January 2013

Project Code 2011BE02

India CCS Scoping Study: Final Report

Prepared for

The Global CCS Institute

GLOBAL CCS INSTITUTE

teri

The Energy and Resources Institute

...towards global sustainable development

Suggested format for citation

T E R I. 2013
India CCS Scoping Study:Final Report
New Delhi: The Energy and Resources Institute. 42pp.
[Project Report No. 2011BE02]

For more information

Project Monitoring Cell
T E R I
Darbari Seth Block
IHC Complex, Lodhi Road
New Delhi – 110 003
India

Tel. 2468 2100 or 2468 2111
E-mail pmc@teri.res.in
Fax 2468 2144 or 2468 2145
Web www.teriin.org
India +91 • Delhi (0)11

Table of Contents

List of tables

List of figures

India CCS Scoping Study: Final Report

1. Introduction

Carbon Capture and Storage (CCS) refers to "the separation of CO_2 from industrial and energy-related sources, transport to a storage location and long-term isolation from the atmosphere" [1]. It is one among the portfolio of measures being considered for reducing Greenhouse Gas (GHG) emissions with a view to mitigating climate change. While no single measure may alone be sufficient for climate change mitigation, CCS, along with energy efficiency improvements, renewable energy, enhancement of biological sinks, and other measures, may be able to achieve the emissions reductions needed to achieve climate stabilisation.

The present report has been prepared as a part of a scoping study for CCS in India carried out by The Energy and Resources Institute (TERI), with support from the Global CCS Institute. The study was conducted to identify the potential role for CCS in India's GHG mitigation strategies through an examination of issues, opportunities and barriers to the deployment of CCS. The conclusions of the report should help in drawing a roadmap for CCS implementation in India.

2. Country background

Located in Southern Asia, India is geographically the world's seventh largest country, with a total area of 3,287,263 sq. km [2]. It is home to more than 1.2 billion people [3], which makes it the world's second most populous country, and the largest democracy. India's economy has witnessed rapid growth over the past two decades; however, due to the large population, poverty eradication remains a massive challenge. Improvement of the standards of living of the population is an avowed objective of the Indian Government, with sustained economic growth being seen as the key means towards this end.

India's economy: Prior to 1991, India's economy was based on socialist policies, characterised by predominant public ownership of industries, extensive regulation, and protectionism, which resulted in a slow economic growth rate. The year 1991 saw liberalisation of India's economy, resulting in reduced regulation, the end of several public monopolies, reduced tariffs and interest rates, and an atmosphere more conducive to foreign investment [4] [5] [6] [7]. Subsequently, the country's economy has seen much higher growth rates, averaging over 6.5% annually since 2003 [8]. While India's economy has traditionally been agrarian, the services sector has seen tremendous growth in recent years, now accounting for more than half of India's GDP [8]. Agriculture, however, continues to supply employment to half the country's workforce, and since high food inflation is one of the major worries of India's policy makers, the sector continues to receive subsidies for fuel and fertiliser. India's industrial sector is fairly well developed, and has both public and private players in key sectors such as steel, cement, fertilisers, petrochemicals, etc.

Present and future CO_2 emissions: India's total GHG emissions in 2007, inclusive of land use, land-use change and forestry(LULUCF), were 1727.71 million tonnes of CO_2equivalent, and gross CO_2 emissions were 1497.03 million tonnes. The CO_2 generation per capita was 1.3 tonnes/capita when not considering LULUCF [9].

Around 66% of India's gross CO_2 emissions came from the energy sector in 2007, with electricity generation alone accounting for almost 48% of the gross emissions. The industrial sector accounted for most of the remaining CO_2 emissions, with 27% of the total emissions.

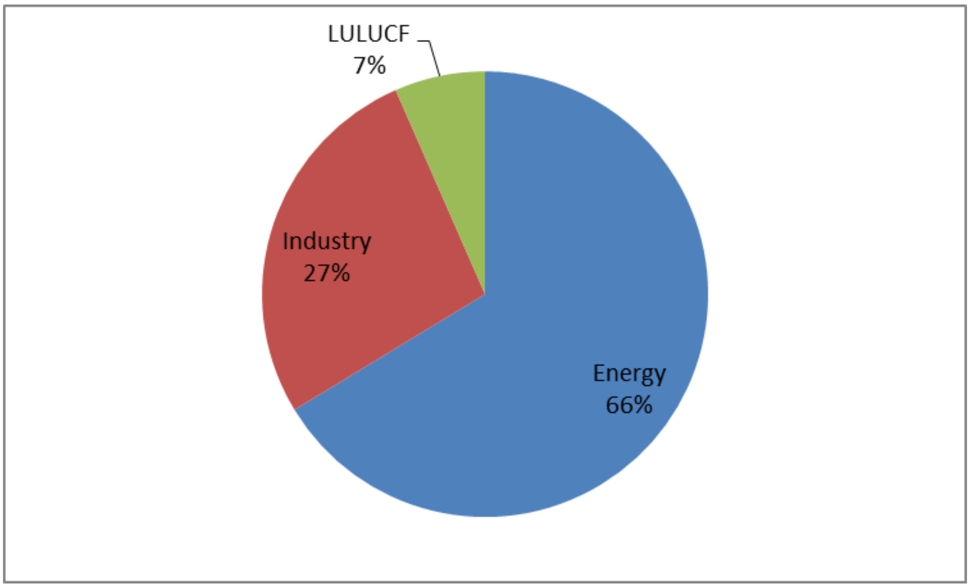

Figure1:Sectoral break-up of India's CO_2 emissions [9]

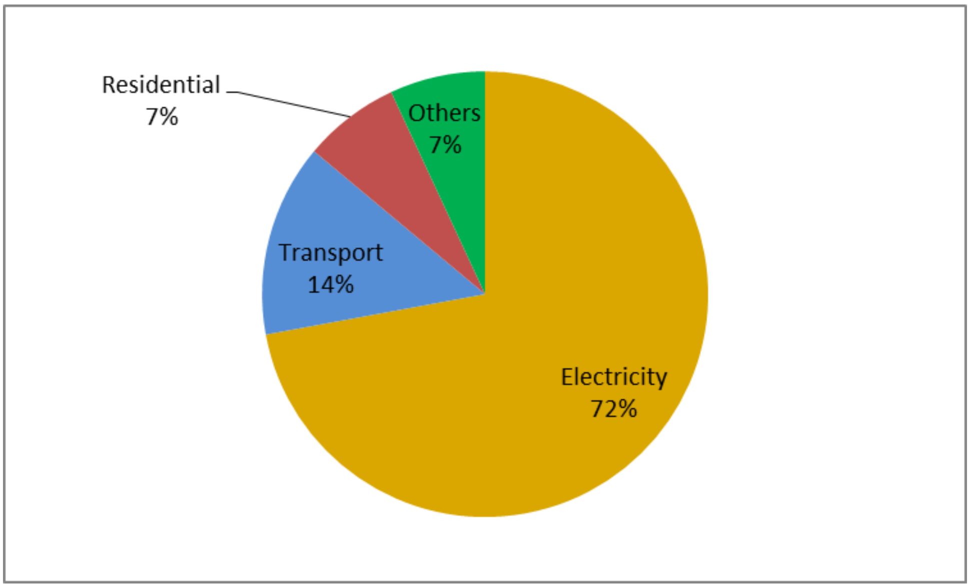

Figure2:Break-up of emissions from energy sector [9]

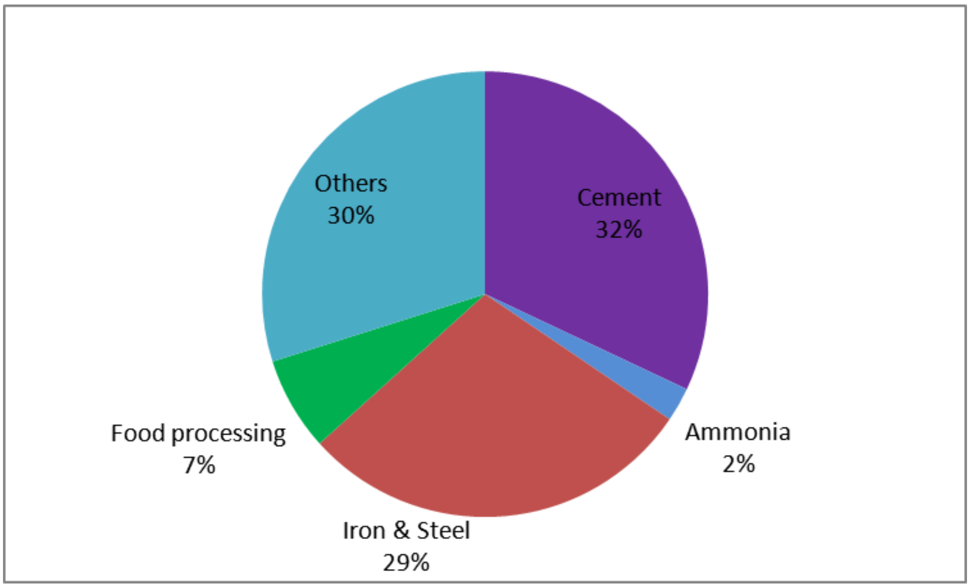

Figure 3:Break-up of emissions from industrial sector [9]

It is interesting to note that ammonia production accounts for a very small portion of India's industrial sector emissions, due partly to an existing utilisation of CO_2. This may be attributed to the fact that urea is the main nitrogenous fertiliser manufactured in India, and in the natural gas-based plants that dominate urea production, CO_2 available from the process streams is actually inadequate for urea production. This shortfall is compensated either by substituting naphtha for a portion of the natural gas or recovering some $CO_2$from the fuel combustion flue gas stream. This means that the net emissions from the Indian urea sector are only 0.7 MT CO_2/MT urea, which are much less than the world average of 0.95 MT CO_2/MT urea [10].

The regional distribution of major CO_2 emission sources in the year 2000, along with theprojected scenarios in 2010, 2020 and 2030 are shown in Figure 4 [11]. The circles in the figure show emissions from Large Point Sources, while the shaded areas denote emissions from area sources.

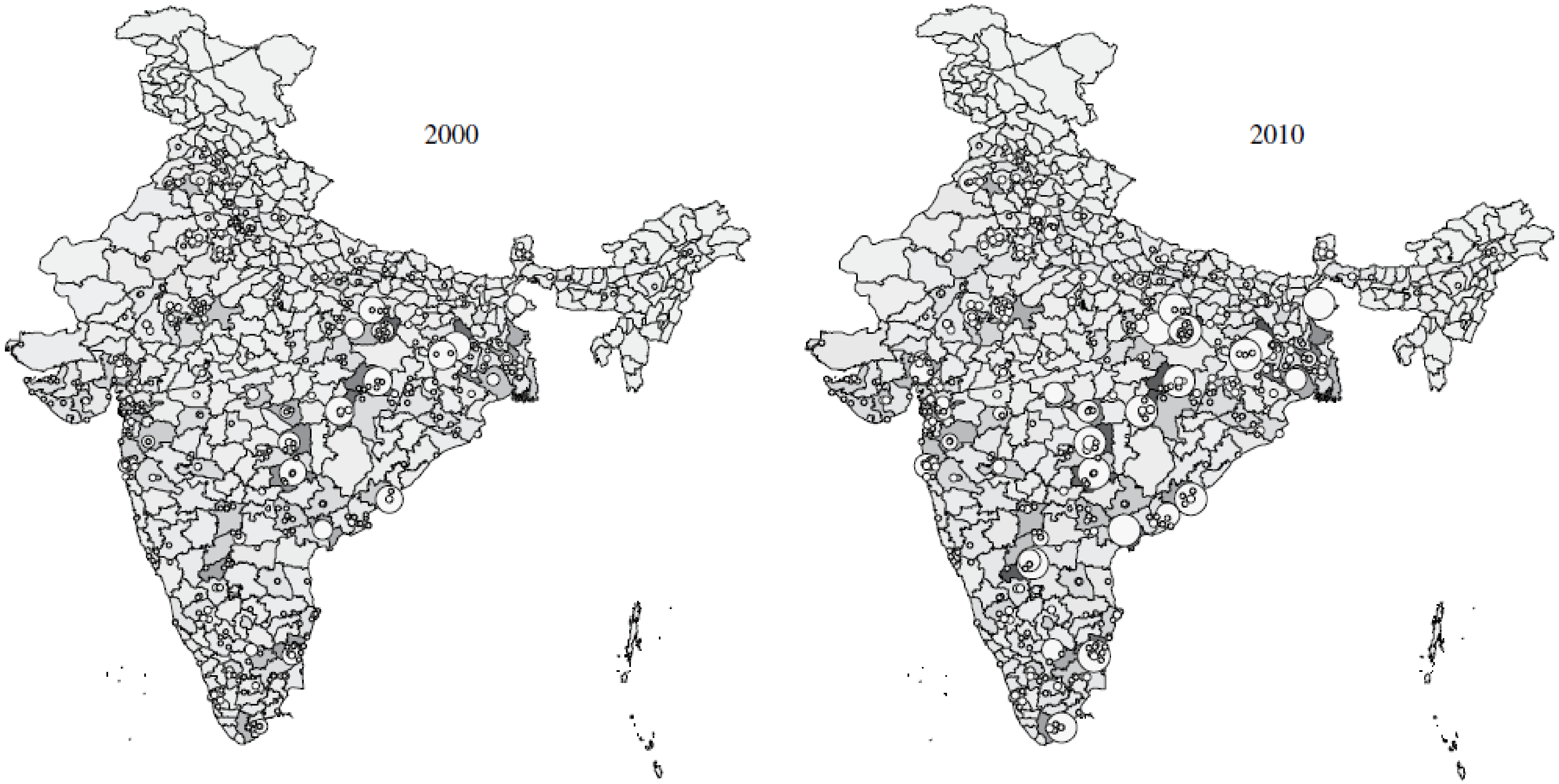

Figure 4(a): Regional distribution of CO_2 emissions in India in 2000, along with projected scenarios for 2010 [11]

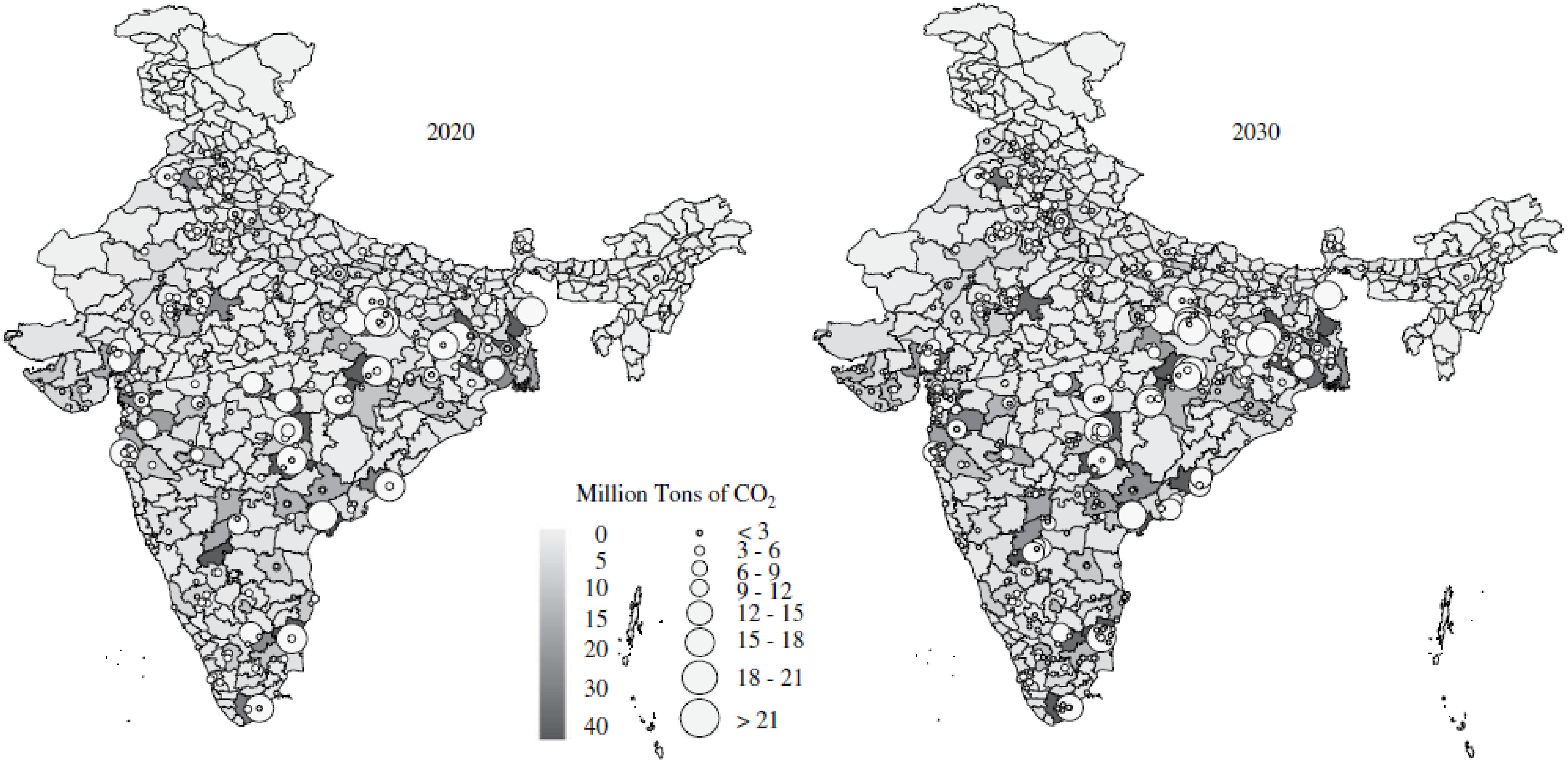

Figure 4(b): Projected distribution of CO_2 emissions in India in 2020 and 2030 [11]

As per India's Integrated Energy Policy [12], India's CO_2 generation in 2031-32 is expected to be in the range of 3.9 and 5.5 billion tonnes, depending on India's economic growth, energy and carbon intensity of the economy, the share of renewables in India's energy mix, and other factors. This, when combined with India's estimated population of 1468 million in that year, means that India's per capita CO_2 emissions in 2031-32 are projected to be between 2.6 and 3.6 tonnes/capita. While the precise proportion of the emissions contributed by the various sectors will depend on the assumptions used to arrive at a particular scenario, in every scenario the share of electricity generation is expected to continue to account for a majority of CO_2 emissions.

Assessment of projected fossil fuel reserves: India is a net importer of both oil and natural gas, and while India is the world's third largest coal producer, the coal is of low quality, necessitating the import of metallurgical coal for steel making.

The Indian Ministry of Coal states that India's proven coal resources are 114001.6 million tonnes, while the indicated resources are 137471.1 million tonnes, and inferred resources are 34389.5 million tonnes [13]. However, the quantity of coal that is actually extractable may be much lower, with estimates of India's extractable coal reserves ranging from 56-71 billion tonnes [14, 15]. The Geological Survey of India has estimated that India's coal reserves up to the depth of 1200 meters amount to 276.81 billion tonnes [16]. It is clear from the table below that, compared to other fossil fuels, India's coal resources are relatively plentiful, and hence coal is a very important part of India's energy portfolio from the standpoint of energy security.

Table 1: India's fossil fuels production, consumption and reserves [13] [17] [18] [19] [20]

Resource	Annual production	Annual consumption	Resources/Reserves
Coal (million tonnes)	570.00	653.00	114001.60
Oil (million tonnes)	37.71	206.15	757.44
Natural gas (billion cubic metre)	52.80	64.95	1240.92

Current climate change policies and targets: India recognises the seriousness of the threat of climate change, but is faced with the simultaneous challenge of ensuring socio-economic development to improve the living conditions of the populace. Combating climate change and improving standards of living are not mutually exclusive aims: associated energy growth that usually underpins improvements in living standards needs to be based on low-carbon energy options. In addition, it's recognised that the impact of climate change may negatively impact on India's development. For instance, changes to India's climate will impact agriculture production, which a significant proportion of the population rely on for their livelihood Consequently, India's government follows an approach which, while being 'development first', ensures that the development is sustainable and climate friendly.

To address the climate change issue, the Indian Prime Minister's Council on Climate Change released the National Action Plan on Climate Change (NAPCC) in 2008. It outlines how, despite not having any fixed, legally binding emission reduction targets being a Non-Annex I country, India takes the issue of global warming seriously, given that the government expenditure on climate change adaptation in India already exceeds 2.6% of GDP, and that climate change is expected to have major impacts on water resources, agriculture, forests, etc. in India [21]. It explains how India's development will be on a sustainable trajectory, stating that 'India is determined that its per capita greenhouse gas emissions will at no point exceed that of developed countries even as we pursue our development objectives.'

Accordingly, eight national missions for managing climate change have been set up, which are the National Solar Mission, the National Mission for Enhanced Energy Efficiency, the National Mission on Sustainable Habitat, the National Water Mission, the National Mission for Sustaining the Himalayan Ecosystem, the National Mission for a "Green India", the National Mission for Sustainable Agriculture and the National Mission on Strategic Knowledge for Climate Change. The Principal Scientific Advisor has announced the Government's interest in adding a ninth 'Clean Coal Technologies' mission that would include CCS.

An important portion of the NAPCC deals with GHG mitigation in India's power sector. It points out that various measures for reducing GHG emissions from power plants, such as increasing the efficiency of existing power plants, using clean coal technologies, and switching to fuels other than coal where possible, must be viewed as being complementary and not mutually exclusive. CCS is held in the NAPCC report to not being feasible at present, and concerns have been raised about the cost as well permanence of the CO_2 storage.

The National Mission for Enhanced Energy Efficiency, mentioned above, incorporates a 'Perform Achieve and Trade' scheme, which is a market-based mechanism aimed at improving energy efficiency in selected sectors [22]. Presently, nine industrial sectors have been selected under this scheme- thermal power plants, fertiliser, cement, pulp and paper, textiles, chlor-alkali, steel, aluminium and railways. An industrial player reducing its Specific Energy Consumption (SEC) below the set target will be provided with Energy Saving Certificates (ESCerts), which it will able to sell to a different player unable to meet its target. The scheme is intended to stimulate energy efficiency improvements which may reduce the energy cost of industries by over 5%.

3. CO_2 sources

As stated in the previous section, power generation is the single largest source of CO_2 emissions in India, with the cement and the iron and steel industries the next biggest contributors.

Power generation: India's installed electricity generation capacity reached 210.9 GW in November2012 [23]. The share of the different resources in India's installed capacity is given below.

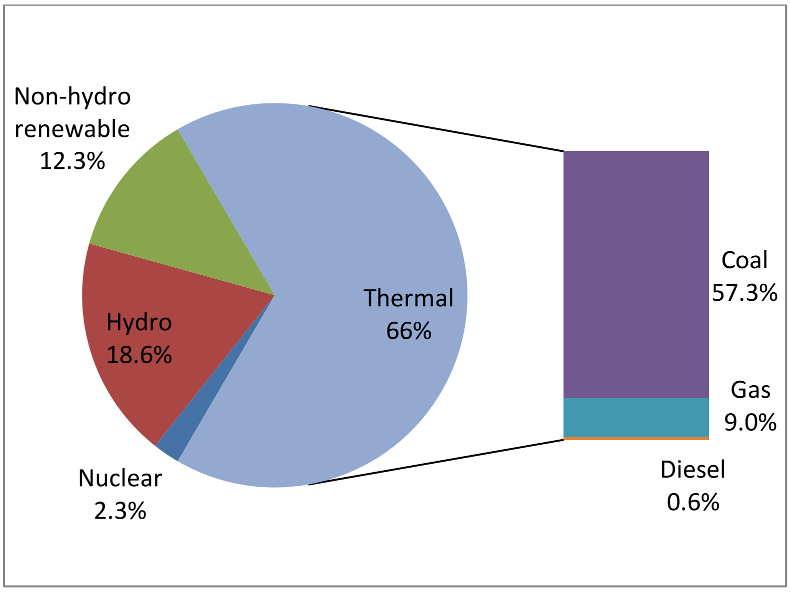

Figure 5: India's installed electricity generation by type [23]

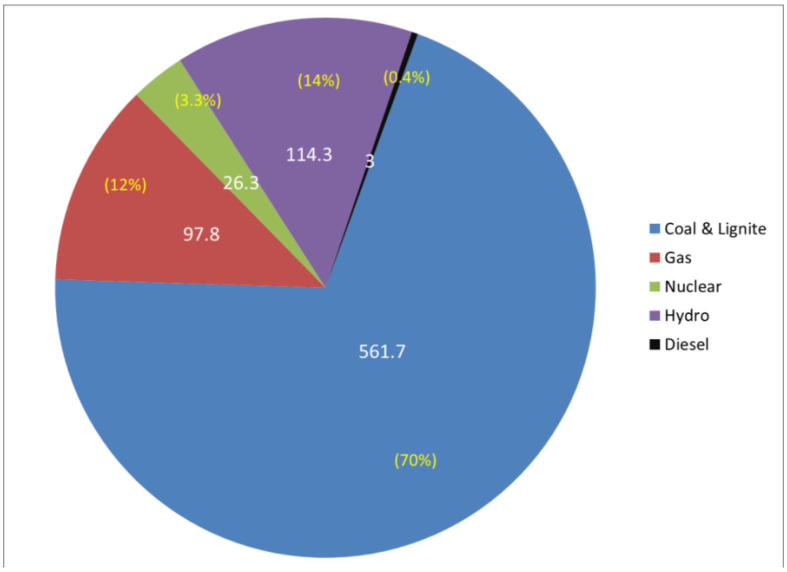

Figure 6:India's actual electricity generation in 2010-11 for different fuel types for plants with capacity greater than 25 MW.

(Note: Numbers in yellow represent percentage of total electricity generation by particular fuel and numbers in white are Billion Units generated [24])

As can be seen in Figure 6, India's actual electricity production is even more dependent on thermal power plants, since hydroelectricity and wind power generally operate at much lower plant load factors than thermal power plants, owing to their dependence on seasonal variations in water level and in wind speeds respectively.

Coal is expected to remain the mainstay of India's power sector in the near future too, with most of the 100 GW of power capacity addition planned in the 12th Five Year Plan period

(2012-17) based on coal based power. However, future capacity addition is expected to increasingly be based on super-critical technology, with 50% of the capacity in the 12th plan period targeted to be through super-critical units, and all coal based plants in the 13th plan period to be super-critical units [25].

In particular, 16 super-critical technology-based Ultra Mega Power Plants (UMPPs) [26], each generating about 4000 MW, have been prioritised as a thrust area by the Indian Ministry of Power. These UMPPs will either be pithead projects with dedicated captive coal blocks, or coastal projects using imported coal. These UMPPs are awarded to developers under the tariff-based competitive bidding route on build, own and operate basis. The Power Finance Corporation (PFC), which is the nodal agency for the development of these projects, sets up Special Purpose Vehicles (SPVs) for each UMPP to act as authorised representatives of the procuring distribution companies. Once the bidding process for selection of the project developer is completed, the SPVs are transferred to the selected bidders [27]. A list of the UMPPs which have already been awarded is given in Table 2, while the UMPPs for which SPVs have been set up, but bidding is yet to take place, is given in Table 3.

Table 2:List of UMPPs awarded [27]

Name of UMPP	Type	Special purpose vehicle	Developer awarded	Current status
Mundra, Gujarat (4000 MW)	Coastal	Coastal Gujarat Power Ltd.	Tata Power Ltd.	4th Unit (each unit of 800 MW) commissioned in Jan 20132 [28]
Sasan, Madhya Pradesh (3960 MW)	Pithead	Sasan Power Ltd.	Reliance Power Ltd.	1st Unit (660 MW) to be commissioned in Jan 2013 [29]
Krishnapatnam, Andhra Pradesh (3960 MW)	Coastal	Coastal Andhra Power Ltd.	Reliance Power Ltd.	Work stopped due to change in Indonesian coal regulations [29]. Central Electricity Regulatory Commission (CERC)approached for tariff hike [30]
Tilaiya, Jharkhand (3960 MW)	Pithead	Jharkhand Integrated Power Ltd.	Reliance Power Ltd.	Land acquisition and financing in progress [31]

Table 3: List of UMPPs for which SPVs incorporated [26]

Name of UMPP	Type	Special Purpose Vehicle
Chhattisgarh	Pithead	Chhattisgarh Sarguja Power Ltd.
Orissa	Pithead	Orissa Integrated Power Ltd.
Cheyyur, Tamil Nadu	Coastal	Coastal Tamil Nadu Power Ltd.
Andhra Pradesh 2nd UMPP	Coastal	Tatiya Andhra Mega Power Ltd.
Orissa Additional UMPP 1	Pithead	Sakhigopal Integrated Power Co. Ltd.
Orissa Additional UMPP 2	Pithead	Ghogarpalli Integrated Power Co. Ltd.
Maharashtra UMPP	Coastal	Coastal Maharashtra Power Ltd.
Karnataka UMPP	Coastal	Coastal Karnataka Power Ltd.

The design efficiency of coal-based power plants in India ranges from 28.20% for the 30-50 MW sub-critical units to 40.5% for new super-critical units, with the average actual thermal efficiency of the plants being 32.70% in 2008-09 [32]. The specific emissions from Indian coal-fired power plants are around 1.07 kg/kWh [33].

Gas-fired power plants account for about 9% of India's installed power capacity, with the plants achieving an average net efficiency of 41.9% [10]. While the share of natural gas in India's power generation may rise in the future, gas supply problems may impact expansion plans.

A large share of the thermal power production in the country is being undertaken either by Central Government utilities like NTPC Ltd. and DVC, or State Government utilities like APGenco and Mahagenco. Increasingly, though, private players like Tata Power, Reliance Power, JSW Energy, Adani Power and LancoInfratech. are beginning to make a mark in this sector. The installed coal-based power plant capacity of major players is given in Figure 7.

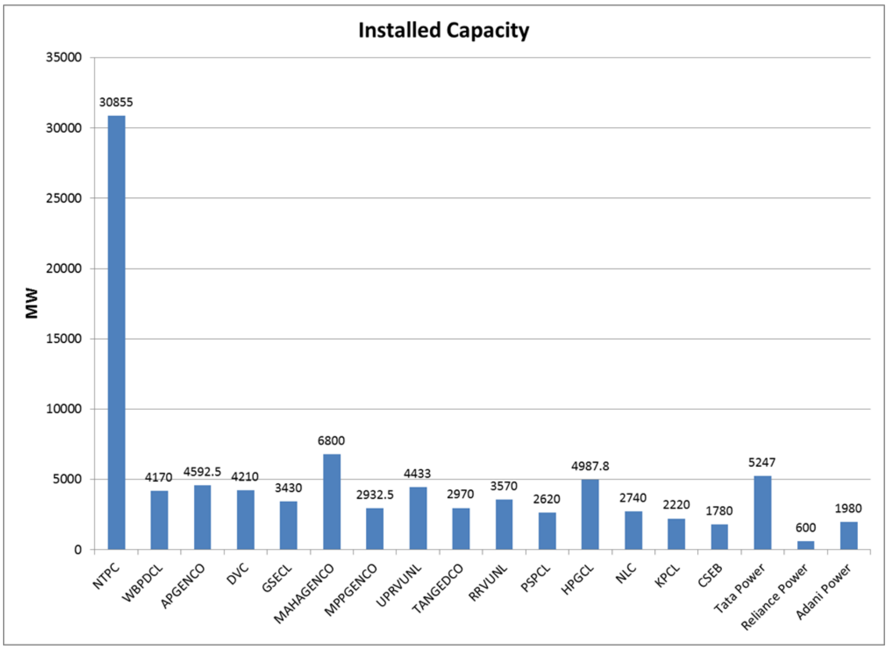

Figure 7:Installed coal-based power plant capacity of major players ([34] to [51])

[WBPDCL: West Bengal Power Development Corporation; APGENCO: Andhra Pradesh Power Generation Corporation Limited; DVC: Damodar Valley Corporation; GSECL: Gujarat State Electricity Corporation Ltd.; MAHAGENCO: Maharashtra State Power Generation Co. Ltd.; MPPGENCO: Madhya Pradesh Power Generating Co. Ltd.; UPRVUNL: Uttar Pradesh RajyaVidyutUtpadan Nigam Ltd.; TANGEDCO: Tamil Nadu Generation and Distribution Corporation Ltd.; RRVUNL: Rajasthan RajyaVidyutUtpadan Nigam Ltd.; PSEB: Punjab State Electricity Board; HPGCL: Haryana Power Generation Corporation Ltd.; NLC: Neyveli Lignite Corporation; KPCL: Karnataka Power Corporation Ltd.; CSEB: Chhattisgarh State Electricity Board].

Oil and gas production:India has recoverable crude oil reserves of 757.44 million tonnes [19]. This is inadequate to meet India's growing energy needs, with the result that the gap between domestic oil production and consumption has steadily been rising (Figure 8). This shortfall is met by imports, with 2.2 million barrels per day imported in 2010.

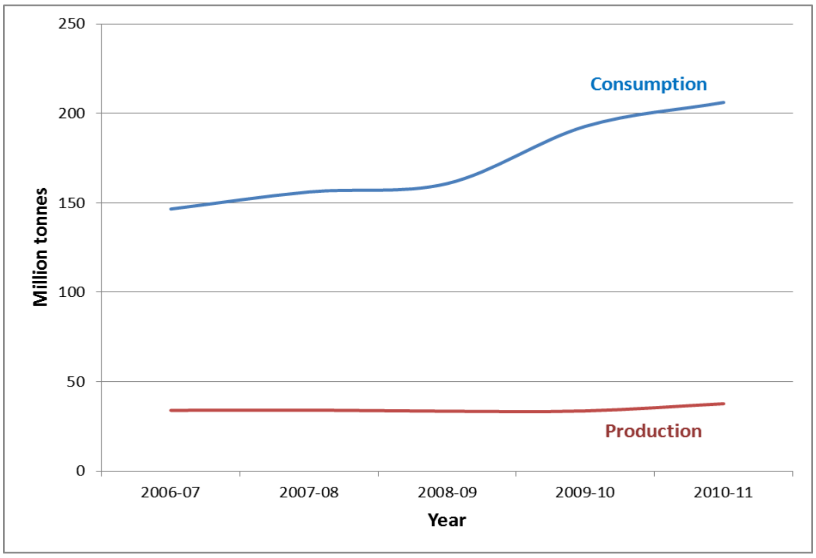

Figure8:India's crude oil production and consumption history [19]

On the domestic oil production front, the largest player is the state-owned ONGC Ltd. In the downstream sector, the government-run Oil Marketing Companies (OMCs) like Indian Oil, Hindustan Petroleum and Bharat Petroleum dominate the refinery and distribution segment. India's oil refining capacity is 193.39 MTPA [52], distributed across 21 refineries, of which 17 are in the public sector. The list of the Indian refineries is given in Table 4. Petroleum refining itself accounts for only around 1 million tonnes of CO_2 emissions per annum [9].

Table 4:Ownership, location and capacity of existing petroleum refineries in India [53]

Sr. No.	Name of the company	Refinery location	Capacity (MMTPA)
1.	Indian Oil Corporation Limited (IOCL)	Guwahati, Assam	1.00
2.	Indian Oil Corporation Limited (IOCL)	Barauni, Bihar	6.00
3.	Indian Oil Corporation Limited (IOCL)	Koyali, Gujarat	13.70
4.	Indian Oil Corporation Limited (IOCL)	Haldia, West Bengal	7.50
5.	Indian Oil Corporation Limited (IOCL)	Mathura, Uttar Pradesh	8.00
6.	Indian Oil Corporation Limited (IOCL)	Digboi, Assam	0.65
7.	Indian Oil Corporation Limited (IOCL)	Panipat, Haryana	15.00
8.	Indian Oil Corporation Limited (IOCL)	Bongaigaon, Assam	2.35
	Total IOCL		*54.2*
9.	Hindustan Petroleum Corporation Limited (HPCL)	Mumbai, Maharashtra	6.50
10.	Hindustan Petroleum Corporation Limited (HPCL)	Visakhapatnam, Andhra Pradesh	8.30
11.	Bharat Petroleum Corporation Limited (BPCL)	Mumbai, Maharashtra	12.00
12.	Bharat Petroleum Corporation Limited (BPCL)	Kochi, Kerala	9.50
13.	Chennai Petroleum Corporation Limited (CPCL)	Manali, Tamil Nadu	10.50
14.	Chennai Petroleum Corporation Limited (CPCL)	Nagapattnam, Tamil Nadu	1.00
15.	Numaligarh Refinery Ltd. (NRL)	Numaligarh, Assam	3.00
16.	Mangalore Refinery & Petroleum Ltd. (MRPL)	Mangalore, Karnataka	11.82

Sr. No.	Name of the company	Refinery location	Capacity (MMTPA)
17.	Tatipaka Refinery (ONGC)	Tatipaka, Andhra Pradesh	0.066
	Total public sector		*116.886*
18.	Bharat Petroleum Corporation Limited & Oman Oil Company, joint venture	Bina, Madhya Pradesh	6.00
19.	Reliance Industries Limited (RIL)	Jamnagar, Gujarat	33.00
20.	Reliance Petroleum Limited	Jamnagar, Gujarat	27.00
21.	Essar Oil Limited (EOL)	Jamnagar, Gujarat	10.50
	Grand Total		**193.386**

Most of India's crude oil reserves are either located offshore in the west of the country, or onshore in the northeast, with substantial reserves also existing in the Bay of Bengal and in the western state of Rajasthan [20].

India's natural gas reserves were estimated to be 1241 billion cubic metres in 2010 [19]. Consumption outstrips production, with 2010 figures of 65 billion cubic metres for annual consumption and 51 billion cubic metres for annual production [20]. Presently, the power and fertiliser sectors together account for nearly three quarters of India's natural gas consumption, and demand in the power sector is expected to grow in the future. The state-owned entities ONGC and GAIL dominate production and transmission, respectively.

Given the predominance of the Public Sector Units (PSUs) in India's oil and gas sector, it is clear that they are among the most important stakeholders for CCS implementation in the country, especially since this sector is significant not just as a source of CO_2 emissions, but possibly also as a sink, via Enhanced Oil Recovery (EOR).

Cement: Cement is one of the most important raw materials in any construction activity, and hence plays an important role in the infrastructure development of any country. It is manufactured by blending different raw materials like lime, silica, alumina and iron and firing them at a high temperature. Depending on how the raw material is handled before feeding to the cement kiln, the cement production process can be categorised as being wet, semi-dry or dry, with the dry process being the most energy efficient.

India's strong economic growth in the recent past has coincided with an infrastructure boom in the country, leading to the cement industry recording aCompound Annual Growth Rate(CAGR) of 8.1% over the last decade [54], which in absolute terms reflects the addition of 100 million tonnes capacity addition between 1999 and 2009 [55]. Today, the Indian cement industry is the second largest in the world, with an installed capacity of 323 million tonnes. The installed capacity and annual production in 2009 for the major cement manufacturers in India are shown in Figure 9.

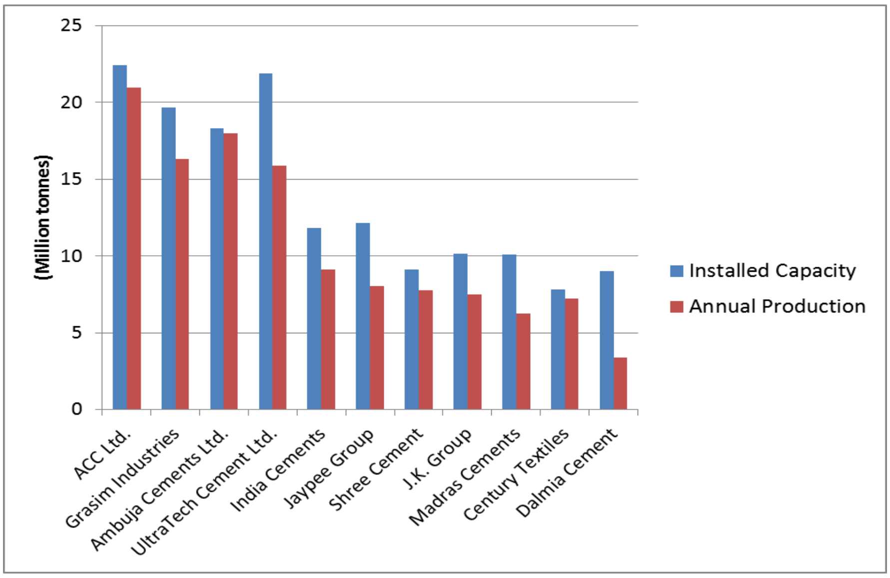

Figure 9:Indian cement industry: Installed capacity and market share of major players in 2009 [55]

In terms of regional distribution, there is an imbalance in cement production in the country, with more than 80% of the production coming from the states of Andhra Pradesh, Rajasthan, Madhya Pradesh, Gujarat, Tamil Nadu, Maharashtra, Karnataka and Chhattisgarh. This imbalance can be attributed to the fact that, world-wide, the location of cement plants is generally determined [56] by proximity to the source of the principal raw material, limestone, with availability of the secondary raw materials like clay and gypsum, as well as fuel, being the other guiding factors.

The Indian cement industry is one of the most energy efficient in the world, with the clinker plants having the lowest final energy use (3.1 GJ/tonne of clinker), and the specific electricity consumption also being the lowest in the world (~ 90 GJ/t for grinding) [57]. Alongside other improvements in technology and energy management, an important factor in this achievement is the fact that the industry started moving from the wet to the dry process for cement manufacture decades ago, with the result that the proportion of the dry process has increased from 1% of cement production in 1960 to 97% in 2008, as against a decline in the share of the wet process from 94% to 2% in the same period [58].

One of the outcomes of the high energy efficiency of the Indian cement industry is the fact that average CO_2 emissions for the sector are among the lowest in the world, at 0.68 MT CO_2/ MT cement, as compared to a global average of 0.84 MT CO_2/ MT cement [10]. The sheer volume of cement production, however, means that the industry emitted 129.92 MT of CO_2in 2007, a figure that may increase substantially in the future, given India's aim of increasing cement manufacturing capacity to 479 million tonnes by 2017 [59].

One salient feature of the Indian cement industry is that large plants, having capacity of over 1 MTPA, account for the lion's share of cement production in the country (88% of total production in 2009) [55]. This may be important from the perspective of CCS deployment, since economies of scale dictate that deployment of new technologies is often more cost effective for larger plants.

Iron and steel: The Indian iron and steel industry was deregulated as part of India's economic reforms programme in 1992. Subsequently, the industry has grown rapidly, and today India is the 4th largest producer of crude steel and the largest producer of sponge iron in the world. In 2009-10, India's production of pig iron was 5.88 million tonnes, while that of sponge iron was 24.33 million tonnes [60]. Total finished steel production in the same year was 60.62 million tonnes, which can be contrasted with a production of 14 million tonnes in 1991 [61]. This rapid growth rate is expected to be sustained in the near future, with the Working Group on Steel for India's 12th Five Year Plan projecting that India's crude steel capacity is likely to be 140 million tonnes in 2016-17 [60].

The Indian iron and steel industry has both public sector companies, like Steel Authority of India Limited (SAIL) and RashtriyaIspat Nigam Limited (RINL), and private sector firms such as Tata Steel, Essar Steel, Jindal Steel and Power, etc. On the basis of production routes, the Indian steel industry can be divided into integrated producers, such as SAIL and Tata Steel, who convert iron ore into steel, and secondary producers, which are mainly Small and Medium Enterprises (SMEs) operating mini-mills, which make steel from scrap or sponge iron. The list of integrated steel plants in India in 2008 is given in Table 5.

Table 5:List of Integrated steel plants in India in 2008 [10]

Plant	Capacity	Specific CO_2emissions MT CO_2/ ton of crude steel
SAIL, Bhilai	3.925	2.82
SAIL, Durgapur	1.802	2.64
SAIL, Rourkela	1.900	3.16
SAIL, Bokaro	4.360	3.03
SAIL, Burnpur	0.500	5.50
RINL, Vishakapatnam	2.910	3.18
Tata Steel, Jamshedpur	5.00	2.04
JSW, Bellary	3.800	2.50
Essar, Hazira	4.600	1.55
Ispat, Dolvi	3.000	2.45
JSPL, Raigarh	2.400	-

Noteworthy aspects of India's steel industry include:

i. The average CO_2 emissions intensity of Indian steel plants, at 2.4 tonnes of CO_2 per tonne finished steel, is considerably higher than the global average of 1.8 t CO_2/t steel. This can largely be attributed to the following factors [62] [10]:

ii. In India, 38% of the hot metal production is from mini-blast furnaces, which typically have 20-30% higher emissions than regular blast furnaces. This is important because the blast furnace is the major source of emissions in the iron and steel industry.

iii. The consumption of reducing agents like coke in blast furnaces in India is 36% above world standards.

iv. Sponge iron production is predominantly coal-based, due to greater local availability.

v. The high emissions intensity Electric Induction Furnace (EIF) route accounts for 30% of India's crude steel production.

vi. The high energy consumption discontinuous casting process accounts for 30% of India's crude steel production.

vii. The facts that Indian steel plants use high ash coking and non-coking coal and the iron ore mined in India is high in silica and alumina content, also partly account for the high consumption of energy.

The fact that the emissions intensity of India's iron and steel sector is much higher than world standards means that CCS may be an attractive option for bringing this figure down to more acceptable levels.

4. Current CCS activity in India

Most Indian Research and Development (R&D) activities related to CCS occur under the **Department of Science and Technology** (DST) of the Indian Ministry of Science and Technology. The DST set up the National Program on Carbon Sequestration (NPCS) Research in 2007, with a view to competing with other countries in this area with respect to both pure/applied research and industrial applications. Four thrust areas of research were identified under this programme, viz. CO_2 Sequestration through Micro algae Bio-fixation Techniques; Carbon Capture Process Development; Policy development Studies; and Network Terrestrial Agro-forestry Sequestration Modelling [63]. An indicative list of projects relevant to CCS approved by the Inter-Sectoral Science & Technology Advisory Committee (IS-STAC) of the DST is given in Table 6.

Table 6:List of DST projects related to CCS (References from [64] to [68])

Sr. No.	Project title	Organisation	Year approved	Duration (years)
1.	Modelling and simulation of Carbon Recycling Technology though conversion of CO_2 into useful multi-purpose fuel	Rajiv Gandhi Technological University, Bhopal	2007-08	3
2.	Pilot Bio-reactor using biological and chemical carbon dioxide sequestration (Integrated Biological and Chemical CO_2 sequestration)	National Environmental Engineering Research Institute (NEERI), Nagpur	2007-08	3
3.	Sequestration of carbon dioxide (CO_2) into geological environment (Gas Hydrate): Laboratory Studies	National Geophysical Research Institute (NGRI), Hyderabad	2007-08	3
4.	Development and Characterization of porous Solid Adsorbents for sequestration of Carbon Dioxide (CO_2) (Metal Silicates for pre-combustion High Temperature CO_2 Removal (IGCC Conditions)	National Chemical Laboratory (NCL), Pune	2007-08	3
5.	Experimental and simulation studies on CO_2 sequestration using solar/ chemical methods	Centre for Energy and Environment Science and Technology(CEESAT), NIT, Tiruchirapalli	2007-08	3
6.	Analysis of Carbon Capture and storage (CCS) technology in the	Integrated Research and Action for Development	2007-08	2

Sr. No.	Project title	Organisation	Year approved	Duration (years)
	context of Indian Power Sector	(IRADe), New Delhi		
7.	Predicting Soil Carbon changes under different bio-climatic systems in India	National Bureau of Soil Survey and Land Use Planning, Nagpur	2007-08	3
8.	Improving carbon and nitrogen sequestration: A Transgenic approach to lower greenhouse gas	Institute of Himalayan Bio-resources Technology, Palampur, Himachal Pradesh	2007-08	3
9.	Carbon Di-oxide Sequestration through Culture of Medically useful Micro-algae in Photo-bio-reactor linked to Gas outlets of Industries	Department of Botany, Andhra University, Vishakhapatnam	2008-09	3
10.	CO_2 Sequestration using Micro algae – Efficient use of CO_2 from bio-hydrogen production facility	AMM MurugappaChettiar Research Center, Chennai	2008-09	3
11.	Carbon Sequestration by higher plants and algae at elevated carbon di-oxide	Jawaharlal Nehru University and Dehi University, Delhi	2008-09	3
12.	Carbon Di-oxide Sequestration Potential of Agro Forestry System under Irrigated and Rain fed Conditions	Director, National Research Center for Agro-forestry, Jhansi	2008-09	3
13.	Mycorrhizal Symbiosis to Promote Carbon Sequestration for Sustainable Fertility and Environment Safety	Department of Soil Sciences & Agriculture Chemistry, Tamilnadu Agriculture University, Coimbatore	2008-09	3
14.	Mechanism and the dynamics of carbon storage in the Sundarban Mangrove	University of Calcutta, Kolkata	2009-10	3
15.	Marine cyanobacteria a promising candidate for carbon-dioxide sequestration with multiple utilization	Bharathidasan University, Tiruchirappalli	2009-10	3
16.	Carbon sequestration potential in wetlands of Vedaraniam, south east coast of India	Bharathidasan University, Tiruchirappalli	2009-10	3
17.	Carbon Sequestration through Afforestation for Mitigating CO_2 emission from Thermal Power Station	Jadavpur University, Kolkata	2009-10	3
18.	Chemo-photosynthetic conversion of carbon dioxide into algal biomass with biotech potentials	Department of Biotechnology School of Life Sciences, North Maharashtra University	2009-10	3
19.	Monitoring of Carbon sequestration through Micro propagating Bamboo Plantation in Himalayan region	G.B.U.A.&T. Ag. Research Station, Nainital, Uttrakhand	2009-10	3
20.	Development of carbon composites	Indian Institute of Chemical	2010-11	3

Sr. No.	Project title	Organisation	Year approved	Duration (years)
	Materials for CO_2 capture	Technology, Hyderabad		
21.	Development of screening criteria for saline aquifers and other geological sinks	Global Hydro geological Solutions, New Delhi	2010-11	3
22.	Aqueous mineral carbonation of silicates and mineral trapping of CO_2 in the tholeiite- picrite assemblage of Thakurvadi Formation, Deccan Basalt Volcanic Province, India: Geological, stable isotope and Experimental studies	National Geophysics Research Institute, Hyderabad	2010-11	3
23.	Carbon sequestration by mineral carbonation in cement kiln dust	Indian Institute of Technology, New Delhi	2010-11	3
24.	Evolution of RuBisCohypermorphs for enhanced CO_2 sequestration and its utilization for polymer products	Bharathidasan University, Tiruchirapalli	2010-11	3
25.	Mineral CO_2 sequestration by carbonation of industrial; Alkaline solid residues	Anna University , Chennai	2011-12	3
26.	Study On Carbon Stock and Response Of Estuarine Phytoplankton To Iron Fertilization	University of Calcutta, Kolkata	2011-12	3
27.	CO_2 sequestration studies on volcano-sedimentary succession of the eastern Deccan volcanic province	University of Delhi, Delhi	2011-12	3
28.	Carbon dioxide sequestration using anoxic microbial consortium for the production of methane fuel and oxygenic microbial consortium for bioconversion of methane to methanol	K S Rangasamy College of Arts and Science, Tiruchengode	2011-12	3
29.	A Bioelectrochemical system for sequestration of carbon dioxide	Dr DYY Patil Biotechnology And Bioinformatics Institute, Pune	2011-12	3

The annual reports of the DST provide information about the work that has been conducted under various projects over the previous year. For instance, information on the projects 1, 3, 11 and 12listed in the preceding table is available in the 2009-10 annual report [69], on projects 5,7, 8, 9, 12 and 14 in the 2010-11 annual report [70], and on projects 2, 5, 10, 13, 14, 19 and 24 in the 2011-12 annual report [71].

In addition, under the Agreement of Cooperation in Science & Technology concluded between Government of India and the Government of Norway, the DST and the Research Council of Norway (RCN) have started a programme for joint funding of Indian-Norwegian joint research projects in Climate research, including CCS [72]. **ONGC Ltd.** was in the process of setting up a pilot experimental EOR project in Gujarat, with CO_2 from the gas processing plant at Hazira to be supplied to the Ankleshwar oil field. The plan was to produce a high purity gas stream from the offshore Hazira plant, which processes 40 MMSCMD of sour gas per day, using amine absorption followed by H2S removal, dehydrate and compress the gas at Hazira, before transporting it via pipelines to the depleted onshore reservoir at Ankleshwar, where it would be recompressed and injected for enhanced recovery of crude oil [73]. However, ONGC is reportedly re-thinking this project owing to its cost.

The state-owned **National Aluminium Company** (NALCO) plans to set up a carbon capture unit at its coal-fired plant at Angul, Orissa state [74]. Nalco has earmarked an area of 0.18 acre for the project to adopt an advanced and innovative technology by engaging the firm M/s Indo-Can Technology Solutions (ICTS), a pioneer in the area of bio-technology solutions, for providing technical consultancy and rendering necessary services to guide Nalco for successful completion of the project within 18 months [75]. Under this project, algae will be grown in shallow ponds and CO_2 produced from the thermal power plant will be tapped and introduced in the pond. The algae may be used for production of bio-fuel, poultry and cattle feed, aquaculture feed, pharmaceutical products, etc. The government-owned **NTPC Ltd.**, which is India's largest power company, has also been conducting some research on CCS. In particular, as part of the Carbon Sequestration Leadership Forum (CSLF), it has partnered the **National Geophysical Research Laboratory India (NGRI)** and the Battelle Pacific North-West National Laboratory, USA, to evaluate the Deccan basalt formation in India as a potential long-term CO_2 storage option [76] [77]. In addition, NTPC also organised a national workshop on CCS in collaboration with the Ministry of Power in September 2011.

The Department of Chemical Engineering of the **Indian Institute of Technology Bombay** (IITB) has been carrying out a study for Cyanobacteria which can be developed as an excellent microbial cell factory that can harvest solar energy and convert atmospheric CO_2 to useful products. The department is involved in the construction of the genetic regulatory networks of cyanobacteria and using them to predict and optimise carbon sequestration and biofuel production [78].

Also, the department is carrying out a study for carbon sequestration using carbon dioxide absorption in aqueous mineral suspensions as a collaborative project with Washington University at St Louis [79]. IITB is also a part of Consortium for Clean Coal Utilization with WUStL where they are working on the following projects: Development of a Microalgal System for Carbon Dioxide Sequestration; Carbon Dioxide Capture and Conversion in Different Modalities (Conventional and Oxy-Coal) of Coal Combustion Systems; Carbon Dioxide Capture and Conversion in Different Modalities (Conventional and Oxy-Coal) of Coal Combustion Systems; Mechanisms and Kinetics of Multiphase Fluid-formation Mineral Reactions in CO_2 Geologic Sequestration [80].

Bharat Heavy Electrical Ltd. (BHEL), the state-owned engineering and manufacturing enterprise, and **APGENCO**, the power generating company of Andhra Pradesh, are setting up a 125 MW demonstration IGCC plant in Andhra Pradesh [81]. While not directly related to CCS, given that IGCC is one of the cheapest options for carbon capture, but is difficult to implement for Indian coal, it may be said that this development can eventually lead to the deployment of pre-combustion capture technology in the power sector in India.

In addition to setting up India's first IGCC plant, BHEL is also coordinating with Indira Gandhi Centre for Atomic Research (IGCAR) and NTPC to design, develop and build ultra super-critical boilers [82], which will be an addition to the supercritical technology boilers that it already manufactures. BHEL is also collaborating with **TREC-STEP** (Tiruchi Regional Engineering College – Science and Technology Entrepreneurs Park) to implement a set of initiatives in CCT and CCS, as part of a three year EU funded project [83].

TREC-STEP, in collaboration with Ernst and Young, also organised an EU-funded 2-day training programme on 'Introduction to CCS and CCT' in December 2011, and a 3-day 'Skill Leverage Programme on CCT-CCS Technologies' in January 2012.

Indian Institute of Petroleum (IIP) has been working on developing new adsorbents for post-combustion CO_2 capture. In this regard, they have set up a three column Pressure Swing Adsorption/Vacuum Swing Adsorption unit in their laboratory in Dehradun. In this column, adsorbents are being tested under flue gas conditions as available in power plants. The work is being carried out in collaboration with **IIT Bombay**, which handles the simulation and process design aspects, **NTPC**, which deals with power plant operation, and **Central Salt & Marine Chemicals Research Institute** (CSMCRI) and **National Environmental Engineering Institute** (NEERI), who are responsible for adsorbent development [84].

Private players in the power sector, like Tata Power and Reliance Power, have also been contemplating CCS seriously, but issues such as regulatory approval and storage challenges appear to have prevented any large scale demonstration activities from taking off.

5. Economic analysis

As was noted in Section 3, the majority of India's emissions come from the power sector, and the development of gigawatt scale power plants in recent years means that the large scale concentrated emission sources that are most suitable for CCS deployment are predominantly in the power sector. Hence, CCS deployment in the power sector will have a significant impact on CO_2 emission reductions, and therefore, it is this sector that has been considered for economic analysis in this study.

Literature review: While there have been a number of studies conducted regarding the cost of both CCS retrofit and built-in capture, the fact that these studies have used widely divergent assumptions regarding plant and other costs, year of installation, capture technology used, type of storage sink, and other parameters, means that it is often not possible to compare the results of the studies meaningfully. After an extensive literature review, the study that was found to be the most suitable for gathering the basic inputs required for the economic analysis carried out was the one conducted by Mott MacDonald (MM) in 2008 [85]. The various parameters and assumptions considered in this study were supplemented by other references and the results arrived at are presented as Case 1 below. This analysis was further refined based on consultation with NTPC Ltd. and other stakeholders, and the findings used to create the Case 2. Finally, the results were compared with those arrived at using the GCCSI figures given in [86], and which are presented in Case 3.

In each case, the Levelised Cost of Electricity (LCOE) in Rs/kWh was calculated using the formula:

$$\text{LCOE} = (C_{cap}+C_{O\&M})*a/h + C_{TS} + C_{fuel}$$

Where C_{cap} = Specific capital cost (Rs/kW)

$C_{O\&M}$ = Specific operating and maintenance cost (Rs/kW)

a = annuity factor, as calculated by the formula

a = $I*(1+I)^n/((1+I)^n-1)$
I = Interest rate (%)
n = Depreciation period (years)
C_{TS} = Specific transport and storage cost (Rs/kWh)
C_{fuel} = Specific fuel cost (Rs/kWh)
h = Annual hours of operation

Case 1:

As stated above, Case 1 was developed largely using the assumptions and figures given in [84], supplemented by other references.

The assumptions and technical specifications considered for the base case power plant are given in Table 7.

Table 7:Assumptions and technical specifications considered for the base case power plant

Item	Value	Units	Explanation/reference
Plant type	Supercritical, capture ready		
Plant size	4000	MW	CCS implementation is expected to be more cost effective for larger power plants, and 4000 MW plants are among the largest presently in operation. This plant is assumed to have 5 units of 800 MW each.
Plant life	40	Years	[85]
Plant start year	2015		-
CCS start year	2020		Since CCS technology is expected to take a few years to mature, it is postulated that the carbon capture will be retrofitted to the plant after 5 years of operation.
Location	Indian coast for imported coal/pithead for Indian coal		Most large scale power plants are being planned either near a captive coal mine or along the coast where coal import is possible.
PLF	90%		-
Net power	3720	MW	Assuming auxiliary power consumption of 7%, as given in [87].
CCS operational life	35	Years	-
Specific CO_2 emissions	1	kg/kWh	As given in Section 3, specific emissions from Indian coal fired plants are 1.07 kg/kWh. Being more efficient than conventional plants, emissions from supercritical units are expected to be lower.
Plant heat rate	8899.2	MJ/MWh	Net heat rate taken from [88]
Calorific value of coal used	5350	kCal/kg	Gross calorific value taken from [88]
Fuel cost	120	USD/t	For imported coal, as per [89], with a transport cost of 39 $/t as per [90]
	65	USD/t	For Indian coal, as per [91], with a transport cost of 39 $/t as per [90]

Given it is assumed that the plan is capture ready, it is important to state the definition of capture ready considered, since the description differs considerably in literature. Here, the following definition given in [85] has been considered.

"A CO_2 capture ready power plant is a plant which is initially not fitted with CO_2 abatement technology but which subsequently can be fitted with a technology to capture the gas when regulatory or economic drivers are in place to drive this. "

Further, it would have the following characteristics:

- Prior to capture, the plant requires low additional expenditure (e.g. 1% additional capital costs) and has no significant performance penalties compared to the standard industry plant options;
- The plant can be converted to capture with no more than standard major maintenance outages, taking the maximum possible advantage of the then available best technology, and with minimal additional expenditure beyond the cost of the capture equipment itself;
- After conversion to capture, the plant operates with comparable performance (in terms of heat integration) as if the base plant and the capture equipment had been designed and built as a single unit;
- It offers a feasible route to CO_2 storage, for which the planning horizon and any required regulatory changes, to overcome current barriers, are understood.

A very comprehensive definition of CCS Ready that was created with the input of many international stakeholders can be found at [92].

Since carbon capture is an energy intensive process, net power output will be significantly reduced when compared to the base case scenario. To compensate for this, an additional unit of 800 MW has been considered to be added, so that the net power output remains reasonably constant. Technical assumptions related to CCS implementation are given in Table 8.

The cost figures for the base plant, as well as for carbon capture, storage and monitoring, are listed in Table 9.

The financial assumptions used for Case 1 are given in Table 10.

A key measure of the affordability of CCS is the increase in the Levelised Cost of Electricity (LCOE) entailed. The values arrived at in Case 1are given in Table 11.

Table 8:Assumptions related to carbon dioxide capture, transport and storage

Item	Value	Units	Explanation/reference
Gross power output	4800	MW	Due to addition of an 800 MW unit.
Net power output	3930	MW	Based on auxiliary energy consumption data from [85].
Heat rate for retrofitted plant	11836	MJ/MWh	For 33% capture penalty.
CO_2 capture rate	90%		[85]
Capture technology	Monoethanolamine (MEA) based post combustion capture		MEA based capture is the most developed method of carbon capture, and post combustion capture is the most suitable for

Item	Value	Units	Explanation/reference
			retrofitting.
Amount of CO_2 captured/stored	34	MT per annum	-
Pipeline specifications	42" pipeline on-shore, with booster stations every 100km, 24" pipelines offshore		[85]
Pipeline onshore distance	200	Km	-
Pipeline offshore distance	50	Km	-
Storage site	Saline aquifers		Although storage data is in general uncertain for India, [93] indicates that saline aquifer potential may be the highest, and hence has been considered.
Injection specifications	12 injection wells each with 8000 t CO_2/day capacity		Modified from [85] based on higher storage requirements for this study.

Table 9: Cost figures considered in Case 1

Item	Value	Units	Explanation/reference
Base plant capital cost	4000	USD mn	[27]
Capture capital cost	2438	USD mn	Value given in [85] adjusted for the larger unit size and lower base plant capital cost in present case.
Transport capital cost	90	USD mn	Adapted from [85] based on the pipeline lengths considered as per Table 8. Since [85] indicates overall capital costs for transport and storage, the ratio of capital costs mentioned in [94] has been used to split the costs.
Storage capital cost	170	USD mn	Storage capital cost arrived at in the same way as the transport capital cost, and then increased by 20% to account for the larger injection rate in the present study as compared to [85].
Monitoring capital cost	26	USD mn	Costs given in [95] extrapolated to injection levels of present study.
Fixed O&M for base plant	72.45	USD mn/y	[87]
Variable O&M for base plant	3.40	USD/MWh	[87]
Fixed O&M for capture equipment retrofitted plant	94.19	USD mn/y	Increase in O&M costs taken to be 30%, in line with [85]
Variable O&M for capture equipment retrofitted plant	4.42	USD/MWh	Increase in O&M costs taken to be 30%, in line with [85]
Operating cost for transport and storage	2	USD mn/y	Taken as average of costs for coastal power plants as listed in [85].
Monitoring operating cost	154	USD mn	Calculated similar to monitoring capital cost.

Table 10:Case 1 financial assumptions

Item	Value	Units	Explanation/Reference
Debt: equity ratio	80 : 20		
Loan amount	3200	USD mn	
Repayment period	15	Years	
Interest rate	7.05%		[96]
Exchange rate	1 USD = 50 INR		

Table 11:LCOE for Case 1

Item	Imported coal	Indian coal
LCOE without capture (Rs/kWh)	2.95	1.85
LCOE with capture (Rs/kWh)	4.02	2.56
LCOE with CCS (Rs/kWh)	4.04	2.59
LCOE with CCS and monitoring (Rs/kWh)	4.06	2.61
Increase in LCOE due to CCS and monitoring	38%	41%

Further, based on the suggestions received from different stakeholders, including NTPC Ltd., a number of changes were made in the assumptions and cost figures, leading to Case 2 described below.

Case 2:

The differences between the assumptions and figures taken in Case 1 and 2 are summarised in Table 12.

In addition, it was suggested that the land costs should also be explicitly considered under the capital costs. However, as calculated from the figures given in [99], land costs for a gigawatt scale power plant are around USD 7 million, the inclusion of which in the capital costs does not affect the calculations significantly. Hence this figure has been neglected.

Using these assumptions, the LCOE values arrived at are given in Table 13.

Table 12:Differences between Case 1 and Case 2, with explanations

Item	Case 1	Case 2	Unit	Explanation
Base plant capital costs	4000	4800	USD mn	Stakeholders stated that the capital cost, while site-specific, should in general be around USD 1.2 million/MW.
Capture capital costs	2438	3005	USD mn	Stakeholders pointed out that the capture capital cost should not be a function of the base plant capital cost, and instead absolute values should be taken. Since the revised base plant capital was similar to that in [85], the capital cost of CCS equipment given there was adopted, with adjustment for the larger unit size.
Plant load factor	90%	85%		As per CERC norms [97].
Plant life	40	25	years	As per stakeholder consultation.
Base plant net heat rate	8899.2	10136	MJ/MWh	CERC norms state a heat rate of 2425 kCal/kWh [97], and this value has been used for Case 2. This figure was also used to recalculate the gross heat rate after

Item	Case 1	Case 2	Unit	Explanation
				capture assuming the same 33% capture penalty as earlier.
Interest rate	7.05%	13%		According to a stakeholder, the debt interest rate taken in Case 1 was unrealistically low, and a figure of around 13% was suggested.
Debt equity ratio	80/20	70/30		As per tariff policy, Government of India [98].
Calorific value of Indian coal	5350	3500	kCal/kg	According to a stakeholder, from their experience, the calorific value of the coal available domestically at 65 USD/t is around 3500 kCal/kg.

Table 13:LCOE for Case 2

Item	Imported coal	Indian coal
LCOE without capture (Rs/kWh)	3.97	3.50
LCOE with capture (Rs/kWh)	5.52	4.90
LCOE with CCS (Rs/kWh)	5.58	4.95
LCOE with CCS and monitoring (Rs/kWh)	5.61	4.99
Increase in LCOE due to CCS and monitoring	41%	42%

In percentage terms, the increase in LCOE is not very different from Case 1. However, in absolute terms, the rise in LCOE is higher due to the increase in the base case LCOE.

Case 3:

The results arrived at in the above two cases were cross-checked by substituting values from [81]. The differences with respect to Case 2 are summarised in Table 14.Using these assumptions, the LCOE values arrived at are given in Table 15.

Table 14:Differences between Case 2 and Case 3, with explanations

Item	Case 2	Case 3	Unit	Explanation
Capture capital costs	3005	3350	USD mn	The capture equipment cost in [86] for a base plant size of 580 MW is USD 418 mn, and capture material cost is USD 15 mn. This has been extrapolated to a plant size of 3960 MW using an extrapolation factor of 0.8, which is higher than the 0.6 factor generally used for scaling up economics, due to CCS technology not being demonstrated at a large scale, and hence possibly not scaling up as smoothly as established technologies. The location specific factors mentioned in [86] have been used to estimate costs for an Indian scenario. The cost of the extra unit has been taken by dividing the capital cost of the base plant by the number of units (6).
Plant size	4000	3960	MW	In this case, a power plant with 6 units of 660 MW, with the addition of another 660 MW unit to compensate for the capture penalty, was considered. This is consistent with changes in UMPP norms as mentioned in [28].
Gross power output with CCS	4800	4620	MW	Same as above.

Item	Case 2	Case 3	Unit	Explanation
Net power output without CCS	3720	3755	MW	The auxiliary power consumption considered is lower in [86], even for the base power plant without capture equipment installed.
Net power output with CCS	3930	3805	MW	The auxiliary power consumption with CCS considered is lower in [86].
Base plant net heat rate	9000	9200	MJ/MWh	As given in [86].
Capture equipment net heat rate	11970	13220	MJ/MWh	As given in [86].
Calorific value of Indian coal	3500	3014	kCal/kg	As given in [86].
Cost of Indian coal	65	56	USD/t	As calculated from [86].
Amount of CO_2 to be captured/stored	34	32.8	MTPA	Reduction in amount of CO_2 captured occurs due to reduction in plant size.

Table 15:Cost of electricity for Case 3

Item	Imported coal	Indian coal
LCOE without capture (Rs/kWh)	3.73	3.31
LCOE with capture (Rs/kWh)	5.39	4.78
LCOE with CCS (Rs/kWh)	5.44	4.84
LCOE with CCS and monitoring (Rs/kWh)	5.48	4.87
Increase in LCOE due to CCS and monitoring	47%	47%

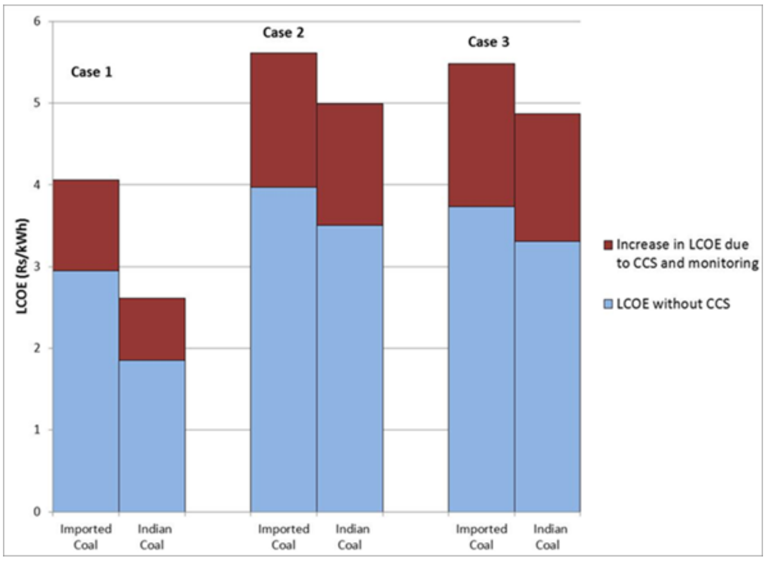

Figure 10: Comparison of the Levelised Cost of Electricity (LCOE) and the increase in LCOE for the different cases

From these three cases, it can be concluded that the increase in the LCOE is roughly 38-47%. However, it may be noted that the analysis has been carried out for a large sized plant, and CCS technology is yet to be demonstrated at such scales. A deployment on a smaller plant will probably lead to a greater increase in the electricity costs owing to reduced economies of scale. Costs will also vary depending on the type of transport and storage mechanism actually used for the plant in question.

Cost of CO2 avoided: The cost of CO_2 avoided is another way in which the relative economic viabilities of various climate change mitigation technologies can be compared. There are a number of formulae available in literature for computing this cost, and the numbers arrived at by applying different methods for the same technology are not necessarily equivalent. In this report, the definition given in [100] has been used to calculate the cost of CO_2 avoided for Case 2 mentioned above. Here, the cost of CO_2 avoided is defined as the difference in Cost of Electricity (COE) divided by the difference in CO_2 emitted per MWh. By this definition, and using the values mentioned above for Case 2, the cost of avoided CO_2works out to be $34.4 /t and $31.2/t for imported and domestic coal respectively.

6. Policy &legislation review

Legislation that may govern CCS activities is limited mostly to the following sectors:

Oil and gas

- Indian Petroleum Act, 1934: Rules for production and transportation of petroleum products. It can be applied for transportation of compressed CO_2.
- The Oilfields (Regulation and Development) Act, 1948 (53 of 1948): Royalties in respect of mineral oils. It can be applied for EOR.
- The Petroleum Mineral Pipelines (Acquisition of Right of User in Land) Act, 1962: Provides for the acquisition of user in land for laying pipelines for the transport of petroleum and minerals and for matters connected therewith. This law may be applied for transportation of compressed CO_2 to storage sites.
- The Oil Industry (Development) Act, 1974: An act to provide for the establishment of a Board for the development of oil industry and for that purpose to levy a duty of excise on crude oil and natural gas and for matters connected therewith. It can be modified for levying a duty of excise on crude oil and natural gas produced during EOR.
- Petroleum and Natural Gas Rules, 1959: An act to provide petroleum exploration license and mining leases. This law will for development of sites for EOR and EGR.
- Directorate General of Hydrocarbon (DGH) under Ministry of Petroleum and Natural Gas, Government of India is looking after development of Coal Bed Methane production.

Transport

The Petroleum Mineral Pipelines (Acquisition of Right of User in Land) Act, 1962: Provides for the acquisition of user in land for laying pipelines for the transport of petroleum and minerals and for matters connected therewith. This law may be applied for transportation of compressed CO_2 to storage sites.

Groundwater

Water (Prevention and Control of Pollution) Act 1974 enacted by Ministry of Environment and Forest, GOI provide for the prevention and control of water pollution, and for the maintaining or restoring of wholesomeness of water in the country [101]. This Act levies and collects cess on water consumed by persons operating and carrying on certain types of industrial activities. This cess is collected with a view to augmenting the resources of the Central Board and the State Boards for the prevention and control of water pollution constituted under the Water (Prevention and Control of Pollution) Act, 1974. CCS has environmental impacts in terms of chances of groundwater contamination and this act could be suitably modified to include contamination of groundwater in case there is any leakage of stored CO_2.

Environmental impact assessment

Amending the Environmental Protection Act, 1986 is likely to be the most effective way to facilitate demonstration projects and may be done on a project-specific basis before broader amendments can be established. Since CO_2 may need to be transported across states and be stored in a region different to the point of collection, regional coordination groups will need to be established to address issues related to CO_2 transport and storage.Retrofitting of CO_2 capture capability to existing power plants may be done under the Environment Impact Assessment Notification S.O.60 (E) (under the provisions of the Environment (Protection) Act 1986) and the applicant must submit an application to the Secretary of the Ministry of Environment and Forests, New Delhi to obtain environmental clearance.

Financing and investment

Given the higher initial investment as well as operating costs, CDM (Clean Development Mechanism) and carbon markets in their present form may not be sufficient to support and promote CCS. Ideally, policy for financing and investment should be such that the additional energy penalty due to retrofitting of the power plant for CCS is partly or wholly covered by earnings from CDM/carbon markets. Towards this, while multilateral financing institutions like the World Bank, International Monetary Fund, and the Asian Development Bank may take a lead in developing specific financial packages and instruments, those countries that are technologically advanced in CCS should come forward in supporting, including capacity development, initial CCS projects in India.

7. Capacity assessment

India’s position in GCCSI CCS Development Lifecycle:

The CCS Development Lifecycle developed by the Global CCS Instituteis a tool that can be used to locate a country’s present position with respect to CCS development and plot a roadmap towards CCS deployment. It is shown in Figure 11. It has been recognised that a country may operate simultaneously in multiple parts of the lifecycle, because different aspects related to CCS may develop to different extents at different rates.[102]

Figure 11: GCCSI CCS development lifecycle

The work done during this study suggests that India lies mostly in Stage 1, since the potential of CCS as a method for emissions reduction in India is fairly well known. There are elements of Stage 2 - putting CCS on policy agenda - being undertaken. For instance, there is some awareness within policy makers of CCS, and good awareness of the technology as a mitigation option within industry. There are forums where governments and business leaders are discussing the potential of CCS for India. However, in general, the disposition towards CCS is not positive. The primary barriers to CCS implementation in India and the capacity development needs in this regard are mentioned in the following sections.

Since CCS is a cross-cutting activity, there are a multitude of stakeholders involved. The important ones among these are listed below.

Government bodies:

Most applications of CCS are large-scale efforts involving infrastructure sector like power, cement and steel. It is therefore quite understandable that there are a number of government bodies whose involvement will be required for any decision-making related to CCS.

Planning Commission of India: The Planning Commission is a Central Government body responsible for formulating the 5 Year Plans. It is tasked with devising plans for the most effective and balanced utilisation of resources and determining priorities for their allocation.

Ministry of Science and Technology (Department of Science and Technology): The Ministry of Science and Technology is the Central Government ministry charged with formulating and administrating the rules and regulations related to science and technology development in the country. From a CCS standpoint, the Climate Change Programme of the Department of Science and Technology (DST), which is one of the three departments under the ministry, is of particular importance. The activities related to CCS that the DST has been pursuing have been mentioned in Section 4.

Ministry of Environment & Forests: The Ministry of Environment & Forests is the country's nodal agency overseeing India's environmental and forestry policies and programmes. The Environmental Impact Assessment Division of the ministry is responsible providing environmental clearances to different types of projects, including mining, coal washeries, and thermal power plants, cement industry, onshore and offshore oil and gas exploration, etc.

Ministry of Power: The Indian Ministry of Power is responsible for the administration and enactment of legislation regarding thermal and hydro power generation, transmission and distribution.

Ministry of Petroleum & Natural Gas: The Ministry of Petroleum & Natural Gas is responsible for the regulation of the exploration, production, distribution and marketing, and import and export of oil and natural gas in India.

Ministry of Coal: The Ministry of Coal has the overall responsibility for deciding strategies and policies with respect to exploration and development of coal and lignite reserves in the country.

Ministry of Steel: The Ministry of Steel coordinates the policies for and facilitates the development of the iron and steel industry in the country.

Ministry of Commerce and Industry (Department of Industrial Policy and Promotion): The Department of Industrial Policy and Promotion is one of the two departments under the Indian Ministry of Commerce and Industry, and is tasked with formulating and implementing policies and strategies for industrial development in conformity with national objectives and development needs. Industries like cement, glass, leather, rubber goods, salt, wood-based, etc. fall under its purview.

Ministry of Mines: The Ministry of Mines is responsible for the survey and exploration of all minerals other than petroleum, natural gas and atomic minerals. From a CCS standpoint, it is important to consider that this ministry is responsible for the administration and management of the Geological Survey of India (GSI). The GSI is the primary provider of basic earth science information in India, and its role would be indispensible during surveys conducted for assessment of underground storage potential.

Ministry of Water Resources: The Ministry of Water Resources is responsible for the development and regulation of water resources in the country. It is in-charge of the Central Ground Water Board, which is the apex national agency for assessment, exploration, monitoring and regulation of ground water resources in India.

Central Electricity Regulatory Commission (CERC): The Central Electricity Regulatory Commission is the key regulator of the Indian power sector. Its primary function is to regulate the tariff of power generating companies in India, with a view to promoting competition, efficiency and economy in the Indian power markets.

Central Electricity Authority (CEA): The Central Electricity Authority is a statutory body that advises the Indian Government on matters relating to the national electricity policy, specifies the technical standards for power plants, specifies the grid standards for transmission lines, records data relating to the generation, transmission, trading, distribution and utilisation of electricity, and discharges other important functions related to the Indian power sector.

National Remote Sensing Centre (NRSC): The National Remote Sensing Centre, Hyderabad, is a centre of the Indian Space Research Organisation (ISRO), responsible for aerial and satellite remote sensing data. This agency will also be important during surveys for assessing underground storage potential in India.

National Geophysical Research Institute (NGRI): In addition to the work related to CCS that NGRI has been carrying out, as mentioned in Section 4 of the report, NGRI's importance as a CCS stakeholder lies in the fact that the institute plays a pivotal role in the exploration of minerals, hydrocarbons and groundwater resources in the country, and will thus be a major player in storage site assessment surveys.

Petroleum Sector:

The petroleum sector is important for CCS implementation, both as a CO_2 source, due to emissions arising from the sweetening of sour natural gas and during petroleum refining, and as a potential CO_2 storage option, either via the Enhanced Oil or Gas Recovery route, or via simple storage in depleted oil and gas reservoirs. In India, the state-owned companies remain the most important players, although certain private entities are beginning to make their mark.

ONGC Ltd.: ONGC is the only fully integrated petroleum company in India, operating along the entire hydrocarbon value chain [103]. It holds the largest share of hydrocarbon reserves acreage in India, and contributes over 79% of India's oil and gas production. Its activities related to CCS have been mentioned in Section 4.

OIL India Ltd.: OIL India Ltd. is an Indian Public Sector Unit (PSU) engaged in exploration, development and production of crude oil and natural gas, transport of crude oil and production of Liquefied Petroleum Gas (LPG) [104]. Presently, OIL has over 1 lakh sq km of Petroleum Exploration Licence/Mining Licence areas for its exploration and production activities, and also owns and operates 1,432 km of cross-country crude oil pipelines [105]. On the production side, OIL produced 3.586 Million Metric Tonnes (MMT) of crude oil in 2010-11, along with 2352.71 Million Metric Standard Cubic Metres (MMSCUM) of natural gas and 45,010 tonnes of LPG [106].

GAIL India Ltd.: GAIL is a state-owned entity that is the largest natural gas processing, distribution and marketing company in India. GAIL presently has the capacity to transport 220 MMSCMD of natural gas through its transmission network [107]. On the processing front, GAIL operates the Pata refinery, which manufactures polymers, Liquefied Petroleum Gas, propane, and other products from natural gas.

Reliance Industries Ltd: Reliance Industries Ltd. (RIL) is a private entity which produces crude oil and natural gas from a number of oil fields, such as the KG-D6 field, the Panna-Mukta field and the Tapti field. In addition, RIL also owns three Coal Bed Methane blocks from which production is yet to commence [108]. RIL also owns the Jamnagar Manufacturing Division, which is the largest grass-roots refinery complex in the world [109].

Power Sector:

The power sector, as has been stated in Section 3, is by far the largest source of stationary emissions, and hence power companies are among the most important stakeholders for CCS in India.

NTPC Ltd.: NTPC is India's largest power company, with 33,150 MW of operational thermal power [33], and 1328 MW of hydro power being built [110]. The company operates 17.75% of India's total national capacity, and generates 27.4% of India's total electricity. In recent years, NTPC has made attempts at business diversification, with forays into consultancy, power trading, ash utilisation and coal mining. It is also expanding its renewable energy portfolio, with an aim of 28% of its generation capacity being non fossil fuel based by 2032 [111].

APGENCO: APGENCO is the power generating company of the state of Andhra Pradesh, and is a state-government enterprise. With an installed thermal power capacity of 4593 MW [35], it is one of the largest public sector power producers in the country. In addition, the fact that it is setting up India's first large scale IGCC plant, as mentioned in Section 4, makes it an important stakeholder from the CCS point of view.

Tata Power: Tata Power is an integrated power company in the private sector, with a total installed generation capacity of 5297 MW [43], and a presence in transmission, distribution and trading. It is responsible for developing the Mundra UMPP.

Reliance Power: Reliance Power is setting up a number of thermal and hydroelectric power projects in India, and in particular, has been awarded the development of three UMPPs. In all, Reliance Power is building 29280 MW of coal based power, 9880 MW of gas based power and 4620 MW of hydroelectricity [40] [112] [113].

Adani Power: Adani Power is setting up 16500 MW of thermal power in India, with the 4620 MW Mundra plant, the 3300 MW Tiroda plant and the 3300 MW Bhadreshwar plant being the largest units [41].

Bharat Heavy Electrical Ltd.: Bharat Heavy Electrical Ltd. (BHEL) is a public sector organisation which is one of the largest engineering and manufacturing companies in the country. BHEL has a share of 62% in India's total installed power generating capacity [114].

BHEL is also one of the main players in India's move towards more efficient power generation technologies.

Steel Sector:

Steel Authority of India Limited: The public sector unit Steel Authority of India Limited (SAIL) is the second largest India-based steel producer, manufacturing 13.6 million tonnes of crude steel in 2010 [115]. It operates five integrated steel mills in India, and produces both basic and special steels.

Tata Steel: Tata Steel is the largest India-based steel maker; however, a majority of its total steel production comes from its overseas subsidiaries [116]. In India, its most important unit is the integrated steel plant in Jamshedpur, which is India's oldest and largest steel plant. Tata Steel is a member of the Carbon Capture & Storage Association, as well as of the Ultra–Low Carbon Dioxide Steelmaking initiative (ULCOS) [116], which is a consortium of 48 European companies and organisations from 15 European countries undertaking an R&D initiative to drastically reduce CO_2 emissions from steel making [117].

Cement Sector:

The major players in the cement sector are indicated in Figure 9.

8. Barriers to CCS implementation in India

The following have been raised by some Indian stakeholders as being the principal barriers for CCS deployment in India.

- Worldwide, CCS is still in the demonstration phase. It is only once a degree of confidence has been gained in the technology via large-scale deployment internationally that it can be considered seriously for India.
- One major barrier to CCS deployment in India is the lack of accurate geological storage site data, since before capture technology can be installed in power plants or other sources, the location, capacity, permeability, and other characteristics of the sinks must be known.
- The issue of CCS drastically increasing the cost of electricity while reducing net power output is often cited as being one of the biggest barriers to acceptability of CCS in India. CCS deployment is held to run counter to India's ambitious goals for electrification, especially given the present electricity deficit and energy situation in the country.
- Enhanced Oil Recovery (EOR) is worldwide one of the most attractive options for CO_2 storage, since the cost of storing the CO_2 is offset by the revenues accrued by the hard-to-extract oil that can be recovered from depleted oil fields by this procedure. In the Indian scenario, however, it has been stated by stakeholders in the petroleum sector that there are few oil fields which are sufficiently depleted for EOR to be required at present; further, since EOR is dependent on the miscibility characteristics of the oil with the extracting fluid, it may not be suitable in all cases.
- Clarity is needed on how CCS implementation via retrofit of capture equipment to existing plants will change the Terms of Reference of the plant. In particular, the fresh environment clearances required, if any, need to be spelt out and standardised.
- Access to funding from financing agencies such as the World Bank, Asian Development Bank, etc. might require further governance requirements in addition to the existing

requirements e.g. around monitoring, measure and verification. These may be dependent on CCS-specific clearances being available from the Ministry of Power and/or other Government bodies, in addition to the existing clearances required.

- Deployment of CCS on a large scale requires specialised manpower and suitable infrastructure, which may not be available in India at present.
- Monitoring the stored CO_2 to assure against leakage is essential if the central purpose of CCS implementation is to be fulfilled. Ensuring rigorous monitoring is needed over long time scales and techniques developed internationally in this area need to be introduced to Indian stakeholders.
- Legal issues related to land acquisition; ground water contamination, CO_2 leakage, etc. need to be addressed before any large scale transport and storage of CO_2 can be permitted.

9. Capacity development needs

Broadly, the following capacity development needs related to CCS require to be addressed so as to create an enabling environment for CCS deployment in India.

1. **Knowledgebuilding and capacity development of policy makers and regulators**

While at the decision-making levels some knowledge regarding CCS does exist, there is a need to go deeper in to the nuances of different elements of CCS and the associated benefits and risks. While the present study has attempted to inform the relevant stakeholders in this regard, more systematic and sustained work needs to be done if India is to be truly considered a country in the 2nd stage of the CCS Development Lifecycle.

This capacity development could be done by organising events specifically targeting policy makers in the relevant sectors, such as electricity, oil & gas, and environment, etc. Regulations and policies in place elsewhere globally, along with progress in CCS related activities in other parts of the world, may be highlighted so as to provide context and direction to these discussions.

2. **Capacity development for storage site assessment, development, operation and monitoring and verification**

It is widely accepted that assessment of potential storage sites is one of the biggest hurdles to CCS deployment in India. To remedy this, two-pronged approach may be considered, namely, (i) the training of geologists in the advanced assessment techniques and (ii) the involvement of Indian agencies in the potential assessment work being carried out elsewhere. If necessary, the global players may be involved in this exercise right from the beginning.

Once the appropriate storage sites have been identified, arrangements will need to be made to make these sites suitable for CO_2 injection and storage. These may involve, for instance, knowledge of advanced drilling techniques, or capacity to assess permeability data, etc. and therefore, expertise in these areas. This may be done by training existing operators in the petroleum and natural gas sectors to the specific needs of CCS operation, including monitoring and verification.

3. Technology sharing and transfer

CCS technology is still in the demonstration phase, and it is important that India is not left behind in this area. While there is a considerable amount of work already underway domestically, there may still be a need for research collaborations and knowledge sharing and transfer. These areas of research include development of new adsorbents, better process integration of capture equipment, and conversion of CO_2 to useful products, among others.

4. Capacity development of Financial Institutions

The financial evaluation of CCS projects will necessitate capacity development of banks and other financial institutions, since the norms and practices differ from those applied for normal power plants and industries. In this regard, informing Indian financial institutions about global practices may be a step forward, enabling them to them adapt these to Indian requirements.

5. Public Engagement

Public acceptance is vital before any CCS project can be implemented, with consensus required especially on the storage side. Various civil society groups are involved in different aspects of public interest, and inclusion of these groups in discussions related to CCS at an early stage may facilitate better acceptability of CCS technologies.

6. Knowledge sharing among different CCS groups

CCS being a cross cutting activity involving several components and myriad stakeholders, it is vital that knowledge sharing between the different CCS groups is done on a regular basis. This will improve the quality of information available to all parties, enabling the emergence of a more accurate picture and more informed decision making at all levels. Web based `virtual’ platform could be one of the options for this.

10. Conclusions and recommendations

India has been moving along a trajectory of high economic growth for last few years, a vital pre-requisite for fulfilling its goal of `inclusive growth’. While recently its growth rate has become more modest, energy remains the key driver of country’s growth engine; not only from the point of view of the economic perspective, but more importantly for accelerating its social development. Given that India has vast coal reserves it is natural that coalis the largest constituent – at 40% - in its primary energy mix. As far as electricity is concerned, India has an installed capacity of over 207 GW, of which about 66% is thermal power generation and majority of this comes from coal. Still, India faces peak electricity shortage to the tune of 10%. In addition, over 289 million people do not have access to electricity. This has implications on all other development parameters including poverty alleviation, health, food security, and education. Therefore, India’s top development priority is to provide electricity to all at affordable prices.

However, even though coal is expected to dominate India’s primary energy in the foreseeable future, it is exploring all the possible means of reducing the resultant GHG emissions. For instance, future capacity is expected to increasingly be based on super-critical technology, with 50% of the capacity in the 12th plan period targeted to be through super-critical units, and all coal based plants in the 13th plan period to be super-critical units. It may be noted that on the emissions front, however, even with 8-9% GDP growth every year for the next decade or two, India’s per capita emissions are likely to be well below developed country averages.

Nonetheless, India supports global efforts at R&D into CCS technologies. However, there are stakeholder concerns pertaining to the capital and operating costs; the energy penalties; and safety and integrity of potential storage; and the social acceptance of CCS. The high cost of electricity and reduced net electricity generation with CCS challenges the country's goal of `electricity to all and at affordable prices'. But given its wide applicability, the role of CCS is not limited to power generation alone but extends to other industrial sectors as well, including utilization of captured CO_2 for Enhanced Oil Recovery (EOR), manufacture of cement substitutes, algal biofuel, fertiliser manufacture, and mineralization. Indeed, the role of CCS as a potential climate change mitigation option for India needs to be explored further, so that issues raised in this report could be suitably addressed. The following section outlines suggested approach for addressing these issues.

- As discussed elsewhere in this report, for CCS to be considered as a viable mitigation option in India, a major challenge is the lack of reliable storage data. The relevant Indian institutions and organisations need to work together for the preparation of an accurate geological storage map for India, utilising recognised assessment criteria. This storage mapping should incorporate the different storage options such as saline aquifers, basalt rocks, and depleted oil fields (on-shore and off-shore). Finally, a matching of sources and sinks and cost optimisation in this regard will need to be carried out.
- The overall cost of capturing and storing CO_2 has not been quantified accurately for an Indian scenario so far, and hence a Life Cycle Analysis (LCA) of the entire system needs to be conducted.
- The whole issue of financial risks and legal liabilities in case of CO_2 leakage from the storage site needs to be addressed appropriately.
- R&D in the areas of improved capture systems, more efficient retrofit, and plant integration should be undertaken for increasing CCS acceptability.

Similarly, from the point of view of (a) carbon, capture, utilisation and storage, includingdeveloping value-added products using CO_2; detailed studies and local R&D-anddemonstrations could be supported.

- To facilitate better interaction with the global CCS community, it may be worthwhile to devise a mechanism – or tap into existing mechanisms - for knowledge and experience sharing among different actors viz. the technology develops/suppliers, global practitioners of CCS, and potential users, research community, as well as decision-makers from India on different aspects of CCS on a regular basis. Such interactions would also be helpful from the policy planning perspective.
- Sustained efforts are required towards capacity development of different stakeholders, including sensitisation of the policy makers and the regulators about the latest developments in this field.
- Public acceptance of CCS being central to its successful deployment, workshops and seminars disseminating information about this technology may be conducted to increase mass awareness.

References

1. Intergovernmental Panel on Climate Change (IPCC), 2005. *Special Report on Carbon Dioxide Capture and Storage*. Intergovernmental Panel on Climate Change.
2. National Informatics Centre, Government of India. *India at a Glance*. Available at: <http://india.gov.in/knowindia/profile.php?id=2> [Accessed 17 April 2012].
3. Office of the Registrar General & Census Commissioner, Government of India, 2011. *Provisional Population Totals Paper 1 of 2011 India- Chapter 3*. Office of the Registrar General & Census Commissioner, Government of India. Available at: <http://www.censusindia.gov.in/2011-prov-results/data_files/india/Final%20PPT%202011_chapter3.pdf> [Accessed 17 April 2012].
4. National Informatics Centre, Government of India. *Indian Economy: Economic Indicators from 1991*. Available at: <http://business.gov.in/indian_economy/eco_indicators.php> [Accessed 15 February 2012].
5. Ahuja S., et al., 2006. *Economic Reform in India: Task Force Report*. University of Chicago.
6. Organisation for Economic Co-operation and Development, 2007. *Policy Brief: Economic Survey of India, 2007*. Organisation for Economic Co-operation and Development.
7. Poddar T. and Yi E., 2007. *India's Rising Growth Potential*. Goldman Sachs.
8. Planning Commission, Government of India. *Data for use of Deputy Chairman, Planning Commission*. Planning Commission, Government of India. Available at: <http://planningcommission.nic.in/data/datatable/index.php?data=datatab> [Accessed 17 April 2012].
9. Ministry of Environment and Forests, Government of India, 2010. *India: Greenhouse Gas Emissions 2007*. Ministry of Environment and Forests, Government of India.
10. Centre for Science and Environment, 2009. *Challenge of the New Balance*. Centre for Science and Environment
11. Garg A. and Shukla P.R., 2009. Coal and energy security for India: Role of carbon dioxide (CO2) capture and storage (CCS), *Energy*, 34, pp. 1032-1041.
12. Planning Commission, Government of India, 2006. *Integrated Energy Policy: Report of the Expert Committee*. Planning Commission, Government of India.
13. Ministry of Coal, Government of India. *Inventory of Coal Resources of India*. Available at: <http://www.coal.nic.in/reserve2.htm> [Accessed March 3, 2012].
14. Batra R.K. and Chand S.K., 2011. *Policy Brief: India's coal reserves are vastly overstated*. The Energy and Resources Institute.
15. World Energy Council, 2010. *2010 Survey of Energy Resources*. World Energy Council.
16. Ministry of Coal, Government of India, 2011. *Annual Report 2010-11*. Ministry of Coal, Government of India.
17. Ministry of Petroleum & Natural Gas, Government of India, 2011. *Indian Petroleum & Natural Gas Statistics- 2010-11*. Ministry of Petroleum & Natural Gas, Government of India.
18. BP p.l.c., 2011. *2011 BP Statistical Review of World Energy*. BP p.l.c.
19. Ministry of Petroleum & Natural Gas, Government of India, 2011. *Basic Statistics on Indian Petroleum & Natural Gas- 2010-11*. Ministry of Petroleum & Natural Gas, Government of India.
20. Energy Information Administration, Department of Energy, USA, 2011. *Country Analysis Briefs: India*. Energy Information Administration, Department of Energy, USA.

21. Prime Minister's Council on Climate Change, Government of India. *National Action Plan on Climate Change*. Prime Minister's Council on Climate Change, Government of India.
22. Kumar S., 2011. India's own emissions trading scheme. *The Hindu Business Line*, December 18, 2011. Available at: <http://www.thehindubusinessline.com/opinion/article2726531.ece>. [Accessed 23 May 2012].
23. Central Electricity Authority, Government of India, 2012. *Monthly Report on Installed Capacity- November 2012*. Central Electricity Authority, Government of India.
24. Central Electricity Authority, Government of India, 2011. *Operation performance of generating stations in the country during the year 2010-11: An Overview*. Central Electricity Authority, Government of India.
25. Press Information Bureau, Government of India, 2010. *Power Minister's Address at EEC 2010*. Available at: <http://pib.nic.in/newsite/erelease.aspx?relid=66577>. [Accessed 19 April 2012].
26. Power Finance Corporation. *Ultra Mega Power Projects (UMPP)*. Available at: < http://www.pfcindia.com/Content/UltraMegaPower.aspx>. [Accessed 25 March 2012].
27. Ministry of Power, Government of India. *Ultra Mega Power Projects (UMPP)*. Available at: <http://www.powermin.nic.in/JSP_SERVLETS/internal.jsp>. [Accessed 21 March 2012].
28. Vora R., 2013. Tata Power synchronises unit 4 of Mundra UMPP. *Business Standard,* January 7, 2013. Available at: <http://www.business-standard.com/india/news/tata-power-synchronizes-unit-4mundra-umpp/201782/on>. [Accessed 10 January 2013].
29. Central Electricity Authority, Government of India. *Brief Status of Progress of Activities for UMPPs*. Available at: <http://www.cea.nic.in/reports/articles/thermal/progress_report_sasan_mundra_krishnapatnam.pdf>. [Accessed 10 April 2012].
30. KSEB Officers' Association, 2012. *Krishnapatnam UMPP – Reliance arm approaches CERC for tariff hike*. Available at: <http://www.kseboa.org/news/krishnapatnam-umpp-reliance-arm-approaches-cerc-for-tariff-hike-26112521.html>. [Accessed 26 November 2012].
31. Reliance Power Ltd., 2012. *Corporate Presentation*. Available at: <http://www.reliancepower.co.in/108/21_101.pdf>. [Accessed 10 April 2012].
32. Razdan A., 2011. Driving efficiency in power sector: route to a sustainable future. *Live Mint*, July 26, 2011. Available at: <http://www.livemint.com/2011/07/26003403/Driving-efficiency-in-power-se.html>. [Accessed 9 March 2012].
33. Central Electricity Authority, Government of India, 2011. *CO_2 Baseline Database for the Indian Power Sector: User Guide*. Central Electricity Authority, Government of India.
34. NTPC Ltd. *Installed Capacity*. Available at: <http://www.ntpc.co.in/index.php?option=com_content&view=article&id=96&Itemid=175&lang=en>. [Accessed 23July 2012].
35. APGENCO. *Operational Performance*. Available at: <http://www.apgenco.gov.in/inner.asp?frm=Performance_thermal>. [Accessed 23July 2012].
36. Damodar Valley Corporation. *Plants*. Available at: <http://www.dvcindia.org/powerplants.htm>. [Accessed 23July 2012].

37. Gujarat State Electricity Corporation Ltd. *Company Profile.* Available at: < http://www.gsecl.in/profile.php#>. [Accessed 23July 2012].
38. Mahagenco. *Installed Capacity*. Available at: <http://www.mahagenco.in/INSTALLED-CAPACITY-01.shtm>. [Accessed 23July 2012].
39. MP Power Generating Company Ltd. *Installed Capacity at a glance*. Available at: <http://mppgenco.nic.in/mpgenco-install-detail.htm#>. [Accessed 23July 2012].
40. West Bengal Power Development Corporation Ltd. *Power Scenario*. Available at: <http://www.wbpdcl.co.in/sildeshow.php>. [Accessed 22 March 2012].
41. Adani Power Ltd. *Power Generation*. Available at: <http://www.adanipower.com/Business/PowerGeneration.html>. [Accessed 23July 2012].
42. Reliance Power Ltd. *Coal Based Projects*. Available at: <http://www.reliancepower.co.in/business_areas/power_projects/coal_based_projects.htm>. [Accessed 23July 2012].
43. The Tata Power Company Ltd., 2012. *Tata Power's generation capacity crosses 6,000MW, with synchronisation of 800MW sized Unit 2 of 4,000MW Mundra Ultra Mega Power Project*. Available at: <http://m.tata.com/article.aspx?var1=v6tGKr347xg=>. [Accessed 23 July 2012].
44. Uttar Pradesh RajyaVidyutUtpadan Nigam Ltd. *Our Vision*. Available at: <http://www.uprvunl.org/#>. [Accessed 31July 2012].
45. Tamil Nadu Generation and Distribution Corporation Ltd. *Generation*. Available at: <http://www.tangedco.gov.in/template1.php?tempno=1&cid=0&subcid=184>. [Accessed 31July 2012].
46. Rajasthan RajyaVidyutUtpadan Nigam Ltd. *Present Installed Capacity*. Available at: <http://www.rvunl.com/Installed%20capacity_RVUN.php>. [Accessed 31 July 2012].
47. PSPCL. *Existing Thermal Projects*. Available at: <http://www.pspcl.in/docs/existing_thermal_projects.htm>. [Accessed 31 July 2012].
48. Haryana Power Generation Corporation Ltd. *Installed Capacity*. Available at: <http://www.hpgcl.gov.in/personal_17.hp>. [Accessed 31 July 2012].
49. Karnataka Power Corporation Ltd. *KPCL Power Projects*. Available at: <http://www.karnatakapower.com/projects.asp>. [Accessed 31 July, 2012].
50. Chhattisgarh State Power Generation Company Ltd. *Current Installed Capacity*. Available at: <http://www.cseb.gov.in/cspgcl/statistics/installed_capacity.htm>. [Accessed 31 July 2012].
51. Neyveli Lignite Corporation Ltd. *Proactive Disclosure under RTI Act 2005*. Neyveli Lignite Corporation Ltd. Available at: <http://www.nlcindia.com/rti/rti_pro_dis_eng.pdf>. [Accessed 10 April 2012].
52. Ministry of Finance, Government of India, 2012. *Economic Survey of India 2011-12-Chapter 11*. Ministry of Finance, Government of India.
53. Ministry of Petroleum & Natural Gas, Government of India. *Refineries in India*. Ministry of Petroleum & Natural Gas, Government of India. Available at: <http://petroleum.nic.in/refinery.pdf>. [Accessed 23 April 2012].
54. Confederation of Indian Industry. *Cement Industry in India: Trade Perspectives*. Confederation of Indian Industry. Available at: <http://newsletters.cii.in/newsletters/mailer/trade_talk/pdf/Cement%20Industry%20in%20India-%20Trade%20Perspectives.pdf>. [Accessed 13 December 2011].

55. Department Related Parliamentary Standing Committee on Commerce, Parliament of India, 2011. *Ninety Fifth Report on Performance of Cement Industry*. Department Related Parliamentary Standing Committee on Commerce, Parliament of India.
56. British Geological Survey, 2005. *Cement Raw Materials*. British Geological Survey. Available at: <www.bgs.ac.uk/downloads/start.cfm?id=1408>. [Accessed 21 March 2012].
57. United Nations Industrial Development Organisation, 2010. *Global Industrial Energy Efficiency Benchmarking*. United Nations Industrial Development Organisation.
58. Saxena A., 2010. *Best Practices & Technologies for Energy Efficiency in Indian Cement Industry*. National Council for Cement and Building Materials. Available at: <http://www.iea.org/work/2010/india_bee/saxena.pdf>. [Accessed 21 March 2012].
59. Press Trust of India, 2012. India's cement-making capacity pegged at 479 MT by 2017. *The Economic Times*, 8 January.
60. Ministry of Steel, Government of India. *An Overview of Steel Sector*. Available at: <http://steel.nic.in/overview.htm>. [Accessed 22 March 2012].
61. Corporate Catalyst India, 2012. *Iron and Steel Industry in India*. Corporate Catalyst India. Available at: <http://www.cci.in/pdf/surveys_reports/iron-steel-industry.pdf>. [Accessed 22 March 2012].
62. GIZ, 2011. *Steel industry in India: Potential and technologies for reduction of CO_2 emissions*. GIZ. Available at: <http://www.hrdp-net.in/live/hrdpmp/hrdpmaster/hrdp-asem/content/e18092/e21298/e25159/e40403/eventReport40420/Presentation-GIZsteelindustryworkshopreport_Corr1_EditedNP-100112-2.pdf>. [Accessed 22 March 2012].
63. Department of Science and Technology, Government of India. *Joint Technology Projects under STAC/IS-STAC*. Available at: <http://www.dst.gov.in/about_us/ar07-08/tech-dru-prg.htm#stac>. [Accessed 28 March 2012].
64. Inter-Sectoral Science & Technology Advisory Committee, Department of Science and Technology, Government of India. *Inter-Sectoral Science & Technology Advisory Committee Project List (2007-08)*. Available at: <http://www.dst.gov.in/scientific-programme/projectlist/2007-08/is-stac-07-08.pdf>. [Accessed 28 March 2012].
65. Inter-Sectoral Science & Technology Advisory Committee, Department of Science and Technology, Government of India. *STAC/IS-STAC & PROBE Pilot Program Project List 2008-09*. Available at: <http://www.dst.gov.in/scientific-programme/projectlist/2008-09/isstac08-09.pdf>. [Accessed 28 March 2012].
66. Inter-Sectoral Science & Technology Advisory Committee, Department of Science and Technology, Government of India. *IS-STAC Projects Funded 2009-10*. Available at: <http://www.dst.gov.in/scientific-programme/projectlist/2009-10/isstac09-10.pdf>. [Accessed 28 March 2012].
67. Inter-Sectoral Science & Technology Advisory Committee, Department of Science and Technology, Government of India. *IS-STAC Projects Funded 2010-11*. Available at: <http://www.dst.gov.in/scientific-programme/projectlist/2010-11/isstac10-11.pdf>. [Accessed 28 March 2012].
68. Inter-Sectoral Science & Technology Advisory Committee, Department of Science and Technology, Government of India. *IS-STAC Projects Funded 2011-12*. Available at: <http://www.dst.gov.in/scientific-programme/projectlist/2011-12/isstac11-12.pdf>. [Accessed 28 March 2012].
69. Department of Science and Technology, Ministry of Science and Technology, Government of India, 2010. *Annual Report 2009-10*. Ministry of Science and Technology,

Government of India. Available at <http://www.dst.gov.in/about_us/ar09-10/annual_report_2009-10.pdf>

70. Department of Science and Technology, Ministry of Science and Technology, Government of India, 2011. *Annual Report 2010-11*. Ministry of Science and Technology, Government of India. Available at <http://www.dst.gov.in/about_us/ar10-11/PDF/DST%20Annual%20Report%202010-11.pdf>
71. Department of Science and Technology, Ministry of Science and Technology, Government of India, 2012. *Annual Report 2011-12*. Ministry of Science and Technology, Government of India. Available at <http://www.dst.gov.in/about_us/ar11-12/PDF/DST_Annual_Report_2011-12.pdf>
72. Royal Norwegian Embassy. *New programme to promote Indo-Norwegian research cooperation*. Available at: <http://www.norwayemb.org.in/News_and_events/Education--Research/New-programme-to-promote-Indo-Norwegian-research-cooperation/>. [Accessed 20 April 2012].
73. Chakraborty A B, 2008. *CO_2 Capture and Storage: ONGC's Perspective and Plan*. ONGC. Available at: <http://www.irade.org/ccs/session%207B/11.%20Mr%20A%20B%20Chakraborty.ppt>. [Accessed 30 March 2012].
74. IANS, 2010. Using algae to trap carbon dioxide, Orissa show how. *Sify Finance*. Available at: <http://www.sify.com/finance/using-algae-to-trap-carbon-dioxide-orissa-show-how-news-default-kjgmubgiehd.html>. [Accessed 28 March 2012].
75. Orissa Diary, 2011. Orissa-based PSU Nalco to set up Pilot Project on Carbon Sequestration in its Power Plant. *Orissa Diary*. Available at: <http://www.orissadiary.com/ShowBussinessNews.asp?id=25424>. [Accessed 28 March 2012].
76. Sonde R.R. *Demonstration of capture, injection and geological Sequestration (storage) in Flood Basalt Formation of India.* NTPC. Available at: <http://www.cslforum.org/publications/documents/Basalt_Formation.pdf>. [Accessed 30 March 2012].
77. Goel M., Charan S.N. and Bhandari A.K., 2008. CO_2 Sequestration: Recent Indian Research, *Glimpses of Geoscience Research in India*. Available at: <http://www.iypeinsa.org/updates-09/art-11.pdf>. [Accessed 19 March 2012].
78. Chemical Engineering, IIT Bombay. *Solar Bio-fuel and Carbon Sequestration with Cyanobacteria: Role of Genetic Networks*. Available at: <http://www.che.iitb.ac.in/online/phdtatopic/solar-bio-fuel-and-carbon-sequestration-cyanobacteria-role-genetic-networks>. [Accessed 28 March 2012].
79. Chemical Engineering, IIT Bombay. *Carbon sequestration using carbon dioxide absorption in aqueous mineral suspensions*. Available at: <http://www.che.iitb.ac.in/online/phdtatopic/carbon%C2%A0sequestration%C2%A0using%C2%A0carbon%C2%A0dioxide%C2%A0absorption%C2%A0in%C2%A0aqueous%C2%A0mineral%C2%A0-suspensions>. [Accessed 28 March 2012].
80. Consortium for Clean Coal Utilization, Washington University in St. Louis. *Ongoing Research Projects*. Available at: <http://cccu.wustl.edu/research-proj.php>. [Accessed 28 March 2012].
81. Bharat Heavy Electricals Ltd. *Press Release: BHEL Takes Over BHPV; Signs MoU with APGenco for setting up Nation's biggest 125 MW Clean Coal Power Plant*. Available at: < http://www.bhel.com/press_release/press_pop.php?press_id=270>. [Accessed 28 March 2012].

82. PTI, 2012. 'India to build Ultra Supercritical Thermal Power Plant'. *The Economic Times*, February 27, 2012. Available at <http://articles.economictimes.indiatimes.com/2012-02-27/news/31104416_1_power-plant-carbon-dioxide-ntpc >. [Accessed 2 November 2012].
83. The Hindu, 2011. EU-funded clean coal project for thermal power sector. *The Hindu*. Available at: <http://www.thehindu.com/news/cities/Tiruchirapalli/article2737672.ece>. [Accessed 30 March 2012].
84. Garg M.O. *Carbon Capture & Storage/Use (Research Priorities for CCS)*. CSIR- Indian Institute of Petroleum, Dehradun. Presented at Carbon Capture and Storage Workshop organised by Ministry of Power, Government of India in New Delhi on September 27, 2011.
85. Mott MacDonald, 2008. *CO_2 Capture-Ready UMPPs, India*. Mott MacDonald.
86. Global CCS Institute, 2011. *Economic Assessment of Carbon Capture and Storage Technolgies: 2011 update*. Global CCS Institute.
87. Mott MacDonald, 2007. *UMPP Risk Analysis*. Mott MacDonald.
88. Coastal Gujarat Power Limited, 2007. *Environmental Assessment Report-India: Mundra Ultra Mega Power Project*. Coastal Gujarat Power Limited.
89. Wulandari F., 2012. Indonesia cuts price of thermal coal to the lowest in 16 months. *BloombergBusinessweek*, April 5, 2012. Available at: <http://mobile.bloomberg.com/news/2012-04-05/indonesia-cuts-price-of-thermal-coal-to-the-lowest-in-16-months?category=>. [Accessed 16 April 2012].
90. Chikkatur A.P., 2008. *Coal Initiative Reports: A Resource and Technology Assessment of Coal Utilization in India*. Pew Center on Global Climate Change
91. Coal India Limited, 2012. *New pricing of non coking coal based on GCV with effect from 00:00 Hour of 1.1.2012*. Available at: <http://coalindia.in/Documents/Revised_2nd_Ver_Coal_Price_for_uploading_310112.pdf>. [Accessed 16 April 2012].
92. Global CCS Institute, 2010. *Defining CCS Ready: An Approach to AnInternational Definition*. Available at <http://www.globalccsinstitute.com/publications/defining-ccs-ready-approach-international-definition>.
93. Holloway et al., 2009. An assessment of the CO_2storagepotential of the Indian subcontinent. *Energy Procedia*, 1 (1), pp. 2607-2613.
94. Global CCS Institute. *Strategic Analysis of the Global Status of Carbon Capture and Storage-Report 2: Economic Assessment of Carbon Capture and Storage Technologies*. Global CCS Institute.
95. Benson S.M., 2004. *Monitoring Protocols and Life-Cycle Costs for Geologic Storage of Carbon Dioxide*. Carbon Sequestration Leadership Forum. Available at: <http://www.cslforum.org/publications/documents/Melbourne/benson_sally_wed_Pal_AB_0915.pdf >. [Accessed 12 March 2012].
96. Misra R., 2011. *Competitive Power Procurement: Guidelines and Recent Experience*. Presented at '4th Capacity Building Programme for Officers of Electricity Regulatory Commissions, 18-23 July, 2011'. Available at: < http://www.iitk.ac.in/ime/anoops/for11/PPTs/14%20-%20Mr.%20Rajat%20Mishra%20-%20Competitive%20Power%20Procurement.pdf >. [Accessed 26 March 2012].
97. National Power Training Institute. *Tariff determination methodology for thermal power plant*. Available at:

<http://www.npti.in/Download/Distribution/Tariff%20Determination%20-%20Write%20up.pdf>. [Accessed 23 July, 2012].

98. Ministry of Power, Government of India. *Tariff Policy*. Available at: <http://www.mahadiscom.com/consumer/national%20tariff%20policy.pdf>. [Accessed 23 July, 2012].
99. Prasad M. Water, land issues stall Orissa UMPP. *Projectmonitor*. Available at: <http://www.projectsmonitor.com/detailnews.asp?newsid=15629>. [Accessed 10 May 2012].
100. Rubin E.S., Chen C. and Rao A.B., 2007. Cost and performance of fossil fuel power plants with CO2 capture and storage, *Energy Policy*, 35, pp. 4444-4454.
101. Ministry of Environment and Forests, Government of India. *Water Pollution*. Available at: <http://moef.nic.in/modules/rules-and-regulations/water-pollution/>. [Accessed 28 March 2012].
102. Global CCS Institute, 2012, *Global Status of CCS 2012*, Global CCS Institute
103. ONGC Ltd. *Profile*. Available at: <http://www.ongcindia.com/profile_new.asp>. [Accessed 27 March 2012].
104. OIL India Ltd. *Expression of Interest (EOI) for Subscription Services on Exploration and Production Database of Petroliferous Basins of the world*. Available at: <http://www.oil-india.com/pdf/tenders/EOI/DOC_OILCCOEOICOE072011.pdf>. [Accessed 23 May 2012].
105. OIL India Ltd. *Pipelines*. Available at: <http://www.oil-india.com/Pipelines.aspx>. [Accessed 23 May 2012].
106. OIL India Ltd. *Performance*. Available at: <http://www.oil-india.com/Performance.aspx>. [Accessed 23 May 2012].
107. GAIL (India) Ltd. *GAIL gets MOU excellence award for the second consecutive year*. Available at: <http://www.gailonline.com/final_site/pressrelease_feb01_12.html>. [Accessed 30 March 2012].
108. Reliance Industries Ltd. *Growth through Energy Security for India*. Available at: <http://www.ril.com/html/business/exploration_production.html>. [Accessed 30 March 2012].
109. Reliance Industries Ltd. *Jamnagar*. Available at: <http://www.ril.com/html/aboutus/manufact_jamnagar.html>. [Accessed 30 March 2012].
110. NTPC Ltd. *Hydro Based Power Projects (Under Implementation)*. Available at: <http://www.ntpc.co.in/index.php?option=com_content&view=article&id=35&Itemid=85&lang=en>. [Accessed 30 March 2012].
111. NTPC Ltd. *Overview*. Available at: <http://www.ntpc.co.in/index.php?option=com_content&view=article&id=42&Itemid=75&lang=en>. [Accessed 30 March 2012].
112. Reliance Power Ltd. Gas *Based Projects*. Available at: <http://www.reliancepower.co.in/business_areas/power_projects/gas_based_projects.htm>. [Accessed 30 March 2012].
113. Reliance Power Ltd. Gas *Based Projects*. Available at: <http://www.reliancepower.co.in/business_areas/power_projects/hydroelectricity_projects.htm>. [Accessed 30 March 2012].
114. Bharat Heavy Electricals Ltd. *About us*. Available at: < http://www.bhel.com/about.php>. [Accessed 30 March 2012].

115. World Steel Association, 2010. *Top steel producers*. World Steel Association. Available at: <http://www.worldsteel.org/statistics/top-producers.html>. [Accessed 12 December 2011].
116. Tata Steel. *Tata Steel*. Available at: <http://www.ccsassociation.org/about-us/our-members/tata-steel/>. [Accessed 30 March 2012].
117. ULCOS. *Overview*. Available at: <http://www.ulcos.org/en/about_ulcos/home.php>. [Accessed 30 April 2012].

Climate change caused by the excessive industrial emissions of greenhouse gases (GHGs) is one of the gravest challenges facing our planet today. Studies have shown that there is no single option for combating this problem, but rather, a portfolio of measures, such as the increased use of renewable energy, improved energy efficiency, etc. will be needed.

Carbon Capture and Sequestration (CCS) is one among these measures, being a collection of technologies that may be able to reduce GHG concentrations beyond what would be possible using other options alone. CCS involves the capture of carbon dioxide (CO), the principal GHG, from concentrated emission sources, and then transporting it to and storing it perpetually in underground geological formations, used oil wells, or other secure locations. However, several challenges must be overcome before large-scale CCS deployment becomes practical, including establishing the technical feasibility of long-term geological CO_2 storage, assessing the economics of capture, transport and storage of CO_2, sensitising the political leadership, industry, and the common man to the potential of this technology, etc.

The Australia-based Global CCS Institute has been working collaboratively with other organisations across the world to address issues related to CCS. Since CCS technology is still in its infancy in India, TERI, in association with the Global CCS Institute, conducted a scoping study to identify the potential role of CCS in India's GHG mitigation strategies, and outline key considerations from a policy making perspective in this regard. The present report presents the outcomes of this study, outlining the key issues from an Indian perspective, and recommending the way forward.

teri

The Energy and Resources Institute

www. teriin.org