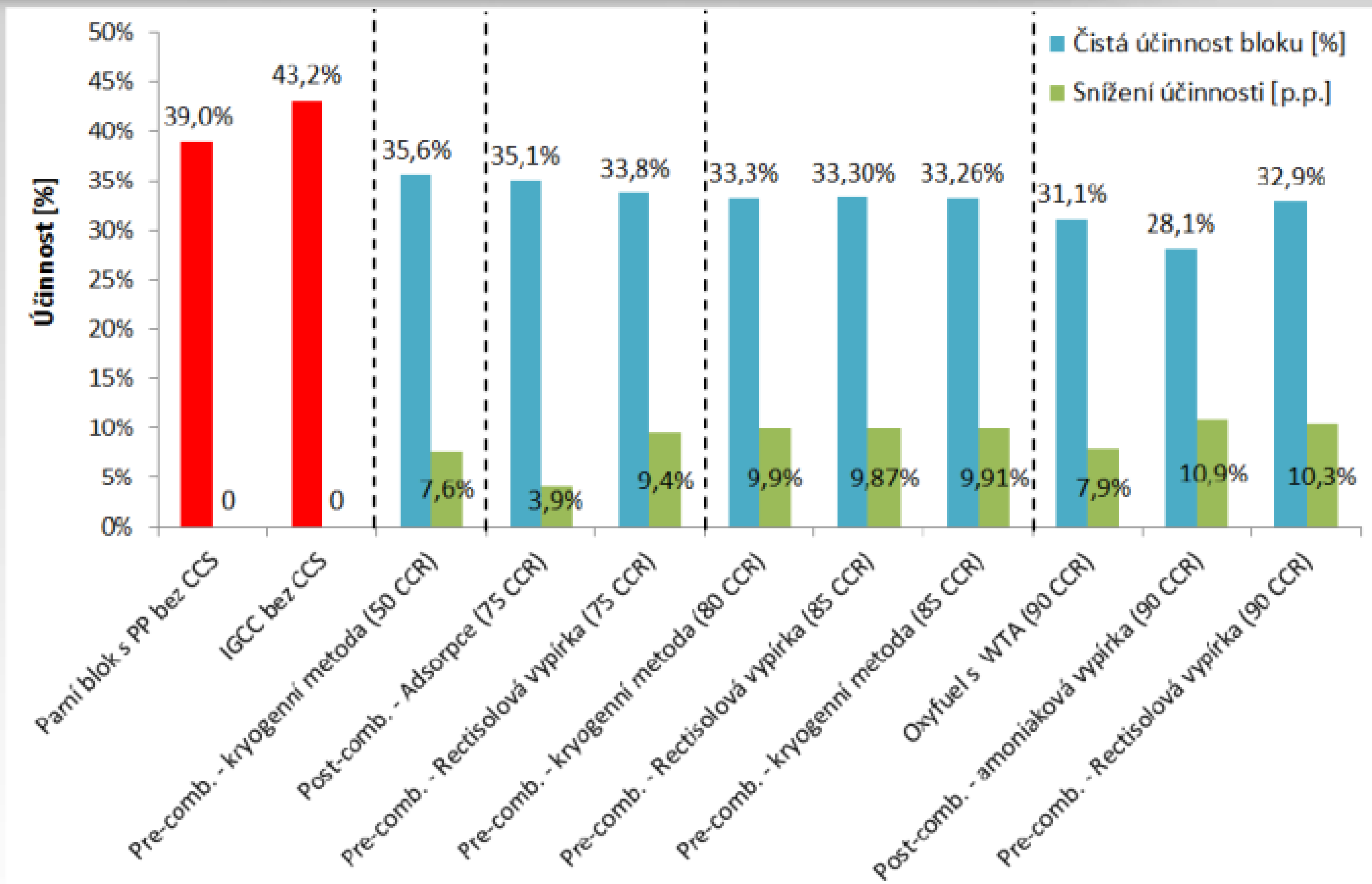


Značná nejistota u akviferů – nedostatek dat

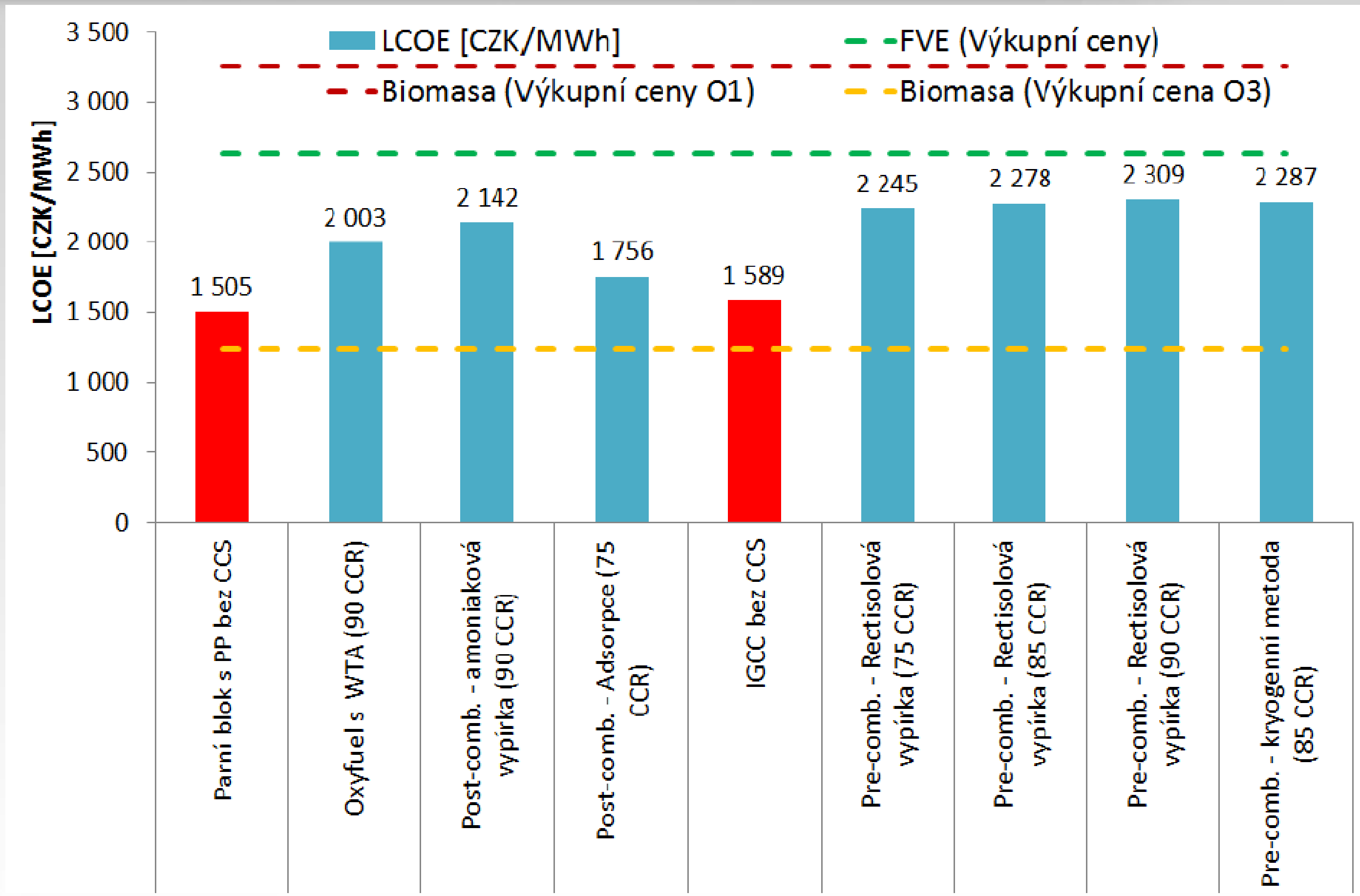
Technicko-ekonomické hodnocení integrace CCS technologií

Parametry	FR-TI/379		TA02020205	NF-CZ08-OV-1-003
Elektrárna	Parní blok s podkritickými parametry			IGCC parní blok
Palivo (Lignit)	LHV = 9.75 MJ/kg, W=31%, A=30%, S=3%			LHV = 16.50 MJ/kg, W=31%, A=13%, S=1.3%
Návrhový výkon bloku	250 MWe			310 MWe
CCS technologie	Oxyfuel, post combustion – Amoniaková vypírka	Post-combustion - Adsorpce		Pre-combustion – Rectisolová vypírka, membrány, nízkoteplotní
CCR	90%	75%		85% (50 – 90%)
Období studií	2013	2015		2016

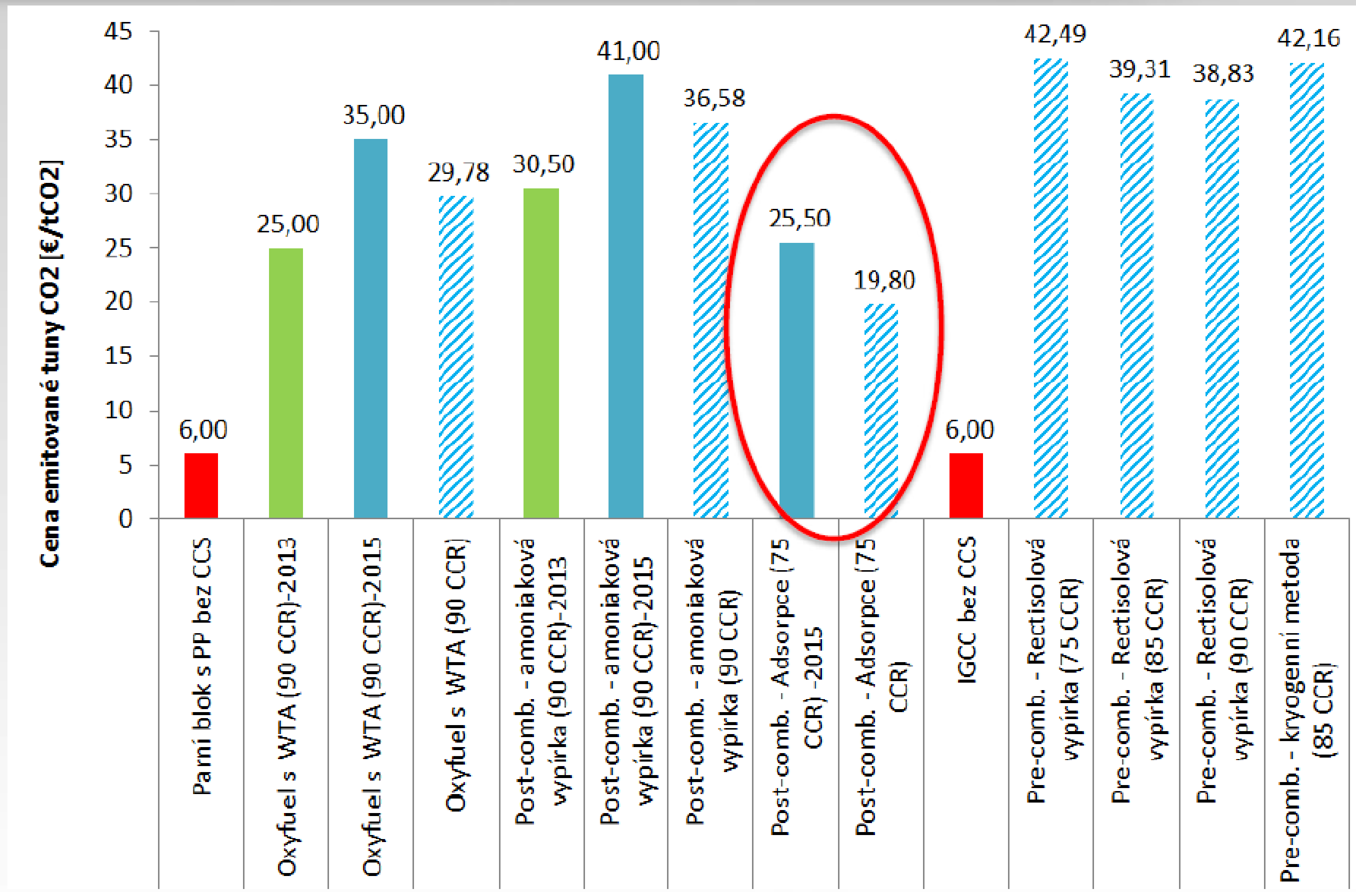
Technicko-ekonomické hodnocení integrace CCS technologií



Technicko-ekonomické hodnocení integrace CCS technologií



Technicko-ekonomické hodnocení integrace CCS technologií



Shrnutí

- Geologické ukládání CO_2 a technologie CCS představují nadějnou a potenciálně důležitou součást opatření ke zmírnění změny klimatu
- Technologie i úložná kapacita jsou k dispozici
- Rozsáhlejšímu zavedení technologie do praxe však brání významné překážky:
  - nedostatečná politická podpora
  - nejistá cena uhlíkových emisí v budoucnosti
  - nejasné financování demonstračních a prvních komerčních projektů
  - odpor veřejnosti k ukládání CO_2 na pevnině (v osídlených oblastech)

Přesto – CCS bude potřeba k dosažení cílů snížení emisí; vývoj proto pokračuje a lze očekávat jeho zrychlení v budoucnosti.

Tato prezentace je výstupem projektu ENOS

www.enos-project.eu

Český informační portál pro technologie CCS najdete na

www.geology.cz/ccs

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 653718

BACKUP SLIDES

introduction to the CCS process chain

- Definition:
  CCS = Carbon dioxide Capture and Storage or CO_2 capture and storage
  (also referred to, in short, as Carbon Capture and Storage)
  For Storage, also terms geological storage, sequestration or geosequestration are used.
- CCS is a climate change mitigation technology (see Lecture 1).
- Main goal = reduction of CO_2 emissions to the atmosphere
- Principle of CCS: separation (capture) of CO_2 from waste gas streams at emission sources and its safe, long-term isolation from the atmosphere in deep subsurface
- CCS process chain has three main components (see next slide for illustration):
  - CO_2 capture – separating CO_2 from the waste gas stream
  - CO_2 transport – delivering the captured CO_2 to the storage site
  - CO_2 storage – injecting the captured CO_2 in a carefully chosen geological structure that will keep it permanently isolated from

CO_2 capture

- Purpose: to produce a concentrated stream of CO_2 at high pressure that can readily be transported to a storage site
- Primary targets = large-scale emission sources emitting hundreds of thousands to millions tons of CO_2 annually (smaller sources can be clustered):
  - power plants combusting fossil fuels and/or biomass
  - oil and gas processing facilities
  - industrial plants (cement, iron and steel, pulp and paper production)
  - refineries and petrochemical plants
- Various capture technologies are used, based on the composition of the waste gas to be treated, concentration of CO_2 in the gas stream, pressure and temperature.

Technologies commercially available at present (1st generation technologies) are based on:

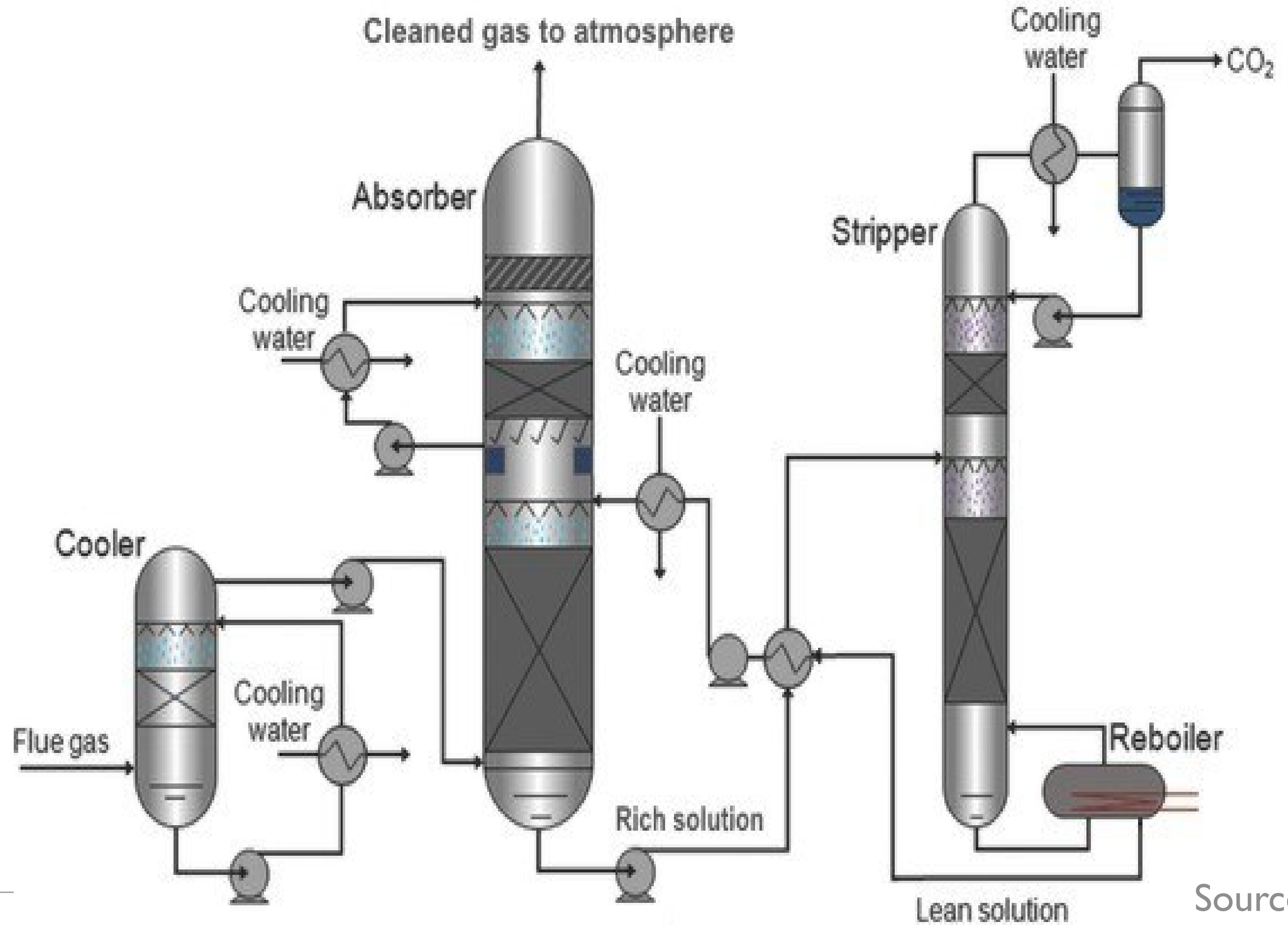
  - chemical absorption
  - physical absorption
  - adsorption

CO_2 capture by chemical absorption

- Chemical absorption is the most common technology used today.
- It utilises a reversible chemical reaction of CO_2 with an aqueous solvent, usually amine or ammonia.
- The principle is shown on the next slide:
  - The flue gas containing CO_2 (left) is cooled (if necessary) and transported (using a blower) to the Absorber. Here the CO_2 is brought into contact with the solvent and is chemically bound (typically at 40-60°C). The flue gas (almost CO_2-free) is water-washed and leaves the Absorber (Cleaned gas to atmosphere).
  - The solvent with chemically bound CO_2 (Rich solution) is then pumped to the Stripper. Here the solvent is regenerated (CO_2 desorption = breaking the chemical bond between the solvent and CO_2) at elevated temperature (100-140°C) and pressure. This causes a thermal energy penalty.
  - The regenerated solvent without CO_2 (Lean solution) is pumped back to the Absorber and the loose CO_2 leaves the Stripper for compression and storage.

[IPCC,2005;Vega et al., 2014; ZEP, 2017]

diagram of CO_2 capture process using chemical absorption



Source: Vega et al. ,2014

CO_2 capture by physical absorption

- Physical absorption is mostly used in cases where the gas stream has a high concentration of CO_2 at high pressure, or high CO_2 partial pressure (e.g. synthesis gas /syngas/).
- The process is similar to chemical absorption; the CO_2 is, however, captured by physical dissolution in the solvent.
- The regeneration of the solvent (stripping of CO_2 from the solution) is mainly achieved by reducing the pressure → lower energy penalty.
- Several well-established commercial technologies are available, e.g.:
  - Selexol (by UOP llc)
  - Rectisol (by Linde and Air Liquide)

[IPCC,2005; ZEP, 2017]

CO_2 capture by adsorption

- Adsorption technology is based on the adhesion of CO_2 molecules to the surface of the adsorbent where the molecules form a film.
- Adsorption may take place physically, involving van der Waals forces, chemically, involving covalent bonding, or due to electrostatic attraction.
- The principle is shown on the next slide:
  - CO_2 contained in the flue gas is adsorbed on the surface of an adsorbent (left)
  - other gases are removed (centre)
  - CO_2 is released (desorbed) by decreasing pressure or increasing temperature (right) and removed from the reactor for compression and storage
- Several examples of commercial applications exist, e.g. the Port Arthur Project (Texas, USA) – hydrogen plant; CO_2 is captured from syngas produced by steam methane reformers.

[Ben-Mansour et al., 2016; IPCC,2005; MIT, 2016;ZEP, 2017]

principle of CO_2 capture by adsorption

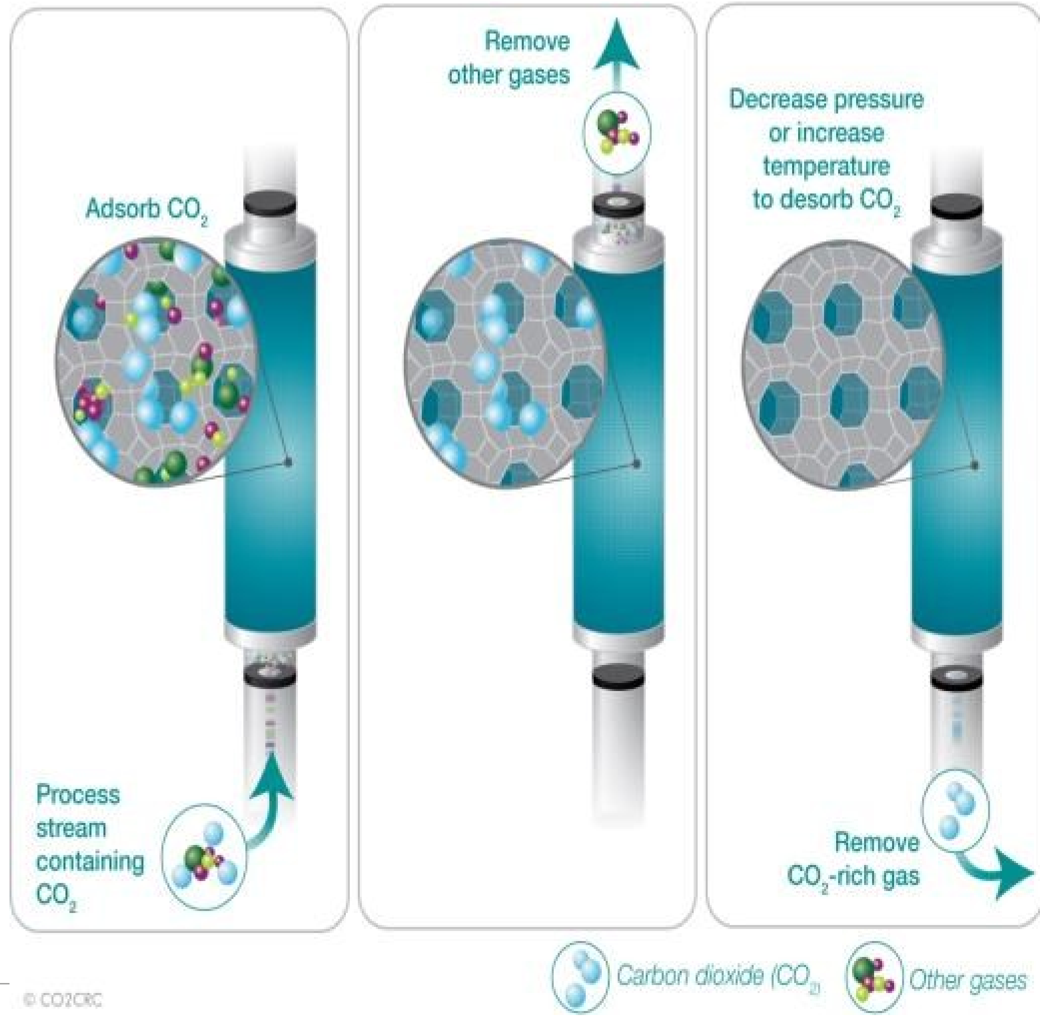


image courtesy CO2CRC

next generation technologies

- 2nd generation capture technologies are currently available at pilot scale (10 or more times smaller than industrial scale); 3rd generation technologies at laboratory scale.
- They include, e.g.:
  - enhanced solvents for chemical absorption
  - novel adsorbent materials and processes for adsorption
  - CO_2 capture by membranes
  - CO_2 separation by cryogenic distillation
  - microbial and algal systems (biogenic capture)

Next generation technologies are expected to deliver cost reduction, lower penalty in energy efficiency, operational flexibility, reduced health, safety & environment issues, etc.

[ZEP, 2017]

Further reading: ZEP report „Future CCS Technologies“

CO_2 capture types at combustion processes

- At fossil-fuelled power plants and other combustion processes, three basic types of CO_2 capture are distinguished:
  - **post-combustion capture** – CO_2 is captured after the fuel is burned
  - **pre-combustion capture** – CO_2 is captured within the fuel treatment process
  - **oxy-fuel combustion** – fuel is burned in a special atmosphere (mixture of oxygen and CO_2) instead of common air
- Emerging technologies – high temperature solid looping cycles (calcium and chemical looping)

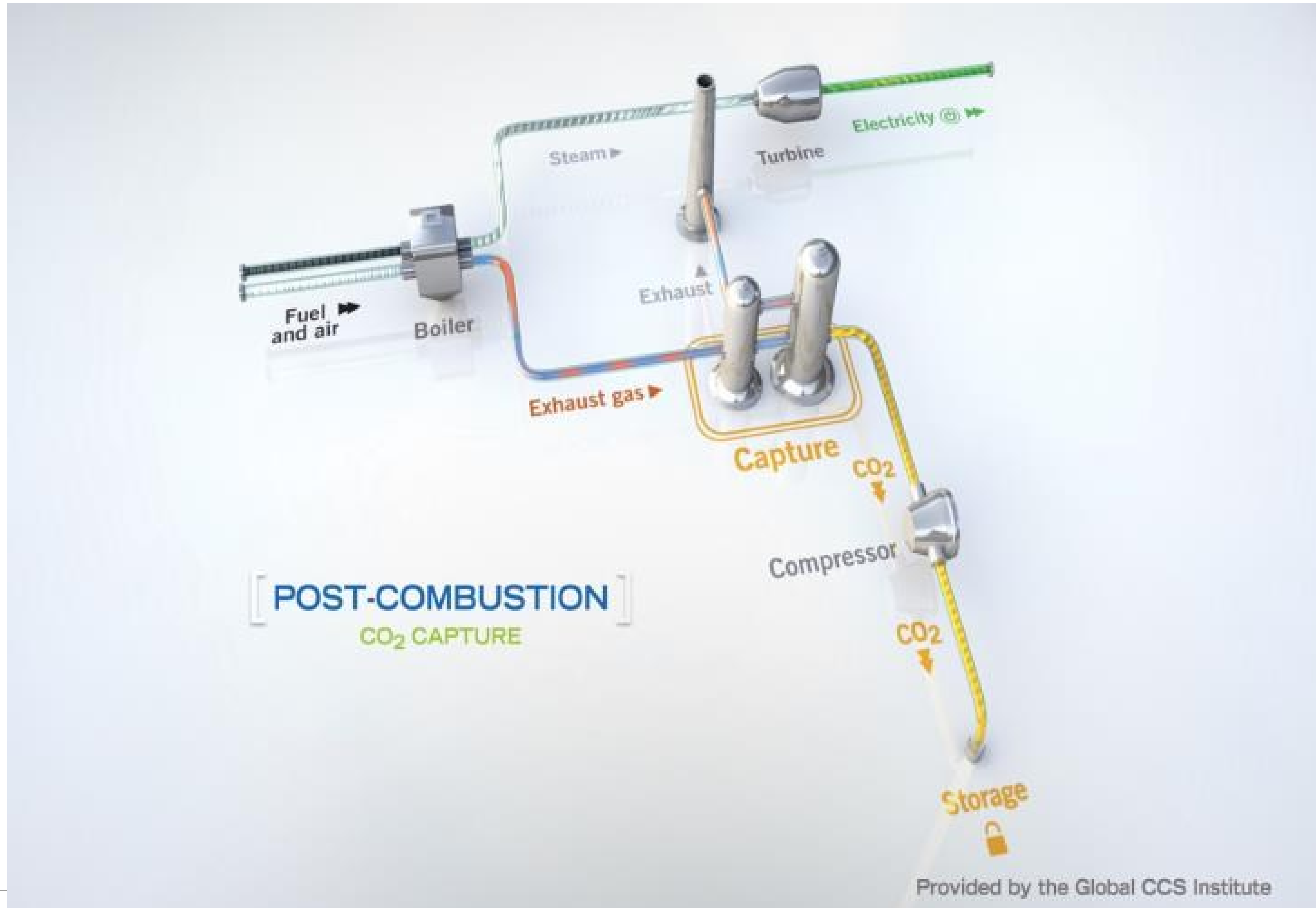
[IPCC,2005; ZEP, 2017]

post-combustion capture

- The principle is shown on the next slide (power plant example):
  - fuel is burned in a boiler in air atmosphere, producing steam that runs a turbine producing electricity
  - flue gas is brought to a capture unit where CO_2 is captured (most commonly using chemical absorption)
  - captured CO_2 is sent for compression and storage while the remaining gas goes to exhaust
- The technology is used at the two currently operating power plants equipped with CCS – Boundary Dam (Canada) and Petra Nova (Texas, USA)

[IPCC,2005; MIT, 2016; ZEP, 2017]

principle of post-combustion capture

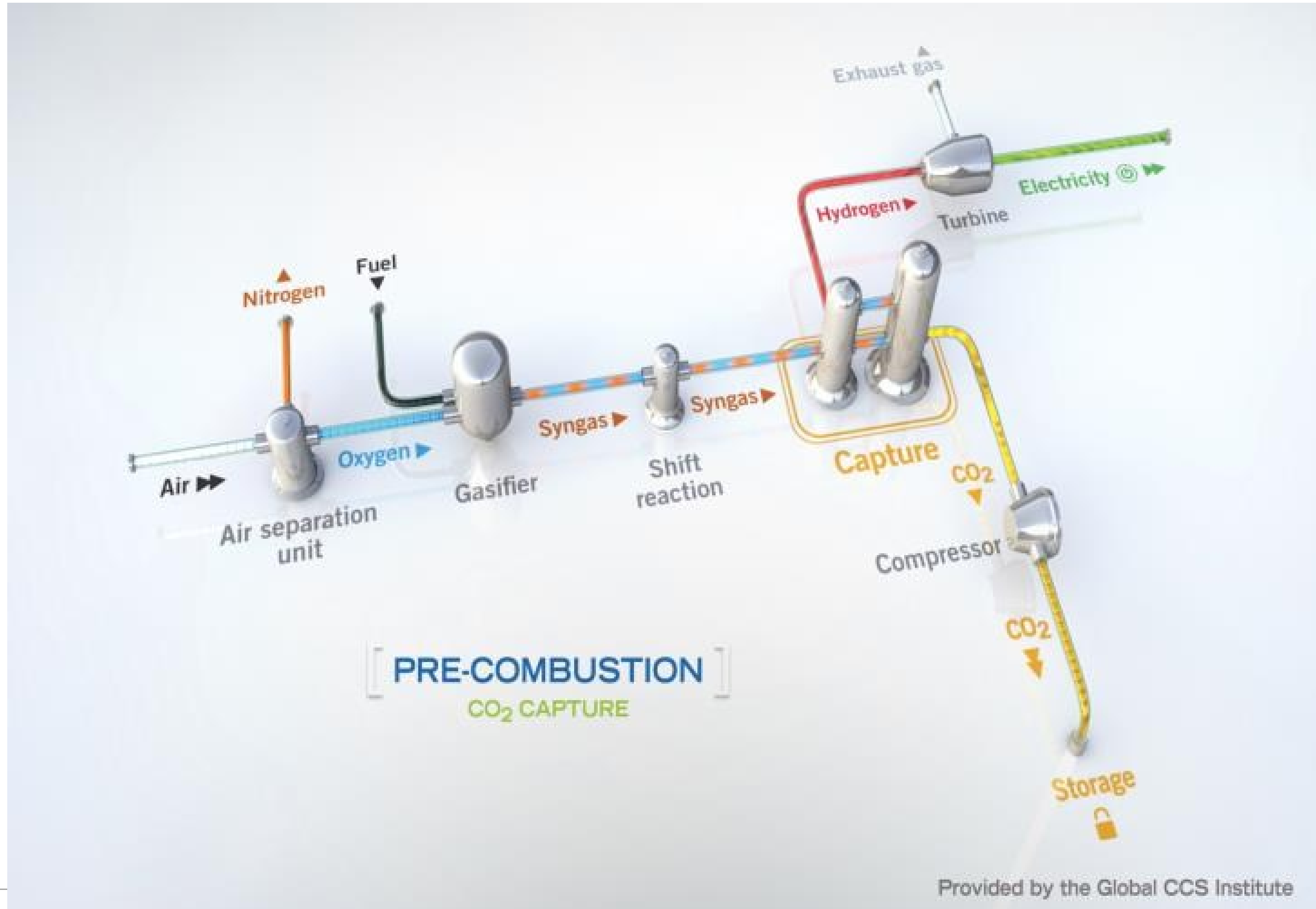


pre-combustion capture

- The principle is shown on the next slide (power plant example):
  - air separation unit /ASU/ separates oxygen from air
  - fuel reacts with oxygen to create synthesis gas /syngas/ – mixture of carbon monoxide /CO/ and hydrogen /H_2/
  - in the shift reactor syngas reacts with steam and a mixture of H_2 and CO_2 is created
  - the capture plant separates CO_2 (usually by chemical or physical absorption), which is sent to compression and storage
  - the remaining H_2-rich gas is burned in a gas turbine to produce electricity
  - in addition, the remaining heat can produce steam, which can be used in a steam turbine to produce more electricity, then we have the Integrated Gasification Combined Cycle (IGCC)
- The technology has been demonstrated at pilot scale so far.

[IPCC,2005; ZEP, 2017]

principle of pre-combustion capture

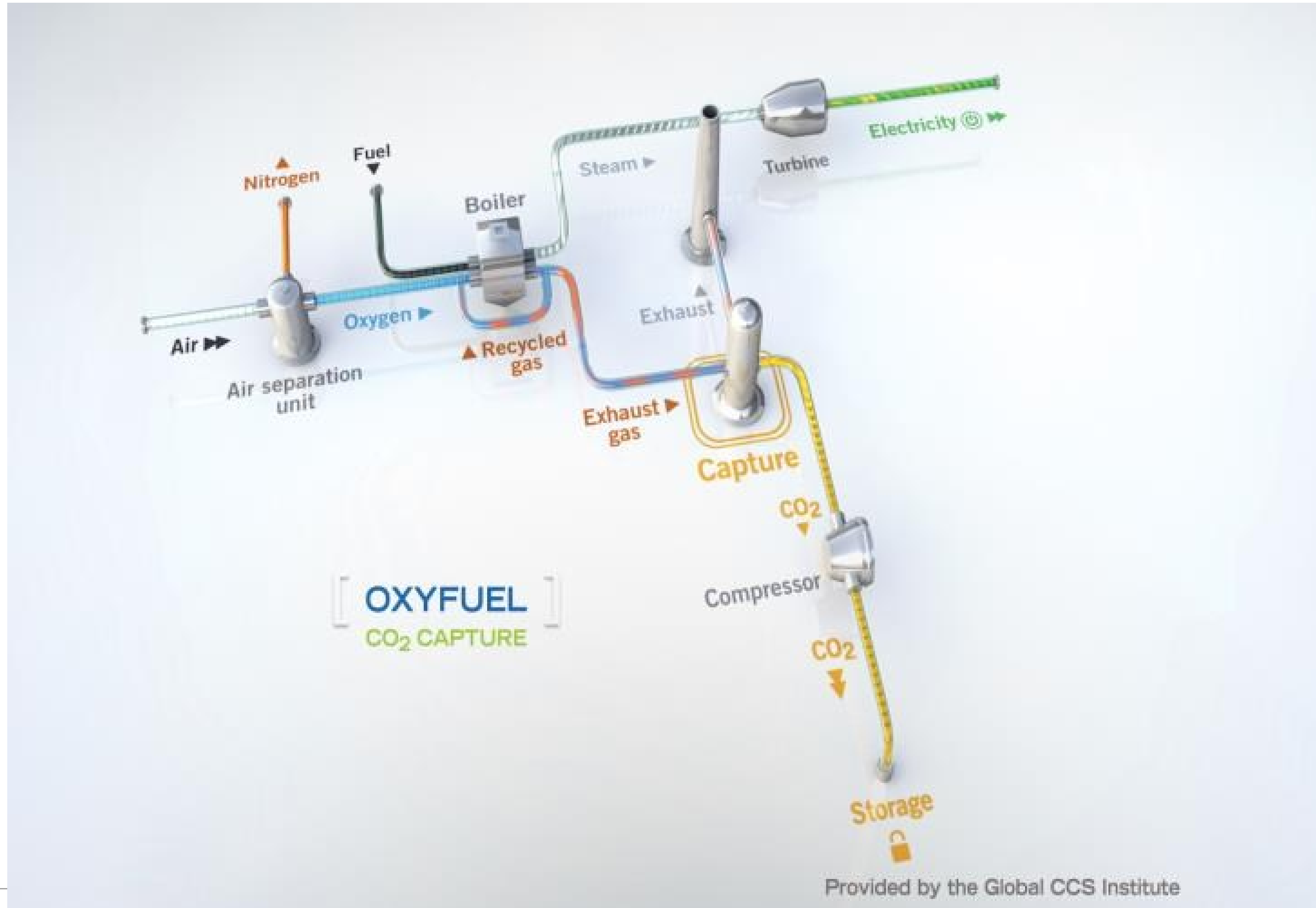


oxy-fuel combustion capture

- The principle is shown on the next slide (power plant example):
  - air separation unit /ASU/ separates oxygen from air
  - fuel is burned in a special boiler in an atmosphere composed of oxygen and recycled flue gas
  - produced steam powers a steam turbine producing electricity
  - exhaust gas (mostly CO_2 />80%/ and water vapour) is moved to the capture unit where CO_2 is separated and sent to compression and storage
- The technology has been demonstrated at pilot scale so far.

[IPCC,2005; ZEP, 2017]

principle of oxy-fuel combustion capture



industrial processes

Examples of processes with CO_2 capture potential:

- natural gas sweetening – CO_2 is separated (by chemical or physical absorption) from natural gas produced from the subsurface in case its content is above limit; this is the most frequent CCS application at present, incl. the two sole large-scale CCS projects in Europe – Sleipner and Snøhvit offshore Norway
- coal/bitumen gasification with CO_2 capture (mostly by physical absorption) in various modifications, demonstrated at industrial scale, e.g. at:
  - synthetic natural gas production (Great Plains Synfuels Plant, North Dakota, USA)
  - hydrogen production (North West Sturgeon Refinery, Alberta, Canada)
- hydrogen production by steam methane reforming with CO2 capture (absorption or adsorption from CO_2-H_2 mixture) – e.g. Port Arthur Project (Texas, USA), Shell Quest Project (Alberta, Canada)

[IPCC,2005; MIT, 2016; ZEP, 2017]

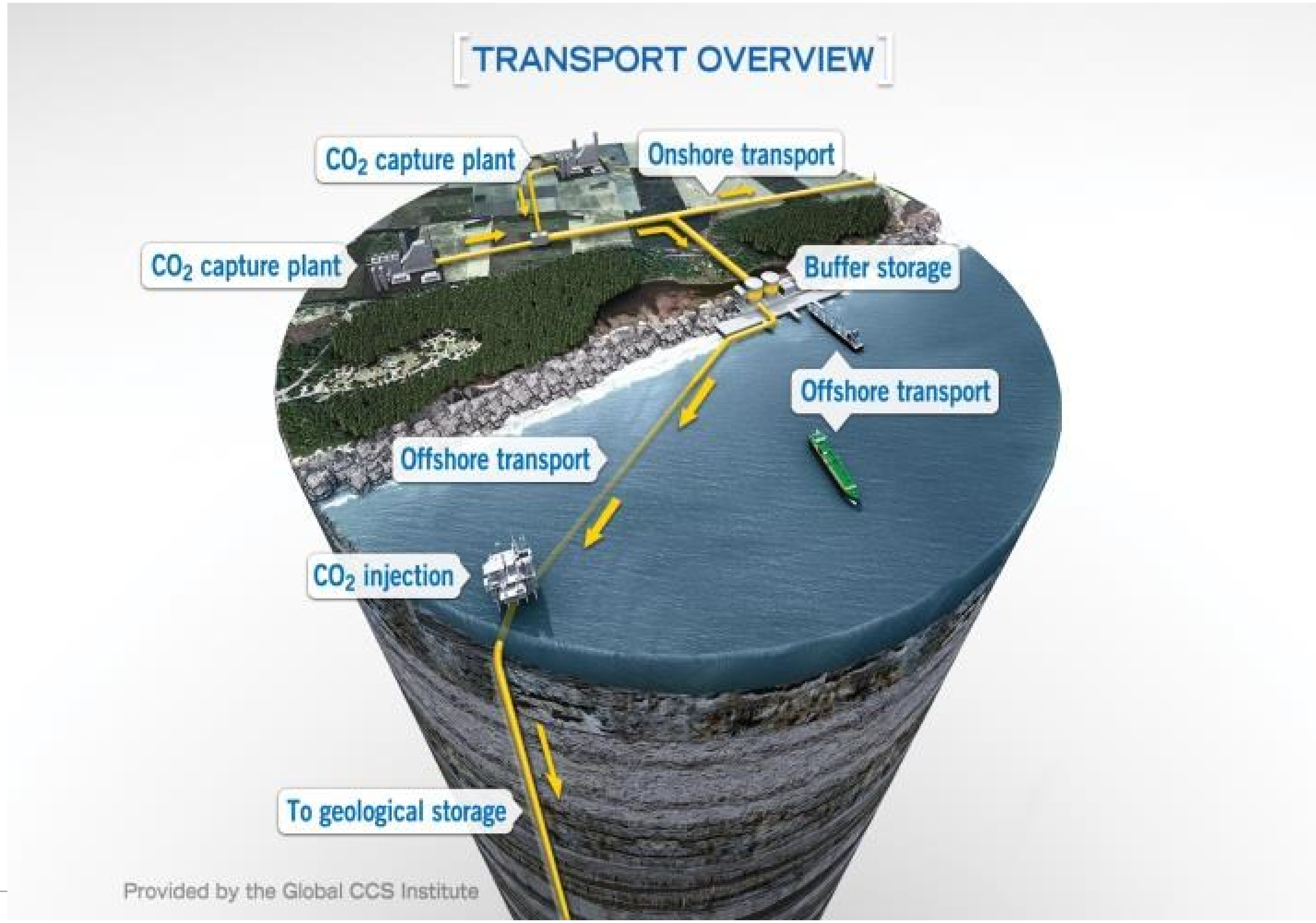
industrial processes (cont.)

Examples of processes with CO_2 capture potential (cont.):

- chemical industry:
  - **ammonia production** – CO_2 is a by-product, usually in form of a highly concentrated stream → easier capture and purification
  - **ethanol production** - commercial-scale example – ADM Illinois Industrial CCS Project (USA) – the first large-scale BioCCS application; CO_2 is a >99% pure stream which is a by-product of ethanol production via anaerobic fermentation
- **steel production** – 1st demonstration project = ESI CCS Project (United Arab Emirates) – CO_2 is captured (chemical absorption) from waste gas produced by Direct Reduced Iron process (iron ore /Fe_2O_3/ is reduced to iron /Fe/ in a reactor, using hydrogen brought in syngas)
- **cement production** – CO_2 capture demonstrated at pilot scale

[Abu Zahra, 2015; IPCC,2005; ZEP, 2017]

CO_2 transport



CO_2 transport

Three main options of CO_2 transport:

- pipelines – big-scale projects, both on- and offshore
- trucks & rail tankers – small onshore projects (typically pilot-scale)
- ships – small- and mid-scale offshore projects, especially with longer distance from capture plant to storage site

CO_2 pipelines are a well-established technology, especially in North America:

- almost 5000 km of CO_2 pipelines are operating in the USA and Canada
- typical operation conditions – pressure 10-15 MPa, temperature 15-30°C $\rightarrow$ CO_2 is transported in liquid phase, with high density
- compressors are used to pressurize the pipeline, booster stations are needed for longer distances
- additional processing of CO_2-rich gas (after capture) is usually required to decrease the content of impurities, especially water vapour to limit corrosion risk

[ESPA 2015; IPCC 2005; Patchigolla & Oakey 2013; ZEP 2017]

CO_2 transport (cont.)

CO_2 transport by trucks and/or rail tankers is a well established industrial technology.

- Liquefaction of captured CO_2 is needed = compression, cooling, dehydration and distillation.
- Typical parameters for truck transport in Europe:
  - capacity of one truck - in the order of ~ 25 tons
  - pressure ~ 1.6 MPa
  - temperature ~ -30°C

Ship transport:

- current ships (capacity ≤ 1800 t CO_2) use similar pressures and temperatures to trucks
- bigger ships are needed for industrial CCS projects – lower temperatures (~ -52°C) and pressures (~ 0.65 MPa) are proposed

[Brownsort. 2015; IPCC,2005; ZEP, 2017]

CO_2 storage (more details in e-books 3-9)

„A geological formation shall only be selected as a storage site, if under the proposed conditions of use there is no significant risk of leakage, and if no significant environmental or health risks exist.“

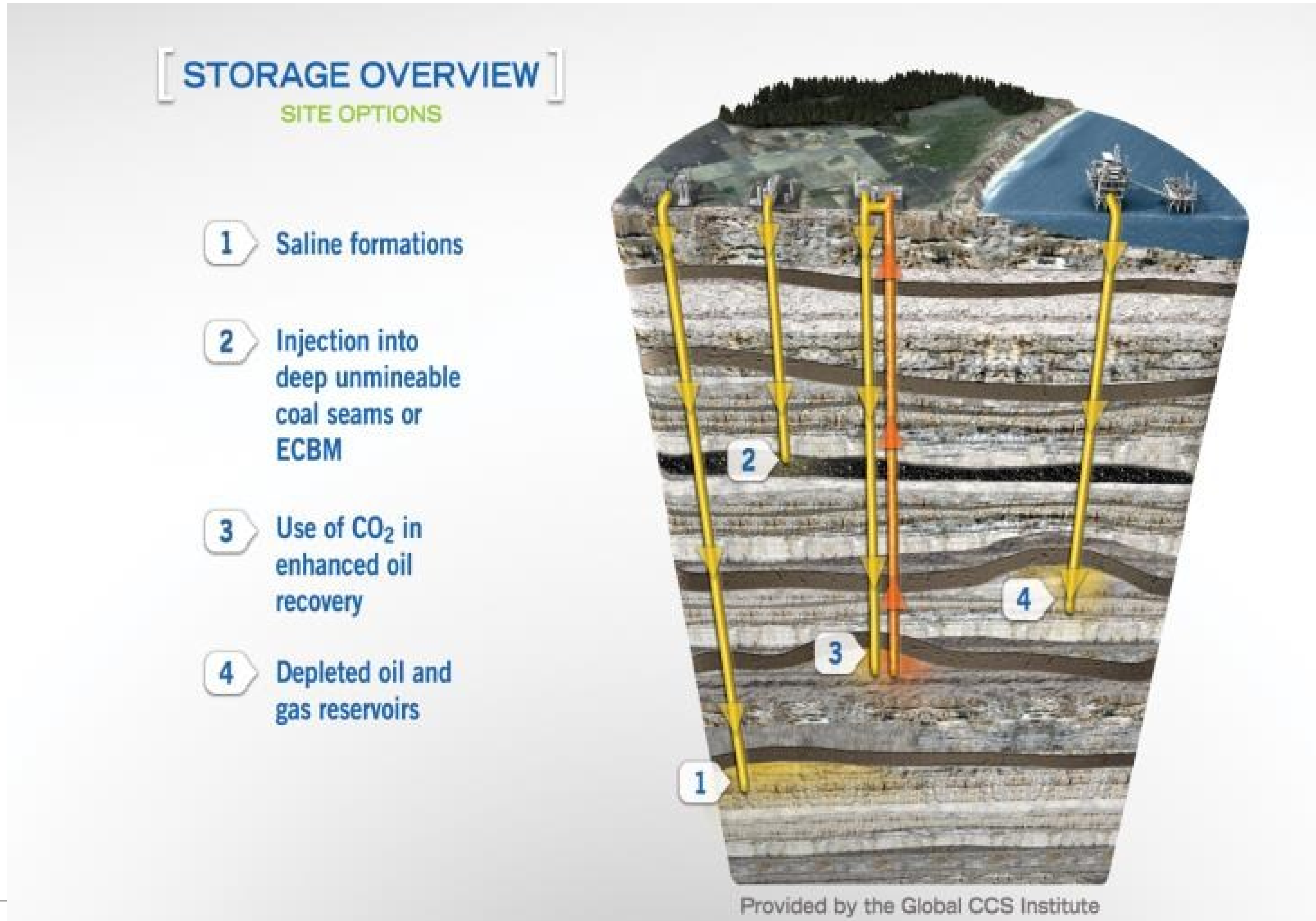
European CCS directive [EU, 2009]

Main types of geological formations suitable for geological storage of CO_2 (see sketch diagram in the next slide):

- Currently used options:
  - deep saline aquifers – more than 800 m below surface, rock pores contain brine (salt water) that is pushed back by injected CO_2
  - depleted hydrocarbon (oil and gas) fields – CO_2 can fill the pore space made „empty“ by oil and gas production
- Emerging options:
  - unmineable coal layers (seams)
  - basalt formations

[IPCC,2005; ZEP,2017]

CO_2 storage options



CO_2 utilisation

CO_2 capture and utilisation (CCU), sometimes also called CO_2 capture and use or re-use, handles CO_2 not as a waste but as a commercial product. If combined with permanent storage (incl. geological), it is abbreviated as CCUS.

CO_2 utilisation routes are shown in the next slide. Two main options are available:

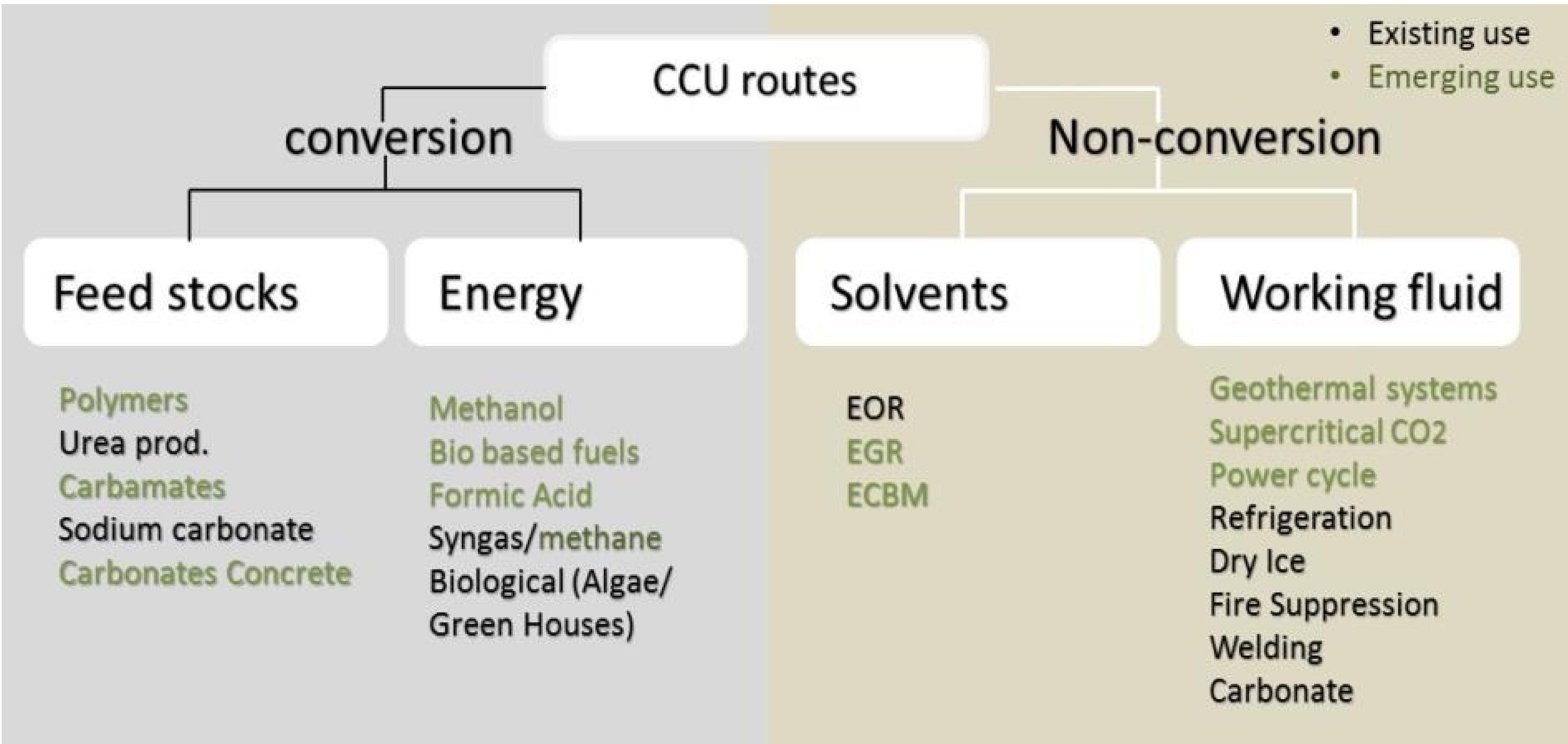
- conversion – uses CO_2 as a source of carbon for various feed stocks or energy products, energy input is required for conversion; in many cases CCU can displace the use of fossil fuels
- non-conversion – CO_2 acts as a solvent, or working fluid

This option includes various modifications of Enhanced Hydrocarbon Recovery where CO_2 is used to stimulate production of hydrocarbons from oil & gas fields and coal seams:

- EOR = Enhanced Oil Recovery
- EGR = Enhanced Gas Recovery
- ECBM = Enhanced Coal-Bed Methane Recovery

[ZEP, 2015]

CO_2 utilisation routes



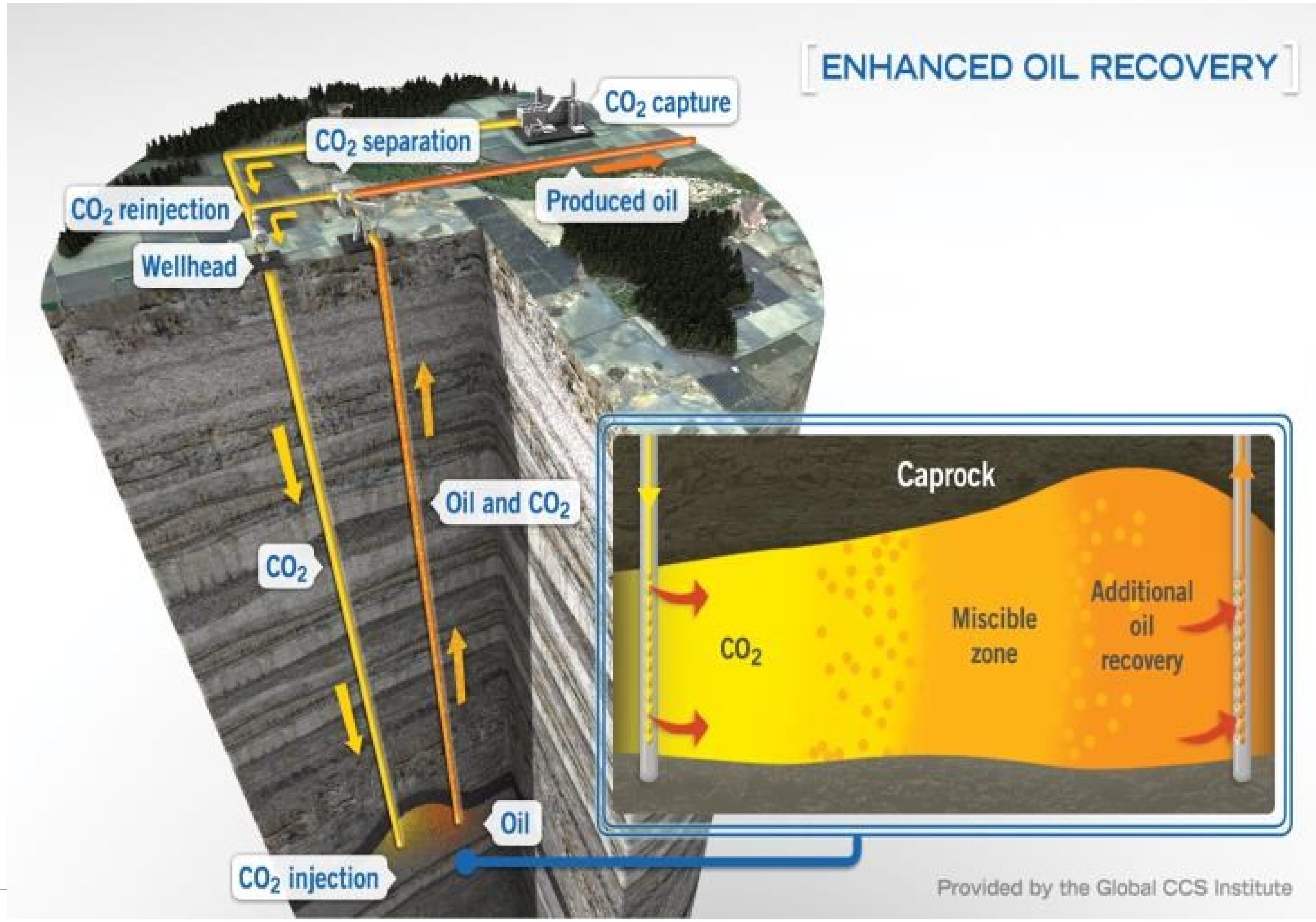
Source: ZEP, 2015

Enhanced Oil Recovery (EOR)

CO_2-driven Enhanced Oil Recovery (CO_2-EOR) is a well-established CCUS industrial activity practiced from 1970s in the USA and Hungary.

- CO_2 acts as agent enabling to gain more oil from the field (see next slide) after primary production and (possibly) water-flooding effects are exhausted → economic revenue
- large part of the injected CO_2 stays in the reservoir; the rest is produced together with oil, separated and recycled
- originally the intention was to just produce more oil; nowadays the CO_2 storage element attracts more attention (so called „EOR+" concept – injection scenarios are optimised to increase the volume of stored CO_2 + after production stops the wells are plugged and the field is turned to CO_2 storage)
- largely developed in the USA (> 120 projects, > 60 mil. tons of CO_2 used /~25% from anthropogenic sources/, > 280,000 barrels of oil produced per day, lack of CO_2 on the market), further projects in Canada, Brazil, Hungary, Turkey, Croatia

principle of CO_2-EOR



limitations of CCU

- Some CCU technologies involve permanent storage of CO_2 (CCUS) but some do not – the storage is just temporary, or new products are delivered. It is always important to assess if the technology contributes to climate change mitigation = reduction of CO_2 emissions to the atmosphere. Carbon footprint and Lifecycle analyses are necessary for this assessment.
- The amount of CO_2 that various CCU(S) technologies can handle varies in the extent of several orders of magnitude. Some technologies can utilise only small amounts of CO_2, without a real potential to increase → their mitigation potential is small.
- Some CCU products compete on the market with commercially well-established ones produced by „classical“ technologies. If the CCU products are more expensive, their market potential is limited. This can be only changed by:
  - incentives and subsidies to support CCU
  - regulation, e.g. ban of carbon-intensive products, carbon tax, etc.

[ZEP, 2015]

costs of CCS

The implementation of CCS technology raises the investment and operational costs for power and industrial projects. New power plants and industrial facilities can be designed to incorporate CCS from their inception, or the technology can be retrofitted to existing sources of CO_2 emissions. Overall, the cost of each project can vary considerably, depending especially on:

- the type of process generating CO_2 – e.g. power generation, cement, steel, hydrogen, ammonia production, etc.
- CO_2 content in the waste gas stream and its composition – generally higher CO_2 content and simpler gas composition mean lower capture costs
- the size of the project – big projects have normally lower per-unit cost due to economy of scale
- CO_2 capture technology used and its maturity – first-of-a-kind projects are generally very expensive, the following ones can benefit from their experience → „learning curve"
- distance to storage site

[GCCSI, 2015; ZEP, 2011]

costs of CCS (cont.)

- type of transport – pipelines are cost-effective for large volumes of CO_2 transported; ship transport can be beneficial for long distances and/or smaller volumes
- location of storage site – offshore storage is more expensive than onshore
- type of storage reservoir – depleted oil & gas fields are cheaper to develop than saline aquifers because of higher level of knowledge (abundant data are usually available from exploration and production of the field)

Other important observations:

- CO_2 capture usually represents the majority of CCS costs – most often reported as 75% or higher.
- CCS projects normally have high investment costs – the technology is not easily scalable, contrary to e.g. some renewable energy sources (wind, solar).
- CCS networks with transport and storage hubs can significantly decrease unit transport and storage costs.

costs of CCS in power generation

CCS is a cost-competitive low-carbon power generation technology – its costs are comparable with other options (renewables, nuclear).

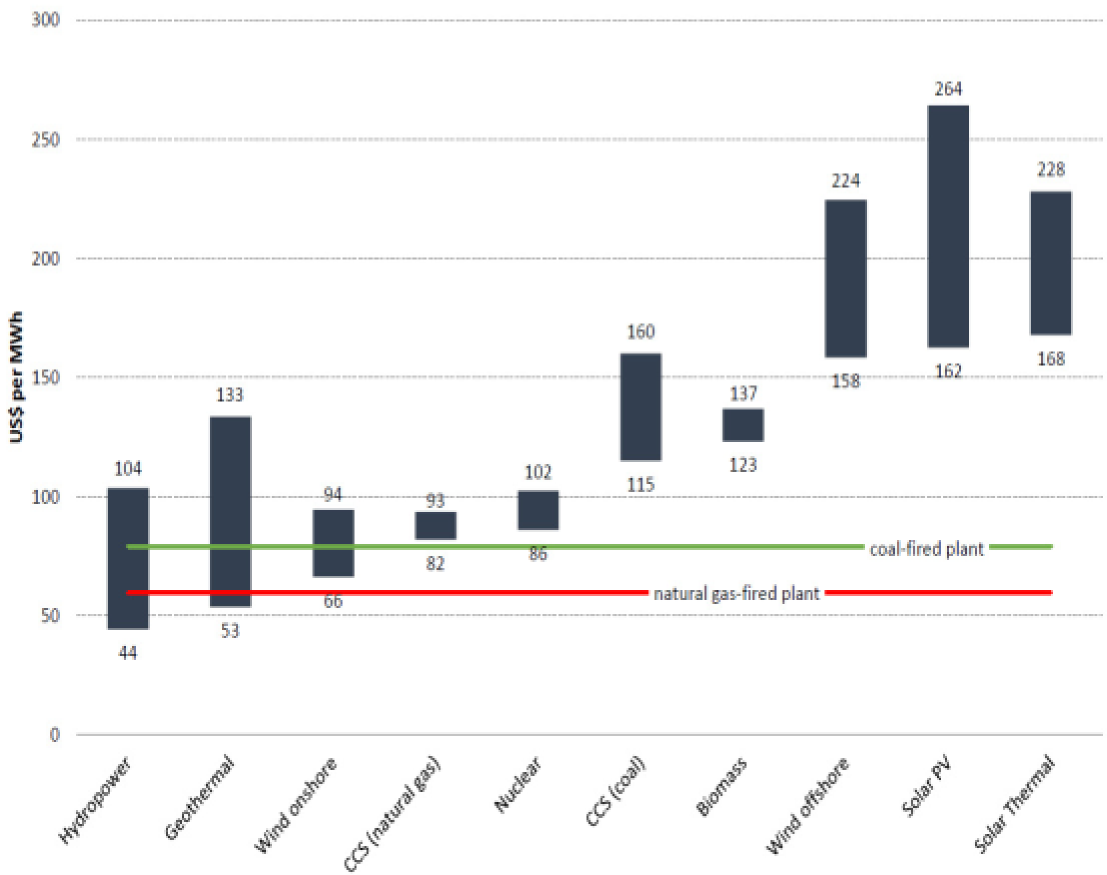
Exact cost comparison is difficult because various factors need to be taken into account, like e.g.:

- load factor (number of operation hours of the power plant per year)
- regime (baseload = continuous delivery of power vs. peak load = delivery on demand, when power supply is lacking)
- intermittency (continuous delivery of power vs. intermittent delivery depending on weather /wind energy/ or daytime /solar energy/)

Levelised cost of electricity (LCOE) is a frequently used measure to compare the costs (see next slide). It represents costs per unit of electricity generated over the life of a particular plant.

[GCCSI,2015; ZEP,2011]

levelised cost of electricity for low-carbon power generation technologies



Source: GCCSI, 2015

ENOS

summary

- CO_2 capture, transport and storage are the three main parts of the CCS technological chain
- CO_2 capture can be applied at big point sources of CO_2 emissions - power plants combusting fossil fuels and/or biomass, oil and gas processing facilities, industrial plants (cement, iron and steel, pulp and paper production), refineries and petrochemical plants, etc.
- currently available CO_2 capture technologies are based on chemical or physical absorption and adsorption
- main CO_2 transport options include pipelines, ships and trucks
- favourable CO_2 storage structures are depleted hydrocarbon fields and deep saline formations (aquifers)
- CCU handles CO_2 not as a waste but as a commercial product that can be further utilised as feed stock, energy source, solvent or working fluid
- implementation of CCS technology raises the investment and operational costs for power and industrial projects

Budeme v ČR potřebovat CCS?

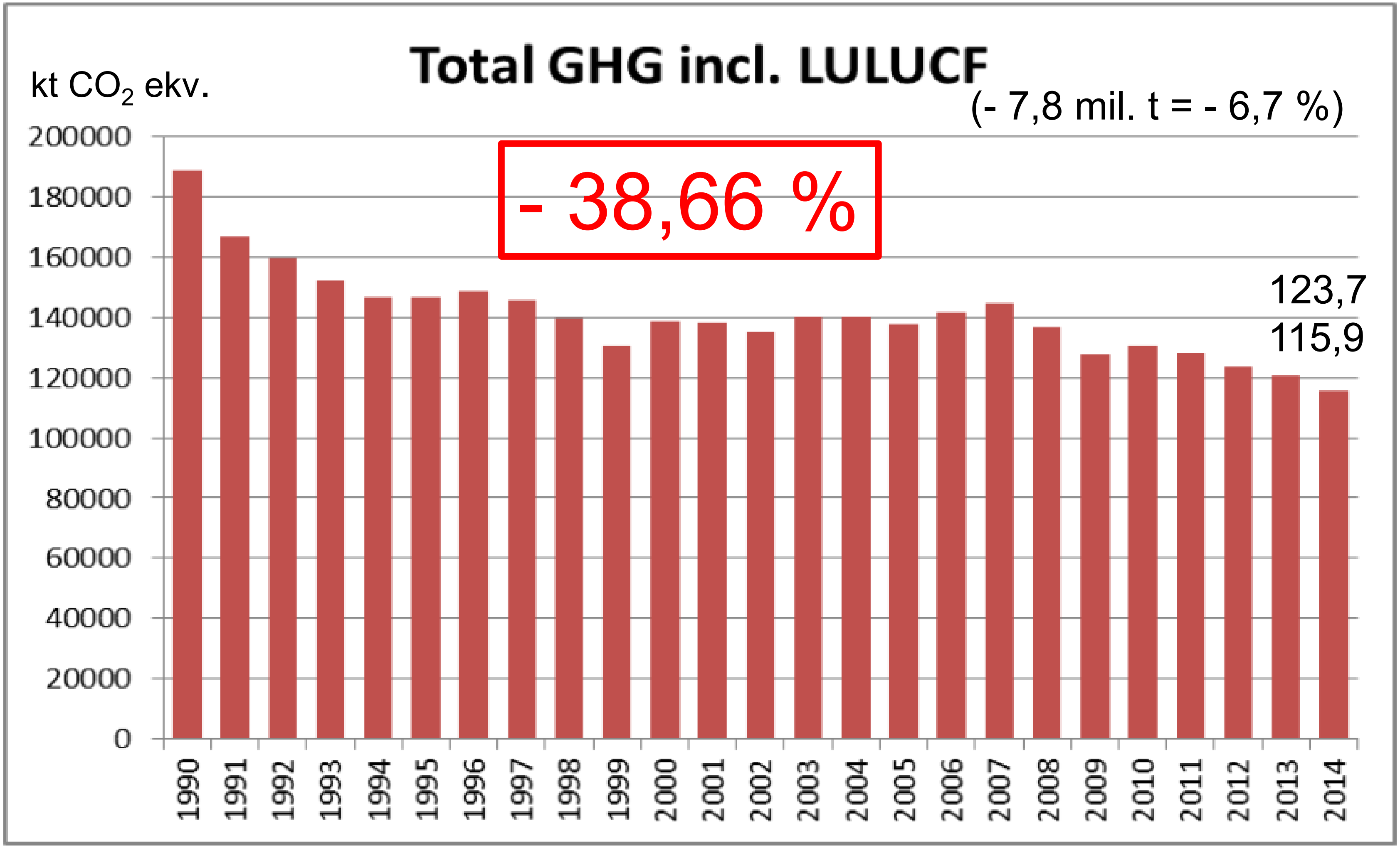
BUDEME!

- Potřebujeme všechny nízkouhlíkové technologie
- S CCS to bude levnější než bez CCS
- CCS umožní spalovat fosilní paliva s nízkými emisemi CO2
- Je to jediná možnost dekarbonizace pro některé technologie
- Umožní negativní emise (bio-CCS)

NEBUDEME!

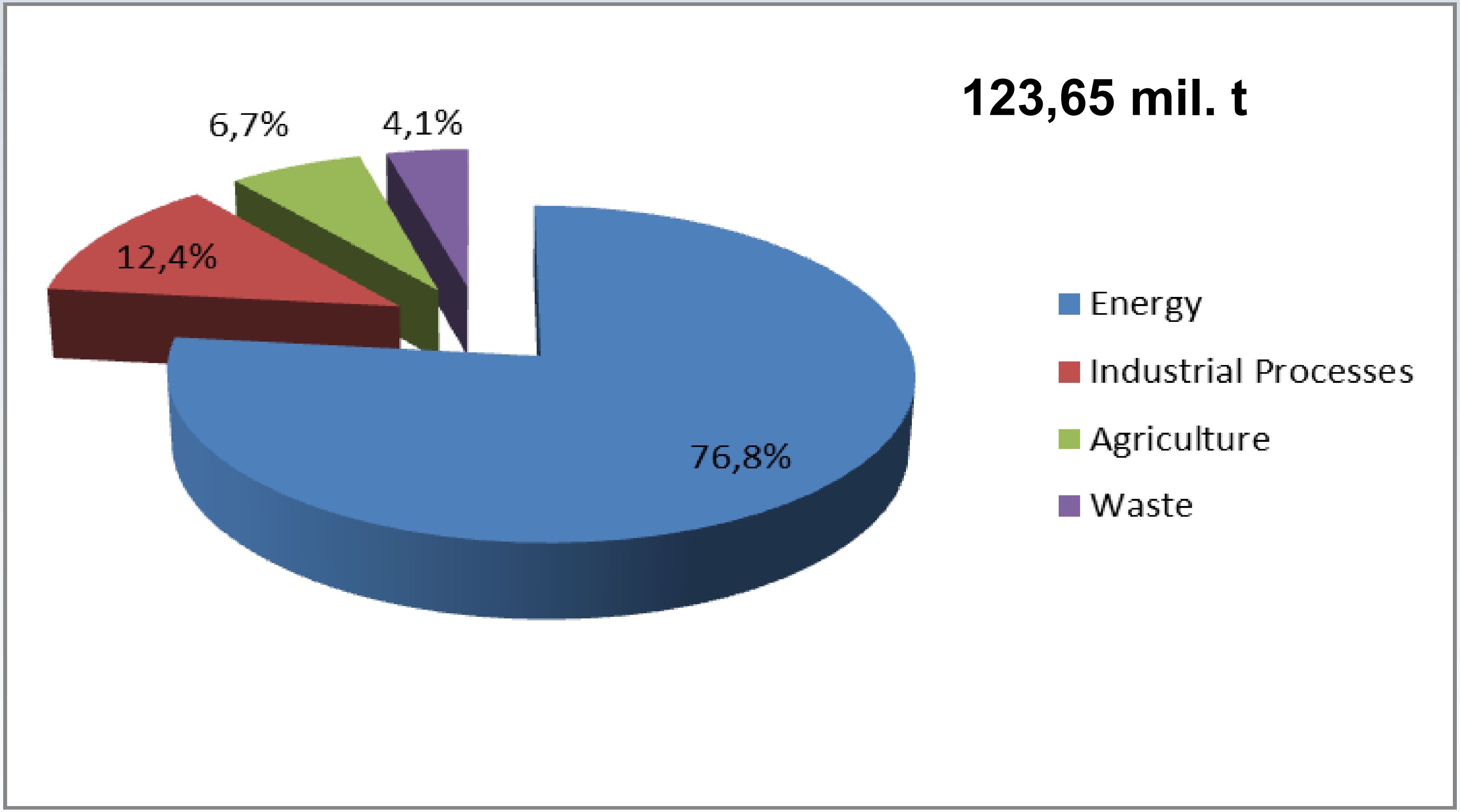
- Je to příliš drahé
- Máme jiné, lepší technologie
- Je to nebezpečné
- Je to nevyzkoušené
- Obyvatelstvo to nedovolí
- Bude to zakázáno

Vývoj emisí skleníkových plynů v ČR 1990-2014



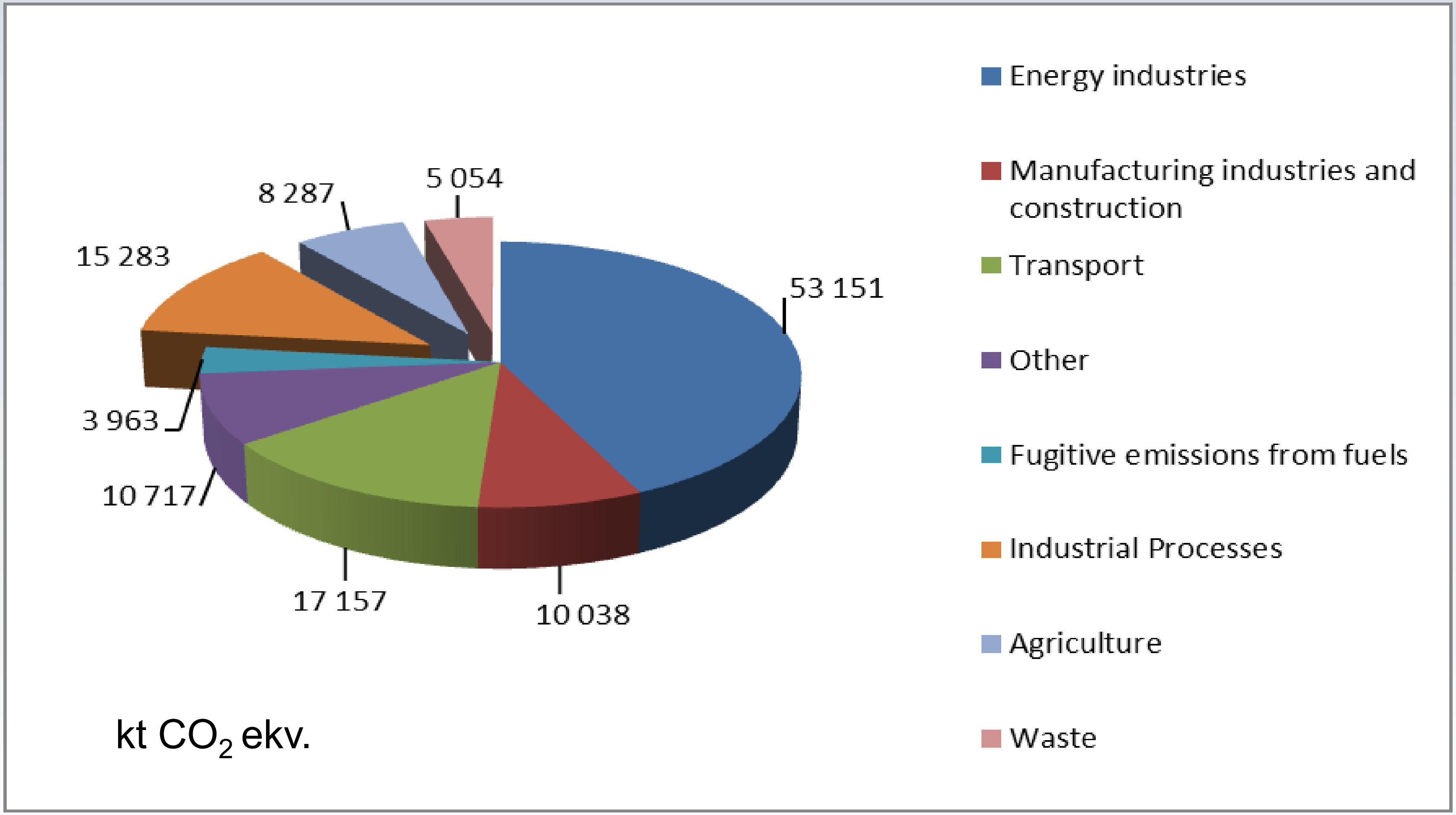
NATIONAL GHG INVENTORY REPORT OF THE CZECH REPUBLIC 1990-2014

Emise skleníkových plynů v ČR 2014 podle sektorů



NATIONAL GHG INVENTORY REPORT OF THE CZECH REPUBLIC 1990-2014

Emise skleníkových plynů v ČR 2014 podle sektorů



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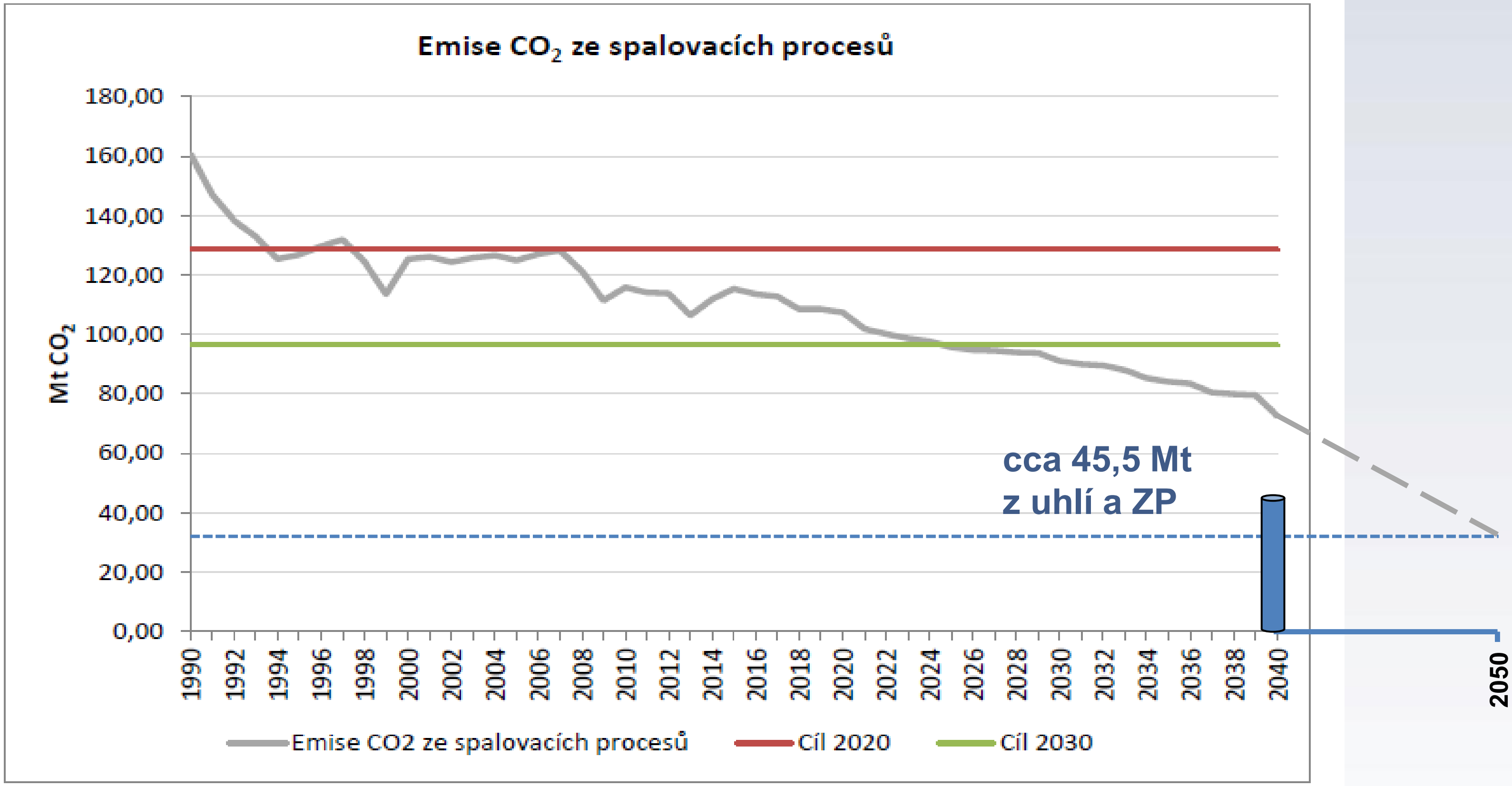
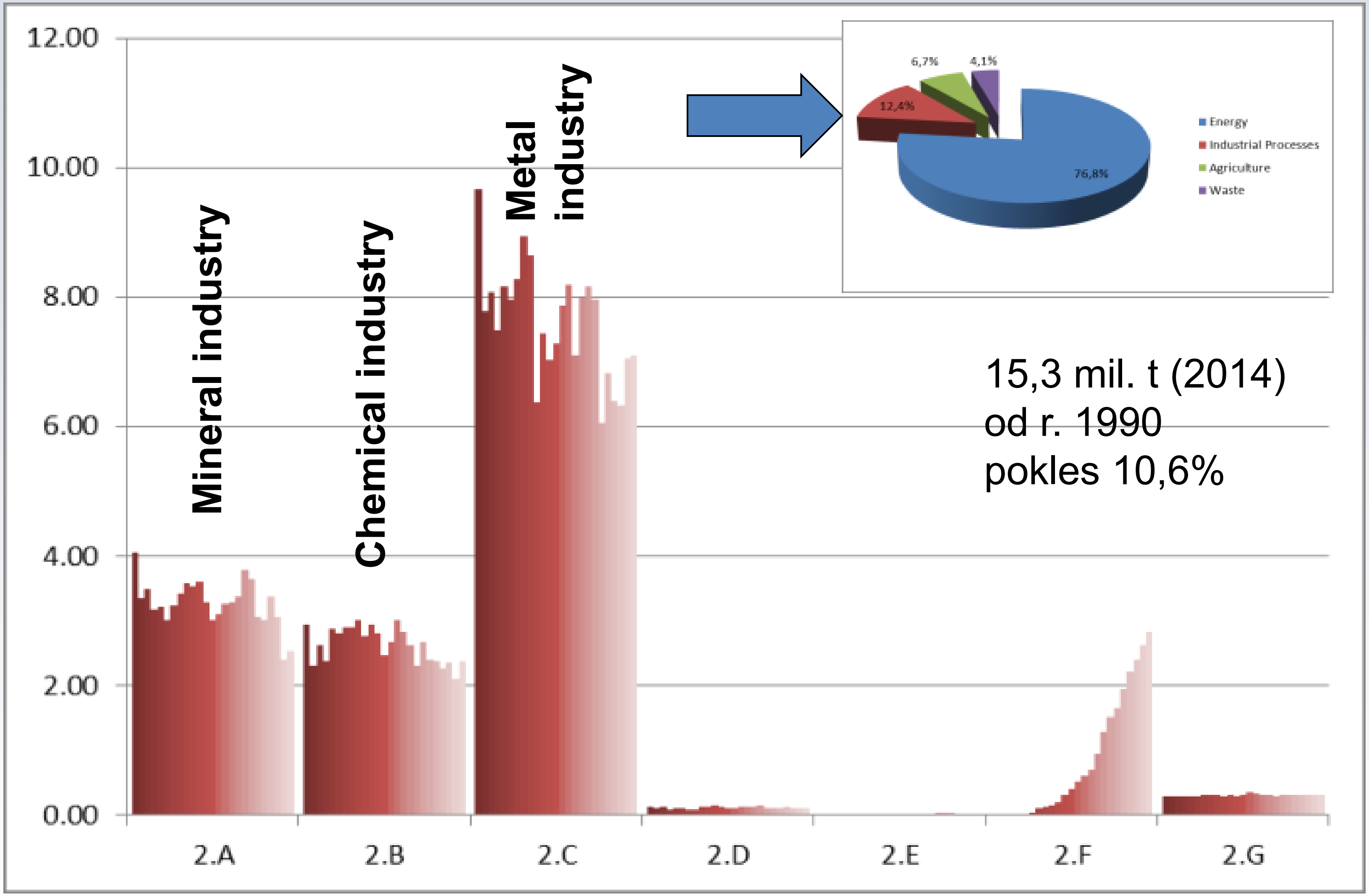
Predikce vývoje emisí CO_2 v ČR - ASEK

Graf č. 33: Emise CO_2 ze spalovacích procesů



Pozn.: Pro emise CO_2 nejsou stanoveny cíle pro jednotlivé země EU, ale pouze cíl pro EU jako celek. Uvedené linie jsou tedy vypočteny z hodnot cíle EU snížení emisí do roku 2020 o 20 % oproti roku 1990 a cíle EU snížení emisí do roku 2030 o 40 % oproti roku 1990 vztažených k hodnotě emisí ze spalovacích procesů na území České republiky.

Emise skleníkových plynů v ČR 1990-2014 – průmyslové procesy



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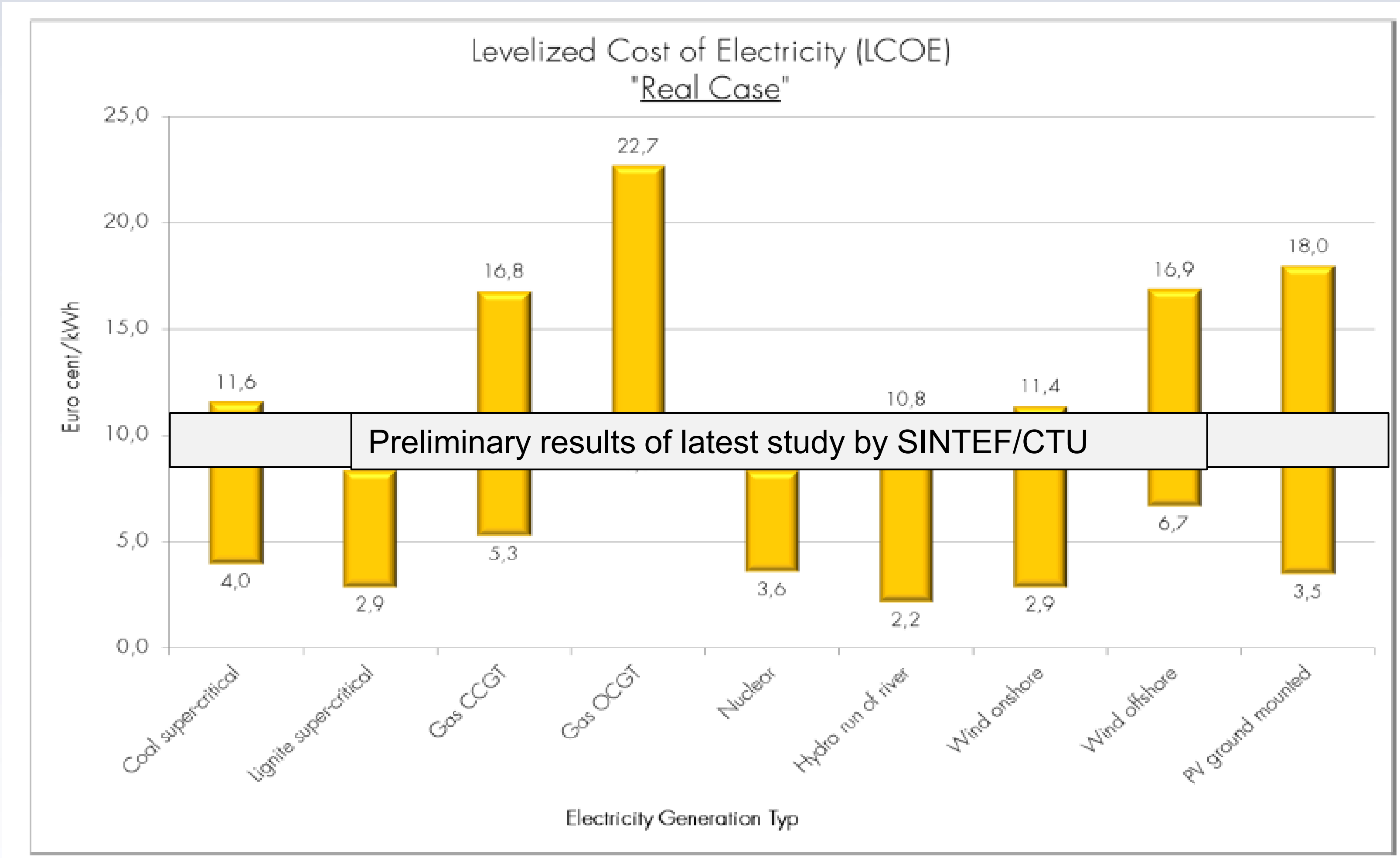
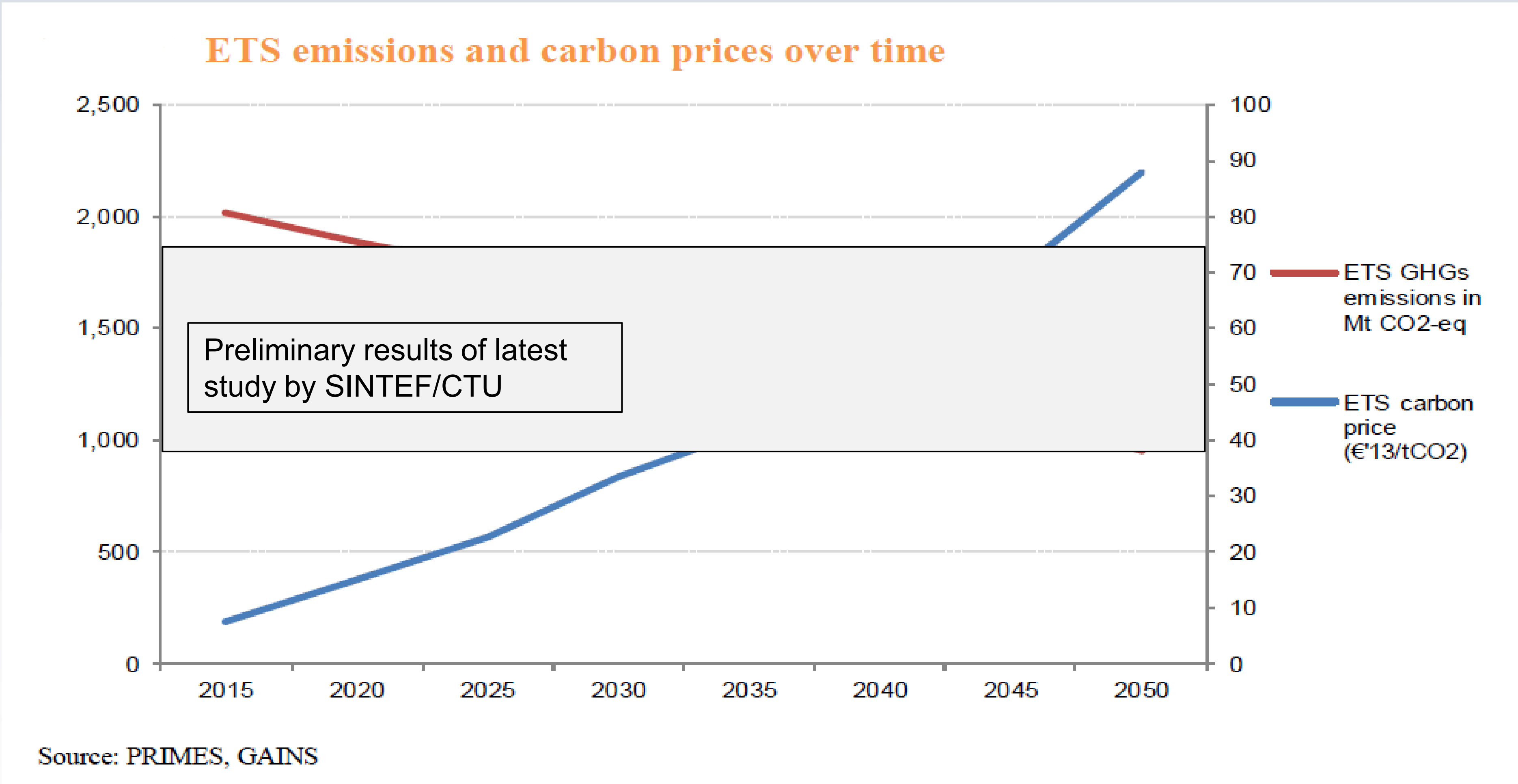
Je CCS drahé?



LCOE 2015 by VGB PowerTech

Je CCS drahé?



EU Reference Scenario 2016

Je CCS nevyzkoušená technologie?

- Od 20. let 20. století se separuje CO2 ze zemního plynu
- 1972 první projekt využití separovaného CO2 k intenzifikaci těžby ropy v Texasu (spolu s využitím přírodního CO2 v USA a v Maďarsku)
- 1977 poprvé navrženo využití CCS jako metody pro snížení emisí skleníkových plynů

Těžba ropy pomocí CO2-EOR v USA