India's CO₂ emissions pathways to 2050: energy system, economic and fossil fuel impacts with and without carbon permit trading

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Abstract

Fast-emerging (yet still relatively less developed) economies such as India are understandably cautious about committing to emissions reduction targets that could be economically costly. The tensions between continuing short-term economic growth whilst investing in low-carbon technologies for long-term decarbonisation could be eased if there were significant financial and non-climate potential benefits of decarbonisation for these economies. This study explores some of the potential benefits for India, by analysing its long-term mitigation options in the context of global action towards a 2°C target, using an energy systems model (The University College London TIMES Integrated Assessment Model, or TIAM-UCL) which represents India explicitly, as one of 16 global regions. The study finds that India could significantly over-achieve against a 2050 low-carbon target based on equal per capita emissions by 2050, at mitigation costs below the global carbon price, implying that it could earn significant revenues through selling international carbon credits, thereby offsetting some of the costs of decarbonisation. In addition, India would see much lower levels of fossil fuel consumption in a low-carbon scenario, thereby alleviating potential economic difficulties in securing access to adequate supplies of these fuels.

Keywords

India's CO₂ emissions;

2050;

Carbon permit trading;

Economic impacts;

Fossil fuel impacts;

Energy system.

1 Introduction

This study presents an assessment of how a range of low-carbon technologies could in combination help India's economy and energy system remain at a relatively low level of CO₂ emissions over the next four decades, even with significant economic growth and development. This would allow India to play its part in an international effort to avoid dangerous levels of global warming. The particular aspects focused upon in this analysis are threefold:

- India's least-cost low-carbon pathway to 2050, as part of a global low-carbon scenario in line with a target to limit global warming to 2°C above pre-industrial levels, considering scenarios with and without international carbon permit trading. This allows an assessment of the potential economic benefits to India of participating in an international carbon permit trading regime.
- A detailed analysis of the changes to the energy system across the major supply and demand sectors in India, when comparing a business-as-usual and low-carbon scenarios. This helps to highlight what energy system changes India would undertake to achieve the low level of emissions required to contribute towards a global target of 2°C, both with and without carbon permit trading.
- An assessment of the changes to fossil fuel and other energy carrier demand when comparing the business-as-usual and low-carbon scenarios. Again, this highlights the potential opportunities and challenges for India in terms of maintaining energy security if it decarbonises as part of a global effort to achieve the 2°C target, and what impact carbon permit trading has on this.

The motivation for such an assessment, focused on the potential impacts of carbon permit trading as well as fossil fuel consumption, is that India currently has a range of energy and economic development requirements which will affect its incentives to undertake a low-carbon development pathway.

India is still poor by global standards, with a Gross National Income (GNI) per capita of around \$3,500 (in Purchasing Power Parity terms) in 2010, compared with the USA's \$47,000 [1]. To develop further, India will need reliable access to increasing supplies of energy. India's total primary energy supply (TPES) per capita stood at 0.53 tonnes of oil equivalent (toe) in 2007, whereas the USA's figure was closer to 8 toe/capita. Even OECD Europe, which is much less energy-intensive than the USA, used 3.6 toe/capita in 2007 [2].

In addition, India is currently highly reliant on fossil fuels to meet its energy needs. Oil net imports made up about 70% of total oil consumption in 2011 [3]. India is the world's third largest coal producer with the sixth largest reserves [4], but these reserves have a high ash content and are concentrated in eastern states, far from the highest demand centres in western and southern India [3], which means there is an increasing reliance on coal imports too.

About 300 million people, mostly in rural areas, lack access to electricity [5]. Even for those connected to the grid, blackouts are common and capacity shortages mean that some 15% of peak power demand is not met [6]. There is chronic under-investment in the power sector generation and transmission system, stemming from capped electricity tariffs which do not repay investments [7].

Clearly economic development, energy security and energy access are therefore primary concerns for India, but there are several reasons why attention has also turned to climate issues in recent years. For one thing, India is vulnerable to climate change, which could have a number of negative economic impacts, such as decreased yields of wheat and rice (two of its major exports), as well as increased sea level and water stress [8]. For another, India's policy-makers are aware of the non-climate change benefits of a more diverse, indigenous energy supply, which is decreasingly reliant on fossil fuels. India's Planning Commission on integrated energy policy has stated that "it is not a question of choosing among alternative domestic energy resources but exploiting all available domestic energy resources to the maximum as long as they are competitive" [9].

This paper is structured as follows: Section 2 reviews recent studies on India's potential low-carbon transition; Section 3 sets out the details of the modelling framework used in this study, and the key assumptions used in the modelling to project future energy demand across India's economic sectors; Section 4 presents the results from the modelling, highlighting the impact of emissions trading on India's decarbonisation options and costs, the changes to India's energy systems across the major economic sectors, when comparing the high and low carbon scenarios, as well as the implications for India's fossil fuel usage; Section 5 discusses the main outcomes from the modelling and concludes.

2 Studies on India's low-carbon options

Energy has in recent years included studies projecting India's energy needs and low-carbon options over the medium-term, to 2020 and 2030. Parikh (2012) reports on the analysis of the Planning Commission's Expert Group to produce a Low Carbon Strategy for Inclusive Growth, in order to assess India's options to achieve its Copenhagen Accord voluntary commitment of a 20-25% reduction in its GHG intensity (per unit GDP) compared to its 2005 level, by 2020 [10]. The four scenarios presented – a "determined" and even more "aggressive" effort scenario for two assumed real economic growth rates (8% and 9% per annum) would in theory achieve an intensity reduction of between 24% ("determined") and 33-34% ("aggressive"). Policy measures would promote more efficient lighting and appliances, implementation of energy efficient building codes, better labelling for industrial equipment and the use of more energy efficient manufacturing plant including variable speed drives, as well as a range of measures to achieve modal shifts towards public transport, and greater efficiency of vehicles. In addition, a range of measures in the power sector, including a 4-6% increase in coal plant efficiency, and a large increase in wind capacity (to 30 GW by 2020) and solar capacity (to 20 GW by 2022) are assumed. The targets are deemed to be achievable, but will need determined policy efforts, as well as reform of energy pricing to remove distorting subsidies, to encourage and support the uptake of energy efficiency measures.

Parikh and Parikh (2011) look to 2030 to assess the potential reduction in CO₂ emissions available from a range of mitigation measures, in an economic scenario with an 8% real annual growth rate to 2030 [11]. They use a cost-optimising Integrated Energy System Model (IESM) (described in detail in [12]) to explore how India's projected energy needs could be met, with and without measures to minimise CO₂ emissions. The most significant measures (maximising hydro and nuclear potential, reducing transport energy demand, accelerating renewables deployment and above all achieving reduced electricity demand through greater energy efficiency) could together reduce CO₂ emissions by about 30% compared to the 5.23 billion tonnes in the base case, at a total discounted present value cost of \$91 billion (US\$2005) over the period 2005-2030.

The role of key technologies in India's potential low-carbon pathways has also been explored in *Energy's* (2009) special issue on "Energy and its sustainable development for India". For example, carbon capture and storage could play an important part in reducing CO₂ emissions in the future, given India's likely continuing reliance on coal use due to its significant reserves, with analysis suggesting that capturing emissions from up to 10 large point sources could save up to 13 GtCO₂ cumulatively over the period 2010-2030 [13]. A range of renewable technologies could also make an important contribution to energy supply in India, with analysis suggesting that renewables could make up to 10% of energy by 2022 [14]. Long-term potentials for key technologies include up to 100 GW for wind (onshore and offshore), up to 15 GW of small hydro, and over 100 GW of biomass generation [15].

A number of additional studies have been undertaken to assess India's longer-term (to 2050) low-carbon possibilities and their implications. For example, the International Energy Agency's *Energy Technology Perspectives 2012* [16] shows a significant role for the power sector to decarbonise, with increased shares of nuclear, renewables and carbon capture and storage (CCS) displacing coal by 2050. Additional low-carbon measures include energy efficiency across all sectors, and increased electrification and use of biofuels in transport.

Shukla et al (2008, 2009) [17], [18] also show the major mitigation measures for India to 2050, again for a business-as-usual scenario and also for two different low-carbon scenarios. The first low-carbon scenario (called "carbon tax scenario") considers a more conventional economic development pathway allied to a carbon tax. The second ("sustainability") scenario places a much greater emphasis on sustainability measures, such as dematerialisation, energy efficiency, and sustainable consumption. Both scenarios achieve a deep decarbonisation in India which is commensurate with a 2°C global warming target, although in the carbon tax scenario, there is a very heavy reliance on supply-side technologies such as CCS and nuclear (which together account for over half of all CO₂ reductions, compared to less than 20% of reductions in the sustainability scenario) and much higher costs (with a carbon price of more than \$200/tCO₂ in 2050, compared to about \$120/tCO₂ in the sustainability scenario).

Masseti (2011) [19] uses the WITCH integrated assessment model to explore the cost impacts of different carbon taxes applied to India in the context of a global effort to reduce GHG emissions. The study concludes that – owing to the assumptions made about the steepness of the marginal abatement cost curves in these countries – a carbon tax in excess of \$10/tCO₂ (which would achieve a 25% cut in emissions relative to business-as-usual in India, by 2050) would be excessively costly, and unlikely to be implemented due to adverse economic impacts (which are defined as costs exceeding 1% of GDP in these countries). The modelling does include a scenario in which trading of emissions reductions is allowed such that the marginal cost of abatement equalises across regions, but this scenario is not compared with a scenario which sets India a given emissions target but disallows trading.

None of these long-term studies explicitly assesses the implications of India's low-carbon energy system development in the context of scenarios with and without emissions permit trading. This study argues that India could lower its economic cost of decarbonisation in a world of carbon permit trading, whilst highlighting the additional potential opportunities and challenges of achieving lower fossil fuel reliance.

3 Methodology, assumptions and data

3.1 The TIAM-UCL model

The study uses the TIAM (TIMES Integrated Assessment Model)-UCL global energy systems model [20], which is an integrated assessment model combining the technology rich bottom-up TIMES model, which is the successor to MARKAL, with a climate module to integrate economic activity with energy usage, and resulting emissions and climate change outputs. It is worth noting that the model as run in this study does not utilise the climate module, however. Rather it takes an externally-imposed global CO₂ emissions pathway which has been determined to be broadly consistent with a goal of limiting global warming to 2 degrees Celsius, as explained in Section 2.3.

The model represents 16 different regions of the world, including a distinct region representing India. For each region, energy service demands are projected using socio-economic drivers, and the model determines a cost-optimal level of deployment of energy end-use and energy conversion technologies and resources to meet the energy service demands. Final energy demands depend on energy end-use technology efficiencies and primary energy demands depend on conversion efficiencies and losses.

3.2 Major assumptions in the model

The TIAM-UCL model works by linking the growth in energy demand in each region that it represents to underlying socio-economic factors. For this study a number of different projections have been reviewed in order to arrive at a set of estimates for these factors.

India's growth rate is taken to be 7.7% per annum over the period to 2030. There are some lower estimates than this, for example International Energy Agency (2011) [2] which assumes growth of about 6% p.a. over this period), but also higher estimates, with Verma (2008) [21], Shukla et al (2008, 2009) [17], [18] assuming 8% per annum to 2030, and the Indian Government's Planning Commission including scenarios with 9% growth per annum to 2030 [9]. Between 2030 and 2050, economic growth is assumed to slow to 5% per annum. This compares to about 6% per annum in Verma (2008) [21] and Shukla et al (2008, 2009) [17], [18] and 3% per annum in International Energy Agency (2011) [2] over the same period. Population growth is taken to follow UN central estimates of an increase from 1.2 billion people in 2010 to 1.7 billion in 2050 [22].

In addition to these factors, specific factors for transport, industry and buildings activity growth have been input into the model. This study projects that manufacturing will play a significant role in India's overall future economic growth, with an average growth rate of over 8% per annum to 2030, and a steady decline to about 4% per annum by 2050. These growth rates follow from an assumption that the overall industrial sector constitutes an increasing share of India's economic output to 2050, increasing from a current level of about 30% to a 2050 level of about 35% (based on Shukla et al (2009) [18]). The result is that, over the period to 2050, there is projected to be a 20-fold increase in industrial activity compared to 2005. The 10-fold increase in activity on 2005 levels by 2035 compares closely with TERI (2006)'s estimates for most industry sectors between 2006 and 2036 in a scenario where India grows at 8% overall between 2010 and 2030 [23], as in this study.

India's future rate of transport growth is likely to be very high but also very uncertain. The nature of the vehicle mix in 2050 will be influenced by the degree of continuing uptake of motor-scooters and other two wheelers, as opposed to a shift to cars as incomes increase, as

well as the provision of efficient public transport as urbanisation continues. Overall road transport demand across two-wheelers, cars, vans and HGVs is assumed to increase broadly in line with economic growth. Freight and passenger rail demand is also closely linked to economic growth (with an elasticity of about 0.8 throughout the period to 2050). Air travel is perhaps even more unpredictable, being more of a luxury good, and probably highly income-elastic. We have assumed an increase in domestic and international air travel almost in line with economic growth (assuming a constant elasticity of 0.9 throughout the period to 2050).

Future projections of residential and commercial energy demand have been made by considering TERI (2006)'s projections to 2036 [23] and then extrapolating from there based on relationships between socio-economic growth and energy usage derived from earlier years. In residential buildings, cooking dominates today's energy demand and this could increase by around 30% by 2036. Much more dramatic energy demand increases will come from refrigeration (a five-fold increase to 2036), lighting (a doubling to 2036) and above all air conditioning (a twenty-fold increase to 2036). As such, the TIAM-UCL model projects total residential energy demand to increase by more than 60% by 2035, and to more than double by 2050. Annex A provides details of the activity and energy demand growth in each sector in the reference scenario, in which no mitigation occurs, as explained further in Section 3.3.

It is important to note that models such as TIAM-UCL are designed to answer questions about how national/regional/global energy systems could develop *given* exogenous assumptions about future economic and energy demand growth. As such, these models are not designed for macroeconomic forecasting. Nevertheless, different scenarios of future economic growth can be run in order to explore the differing implications on energy systems in business-as-usual and mitigation scenarios. Section 4 therefore presents sectoral results not just for the central GDP growth estimate case as outlined earlier in Section 3.2, but also includes for comparison purposes results from a scenario incorporating lower GDP growth of 6% per annum to 2030, in order to reflect more recent economic forecast data which sees India's growth rate slowing to 5.6% to 2030 [24], with other sources showing growth at between 5.4% and 7% in the next few years [25], [26]. Resulting changes in energy demand growth in each sector of the economy (industry, buildings and transport) are linked to this GDP growth projection, as well as the central estimate of population growth and household size, using the same elasticity figures as used for the original scenario with the higher rate of GDP growth.

It should also be noted that the scenarios as given do not account for fossil fuel subsidies or other non-market distortions in fuel and technology costs. Whilst in the short term there are several such effects, the approach is focused on the long term energy system transformation that would occur at least macroeconomic cost, and hence does not include such subsidies.

3.3 Details of the scenarios

The **reference scenario** is run to show which least-cost mix of energy technologies India would deploy without any specific policy constraints or preferences, as well as no CO₂ constraints. One aspect of the model is that it will undertake energy efficiency options where these are cost-saving over the long run, as these would be an integral part of a least cost pathway, be it in a high-carbon or low-carbon world. Clearly this will not always be realistic, given the number of political, financial and behavioural barriers which could prevent the uptake of these options (see for example Sorrell (2004) [27], for a detailed review on energy

efficiency barriers). However, this approach also avoids any overly-optimistic estimates of the costs of transitioning from a high-carbon to low-carbon energy system, since it does not rely on cost-saving energy efficiency measures to offset more costly technological options.

The **low-carbon scenario** operates under the constraint that India's per-capita CO₂ emissions reach 1.3 tCO₂ per person per year by 2050, as part of a global pathway which sees global per-capita CO₂ emissions converging to this level by 2050, so that global CO₂ emissions are 12 GtCO₂ in 2050, reducing by an equal annual percentage (3.6% per annum) from a peak of 36 GtCO₂ in 2020. Such a pathway has been demonstrated to be broadly consistent with a 50% chance of limiting global warming to 2°C, assuming a low emissions floor is reached post-2050. The pathway as used in this study focuses only on CO₂ emissions from energy and industrial sources. Total greenhouse gas emissions from the pathway would be about 2 tCO₂e per capita in 2050 [28].

Two variants of the low-carbon scenario are run: the first without any trading of emissions credits between India and the rest of the world; the second with emissions trading from 2020, the year in which emissions reductions begin to deviate from the business-as-usual pathway in India. These scenarios represent two extremes of a range in which a potential global climate agreement could operate from 2020.

4 Results

The results of the modelling analysis are presented so as to address four separate questions, as follows:

- How do the CO₂ emissions in India develop to 2050, in a reference scenario and in low-carbon scenarios in which India participates in an international climate change agreement with an equal per-capita emissions target by 2050, with and without permit trading?
- What are the economic implications of India's low-carbon scenarios with and without permit trading?
- How would India's energy system change in the low-carbon scenarios compared to reference case, and what technological and other challenges would this imply?
- What is the impact of energy system changes on fossil fuel demand in India, in the low-carbon scenarios with and without permit trading, when compared to the reference case?

4.1 CO₂ emissions in reference and low-carbon scenarios

Figure 1 shows the emissions projections in both the reference scenario and the low-carbon scenario without emissions trading, for the central GDP growth case. In the reference scenario, India's emissions increase from just below 2 GtCO₂ in 2010 to almost 8 GtCO₂ in 2050. This quadrupling of emissions is driven by a combination of population increase (up by almost 50% by 2050) and economic development, with GDP per capita increasing over eight-fold between 2010 and 2050. This results in a particularly large increase in (largely coal-based) electricity demand, up about six-fold between 2010 and 2050.

Figure 1: CO₂ emissions in India to 2050 in Reference and Low Carbon (no trading) scenarios

Notes: Emissions for industry, transport and buildings do not include indirect emissions from electricity

Emissions from electricity are negative after 2040, which is why the Industry wedge sits below the time axis

The low carbon scenario shows that the majority of emissions savings, relative to the reference scenario, occur in the electricity generation and industry sectors. In particular, the uptake of biomass-based power generation with CCS makes the electricity sector carbon-neutral by 2040 and carbon-negative by 2050, effectively subtracting emissions from the other sectors of the Indian economy which use electricity. The result of these technologies is that the total emissions for India are relatively flat at about 2.4 GtCO₂ after 2020. The first low-carbon scenario sees CO₂ emissions per unit GDP decrease to 40% below the level of 2005 emissions per unit GDP, by 2020. This compares very optimistically with India's Copenhagen Accord pledge to reduce its GHG intensity by 20-25% by 2020, on 2005 levels. This is a reflection of the fact that the TIAM-UCL model selects the most cost-efficient technologies to meet growing energy demand, which may in reality be very difficult to implement from a policy perspective. Such limitations are shared by other energy-technology models (e.g. Massetti, 2011, using the WITCH model, shows India's business as usual scenario achieving a 45% reduction in CO₂ intensity relative to 2005 levels [29]).

Figure 2 compares the reference scenario with the low-carbon scenario with emissions trading. It can be seen that India undertakes additional emissions reductions relative to the “no trade” low-carbon scenario. India then sells the resulting emissions reductions to other world regions in which emissions reductions are more costly than they are in India. The pattern of emissions reductions relative to the “no-trade” low-carbon scenario bears consideration. There is approximately an equally dramatic reduction in electricity sector emissions by 2050 (though electricity becomes carbon-negative before 2040 when trading is allowed), and greater levels of emissions reductions in the industry and transport sectors. Overall, the additional emissions reductions result in 2050 emissions of 1.7 GtCO₂, compared to 2.4 GtCO₂ in the scenario without emissions trading.

Figure 2: CO₂ emissions in India to 2050 in Reference and Low Carbon (with trading) scenarios

Notes: Emissions for industry, transport and buildings do not include indirect emissions from electricity

Emissions from electricity are negative after 2040, which is why the Industry wedge sits below the time axis

4.2 Impact of emissions trading on marginal abatement cost and economy-wide cost

Without emissions trading, India's marginal cost of abatement, as shown by the shadow price of carbon, rises to around \$150/tCO₂ by 2050 (with all costs in \$2005 US). With trading, however, India undertakes additional abatement up to the international traded price of carbon, which by 2050 reaches about \$240/tCO₂. The development of the carbon price in both of these scenarios is shown in Figure 3. In principle, then, there is a significant opportunity for India to gain financially from undertaking this additional abatement.

Figure 3: Shadow price of carbon in Low Carbon scenarios

It should be noted that carbon price values in general increase in mitigation scenarios, as marginal mitigation costs increase to reflect the increasingly deep emissions reductions required, using increasingly costly low-carbon technologies. However, models such as TIAM-UCL also include assumptions of technology cost reductions over time, which creates the possibility of increasing deployment of some technologies resulting in decreasing carbon prices. This occurrence happens temporarily in the “no-trade” scenario in the period 2035 to 2040, although the total energy system cost relative to the reference scenario continues to increase, because the increasing volume of mitigation more than offsets this temporary per-unit mitigation cost reduction.

Figure 4 confirms this, by showing the annual additional energy system cost of the low-carbon scenarios in India when compared to the Reference case, as a share of India's future GDP as projected in the central GDP scenario. By 2050 the annual additional cost of the low carbon scenario without carbon permit trading would be about (US\$2005)30 billion, compared to the scenario where trading is allowed. This is equivalent to about 0.15% of 2050 GDP, or about 15% of the total 2050 mitigation cost without carbon permit trading. In addition, there would not only be an economic benefit to India of this lower cost of mitigation, but to the world as a whole, since it implies other countries (those with more stringent emissions reductions targets, given their current higher levels of emissions) are purchasing emissions reduction permits from India in preference to undertaking additional mitigation domestically, which would be more costly.

In the emissions trading scenario, the period 2020 to 2025 sees India undertaking relatively little mitigation to meet its own emissions reduction target but, with a lower mitigation cost than the global average during this period, international trading of emissions means that India undertakes emissions reductions to create carbon permits which are then traded to other countries at a net economic gain. Energy system costs subsequently increase relative to the reference case as India's emissions reduction effort deepens after 2025.

Figure 4: Additional energy system cost as share of India's GDP in Low carbon scenarios, relative to Reference case

The GDP cost of mitigation from a business-as-usual or reference case of between 7 and 8 GtCO₂ in 2050 to a low-carbon scenario of less than 2 GtCO₂ in 2050, compares reasonably closely to analysis by Shukla et al (2008) [17], who estimate a GDP loss of 1.35% in 2050 to achieve an approximate 1.3 GtCO₂ in India by 2050 (in their "carbon tax" scenario), compared to a base case of about 6.5 GtCO₂ in 2050.

4.3 Energy system differences between the reference case and low-carbon scenarios

In this section the major differences between the reference and low-carbon scenarios are presented and discussed, in order to understand what drives India's decarbonisation and what technical challenges this presents.

4.3.1 Power sector

India has a significant challenge ahead if it is to develop a power generation system that effectively underpins its future economic development whilst keeping CO₂ emissions under control. However, given the high projected growth in demand for electricity over the next few decades, the majority of the power generation technology in operation in 2050 is likely to be new build, which means India is in a good position to choose a low carbon pathway.

Figure 5 shows the electricity generation mix in the Indian power sector in 2010 and 2050 in the reference and low carbon scenarios with and without trading (labelled "Trade" and "No Trade"). In addition, the "Trade" low-carbon scenario power generation mix is also shown for the lower GDP growth case. The "Trade" scenario has significantly higher electricity demand than the "No Trade" scenario. This indicates that additional electrification of the economy (combined with decarbonisation of electricity) is one of the measures undertaken by India in undertaking mitigation beyond its emissions target so as to benefit from carbon permit trading. In fact (as shown in Figure 7 in Section 4.3.2) this additional electrification is most marked in the industrial sector, where electricity replaces gas to provide process heat in several industrial sub-sectors. The lower GDP "Trade" scenario has a similar power generation mix to the central GDP "Trade" scenario, but as expected a significantly smaller electricity demand, since by 2050 the Indian economy is some 40% smaller than in the central GDP growth case.

Figure 5: Electricity generation mix in India in 2010 and 2050

Achieving any of these (Reference and Low-carbon) scenarios would present India with challenges. Currently, electricity makes up just 12% of final energy consumption in India, compared to around 21% in OECD countries [2]. Almost half of all houses do not have access to electricity [30]. As a result of high economic growth, government-led rural electrification programmes (especially the “Rajiv Gandhi Grameen Vidyutikaran Yojana” Electrification Programme [31], which aims to provide electricity access to all rural households), increased industrial activity and demand for white goods (refrigerators, washing machines, dishwashers, televisions) in the residential sector, electricity demand has been increasing rapidly in recent years. Between 1995 and 2008, electricity demand grew at an average annual rate of 5.3% [2], with a chronic supply deficit meaning that in recent times around 15% of peak power demand has not been met [6]. Despite a significant improvement in plant load factors over recent years from around 52% in the 1970s/1980s, to now around 79% (in line with OECD countries [32]), the electricity sector in India is still inefficient by international standards. Coal plants are still largely sub-critical and there is a high electricity consumption of auxiliary equipment of 8.3% compared to 5.7% for EU plants, largely as a result of poor operation and maintenance of equipment. Transmission and distribution losses in India are also very high at around 25% compared to less than 10% in developed countries and China [2]. So even in the Reference scenario, in which electricity generation remains dominated by coal, the challenge of increasing installed capacity, plant and transmission efficiency remains. As a part of the National Mission on Enhanced Energy Efficiency [33], India aims to employ a number of tools to support and drive the deployment of energy efficient technologies, including market-based mechanisms, innovation and fiscal instruments.

In the “No-trade” low-carbon scenario, CCS plays a major role in decarbonising the power sector. By 2050, almost all unabated (i.e. non-CCS) coal is phased out, whereas installed capacity of coal with CCS reaches 158 GW by 2050. CCS is also applied to gas and biomass with installed capacities of 98 GW and 111 GW by 2050, respectively. Installed capacity of renewables and nuclear is also high amounting to 73% of non-fossil fuel power generation capacity. In the “Trade” low-carbon scenario, gas with CCS, nuclear and solar (photovoltaics and concentrated solar power) are selected as additional low-carbon generation sources, all with zero or near-zero operational emissions factors. Coal with CCS is not selected further as lower cost emissions reductions are available from gas with CCS (which has lower residual emissions than coal with CCS). In practice, India might prefer to combine its more readily available coal resources with CCS if there are restrictions on gas supply.

Several technology-specific challenges must be overcome in order to develop and deploy this range of low-carbon technologies. Considering renewables, scale-up of solar PV will require an enhancement of indigenous manufacturing capabilities of silicon wafers [34], grid development to areas where wind and hydro could be deployed [35], [36], as well as a full assessment of offshore wind resources [37]. Grid development to support nuclear is also necessary, since many future reactors are planned to be in coastal regions due to high water consumption of some designs [38], and India’s limited uranium resources mean it will rely heavily on foreign supplies unless it successfully develops its thorium-fuelled reactor programme [39], [2].

Perhaps most significantly, it is highly uncertain whether such a large role for CCS in India is feasible. For coal CCS, given the poor efficiency performance of current coal fired power stations in India, the additional efficiency penalty associated with CCS would be prohibitive.

A major overhaul of the current coal power plant and significant penetration of super- and ultra-super critical technology would be required before CCS could feasibly be deployed. More generally, there is currently no political will behind CCS in India as it is perceived that the cost of development of the technology should be borne by others [40].

Figure 6 shows the investment in power sector technologies (in GW terms and also US \$2005) in the Reference scenario, and also in the “Trade” low carbon scenario, which has the most aggressive investment in power sector technologies of all of the low-carbon scenarios.

Figure 6: Annual investment in electricity generation in Reference and Trade scenarios

Figure 6 indicates that the annual investment in power generation is set to grow considerably from about \$10 billion currently to about \$30 billion by 2025, in order to service the growing electricity needs of India as its population and wealth increases. From 2025 to 2030 the low-carbon scenario annual investment needs begin to diverge from those of the Reference scenario, with significant investments in solar power, nuclear and gas generation leading to an increase in annual power generation investment about twice the rate in the Reference scenario (in which the coal generation continues to dominate power generation investments). This indicates that in order to achieve the most aggressive low-carbon scenario, India and the international community would need to mobilise significant additional capital for power sector generation investments in the period starting approximately a decade from now. Until this point there is no significant trend break in the power sector generation investment profile, and it is important to note that additional electricity generation investment will be required worldwide in a low-carbon scenario where increasing electrification of energy in the industry, transport and buildings sectors occurs. The mobilisation of additional power sector capital investment is, therefore, a shared challenge globally.

4.3.2 Industry sector

Energy consumption in the Indian industrial sector was 6.5 EJ in 2010, as shown in Figure 7. India is the world’s fourth largest consumer of energy for industrial activities. Almost 60% of this is used in the chemicals and iron and steel sectors. Due to data reporting issues, a large fraction (32%) of industrial energy use is unspecified and lumped together as ‘other industry’. Currently, around 28% of industrial energy demand in India is supplied by coal. Unlike developed countries, biomass supplies the next largest share of energy (22%). This is largely for combustion in small boilers. Gas supplies 19%, oil also supplies 19% and electricity makes up the remaining 12% [41].

Figure 7: Industrial sector energy demand in India in 2010 and 2050

Industrial energy demand is projected to increase more than five-fold to 2050 in the reference scenario, reaching 35 EJ in 2050. Energy demand in the low-carbon scenarios is slightly lower – at about 30 EJ in both, implying an energy efficiency improvement of about 13-14%, mainly as a result of fuel-switching to more efficient forms of energy usage. In the low GDP growth case, industry energy demand is some 40% lower than in the central case, reflecting assumptions about India’s considerably smaller economy by 2050 should this lower growth path be followed.

In the reference scenario to 2050, coal increases to 33% of total energy demand, and gas to a similar share, as shown in Figure 6. By comparison, in both low-carbon scenarios, coal is almost completely phased out by 2050. In the “no-trade” low-carbon scenario this is achieved largely through switching the majority of coal to gas (making up 64% of demand by 2050) and the remainder of energy is supplied by electricity, oil and some biomass. A very large driver of this switch is India’s iron and steel sector, which sees an almost total reliance on coal-based process heating from the reference scenario shift to predominantly gas in the “not-trade” low-carbon scenario. The “trade” low-carbon scenario sees similar switching from coal, but in contrast to the “no-trade” low-carbon scenario, this scenario sees coal switching to a mixture of gas, electricity and CHP heat (as a by-product of increased captive electricity generation). Increased electrification of the industrial sector in the “trade” versus “no trade” low carbon scenario is largely driven by the “other” industrial sector, which is made up of lower energy-intensity processes (such as textiles, machinery and food). Fuel input into this sector shifts from gas to electricity as additional mitigation is undertaken. This shift is shared in the lower GDP case, as shown in Figure 6, which attains a similar fuel mix (dominated by electricity) by 2050. It should be noted that a large share of the “other” industry category is not directly specified for historical data, so more detailed analysis of this sector is required to assess the full feasibility of electrification of this sector.

In 2010, total CO₂ emissions from the Indian industrial sector (including direct and indirect emissions) were 633 MtCO₂, making up 38% of total CO₂ emissions from India. Of this, direct emissions (including process emissions) were 423 MtCO₂. In the reference scenario it is projected that CO₂ emissions from industry would increase to 4.2 GtCO₂ in 2050 (54% of total CO₂ emissions in 2050). By contrast, the “trade” and “no-trade” low-carbon scenarios see much lower industrial emissions in 2050, at 1.2 GtCO₂ and 0.9 GtCO₂ respectively.

In order to achieve the emissions reductions described in this section, India will have to build capabilities in a number of new technologies to allow the projected fuel switching to lower-carbon sources of heat, for which it will require leadership and assistance from OECD countries [42].

4.3.3 Transport sector

Road transport (especially cars and light good vehicles) is projected to demand the majority (about 90%) of final energy in the overall transport sector by 2050. As shown in Figure 8, the reference scenario sees petrol and diesel dominating the transport fuel mix, although for light goods vehicles natural gas becomes the most cost-effective fuel, dominating in 2050. In the “no trade” low-carbon scenario, there is no significant change to this fuel mix, in large part because India is deemed to achieve a least-cost decarbonisation pathway via low-carbon electricity and electrification of the buildings and industry sectors, leaving sufficient carbon space for transport to continue emitting CO₂. One consequence of this is that there is no large-scale electrification of the transport sector, since according to the cost projections of electric vehicles in the TIAM-UCL model, these are relatively more expensive options. In addition, there is no large-scale take-up of biofuels in the transport sector, since as a relatively limited resource it is prioritised in the power generation, buildings and industry sectors, avoiding relatively large energy conversion losses associated with biomass to biofuel transformation processes. However, one major low-carbon technology shift that does happen is the increasing penetration of hybrid cars from the 2030s, which account for about one third of total vehicle (car) km by 2050.

The “trade” low-carbon scenario sees little change over and above the “no-trade” scenario, with the exception that in most sectors there is a downward shift in demand resulting from the higher carbon price (see Figure 3) which raises the costs of fossil fuels. The lower GDP growth case suggests this reasonably unchanged transport sector fuel mix would be independent of the future economic growth scenario.

Figure 8: Road transport sector energy demand in India in 2010 and 2050

In the reference case emissions are projected to increase from 185 MtCO₂ in 2010 to 1.4 GtCO₂ in 2050, whereas in the “no-trade” low-carbon scenario, emissions reach 1.2 GtCO₂ in

2050 and in the second low-carbon scenario 1.1 GtCO₂ in 2050. In summary, emissions reductions in other sectors provide some headroom for transport emissions to continue to grow, which is to be expected from India given its relatively early stage of development, its strong projected transport growth, and the assumed higher costs of low-carbon vehicle options such as electric and fuel cell vehicles.

4.3.4 Buildings sector

As a result of the assumptions outlined in Section 2.2, the TIAM-UCL model projects total residential energy demand to more than double by 2050 in the central GDP growth case, as shown in Figure 8. In the lower GDP growth case, residential energy demand still rises substantially, and is about 30% lower than the central GDP growth case by 2050, in spite of the economy being about 40% smaller – this reflects the fact that energy demand is in significant part driven by population growth, which is assumed to increase in line with UN central estimates in both the central and low GDP growth cases. Looking to 2020, the major planned investments in buildings low-carbon technologies are in lighting and appliances, which could together save between 15% and 30% of electricity against a reference in which present technologies are used [43]. By comparison, the scenarios in this model assume that even in the reference case there would be an increased penetration of lower-energy technologies, which over the long run would be cost-saving. As such, the low-carbon scenarios achieve only a 3-5% saving in electricity demand against the reference case by 2020.

Figure 9 shows that the residential buildings sector energy mix by 2050 is largely unchanged in the reference and low-carbon scenarios. It is already a relatively low-carbon sector with its predominant use of biomass. Future increased electrification of cooking, cooling and heating, as well as significant electricity demand growth as a result of the uptake of household appliances, is projected to be seen in all three scenarios, with the low-carbon scenarios seeing this growth go in concert with the deep decarbonisation of electricity.

Figure 9: Residential buildings sector energy demand in India in 2010 and 2050

The commercial buildings sector, as shown in Figure 10, is projected to see increasing substitution of gas (for heating and cooking) with increasingly decarbonised electricity, with the “trade” low-carbon scenario experiencing a near-complete substitution by 2050, an outcome shared in the lower GDP growth scenario.

Figure 10: Commercial buildings sector energy demand in India in 2010 and 2050

The increased use of decarbonised electricity in the buildings sectors mean that the low-carbon scenarios have very low CO₂ emissions in 2050. Whereas the reference scenario has buildings emissions of over 2 GtCO₂ by 2050, both low-carbon scenarios would see net savings from carbon-negative electricity generation slightly offsetting direct emissions by 2050, such that overall emissions are about -0.07 GtCO₂ in both (central GDP case) low-carbon scenarios by 2050.

Achieving even the reference scenario, with its assumed uptake of efficient lighting and appliances, is not a given in reality. For example, the penetration of more efficient lighting would require funding models to allow access to higher up-front cost technologies [11]. Enforcement of energy efficient building codes is likely to be complicated with many State-level initiatives having to implement this [43]. Above all, the reliance on electrification will require very significant infrastructure investment to ensure that households can be increasingly served by either grid or off-grid electricity.

4.4 Implications for fossil fuel demand

Figure 11 shows the primary fossil fuel demand in India in the reference and low-carbon scenarios. Immediately obvious is the substantial demand reduction in coal when moving to the “no-trade” low-carbon scenario. This is further decreased in the “trade” scenario, with a shift away from coal with CCS power generation to (even lower carbon intensity) gas with CCS power generation. This could be advantageous to India, given that access to high quality

coal is problematic. Although this overall continued reliance on coal in the reference scenario is shared with several other reference or business-as-usual projections of India's future energy demand (e.g. [2],[16],[17],[44]), it is unlikely to represent an optimal energy development pathway, even ignoring climate change considerations, because of energy security, environmental and social concerns [11]. Observing the central and lower GDP growth case for the “trade” scenario, it is apparent that the overall energy mix develops in a similar way regardless of the growth level.

Figure 11: Fuel demand in reference and low-carbon scenarios

One consequence of this switch away from coal is that the low-carbon scenarios show an increased demand for gas over time, resulting from coal to gas fuel switching in the power generation and industrial sectors. This is more pronounced in the “trade” low-carbon scenario, where (compared to the “no-trade” scenario) a significant increase in gas with CCS power generation more than offsets the decrease in gas-based industrial heating (because of further electrification of industrial heating). An implication is that it is unlikely that India would be able to avoid gas import dependency (with greater dependency in the “trade” scenario) in the coming decades unless any unconventional reserves could be tapped. India's potential shale gas reserves have not yet been assessed, although the US agreed in 2010 that the US Geological Survey would help with this assessment. Development of India's unconventional gas reserves could, therefore, significantly change the picture [2].

There would be relatively little change in oil demand between the scenarios, as a result of relatively little mitigation in the transport sector, the main user of oil in the form of petrol and diesel. India has long recognised that its (still growing) level of oil imports “raises serious concerns about India's energy security, our ability to obtain the oil [it] needs, and the impact of constrained supply and the consequent increase in oil prices on [its] economy.” [9]. In addition, by far the largest share of India's energy subsidies, at more than \$20 billion per year and the largest of any country other than the major oil exporters, are on oil, exacerbating

India's oil import dependency [5]. It may therefore be attractive to India to further develop low-carbon vehicles which further reduce its oil dependence, even if these are a relatively high cost option. Of course, the removal of oil subsidies is first required in order that this makes economic sense.

In summary, the picture provided by the low-carbon scenarios is a strategically important one for India. There is clearly a possibility to lower coal demand, which could be highly beneficial given constraints on coal quality, production and transport. However, increasingly deep decarbonisation, at least according to the scenarios presented here, implies an increasing reliance on gas, which raises questions of securing adequate supplies either through pipeline and LNG imports or domestic unconventional resources. Oil demand would be largely unaffected by a low-carbon pathway unless the transport sector were more deeply decarbonised, through increased uptake of unconventional vehicles.

5 Discussion and conclusions

India could reduce its emissions from a projected 7.8 GtCO₂ in 2050 to 2.4 GtCO₂ (as part of a global per-capita emissions level of 1.3 tCO₂/capita by 2050), through a range of low-carbon technologies. Without emissions trading, the economic cost of doing so would be about (US2005) \$200 billion per year by 2050 – equivalent to just over 1.1 % of India's projected 2050 GDP. If trading were allowed, India could undertake additional abatement and sell this effort to the rest of the world, at an economic gain of about \$30 billion annually by 2050. This would reduce India's mitigation cost by about 0.15% of 2050 GDP, to just less than 1% of 2050 GDP.

In the low-carbon scenarios, the greatest contribution to emissions reductions comes from the electricity sector, where coal-dominated power generation in the reference scenario is replaced by a mix of nuclear, renewables (principally wind and solar) and coal and gas with CCS, as well as CCS with biomass, to give a net negative emissions electricity sector. Overall electricity demand would increase when trading is allowed, principally because of the increased electrification of heating in the industrial sector. However, even in this trading case, which requires the most aggressive increase in electricity generation, the major acceleration in total electricity generation investment would not occur until the mid-2020s, which provides a useful window of opportunity for India and the international community to arrange for the financing of this increased electricity sector investment.

In both low-carbon scenarios, buildings would see widespread electrification of cooking and heating (particularly in the commercial sector) and continued usage of (increasingly efficient) biomass in the residential sector. Allowing trading would see almost complete electrification in the commercial sector, as opposed to a mixture of electrification and gas usage (for cooking and water heating) in the no-trade scenario.

Transport would contribute relatively little to overall emissions reductions according to these scenarios, since according to the cost database in the modelling, the decarbonisation options such as electric vehicles are relatively expensive. Nevertheless, uptake of hybrids would lead to still-significant emissions savings in the sector in both low-carbon scenarios. The low-carbon scenario with trading sees little change over and above the scenario without trading, with the exception that there is a downward shift in demand resulting from the higher carbon price which raises the costs of fossil fuels.

Energy efficiency does not feature heavily in these scenarios, since the cost minimisation nature of the modelling implies that cost-saving energy efficiency measures are taken up in

the reference case. It is unlikely this would happen in reality, given that there will need to be a number of social, political and operational actions to support the take-up of technologies which in many cases may more than pay back over a few years, but which have higher up-front costs.

The low-carbon scenarios would see future coal demand fall significantly compared to the reference case. However, gas demand would increase in both low-carbon scenarios, and allowing trading would see this demand increase further by 2050, as gas with CCS power generation is taken up under the higher carbon price. Total oil demand (including crude oil and refined oil products, for use as fuel and in the chemicals sector), according to these scenarios, is not projected to change significantly. A lower GDP growth case for the low-carbon scenario with carbon permit trading shows that the total and sectoral energy mix in the low-carbon scenario is, broadly speaking, independent of the future GDP growth trajectory.

In summary, the economic cost of mitigation towards a global equal per-capita CO₂ emissions target by 2050 could be eased through carbon trading. At the same time, coal demand could be reduced dramatically. In these scenarios the demand for gas does increase as a result of greater mitigation, which does raise a strategic issue for India in terms of its securing access to supplies from overseas or through indigenous (possibly unconventional) reserves. The major additional mitigation measures undertaken in order to create carbon credits to sell overseas are increased electrification of the industrial and buildings sectors.

It is important to note that in any future scenario of India's economic development, whether for low-carbon scenarios or a reference scenario, one of India's greatest challenges will continue to be how to develop an economically and technically functional electricity generation, transmission and distribution system which can respond to growing electricity demand. In the low-carbon scenarios in which wind and solar resources play a large role, the challenge will be compounded by the need to consider where to site such generation, so that it can either be connected to grid infrastructure in demand centres in very different regions, or form part of off-grid and mini-grid applications. This will require very detailed electricity grid system planning, accounting for land, water and other resources which could become increasingly scarce. Such considerations form the basis for a number of ripe areas for further research, at increasingly regional and local levels within India, so that an effective low-carbon strategy that achieves long-term reductions can be implemented over the next few years.

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Annex A Reference case activity and energy demand in India's end-use sectors to 2050

	Activity driver for energy service	2010	2020	2030	2040	2050
Industry	Chemicals-PJ	1,496	3,136	5,943	9,868	13,707
	Iron and Steel-Mt	30	63	120	199	277
	Pulp and Paper-Mt	5	11	20	34	47
	Non-ferrous metals-Mt	1	2	3	6	8
	Non Metals-PJ	642	1,346	2,551	4,236	5,884
	Other Industries-PJ	3,465	7,264	13,766	22,857	31,747
	Industrial and Non Energy Uses-PJ	735	1,352	2,488	4,017	5,439
	Other non-specified - PJ	361	664	1,222	1,972	2,671
Buildings - commercial	Cooling-PJ	27	52	98	164	229
	Cooking-PJ	333	636	1,213	2,024	2,823
	Space Heat-PJ	30	46	70	98	123
	Hot Water-PJ	52	99	188	313	437
	Lighting-PJ	294	560	1,067	1,781	2,485
	Office Equipment-PJ	57	109	208	348	485
	Refrigeration-PJ	30	58	111	185	258
Buildings - residential	Cooling-PJ	83	203	400	680	945
	Clothes Drying-PJ	3	8	18	34	52
	Clothes Washing-PJ	6	16	36	68	103
	Dishwashing-PJ	3	8	18	34	52
	Other Electric-PJ	177	481	1,072	2,035	3,104
	Space Heat-PJ	179	221	242	261	276
	Hot Water-PJ	522	635	704	757	790
	Cooking-PJ	3,873	4,547	4,903	5,169	5,325
	Lighting-PJ	1,179	3,123	6,777	12,500	18,357
	Refrigeration-PJ	100	273	607	1,153	1,759
Transport - aviation	Domestic Aviation-PJ	82	162	317	540	771
	International Aviation-PJ	124	243	476	810	1,157
Transport - road	Bus-Bv-km	22	35	50	64	74
	Commercial Trucks-Bv-km	56	116	243	435	644
	Three Wheels-Bv-km	52	125	242	363	446
	Heavy Trucks-Bv-km	28	59	124	222	328
	Light Vehicle-Bv-km	64	134	281	503	744
	Medium Trucks-Bv-km	29	60	125	224	331
	Car-Bv-km	134	466	847	1,154	1,388
	Two Wheels-Bv-km	123	309	715	1,291	1,899
Transport - rail	Rail-Freight-PJ	70	129	237	382	526
	Rail-Passengers-PJ	89	164	303	489	673
Transport - marine	Domestic Internal Navigation-PJ	50	80	128	186	237
	International Navigation-PJ	2	3	5	7	9

Bv-km = Billion vehicle kilometres

PJ = Petajoules

Mt=Megatonnes