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The global carbon nation: Status of CO_2 capture, storage and utilization

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Summary. — As the world transitions toward cleaner and more sustainable energy generation, Carbon Capture and Sequestration/Storage (CCS) plays an essential role in the portfolio of technologies to help reduce global greenhouse gas (GHG) emissions. The projected increase in population size and its resulting increase in global energy consumption, for both transportation and the electricity grid —the largest emitters of greenhouse gases, will continue to add to current CO_2 emissions levels during this transition. Since eighty percent of today's global energy continues to be generated by fossil fuels, a shift to low-carbon energy sources will take many decades. In recent years, shifting to renewables and increasing energy efficiencies have taken more importance than deploying CCS. Together, this triad —renewables, energy efficiency, and CCS— represent a strong paradigm for achieving a carbon-free world. Additionally, the need to accelerate CCS in developing economies like China and India are of increasing concern since migration to renewables is unlikely to occur quickly in those countries. CCS of stationary sources, accounting for only 20% reduction in emissions, as well as increasing efficiency in current systems are needed for major reductions in emissions. A rising urgency for fifty to eighty percent reduction of CO_2 emissions by 2050 and one hundred percent reduction by 2100 makes CCS all that more critical in the transition to a cleaner-energy future globally.

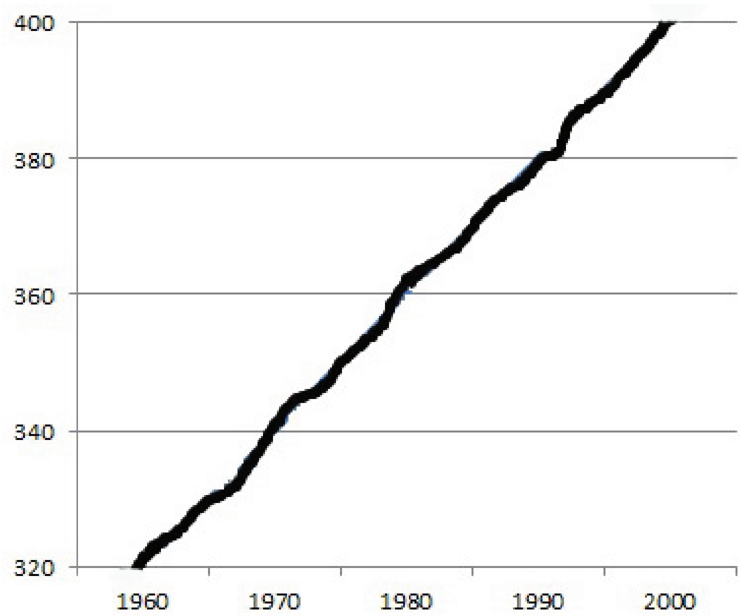

Fig. 1. – 30% rise in atmospheric CO_2 levels in 50 years (1960 to 2013.) (Source: Global CCS Institute 2015 Report & Mauna Loa Observatory).

1. – Background

Increasing use of fossil fuels, such as coal, oil and gas, since the mid-18th century, marked by the beginning of the Industrial Revolution, has led to a steady increase in carbon dioxide (CO_2) in the Earth's atmosphere. The last fifty years have demonstrated an intense increase that has put the rate of CO_2 permanently over 400 parts per minute (ppm) [1]. (See fig. 1.)

The world continues to be reliant on fossil fuels for transportation and electricity generation. In fact, the impact of a growing global population predicted to rise to 9 billion by 2050 is expected to increase world energy demand by fifty percent [2]. Reducing the global greenhouse (GHG) emissions from these sources cannot be achieved solely through increasing energy efficiency and deploying more renewable energy production [3]. Based on United States Environmental Protection Agency (EPA) estimates, a passenger car emits a little over 5000 kg of CO_2 a year (5 metric tonnes). Twenty-two million tonnes of stored CO_2, therefore, is equivalent to mitigating 4.2 million cars. (See fig. 2.)

Global CO_2 emissions from transportation and the electricity sector can be achieved in a number of ways. Improving energy efficiency by requiring people and industries to waste less energy, utilizing methods and techniques to enhance current systems, and changing behavior to use energy more efficiently is one area that can and has seen considerable impact on both energy consumption and resulting emissions reductions. Increasing the

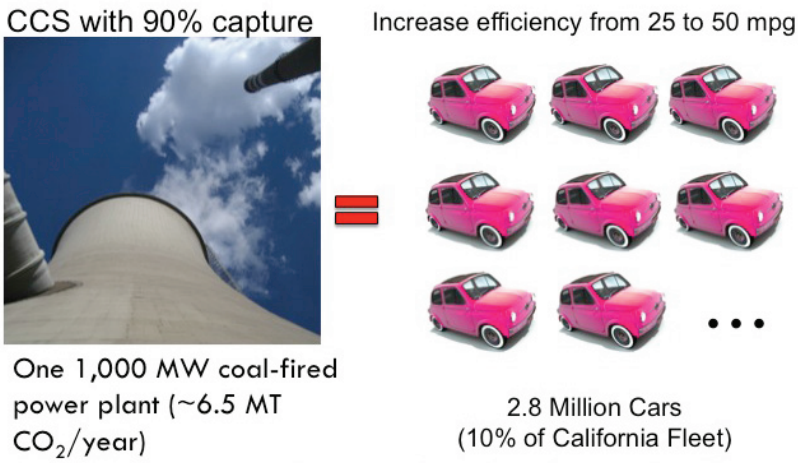

Fig. 2. – CCS can be an efficient means of large emissions reductions. (Source: EPA).

deployment of renewable energy sources, such as wind, solar, wave and geothermal is another area where the transition to a cleaner-energy future has and will continue to have influence on emissions. Lastly, emissions reduction through capture and storage and/or reuse can help by preventing additional emissions from entering the atmosphere.

Over sixty percent of energy use and GHG emissions are known to be from the electricity sector and transportation [4]. (See fig. 3.) There is a direct relationship between energy use and CO_2 emissions. Greater use of fossil fuel energy production

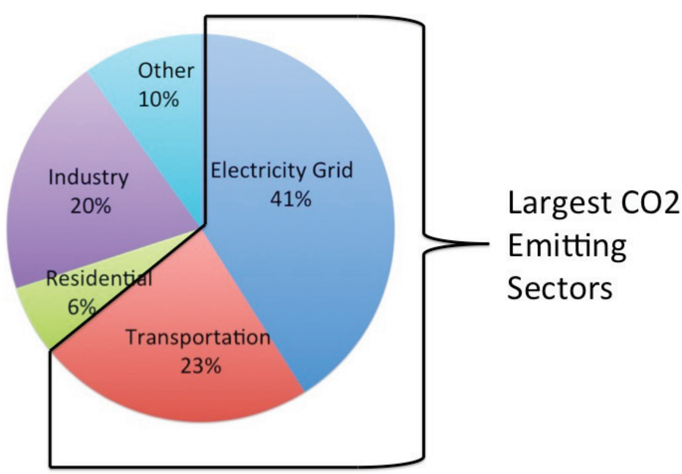

Fig. 3. – CO_2 emission by sector (Source: IEA).

leads to higher CO_2 emissions. Gasoline cars replaced by electric or biofuels ones and the transition from fossil fuel power plants to renewable electricity generation will change the amount of GHG emitted by these sources. CCS allows the continued use of fossil fuels during the decades it will take for the entire world to transition to non-carbon-dioxide-emitting energy sources. As noted earlier, the world still relies on fossil fuels today and it will remain the main source of energy generation for decades to come [5]. Fossil fuels (coal, oil, gas) represent eighty percent of the global energy mix, while renewables only account for thirteen percent, and are only projected to contribute to thirty percent of the global energy mix by 2030 [6].

2. – Why is CO_2 capture and storage important?

Technologies for carbon dioxide capture and storage have the potential to reduce carbon dioxide emissions from energy generated by fossil fuels. As noted earlier, CCS is not sufficient on its own to achieve the fifty to eighty percent reduction in emissions needed by 2050 and the one hundred percent needed by 2100. To achieve this type of emissions reduction, CCS must work in conjunction with a transition to renewable energy generation and increased energy efficiency. Since more than eighty percent of today's energy comes from fossil fuels and the transition to low or no carbon energy sources is time consuming, challenging and costly, CCS is necessary to achieve large and rapid carbon dioxide emissions reductions.

In the United States alone, more than 40% of CO_2 emissions are from power generation for the electricity grid. CCS can reduce emissions from electric power generation by eighty to ninety percent, a dramatic decrease that can have broad impacts across the electricity sector. Industrial sectors, such as natural gas production, cement, steel, and chemicals, can also benefit greatly from implementation of CCS by reducing emissions from industrial processes [7]. These industries typically generate CO_2 during production processes, in addition to using it as fuel, and have no alternatives for reducing emissions. (See fig. 4.) Implementing CCS technologies in the industrial sector will allow for these industries to continue to be viable and bring economic benefits [8]. Additionally, countries that have the geographic capacity to provide storage for captured CO_2 have the potential to benefit from an emerging and needed market.

The growing and continued demand for energy makes CCS a needed and desirable solution to global CO_2 emissions, given projections that fossil fuels will continue to be needed in the transition to renewables over the coming decades [9]. CCS can reduce emissions from many sources, and is applicable to sixty percent (15 billion tonnes) of CO_2 emissions per year coming from stationary sources such as power plants and industry. (See fig. 5.) Over seven thousand four hundred sources greater than 0.1 Mt/yr. currently exist globally. CCS continues to expand worldwide with approximately fourteen megatonnes per year coming from operating industrial scale projects. Thirteen megatonnes per year are currently under construction to expand the industrial scale projects [10].

Global energy-related CO_2 emissions coming from industrial applications are currently at about twenty-five percent of the total and are projected to grow to more than 50% by

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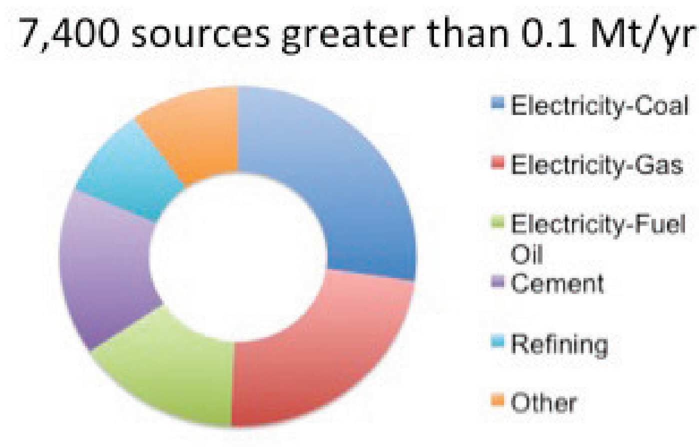

Fig. 4. – 7400 sources greater than 0.1 Mt/yr (Source: IEA).

2050, if emissions are not addressed as a more critical issue [11]. Successful demonstration of CCS in industrial sectors is and will continue to be vital to future emission reduction efforts. Currently, around 40 million tonnes per year (Mtpa) —similar to the total annual CO_2 emissions of Denmark or Switzerland— are being captured by twenty-two projects around the globe.

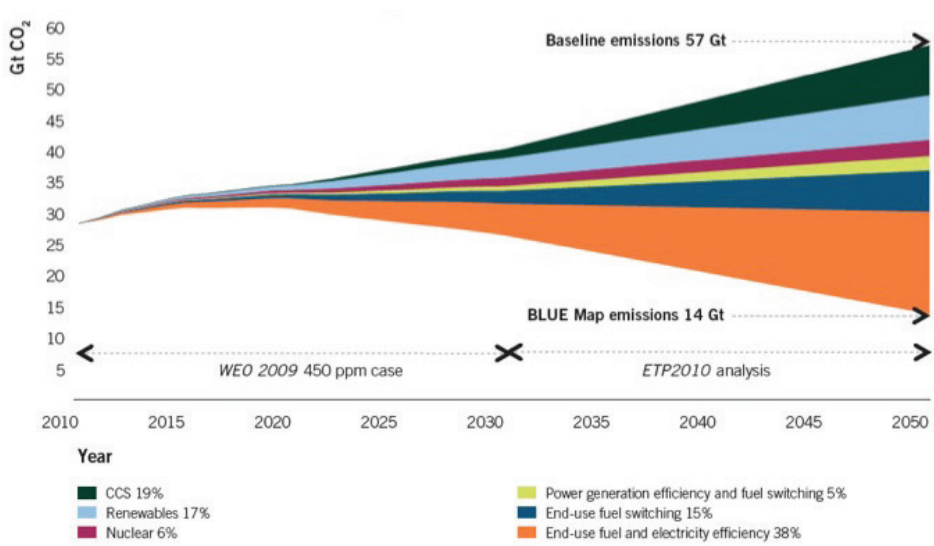

Fig. 5. – CCS is expected to contribute about 20% to CO_2 reductions. (Source: IEA).

3. – CCS is expected to contribute to the needed CO_2 emissions reduction

De-carbonizing the power and transportation sectors by controlling emissions as well as reducing the demand for fossil fuel energy and supplying low- or no-carbon energy continues to be the key to a clean energy future. Developing countries such as China and India have been the largest contributors to increasing CO_2 emissions due to the use of coal, the dirtiest and most easily accessible fossil fuel worldwide. Similar trends in other developing countries could potentially double or triple CO_2 emissions by mid-century, making CCS even more critical in working toward reversing or mitigating the existing GHG emission problem [12]. CCS is not without controversy, which will be discussed later, where questions about its stability to remain stored is an actuality over longer time periods. CCS technology exists and can continue to be perfected. What remains to be seen is whether CCS finds itself equal to other strategies, such as increased deployment of renewables and enhanced energy efficiency, and how quickly and broadly it can be implemented. The CO_2 in the atmosphere is not going anywhere, and in fact, will only continue to rise unless CCS is deployed where it counts the most —the power and industrial sectors.

4. – CCS is an efficient means of large emissions reductions

Understanding the scale and scope of CCS is important for realizing the value it adds. CCS that can capture ninety percent of CO_2, *i.e.*, one 1000 MW coal-fired power plant which emits approximately 6.5 MT of CO_2 per year is equal to an increased car efficiency from 25 to 50 mpg of 2.8 million cars, which is about ten percent of California's personal vehicle fleet (see fig. 2). At this scale, CCS has greater significance for increasing reductions through both the number of ways and locations for greatest impact. In looking at new power plants (typically natural gas) *versus* old power plants (many of which are coal-fired plants), newer natural gas plants can utilize efficient generation technology to achieve CO_2 reduction standards, whereas new coal plants cannot and must use CCS to reach CO_2 reduction standards [13].

Currently, fifteen active commercial-scale industrial CCS projects, ten of them in the United States, are currently deployed worldwide including the Boundary Dam Power Station in Saskatchewan, Canada in operation since late 2014, and other coal-fired commercial power plants, such as NRG Energy's Petra Nova project in Texas opening in 2017. Globally, another fifty commercial-scale CCS projects will come online in the electricity and industrial sectors in the coming decade.

For the United States, and for the world, all options need to be considered in the race against GHG emissions. All efforts, expanding renewables, enhancing energy efficiency and conservation, and even creating a carbon trade market, are part of the solution along with CCS, and will need to be implemented simultaneously to have the greatest impact. (See fig. 6.) CCS can serve as the bridge to a low-carbon energy future and economy by reducing carbon dioxide emissions from power generation while expanding renewables and increasing energy efficiency [14].

Fig. 6. – Quote from IEA.

5. – The opportunity

CCS alone can provide up to 20% of the CO_2 emission reductions we need to make by 2050, and is the only way to greatly reduce carbon emissions from electricity generation while working toward expansion of renewable energy capacity and increasing energy efficiency and conservation. (See fig. 7.) Many question the necessity of CCS, given the success of energy efficiency and the investments in expanding renewable energy. Renewable energy sources currently account for minimal electricity generation (just four percent for the United States) and would be highly unlikely to be deployed at a rate that could meet large portions of energy demands within the next decade. In fact, such large-scale transitions to renewables are projected to take place across multiple decades as investments increase in renewables and older, less efficient, and dirtier power generation

Fig. 7. – Role and Opportunity for CCS in clean energy future (Image after Zero Emissions Platform (ZEP), Source: `http://www.zeroemissionsplatform.eu/`).

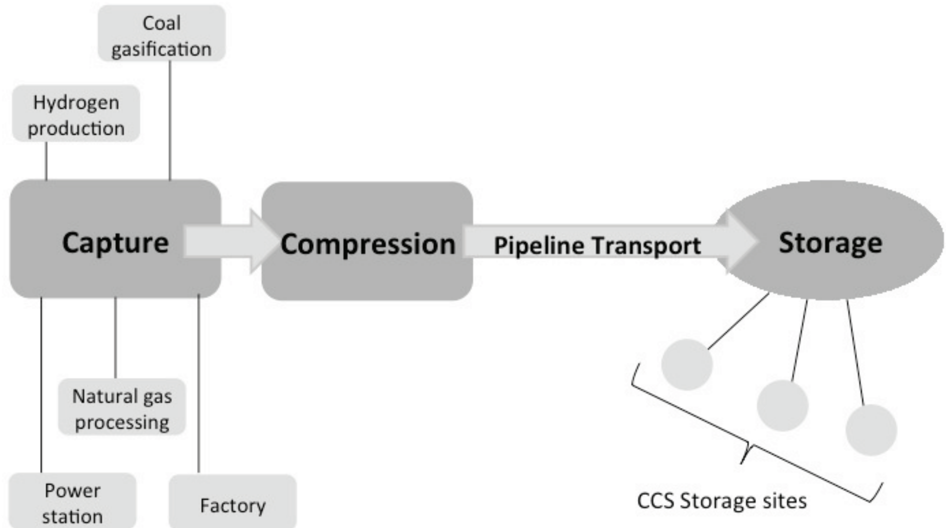

Fig. 8. – CCS Network (Source: WRI).

systems become retired [14]. The time gap for this transition as well as the existing global reliance on coal allows CCS to step in to provide needed CO_2 reductions while continuing to meet future energy demands.

6. – How does CCS work?

CO_2 Capture and Storage involves 4 steps. (See fig. 8.) CCS is a system of technologies that captures carbon dioxide from power plants and industrial sources, compresses it, transports it typically via pipeline to appropriate locations, and injects the CO_2 into geological formations deep below the subsurface of the Earth for long-term sequestration [14]. At least ninety percent of emissions from fixed emitters can be captured and stored safely and permanently using natural trapping mechanisms. Transporting CO_2 is not new. It has been around for decades.

Three technologies exist to capture CO_2 —pre-combustion, where CO_2 is captured before fuel is burned; oxy-fuel, where CO_2 is captured during fuel combustion; and post-combustion, where CO_2 is captured after fuel has been burned (this technology can be retrofitted to existing power and industrial plants). (See table I.)

Cost and performance of today's CCS technology has its limits. Firstly, there is immediately an energy penalty of ten to thirty percent, meaning that energy is lost to the CCS process, reducing efficiencies for the overall system. Cost is the second largest limitation to implementing CCS. Typically the cost of integrating CCS into power plants ranges from \$60 to \$110 per tonnes of CO_2 for an "X" number of power plants, and yet the first plant will always cost more, anywhere from \$150 to \$250 per tonnes of CO_2.

Table I. – *Comparison of capture options (Source: Global CCS Institute 2015 Report).*

Technology	Advantages	Challanges
Post-combustion	• Mature technology • Standard retrofit	• High energy penalty (20–30%) • High cost for capture
Oxygen-Combustion	• Avoid complex post-combustion separation • Potentially higher generation efficiencies	• Oxygen separation • Repowering
Pre-Combustion(IGCC)	• Lower costs than post-combustion • Lower energy penalties (10–15%) • H2 production	• Complex chemical process • Repowering • Large capital investment

This additional cost for each power plant can increases the cost of electricity generation from fifty to one hundred percent. Thirdly, reliability remains a question for both the system's ability to capture the CO_2 but also for the ability of the system to store the CO_2 for indefinite lengths of time without impacting any other Earth system while being stored. (See table II for technological advantages and challenges of advanced materials and processes for CO_2 capture.) Further research and development is needed not only to advance existing CCS technologies but also to find new and better ways to utilize the CO_2.

Other risks and limitations to CCS continue to raise more questions than provide the necessary answers. Many are concerned about the capacity to sequester all this carbon dioxide, and whether it will really remain underground indefinitely. Geological formations have stored CO_2 oil and gas for millions of years and would be highly likely to sequester CO_2 as well indefinitely with the proper site selection and post-storage management. Many existing CCS sites have stored CO_2 for well over a decade without any leakage [14]. This does not mean CCS is without risk. In fact, the risks are comparable to other industries that utilize underground storage, such as natural gas. Like all risks, they can be managed and more importantly weighed against the alternative, emitting the CO_2 into the atmosphere. This is where best practices, regulatory oversight and development of guidelines for siting, monitoring, and caring for CO_2 storage sites over the long-term become critical to the success of CCS.

The challenges for CCS are three-fold —technical, regulatory and economic. CCS will certainly be more accepted by society if it can be shown to be safe and effective, as well as economical. The large-scale projects already deployed and the ones under development will play a critical role in determining the future of CCS. Research and technological development, like other large and infrastructure oriented technological advances, will require considerable investment to lower the cost of development and integration, and the

Table II. – *Advanced materials and processes for* CO_2 *capture (Source: De Coninck and Benson, S., 2014).*

Separation Approach	Absorption	Adsorption	Cryogenic	Membranes	Mineralization
Example Materials	Aqueous amine solutions Chilled ammonia Ionic liquids	Zeolites Metal organic frameworks (MOFs) Activated carbon	No specific material requirements	Polymer membranes Inorganic membranes	Magnesium silicates Alkalai-rich waste streams
Advantages	Numerous solvent options Rapid improvements in energy requirements achieved	Potentially lower energy requirements for regeneration	Avoid need for solvents or sorbents Lower energy requirements	Avoid regeneration energy requirements	Co$_2$ is converted to a solid substrate that can be reused as a building material or diposed of in surface facilities
Technological Challenges	Reducing energy for regeneration Solvent degradation	Adsorption capacity and kinetics	Solid separation and handling	Permeability Selectivity	Rate of reactions Large mass of reactants (*e.g.* source of Mg, Ca)

skills needed to install, maintain and manage the systems. Additionally, a regulatory framework is necessary at various scales, national and international, for responsible parties, rights and liabilities, and for global standards to which each must adhere [9]. Clear policies will provide direction for the value of CCS to the world both from an environmental perspective as well as an economical one.

7. – Prospects for CO_2 storage globally

CO_2 storage resources are currently available to support CCS deployment. (See fig. 9.) They are vast and appear to be greater than the projected capacity requirements for the coming decades [15].

How much CO_2 storage actually exists? (See fig. 10 for potential global CO_2 storage capacity.) There are a few best options for underground CO_2 storage: deep saline aquifers, depleted oil and gas reservoirs (including sub-sea reservoirs) and non-mineable coal seams. When storing CO_2 in underground reservoirs, the bubble of CO_2 is under impermeable rock deeper than 800 meters, which itself is at the very top of a water-filled reservoir rock. With potential capacity for decades or hundreds of years, deep saline aquifers with 1 000-10 000 Gt or more potential CO_2 storage appears to be the

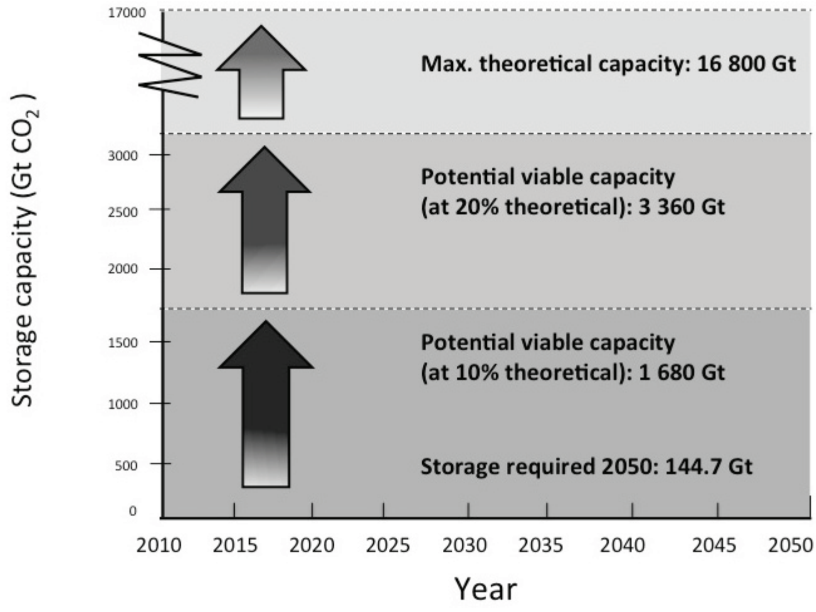

Fig. 9. – World total storage capacity (Source: IEA).

most significant storage source globally. Depleted oil and gas fields can store around 920 Gt. Non-mineable coal seams have considerably smaller potential capacity, however when combined with enhanced oil recovery (EOR), enhanced coal-bed methane recovery

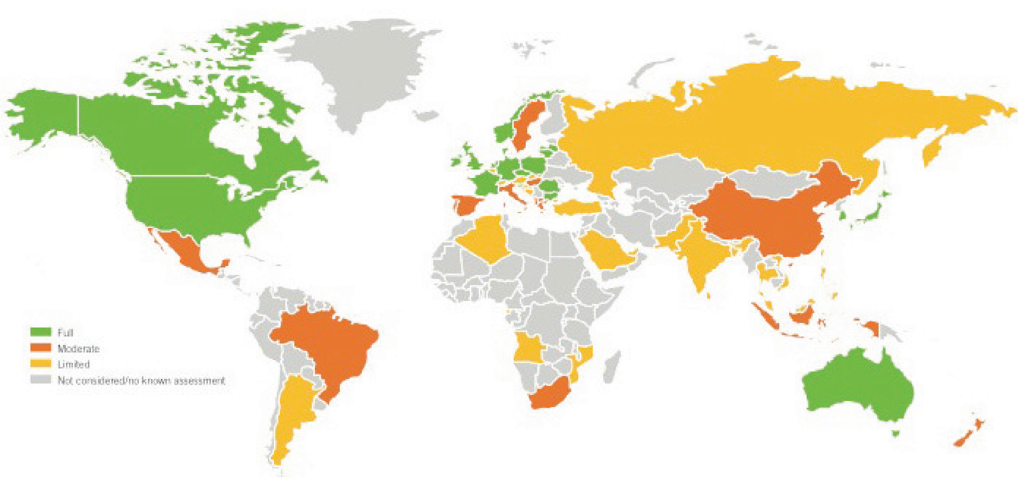

Fig. 10. – Prospects for CO_2 Storage Globally. (Source: Global CCS Institute 2015 Report).

Table III. – *Capacity of* CO_2 *storage options (Source: De Coninck and Benson, S., 2014).*

Reservoir	Gigatons Carbon
Atmosphere	720
Surface Ocean	670
Deep Ocean	36.730
Carbonate Rocks	> 60.000.000
Fossil fuels	4.130

(ECMR), and enhanced gas recovery (EGR) these fields have uncertain but considerably greater potential for CO_2 storage. When used in such combinations, the additional cost of CO_2 transportation and storage can be offset. Some deterrents for utilizing these options include: large distances of storage sites from emissions sources, and high cost of intercontinental transportation of CO_2.

Surface mineralization of CO_2 has the potential to be a permanent and benign form of storage that requires no follow-up or regular monitoring. (See table III for a comparison of capacity of CO_2 storage options.) The most important component of this type of storage is that the capacity far exceeds any current or future emissions. This process as noted earlier is not without its challenges, specifically scientific ones. The process is very slow. The kinetics needed to transform CO_2 to rocks needs to be faster and the right catalysts are yet to be identified. Additionally during the process of mineralization, the surface chemistry still needs to be controlled so as to prevent the CO_2 from releasing or reacting with another airborne particle. For this, ideally a non-reactive coating would need to be developed.

Other options for potential CO_2 storage are: oceanic storage and surface mineralization, however these two are not current viable options since environmental impacts of storing CO_2 in the water column are currently unknown and transforming CO_2 in rocks is still very much in the development stage since mineralization of CO_2 is a lengthy process and catalysts are needed to speed up the process. Besides energy generation and enhanced oil recovery, which are two major contributors to CO_2 emissions, the following industrial sectors should also be considered for CCS: cement, iron and steel, downstream oil, biomass, and other high-purity sources of CO_2 (*e.g.*, liquid natural gas and gas processing) [16].

One topic that has been part of the discussion for CCS is reusing CO_2. Currently the potential for CO_2 reuse is extremely limited, in particular for the chemical industry since the top 100 chemicals produced globally that can utilize CO_2 are only 0.5 Gt/yr, while CO_2 emissions are 35 Gt/yr. Fuels are currently the best option for CO_2 reuse at scale. One major challenge for CO_2 reuse, similar to surface mineralization, is the need for catalysts. Recent research on a novel copper oxide derived catalyst that converts carbon monoxide (CO) to ethanol and acetate at room temperatures shows progress in this area.

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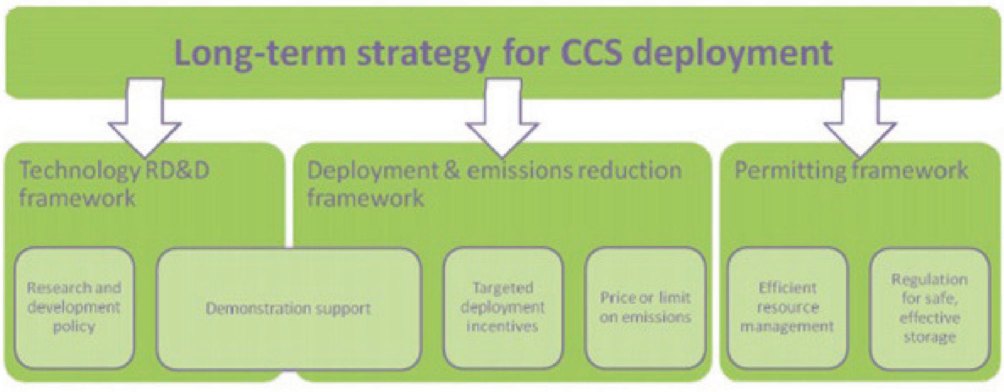

Fig. 11. – Key elements of comprehensive CCS policy framework (Source: IEA).

Key elements for the safety and security of geological storage for CO_2 requires a complete understanding of the following: financial responsibility, regulatory oversight, contingency planning and remediation, monitoring, safe operations, storage engineering, site characterization and selection, and fundamental storage and leakage mechanisms [17]. (See fig. 11 for the diagram of a comprehensive CCS deployment strategy.)

Critical issues for CCS include: gaining practical experience with CCS and power generation, whereby reliability and operating costs are aligned with expectations; lowering the cost of CCS by 50% or more since current technology adds approximately 3–6 cents per kWh of additional cost; increasing societal confidence in the safety and security of CCS, by understanding the impacts of CO_2 retention on groundwater and potential for increased seismic activity; sustaining research and development on the science and technology needed to bring new capture technologies to market and strengthen storage security, site characterization, and monitoring; and introducing a favorable policy and regulatory environment [14].

Since we are not yet in a position to utilize CCS widely, what do we still need for greater deployment? (See table IV for an overview of CCS projects worldwide.) When it comes to policies, it appears relatively straightforward. First and foremost, large- and commercial-scale projects are needed to better inform economic, technical and regulatory decision-making. These projects will provide information for different capture and storage technologies, and better monitoring practices and technologies for storing large volumes of CO_2 for long periods of time. The end result will be lower costs and creating a competitive market for deploying CCS. Secondly, policies that incentivize the use of CCS for power plants would accelerate its deployment as well. Currently, the cost to emit CO_2 is zero, and without both market incentives and a complimentary policy, investments in CCS will be few and far between. Thirdly, regulations are needed to guarantee CCS is a safe process. These regulations have already started to emerge at different levels (*e.g.*, in the U.S. both at national and state level), and work remains to be done on how to

TABLE IV. – *Overview of CCS projects globally (Source: IEA).*

	No. of projects
CO_2 capture demonstration projects	11
CO_2 capture R&D projects	35
Geologic storage projects	26
Geologic storage R&D projects	74
Ocean storage R&D projects	9

address long-term challenges and liabilities as well as rights to property. Lastly, one of the most controversial and challenging of all is public acceptance of CCS. Due to the lack of adequate knowledge, certainty and public dialogue about CCS, very little confidence from the general public exists currently for the successful deployment of CCS. Through addressing these four key areas for policy, CCS can have greater deployment potential and future success [18].

8. – Conclusion

Without any changes to current policies, by 2030 emissions are projected to increase by 63% from today's levels and 90% from 1990 levels. Even with implementation of some global mitigation policies through 2030, the increase can still be up to 40% globally from today's levels [19]. CCS holds promise for reducing emissions and having significant benefits environmentally, economically and for worldwide energy security [12]. There is no one solution to the CO_2 emissions challenges we face globally. A portfolio of solutions is needed (as suggested in fig. 12). Alongside the deployment of more renewables and increasing and enhancing energy efficiency across all sectors, CCS is a critical part of a sustainable energy future, one upon which the climate depends.

Rapid and widespread deployment of CCS across power generation, EOR, and industrial sectors is necessary. Globally, we need to move from the successful, existing small-scale CCS projects in operation today to building at the very least 3 400 commercial-scale projects worldwide by 2050, if CCS is to provide 20% of the CO_2 reductions needed [20].

Fig. 12. – A portfolio of solutions for CO_2 emissions.

On the demand side of the equation, changing behaviors and building infrastructure that uses energy more efficiently could lower the amount of energy needed. "Lifestyle and behavioral changes could reduce energy demand by up to 20 percent in the short term and by up to 50 percent of present levels by mid-century" [12]. Any solutions for CO_2 emissions need to be integral to planning and should seek to create "cities of the future", whereby energy infrastructure improves urban resiliency, sustainability, and regeneration and looks for ways to integrate the potentials of nature with our human demands for energy.

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