Carbon Capture Technologies Overview, Assessment and Potential Development and Deployment in the ESCWA Region

Dr. Mohammad Abu Zahra

Chemical and Environmental Engineering Department

Expert Group Meeting on "Carbon Capture, Utilization and Storage in ESCWA Member States: Enhancing the Sustainability of the Energy System in a Carbon Constrained Development Context"

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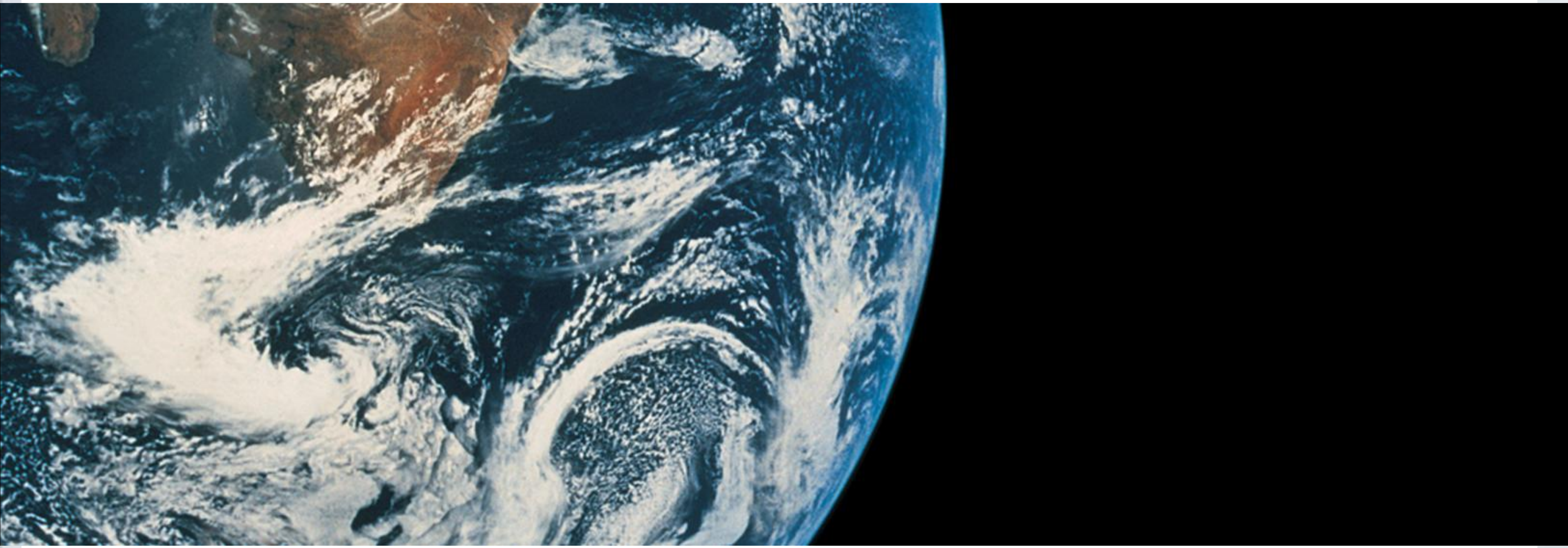
PRESENTATION OUTLINE

- Introduction
- CO_2 capture technologies overview
- CO_2 capture status and outlook
- Techno-economic and environmental aspects of CO_2 capture deployment
- CO_2 capture an option for the ESCWA region!
- Concluding Remarks

Introduction and importance of fossil fuels and CCS



- Research university
- Graduate level (MSc & PhD) only
- Focused on sustainable technology and clean energy
- In collaboration with Massachusetts Institute of Technology (MIT)

Masdar Institute – 100% solar powered campus

ACADEMIC PROGRAMS

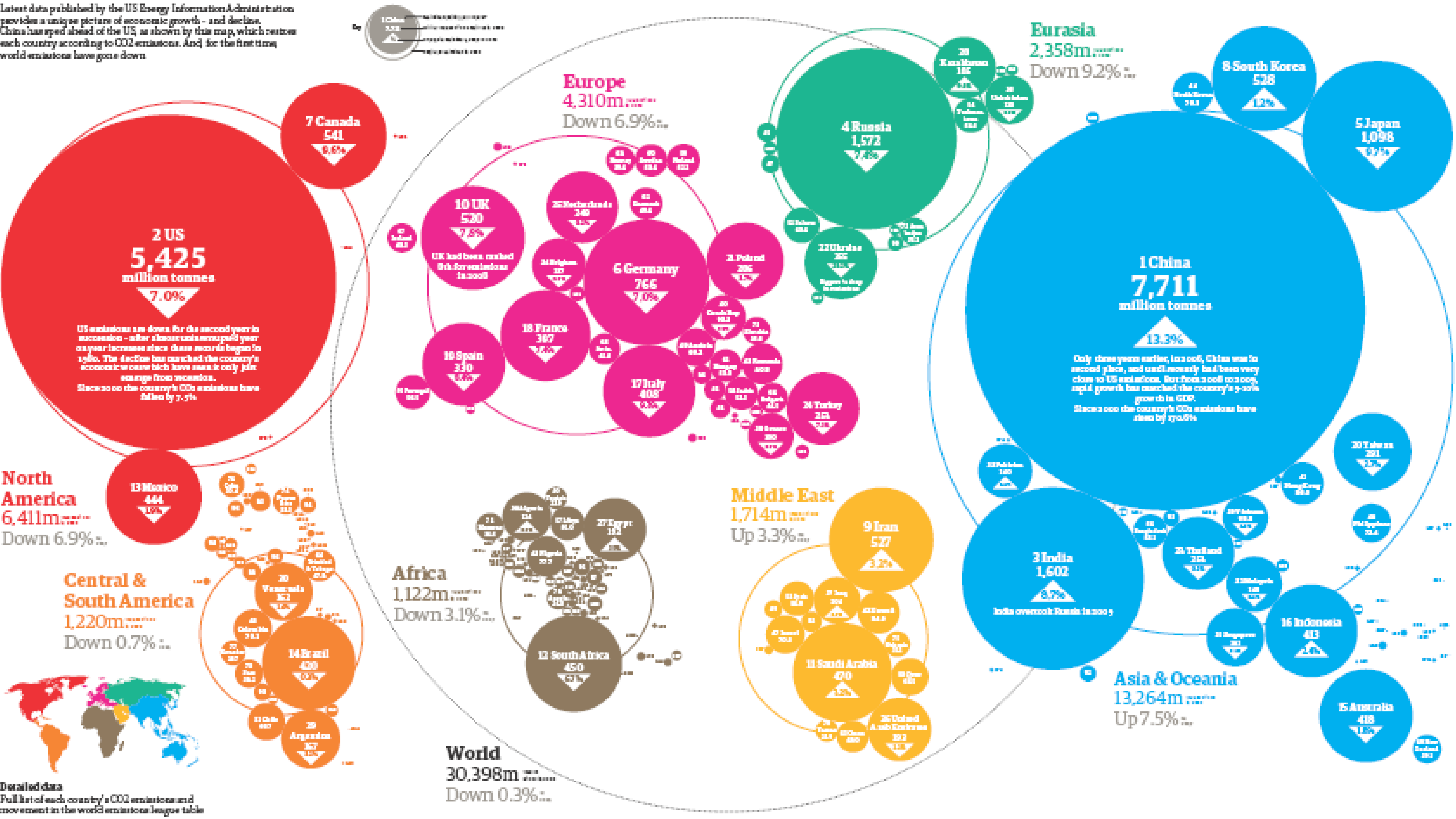
2012
- + MSc Critical Infrastructure

2011
- + MSc Chemical Engineering

2010
- + MSc Electrical Power Engineering
- + MSc Microsystems Engineering
- + Interdisciplinary PhD

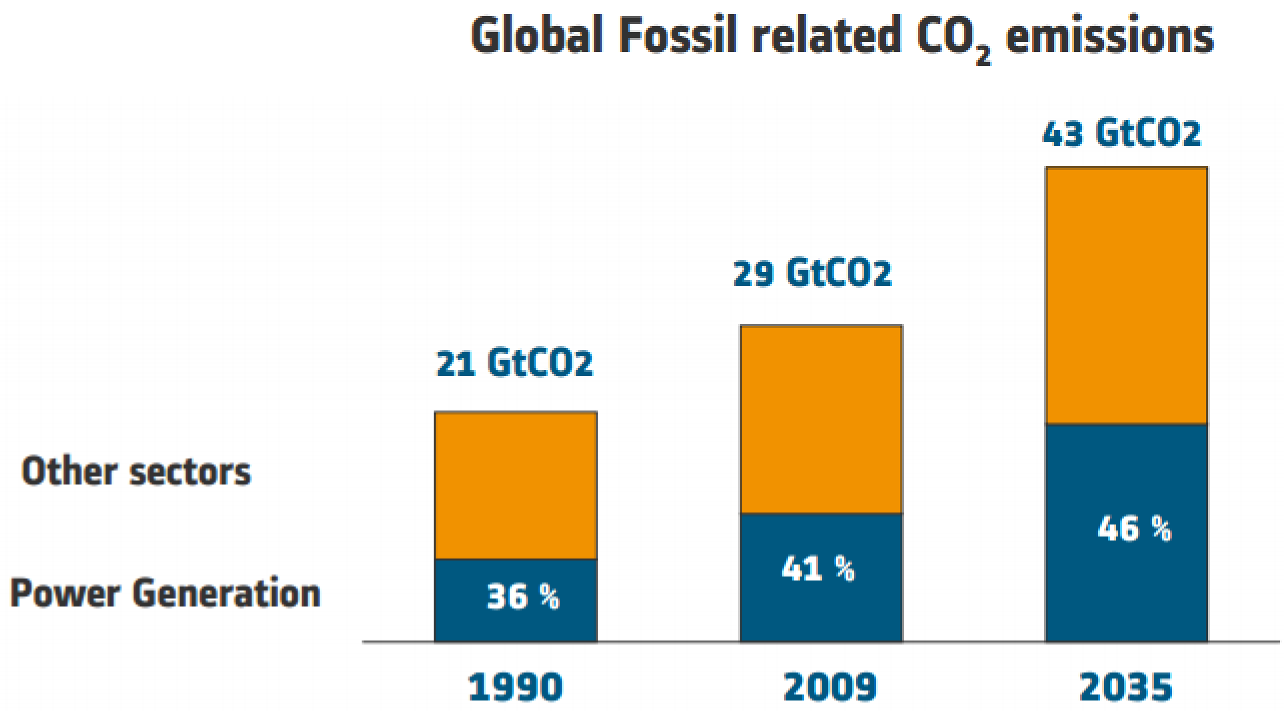
2009
- MSc Materials Science and Engineering
- MSc Mechanical Engineering
- MSc Engineering Systems and Management
- MSc Computing and Information Science
- MSc Water and Environmental Engineering

WORLD'S CO_2 EMISSION



Source: Guardian February 2011, from US Energy Information Administration

SOURCES OF CO_2



* Source: IEA 2011 - Current Policies Scenario

Power generation is the largest contributor!

MITIGATION OPTIONS

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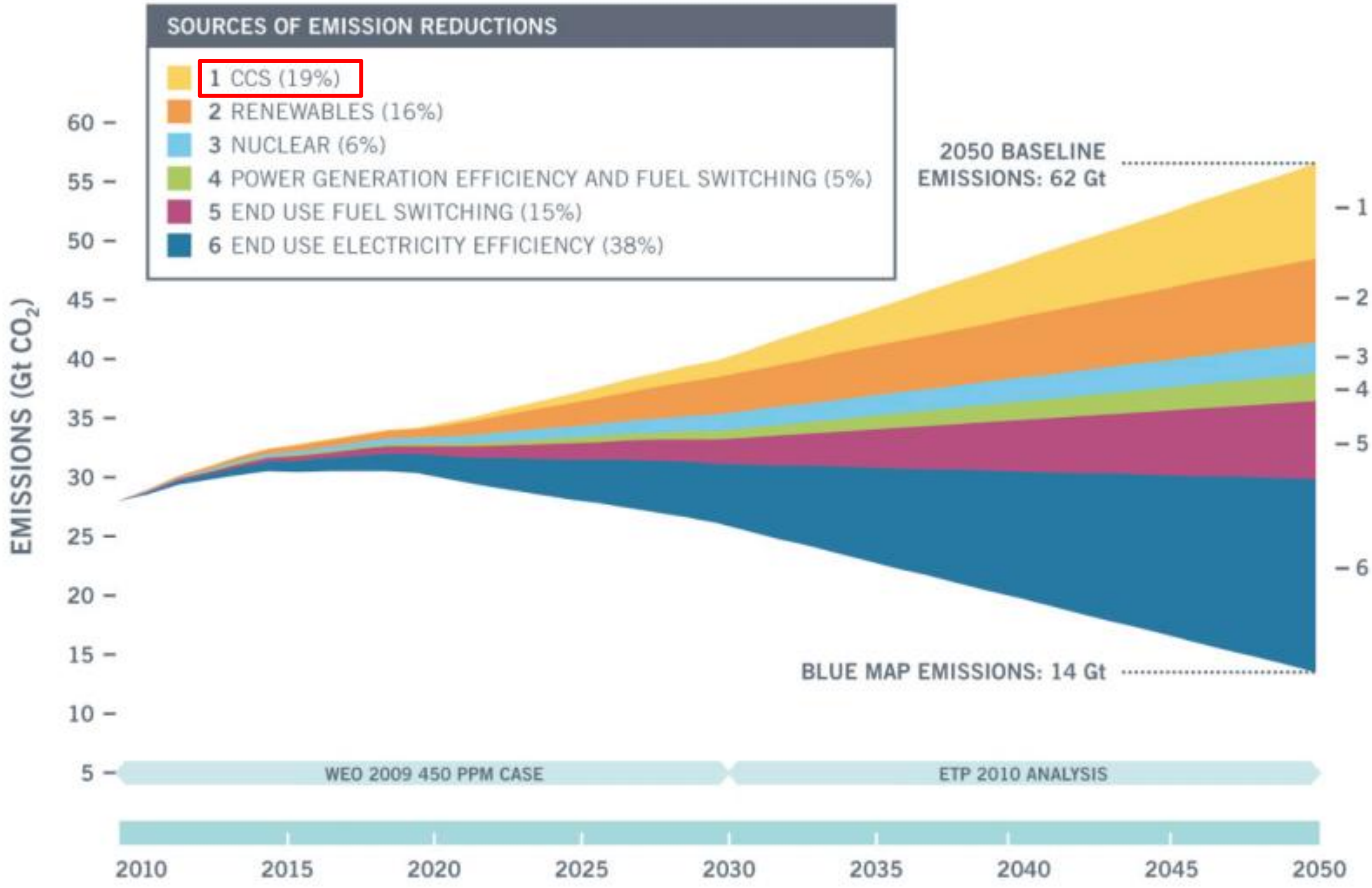
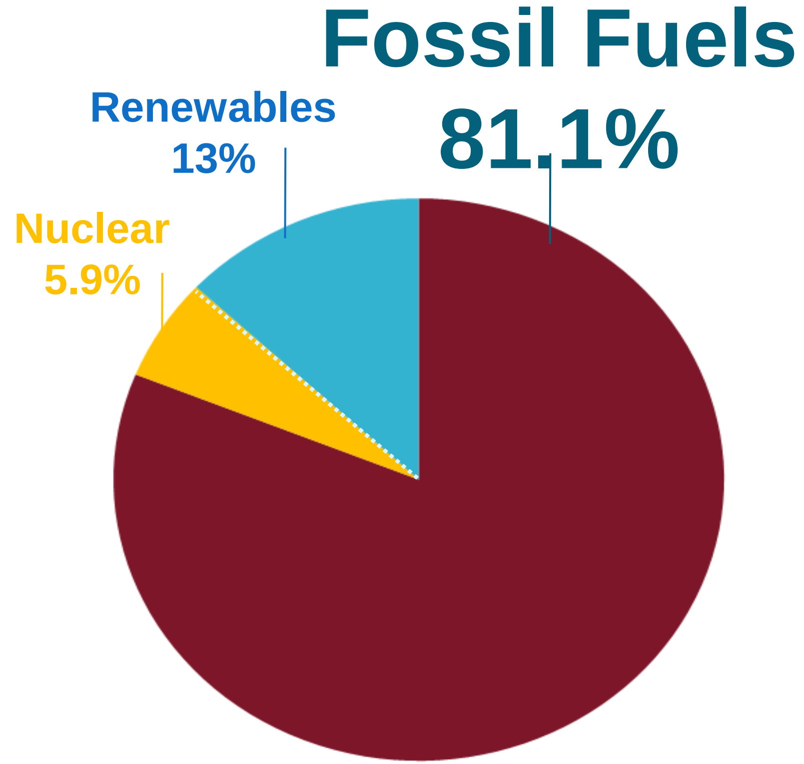


Source: IEA Energy Technology Perspectives (2010)

Today

- Fossil fuels (coal, gas and oil) represent **80%** of the global energy mix
- Renewables only account for 13% of our total energy supply



Source: IEA, Key World Energy Statistics, 2009

… AND WILL CONTINUE TO DO SO FOR DECADES TO COME

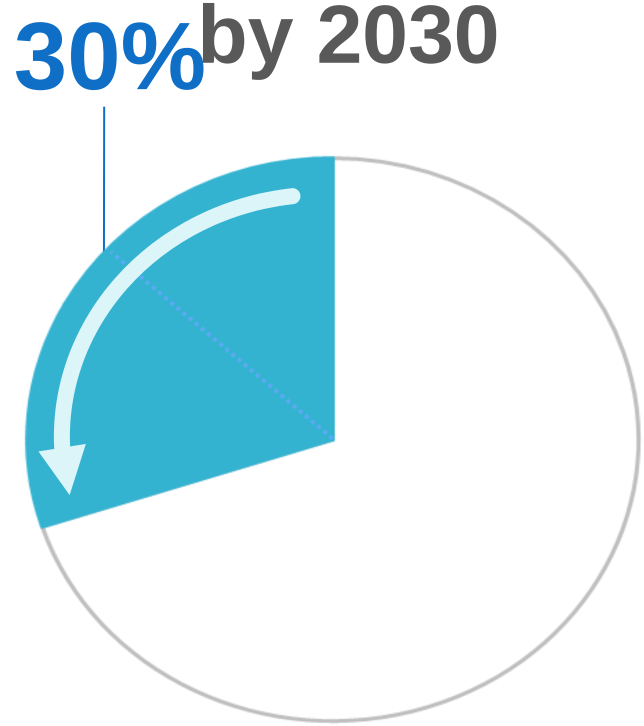
By 2030

Renewables could make up 30% of the global energy mix*

↓

But fossil fuels will remain our main source of energy for decades to come

Estimated share of renewables by 2030



*Average taken across multiple estimates: IEA WEO 2008; European Commission baseline scenario; German Ministry of Environment, EUROPROG

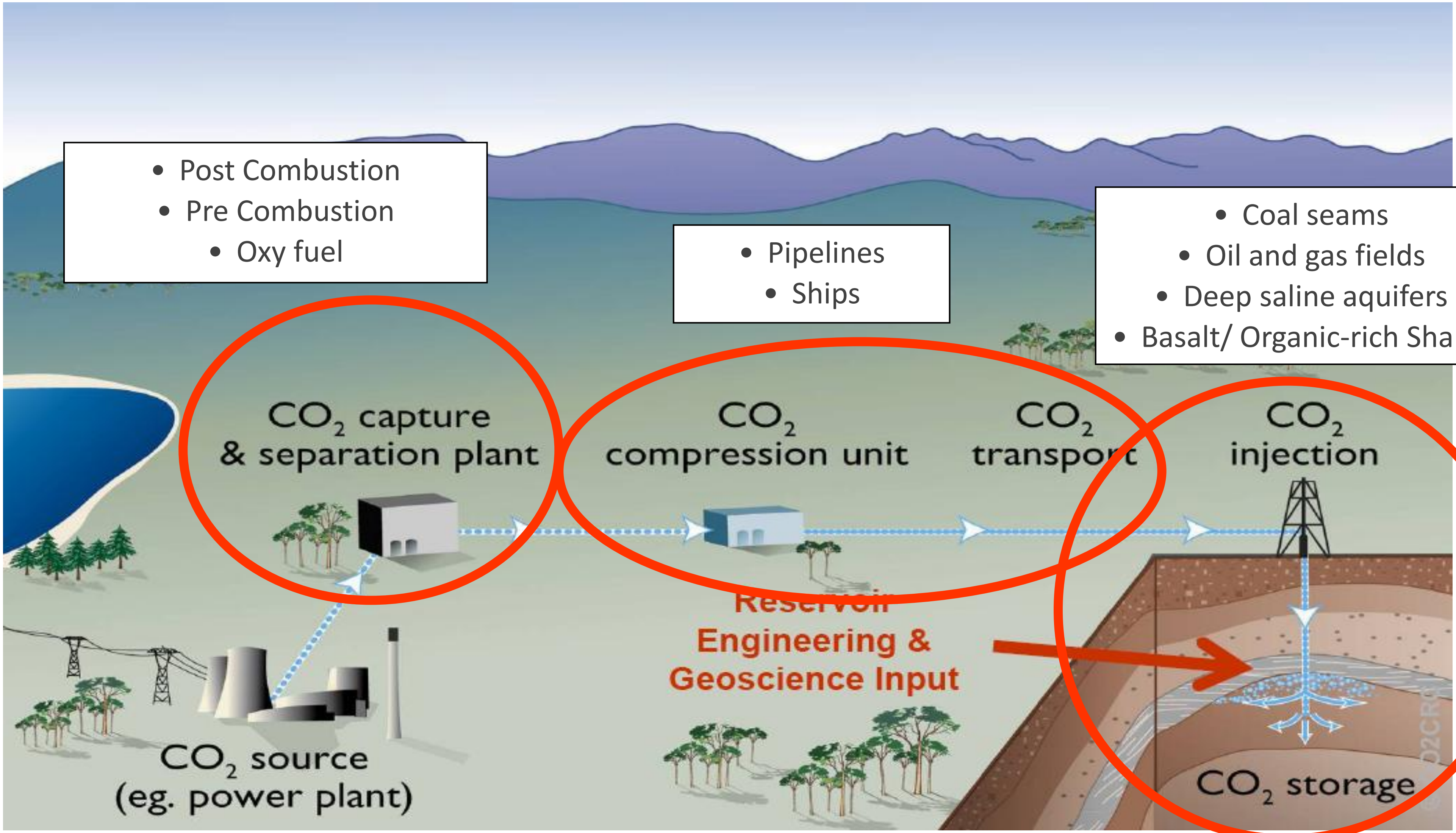
Source: ZEP Presentation

WHAT IS CO_2 CAPTURE, TRANSPORT AND STORAGE?

- Post Combustion
- Pre Combustion
- Oxy fuel

- Pipelines
- Ships

- Coal seams
- Oil and gas fields
- Deep saline aquifers
- Basalt/ Organic-rich Shales



Source: CO2CRC

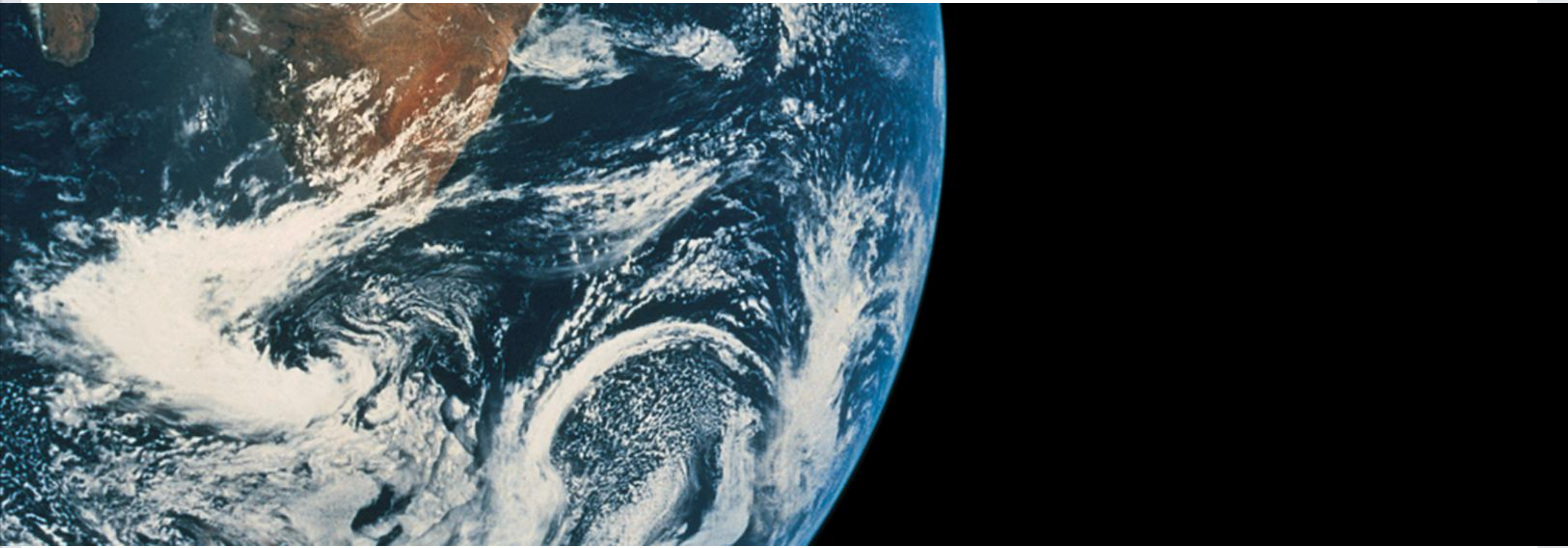
FAVORABLE FOR CCS

- Global dependency on fossil fuel
- Low cost option compared with many others
- High capacity option (whilst storage resources last)
- Rapid implementation is technically feasible
- Relatively low environmental impact
- Elimination virtually all gaseous emissions is possible
- Can be retrofitted
- Potential lead in to Hydrogen economy
- Skilled staff exist (but many more needed)

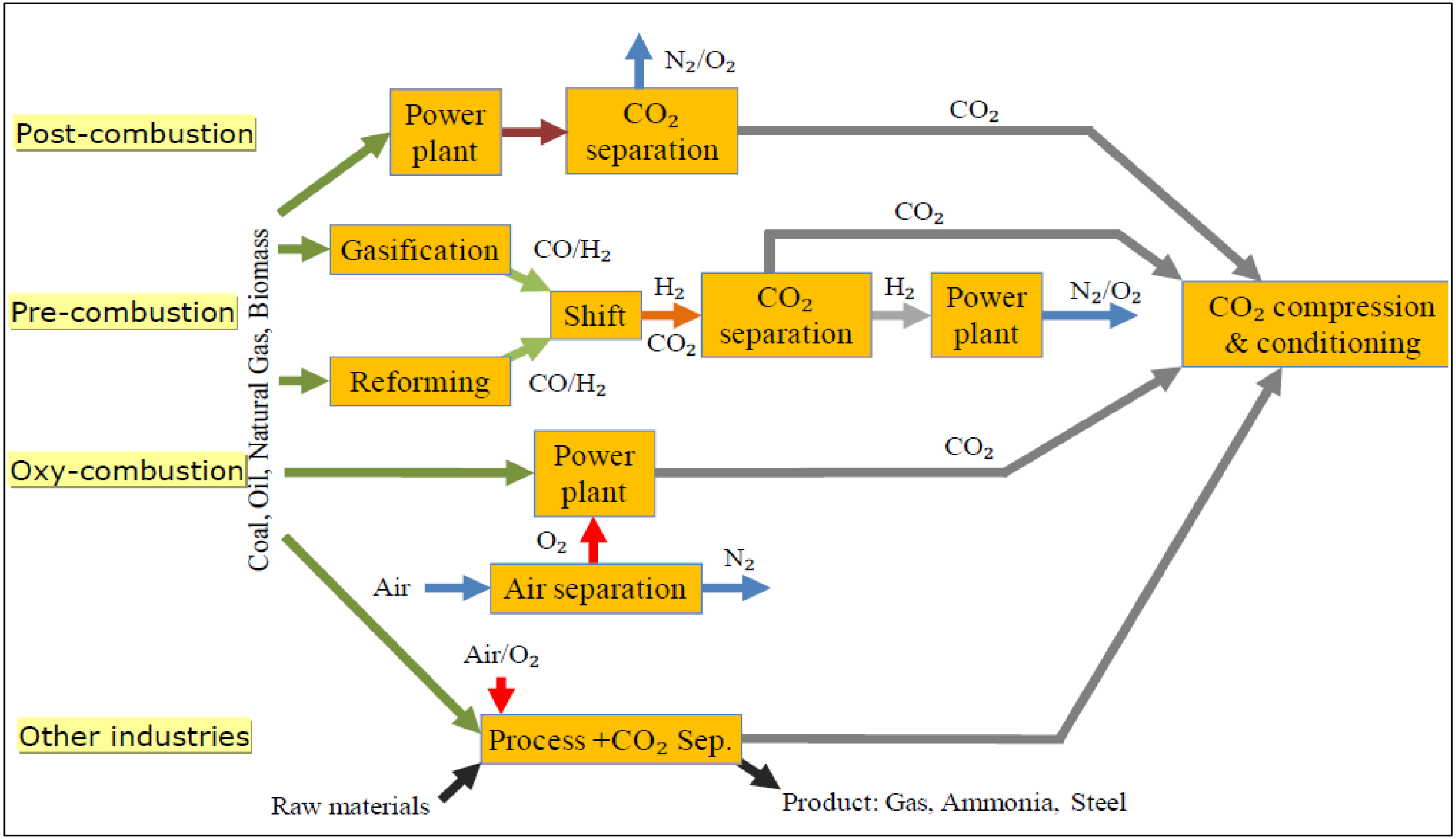
BARRIERS TO CCS

- Proving security of storage sites
- Regulations not fully in place
- Public resistance at some land storage sites
- Increased consumption of fuel
- It is an interim measure, some do not support it as it rivals renewable energy

Capture technologies



GENERAL OVERVIEW OF CO_2 CAPTURE TECHNOLOGIES



NO "WINNER" TECHNOLOGY

Source: EPRI 2007

CO_2 Capture Technological Routes:

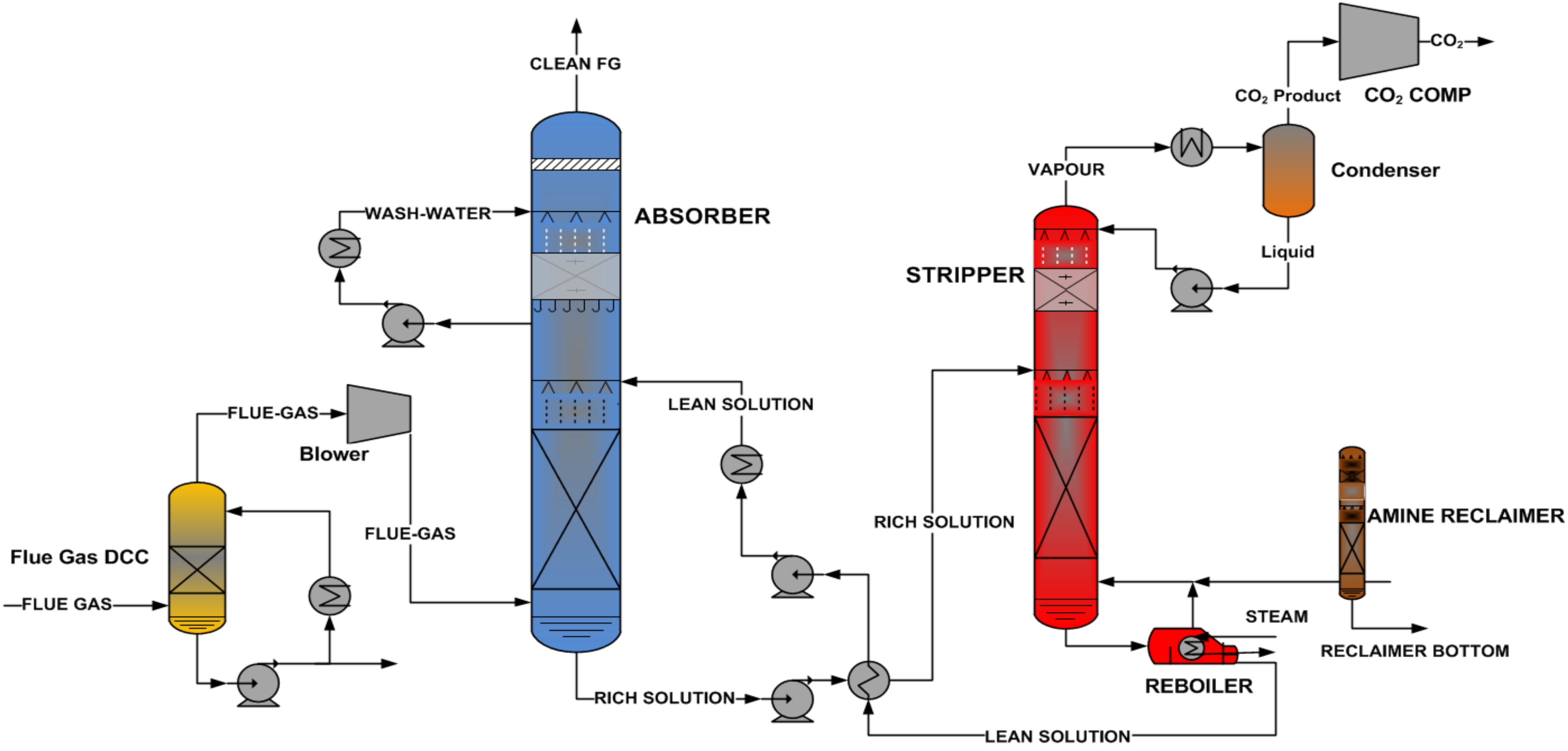
Post-Combustion Capture: CO_2 removal from flue gas after flue gas cleaning

Pre-Combustion Capture (IGCC): CO_2 separation from syngas after WGS reaction

Oxy-Fuel Combustion: use O_2 for combustion, CO_2 separation from water / other impurities

	Post-Combustion (flue gas)	Pre-Combustion (shifted syngas)	Oxy-Fuel Combustion (exhaust)
P (bar)	~1 bar	10-80	~1 bar
[CO_2] (%)	3-15%	20-40%	75-95%

CONVENTIONAL POST-COMUSTION CAPTURE FLOW DIAGRAM



ADVANTAGES OF POST-COMBUSTION CAPTURE

- The possibility of add-on to existing power plants (retrofit possibility)
- Capture technologies are considered available and the solvent technologies are proven on a smaller scale.
- Capture readiness makes the post combustion capture relatively easy to incorporate into power plants.
- It has more operational flexibility in switching between capture – no capture operation mode.
- Experience allows reductions in cost (similar to desulfurization)
- Learning by searching will lead to better solvents and processes

Picture: CASTOR pilot plant -Esbjerg

POST -COMBUSTION CAPTURE PROCESS CHALLENGES

- Low CO_2 partial pressure in the flue gas
- Huge quantities of flue gas to be treated (Huge columns)
- High energy demand in the reboiler (25-35% of power plant output)
- Solvent losses and waste products
- High cost of the current conventional capture process

Picture: CATO pilot plant -Rotterdam

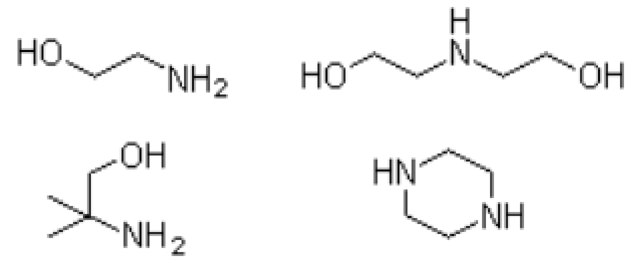
ISSUES FOR SOLVENT-BASED POST - COMBUSTION CAPTURE

- Solvent technologies are leading option but currently:
  - Power cost increases >50%
  - Generation efficiency decreases by 15 – 35%
- Solvent process break-through required
  - Energy requirements
  - Reaction rates
  - Contactor improvements
  - Liquid capacities
  - Chemical stability/corrosion
  - Desorption process improvements
  - Hence cost reductions
- Integration with power plant
  - Heat integration with other process plant
  - Concepts for "capture readiness"

PCC CAPTURE RESEARCH EFFORTS

PCC Research Efforts Include:

Development of better solvents that have a lower regeneration requirement and higher CO_2 absorption capacity



Development of novel processes that utilize different technologies

solid sorbents

membranes

Development of process modifications to the existing conventional process aimed at lowering the overall energy requirement

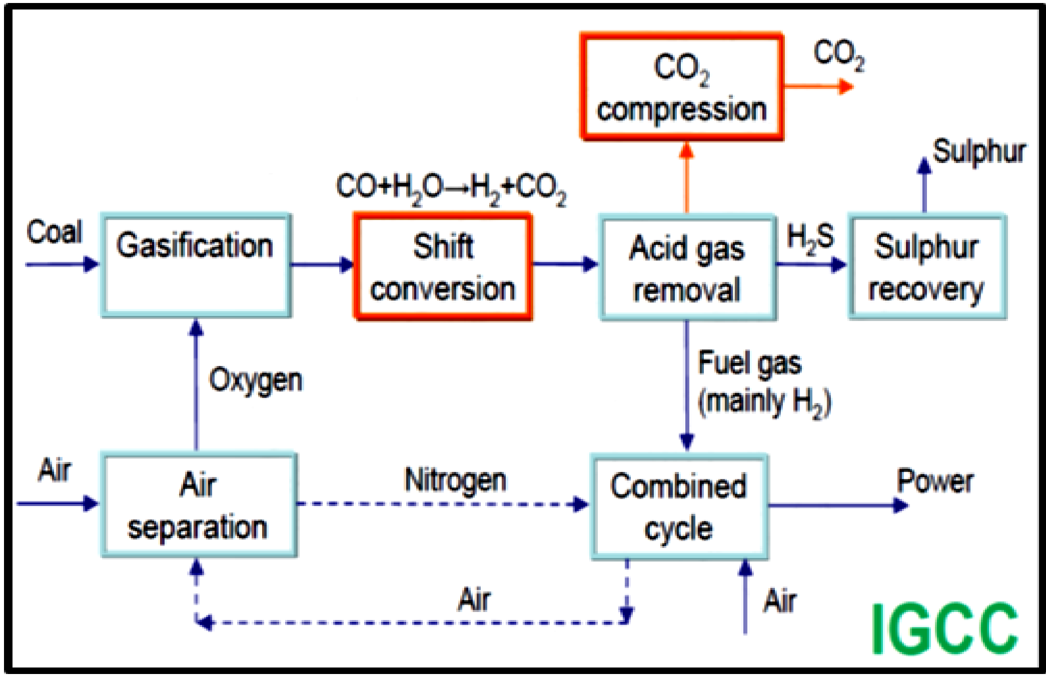
Split flow

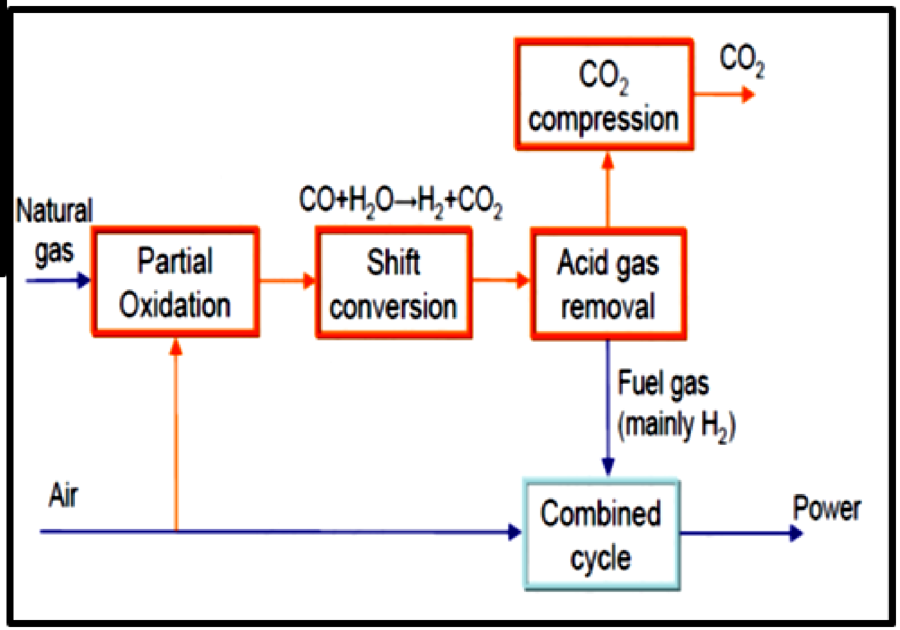
Vapor recompression

Heat-integration

Multi-component columns

Integrated Gasification Combined Cycle (IGCC) with CO_2 capture Process Flow Diagram





INTEGRATED GASIFICATION COMBINED CYCLE (IGCC) WITH CO_2 CAPTURE

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Advantages

- High CO_2 concentration and high overall pressure
- Lower energy consumption for CO_2 separation as compared to post-combustion capture
- Proven CO_2 separation technology
- Possibility of co-production of hydrogen

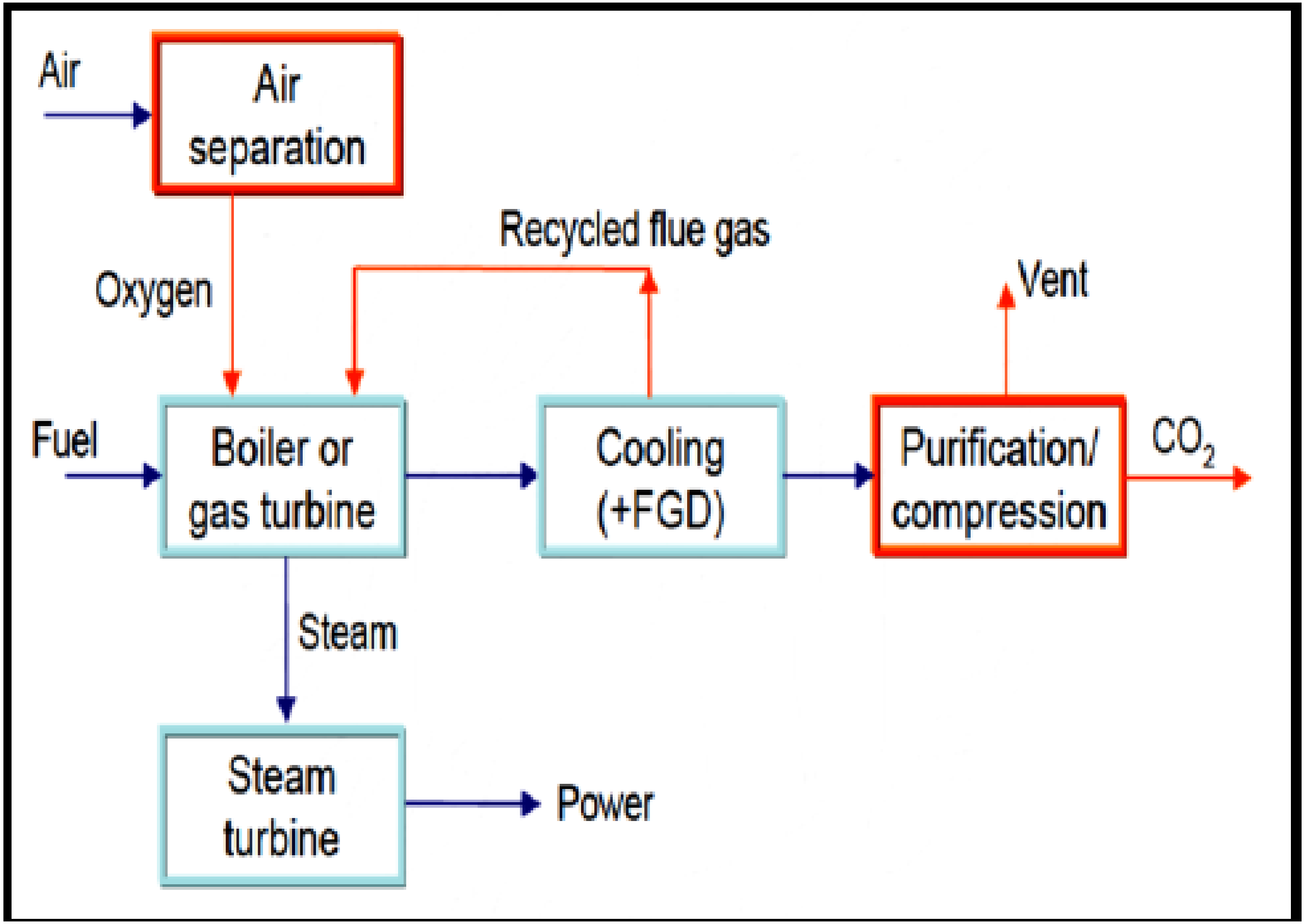
Disadvantages

- IGCC is unfamiliar technology for power generators and the process is more complex
- Existing coal fired plants have low availability
- IGCC without CO_2 capture has generally higher costs than pulverised coal combustion

IGCC: KEY ISSUES

- Development in gasifier technology
- Development in shift reactor
  - – Choice of sour versus sweet shift reaction
- Development in separation of CO_2 using physical absorption technologies
- Development in the gas turbine technology:
  - – Development of gas turbine firing H_2 rich
- Advanced concepts to decrease energy penalty/costs:
  - – Sorption enhanced WGS/reforming
  - – Membrane WGS/reforming

OXY-FUEL COMBUSTION: PROCESS BLOCK DIAGRAM



OXY-FUEL COMBUSTION: GENERAL OVERVIEW

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Advantages

- – Boiler and burners could be fairly conventional
- – Possibility of compact boilers with lower quantities of flue gas recycle
- – Possibility of avoiding FGD

Disadvantages

- – Testing for the large scale burners are still on-going. Oxyfuel fired boiler for power generation is not yet commercially available
- Deployment of demonstration plant is needed to gain confidence
- – High cost of oxygen production
- Advanced oxygen separation membranes with lower energy consumptions at pilot plant scale

OXY-FUEL COMBUSTION: KEY ISSUES

- Boiler and burner development:
  - Build confidence in running an oxy-fuel burner boiler especially at the same scale of current PC boiler
  - Various technical issues elucidated: heat transfer aspect, combustion behaviour, ash and slagging, equipment scaling up, emissions control,…
- Air separation unit: cost and capacity of oxygen production
- Air ingress:
  - Estimated that every 1% air ingress should result in about 3-5% reduction of the CO_2 concentration in the flue gas
  - This is a big challenge especially for retrofitting a power plant
- CO_2 processing (removal of impurities)

CO_2 SEPARATION CURRENT AND FUTURE TECHNOLOGIES

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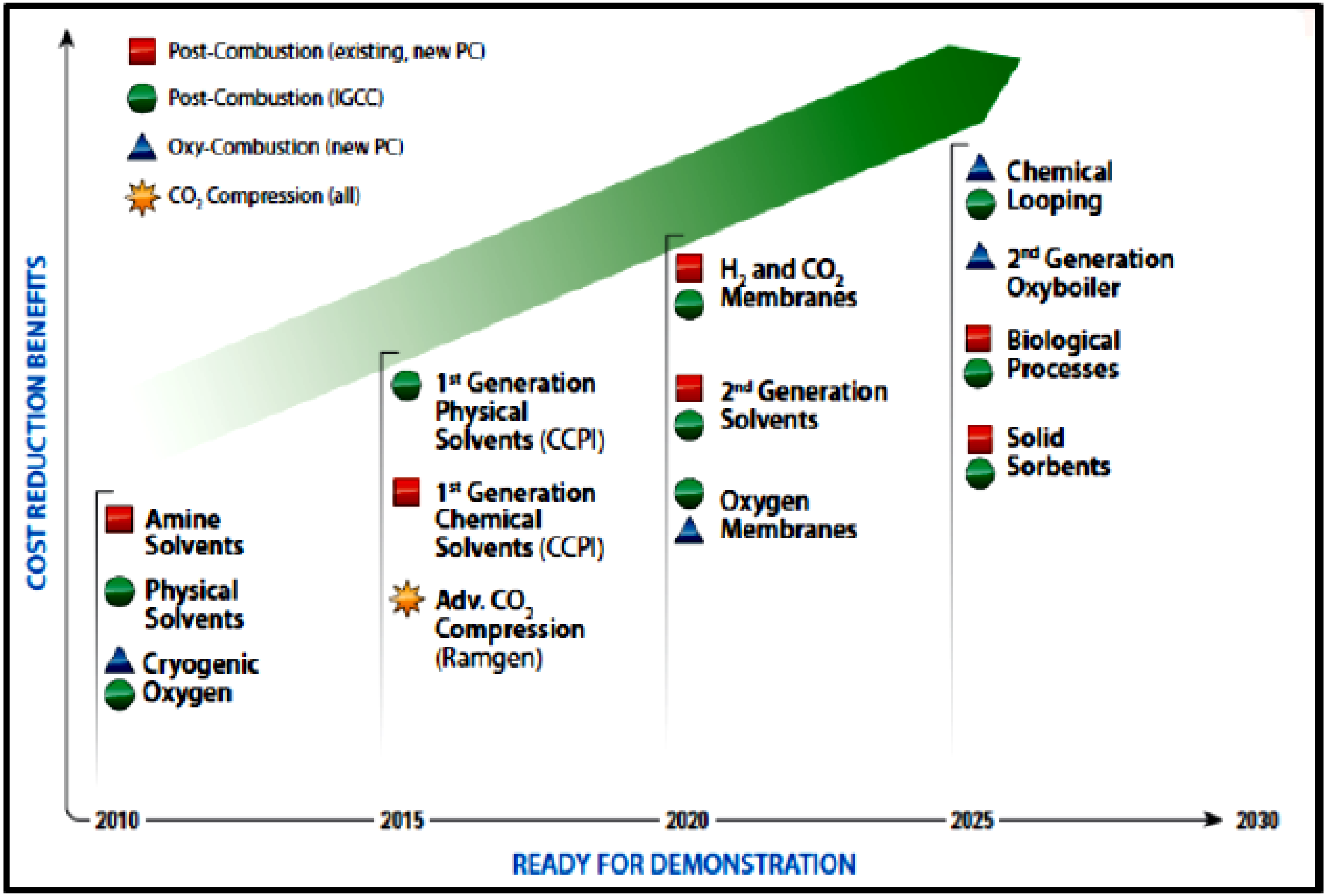
Capture method	Post-combustion decarbonisation (CO_2/N_2)		Pre-combustion decarbonisation (CO_2/H_2)		Oxyfuel conversion (O_2/N_2)	
Principles of Separation	Current	Future	Current	Future	Current	Future
Solvents/Absorption	Chemical solvents	Improved Porcess Design Improved Solvents Novel contacting equipment	Chemical solvents Physical solvents	Improved Process deisgn Improved solvents Novel contacting Equipment	NA	Bio-mimetic solvents
Membranes	Polymeric	Ceramic faciliated transport Carbon molecular sieve	Polymeric	Ceramic Palladium Reactors Contactors	Polymeric	Ion-transport facilitated transport
Solid Sorbents	Zeolites Activated Carbon	Carbonates Carbon based solvents	Zeolites Activated carbon Alumina	Dolomites Hydrotalcites Zirconates	Zeolites Activated carbon	Caronates Hydrotalcites Silicates
Cryogenic	Liquefaction	Hybrid Process Anti-sublimation	Liquefaction	Hybrid process	Distillation	Improved distillation
Biotechnology		Algae production		High pressure		Bio-mimetic

Source: IPCC Report 2005

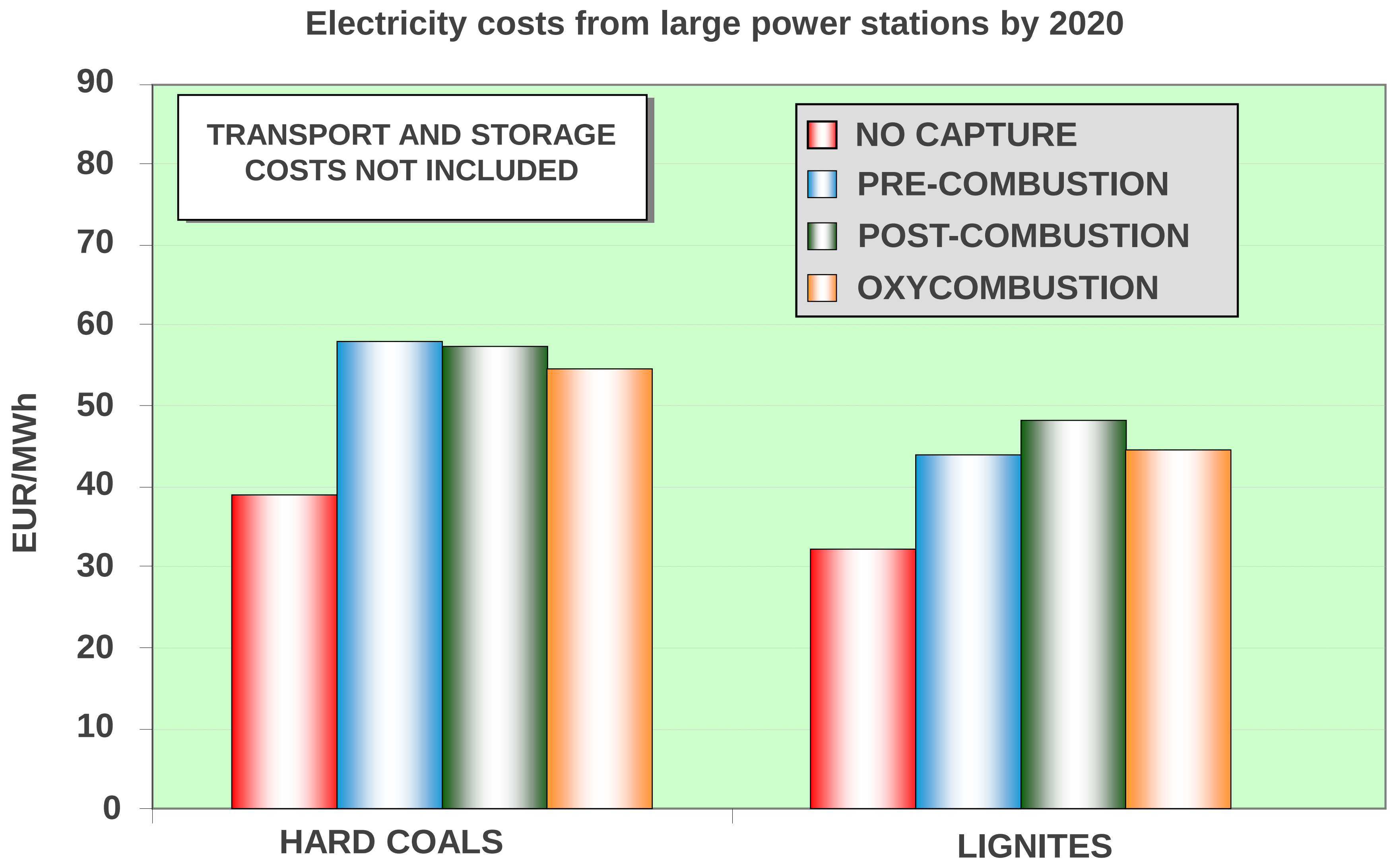
CO_2 CAPTURE TECHNOLOGIES FOR INDUSTRIAL APPLICATIONS

Industries	Suitable CCS technologies
Iron and Steel	1. Oxyfueling to generate a pure CO_2 off-gas 2.Using waste heat for chemical absorption 3. Substituting coke and coal with hydrogen or electricity 4.Re-deisgning the blast furnace to use oxygen and removing the CO2 with physical absorbents 5. Post-combustion capture using chemical absorbents is not suitable for CO2 capture in the iron and steel industry as insufficient waste heat is available 6. Only about half of the necessary heat could be recovered, therefore Integrated oxyfueling is preferred
Cement Industry	1. Back-end chemical absorption 2. Oxyfueling 3. Chemical looping using calcium oxide 4. Using oxyegn instead of air in cement kilns would result in a pure CO_2 off-gas
Petrochemicals	1. Chemical absorption
Pulp and Paper	1. Chemical absorption 2. NGCC electricity coupled with CCS 3. Biofuels 4. Black liquor IGCC with CCS
Fossil Fuel Production and Transformation	1. Chemical absorption (for lower CO_2 content sour gas) 2. Physical absorption (for higher CO_2 content sour gas, natural gas) 3.Membranes (for higher CO_2 content sour gas, natural gas)
Heavy Oil and Tar sands	1. Chemicla and Physical absorption
Refinery	1. Post combustion cpature like chemical, physical and membrane absorption
Hydrogen production	1. Large scale IGCC
Gasification and Hydrocarbon Synfuel Production	1. Chemical absorption and membranes

STATUS AND DEVELOPMENT LINE OF THE CO_2 CAPTURE TECHNOLOGIES



COST OF ELECTRICTY WITH CCS



COST OF CO_2 AVOIDED

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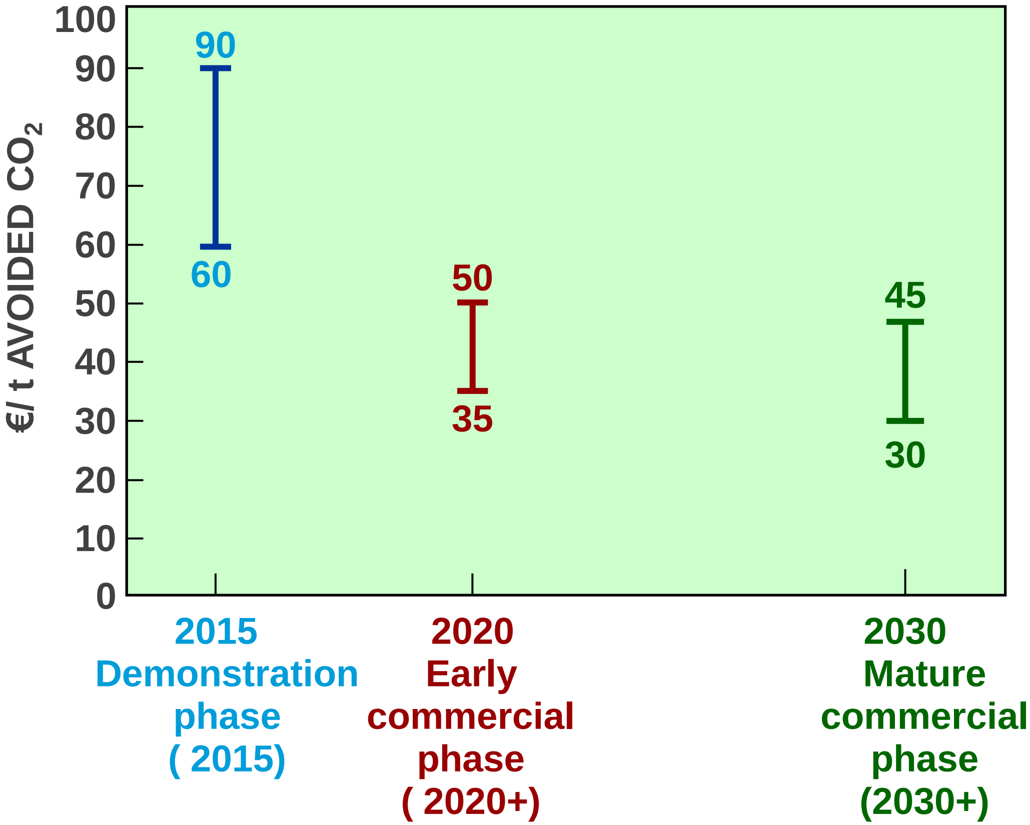
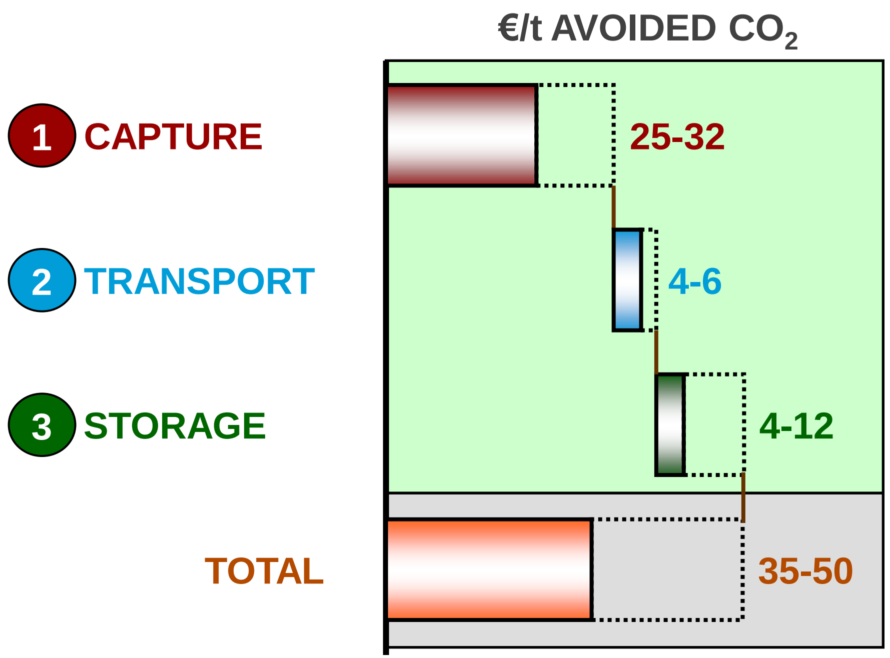
CO_2 Costs



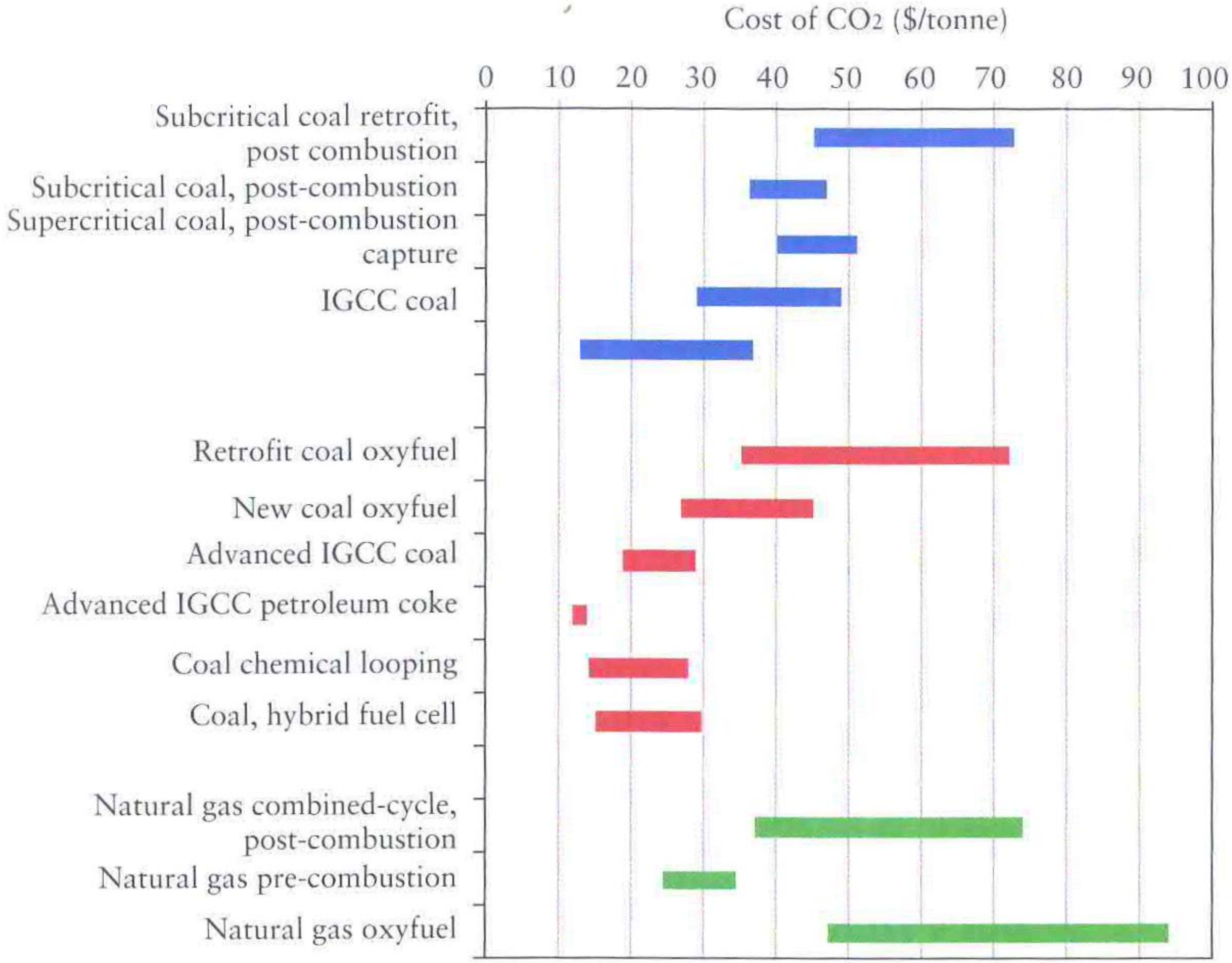
Avoided CO_2 cost



CO_2 cost breakdown of early commercial units

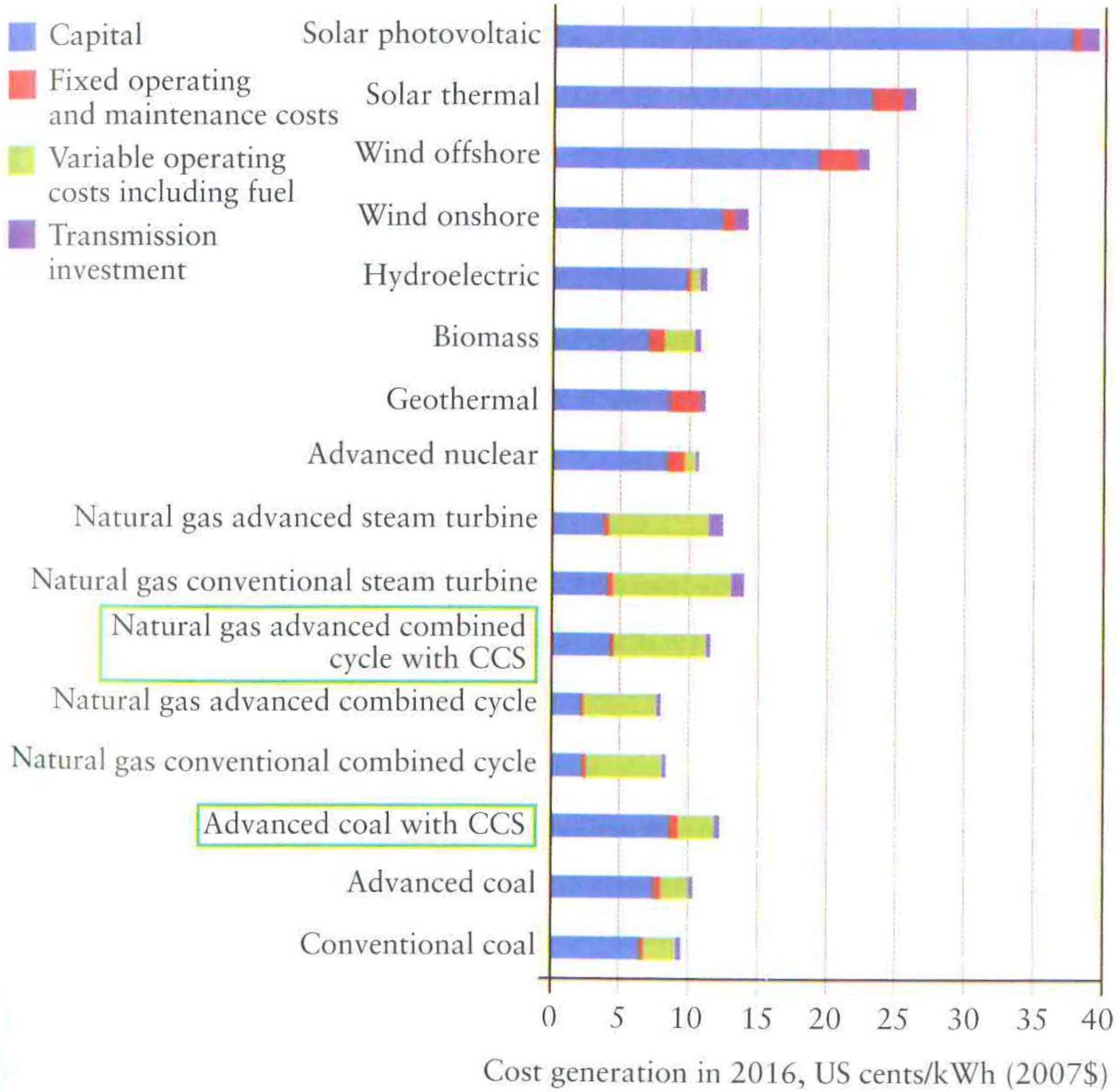
From Carbon Capture & Storage: Assessing the Economics. The McKinsey Company. September 2008

COST OF CO_2 CAPTURE FROM COAL-FIRED PLANTS WITH CONVENTIONAL AND ADVANCED TECHNOLOGICAL OPTIONS



Source: R. Mills, Capturing Carbon 2010

ESTIMATED ELECTRICITY GENERATION COSTS FOR VARIOUS TECHNOLOGIES IN THE USA



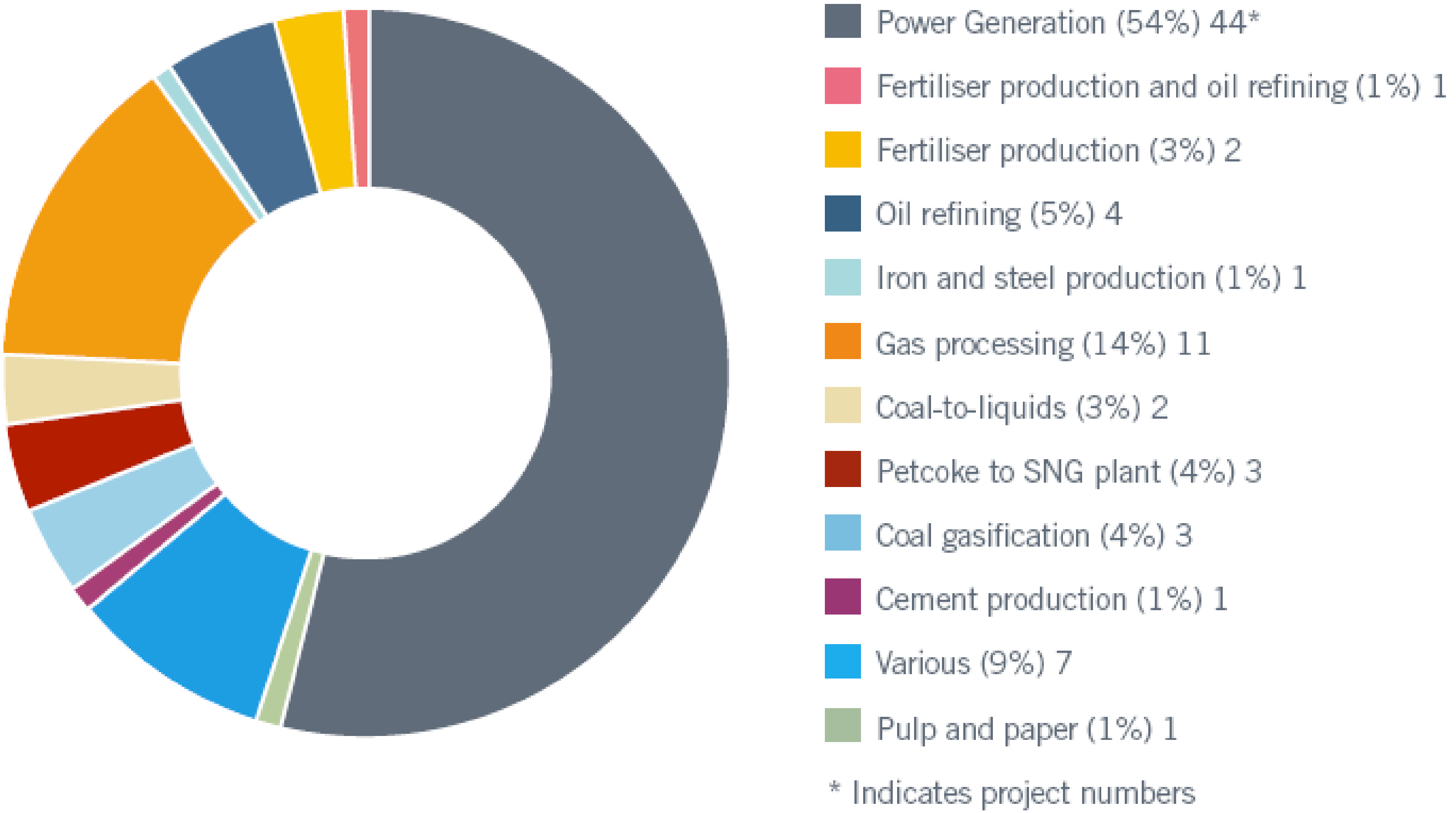
Source: R. Mills, Capturing Carbon 2010

- Post combustion capture demonstrated at 1Mt scale on natural gas
  - Pilot plants on flue gas need to be scaled up
- Pre combustion capture (IGCCS) not yet demonstrated in integrated mode at scale
- Oxy fuel
  - Pilot plants (30 MW) need to demonstrate technology then scale up needed

OTHER INDUSTRIAL SECTORS

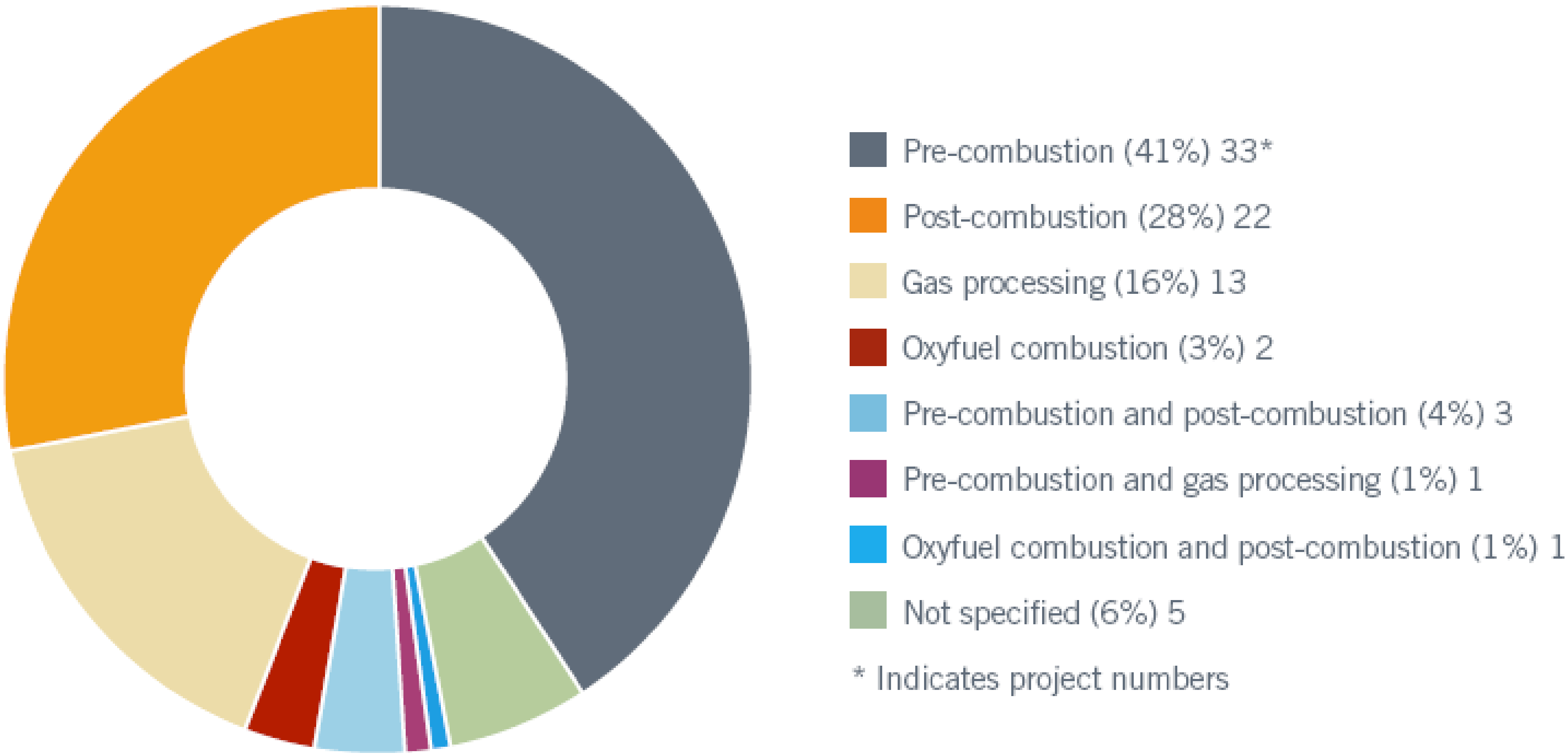
- On going study looking at iron and steel industries
- Recently looked at cement industry
- Technically feasible to introduce CCS technology into cement plants
- Costs are high
  - €107/t CO_2 avoided for a typical EU plant
  - €60/t CO_2 avoided for a typical Asian plant
  - Integration could halve costs
- May be commercial implications for CCS deployment
- 50% of current cement production in China
  - No driver to implement CCS

ACTIVE OR PLANNED LARGE SCALE CCS PROJECTS BY FACILITY/APPLICATION TYPE



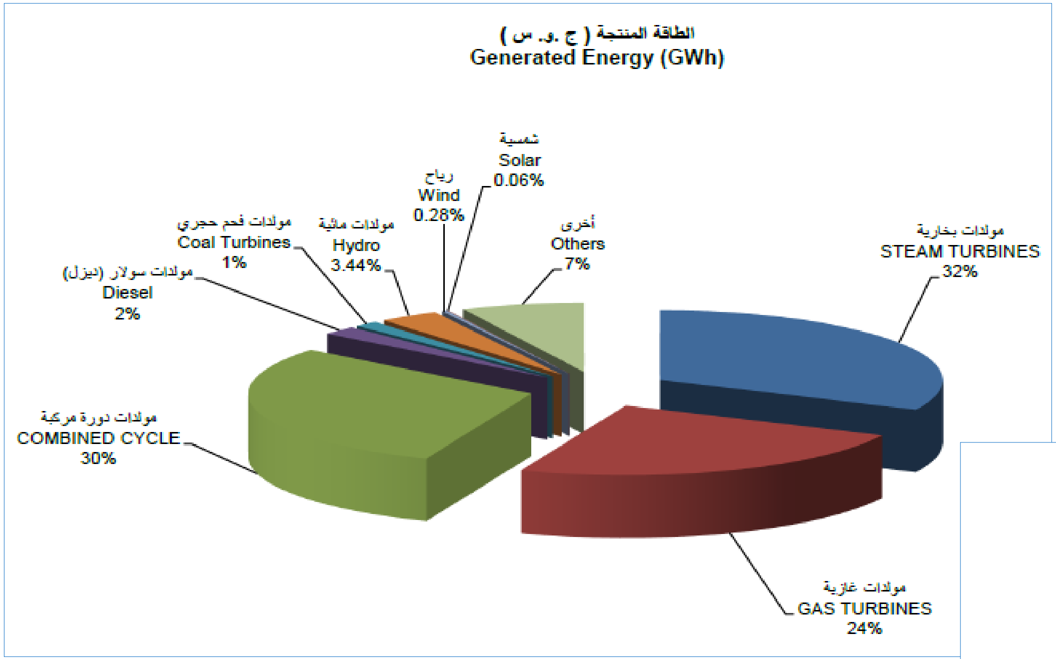
Source: Status of CCS Projects, GCCSI Report , Updated April 2010

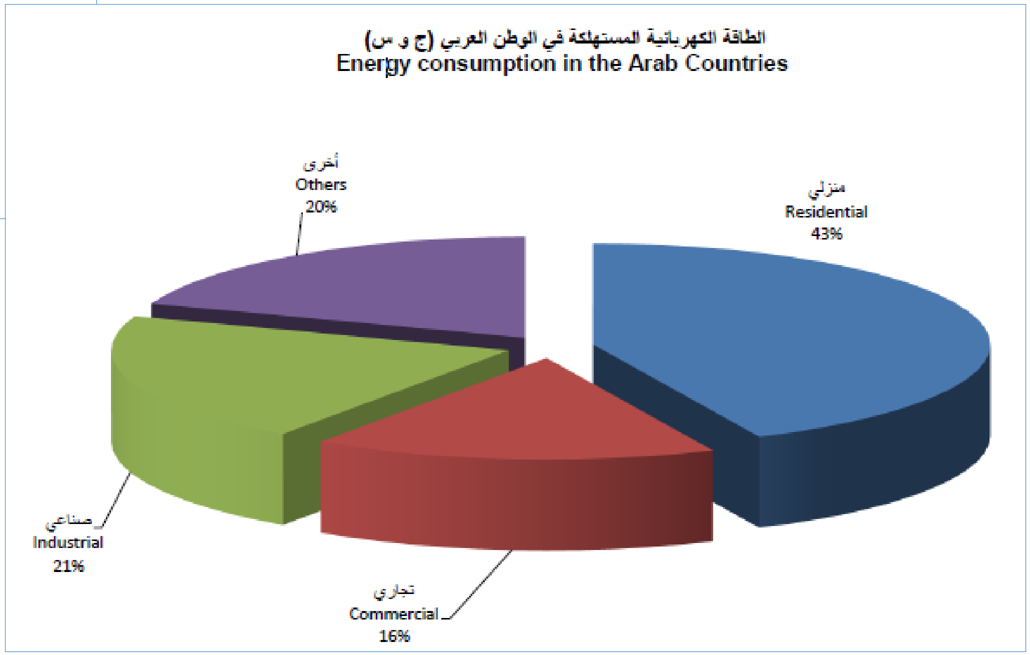
ACTIVE OR PLANNED LARGE SCALE CCS PROJECTS BY CAPTURE TYPE



Source: Status of CCS Projects, GCCSI Report , Updated April 2010

ESCWA REGION ENERGY SUPPLY AND CONSUMPTION BY SECTOR





Source: AFED 2013 report

ESCWA REGION ENERGY DEMANDS

Electricity consumption (TWh) in ESCWA Region													
	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
World	13514	14133	14272	14772	15329	16019	16716	17387	18194	18569	18462	19762	20407
Algeria	20.0	21.2	22.3	23.3	25.4	26.3	29.5	29.0	30.6	32.9	30.6	36.6	41.2
Bahrain	5.6	5.7	6.2	6.7	7.5	8.1	8.5	9.3	10.8	10.2	10.8	12.4	13.0
Egypt	63.6	67.2	72.2	77.1	83.5	88.3	95.3	102.5	110.8	116.2	123.4	130.4	138.4
Iraq	29.2	29.2	30.0	31.5	26.7	31.6	22.5	27.0	21.8	21.8	32.8	36.8	42.6
Jordan	6.3	6.6	6.9	7.5	7.8	8.7	9.1	10.1	11.2	12.1	12.5	13.4	14.2
Kuwait	28.1	28.8	30.5	32.4	35.4	36.7	38.8	42.2	42.8	45.2	46.6	50.1	50.4
Lebanon	9.6	9.8	10.0	10.7	11.1	11.1	11.3	11.0	11.5	12.2	13.1	15.1	15.3
Libya	11.5	11.9	12.3	15.3	16.6	17.7	19.9	22.3	22.7	26.7	26.9	28.4	24.0
Morocco	12.9	14.1	15.3	15.8	17.3	18.4	19.3	21.2	22.4	23.2	23.9	24.8	26.5
Oman	7.0	7.3	7.9	8.2	8.5	9.4	10.3	11.1	11.8	13.5	15.2	16.5	19.0
Qatar	8.0	8.5	9.3	10.2	11.2	12.3	13.4	15.9	18.1	20.1	22.6	26.4	30.1
Saudi Arabia	113.3	117.1	126.1	131.9	146.0	146.9	157.5	167.6	174.8	186.5	199.1	218.7	226.6
Sudan	2.1	2.2	1.9	2.2	2.4	2.5	3.0	3.5	3.8	4.3	5.1	6.0	6.7
Syria	16.2	17.5	19.2	21.1	22.5	24.9	27.5	29.3	30.6	32.2	32.1	39.0	37.7
Tunisia	9.0	9.5	10.1	10.5	9.9	10.4	11.0	11.3	11.9	12.4	13.4	14.2	13.8
UAE	36.2	38.6	40.1	43.8	46.2	49.0	56.3	61.9	70.5	73.5	77.2	83.2	83.8
Yemen	2.2	2.5	2.6	2.8	3.1	3.4	3.7	4.0	4.5	5.0	5.1	6.0	4.5
ESCWA total	360.7	376.3	400.5	427.8	455.7	479.4	507.3	550.1	580.0	615.2	659.9	721.4	746.5
share of the World	*2.7%*	*2.7%*	*2.8%*	*2.9%*	*3.0%*	*3.0%*	*3.0%*	*3.2%*	*3.2%*	*3.3%*	*3.6%*	*3.7%*	*3.7%*

- Continuous increase in energy demands
- Continuous major dependency on fossil fuels

Source: AFED 2013 report

ESCWA REGION TOTAL POWER GENERATED AND CO2 EMITTED

Region		1971	1980	1985	1990	1995	2000	2005	2008	2009	2010
Algeria	TPES	3.5	11.2	17.7	22.2	24.1	27.0	32.4	37.4	40.7	40.4
	TCO_2*	8.9	28.4	43.2	52.7	56.8	63.5	79.6	89.7	99.1	98.6
Egypt	TPES	7.8	15.2	25.7	32.3	35.3	40.7	62.7	71.9	71.4	73.3
	TCO_2	20.3	41.9	64.8	78.4	83.1	101.3	152.6	175.3	172.7	177.6
Libya	TPES	1.6	6.9	10.0	11.3	15.8	16.6	17.6	19.2	21.9	19.1
	TCO_2	3.7	18.6	22.5	27.4	35.1	39.7	42.5	47.0	49.8	51.6
Morocco	TPES	2.4	4.9	5.6	6.9	8.6	10.2	13.1	15.0	15.1	16.5
	TCO_2	6.8	14.0	16.5	19.6	26.0	29.4	40.1	43.5	42.7	46.0
Sudan	TPES	7.0	8.4	9.5	10.6	12.0	13.3	15.1	15.1	15.9	16.2
	TCO_2	3.3	3.7	4.2	5.5	4.6	5.5	9.2	12.4	13.5	13.7
Tunisia	TPES	1.7	3.3	4.2	4.9	5.8	7.3	8.3	9.4	9.0	9.6
	TCO_2	3.7	7.8	9.6	12.1	14.2	18.0	20.2	21.5	21.3	21.9
Bahrain	TPES	1.4	2.8	4.2	4.4	4.9	5.9	7.5	9.2	9.5	9.8
	TCO_2	3.0	7.4	10.4	11.7	11.6	14.1	18.1	22.3	22.8	23.6
Iraq	TPES	4.1	9.6	13.8	19.7	34.5	25.9	26.9	28.5	32.5	37.8
	TCO_2	10.4	27.0	36.8	53.4	97.5	70.3	74.9	73.4	91.9	104.5
Jordan	TPES	0.5	1.5	2.6	3.3	4.3	4.9	6.7	7.1	7.5	7.2
	TCO_2	1.3	4.3	7.4	9.2	12.2	14.4	18.0	18.5	19.3	18.6
Kuwait	TPES	6.1	10.5	14.0	9.1	14.9	18.8	26.4	27.9	30.2	33.4
	TCO_2	14.0	26.6	37.1	28.7	36.1	49.1	70.1	73.9	80.7	87.4
Lebanon	TPES	1.8	2.5	2.3	2.0	4.4	4.9	5.0	5.4	6.6	6.5
	TCO_2	4.5	6.6	6.5	5.5	12.8	14.1	14.5	15.8	19.1	18.6
Oman	TPES	0.2	1.1	2.1	4.2	6.1	8.1	10.8	15.9	14.9	20.0
	TCO_2	0.3	2.2	5.7	10.2	14.7	20.2	28.2	36.5	40.0	40.3
Qatar	TPES	0.9	3.3	5.4	6.2	7.9	10.4	16.9	21.5	23.5	30.2
	TCO_2	2.2	7.7	12.1	14.1	18.7	23.7	37.6	49.8	56.4	66.1
KSA	TPES	7.4	31.1	46.0	59.8	87.5	101.3	145.5	154.1	157.9	169.3
	TCO_2	12.7	99.1	122.6	159.1	207.8	252.8	333.8	387.1	411.4	446.0
Syria	TPES	2.4	4.5	7.8	10.5	12.1	15.8	20.8	23.1	21.2	21.7
	TCO_2	6.0	13.1	21.1	28.2	32.8	39.8	54.9	62.7	57.2	57.8
UAE	TPES	1.0	7.2	13.7	20.4	27.7	33.9	43.2	58.3	60.4	62.1
	TCO_2	2.4	19.1	35.6	51.9	69.6	85.6	108.4	145.6	149.4	154.0
Yemen	TPES	0.7	1.3	1.7	2.5	3.4	4.7	6.6	7.1	7.4	7.2
	TCO_2	1.2	3.4	4.8	6.4	9.3	13.2	18.8	21.1	21.6	21.7

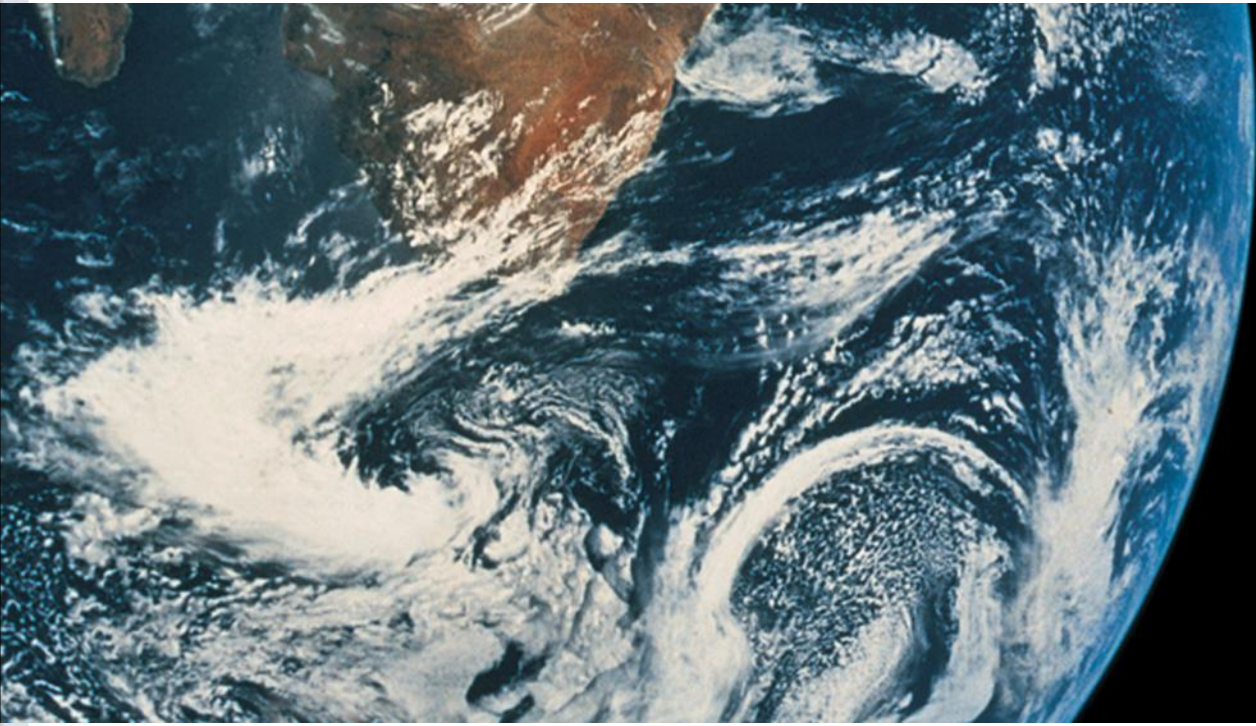
* Total CO2 emissions from fuel combustion in the Arab countries, sectoral approach.
Source: IEA: CO2 Emissions from Fuel Combustion – Highlights, 2012.

Source: AFED 2013 report

ESCWA REGION AND CCUS!!

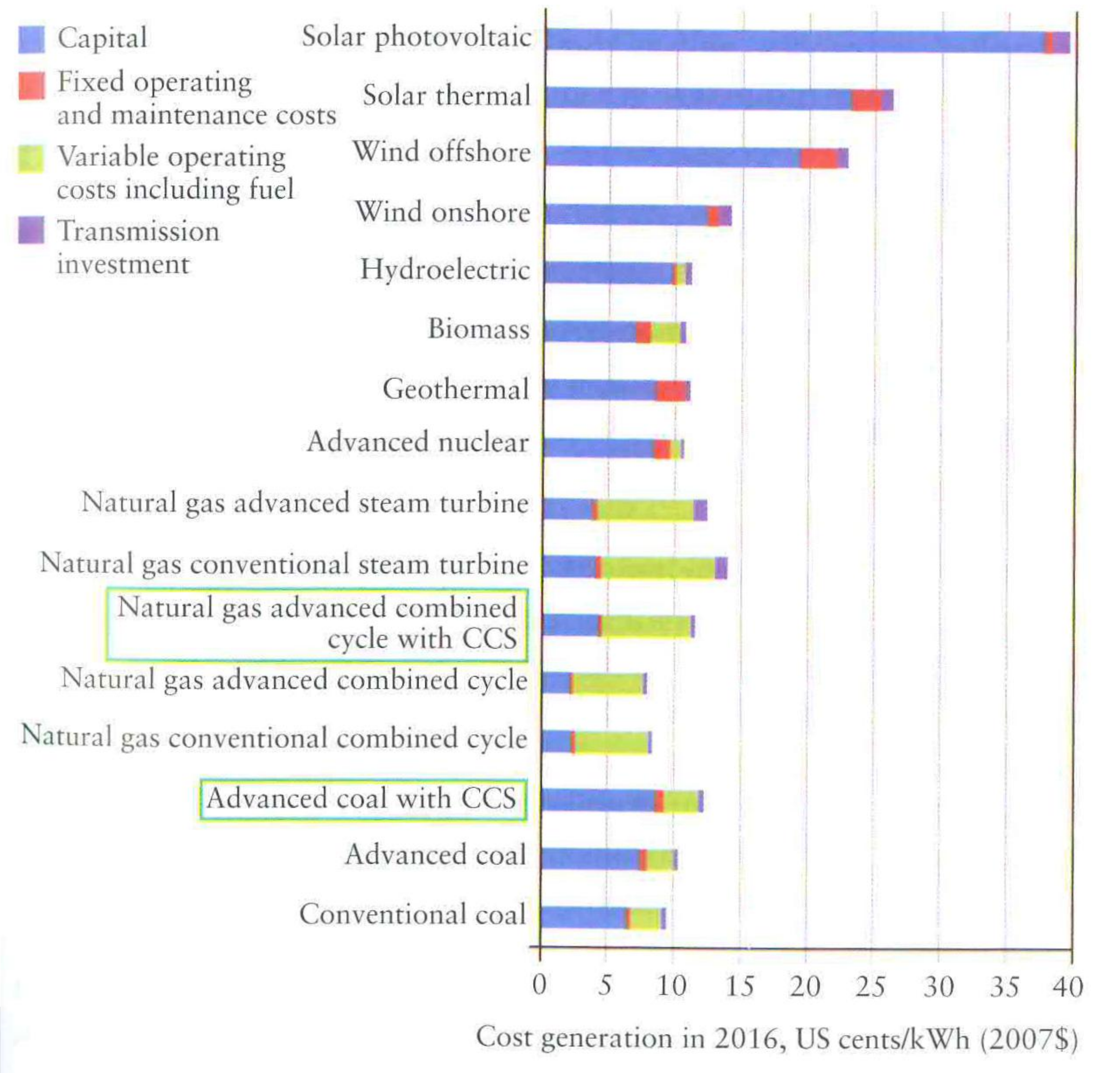
- Continuous increase in energy demand
- Continuous dependency on fossil fuels as major sources of energy
- The high energy consumption resulted in high CO_2 emissions per capita in the ESCWA region
- There is a clear need for CCUS deployment in large scale.
- CCUS deployment in the ESCWA region should target the power generation sector from both natural gas and oil fired plant in addition to smaller industrial locations.
- Questions need to be answered:
  - What technologies to deploy?
  - What sector to start with and do we have a low hanging fruits?
  - How to build the knowledge and human capacity to deploy this technology?
  - How to establish cross-boarders projects to fulfill all the region needs?
  - How to interact with the international communities to benefit from their knowledge?
  - What is the rule of both the governments and the private sectors to support the starting phase of CCUS deployment in the region?

THANK YOU



Dr. Mohammad Abu Zahra
Chemical Engineering Program
CCS R&D Activities Coordinator
mabuzahra@masdar.ac.ae
+971 (0)2 810 9181

ESTIMATED ELECTRICITY GENERATION COSTS FOR VARIOUS TECHNOLOGIES IN THE USA



Source: R. Mills, Capturing Carbon 2010

THANK YOU

QUESTIONS??

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Chemical Engineering Program
CCS R&D Activities Coordinator
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+971 (0)2 810 9181

THERMAL ENERGY

Regeneration of solvents; Extracted from steam cycle in power plant

Sum of sensible heat, desorption enthalpy and stripping steam production

$$Q_{total}[J / mol CO_2] = Q_{Sens} + Q_{Des} + Q_{Strip}$$

$$Q_{Sens} = \frac{\rho C_p \Delta T}{(\alpha_{rich} - \alpha_{lean}) C_{Ab}}$$

$$Q_{des} = \Delta H_{absCO_2}$$

$$Q_{Strip} = \frac{P_{H_2O}(T_{rich}, \alpha_{rich})}{P^*_{CO_2}(T_{rich}, \alpha_{rich})} \Delta H^{Vap}_{H_2O}$$

Energy impact determined by:

- **Solvent properties** (reaction enthalpy, rich loading, cyclic loading, solvent concentration);
- **Process design** (heat exchanger temperature approach, regeneration temperature and pressure);
- **Integration into power plant**