TITLE: India in 2 °C and well below 2 °C worlds - Opportunities and challenges

ABSTRACT

India's contributions to meeting global mean temperature 2 °C and well below 2 °C is set to require transformational changes. A bottom up model analyses reference, intended nationally determined contributions and low-carbon scenarios assuming equal per capita cumulative emissions rights from 2011 through 2050. The cumulative CO_2 budget for India for low-carbon scenarios during this period is estimated to be around 115 Bt-CO_2, as against 165 Bt-CO_2 for the reference scenario. To achieve such emission reduction, while maintaining high economic growth and meeting sustainable development goals, will require transformations to manifest at sub-national levels through technological transitions and strong social engineering. Our analysis shows that transitions are endemic such as shifting towards cleaner fuels, resource efficient technologies, widespread use of ICTs to balance demand-supply (e.g. smart grids), substituting demand in transport (e.g. work from home), aggressive promotion of renewables, lifestyle changes, and CCS. Modelling decarbonisation to meet the needs of increasing population and urbanization is a challenge due to the myriad and distributed nature of technologies used to provide various services, involving risks and uncertainties. The paper finally outlines specific opportunities and challenges faced to meet the increased mitigation ambition to limit the warming to 2 °C and below.

Keywords: Decarbonization, sustainable development, modelling, well below 2 °C , 2 °C , INDC

1. Introduction

In November 2016, the Paris Climate Change Agreement entered into force to limit global greenhouse gases (GHG) emissions for keeping the global mean temperature rise 2 degree Celsius (2 °C) and well below 2 °C by 2100 with respect to pre-industrial times (UNFCCC 2016). This will have major implications for energy systems all over the world to transform towards low-carbon trajectories, especially for large emerging economies like China and India. To achieve the cumulative carbon dioxide (CO_2) budget of 115-130 billion tonnes (bt) of CO_2 for the 2 °C scenario and less than 115 bt-CO_2 for well below 2 °C (referred to 1.5 °C in this study) scenarios between 2011 and 2050 (Shukla et al. 2015; Gignac and Matthews 2015; Tavoni et al. 2014) to meet the global targets, as against 165 bt-CO_2 for the reference scenario, India requires to follow unchartered territories. The energy sector needs to reduce its greenhouse gas (GHG) emissions through mitigation, offset, capture and storage by cost-effective, energy-efficient technologies and processes. Aggressive technology transitions are manifesting at sub-national levels in both supply and demand sides through diversification of fuel mix to include low-carbon, renewable technologies and improving efficiency of both the technologies deployed and fuels consumed. Additionally, decarbonization on the demand side includes policy measures that support reduction and stabilization of demands in energy intensive industries, significant increase in energy-efficient technologies in the building sector, rise in electric vehicles in transport sector, enhanced deployment of smart grids, and changes in consumer behaviour.

Energy efficiency remains the touchstone of energy transitions in India till 2030 (Garg et al. 2017; Vishwanathan et al. 2017). It is one of the most cost-effective measure because it not only conserves energy at end-use, but also saves on the cost of the energy not required to be generated. Concerns regarding energy affordability, accessibility, availability and security, as well as environmental considerations, have only amplified the interest in the energy efficiency potential of all sectors. Acts, policies, missions and programmes under National Action Plan on Climate Change (NAPCC), Intended Nationally Determined Contributions (INDC), and India's Biennial Update Report (BUR) to UNFCCC detail GHG mitigation to be achieved through reductions in energy use at the national, state and local levels covering both the supply and demand sides of energy management (BUR 2016; INDC 2015; NAPCC 2008).

With growing shift towards renewables, the once strong relationship between rising economy, growth in energy demand and subsequent carbon dioxide emissions has started to decline. However, India's economic growth is still heavily dependent on fossil energy. Increasing urbanization and industrialization lead to increase in material and final product demand, thus enhancing the challenges of deep decarbonisation of the Indian economy (Shukla et al. 2015). A considerable portion of reduction of carbon emissions in the coal supply chain is being achieved through retirement, efficiency improvements, renovation and modernization (R&M) of existing coal based sub-critical power plants and commissioning of super-critical (SC) and ultra-super-critical plants (USC) (Singh and Rao 2015; Verma 2010). However, Shukla et al. (2015) suggested that for decarbonisation to achieve a 2 °C stabilization, at least a tenfold reduction in the overall emission intensity of the power sector is required. For this, carbon dioxide (CO_2) capture and storage (CCS) technology needs to be implemented if coal is to occupy a sizeable share of the energy mix.

This paper analyses all the possible options for deep decarbonisation in India through transitions that are 1) prevalent such as shifting towards cleaner fuels and resource efficient technologies, 2) aggressive promotion of renewables, 3) unconventional measures such as demand reduction and lifestyle changes, and 4) possible mitigation through CCS in the current and alternate futures. Section 2 describes the methodologies deployed for our estimations including model set up, scenario architectures, and national level marginal abatement cost (MAC) curves for carbon during 2011-2050. Section 3 discusses the model outputs that detail projections until 2050. Finally, we outline the implications of near, medium and long term policy targets to meet the increased mitigation ambition to limit the warming to 2 °C and 1.5 °C.

2. Model description

In the current study, Asia-Pacific Integrated Model (AIM)/End use, a bottom-up optimization model has been used to provide techno-economic perspective at a national level. The model is built on a disaggregated sectoral representation economy, and presents detailed characterization of technology, fuel and material flow based on their availability, efficiency and costs. There is an emerging narrative for the need to decouple fossil fuel energy demand from the energy intensive economic activities within the constraints of emission intensity (WEO 2016). In the past decade, the costs in power sector especially renewables have undergone drastic changes. Bottom up techno-economic models are well suited for this kind of analysis, hence, AIM/Enduse has been used in the current study as it can provide a techno-economic perspective at the national level with sectoral granularity. It uses linear programming to provide a set of technologies that will meet the exogenous service demand at the least cost, while satisfying the techno-economic, emission as well as energy constraint. Simulation of the policy mixes are quick which in turn, helps to communicate the impact of policy options on energy and water system to policy makers and stakeholders in a short time. The model is driven by exogenous sectoral service demands and assume that the agents of change (in this case policymaker and stakeholders) are myopic in nature. Another important in this model is that, unlike other bottom-up models the cost of device/technology/system is annualized over time (Vishwanathan et al. 2017; Shukla 2013; Shukla et al. 2004; Kainuma et al. 2003).

[Figure 1: AIM/Enduse Framework]

2.1 Scenario Architecture

2.1.1 Reference Scenario

Reference scenario in the current study assumes the continuation of policy and economic business as usual (BAU) dynamics provides. It takes into account the on-going mitigation and adaptation strategies encompassing the broad framework laid down by the National Environmental Policy (2006), National Action Plan on Climate Change (2008) and State Action Plans on Climate Change (SAPCC). The scenario also adopts the long-term policy interventions related to energy, technology and services in every major sector (NAPCC 2008).

2.1.2 INDC Scenario

The INDC scenario takes into account India's contributions in response to the Conference of Parties (COP) decisions 1/CP.19 and 1/CP.20 for the period of 2021 to

2030 in every major sector. The scenario has an overall emission intensity reduction by 33-35 per cent from 2005 level during 2005-2030 and assumes 40 per cent of electric generation capacity is based from non-fossil fuels (BUR 2016; INDC 2015).

2.1.3 2 °C scenario

The 2 °C scenario follows policies, and programs that will not only support development but also attempt to meet the carbon budget constraints likely for India for a global 2 °C target. These are projected to be in the range of 115-130 bt-CO_2 during 2011-2050 (Tavoni et al. 2014), as against 165 bt-CO_2 for the reference scenario. On the energy supply side, a strong push is required to retire the low-efficiency coal based thermal power plants, and enhance energy efficient technologies such as super-critical pulverized coal, and integrated gasification combined cycle (IGCC). India's renewable potential needs to be extended along with introduction of storage technologies to balance the grid. Gas based generation are enablers for renewables, so need to be encouraged, in addition to nuclear and co-firing with CCS. Assuming the same rate of urbanization as the reference and INDC scenarios, the 2 °C scenario focuses on policies that will support large and small cities, towns, and rural centres to grow and improve quality of life that is sustainable. It takes into account policies that facilitate low carbon (LC) mobility and infrastructure plans. The low carbon mobility plans includes encouraging electric vehicles and increasing the share of rail in both urban and freight transport. The LC infrastructure plans takes into consideration a series of sustainable actions that need to be implemented in urban areas. Some of which include energy efficient cooking, lighting, heating and cooling systems, increasing green cover, smart metering for energy and water systems, and municipal sector responses (such as solar street-lighting, solid water and sewage to energy). Assuming successful technological transfer, and rapid adoption and adaption of cleaner and energy efficient technologies in addition to technological innovations, this scenario also emphasizes on dematerialization and resource efficiencies by encouraging reduce, reuse and recycle.

2.1.4 1.5 °C Scenario

The 1.5 °C represents an alternate future that will be in the same direction but more aggressive than the 2 °C stabilization scenario for CO_2 mitigation, requiring less than 115 bt-CO2 during 2011-2050 (Shukla et al. 2015). In order to prevent technology and behavioural lock-ins, this scenario drives transitions early towards low-carbon pathways. Banking on aggressive perform, achieve and trade (PAT) to improve energy efficiency standards for energy intensive industries and stronger switching over to cleaner fuels, the scenario considers reduction of heat losses in the new systems and recovering waste heat, as well as a shift to sustainable and cleaner technologies of production and end-use. Dematerialization, recycle and reuse are promoted in all sectors of the economy to make development more sustainable in the long run. Urban and rural planning is influenced not only by the demographics, industrialization and urbanization but also by how the rural and urban transformations occur in a more sustainable manner. In addition to the existing low carbon pathways mentioned above, there is a need to reduce and substitute demand in transport and infrastructure sectors with behavioural changes and use of information and communication technologies. The scenario, hence assumes more proactive measures on the demand side by encouraging smart, micro-grids along with smart metering, complete shift to cleaner fuels (electricity) after 2035 in both urban and rural areas, low-carbon, zero energy residential and commercial areas, and encouraging use of information and communication technologies (ICTs) to reduce transport demand (e.g. work from home). The thrust lies on making the development more sustainable through adopting low carbon pathways early on.

[Table 1: Scenario Assumptions in current and alternate futures]

2.2 Marginal Abatement Cost Curves

We have used the model outputs to create expert based marginal abatement cost (MAC) curves to assess the cost and reduction potential of selected set of technologies, and link it with carbon budget for each scenario. The MAC curve in a target year (t) for target sector (i) and service type (j) is described as follows. First, the carbon dioxide emissions of technology/device l, $\Delta Q^{CO2}_{l,i}$, additional annualized cost of energy technology/device l, $\Delta C^{CO2}_{l,i}$, and maximum potential of stock energy technology/device l, $\Delta S^{CO2}_{l,I}$ were calculated [16] (Hanaoka et al. 2015). Then the abatement cost unit for selected set of technologies per unit technology at sectoral level is plotted on y-axis and corresponding CO_2 reduction is plotted on x-axis in order of ascending cost per unit reduction.

3. Results and comparison across scenarios

3.1 Aggregate energy-mix and emissions

India's emissions in the INDC scenario decline from the reference scenario levels in all sectors from 2020 and beyond. Total carbon dioxide emissions are projected to decline by about 20%, 46% and 62% in the INDC, 2 °C and 1.5 °C scenarios compared to BAU in 2050.

[Figure 2: Aggregate carbon dioxide emissions under various scenarios]

By 2030, energy supply (power generation) is responsible for 72% of CO2 reductions with industrial contributing to about 15% of overall CO_2 abatement effort in INDC. The reduction increase under 2 °C and 1.5 °C with demand reduction and addition of CCS as presented in the following section. After 2030, the transport sector also starts decarbonizing driven by shifts towards public transportation, higher vehicular emission standards and electrification of passenger vehicles. Thus, transport accounts for 14% of overall CO_2 reductions in low carbon scenarios achieved from BAU in 2050.

The emission intensity to GDP reduces considerably in the 2 °C and 1.5 °C in 2030 and 2050 when compared to 2010 as presented in Table 2. The emission intensity to GDP for INDC scenario will be more than 33-35% as stated in the INDC report if India strictly adheres to the renewable generation capacity (40%) of the power sector. The CO_2 per capita remains constant till 2020, is observed to increase in INDC scenario in 2050. The indicator remains the same in 2 °C and 1.5 °C scenario in 2030, however the per capita emission decreases by 1.9 times in 2 °C and 2.6 times in 1.5 °C when compared to reference scenario in 2050. The carbon intensity of energy decreases at the rate of 0.15%, 1.3% and 1.9% for INDC, 2 °C and 1.5 °C scenarios respectively.

[Table 2: Indicators – Population, Economy and Emission intensities over time in all scenarios]

3.2 Impact of policies on sectors

This section presents a comparative picture of the four scenarios over a time horizon spanning 2010 to 2050. The assessment shows, for each scenario, the implications of scenario specific policies on sectoral carbon emission and marginal abatement cost of specific technologies required to meet the set carbon budgets.

3.2.1 Power Sector

Coal based power plants have remained the mainstay of India's electricity generation, contributing 194.55 GW (59% of total installed capacity) and 77.9% of electricity generation (CEA 2017). The government had provided clearances for installation of additional 178.7 GW of coal based thermal power plants (TPP) in 2012 (CEA 2017; Buckley 2017; CSE 2012). Although, the coal thermal power plant capacity target was 72.3 GW during 2012-17, 91.7 GW have been commissioned/achieved until May 2017, of which ~35.9 GW (39 %) is super -critical technology (CE, 2017; GOI 2016).

The load curve with renewable storage potential have been synchronized in the model (Annaluru and Garg, forthcoming). New technologies including improved coal technologies (IGCC, pulverized coal, super-critical, ultra super-critical coal), advance gas technologies, carbon capture and storage technologies, and advanced renewable technologies (solar with storage) have been added to the model as per the policies that exist and likely to be introduced in future. We have also modelled for the improvement in transmission and distribution losses in the power sector

[Figure 3: Aggregate carbon dioxide emissions under all scenarios in power sector]

Coal remains the major fuel, constituting 73 per cent of the total fuel mix for power in 2010 and 32 per cent in 2050 under BAU conditions, mainly due to path dependencies, abundant availability, matured industrial base and improved technical competence. The share decreases to 24% in 2050 in INDC and less than 21% for low carbon scenarios. While the share of gas increases from 12% in 2010 to about 38% in 2050. The share of renewables (solar, wind, biomass) increased from 3% in 2010 to 22% in 2050 under the BAU scenario, whereas in the alternate scenarios the share increases to 32%, 36% and 45% in INDC, 2 °C and 1.5 °C scenarios respectively. The shares of hydropower and nuclear remains constant at 7-9% in the fuel mix respectively. While retrofitting existing coal option seems to have very attractive returns and negative carbon prices, it also requires that a majority of the old inefficient coal power plants are capable of being retrofitted. A sizable amount of coal capacity need to be phased out for flexibility upgrades given that 52 GW of coal capacity will be older than 35 years by 2027.

Using natural gas as a source of flexible power generation would face challenges from new renewables along with coal TPPs running as peaker plants (Annaluru and Garg, forthcoming) since the cost of green field natural gas plants including gas infrastructure is higher as compared to coal plant retrofits or new capacity based on emerging technologies. With increasing pressure on shifting to cleaner and renewable forms of energy, unintended impacts of climate, global markets, technical and local socio-economic conditions are creating unanticipated challenges to scale up at national level. For example, in case of hydropower, hotter summer and uncertain rainfall patterns have decreased the live storage levels of reservoirs in western (19 % of full capacity), eastern (22 %), southern regions (20 %) as compared to northern (28%), and central region (42 %) in July, 2016 (CMIE 2017). Energy production from nuclear energy has not gained momentum due to trade bans and lack of indigenous uranium, hence not fully developed as envisaged. However, in May 2017, the current cabinet gave it a major push to triple the capacity to 17 GWe by 2024 through addition of pressurised heavy water reactors (PHWRs). It is stated to be a "fully home-grown initiative with likely manufacturing orders to Indian industry of about US $11 billion" in order to transform the domestic nuclear industry (WNA 2017; Sasi and Sinha 2017).

CCS plays an essential role in 2 °C and 1.5 °C scenario. The difference in the scenarios are dependent on the time frame when the technology is deployed. In the 2 °C scenario, we observe CCS after 2025, however in 1.5 °C scenario CCS needs to be employed after 2020 as observed in Figures 4. Garg et al. (forthcoming) have developed source-sink mapping by plotting the large point sources (LPS) on map and have created LPS location clusters through predictor modelling. The large point sources include power plants, and energy intensive industries such as cement, steel, fertilizer and refinery, while the sinks include basalt, saline aquifers and relinquished oil and gas wells. Radial basis function was used in ArcGIS software to obtain emission pattern coverage. Scenarios were established at theoretical, available, integrated and optimized level to narrow down on clusters that are cost-effective to discuss the feasibility of CCS technology in India. The study presents storage capacity, energy penalty, capture efficiency, and corresponding costing analysis using Integrated Environmental Control Model (IECM). The optimized and integrated scenario from the study correspond to the 2 °C and 1.5 °C stabilization scenario respectively of this paper. Figure 5 illustrates the sources of carbon capture in power and industry sector and sink/storage capacities across India.

[Figure 4: Fossil Fuels - Capacity under all scenarios (2010, 2030, 2050)]

[Figure 5: Map of large point carbon sources and sinks]

3.2.2 Industrial Sectors

Industry is the second largest energy consumer in Indian economy. Industrial energy demand has been growing since 2000 and is targeted to increase further due to renewed thrust on industrial growth under the 'Make in India' policy of the present government (Vishwanathan et al. 2017). The introduction of perform, achieve and trade (PAT) represents an attempt to reduce energy intensities along with overall energy consumption by targeting LPS that have been identified as energy-intensive designated consumers. It is a market mechanism, administered by Bureau of Energy Efficiency (BEE) covering 478 facilities from seven energy-intensive sectors, namely aluminium, cement, chlor-alkali, fertilizer, iron and steel, pulp and paper, and textiles (Garg et al. 2017). The model covers over fifteen industries, however PAT cycle I only comprises of seven of these industries, while PAT II cover eleven industries which constitute more than 20 per cent of total energy demand. Figure 6 present the total carbon dioxide emissions in the industry sectors accommodating for the industrial growth and the implementation of PAT.

[Figure 6: Aggregate carbon dioxide emissions under all scenarios in industry sector]

The first phase (PAT Cycle I) runs from 2012-2015 covering 478 facilities while the second phase (PAT Cycle II) focuses on deepening and widening of PAT-I (BEE 2016; BEE 2014). This comprises of inclusion of 170 DCs from three new sectors namely railways, refineries, and electricity distribution companies (DISCOM) in addition to 61 new DCs from existing 7 sectors. This will expand the coverage from 30% to 57% of total primary energy consumption by the industries and railways. To maintain consistency with model sector, DISCOMs are part of power sector, while railways are part of transport sector. Comparison of PAT cycle I and PAT cycle II targets, in addition to PAT cycle I achievements are provided Table 3.

[Table 3: Energy Savings Targets for PAT Cycle I and PAT Cycle II, and Energy Savings Achievement of PAT cycle I]

The model attempts to capture the all the major industries. **Error! Reference source not found.**7 provides a comparative assessment of PAT cycles I II for iron and steel DCs. A gradual shift towards left can be observed to indicate reduction of specific energy consumption (SEC) targets from PAT I to PAT II cycles. The plants with extremely high SEC have been targeted initially to reduce much faster than the plants that have low SECs in PAT cycle I. There is decrease in CO_2 emissions between INDC and low carbon scenarios due to intensification of energy efficient technologies in intensive industries through PAT. Water heat is another potential form of energy that is being explored to reduce the overall energy in industries such as cement and steel. The model considers the broadening and deepening of PAT cycle II that is implemented from 2017.

[Figure 7: Specific Energy Consumption under PAT cycle I and II for Iron and Steel Industry]

[Figure 8: Specific Energy Consumption in Iron and Steel Industry]

Figure 8 illustrates the decrease in the intensity of energy input per service demand under BAU, INDC, 2 °C and 1.5 °C scenarios in iron and steel industry as an example that will decreased carbon emissions in comparison to best available technologies across the world. The intensity in the aluminium and iron & steel is found to decrease in the INDC and low-carbon scenarios as these industries increase use of recycled material and switching to electricity. However, introduction of CCS in the steel and cement industries near the storage sites increases SEC after 2025 compared to INDC scenario.

Demand reduction in these major industries where dematerialization, reuse and recycle of raw materials increase after 2045, leading to decrease in SEC after 2040.

3.2.3 Transport Sector

The transport sector accounted for more than 15% of total energy demand in 2015. The increase in energy demand from this sector presents a challenge to energy security, since more than 95% of demand is met by oil, almost 75 per cent of which is imported. Another concern is related to its impact on air quality, which impacts adversely on human health, especially in urban areas. In India, road and rail have been the preferred modes when compared with air and waterways for both passenger as well as freight transport.

The demand for passenger transport is dependent on a variety of factors, including travel demand in terms of time and distance, in addition to changes in lifestyle due to increasing levels of income and types of vehicle at the individual level, as well as the policy environment (for example, odd-even rule in New Delhi where, either odd or even registration numbered road vehicles were allowed on any single day) and traffic management, which are exogenous but equally important. The transport sector accounted for about 11 per cent of total carbon emissions in 2010, and is expected to increase to about 12% in 2050 in reference and 14% in INDC scenarios while decreases to almost 9% of the total carbon emission in 1.5 °C scenario as observed in Figure 9. This is due to a combination of policy measure which include: technological change driving change of energy source with no structural evolution (electric vehicles), modal shift to low-carbon modes with no change in distances covered (metro) and behavioural change affecting mobility demand (telecommuting).

[Figure 9: Aggregate carbon dioxide emissions under all scenarios in transport sector]

As observed in Figure 10, the decline in the consumption of oil after 2030, due to the shift towards hybrid and electric vehicles, along with the increased share of public transport by road and rail decreases the CO_2 emissions in the INDC and low-carbon scenarios. In passenger traffic, bus use is expected to increase, though due to the shift towards compressed natural gas (CNG) the energy intensity is improved, thereby reducing overall energy consumption and CO_2 emissions. There is a marked increase in the demand for electric two-wheelers and three wheelers in low carbon scenarios. . Electric vehicles get increasingly charged by solar power instead of coal based electricity. With increasing public transport in cities, the share of four wheelers decreases in below 2 °C scenario. This is due to multiple factors, such as high parking charges for private vehicles, congestion on roads, efficient safe and comfortable public transport that is integrated across different modes. The cities are expected to transform and designed to increase public transport, with a strong push for electric vehicles expected to grow in line with population growth. For the low carbon scenarios, the road to rail ratio is projected to decrease from around 70:30 currently to 50:50 in 1.5 °C scenario by 2050. For 1.5 °C scenario, there are also expected deeper changes in modes of transport such as increase in non-motorized transport (such as cycling) through urban transformation, electric vehicles and use of rail transit (metro) in addition to behavioural changes such as work from home. The freight sector shows an increase in the share of rail traffic, with a significant increase in coastal shipping and inland waterways traffic under low carbon scenarios.

3.2.4 Building Sector

Rapid urbanization and increased levels of income have created demands for an improved quality of life. The increased penetration of electrical appliances accounting for the increasing demand for energy in both residential and commercial sectors. With urbanization expected to affect 60 per cent of the population in 2050, household energy demand will also increase in the future.

[Figure 10: Aggregate carbon dioxide emissions under all scenarios in building sector]

There is an observed shift in energy demand with the introduction of smart grid in both residential and commercial sector in the low carbon scenarios. Carbon dioxide emissions illustrated in Figure 10 depend on the type of fuel and technology used for the various services. There is an increase in energy consumption in cooking, and space cooling services in the low carbon scenarios due to increase in new stock and different kinds of fuel to accommodate increasing urban transformation. The new, energy efficient buildings will consume less energy overall after 2040.

[Figure 11: Energy transition in cooking services under INDC and low carbon scenarios]

Switching fuel to liquefied petroleum gas (LPG), which commenced in the late 80s in urban areas, picked up after 2000 at the different rates, depending on the type of technology and the geographical location. This is due to current policy interventions through regulations, as well as the economic instruments used and required to shift towards cleaner fuels to meet the demand for cooking as presented in Figure 11. The rate of adoption of cleaner technologies has been assumed to be slower, and the rate of use of biomass is found to decline only after 2040. Solar is found to increase due to increased demand for rooftop water heaters. An increase in electricity is observed due to the electrification of residential and commercial building, especially for space cooling, electric stoves, and refrigeration. Smart grids through ICTs will reduced the overall electricity demand in the low carbon scenarios for building sector through being more receptive to the demand –supply woes through integration with renewable sources of energy and enhanced energy efficiencies.

3.3 Marginal Cost Abatement Curves

This paper focuses on sectoral MAC curves at a national level and does not consider MAC curves as the marginal profit of one more unit of emissions of a single firm. Many factors have been studied for their influence concerning the shape and structure of a MAC curve, such as fossil fuel prices, various technologies and their learning/innovation, policy driven energy efficiency and technology phase out targets, dematerialization and recycle-reuse targets and market mechanisms, lifestyle changes, carbon capture and storage. Their depth and coverage are different under 2 °C and 1.5 °C targets. Therefore some of similar MAC components with negative costs could have different potential mitigations under the two scenarios. We have calculated the average marginal cost of abatement over the selected duration for each of these.

MAC curves are a static snapshot of emission reduction from 2011-2050 in this study. The inter-temporal aspect due to technology transition through efficiency and choice of fuel can be captured as the model has rich technology characterization. However, only major mitigation measures/technologies in each sector have been selected in the current representation to emphasize the influence of these selected technologies in emission reduction.

Kesicki and Ekins (2011) and Fei et al. (2014) pointed that MAC curves change based on the applied methodology and underlying assumptions, hence should be used as an 'illustrative tool' to discuss and analyze climate policies. In the figures 13 and 14, the height of each bar represents the marginal abatement cost, while the width represents the emission abatement and the colour indicates the sector. Model results indicate that cumulative energy-related CO_2 emissions during 2011-50 for reference scenario to be around 165 bt-CO_2. In the model run for INDC, 2 °C and 1.5 °C scenarios, these emissions have been estimated to be 147 bt-CO_2, 123 bt-CO_2 and 104 bt-CO_2 respectively. This corresponds to an emission reduction of 12%, 23% and 33% compared to the reference run. The reductions in 2 °C with respect to INDC scenario is 24 bt-CO_2 and for 1.5 °C is 43 bt-CO_2 (Figures 12 and 13).

Most of the low-cost abatement potential can be found in the electricity sector, which accounts for almost 44% of all CO_2 emissions by source, followed by the transport sector with 24%, industry with 9% and the residential sector with 7%. It is apparent that there are some low-cost abatement options in industry, transport and the residential sector is energy efficiency, shift to renewables and demand reduction. The contribution by CCS becomes dominant when the carbon price increase to a range of \$60/t-CO_2 to \$100/t-CO_2. CCS is projected to play an essential role for India in order to meet the global carbon budget for 2 °C and 1.5 °C.

[Figure 12: MAC Curve-2 degree over INDC]

[Figure 13: MAC Curve-1.5 degree over INDC]

4. Discussions

Deep decarbonization of the economy requires attention to four thrust areas: a) increased energy efficiency in energy supply (power sector) and demand sectors (industry, transport, building and agriculture); b) enhanced deployments of renewables;

c) demand reduction in the end-use sectors through dematerialization, recycling, reuse and changed behaviour; and d) deployment of CCS as required and feasible. A mixture of these are instituted through policies to reduce final demand for energy across end-use sectors in the alternate scenarios, thereby reducing the overall CO_2 emissions. Demand-side measures are implemented through participative governance and coordinating institutions, which assumes to reduce the transaction costs of executing demand-side interventions.

4.1 Energy Efficiency

Strategies to decrease emission intensities through energy-efficiency improvements have been suggested in the 12th Five-Year Plan and reported in the first biennial update report (BUR 2015; INDC 2015). The past and current policy packages of the Indian government have aimed for accelerated energy efficiency. Energy efficiency is modelled through changes according to the set of technologies available. These technologies improve over time as they move to a more advanced, more efficient 'vintage', thus simulating the improved efficiency.

Industry sector saves the most due to aggressive PAT mechanism followed by power. However this may get challenging as the PAT deepens in each of the industry and broadens to new industries/sector. It is easier to bring about efficiency measures in large point sources as compared to decentralized, smaller point sources. Additionally, sectoral targets in PAT scheme require specific interventions such as raw material management, process improvement, installation of new systems such as waste heat recovery, reducing output wastages through better quality control etc. These vary at both industry and plant level. For instance, around 40 to 50 % of units in the iron and steel sector and cement industry across India have selected waste heat recovery projects as a new source of energy. The capital cost may outweigh the benefits gained in heat recovered by the introduction of a waste heat recovery system. The cost implications for only installing waste heat recovery boilers (WHRB) along with other accessories is around US $ 0.75 Million. The cost of installing whole unit along with waste heat recovery in large plant is USD 22.23 million in an iron and steel plant, while in cement plant is of the order of USD 11.25 million (Garg et al. 2017).

Transport sector requires a huge upfront investment while building sector has been the one of the most cost-effective options. This is because end-use energy efficiency saves not only in end-use services but also in generation, after accounting for auxiliary consumption and transmission and distribution (T&D) losses[1] (Vishwanathan et al. 2017; BEE 2016). The building sector may save during 2020-2030 due to shift to light-emitting diodes (LEDs), cleaner cook stoves, solar water heaters and energy efficient space cooling systems. However, ACs and more electric technologies result in higher energy demand after 2035 with increasing population. Smart grids will face technical challenges in event of constantly changing technologies, business challenges in the need to align service and end use providers with technology, and financial risks as the value proposition for each stakeholder will be different, and no structured regulatory policy to achieve set targets. Better understanding of the demand load curves will be essential to implement smoother installation and working of smart and micro grids in residential, commercial as well as industrial areas of a zone, city and/or region.

4.2 Transitions towards Renewables

The major barriers for India to shift from domestic coal to cleaner forms of fuels are the obligations to achieve energy security and reduce energy poverty (Garg & Shukla 2009). Additionally, the entire supply chain of coal from production, transport, use and ash disposal employ more than one million people. For example, coal mining is the second largest employer in India (MOSPI 2016; GOI 2014). Some of the least developed Indian states like Chhattisgarh, Jharkhand and Odisha earn more than 30 per cent of their income from coal royalties and e-auction proceeds (Chakraborty et al. 2016). Path dependencies of fossil fuels such as coal are entrenched in India, hence will have not only socio-economic but also socio-political relationships. Case studies have shown that coal transitions have long lasting effect on individuals due to inflexible labour market and skill shortages (miners) change and in regions based on their dependence on coal mining as the main economic activity. Therefore, shift from coal in India requires a broader perspective that includes sustainable development along with economic growth and measures that balance the transformation socially, especially for displaced workers (Caldecott et al. 2017; Reddy 2016; Khosla et al. 2015).

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[1] End-use efficiency can also apply to technologies that do not consume electricity.

There has been an increase in power generation from renewable sources of energy in the past decade due to the government push. The majority of renewable electricity generation in India is decentralized for both solar and wind. The INDC has been observed to lead to accelerated energy efficiency improvements in all demand sectors. The 2 °C and 1.5 °C scenario with massive deployment of solar and other renewable energy especially in electricity production constitute more than 40 per cent of the generation capacity in the short and medium terms (Figure 14). The sector continues to decarbonize after 2035, with low-carbon options (intermittent renewables coupled with power storage) substituting fossil fuel power plants.

[Figure 14: Clean and Renewables - Capacity under all scenarios (2010, 2030, 2050)]

For other renewables such as solar and wind, in addition to variability of resource, location specific potential and higher costs, the issue of how much renewable power the grid can handle and provision of ancillary services such as storage have not been addressed at a national level (Annaluru and Garg, forthcoming). Hence, with around 60% of the net installed capacity of the electricity generation units (EGUs) being coal-fired, these challenges will tend to support coal to remain the mainstay of the Indian energy sector in the short- to medium-terms. Hence, mitigation of carbon dioxide emissions need to be prioritized in power sector, especially for coal power plants.

In May 2017, the Indian government stated no further requirement of lowering taxes on renewables with low tariffs. The Ministry of New and Renewable Energy (MNRE 2017) analyses that increase in tax cost for renewable energy sector will have a possible negative impact on cost of setting-up renewable energy plants. It will also increase the working capital requirements leading to higher financial as well as operating costs.

4.3 Demand reduction

Allwood et al. (2017) discusses about the challenges and possible solutions to transition in industry with reduced material demand especially in industry sector. Material reduction plays an important role in cement and iron and steel industry where technologies such as 3-D printing not only decrease material waste in addition if reduction in carbon emissions. Recycling and reuse play an equally important role in metal (such as aluminium, iron and steel) and plastic industry saving on energy required to process raw materials (for example: ore to metals).

Increasing urbanization leads to cleaner technologies and more energy-efficient technologies, to provide the basic services. For example, a biomass/coal cook stoves was replaced by LPG stove in late 80s and early 90s in urban areas, is now replaced by liquefied natural gas (LNG) to electric stove, microwave, and/or ovens. In transport sector, fuel switch (e.g., electric vehicles) in addition to sustainable behavioural choices such as metro and telecommuting (use of internet, phone) will reduce emissions. However a slight increase in overall energy consumption in residential sector due to introduction of telecommuting in low carbon scenarios has been observed in various studies (Horner et al. 2016; Shimodo et al. 2007; Matthews et al. 2005).

4.4 Carbon dioxide Capture and Storage

CCS will become a critical technology to mitigate emissions mitigation as coal continues to remain the dominant fuel. It should also be noted that McGlade and Ekins (2015) estimated that 66% of Chinese and Indian coal reserves could become stranded assets if the 2 °C carbon budget targets are to be met. It is to be noted that the aforementioned discussion has been carried out with the underlying assumption that there is abundant sink availability. The MAC curves for 2 °C and 1.5 °C show that CCS will be picked up at US$40-60/t-$CO_2$ for gas and at US$60-100 for coal power plants. Additionally, CCS in industries that are located within 180-200 km from the selected storage localities can be feasible at US$40-70/ t-$CO_2$. Garg et al. (Forthcoming) have also reported that India could mitigate around 780 M t-CO_2 per year below 60 US$/ t-$CO_2$ (2005 prices) over 30 years, and another 250 M t-CO_2 per year for up to 75 US$/ t-$CO_2$ prices through CCS. We have not explored bio-energy (includes biomass and biomass residue) with CCS (BECCS) in detail here, however the potential could be mainly constrained by water and land availability resulting in food-fuel conflicts. Additionally, the use of biomass residue for power generation faces a number of physical challenges such as different grades of thermal efficiency of each plant, technical challenges that include pre-treatment and conversion of biomass to gas, cleaning and utilization of gas, and logistic challenges such as supply chain management from collection to transport to storage (Garg et al. 2016; Singh 2016; Gambhir et al. 2014; Hiloidhari et al. 2014).

5. Conclusions

Low carbon growth is inevitable for India's future sustainable development, however there are a number of challenges that India will face to achieve its low carbon budget targets. This study highlights the increasing need to decouple CO_2 emissions from economic growth and energy basket through adoption of deep decarbonization measures such as energy efficiency, increase in renewable generation, demand reduction and deployment of CCS. The Indian CO_2 emissions during 2011-2050 are projected to be 165 Bt-CO_2 under the BAU scenario, 147 (INDC), 123 (2 °C) and 104 (1.5 °C). The main contributors to CO2 mitigation are energy efficiency enhancements across supply and demand sides (10 bt-CO_2 CO2 emissions mitigated due to BAU to INDC transition, 2 bt-CO_2 for INDC to 2 °C transition, and 4 bt-CO_2 for INDC to 1.5 °C transition), increased renewable energy (7 bt-CO_2 emissions mitigated due to BAU to INDC transition, 5 bt-CO_2 for INDC to 2 °C transition, and 6 bt-CO_2 for INDC to 1.5 °C transition), demand reduction and lifestyle changes (1 bt-CO_2 emissions mitigated due to BAU to INDC transition, 4 bt-CO_2 for INDC to 2 °C transition, and 6 bt-CO_2 for INDC to 1.5 °C transition), and CCS (no contribution for BAU to INDC transition, 13 bt-CO_2 for INDC to 2 °C transition, and 27 bt-CO_2 for INDC to 1.5 °C transition).

It can be inferred that energy efficiency and renewable energy will play almost equal roles for CO_2 mitigation under INDC. However as global mitigation regimes become stricter, lifestyle changes and CCS would need to come in the low-carbon scenarios. Even as the scenarios show considerable decrease in CO_2 emissions, implementing the measures will be difficult with growing urbanization, rising incomes and aspirations, in addition to policy thrust for more infrastructures and indigenous industrialization through 'Make in India' policy. In order to realize the low carbon targets, India needs to not only transform its urban infrastructure but also cultivate the young generation to adopt low-carbon and sustainable consumption lifestyle. Reliability and uncertainty in adopting technologies such as CCS due to lack of field experiments and feasibility data will remain a challenge. To achieve the aforementioned mitigation targets, socio-economic costs of multiple transitions have to be met – either domestically or through international support. However abrupt changes such as fast coal phase-out will be difficult to handle politically and may create opposition to change from entrenched stakeholders.

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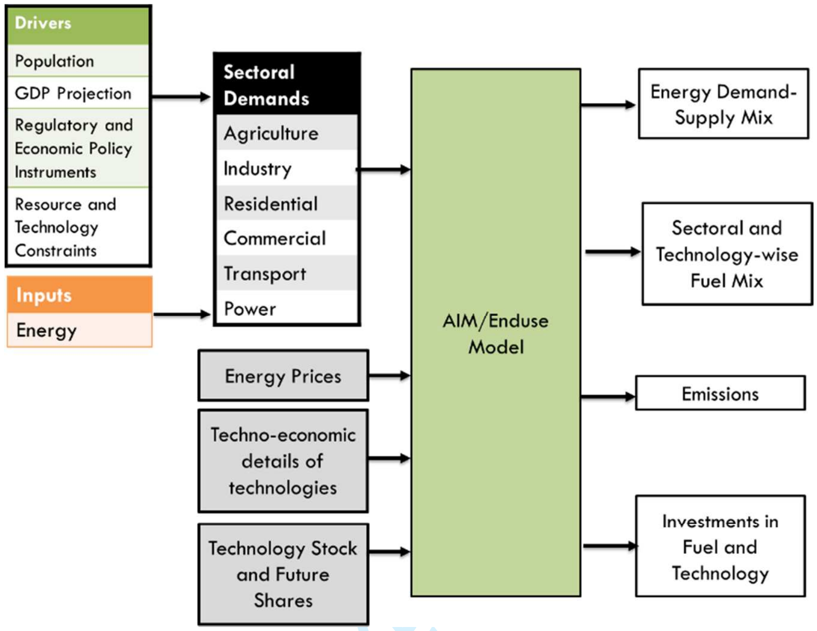
FIGURES

Figure 1: AIM/Enduse Framework



Adapted from Shukla, et al. (2004) and Kainuma, et al. (2003)

Figure 2: Aggregate carbon dioxide emissions under various scenarios

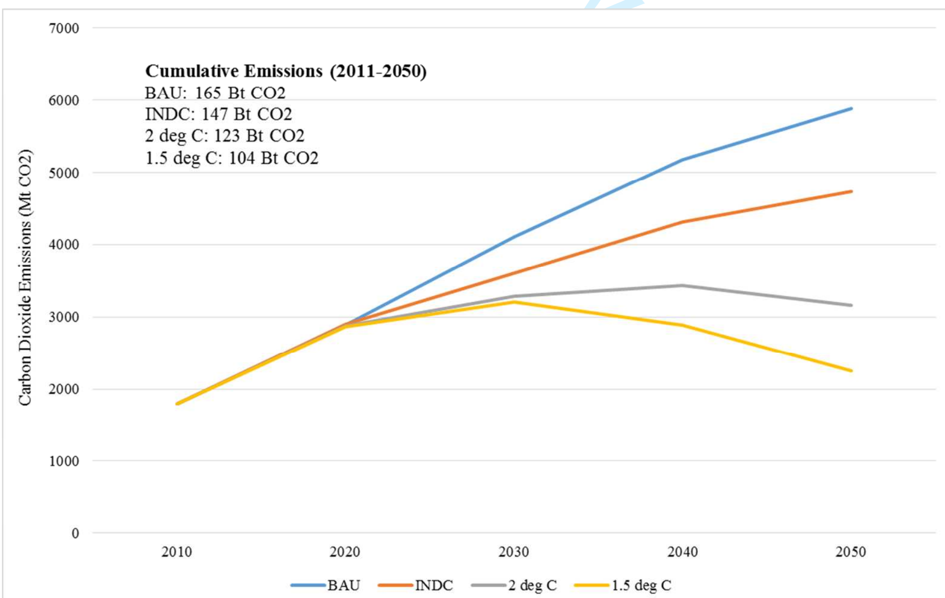


Figure 3: Aggregate carbon dioxide emissions under all scenarios in power sector

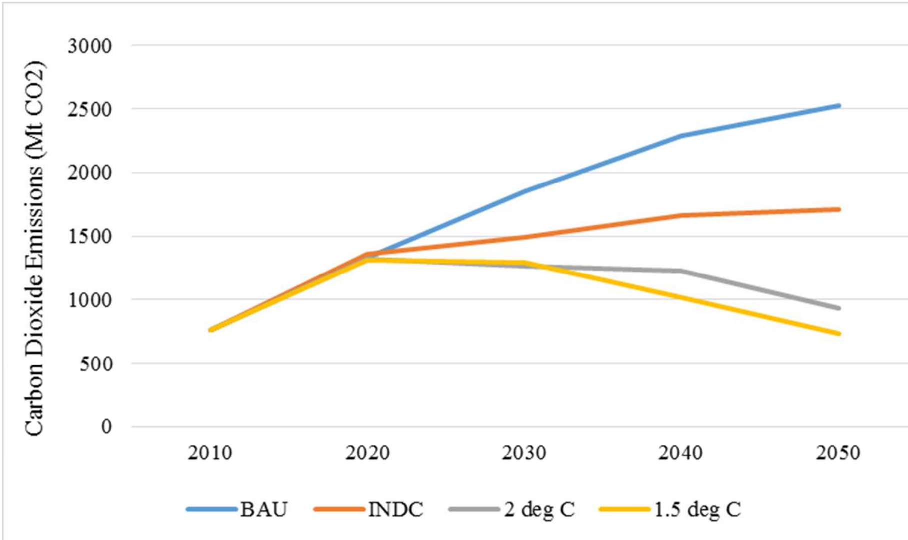


Figure 4: Fossil Fuels - Capacity under all scenarios (2015, 2030, 2050)

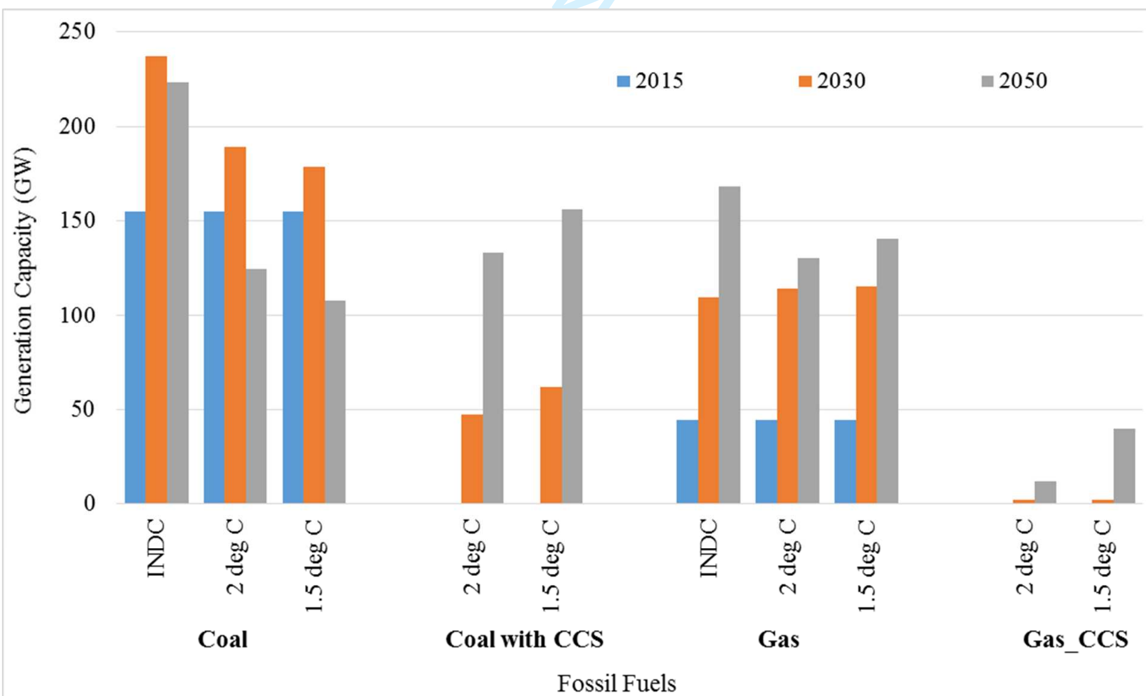
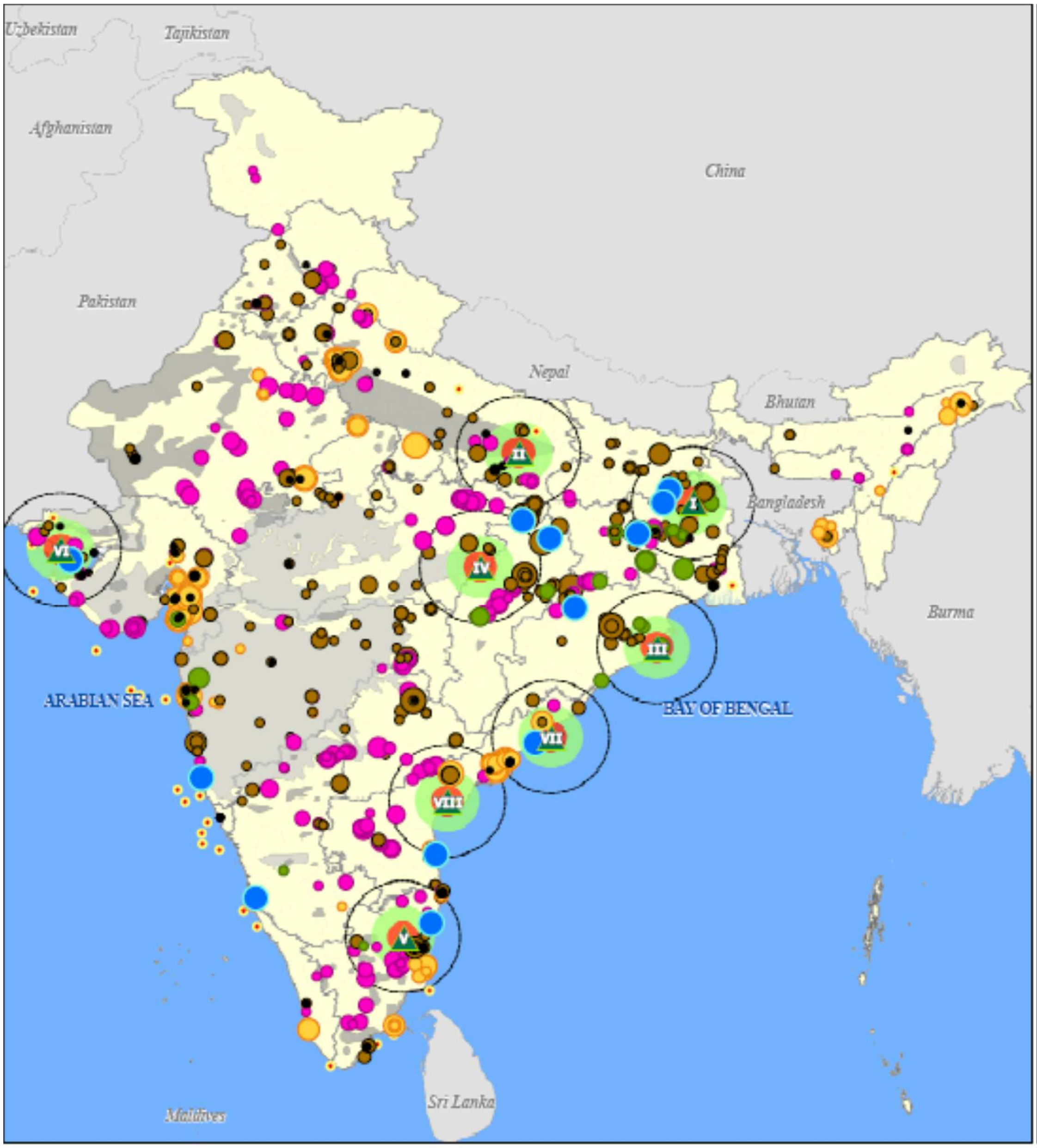


Figure 5: Map of large point carbon sources and sinks



Source: Adapted from Central Electricity Authority, 2011*; Cement manufacturers Association, 2012**; Joint Plant Committee, 2012***; The Fertilizer Association of India, 2012 and Ministry of Petroleum & Natural Ga 2012^; Directorate of Hydrocarbon (DGH), Noida, India^^ Infraline 2015^^^; Dr Ajay Singh ppt on Coal Bed Methane and Basalts during CCS workshop at IIM Ahmedabad on 5 November 2014#; Central Ground Wat Board Ministry of Water Resources Government of India (2012)##; National Boundaries as per Survey of India###.

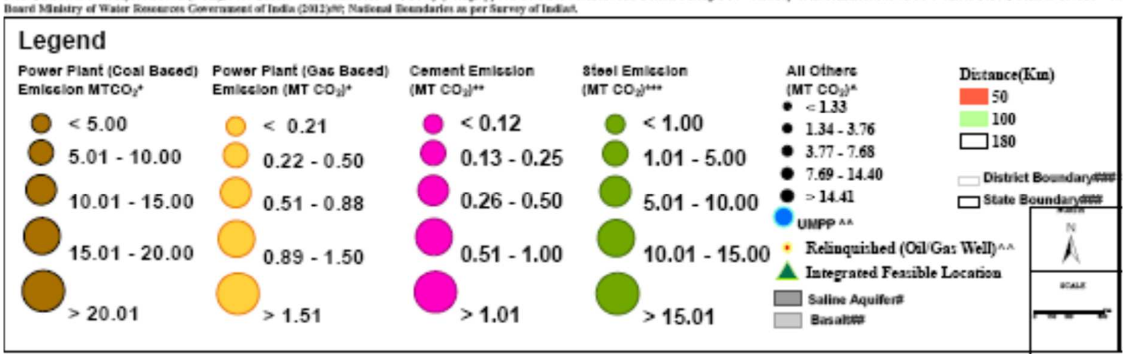


Figure 6: Aggregate carbon dioxide emissions under all scenarios in industries

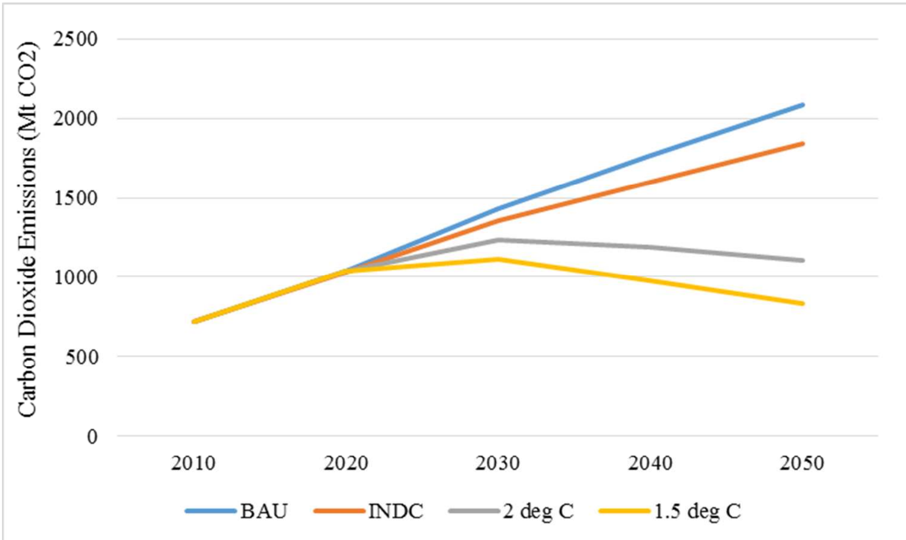
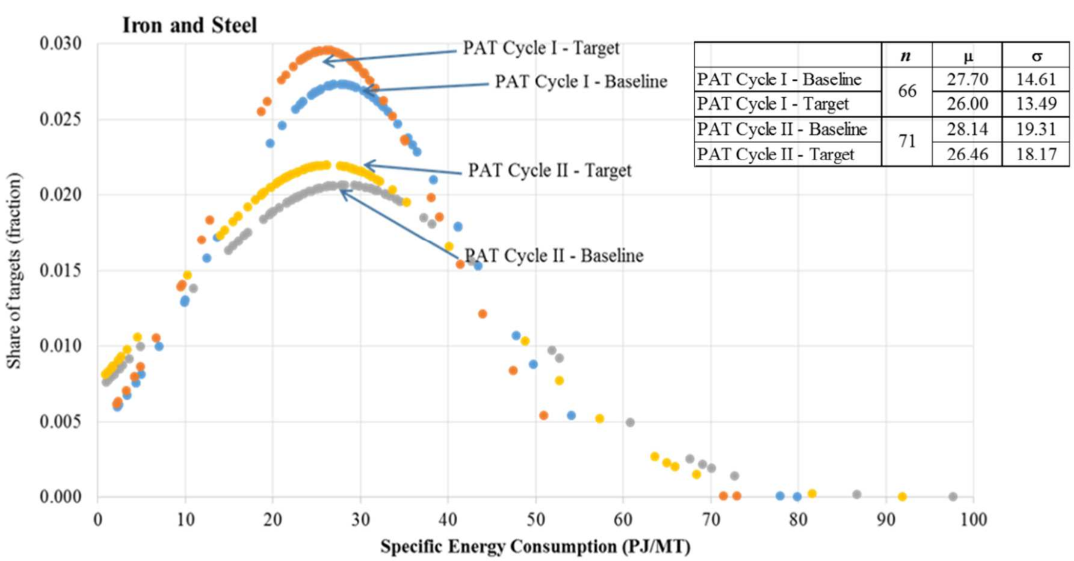


Figure 7: Specific Energy Consumption under PAT cycle I and II for Iron and Steel Industry



Note:

Baseline refers to the current SEC of the designated consumers (BAU)

Target represents the PAT cycles targets to be achieved by the designated consumers (INDC)

Figure 8: Specific Energy Consumption in Iron and Steel Industry

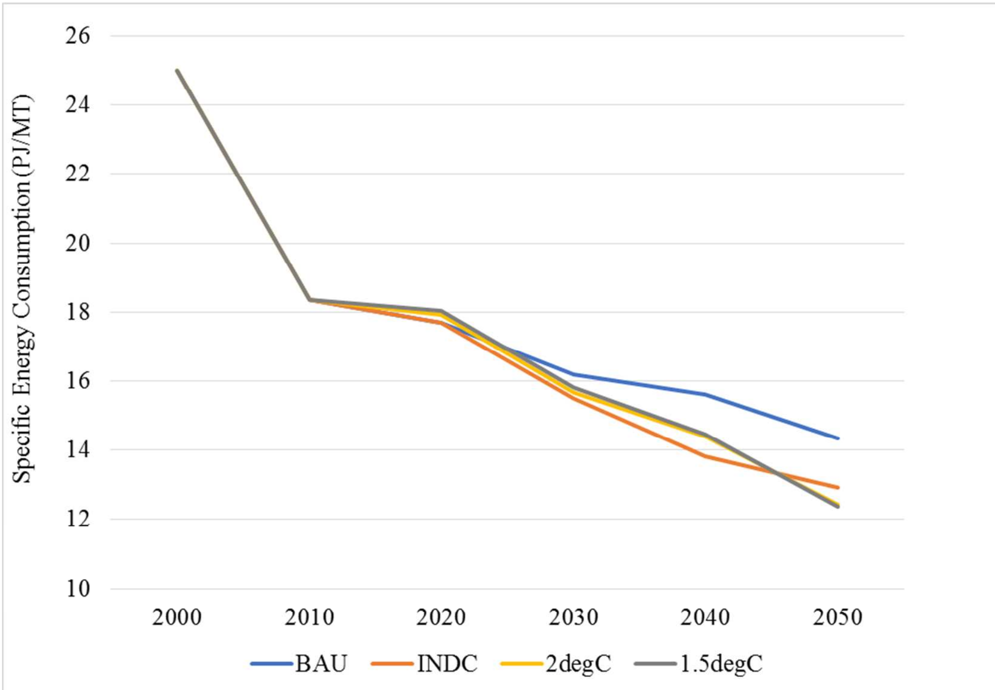


Figure 9: Aggregate carbon dioxide emissions under all scenarios in transport sector

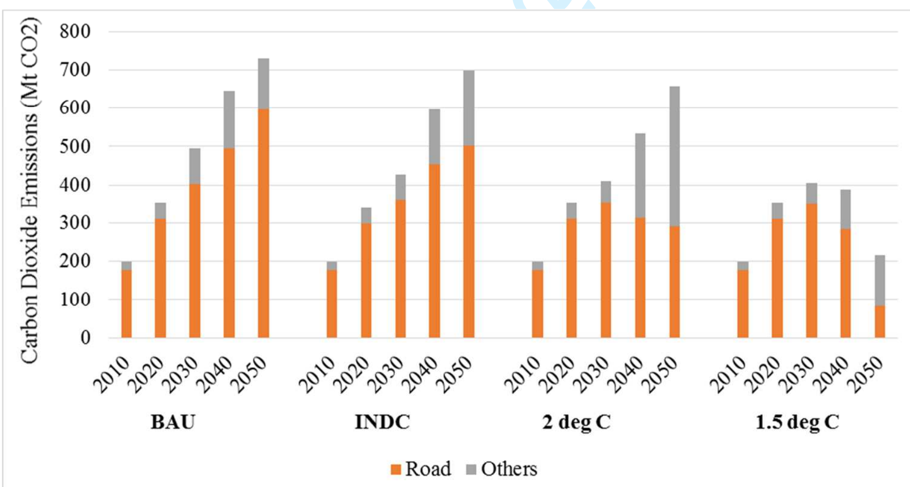


Figure 10: Aggregate carbon dioxide emissions under all scenarios in building sector

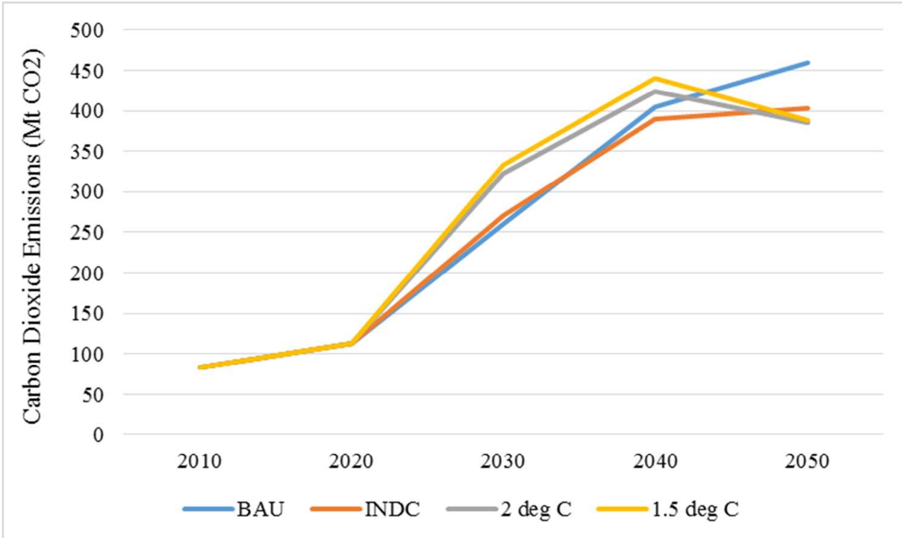


Figure 11: Energy transition in cooking services under INDC and low carbon scenarios.

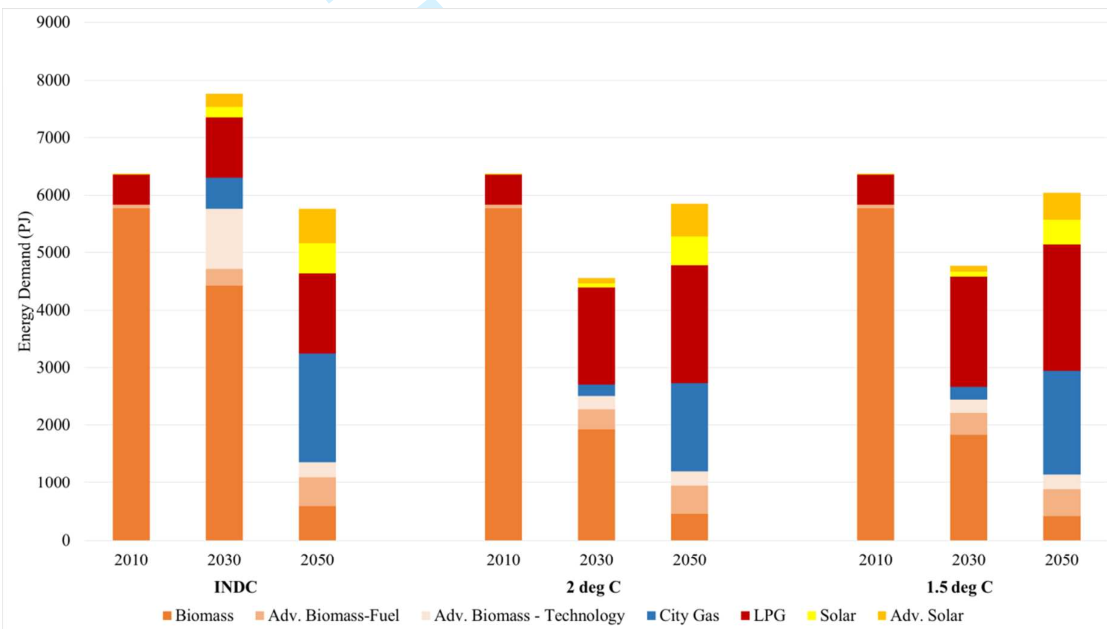


Figure 12: MAC Curve-2 degree over INDC

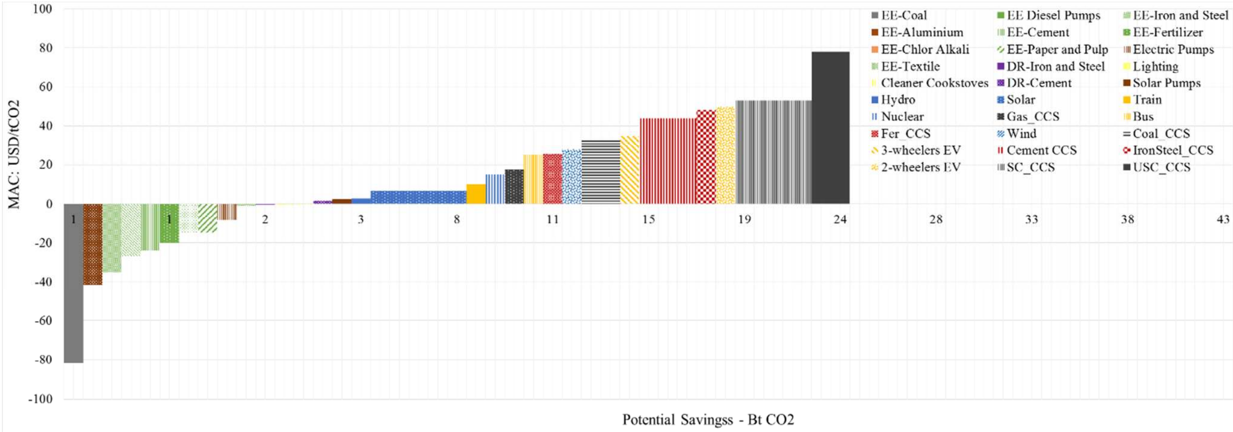


Figure 13: MAC Curve-1.5 degree over INDC

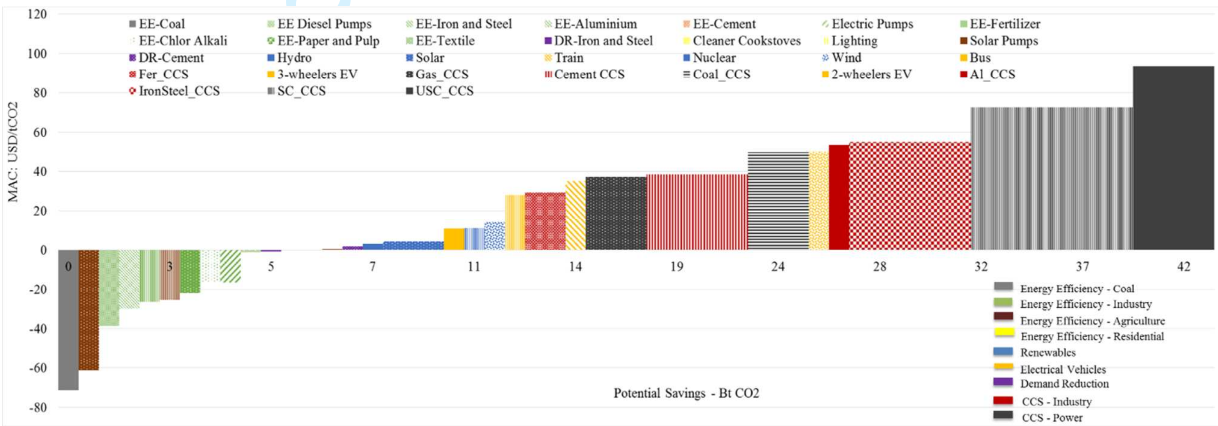
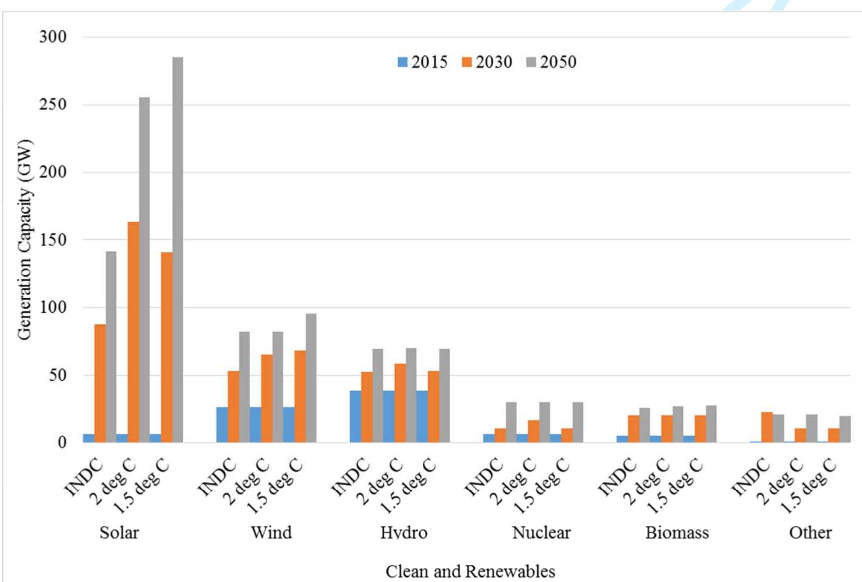


Figure 14: Clean and Renewables - Capacity under all scenarios (2015, 2030, 2050)



TABLES

Table 1: Scenario Assumptions in current and alternate futures

Sector	Reference	INDC	2 degree C	1.5 degree C
Emission Intensity	20-25% during 2005-2020	33-35% during 2005-2030	Carbon budget : 115-130 Bt CO2during 2011-2050	Carbon budget : Around 100-115 Bt CO2
Power	Solar: 20 GW by 2022 Wind: 38.5 GW by 2022 Small hydro: 6.5 GW by 2022 Biomass: 10 GW by 2022	Solar: 100 GW by 2030 Wind: 60 GW by 2030 Small hydro: 15 GW by 2030 Biomass: 25 GW by 2030 AT&C losses: Reduce to 6-8 % Introduction of smart and micro grids	Additional P&Ms being included Early retirement of low efficiency coal based power plants Super Cr PC, IGCC brought in more strongly Gas based power generation (gas sourcing) Increased Nuclear (NSG entry) Increase in renewables with storage Enhancing smart and micro-grids	Aggressive measures required with carbon price Efficient coal and gas power plants with CCS Enhancing micro-grids
Agriculture	Energy Efficient (EE) Pumps	EE and solar Pumps	EE, Solar Pumps with drip irrigation	Solar Pumps with drip irrigation
Building (Residential and Commercial)	Energy Saving Potential of 20-30%- CFL, S&L programme	LED to save 100 TWh annually, S&L programme for 21 equipment, LEED and ECBC std.	Shift to electric appliances for residential, increased S&L programme, dematerialization	Complete shift to EE electric appliances, LEED and ECBC std. buildings, demand side management
Transport	Ethanol blending: 5%	Share of railways: 36 to 45%, DFC, improve vehicle efficiency, introduce EV, increase public transit (metro)	Encourage 0-5 % work from home, encourage non-motorized transportation	Electrification of passenger and freight transport, Demand reduction e.g. Encourage 5 - 15% Work from home, encourage non-motorized transportation

Industry	PAT, switch to cleaner fuels Energy Saving Potential: 5-15%	PAT (enhanced sectoral and plant coverage) Addition of railways, refineries and distributed companies	More aggressive PAT -Addition of MSMEs and SMEs; Demand reduction	More aggressive PAT. Reduction in energy intensity the reuse, recycle of energy (waste heat) and material (aluminium, steel), demand reduction for end-use materials

Table 2: Indicators – Population, Economy and Emission intensities over time in all scenarios

[redacted]							**2010=100**	
		2010	**2020**	**2030**	**2040**	**2050**	**2030**	**2050**
Population	**Million**	1201	1370	1523	1651	1751	127	138
GDP	**Trillion US$2010**	0.9	2.1	3.5	7.5	10.1	222	489
CO2	**MT CO2**							
	Reference	1800	2893	4104	5170	5882	228	327
	INDC	1800	2889	3604	4317	4721	200	262
	2 degree	1800	2882	3230	3409	3163	179	176
	1.5 degree	1800	2866	3135	2823	2230	174	124
Energy	**PJ**							
	Reference	28.6	43.4	62.3	79.4	91.3	218	319
	INDC	28.6	43.1	58.4	72.1	79.6	204	278
	2 degree	28.6	43.3	59.2	75.3	85.0	207	297
	1.5 degree	28.6	43.4	59.0	73.1	76.5	206	267
CO2/GDP	**MT CO2/ Billion US$2010**							
	Reference	2000	1377	1173	689	582	59	29
	INDC	2000	1376	1030	576	467	51	23
	2 degree	2000	1372	923	455	313	46	16
	1.5 degree	2000	1365	896	376	221	45	11
CO2/capita	**t CO2/capita**							
	Reference	1.5	2.1	2.7	3.1	3.4	180	224
	INDC	1.5	2.1	2.4	2.6	2.7	158	180
	2 degree	1.5	2.1	2.1	2.1	1.8	142	121
	1.5 degree	1.5	2.1	2.1	1.7	1.3	137	85
CO2/energy	**MT CO2/EJ**							
	Reference	62.8	66.7	65.8	65.1	64.4	105	102
	INDC	62.8	67.0	61.7	59.9	59.3	98	94

	2 degree	62.8	66.6	54.6	45.3	37.2	87	59
	1.5 degree	62.8	66.0	53.2	38.6	29.1	85	46

Note: GDP and Population are input assumptions. Energy and CO2 are model outputs.

Table 3: Energy Savings Targets for PAT Cycle I and PAT Cycle II, and Energy Savings Achievement of PAT cycle I

S.No	**Sectors**	**Unit of SEC**	**PAT I cycle**			**PAT II cycle**	
			Number of DCs	**Target (PJ)**	**Achievements (PJ)**	**Number of DCs**	**Target (PJ)**
1.	Iron and Steel	PJ/MT of product	67	61.5	87.9	71	95.5
2.	Cement	PJ/MT of product	85	34.3	60.3	111	46.9
3.	Aluminium	PJ/MT of product	10	19.3	30.6	12	19.7
4.	Fertilizer	PJ/MT of product	29	20.1	34.8	37	18.8
5.	Paper & Pulp	PJ/MT of product	31	5.0	10.9	29	6.3
6.	Textile	PJ/MT of product	90	2.9	5.0	99	3.8
7.	Chlor - Alkali	PJ/MT of product	22	2.1	4.2	24	4.2
8.	Petroleum Refinery	Million British Thermal Unit per Thousand Barrel per Energy Factor	-	-		20	1.11
9.	Railways	Litres /1000 GTKm	-	-		100	Na
10.	DISCOMs	% of Transmission and Distribution losses	-	-		50	0.94
	Total		**478**	**145.3**	**233.6**	**707**	**195.1**