Links between energy usage and climate: implications on increasing CO_2 emissions and carbon capture and storage

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Global climate change due to increase in greenhouse gases in the atmosphere resulting from persistent use of fossil fuels over the past century is one of the major challenges of the contemporary industrial world. The exploitation of natural resources including fossil fuels has not always been done in a sustainable way. One of its adverse effects, faced by our generation, is climate change. We must not only be alert to these changes, but also make necessary efforts to adopt scientific measures to combat their ill effects. The combustion of fossil fuels together with added emissions from cement production, and land use change result in net annual increase in CO_2 in the atmosphere by 4 GtC. Scientists have clearly demonstrated the role of CO_2 emission in global warming. Carbon capture and storage (CCS) is an advanced technology to capture CO_2 from its source, isolate it from the atmosphere and store it typically in underground geological formations. We highlight the need to invest in obtaining cleaner energy from fossil fuels by implementing technologies like CCS along with technological advancements in renewables. We present here a review on the general debate around implementing CCS technology and dwell on some developments in India to understand if CCS will be effective in the future towards reducing the carbon footprint in our growing economy.

Keywords: Climate, CO_2, carbon capture and storage, energy, fossil fuel.

ENERGY resources are a key element of our technology-dependent existence in the twenty first century. Our industrialized and technology-based global economy is facing major challenges linked to the utilization of key earth resources, particularly the continued exploitation and use of fossil fuel energy resources over the past century. The challenges are more severe in underdeveloped and developing countries because of increase in population density and related requirements for energy production. These challenges are multi-dimensional and often interlinked. Some of the primary issues are: (a) ever increasing population and its uneven distribution, (b) scarcity of potable water resources, (c) providing food security for an expanding global population, (d) rapidly decreasing mineral resources, fossil fuel reserves and lack of renewable replacements of similar scale, and (e) challenges around global climate change. Mineral resources have always been in demand since the dawn of human civilization, although the need for the type of resource has changed significantly with time. Since the advent of scientific and industrial revolution, the demand for aluminium, nickel, sulphur, coal, steel and ultimately petroleum started to grow. Since the last century, the demand for nuclear mineral resources has increased. With advances in industrialization, the consumption of mineral and energy resources has not only grown, but also diversified. So far, the supply of natural resources has been broadly adequate; new mineral resources have been continuously discovered because of developments related to exploration methods and techniques.

Growing human populations have exploited earth's resources increasingly over several centuries with resultant cumulative effects. This usage has resulted in global challenges for sustainable resource development. Hence, several adverse effects manifested, particularly in global climate change. The emission of rapidly increasing greenhouse gases like CO_2 is an inevitable effect of fossil fuel-driven prolonged industrial growth extending over nearly two centuries. We are the first generation to recognize that large scale interventions in the earth by humans are impacting its ecosystems; therefore, we should be the first to redefine our relationship with the planet.

It is imperative that capabilities are developed to forecast significant environmental changes that are likely to result from human actions to optimally progress towards sustainability. Further, we should assess the threats that global environmental changes pose for vulnerable communities and the responses that could be most effective in reducing harm to those communities. To achieve this, observational platforms that monitor multiple changes in a coupled socio-environmental system require continuous strengthening in order to respond and adapt to them[1]. We must also assess the risk of 'positive feedback' with harmful consequences that may be caused by the

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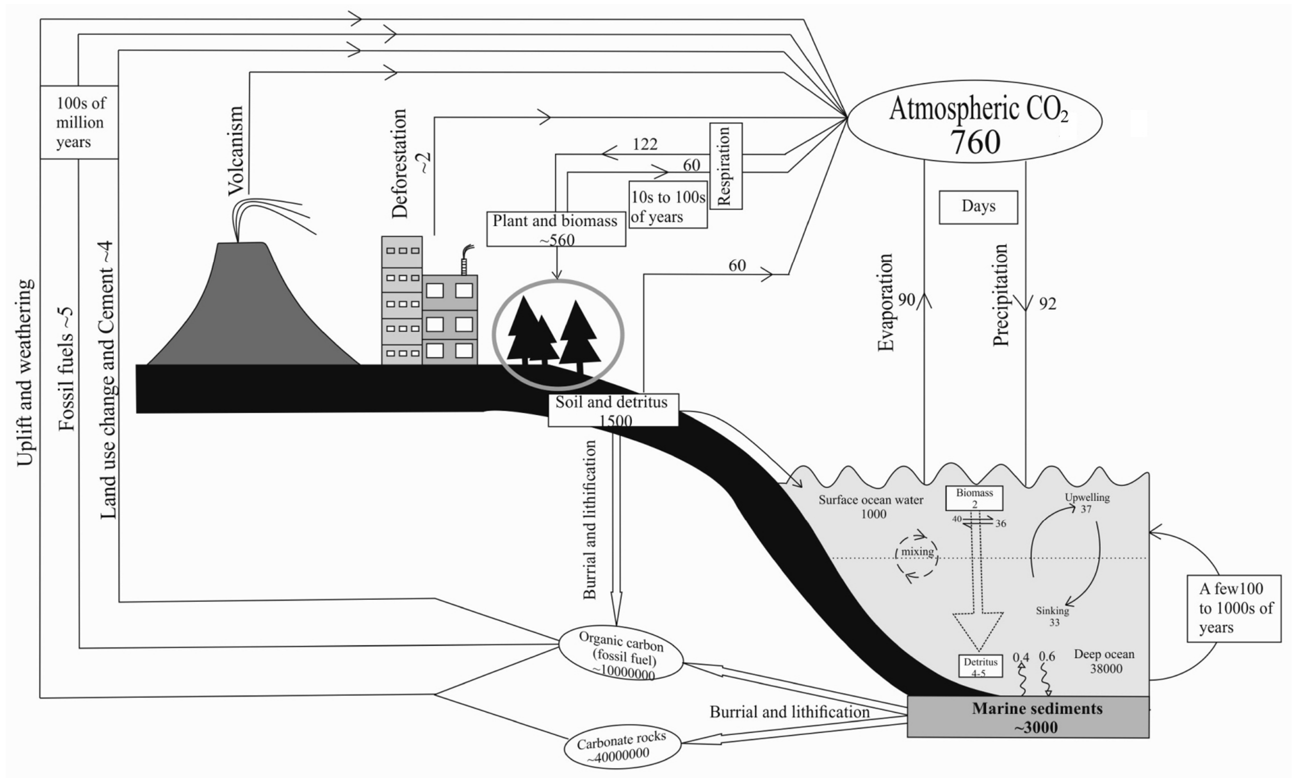

Figure 1. The carbon cycle showing the movement of carbon between land, atmosphere and oceans. The total annual contribution of atmospheric carbon from burning fossil fuels, land use change and cement production in ~9 GtC causing a net annual surplus of ~4 GtC (refs 2, 3).

socio-environmental system. Further, an analytical system needs to be established in order to identify and monitor the proximity to thresholds and discontinuities in a coupled socio-environmental system[1].

The CO_2 challenge

The dynamics of natural carbon cycle is a process where the total release of CO_2 into the atmosphere is balanced in the long term with the total withdrawal from it. This balance is necessary to maintain a stable mean average temperature of the earth. Cockell[2] and the biological and environmental Research Information System (US DOE)[3] have provided a comprehensive estimate of the movement of carbon among land, atmosphere and oceans (Figure 1). It is to be noted that the use of fossil fuels, cements and land use changes contribute 9 GtC/year (giga tonnes of carbon per year). As a consequence, the net annual increase in CO_2 in the atmosphere is 4 GtC. Past CO_2 concentrations determined from air entrapped in ice cores reveal that in the past 420,000 years, the concentration of atmospheric CO_2 has ranged from 180 to 280 parts per million (Figure 2) by volume (ppmv). As against this, the current CO_2 atmospheric concentration is ~400 ppmv; this dramatic increase is mostly attributed to be the result of combustion of fossil fuels by humans[4]. It is also to be noted that CO_2 concentration in the atmosphere increased by 40% from 278 ppm in 1750 CE to 390 ppm in 2011, whereas CH_4 concentration increased by 150% from 722 ppb (1750 CE) to 1803 ppb (2011); N_2O concentration increased by 20% from 271 to 324 ppb in the same time interval[5] (present levels are highest as evident compared to ice core records of 420,000 years).

The relationship of surface temperature with CO_2 concentration in the atmosphere is an established fact[5]. Figure 2 shows the combined palaeo data from Antarctic and Greenland ice-cores, and atmospheric data from Cape Grim, Tasmania[6–8] which demonstrate the close correlation of temperature changes and change in concentration of greenhouse gases in the atmosphere. In the last ~100 years, CO_2 emission has increased up to 9 GtC/year[3] solely due to anthropogenic activities resulting in a net increase in temperature of ~0.8°C.

Energy, people and emissions

The annual energy consumption has increased by 5 times in the last 60 years (Figure 3); the global carbon emission has also increased 6 times[9] during this period (Figure 4). In India, the increase in carbon emission over the same period of time has been 3.5 times[9] (Figure 5); it may be noted that the acceleration in emission eventually started post ~1960 in India, a little later than the global scenario.

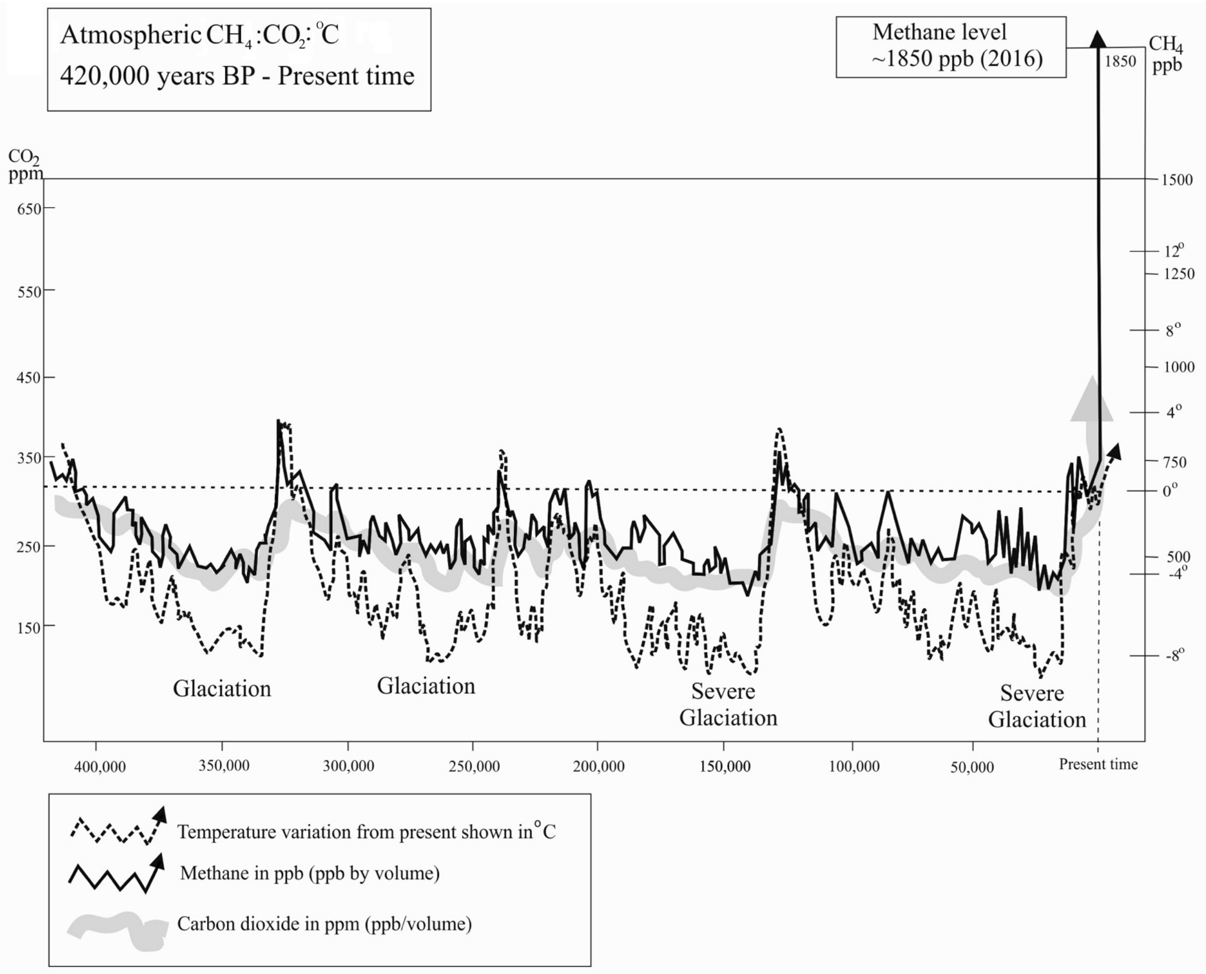

Figure 2. Chart shows the change in global temperature in response to the change in CO_2 level in the atmosphere. Past CO_2 concentrations determined from air entrapped in ice cores reveal that in the past 420,000 years, the concentration of atmospheric CO_2 has ranged from 180 to 280 parts per million by volume (ppmv). As against this, the current CO_2 atmospheric concentration is ~400 ppmv (refs 5–7).

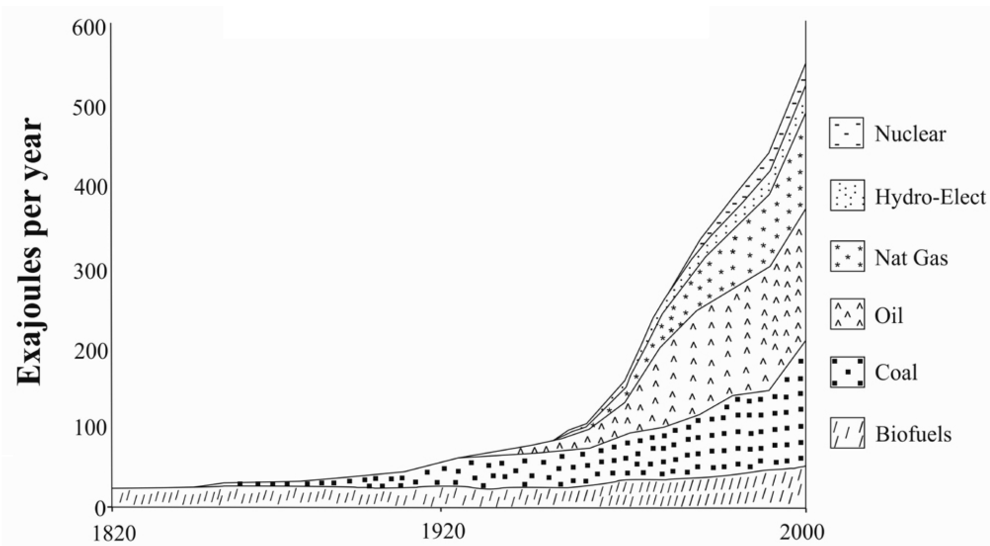

Figure 3. World energy consumption by fuel source, based on Vaclav Smil estimates from energy transitions: history, requirements and prospects together with BP statistical data for 1965 and subsequent. The annual energy consumption has increased by 5 times in the last 60 years with a major contribution from fossil fuels[25].

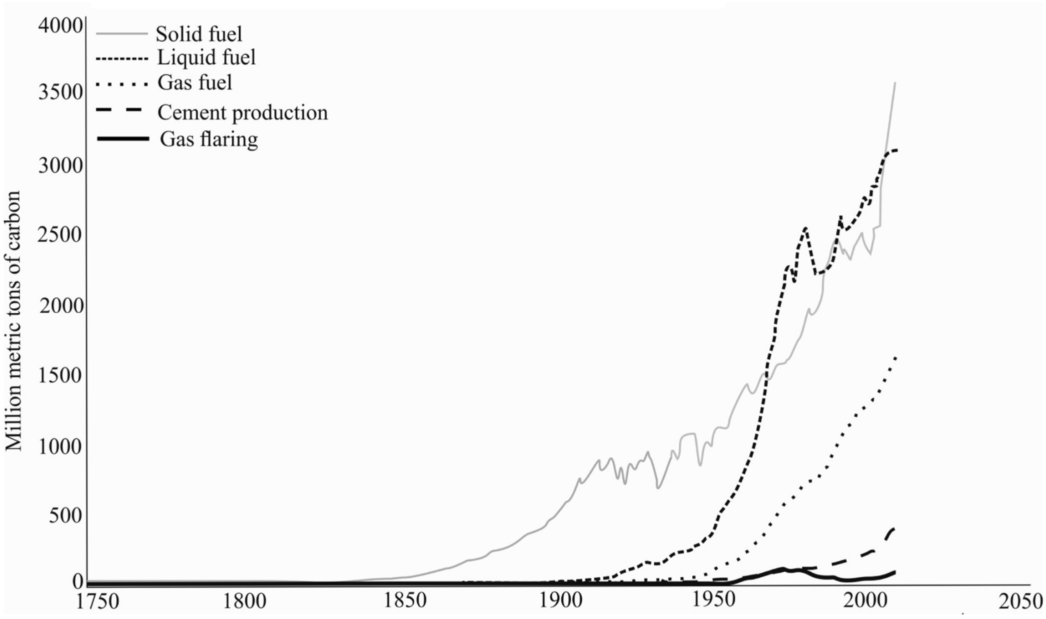

Figure 4. Long term trend in global carbon emission from 1750 onwards, a sharp increase in emissions due to fossil fuel burning can be observed post 1950 (ref. 9).

Till today, we are highly dependent on fossil fuels, almost 80% of the total energy comes from burnt fossil fuels. In India, we have a large demand for coal. Coal India Limited (CIL) being the largest supplier of coal, was itself expected to supply 615 mt of coal in 2016–17 which is lesser by 366 mt than the total demand of 981 mt of coal (Figure 6). The demand increased by more than 3 times in the last 20 years. The World Energy Outlook (2013)[10] forecasted that the growth in primary energy demand will shift to South East Asia, contributing 65% of the total energy demand (Figure 7). It is accepted that today's share of fossil fuels in global energy mix is around 80% and is about the same as it was 40 years ago. If there is a steep increase of renewables in the future, it is expected that the demand for fossil fuel may decrease to 75% by 2035. In the cumulative energy related CO_2 emissions of 800 GtC during 1900–2035, OECD (Organisation for Economic Co-operation and Development) countries are expected to contribute about 51% (Figure 8)[10]. Non-OECD countries account for a rising share of emissions, although per capita emission levels are expected to be only half that of OECD countries by 2035. In 2008, India contributed 6% of global CO_2 emissions whereas USA, China and the European Union contributed 19%, 23% and 13% respectively[10].

The carbon capture and storage debate

The major challenge in energy sector over the next several decades is to meet the ever-growing demand for affordable and reliable supply of energy while ensuring environmental sustainability. Today, coal supplies ~28% (relative percentage), gas supplies 22% and liquid fossil fuel supplies 33% of total energy consumption budget (Figure 3). Consequently, coal burning contributes to 44% of total fossil fuel emission, whereas liquid fossil fuel and gas contribute 33% and 22% of total emissions respectively[11]. Hence, it has been argued that the use of more gas together with adoption of a robust carbon sequestration programme may be a viable future strategy. To avoid dangerous interference with the climate system, it is mandatory to reduce emission by 50–80% by 2050. According to the current scenario, the use of fossil fuel will most likely continue to grow in the next few decades. The replacement of fossil fuels to a large extent by renewables does not seem likely in the foreseeable future. Carbon capture and storage (CCS) is one way to reduce emissions from fossil fuel use especially in the power generation and industrial sectors. It is commonly believed that for future economic development both fossil fuels and renewable energy resources will be required. We will still need to consume significant amount of energy from less environment friendly energy sources like coal, even if we explore renewables in their current form to the maximum extent.

CCS mainly consists of three major steps: (a) capture: removal of CO_2 directly from anthropogenic sources. (b) sequestration: its disposal in a geological formation like depleted hydrocarbon reservoir, saline aquifer, non-economic coal bed, fractured basalt, shales, etc. permanently, and (c) storage: disposal for a significant period ($>10^3$ years), exceptionally long when compared to human lifetime. CCS is a debatable issue because it requires advanced commercial scale technology. It also requires a

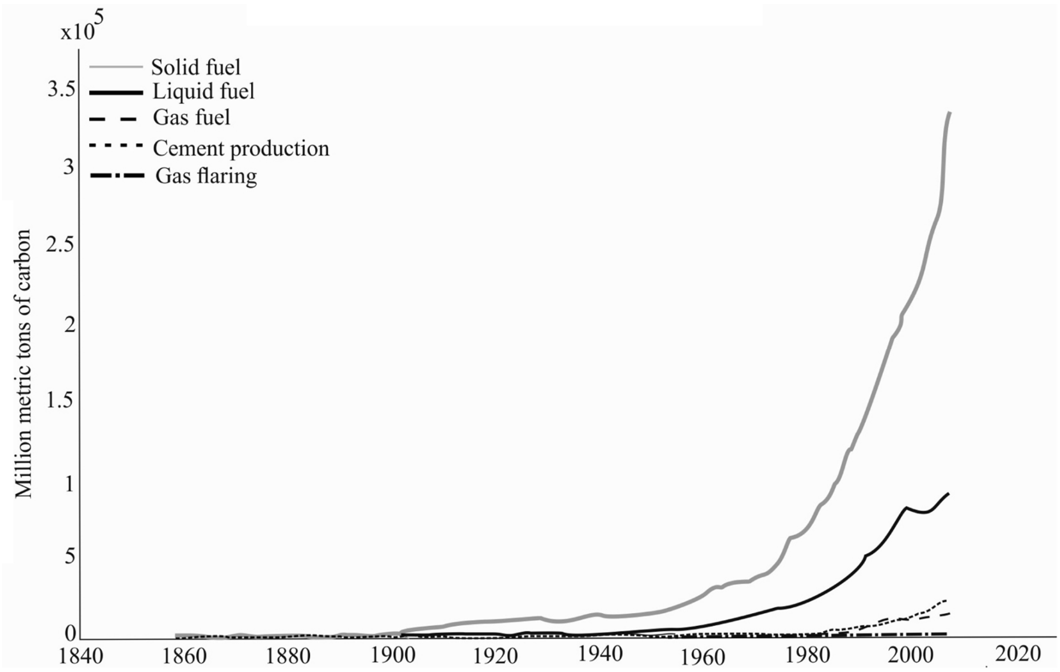

Figure 5. Long term trend in carbon emission in India, the acceleration in emission eventually started post 1960 in India, little later than the global scenario[9].

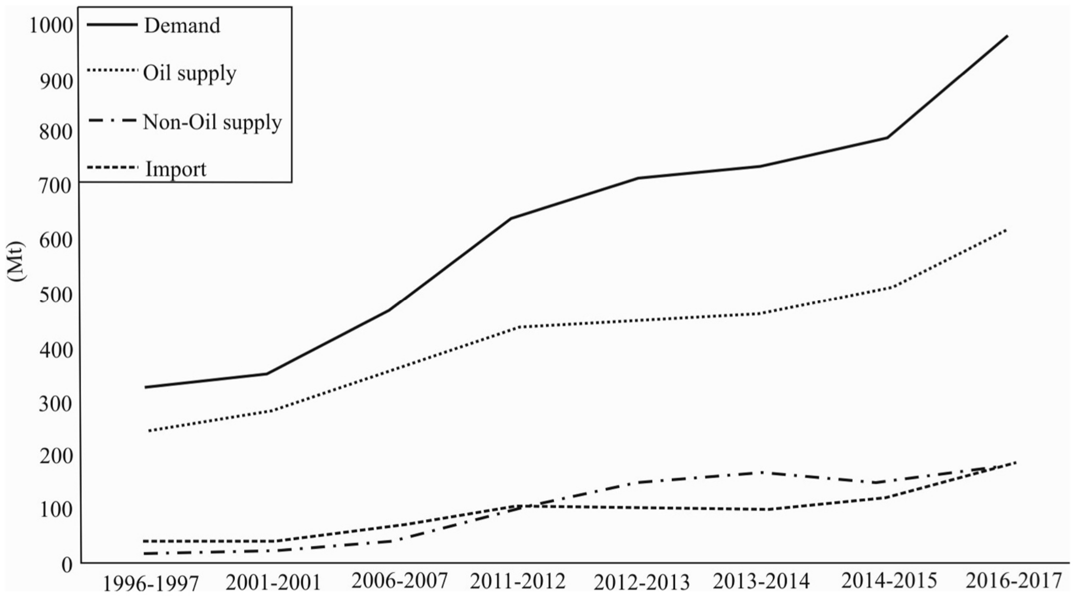

Figure 6. Demand and supply of coal in India; Coal India Limited expected to supply 615 mt of coal in 2016–17 which is lesser by 366 mt than the total demand of 981 mt of coal (Data source: Coal India Limited).

higher efficiency thermal power generation system which is a key first step in lowering emissions. We have to look into the possibility of CCS and enhanced oil recovery together to increase the commercial value. After CO_2 is captured from a source, it requires to be compressed to a liquid or a denser gas. It then requires transport from the source to the storage location. The conceptualization of CCS lies in the domain of a non-disruptive 'end-of-pipe' technological solution which allows continuity in a situation of high fossil fuel lock-in[12,13].

The major issues in CCS debate are focused on the following questions: (a) whether CCS should be part of the technological mix where society is moving towards developing a non-fossil fuel low-carbon energy system?

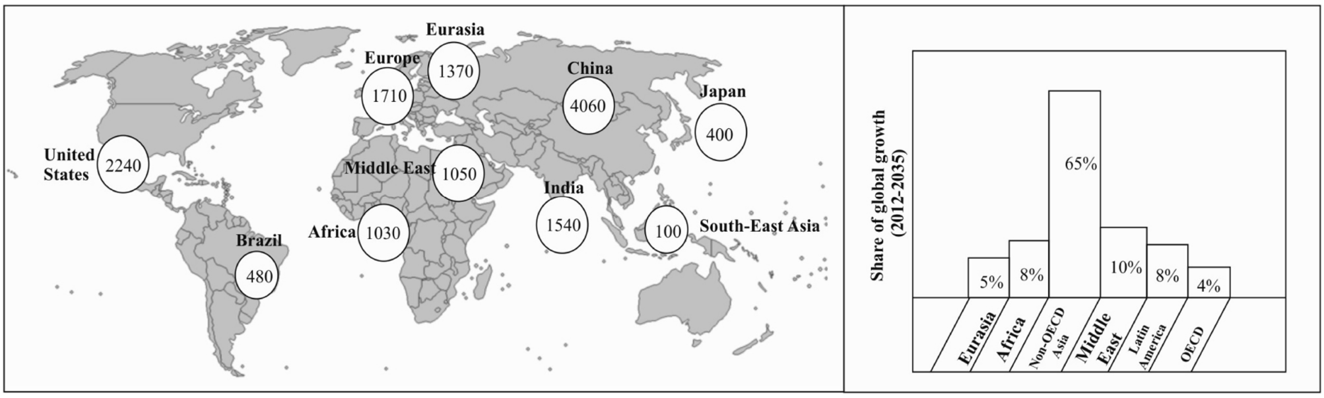

Figure 7. Energy outlook 2013 showing increasing energy demand in the SE Asia[10]. Non-OECD countries will in Asia share a growth of 65% during 2012–2035.

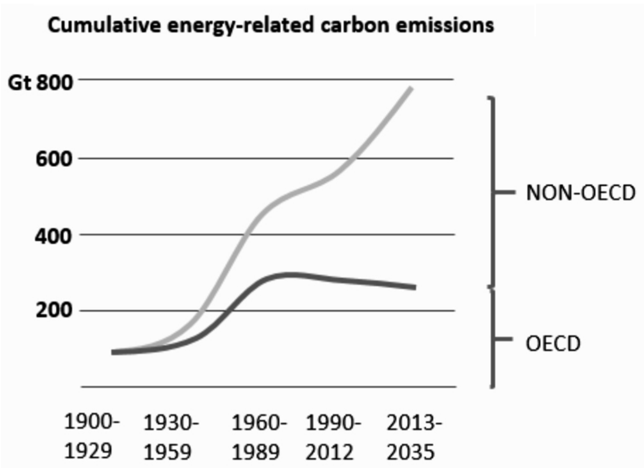

Figure 8. Contribution of carbon emission of OECD and non-OECD countries[10]. Non-OECD countries account for a rising share of emissions.

(b) whether including CCS in the technological mix that is supposed to lessen the fossil fuel impacts will bog us down even deeper? (c) Will CCS technologies simply deepen the current carbon and fossil fuel lock-in[12,13] or does their inclusion in the mix allow a breathing space whilst the longer term transition to a new low-carbon pathway is engineered?[12,13]

CCS in India

The current economic growth and post-independence industrialization came with rapid increase in the amount of CO_2 emission. India now accounts for 6% of global CO_2 emission[10]. CO_2 emission in India is expected to grow by 3.5% till 2035 by when it would account for nearly 10% of the global CO_2 emission[9]. Electricity generation accounts for almost 48% of gross CO_2 emissions in India, as most of the power stations are coal-fired in nature[14]. Viebahn *et al.*[15] describe three pathways for future energy scenarios for India: (a) pathway E1 (high) is based on the World Energy Outlook (WEO) 2009 which is the reference scenario for India; (b) pathway E2 (middle) is based on advanced technology, where deployment of Integrated Gasification Combined Cycle (IGCC) as 'clean coal' technology is integrated and there is huge increase in both conventional and advanced nuclear energy technologies, and (c) pathway E3 (low) is based on the sustainable India energy outlook where the target is to reduce worldwide energy-related carbon dioxide emissions by 50% up to 2050. The electricity demand is expected to grow rapidly; by 2030 even in the low carbon development scenario, the electricity generation will be mostly from coal (315 GW; 63% of total power generation).

Scientists have developed scenarios showing some devastating natural calamities that might take place as a result of global warming in India. Few of them include, extreme rainfall over North-East, West coast and Central India[16], resultant adverse impact on agriculture, more floods and landslides, and substantial mass losses of glaciers in most parts of the Himalayas[17]. Therefore, India pledged to reduce emission intensity by 20–25% by the year 2020 from the 2005 level.

The theoretical CO_2 storage capacity in India is highly uncertain and varies from 47 to 572 GtC (ref. 15). The storage capacity of oil fields in India is estimated around 1.0 to 1.1 GtC and the same for the gas fields; gas caps on oil fields is 2.7 to 3.5 GtC (ref. 18), with Mumbai basin having the highest capacity of 469 Mt. The deep saline aquifers in India have been assessed to have a storage capacity ranging from 138 GtC to 360 GtC (ref. 15). The total storage capacity in coal beds is estimated to be 345 Mt CO_2, with Talcher Coal Field in Orissa being the highest with a capacity of 72 Mt (ref. 19). The total storage potential in basalt rocks is estimated to be 200 GtC (ref. 18). The CO_2 Enhanced Oil Recovery (EOR) operations might provide a potential way for compensating some of the costs associated with CCS projects. There are only few Indian oil fields that are depleted enough to go for an EOR operation.

India lies mostly in 'stage 1' in CCS development[19], as the potential of CCS as a method of emission reduction is fairly well known. To reach to the next stage, CCS needs to be put on environmental policy. Most R&D activities related to CCS are under the Department of Science and Technology (DST), New Delhi. DST had set up the National Programme on Carbon Sequestration (NPCS) Research in 2007.

In the context of growth and resulting emission, Viebahn *et al.*[15] discussed the scenarios of CCS in India as follows: (a) initiation of a CCS venture largely depends on the success of the technique in the industrialized nations. CCS is not expected to be applied in India before 2030. (b) A reliable storage capacity assessment is primarily necessary. This suggests that the available literature indicates a huge uncertainty in the assessment of storage volume and is often too optimistic. (c) Based on rigorous and scientific assessments of storage sites and volume, an optimization model should be applied to identify cost-effective sites for CCS power plants keeping in view the constraints like electricity, coal, the separated CO_2 emissions and even the cooling water. (d) There exists an economic barrier for a developing country like India to implement CCS technology even if the carbon credit system is in place. (e) The total emissions per unit of produced electricity are notably reduced. The rate of carbon reduction over the total life cycle is only 71–74%. This puts doubts on the benefits of huge investments for CCS infrastructure deployment in India[19]. (f) Public support would be at a bare minimum to establish conditions for CCS development in India. (g) CCS plants will face strong competition from renewable energy technologies.

Singh[20] concluded that CCS could be an important transition technology for India such that CO_2 emissions are minimized while renewable resources are being fully developed. He recognized the fact that CCS needs a highly multi-disciplinary working group comprising of members from oil and gas companies, national research laboratories and academic institutions.

India could also be a potential candidate for biosequestration. Sequestration of carbon in the form of soil organic carbon (SOC) and soil inorganic carbon (SIC) through restoration of degraded soils is known as biosequestration[21]. The soil organic carbon content in agricultural land can be enhanced through the use of nutrients like N, P and K (NPK) in the fertilizer and farmyard manure[22,23]. This will prevent the release of SOC from the soil to the atmosphere. Experiments suggest a rate of sequestration from 0.33 Mg C ha^{-1} yr^{-1} to 0.015 Mg C ha^{-1} yr^{-1} for different regions of the country[21].

Concluding remarks

Global CO_2 emission is expected to grow with population and with increase in per capita usage of energy. It is unlikely that renewables will widely replace fossil fuels on a large scale in the next two decades. To meet the increasing demand of energy, we need both clean fossil fuel combustion as well as energy from renewables. We are one of the first few generations of human beings to experience the tangible effect from climate change, with the opportunity to reduce greenhouse gases in the atmosphere. In a developing country like India, we are going through a faster rate of growth in GDP (GDP having increased substantially between 1990 and 2010). This growth is associated with significant increase in the amount of CO_2 emission. CCS can be one of the measures in controlling emissions along with advancement in renewables[24]. CCS can be particularly relevant for India as most of the emissions come from coal-fired power stations. As our awareness on CCS technology is increasing within the scientific and environmental community in India, there is an opportunity to include it as an integral part of the environmental policy.

CCS comes with its own challenges in India in terms of its affordability. There must be thorough and reliable studies where the actual amount of storage capacity is evaluated and 'source–sink' relationships are mapped in detail. CCS can be clubbed with commercial opportunities like EOR to make the technology more affordable. Technological developments in CCS at a global scale and commercial demonstration by the industrialized countries can inspire developing countries like India to adopt CCS technology. Access to funding from agencies such as World Bank, Asian Development Bank, etc. might have further governance requirements, e.g. around monitoring and safety. India will also need specialized manpower and proper infrastructure to bring advancement in CCS technology as a possible solution for clean energy.

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