Overview on

CO_2 Geological Sequestration

M. Lemos de Sousa, C.F. Rodrigues,

M.A. Dinis and G.M. Oliveira

Porto 2009

CO_2 Geological Sequestration

A permanent home to CO_2
i.e. a location in which CO_2 could really stay securely trapped

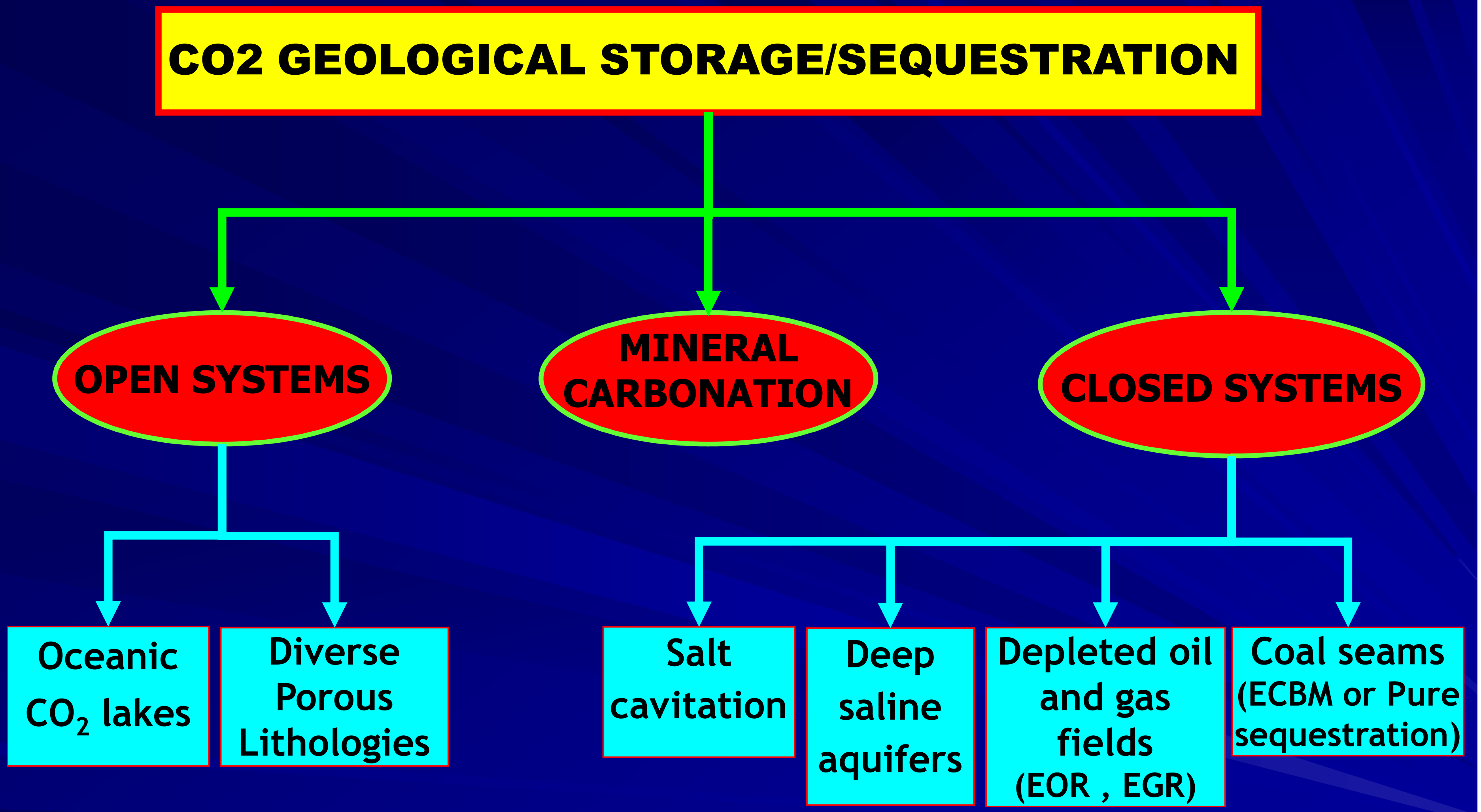
"Is carbon sequestration a dangerous and desperate effort to cling to an energy technology we are now better off abandoning, or is it a reasonable way to make palatable a still critical source of energy?

The answer depends mainly on what other sources of energy we can feasibly turn on"

Barbara Freese 2005 – Coal, a human history

WHAT IS

CO_2 Geological Sequestration ?



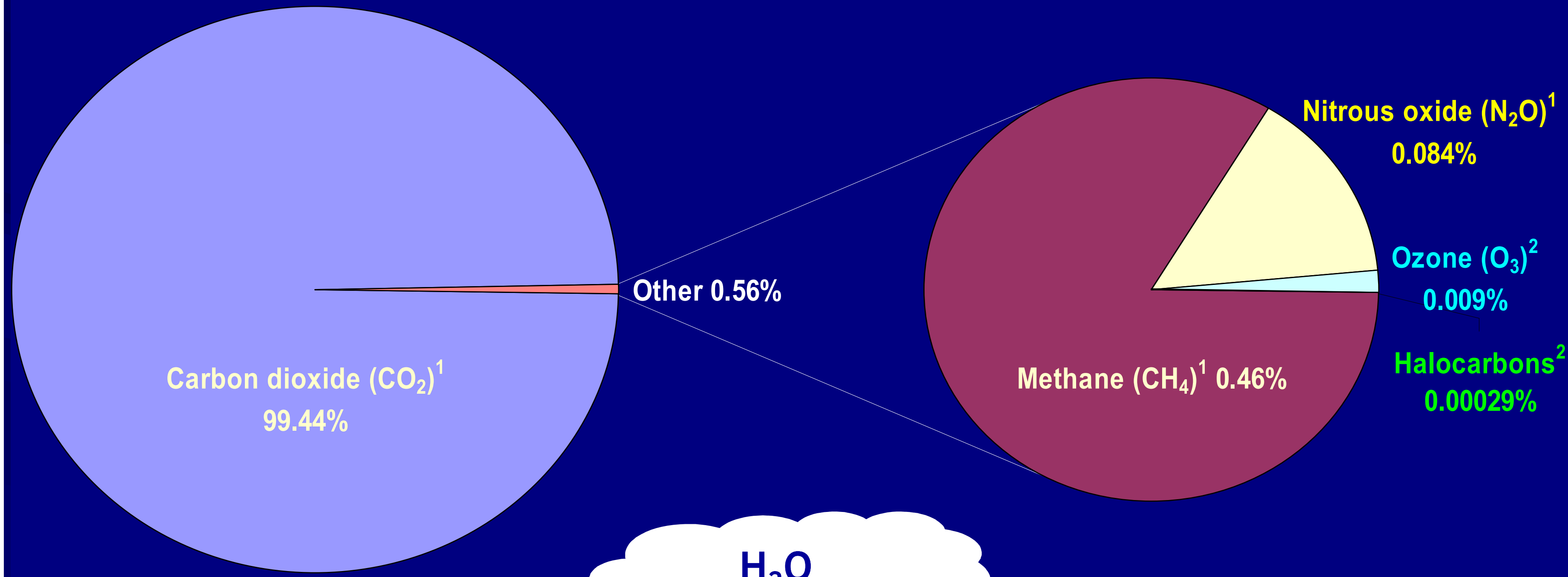
M. Lemos de Sousa and C.F. Rodrigues, UFP – CIAGEB, 2008

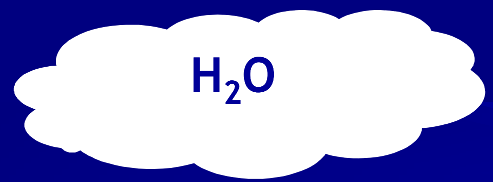
WHY

CO_2 Geological Sequestration

?

Atmospheric GHG concentrations
(expressed as % of dry air)





Water Vapour is the most abundant GHG, but its concentration in atmosphere is very variable and dependent

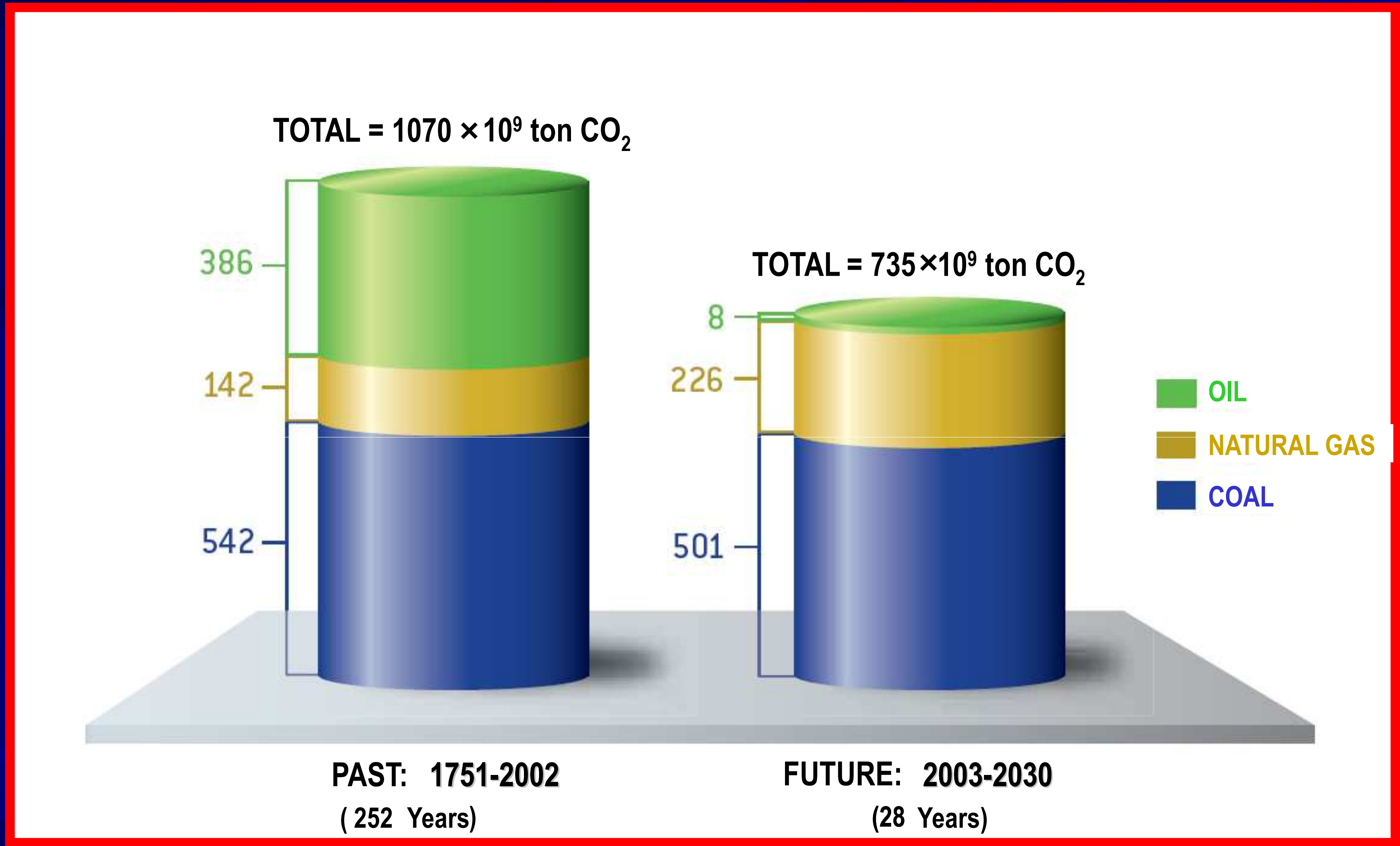
Information sources:

[1] World Meteorological Organization: WMO Greenhouse Gas Bulletin, No.3, 2007

[2] Blasing, CDIAC – Carbon Dioxide Information Analysis Centre (December 2008)

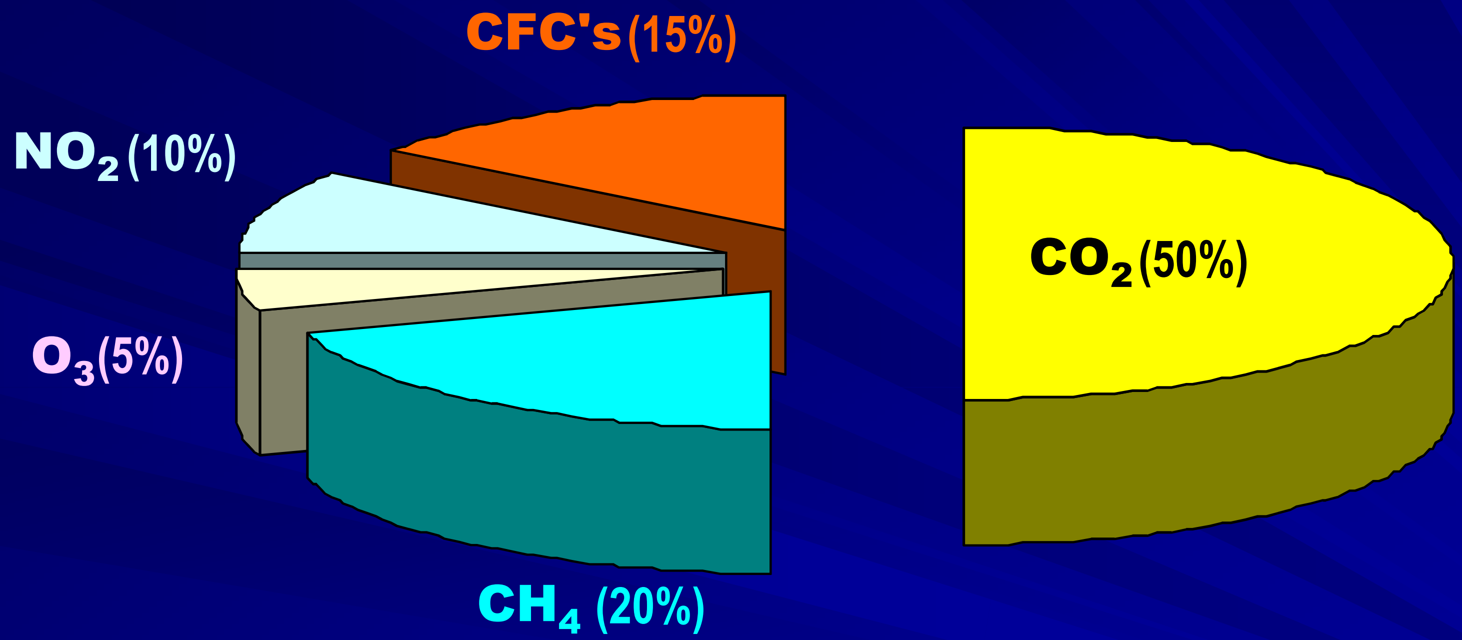
Global average radiative forcing (RF) estimates and ranges in 2005 for anthropogenic carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other important agents and mechanisms, together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding.

CO_2 Emissions by Fossil Fuel Combustion



Socolow 2005

Origin of Greenhouse Effect Gases



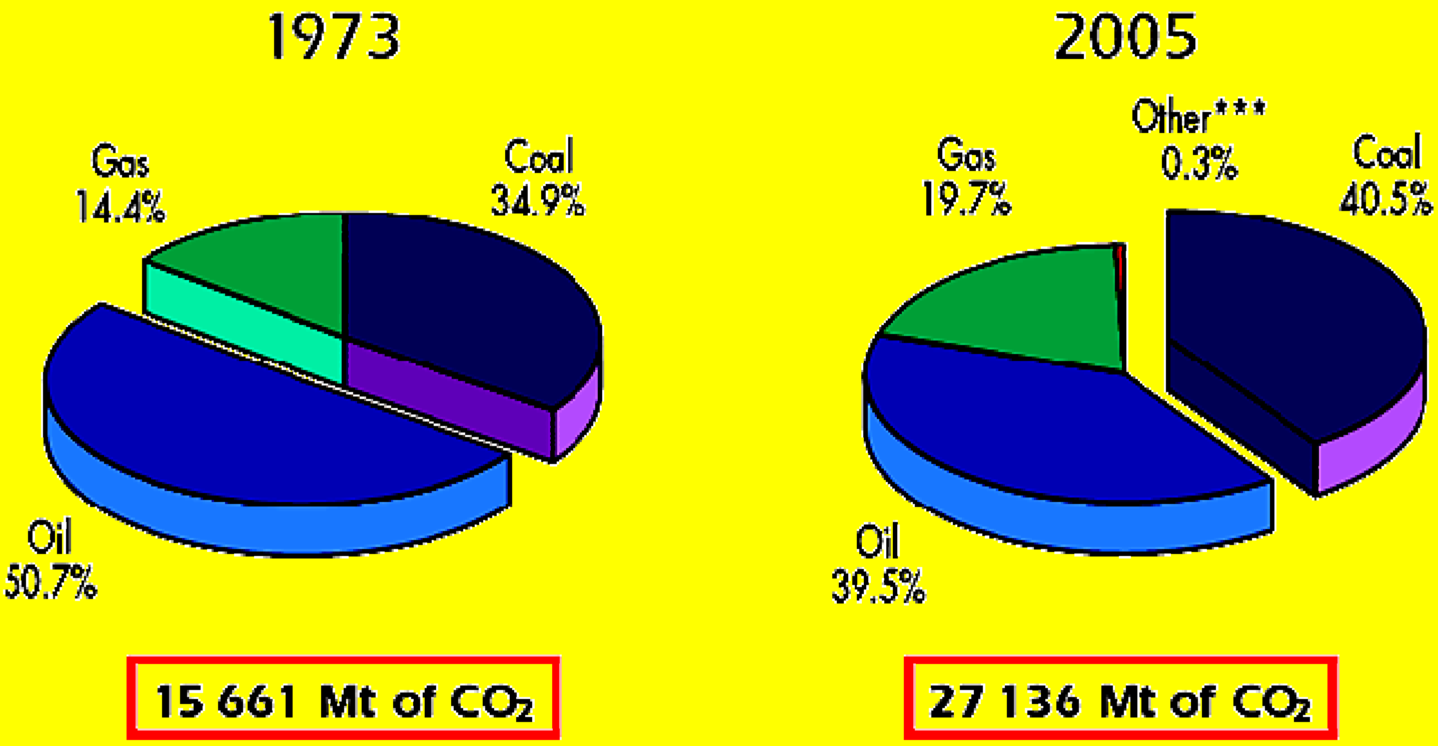
Methane (20%)
16% Biomass combustion
14% Fossil fuel combustion
26% Rice cultivation
22% Swamps
22% Other

Carbon dioxide (50%)
2% Cement industry
25% Deforestation
73% Fossil fuel combustion

IEA 2007

CO_2 Emissions by Fuel

1973 and 2005 Fuel Shares of CO_2 Emissions**



* World includes international aviation and international marine bunkers.
** Calculated using IEA's Energy Balance Tables and the Revised 1996 IPCC Guidelines. CO_2 emissions are from fuel combustion only. *** Other includes industrial waste and non-renewable municipal waste.

IEA 2007

ENVIRONMENTAL

POLITICS

CO_2 ABATEMENT

SOCIAL

ECONOMICS

"Quand on sait tout on ne prévoit rien

… et quand on ne sait rien on prévoit tout"

Claude Allègre 2004

When everything is known, one foresees nothing,

… and when nothing is known, one foresees everything

Quando se sabe tudo não se prevê nada

… e quando não se sabe nada prevê-se tudo

Main reasons /incentives are:

1- CARBON Dioxide (and other GHG) TRADING SYSTEM

CARBON (Climate) EXCHANGE MARKETS

2- ENHANCED HYDROCARBON (Oil & Gas, including CBM) PRODUCTION, i.e. the current most promising way to increase hydrocarbon recovery

CCS TECHNOLOGIES

Capture

Transport

Sequestration/Storage

Public Perception

1-CARBON Dioxide (and other GHG) TRADING SYSTEM

CARBON (Climate) EXCHANGE MARKETS

UN Framework Convention on Climate Change

Kyoto Protocol

- GHG Allocation Plans
- Monitoring GHG Emissions
- Standardised and Secure System of GHG Emissions Registries

- ED 2003/87/EC, October 13
- ED 2004/101/EC, October 27 (“Linking Directive”)
- ED 2009/29/EC, April 23

Implementation through Decisions, Regulations, etc

“European GHG Emissions Allowances Trading Scheme”

Additionally, in EUROPE

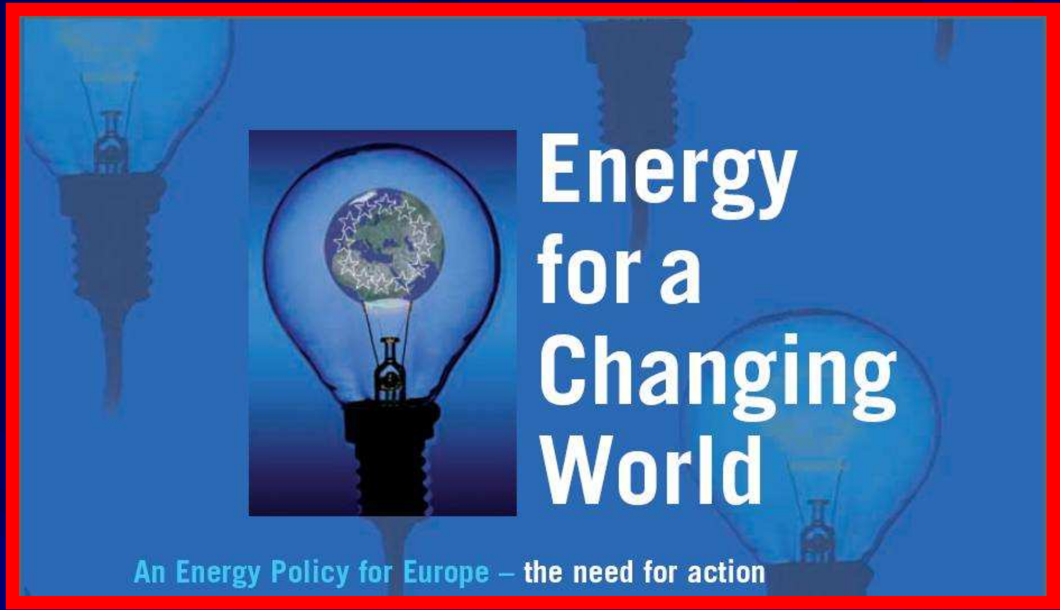
- The 2020 EU Energy Policy Target and Objectives – The need for action
- Europe's Climate Change Opportunity
- Energy for a Changing World

20(30) 20 20 → 2020

European Directive 2009/31/EC (23 April) on
Geological Storage of Carbon Dioxide

P. Russ, T. Wiesenthal, D. van Regemorter and J.C. Ciscar
"Global Climate Policy Scenarios for 2030 and beyond; Analysis of Greenhouse Gas Emission Reduction Pathway Scenarios with the POLES and GEM-E3 models"
European Commission 2007

Limiting Global Climate Change to 2 degrees Celsius – The way ahead for 2020 and beyond"
January 10, 2007



EU 2007

Targets for 2020

Proposed EU Energy Policy
Targets and Objectives

- Reducing **greenhouse gas emissions** from developed countries by 30% by 2020; the EU has already committed to cutting its own emissions by at least 20% and would increase this reduction under a satisfactory global agreement
- Improving **energy efficiency** by 20% by 2020
- Raising the share of **renewable energy** to 20% by 2020
- Increasing the level of **biofuels** in transport fuel to 10% by 2020

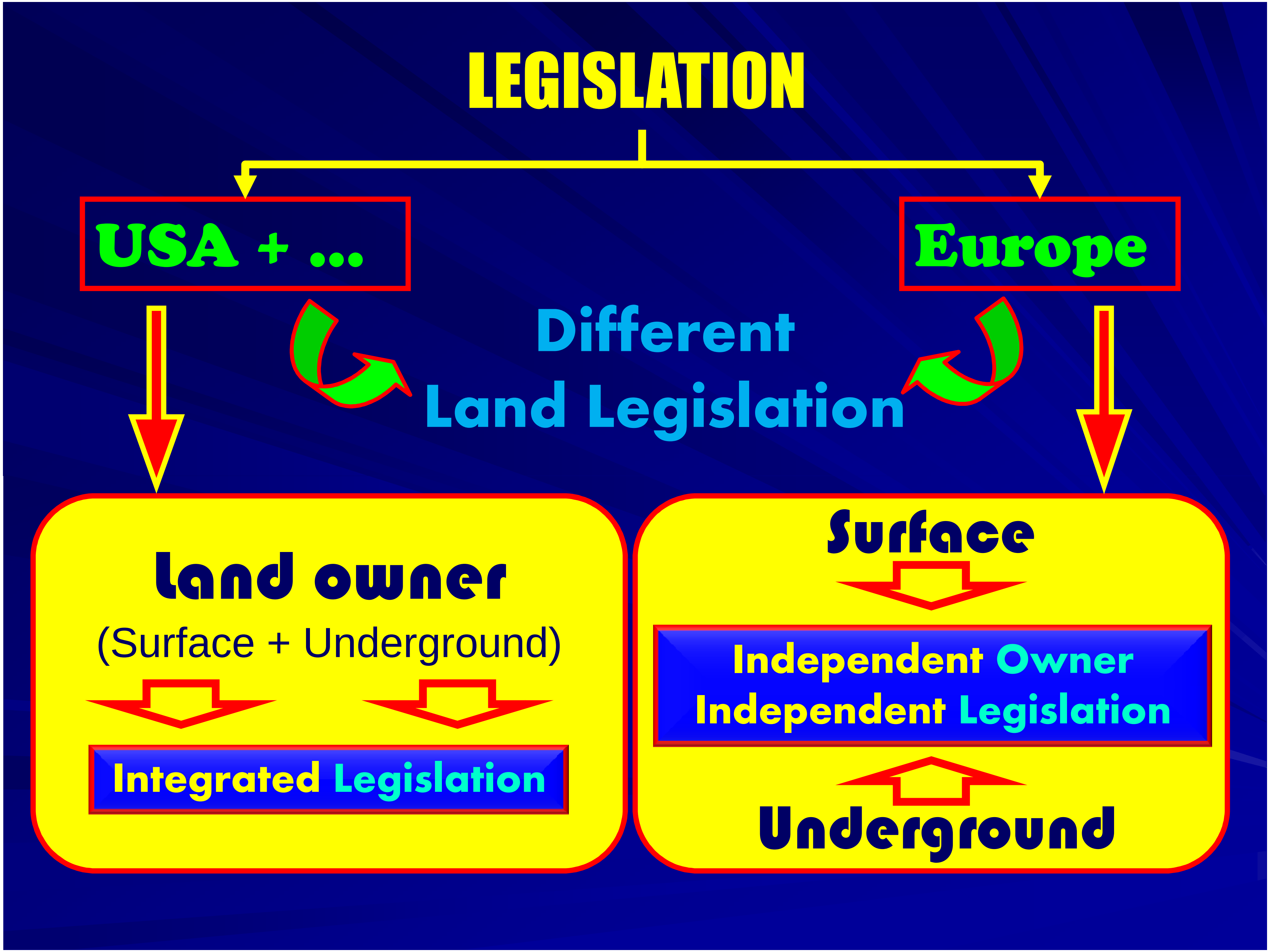
European Council Climate – Energy Legislative Package

April 6, 2009

Directive 2009/31/EC

of the European Paliament and of the Council of 23 April 2009
on Geological Storage of Carbon Dioxide

Official Journal 5. 6. 2009


LEGISLATION
USA + ...
Europe
Different
Land Legislation
Land owner
(Surface + Underground)
Integrated Legislation
Surface
Independent Owner
Independent Legislation
Underground

The Real Problem

Is the European Union able to:

- reduce fossil fuel industrial emissions by CO_2 capture + sequestration/storage, and

- implement CO_2 capture + storage technologies economically, i.e., in a competitive way with the emissions allowance trading system of the EU Directives 2003/87/EC and 2004/101/EC,

thereby permitting medium and long term sustainable competitiveness, both in energy production and industrial development ?

CO_2 European Allowance Allocation Plan

(in 10^6 ton)

Member State	1st period cap	2005 verified emissions	Proposed cap 2008-2012	Cap allowed 2008-2012 (in relation to proposed)	Additional emissions in 2008-2012[	JI/CDM limit 2008-2012 in %
Austria	33.0	33.4	32.8	30.7 (93.6%)	0.35	10
Belgium	62.1	55.58	63.3	58.5 (92.4%)	5.0	8.4
Bulgaria	42.3	40.6	67.6	42.3 (62.6%)	n.a	12.55
Cyprus	5.7	5.1	7.12	5.48 (77%)	n.a.	10
Czech Rep.	97.6	82.5	101.9	86.8 (85.2%)	n.a.	10
Denmark	33.5	26.5	24.5	24.5 (100%)	0	17.01
Estonia	19	12.62	24.38	12.72 (52.2%)	0.31	0
Finland	45.5	33.1	39.6	37.6 (94.8%)	0.4	10
France	156.5	131.3	132.8	132.8 (100%)	5.1	13.5
Germany	499	474	482	453.1 (94%)	11.0	20
Greece	74.4	71.3	75.5	69.1 (91.5%)	n.a.	9
Hungary	31.3	26.0	30.7	26.9 (87.6%)	1.43	10
Ireland	22.3	22.4	22.6	22.3 (98.6%)	n.a.	10
Italy	223.1	225.5	209	195.8 (93.7%)	n.k.	14.99

European Commission 2008

CO_2 European Allowance Allocation Plan

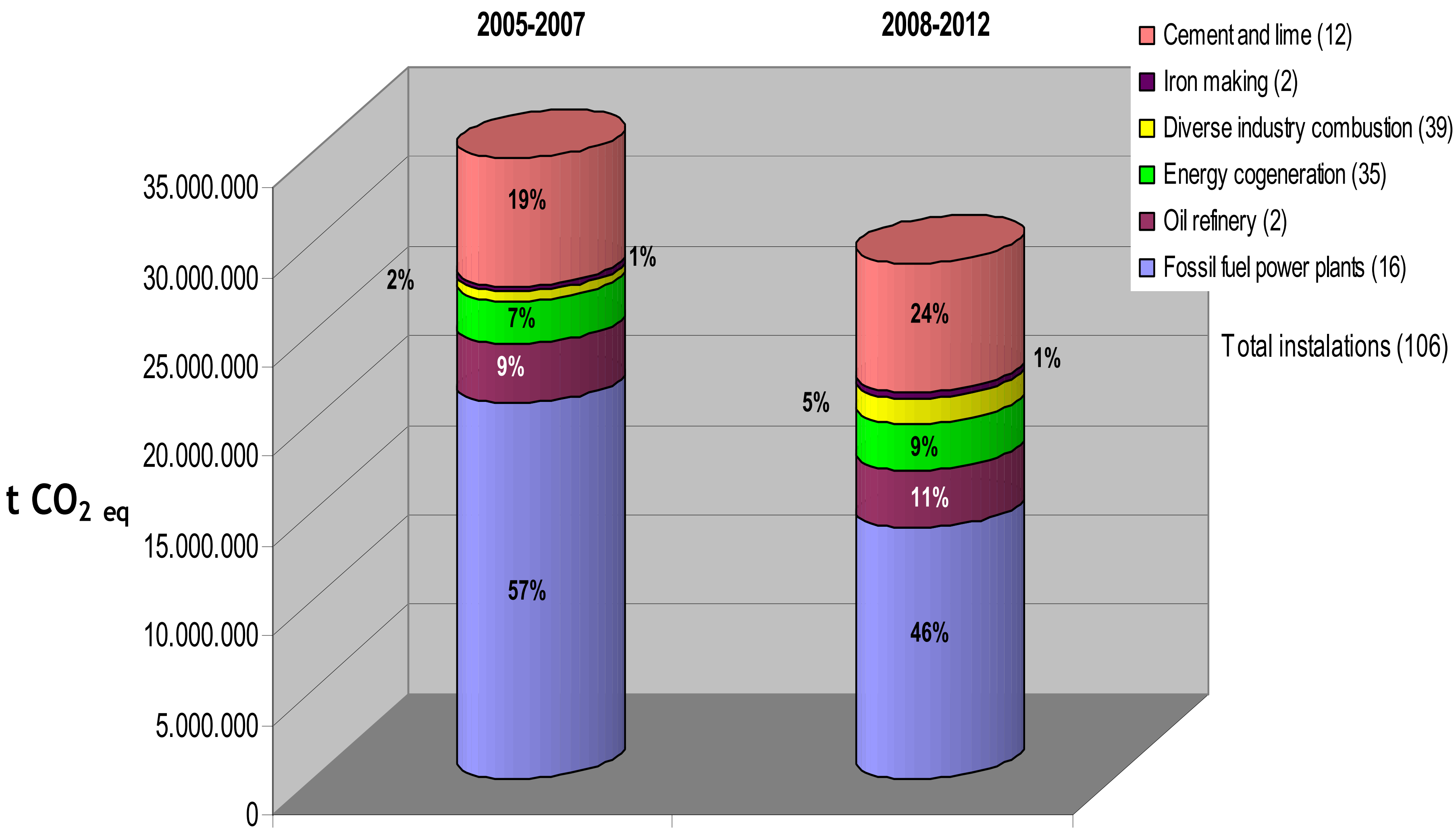
(continuation)

(in 10^6 ton)

Member State	1st period cap	2005 verified emissions	Proposed cap 2008-2012	Cap allowed 2008-2012 (in relation to proposed)	Additional emissions in 2008-2012[	JI/CDM limit 2008-2012 in %
Latvia	4.6	2.9	7.7	3.43 (44.5%)	n.a.	10
Lithuania	12.3	6.6	16.6	8.8 (53%)	0.05	20
Luxembourg	3.4	2.6	3.95	2.5 (63%)	n.a.	10
Malta	2.9	1.98	2.96	2.1 (71%)	n.a.	Tbd
Netherlands	95.3	80.35	90.4	85.8 (94.9%)	4.0	10
Poland	239.1	203.1	284.6	208.5 (73.3%)	6.3	10
Portugal	38.9	36.4	35.9	34.8 (96.9%)	0.77	10
Romania	74.8	70.8	95.7	75.9 (79.3%)	n.a	10
Slovakia	30.5	25.2	41.3	30.9 (74.8%)	1.7	7
Slovenia	8.8	8.7	8.3	8.3 (100%)	n.a.	15.76
Spain	174.4	182.9	152.7	152.3 (99.7%)	6.7	ca. 20
Sweden	22.9	19.3	25.2	22.8 (90.5%)	2.0	10
UK	245.3	242.4	246.2	246.2 (100%)	9.5	8
SUM	**2298.5**	**2122.16**	**2325.34**	**2080.93 (89.5%)**	**54.61**	**-**

European Commission 2008

Portugal - National CO_2 Emission Allowance Allocation Plan



Total allowance (100%) 36 886 068 tCO_2 eq

Total allowance (94%) 34 640 275 tCO_2 eq

Total allowance (100%) 30 500 000 tCO_2 eq

Total allowance (94%) 28 787 349 tCO_2 eq

Portugal – National Allowance Allocation Plan 2008 – 2012

Main Sectors and Installations (Allowances ≥400x10^3 tCO_2eq)

PNALE II/Despacho conjunto nº2836/2008, 8 Jan 2008 (DR 2s 25, 5 Fev 2008)

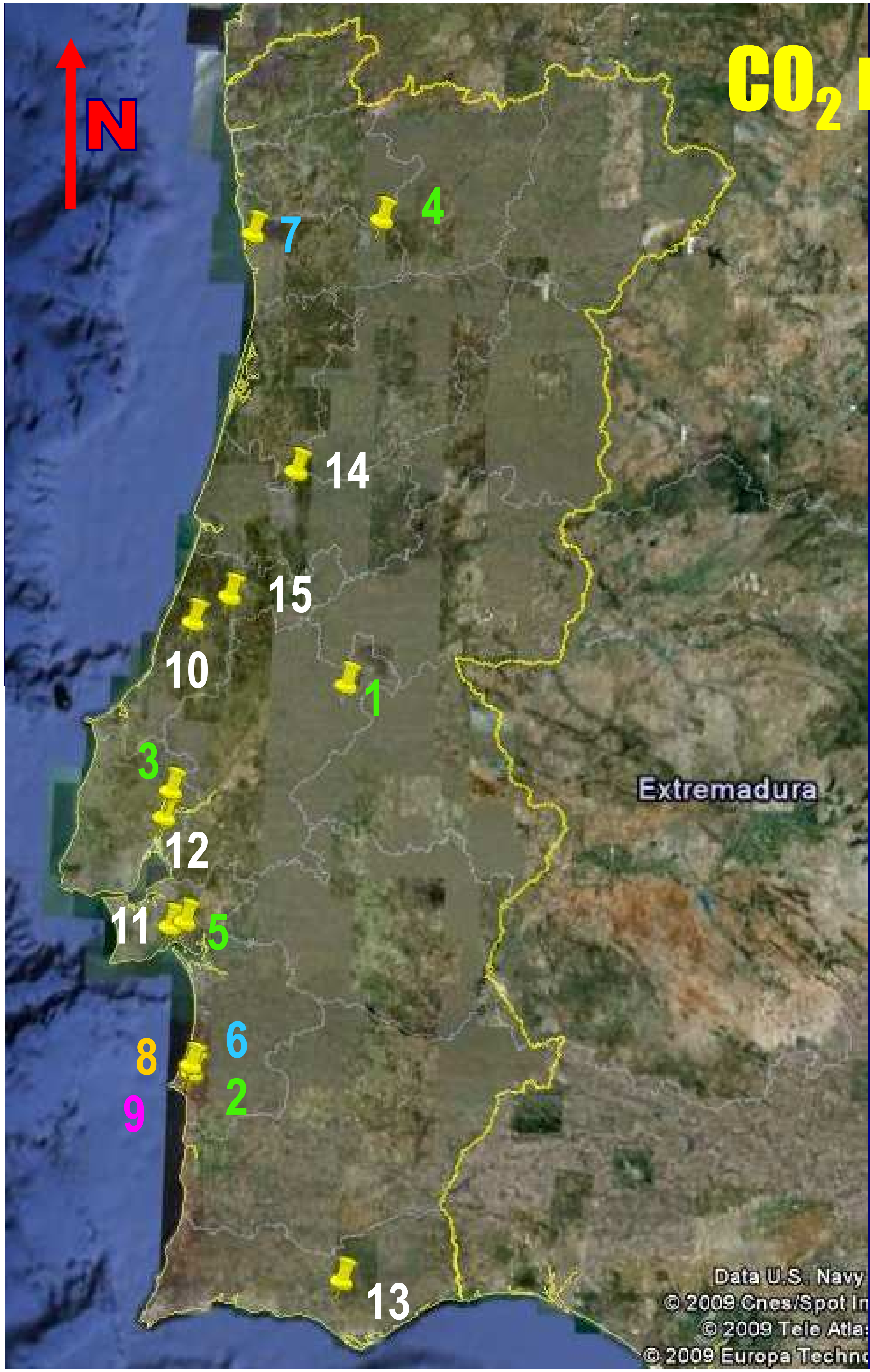
Nr	Sector	Sub-sector	Installations	Allowances/year ($t\ CO_2eq$)
1	Energy - Thermal Plants	Coal	Central Termoeléctrica do Pego (Tejo Energia)	2 723 011
2		Coal	Central Termoeléctrica de Sines (CPPE)	5 833 317
3		CCGT	Central Termoeléctrica do Ribatejo (CPPE)	1 423 103
4		CCGT	Central de Ciclo Combinado da Tapada do Outeiro (Turbogas)	1 198 020
5		Fuel	Central Termoeléctrica de Setúbal (CPPE)	1 118 999
6	Energy - Petroleum Refining	P. Refining	Refinaria de Sines (Petrogal)	2 137 550
7		P. Refining	Refinaria do Porto (Petrogal)	1 098 025
8	Energy - Cogeneration	Chemistry	Sines (Repsol)	411 058
9	Energy - Chemical Industry	Chemistry	Sines (Repsol Polímeros - Olefinas)	620 936
10	Cement & Lime	Cement	Maceira-Liz (CMP)	762 823
11		Cement	Secil - Outão (Secil)	1 489 648
12		Cement	Alhandra (Cimpor)	1 748 681
13		Cement	Loulé (Cimpor)	503 429
14		Cement	Souselas (Cimpor)	1 750 901
15		Cement	Cibra - Pataias (CMP)	421 805

Total 23 241 306 (72.2%)

Others 7 258 694 (23.8%)

Total Portuguese Allowances 30 500 000 (100%) ➡ **1.47% of total EU27 Allowances**

CO_2 main production sites



1 - Central Termoeléctrica do Pego (Tejo Energia)
2 - Central Termoeléctrica de Sines (CPPE)
3 - Central Termoeléctrica do Ribatejo (CPPE)
4 - Central de Ciclo Combinado da Tapada do Outeiro (Turbogás)
5 - Central Termoeléctrica de Setúbal (CPPE)

6 - Refinaria de Sines (Petrogal)
7 - Refinaria do Porto (Petrogal)

8 - Sines (Repsol)

9 - Sines (Repsol Polímeros - Olefinas)

10 - Macieira - Liz (CMP)
11 - Secil - Outão (Secil)
12 - Alhandra (Cimpor)
13 - Loulé (Cimpor)
14 - Souselas (Cimpor)
15 - Cibra (Pataias)

Total Allowances for the sites represented in the map: 23 241 306 (72.2%)

Total Portuguese Allowances: 30 500 000 (100%)

(Geographic basis: Google Earth)

The Portuguese Research Community in CCS:

- ► Capture (C)
  - ► Transport (T)
    - ► Geological Storage
      - ✓ Coal (SC)
      - ✓ Saline Aquifers (SA)
      - ✓ M. Carbonation (SM)
    - ► Public Perception (PP)

FCUL - Faculdade de Ciências, Universidade de Lisboa (S, SM)

FEUP - Faculdade de Engenharia, Universidade do Porto (C)

IST - Instituto Superior Técnico (C, SC, SA)

LNEG (INETI) - Laboratório Nacional de Energia e Geologia (C, T, SA, PP)

UE - Universidade de Évora (C, SA, PP)

UFP - Universidade Fernando Pessoa (C, SC, SA, PP)

WHY

CO_2 Geological Sequestration

?

2- ENHANCED HYDROCARBON (Oil & Gas, including CBM) PRODUCTION, i.e. the current most promising way to increase hydrocarbon recovery

PRIMARY ENERGY

FOSSIL FUELS (Non-Renewable)

Conventional Hydrocarbons
- Oil
- Natural Gas
- Coal

Non-conventional Hydrocarbons
- Natural gas
  - Tight lithologies gas
  - Gas shales
  - Gas hydrates
- Heavy oil
- Oil shale
- Tar sand

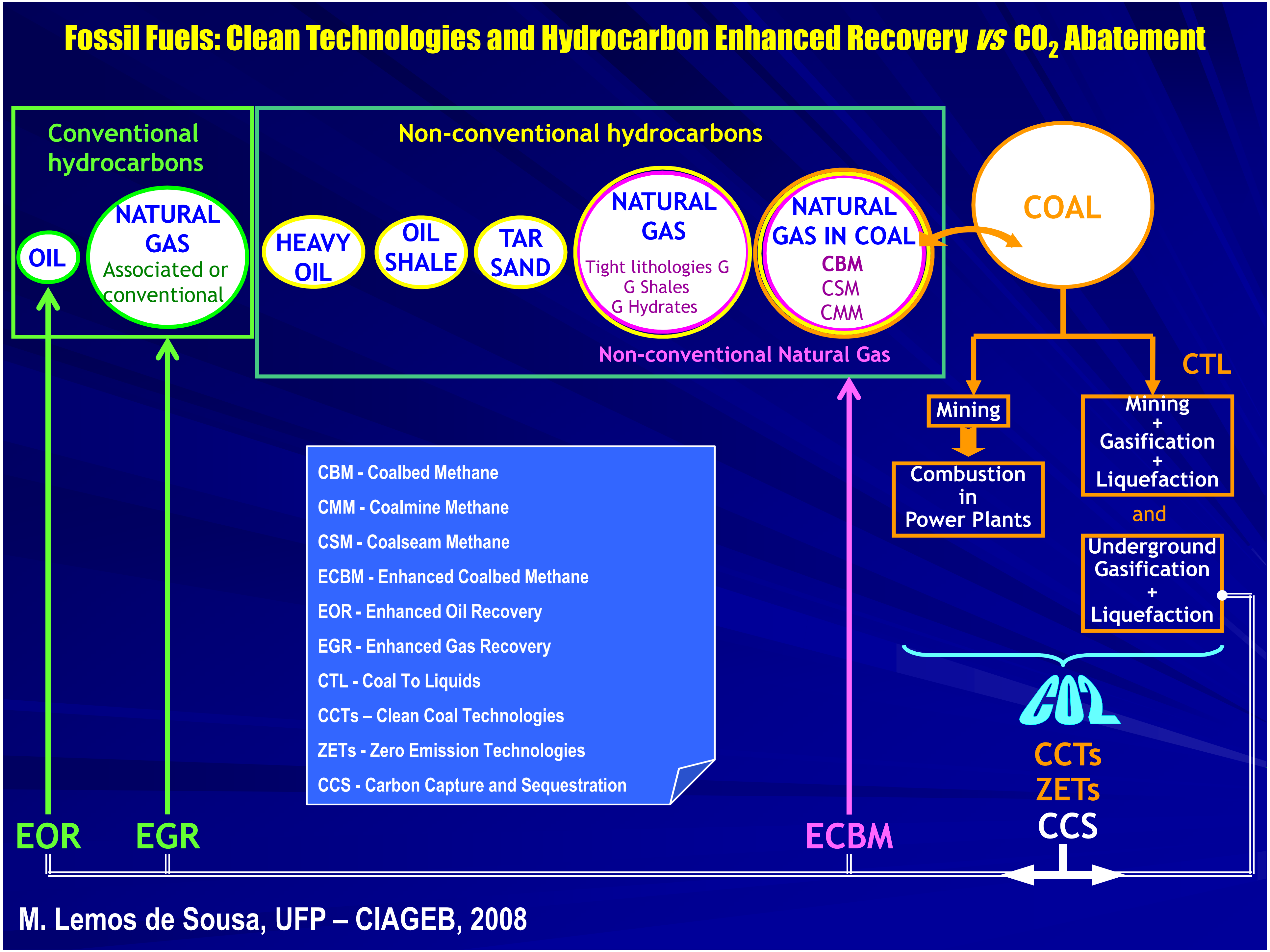
Natural gas in coal
- Coalbed Methane (CBM)
- Coalseam Methane (CSM)
- Coalmine Methane (CMM)

NON-FOSSIL FUELS

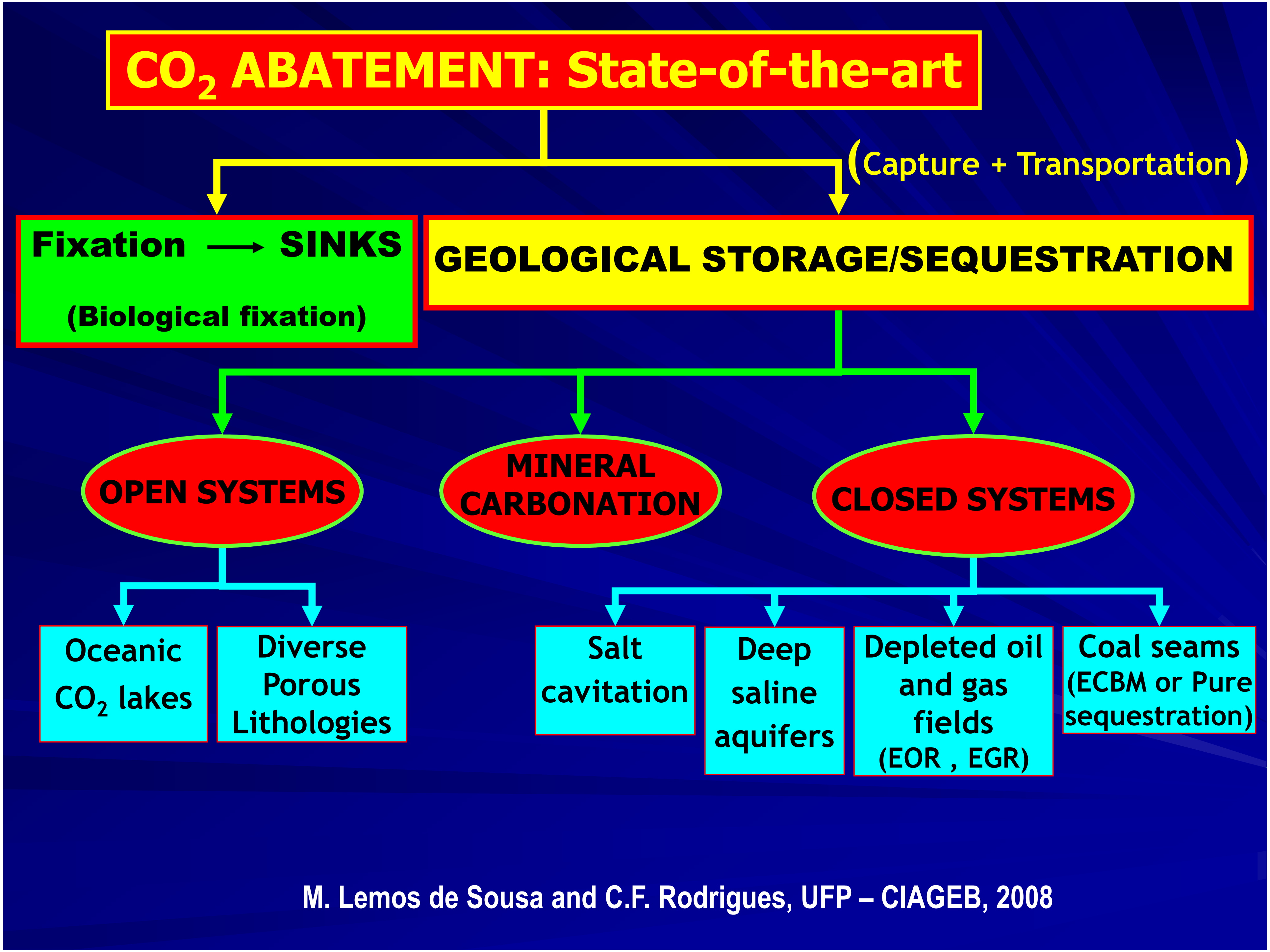
Non-renewable
- Geothermal
- Nuclear

Renewable
- Hydric
- Solar (Thermal; Photovoltaic)
- Wind
- Ocean (Tides; Waves)
- Biofuels (and Biomass)

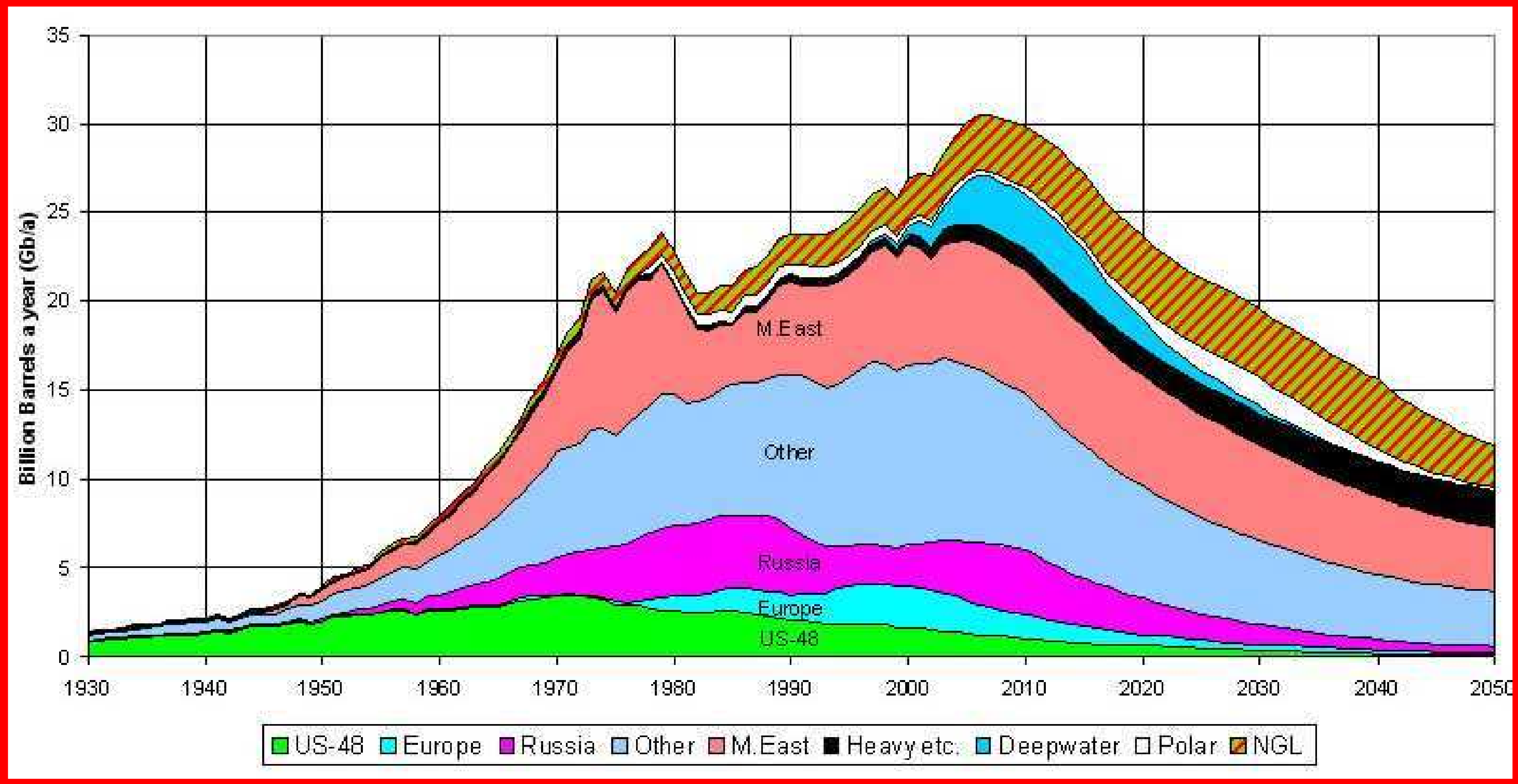
M. Lemos de Sousa and C. Rodrigues UFP – CIAGEB, 2008



Fossil Fuels: Clean Technologies and Hydrocarbon Enhanced Recovery *vs* CO_2 Abatement
Conventional hydrocarbons
OIL
NATURAL GAS
Associated or conventional
Non-conventional hydrocarbons
HEAVY OIL
OIL SHALE
TAR SAND
NATURAL GAS
Tight lithologies G
G Shales
G Hydrates
NATURAL GAS IN COAL
CBM
CSM
CMM
Non-conventional Natural Gas
COAL
CTL
Mining
Combustion in Power Plants
Mining + Gasification + Liquefaction
and
Underground Gasification + Liquefaction
COAL
CCTs
ZETs
CCS
EOR
EGR
ECBM
CBM - Coalbed Methane
CMM - Coalmine Methane
CSM - Coalseam Methane
ECBM - Enhanced Coalbed Methane
EOR - Enhanced Oil Recovery
EGR - Enhanced Gas Recovery
CTL - Coal To Liquids
CCTs – Clean Coal Technologies
ZETs - Zero Emission Technologies
CCS - Carbon Capture and Sequestration
M. Lemos de Sousa, UFP – CIAGEB, 2008

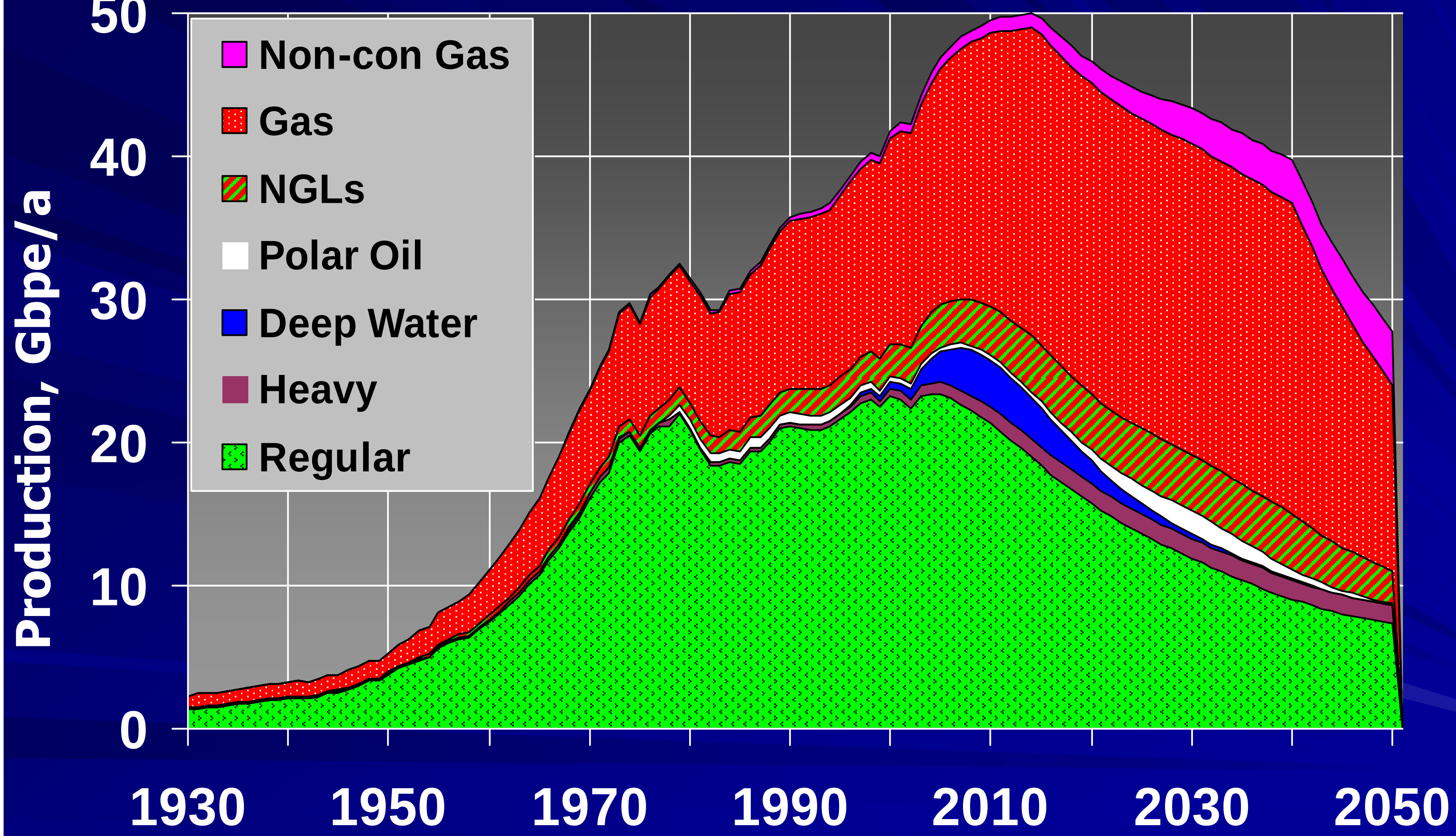

CO2 ABATEMENT: State-of-the-art
(Capture + Transportation)
Fixation → SINKS
(Biological fixation)
GEOLOGICAL STORAGE/SEQUESTRATION
OPEN SYSTEMS
MINERAL CARBONATION
CLOSED SYSTEMS
Oceanic CO2 lakes
Diverse Porous Lithologies
Salt cavitation
Deep saline aquifers
Depleted oil and gas fields (EOR , EGR)
Coal seams (ECBM or Pure sequestration)
M. Lemos de Sousa and C.F. Rodrigues, UFP – CIAGEB, 2008

Oil and NLG - 2004 Scenario



Campbell 2005, ASPO Lisbon Meeting

Oil and Gas - 2005 Scenario



Campbell 2005, ASPO Lisbon Meeting

The Age of OIL
The Mythology, History, and Future of the World's Most Controversial Resource
Leonardo Maugeri
Géopolitiques du pétrole
Philippe Sébille-Lopez
ARMAND COLIN
DAVID GOODSTEIN
Out of Gas
The End of the Age of Oil
WITH A NEW POSTSCRIPT
THE LAST OIL SHOCK
A Survival Guide to the Imminent Extinction of Petroleum Man
DAVID STRAHAN
NOS BASTIDORES DA GEOPOLÍTICA MUNDIAL
PETRÓLEO QUAL CRISE?
CHINA E RÚSSIA ESTÃO A ESMAGAR O ORGULHO OCIDENTAL
Reveja a sua forma de vida
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O GRANDE DESAFIO DO SÉCULO XXI
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Bizâncio
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Dale Allen Pfeiffer
BEYOND Oil
THE VIEW FROM HUBBERT'S PEAK
UPDATED WITH A NEW PREFACE
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REVISED AND UPDATED PAPERBACK EDITION
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With a new preface by the author
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Duncan Clarke
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PETRÓLEO
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Éric Laurent
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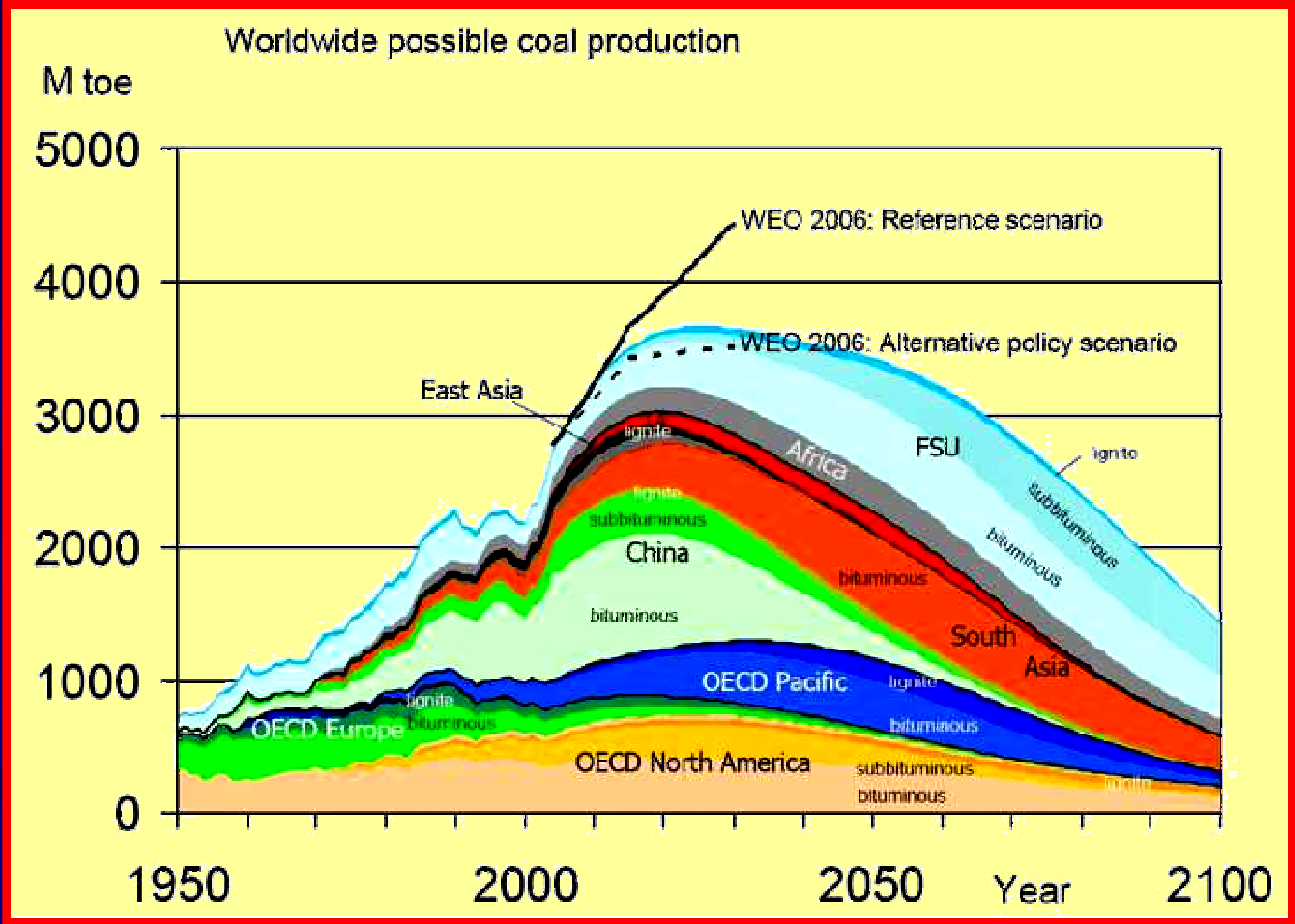
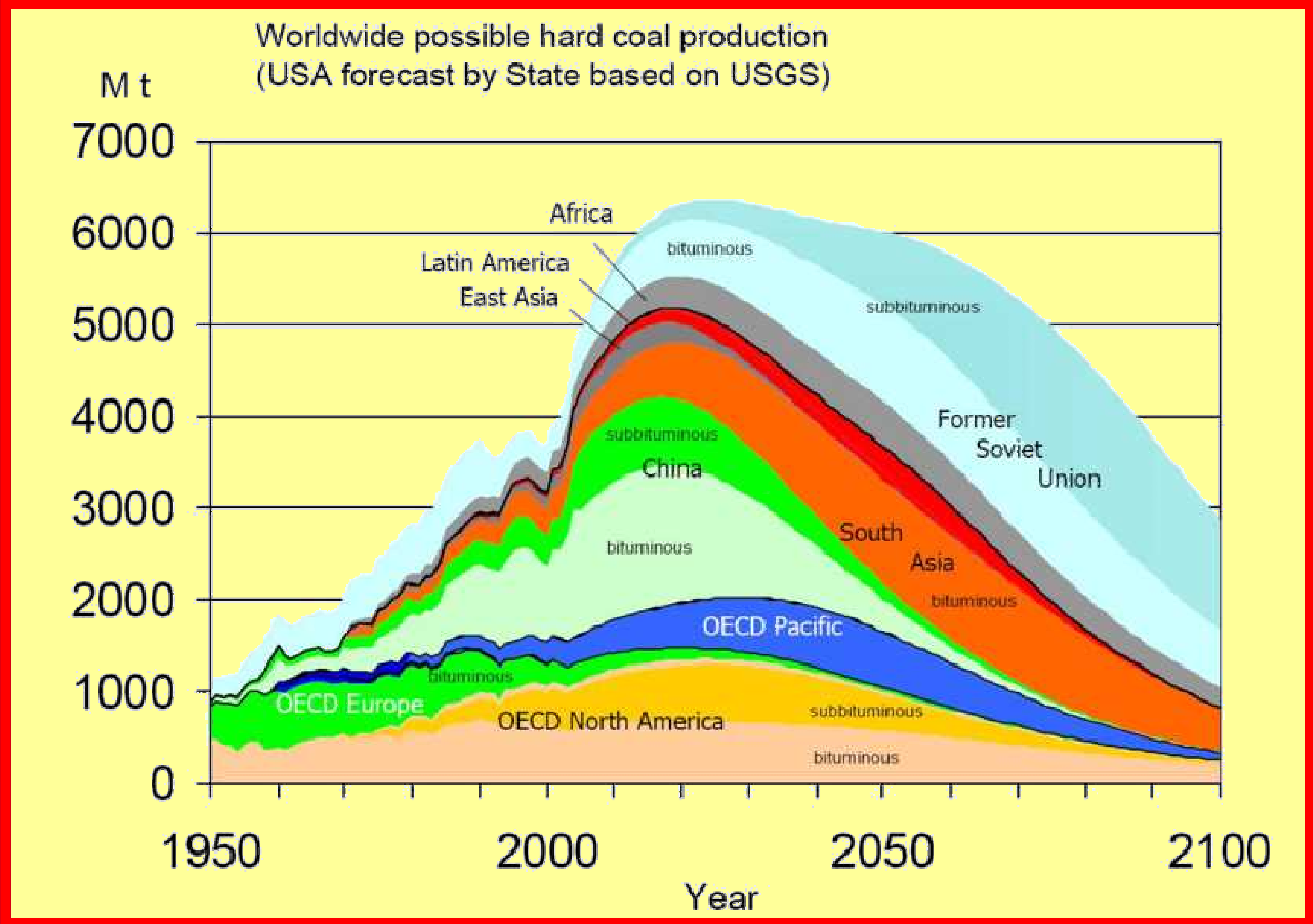
HALF GONE
OIL, GAS, HOT AIR AND THE GLOBAL ENERGY CRISIS
Géopolitiques du pétrole
Philippe Sébille-Lopez
ARMAND COLIN
UN MONDE DE BRUT
SUR LES ROUTES DE L'OR NOIR
Serge Enderlin Serge Michel Paolo Woods
Seuil

“Peak Coal” – 2007 Scenario



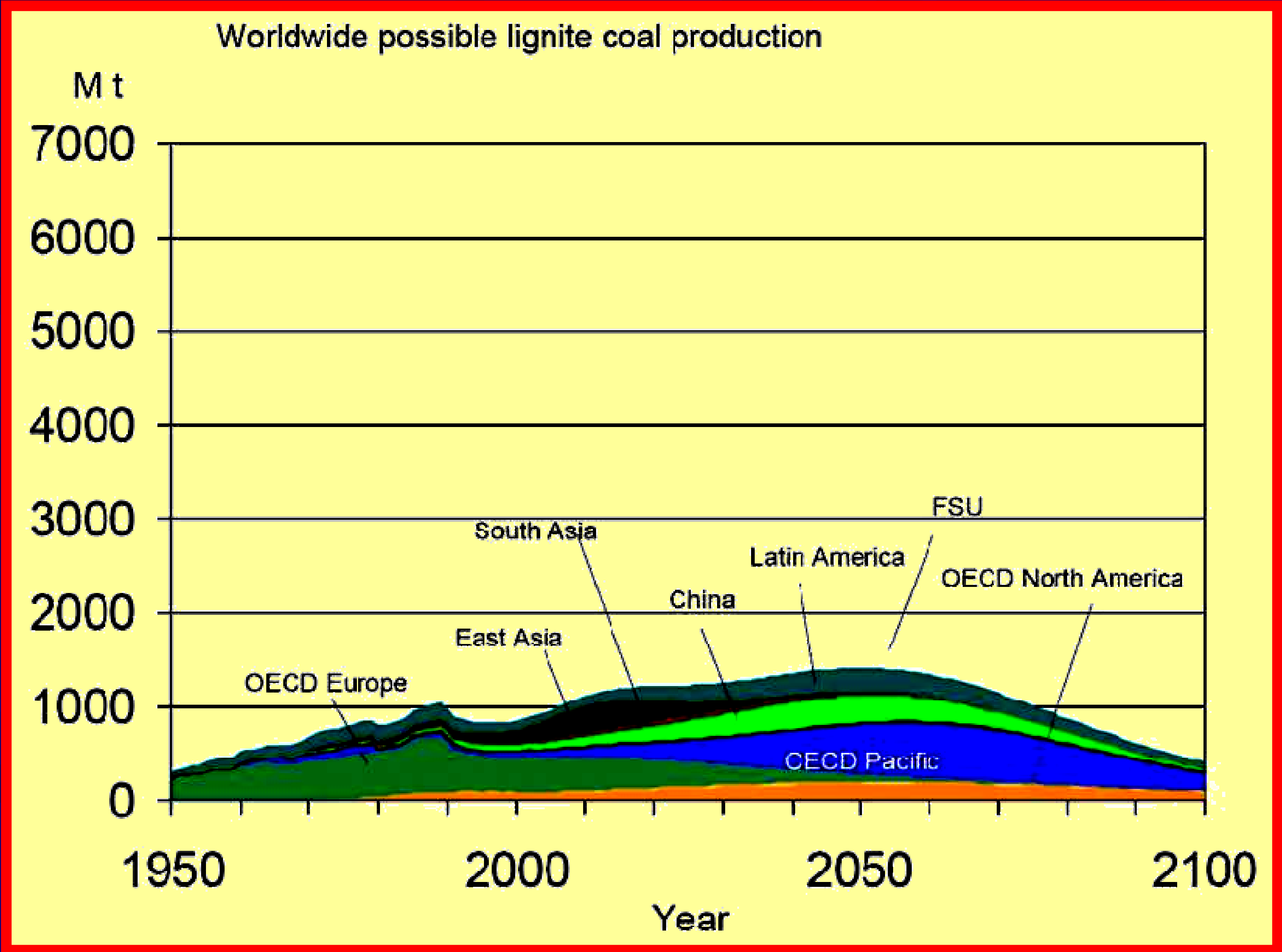
EWG 2007 and Laherrère 2007

"Peak Coal" – 2007 Scenario
Hard and Subbituminous Coals



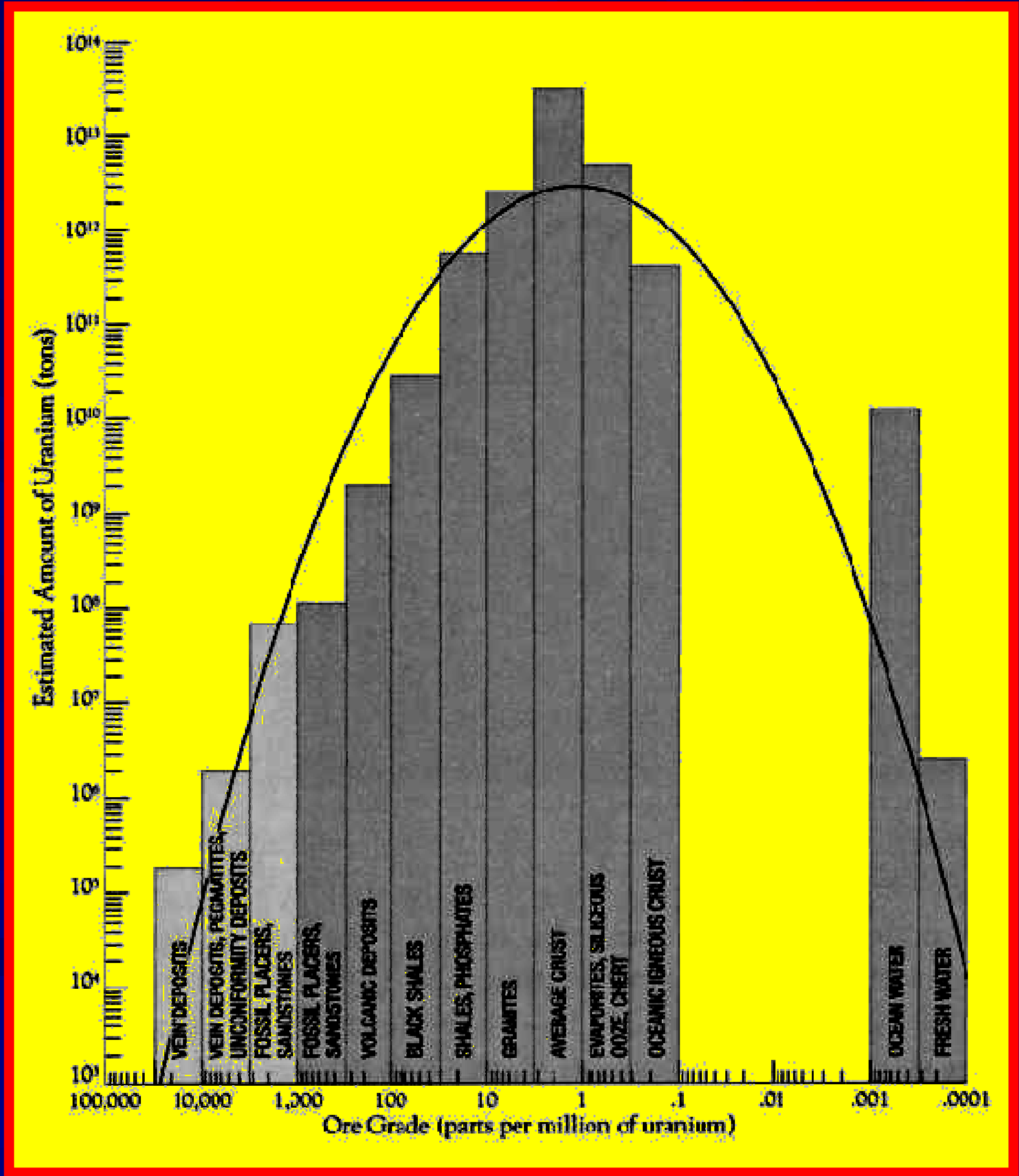
EWG 2007

"Peak Coal" – 2007 Scenario
Lignite



EWG 2007

Uranium Distribution in Earth Crust



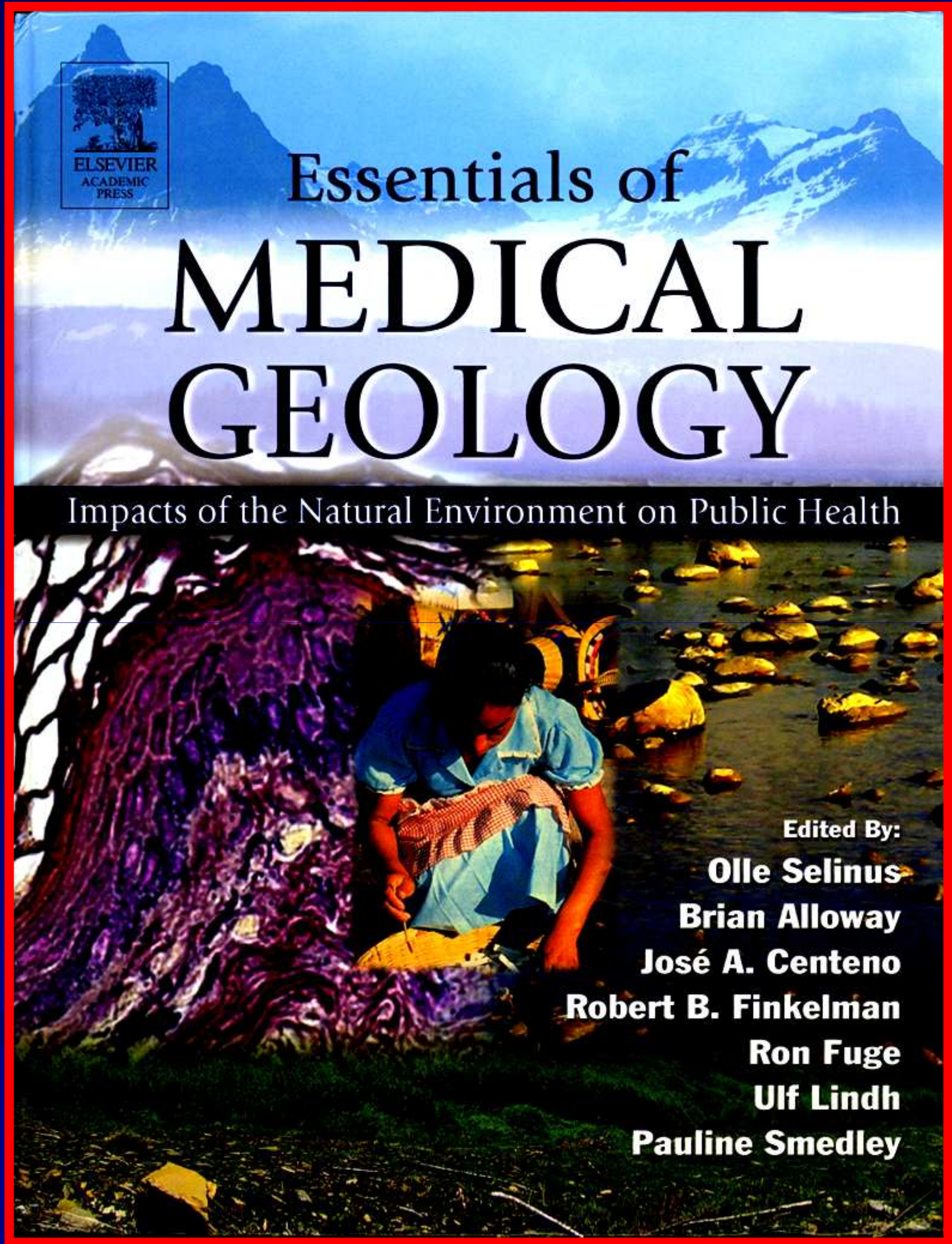
Deffeyes 2005

“With energy demand growing and oil and gas supplies dwindling, a once-dismissed dirty fuel gets a second look”

"Coal's Bright Future"

Time, July 24, 2006


The Economist
JULY 6TH-12TH 2002
Vivendi's fall from grace
PAGES 12 AND 62
The politics of America's scandals
PAGE 43
Why Arab countries have failed
PAGES 24-26
THE GLOBAL ENVIRONMENT
SURVEY, AFTER PAGE 52
CO$_2$AL
Environmental enemy No.1


ELSEVIER
ACADEMIC PRESS
Essentials of
MEDICAL
GEOLOGY
Impacts of the Natural Environment on Public Health
Edited By:
Olle Selinus
Brian Alloway
José A. Centeno
Robert B. Finkelman
Ron Fuge
Ulf Lindh
Pauline Smedley

Zero Emissions Technologies - ZETs

Clean Coal Technologies - CCTs

Coal Combustion and Gasification
(PF, PCC, CFBC, PFBC, IGCC)
(pre-C, pos-C, oxifuel)

Coal To Liquids (CTL)

Underground Coal Gasification

Carbon Capture and Sequestration - CCS

- CBM Enhanced Production (ECBM)
- CO_2 Pure Sequestration

Nomenclature from “International Conferences on Clean Coal Technologies for our Future”

I ♥

CLEAN COAL

I ♥

CLEANER

COAL

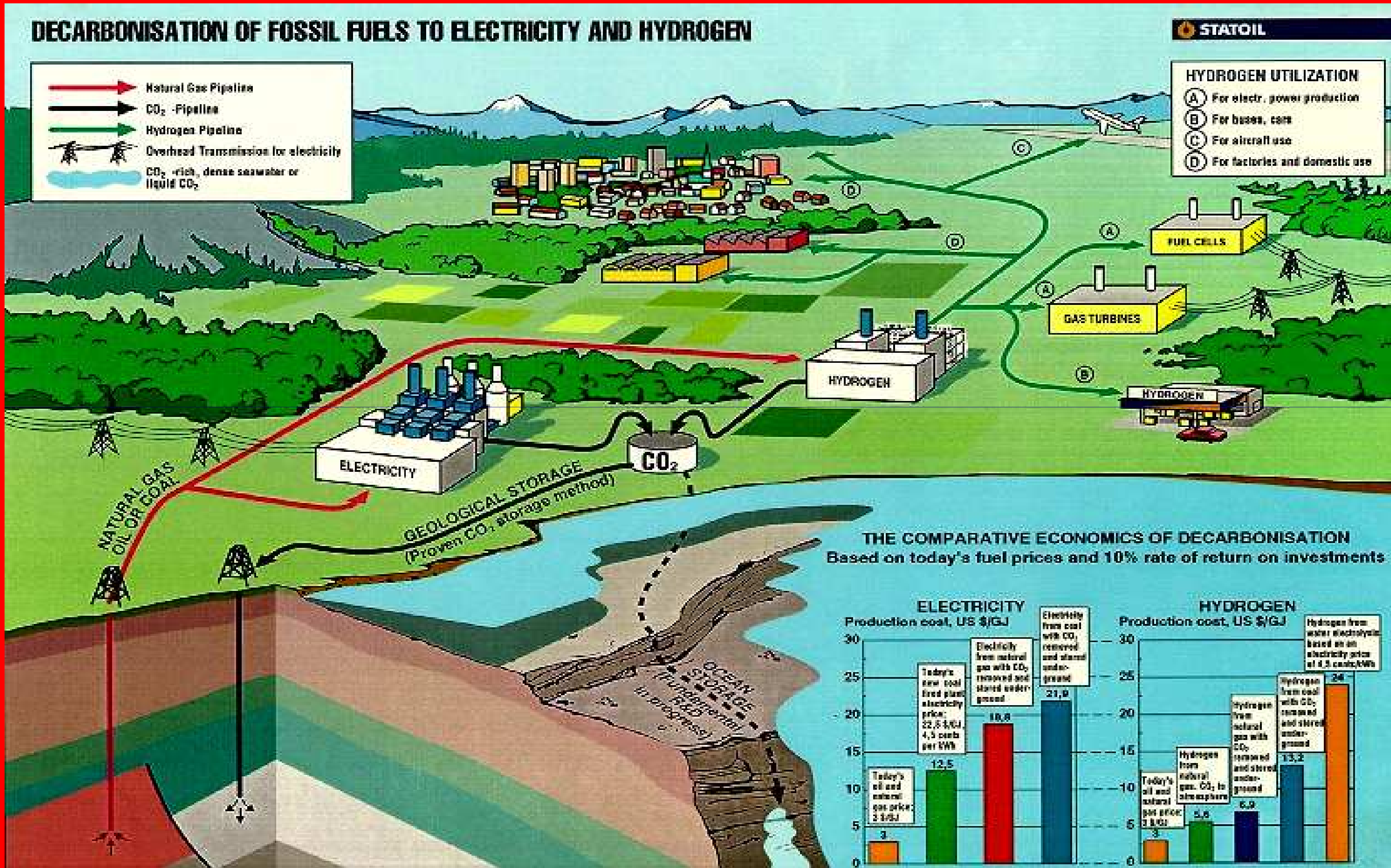
“BENIGN ENERGY?”

The environmental Impact of Renewables

IEA/OECD

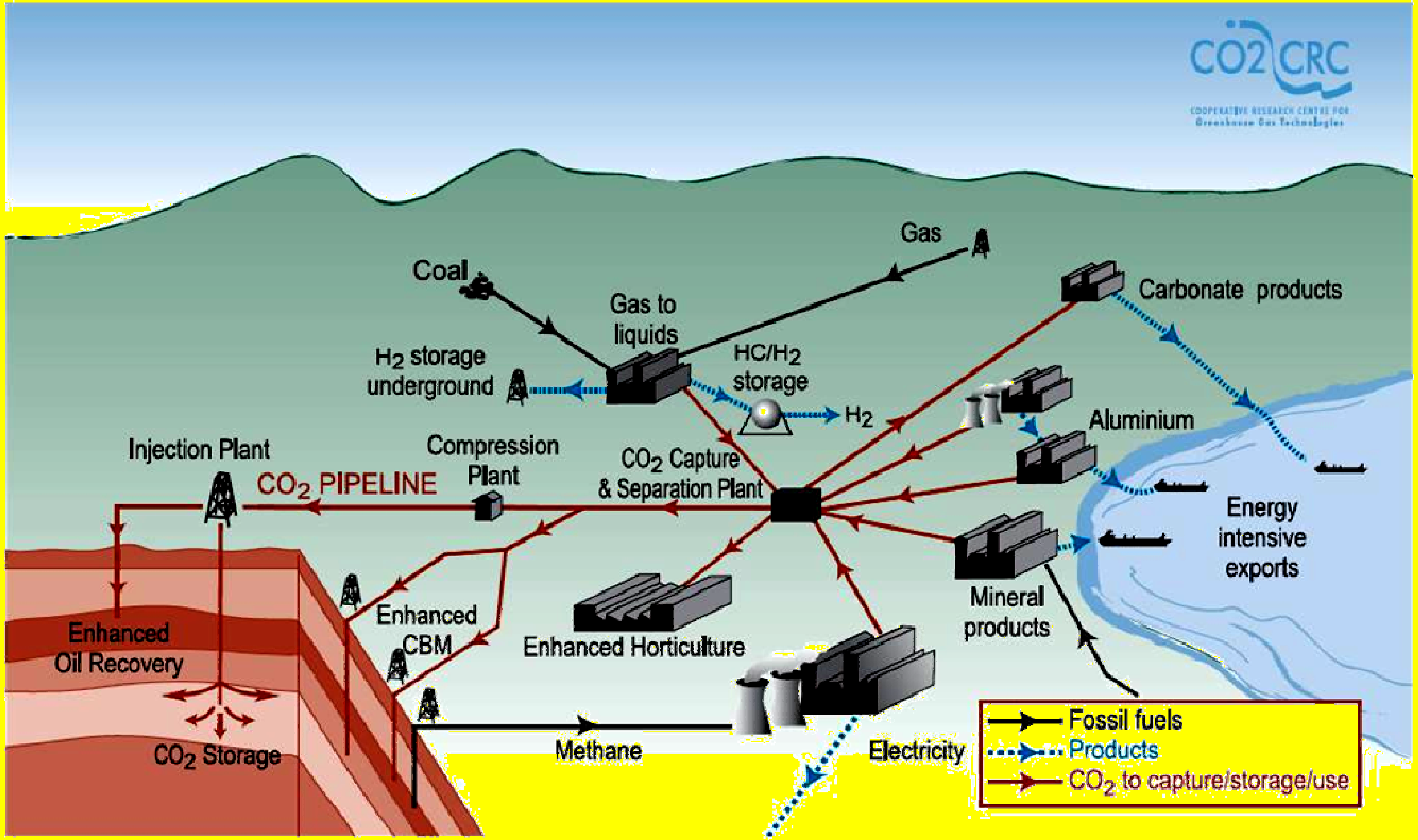
1998

Vision of a Clean Future



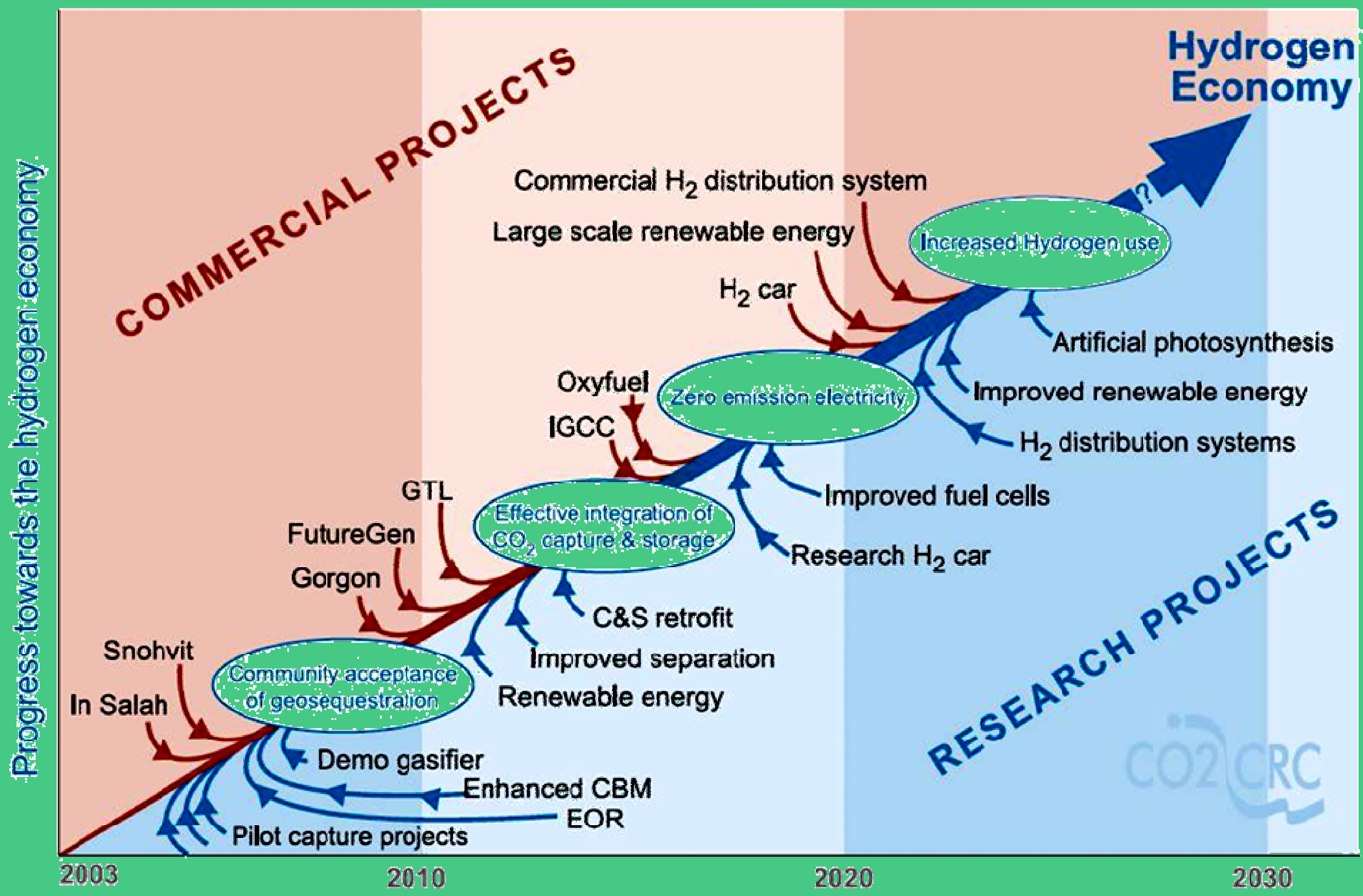
Vision of a Clean Future

An emission-free vision for the future



"The Society of Hydrogen"

Commercial and research projects leading towards the hydrogen economy (Level 3 technology roadmap)



carbon sequestration leadership forum

IEA GREENHOUSE GAS R&D PROGRAMME

CO2CRC

Zero Emissions Technologies - ZETs

Clean Coal Technologies - CCTs

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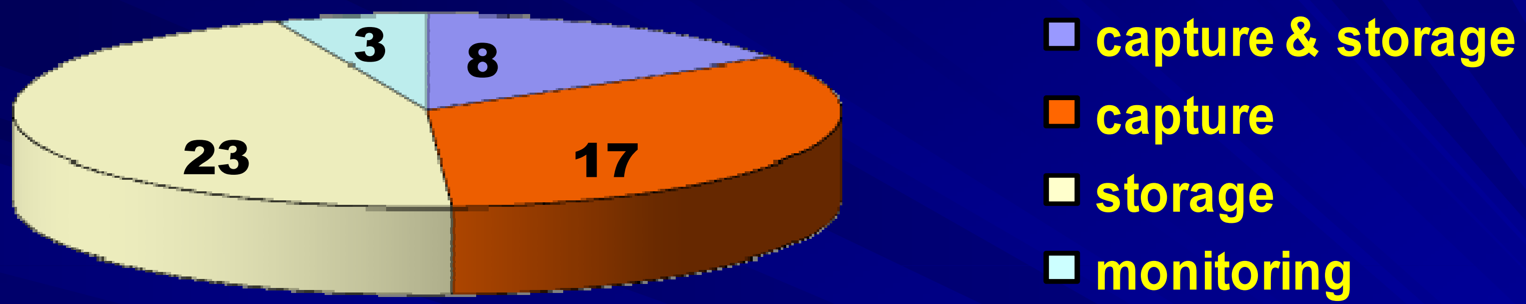
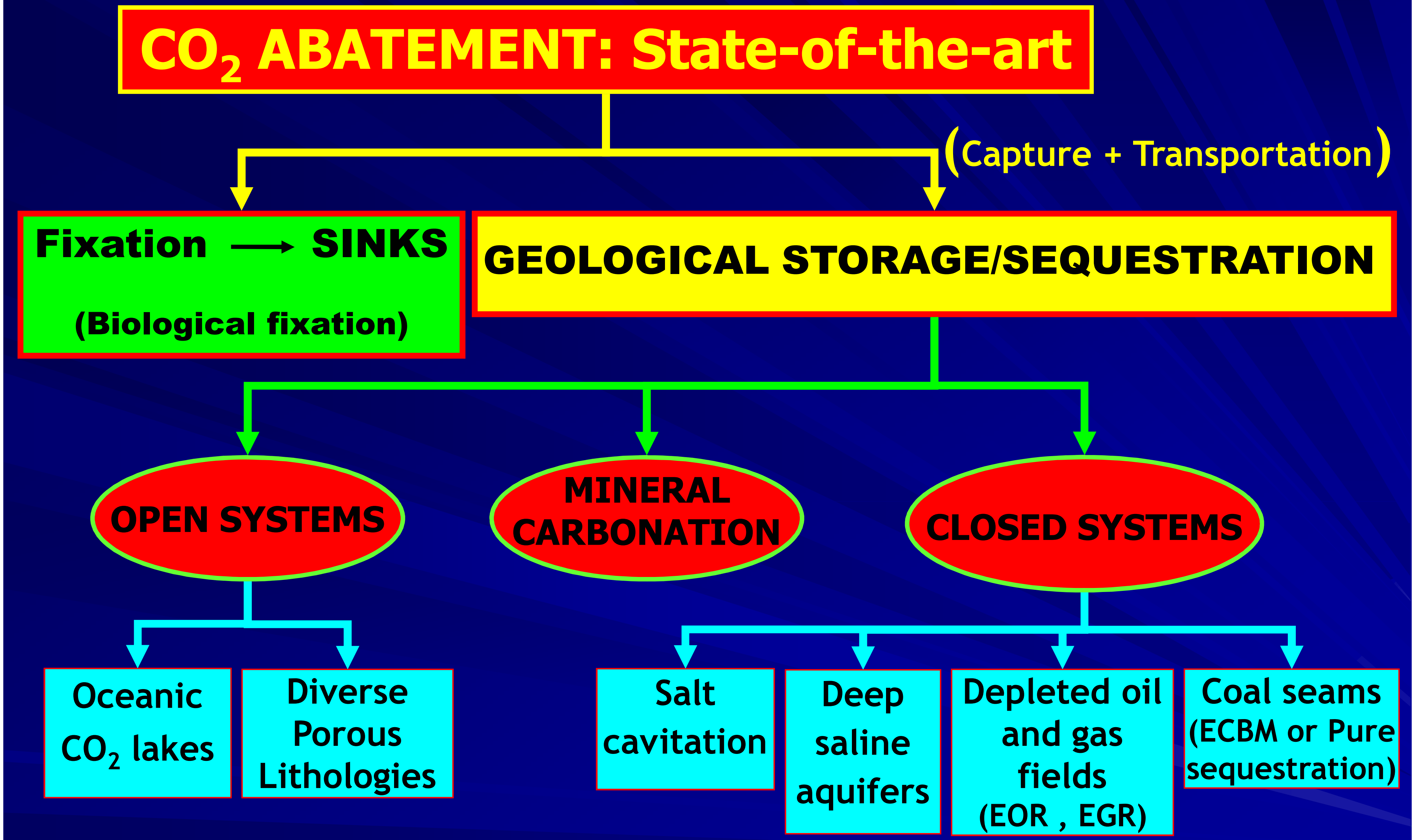
Nomenclature from "International Conferences on Clean Coal Technologies for our Future"

CCS Current Projects (total 51)



- CSLF endorsed: 19
- European Commission funded: 24
- CSLF endorsed and EC funded: 6

IEA Green R,D & D Projects Database, September 2008



M. Lemos de Sousa and C.F. Rodrigues, UFP – CIAGEB, 2008

CO_2 Geological Sequestration

Some CSLF and CO_2CRC main concepts

The FEASIBILITY of any project depends on:

1. Public Perception and Acceptance	
2. Security of Storage ➢ Estimation of storage capacity potential ➢ Long term risk assessment	**Technical viability**
3. Natural Analogues	
4. Commercial Analogues	**Economic viability**

ANALOGUES are data compilations or case studies of areas with high quality data (modern, outcrop or subsurface), which can be used to provide levels of expected heterogeneity for a reservoir of a given depositional setting.

(Kaldi & Gibson-Poole 2008)

- **Feasibility - Pilot Projects (100% risk)**
  - ✓ **Technical viability** → Field Scale / Laboratory Scale
  - ✓ **Modeling** → Model validation
  - ✓ **Implementation – Security of storage by:**
    - Estimation of storage capacity potential
    - Long term Risk Assessment
  - ✓ **Economic viability** (Technology costs *vs* Allowances trading costs)
- **Commerciality - Industrial Project**

RESERVOIRS

Conventional

Depleted oil and gas fields
(EOR , EGR)

Deep Saline Aquifers

Non-Conventional

Coal seams
(ECBM or Pure sequestration)

... AND MUCH MORE !?

COAL

is the only sedimentary rock with two main roles on the “Petroleum System”

Coal acts, simultaniously, as...

Source Rock | **Reservoir**

Trap

Conventional *vs* Unconventional Reservoir Efficiency for long term CO_2 storage

Reservoir Characteristics

		Coal	Saline Aquifer
Reservoir	Gas storage (gas state)	Adsorption (surface area) + Absorption (cleat) (Naturally in liquid state) + (gaseous or liquid)	Absorption (pore volume) (Liquid or gaseous depending on P and T)
	Gas flow	Diffusion (Low) + Laminar (Low)	Laminar (High)
Caprock/seal		Coal is simultaneously source-rock, reservoir, caprock and trap	**Independent** caprock (pelitic sediments and/or structural features)
Trap		Ibid	**Independent** trap (vital to avoid gas leakage)
Depth		Any depth	Depth compatible with the presence of saline water

Conventional *vs* Unconventional Reservoir Efficiency for long term CO_2 storage

(continuation)

Technological Characteristics

	Coal	Saline Aquifer
Leakage risk	2% - 5% of gas injected, depending on "cleat system"	Wide range of variation, depending mainly on tectonic settings and/or seal characteristics
Gas injection state	Gaseous (except for seams at high depths)	Liquid
Reservoir water behaviour	Water disposal corresponds to free moisture, mostly in the "cleat system" (2% - 5%)	Water disposal volume similar to CO_2 injected volume; only 5% to 7% will dissolve (long term) in water
Frequent Criticism about reservoir eventual future use	New Coal Technologies ???	Needs of fresh water obtained by desalination !!!

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