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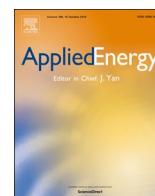Abhyankar, Nikit
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Modeling India's energy future using a bottom-up approach

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HIGHLIGHTS

- India's forecasted economic growth suggests that emissions will almost quadruple by 2050.
- Our analysis shows that India can achieve its NDC target with currently implemented policies.
- India's emissions intensity in 2030 will be 36% below 2005 levels in baseline scenario.
- Much of the emission growth will come from the industry sector.
- Four industry subsectors are projected to represent 78% of total direct emissions in 2050.

ARTICLE INFO

ABSTRACT

India and China are the world's most populous nations, but they have experienced a very different pattern of economic development. As a result, India currently contributes less than one-quarter of the amount of China's carbon dioxide (CO_2) emissions. However, India's forecasted economic growth suggests that those emissions will almost quadruple, with much of this rise coming from the industry sector. Whole-economy scenarios for limiting global warming suggest that direct CO_2 emissions should decrease significantly, but leave unanswered the question of how this can be achieved by real-world policies. This study describes a bottom-up model that can be used to assess the impacts of emissions mitigation policies and the linkages between the physical drivers and energy growth of India's key industries. It focuses on capturing the main physical drivers of this growth, to identify and prioritize the subsectors to address and develop sustainable, low carbon pathways to support economic growth. This analysis shows that India can achieve its Nationally Determined Contribution (NDC) while achieving substantial economic growth using its currently planned policies. The study describes in detail the methodology and underlying assumptions that are needed by policy makers to inform targeted policy interventions and provide a baseline scenario in the case of no major new technology breakthroughs and no new adopted policies.

1. Introduction

India and China are two of the most populous countries in the world, each home to nearly a fifth of the world's population. However, their contributions to global carbon dioxide (CO_2) emissions differ substantially. India contributes only 6% of global CO_2 emissions, while China contributes 28% [1]. India's per capita emissions today (1.5 metric tons per capita [t/ca]) equal those of China 35 years ago. India is at an early stage of economic development and is poised to grow rapidly over the next few decades. India's economy has consistently been among the top five fastest-growing economies for the last four years as measured in terms of gross domestic product (GDP) and the trend is expected to continue, favored by recent policy reforms, urbanization, and planned public infrastructure investments [1,2]. As a result, a growing middle class is emerging with aspirations for a better quality of life [3,4]. As household incomes rise, consumers will purchase more

energy-using assets like appliances and cars and demand access to better infrastructure [5]. The industry sector will grow in tandem to meet the increased demand of manufactured goods and raw materials essential for infrastructure development.

The energy needed to support this growth is likely to constitute a large portion of the increase in India's greenhouse gas (GHG) emissions unless new low carbon pathways are identified and promoted. As new investments are made by the private and public sectors in purchasing, building, and constructing energy-using equipment, unique opportunities exist to move away from carbon-intensive technologies to low carbon options to avoid the lock-in effect of long-life inefficient technologies. Understanding and better analyzing the growth of India's subsectoral energy consumption is therefore critical to effectively identifying potential opportunities for adopting low carbon pathways. Therefore, models that can identify low carbon options for investment and describe climate impact benefits at an end use level are necessary

tools to support policy decisions and promote low carbon development. India's forecasted economic growth provides the ideal opportunity to demonstrate how low carbon development can be achieved while simultaneously improving living standards.

In its Nationally Determined Contributions (NDCs), India pledged to reduce Gross Domestic Product (GDP) emissions intensity[1] by 33% to 35% by 2030 from its 2005 level and to achieve about 40% cumulative electric power installed capacity from non-fossil fuel based energy resources by 2030.[2] India has taken bold actions to achieve these targets. For example, the Bureau of Energy Efficiency (BEE) has initiated a number of energy efficiency initiatives in the areas of large industry emissions reduction targets, standards and labeling, commercial buildings codes, and demand side management in agriculture/municipalities [6,7]. However, questions remain on how these demand sector specific policies translate to meeting India's emissions intensity target. To achieve its renewable targets, India is running one of the largest renewable energy capacity expansion programs in the world and has made the development of solar energy technologies a national mission to establish India as a global leader in solar energy.[3] India's NDC also calls for enhanced international actions on technology development and transfer to accelerate low carbon technology diffusion in the country. However, while the NDC commitments show significant strides toward a low carbon pathway, many more actions and investments are needed to achieve 2 °C and 1.5 °C pathways. The Paris Agreement calls for countries to submit mid-century strategies by 2020 [8]. India has yet to identify the low carbon investments required to drive the energy transformation necessary to limit global warming. In addition, the international community has yet to identify how climate funds and other support can help to accelerate this transition.

This paper's purpose is to describe in detail the development of a bottom-up model to assess the largest source of emissions growth in India over the next 35 years and the linkages between the physical drivers and energy growth of India's key economic sectors. The paper focuses on emissions from the energy sector which represents 80.1% of all GHG in India and which is by far the fastest growing source of emissions [9].

The main research question being addressed is how energy consumption and CO_2 emissions will grow if India follows an economic growth trajectory pathway similar to the one China followed over the last 35 years. The paper focuses on capturing the main physical drivers of this growth in order to identify what subsectors need to be addressed on a priority basis to develop sustainable low carbon pathways to support the forecasted economic growth. This paper presents detailed assumptions on subsectoral activity and energy intensity to develop energy consumption calculations in the model. The originality of the paper is to provide detailed energy intensity indicators at the end use level that can be used by policy makers in setting energy efficiency initiatives and link them to India's overall emissions intensity reduction goal of 33% by 2050. By providing a comprehensive economy-wide bottom-up accounting of sectoral energy demand the analysis is able to answer important questions regarding how India will meet its NDC emissions intensity commitments. Only a transparent and detailed end-use analysis can provide this type of assessment and answers these questions. Additionally, the paper also provides the sectoral energy demand decomposition equations that can be used in the LEAP simulation modeling platform to replicate this type of analysis. Finally, the

originality of the model presented herein is also to take a physical accounting approach of material production that interlinks growth in activity across sectors.

The goal is to use the results from this analysis to form a solid and transparent baseline on which low carbon pathways can be built to prioritize actions.

The paper first provides a literature review of recent modeling approaches developed to estimate the future growth in energy consumption in India. In the next section, the methodology of the bottom-up model is described, followed by a section describing the detailed assumptions made to establish a baseline scenario. Finally, the authors show the results of the modeling approach being considered.

2. Literature review

There are two main approaches to project energy consumption and GHG emissions [10–13]. One makes use of aggregate macro data at the country or sub-national/state level to estimate the income elasticity of consumption by econometric analysis over a relatively long period of time. These models include computable general equilibrium (CGE) models and are often referred to as "top-down" models. The other approach uses micro-level data that reflects individual technologies and household behavior. These models are referred to as "bottom-up" engineering models and enable a detailed assessment of technology investments. While top-down models analyze an energy-demand relationship through a reduced-form equation, bottom-up models examine the ownership and the use of energy-consuming products and consider end-use technology scenarios from an engineering point of view. Previous work has shown the limited ability of economic models to forecast technologies trends [14]. For example, Creutzig et al. [15] shows the inability of these models to forecast solar photovoltaic deployment. Anderson and Peters [16] question the overrepresentation of supply-side technologies such as bioenergy with carbon capture and storage (BECCS) and afforestation as solutions. The potential of demand-side low carbon technologies is often underestimated [17] because end-use technologies are not included in top-down assessments.

With India's forecasted economic growth, many economy-wide models have been developed to forecast how such growth will affect India's carbon footprint. These include government forecasts [18], multilateral organizations [19–21]; and nonprofits [22,23]. In addition, sector specific models have been developed to forecast how sectoral demand growth will contribute to India's increasing emissions [24,25,21].

The NITI Aayog India Energy Security Scenarios (IESS) 2047 is an open source web-based scenario tool that simulates alternate energy pathways based on predetermined levels of effort to deploy clean energy technologies [18]. It is a tool for policy makers to better understand the impact of different policy options. However, the tool does not "forecast" likely trajectories and technology options are provided in broad level categories. The International Energy Agency (IEA) developed an India Energy Outlook which analyzes future pathways of India's energy consumption up to 2040 based on a computable general equilibrium model. The IEA provides some results at the subsectoral level, but does not provide detailed information on technology assumptions.

The United Nations Environment Program (UNEP) uses AIM/End-Use, a bottom-up optimization model that integrates a detailed breakdown of end-use technologies [20]. The key outcomes include the identification of technology options for designing near-term (2015–2020), medium-term (2020–2030) and long-term (2030–2050) policies. The end-use energy demands are introduced exogenously and technology costs are the main drivers that change output results. The Research and Energy Institute [22] also uses a bottom-up optimization model based on the MARKAL system and models a business-as-usual (BAU) and a 100% renewable energy scenario for India. The model results identify energy efficiency as a key approach to gain savings

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(~59%) by 2051. Dhar et al. [21] modeled three scenarios for India's low carbon transformation: a Nationally Determined Contribution (NDC) scenario, a 2 °C scenario, and a NDC + 2 °C scenario using the ANSWER/MARKAL energy optimization model. The time horizon for the model was medium term (until 2030) and long term (2030–2050). The main conclusion of the paper is the need to adopt a socio-economic approach to energy efficiency instead of using it simply as a technological intervention in order to achieve transformational change toward a low carbon transition. While these models are based on a bottom-up representation of technologies, they rely on optimization of technology costs to model demand projections. In the optimization approach the share of any technology is based on its cost relative to the cost of all other technologies. However, the information on investment and operating costs are not always available and often a source of uncertainty, notably in mid-term scenario analysis. In addition, optimization models neglect the implication of market imperfections and local circumstances that contribute to investment decisions.

Others have looked at emission reduction scenarios using global models that provide results for India as a region [26,27] with limited details on the end use sectors. Finally, Rajan [28] developed a LEAP model for India in 2006 focusing on the impact of climate policy on energy access. While the study provide interesting results on household energy demand, little is provided in terms of energy end-use demand, technology penetrations or energy efficiency assumptions.

The Lawrence Berkeley National Laboratory (LBNL) India Demand Resources Energy Analysis Model (DREAM) takes a different approach. It is a simulation model which provides a descriptive quantitative projection of energy demand based on exogenously determined drivers and technologies penetration with the objective to model observed and expected decision-making that does not necessarily follow a cost minimizing pattern. LBNL DREAM is also a stock accounting model where the lifetime of equipment is taken into account to determine technology change. Alternative scenarios are built to model the impact of policy or program interventions. LBNL DREAM model also comprises a physical accounting of material production that is interlinked to the demand for material based on increased technology penetration as explained in the Methodology section below.

In addition to these economy-wide modeling efforts there have been a few sector specific modeling efforts in India, particularly in the transport and buildings sectors. The Alliance for Energy Efficient Economy [23] conducted a bottom-up market sizing exercise for energy efficiency in India to identify key opportunities for Energy Service Companies (ESCOs) in the commercial building, industry, agriculture, and municipality sectors. Detailed information is provided on the technology options and their penetration in the economy. The key conclusion is that there is a potential market of between $14 billion and $18 billion for ESCOs. The National Transport Development Policy Committee of the Planning Commission of India developed subsectoral demand projections of the transport sector up to 2032. However, they modeled energy demand simply as an outcome of projected demand without any technology considerations. Dhar et al. [21] modeled the transport sector by modeling sectorwide transport demand using the ANSWER-MARKAL framework and then decomposing this demand into specific subsectors such as intra-city demand. The residual demand was allocated to other subsectors based on historical trends.

Efforts in India to develop detailed end-use technology-based models have increased significantly in recent years. Those models provide interesting discussions and insights for understanding India's medium and long-term energy use and CO_2 emission trajectory. However, a description of sectoral activity variables is often missing and end-use sector-level assumptions for buildings, industry or transportation or analysis of adoption of particular technologies and policies are generally not provided in energy modeling efforts. This is an important omission for energy analysts and policy makers who need to understand detailed underlying assumptions to be able to interpret results [29]. Energy consumption is driven by the diffusion of various types of equipment; the performance, saturation, and utilization of the equipment has a profound effect on energy demand.

Rapid decarbonization of the economy requires modeling that can capture the potential trends in new low carbon technology deployment at the end-use level. End-use sector-level results for buildings, industry or transportation, or analysis of the adoption of particular technologies and policies are essential for informing mid-century strategies to limit global warming to 2 °C or 1.5 °C. This outlook is based on the LBNL India DREAM model, a bottom-up model with primarily physical drivers for energy activities for technologies and end uses. The modeling framework is similar to the LBNL China DREAM model [30]. Unlike most of the existing models and medium to long-term studies on India's energy outlook, this model addresses end-use energy demand characteristics including sectoral patterns of energy consumption, change in subsectoral industrial output, trends in saturation and usage of energy-using equipment, technological change (including efficiency improvements) and links between economic growth and energy demand.

3. Methodology

The development of the model required the research team to gather detailed data on activity variables that drive energy consumption such as car ownership, refrigerator saturation, steel production, and surveys to assess energy use at the end-use level. Activity variables are generally measured in physical terms (tons of steel or number of passenger-kilometers) or in terms of consumption (e.g., per vehicle or dwelling) [31,32]. Data on energy use are then combined with data describing activities to form intensity of energy use. Data were organized in an accounting and scenario-based modeling platform called LEAP (Long-range Energy Alternative Planning System). LEAP is a scenario-based software tool for integrated energy-environment and greenhouse gas mitigation analysis developed by the Stockholm Environment Institute [33].

The time scale of DREAM is on the mid-century time scale which is better suited for analyzing demand side technology turnover and provide insights to policy makers on the impacts of their actions in the short term.

The following subsections describe the decomposition of energy use between drivers and end use energy intensity for each sector and present original equations that can be used in LEAP modeling for conducting similar bottom-up economy wide analysis.

3.1. Macroeconomy

Changes in energy demand in the model are in part a function of (1) driver variables, e.g., GDP, population, household size and urbanization rate, which were determined exogenously and included in the model and (2) energy intensities. The following equations provide the modeling framework developed to be used in LEAP. The variable E represents energy consumption in each sector.

3.2. Agriculture

Food grain production was used as the main driver of activity in the agricultural sector and aspects of agricultural practices were used to estimate how energy intensity potentially will evolve over time. This is because grain, which includes rice, wheat, coarse cereals and pulses, represents a major output of the agriculture sector (67% in 2015 in India) [34]. It is also an indicator closely monitored by the government of India to measure the level of domestic primary food production. Energy consumption in the agricultural sector was divided into energy use for pumping water per hectare of cultivated land irrigated and energy use for powering farm machinery per hectare of cultivated land.

Eq. (1) shows the decomposition used:

$$E_{Agr} = \sum_k (IL \times Pu_k \times IPu_k + L \times Fa_k \times IFa_k) \qquad (1)$$

where

- k = fuel type
- IL = irrigated arable land
- Pu_k = number of pumps per irrigated arable land hectare by fuel type (electric or diesel pump) in number per hectare
- IPu_k = average intensity of energy use per pump type *k*
- L = arable land in hectares
- Fa_k = number of farm tractors per arable land hectares by fuel type in number per hectare
- IFa_k = average intensity of energy use per tractors type *k*.

3.3. Industry

The industry sector is divided into two major subsectors: mining and manufacturing. The manufacturing subsector is further divided into thirteen energy intensive industries and eleven non-energy intensive industries.

The energy intensive industries include: steel, cement, ethylene, ammonia, aluminum, paper, plastics, glass, copper, caustic soda, soda ash, and calcium carbide. Energy demand is calculated as energy use for the production of physical material in each energy intensive industry multiplied by the energy intensities. Hence, physical energy intensities in terms of energy use per ton (or other unit) were used for the energy-intensive industries. For the most energy intensive industries, energy intensity was further broken down by process to differentiate the energy intensity of technologies and to project a gradual technology shift. For example, the iron and steel industry is structured according to three main routes: (1) a blast furnace – basic oxygen furnace route, (2) direct reduction of iron ore in an electrical furnace, and (3) a scrap-based electrical arc furnace route. Similarly, the glass industry is disaggregated into production of flat glass versus container glass because these processes have different energy intensities. The aluminum industry is further disaggregated into production of alumina, primary aluminum, and secondary aluminum produced from recycled materials.

For the non-energy intensive industries and the mining sector, energy consumption was analyzed using the total value added. The non-energy intensive sector includes food, beverage and tobacco, wood products, textile, printing, medicine, rubber and plastics, metal products, machinery, transport equipment, electric and electronic equipment, and others that cover all remaining manufacturing sectors.

Eq. (2) summarizes the industry sector decomposition for both the energy-intensive and the non-energy-intensive industry sectors.

$$E_{IN} = \sum_k^{OPTION} \left(\sum_c^{OPTION} Q_c \left(\sum_c P_c \times EI_{k,c} \right) + \sum_v G_v RI_{v,k} \right) \qquad (2)$$

where

- k = fuel type
- c = commodity type (steel, cement, ethylene, ammonia, aluminum, paper, plastics, glass, copper, caustic soda, soda ash, or calcium carbide)
- Q_c = quantity of energy intensive commodity *c* produced
- P_c = industrial process used per commodity type
- $EI_{k,c}$ = average intensity for producing energy intensive industrial commodity *c* in gigajoules (GJ) per metric tonne (or other physical unit)
- v = non-energy intensive industries (food, beverage and tobacco, wood products, textile, printing, medicine, rubber and plastics, metal products, machinery, transport equipment, electric and electronic equipment, others)
- G_v = value added of *v* industries

Table 1
Drivers of Material Intensity Production.

Material	Drivers
Steel	Building floor space (rural, urban, commercial), railways, vehicle, steel finished products, infrastructure and net exports
Cement	Building floor space (rural, urban, commercial), roads, railways, urban paved area, industrial construction and cement net exports
Ethylene	Per capita demand for plastics and population
Ammonia	Sown area and fertilizer intensity
Aluminum	Vehicles, additional power generation capacity, new urban construction and other aluminum products
Paper	Per capita demand for paper and population
Glass	Flat glass: vehicles production, building construction, vehicles Container glass: per capita demand for container glass
Copper	New urban construction, additional power generation capacity and vehicles

- $RI_{v,k}$ = energy intensity for *v* industries

Growth in the most energy intensive industry sectors is driven by material demand from urbanization and infrastructure development. For example, building construction represents the largest driver for cement production accounting for 78% in India [35]. In the case of steel, building and infrastructure construction represents 62% of steel consumption and automobile represents 10% [36]. The model was developed to take into account the linkages that exist between the consumer sectors' material demands and the productive sector's material production. For each sector, material productions are derived from demand from other sectors and average material intensity values. For example, cement production is a factor of projected annual construction of urban, rural and commercial floor space construction area, highway and paved road area, and railway length, combined with material intensity values to determine the resulting demand. The equations originally developed by Fridley et al. [37] were used and adapted with ratios that were found in the literature to represent India material intensity for each material end use. References on default values for material intensity were taken from Hasanbeigi et al. [38] when no India-specific data could be found. Table 1 provides the details of these linkages and how material production was calculated for each sector. Net exports of these major energy intensive industrial products are small, ranging from −15% in the case of pulp and paper to 4% in the case of steel and were therefore held constant at the base year level. Ammonia production was modeled as a function of sown area and fertilizer intensity, while ethylene and paper production were based on population and per capita demand for plastics and paper, respectively.

3.4. Transport

In the transport sector final energy is employed in a large variety of modes and technologies to provide two primary services: the transport of passengers and the transport of goods ultimately representing a single service: *mobility*. Transport demand is driven by macroeconomic drivers such as GDP, urbanization, and population. For the purpose of estimating final energy demand from transport, the sector was divided into passenger transport and freight transport demand. This was then further divided into transport modes for both passenger and freight as follows:

- water (inland and coastal waterways)
- air (national and international air transport)
- rail (intracity and intercity mass transit)
- road transport (further divided into cars, taxis, motorcycles and buses)

The physical energy intensities used are given in terms of energy use per kilometer (km), per passenger-km or per ton-km. This can be

summarized as shown in Eq. (3):

$$E_{TR} = \sum_t^{OPTION} \sum_r^{OPTION} \sum_j^{OPTION} \sum_k^{OPTION} (V_{t,j,k} \times K_{t,j} \times EI_{TR,t,r,j,k}$$
$$+ Q_{t,r} \times S_{t,r,k} \times EI_{TR,t,r,j,k}) \quad (3)$$

where

- t = transport type (passenger, freight)
- r = mode type (road, rail, water or air)
- j = vehicle technology class (passenger car, multi-purpose vehicle, two-wheeler, three-wheeler, bus, heavy truck and light truck)
- k = fuel type (motor gasoline, diesel, kerosene, coal and electricity)
- $V_{t,j,k}$ = number of vehicles of type j of transport service of type t using k fuel type in millions of units
- $K_{t,j}$ = distance driven from vehicle of type j of type t in km per year
- $EI_{TR\ t,r,j,k}$ = average energy intensity of energy type k for transport service of type t and in mode r in km per liter of fuel used or in MJ per (passenger-km-year) and MJ per (tonne-km-year)
- $Q_{t,r}$ = quantity of transport service of type t in mode r in passenger-km and tonne-km
- $S_{t,r,k}$ = share of transport services t, delivered through the mode r employing the fuel k.

3.5. Residential buildings

Residential energy provides numerous services associated with household living including space cooling, water heating, cooking, refrigeration, lighting, and powering a wide variety of other appliances. Energy demand is shaped by a variety of factors including location (both geographic and urban vs. rural) and climate. In developing countries such as India it is important to divide households into rural and urban locales due to the different energy consumption patterns found in these locations. Within the locales, end uses were broken out into air conditioning, appliances, cooking and water heating, lighting, and a residual category. The end uses were further broken out by technology. Each end use was assigned appropriate devices and fuel types with diffusion rates and energy efficiencies based on survey data and literature research. Eq. (4) shows the decomposition of energy use in the residential sector that serves for modeling its growth:

$$E_{RB} = \sum_m^{OPTION} \left[\frac{P_m}{F_m} \times \left(\sum_j S_{j,m} \times UEC_{j,m} + E_m \sum_i^{OPTION} L_{i,m} \times Ca_{i,m} \times H_{i,m} \right) \right.$$
$$\left. + P_m \times \sum_k^{OPTION} (CW_{m,k} + LK_{m,k}) \right] \quad (4)$$

where

- m = locale type (urban, rural)
- P_m population in locale m
- F_m = number of persons per household (family) in locale m
- j = type of appliance or end-use device
- $S_{j,m}$ = penetration of appliance or device j in percent appliance owned by household (values in excess of 100% would indicate more than one device per household on average)
- UEC_j = energy intensity of appliance j in MJ or kilowatt-hours (kWh) per year
- E_m = electrification rate in locale m
- i = type of lighting bulb (incandescent, fluorescent, LED)
- $L_{i,m}$ = number of lighting bulb of type i per household in locale m
- $Ca_{i,m}$ = power of bulb of type i in locale m
- $H_{i,m}$ = hours of use of bulb of type i in locale m
- k = fuel type
- $CW_{m,k}$ = cooking and water heating energy use of fuel k per capita per month in locale m in MJ/ca/month

- $LK_{m,k}$ = Lighting energy use of fuel k per capita per month in locale m in MJ/ca/month.

3.6. Commercial buildings

Energy use in the commercial buildings sector was based on building types and energy use per square meter of floor space. Six major categories of buildings were identified based on their use. Each category was then further divided into two or more sub-categories of buildings based on their area, number of occupants or energy consumption. Each sub-category was assigned a particular energy intensity based on available performance and survey data. Eq. (5) describes the decomposition of energy use in the commercial sector:

$$E_{CB} = \sum_k^{OPTION} \left(FS_{2010} \times EI_{2010,k} + \sum_s^{OPTION} FS_{new,s} \times EI_{new,k,s} \right) \quad (5)$$

where

- k = fuel type
- s = building type (retail, hotel, private office, government office, other)
- FS_{2010} = total remaining 2010 stock service floor area in square meters (m^2)
- $EI_{2010,\ k}$ = intensity of energy use per fuel type k of building 2010 stock
- FS_{new} = annual new construction of service floor area in each building type in m^2
- $EInew_{k,s}$ = intensity of energy use per fuel type of new construction of building types.

4. Assumptions: Energy drivers

The main motivation for the development of the baseline scenario presented in this paper was to determine the level of energy and emissions that will result if, over the period from 2015 to 2050, India accelerates its economic growth similar to the economic growth China experienced over the last 35 years. The methodological approach taken, which consisted of dividing energy consumption into activity drivers and energy intensity values, allowed us to consider the diffusion levels of energy-using equipment among the population and the level of material production and compare them with economies at a more advanced stage of development.

While many pathways are possible and no path is certain, the goal of this baseline scenario analysis is not to determine the most likely future, but to provide information for consideration on how energy and emissions are likely to grow if no major technological breakthroughs are introduced and no new major mitigation policy adopted. The goal is therefore to provide a plausible storyline and transparent assumptions to better understand the implications of future technological investments that will be made in India up to 2050 years if the announced policies are implemented and sustained.

In this section, we describe the activity assumptions that will drive future energy demand in the baseline scenario. For each subsector and end-use considered the current level of activity in India is provided, as well as the level projected in 2050 and the comparative level of China today. In most cases the activity level of India in 2050 is projected to reach the level of China today. In other cases activity drivers were projected based on official sources and experts' projections to take into account country specificities.

4.1. Macroeconomy

Population and Gross Domestic Product (GDP) are two fundamental activity drivers that influence energy demand from all the sectors. Between 1980 and 2015 India's population increased at an annual

Table 2
Macroeconomy Driver Projections.

Drivers	Units	India 2015	China 2015	India 2050
Population	millions	1294	1364	1659
GDP per capita	constant 2010 US$	$1758	$6497	$10,179
Urbanization	%	32.7%	55.6%	50.3%
Urban household size	person	4.1	2.88	2.88
Rural household size	person	4.8	3.95	3.95
Commercial buildings	billions of m^2	1.0	11.9	3.6
Urban residential buildings	billions of m^2	3.3	22.9	21.5

average growth rate (AAGR) of 1.8% and that rate is projected to slow to 0.8% on average to reach 1.66 billion in 2050 according to United Nations (UN) projections [39]. GDP grew at an average rate of 6.5% per year [1] and is projected to accelerate to 7.4% per year in the next five years [1,2]. Table 2 summarizes the main assumption for the macroeconomic drivers of energy use. The urbanization rate remains low at 34% (2015), but the UN projects urbanization to reach 50.3% by 2050—close to the actual urbanization rate of China (55.6%) in 2015. We assume a 7% annual increase in GDP to 2030 and then a rate of 5% until 2050. Projections of value added for each of the remaining manufacturing sectors, as well as for the mining sector, are based on assumptions from the Planning Commission's Manufacturing Plan up to 2024–25 extrapolated to 2030 [40]. From 2030 to 2050 growth rates are projected to slow and be reduced by half.

In addition, other factors, such as the diminution in household size and increase in housing floor space represent major drivers of energy demand. A shift toward smaller household size increases the total number of households and hence the number of appliance sales and energy services demanded.

The number of persons per household in India is, on average, 4.1 persons in urban areas and 4.8 persons in rural areas, and has declined over time, particularly in urban areas [41]. The average floor space is 40 m^2 in rural India and 39.2 m^2 in urban India. Projection of urban and rural household size and floor space in 2050 are based on China's current (2015) levels. In the case of the commercial building floor space projection assumptions from the Alliance for an Energy Efficient Economy [23] were used because the estimates are consistent with projected growth by the IEA.

4.2. Agriculture

Agriculture plays a critical role in India's economy with 54.6% of the population engaged in agriculture and allied activities that contribute 17.4% to the country's gross value added in 2016–17 [34]. At the same time, the sector consumed 17% of the total electricity (in 2012) and 12% of the total diesel in the country (in 2011) [18]. Irrigation pump-sets and tractors account for most of the energy requirement in the sector [18].

However, in India, mechanization within the agricultural sector is very low with 19% of the total potential market for tractors being exploited [18]. Therefore, the main drivers of agricultural energy use are agricultural production, the quantity of land used, and the penetration of the two key technologies in use: pumps and tractors. Table 3 summarizes the drivers for agriculture in India and also compares them to the statistics in China [42] in 2015.

A projection of future food grain production was adapted from Indian government plans and expert estimates. The penetration of electric pumps stock was forecasted using sales data and historical stock data [43]. We also assumed that by 2050, 95% of all the deployed pumps would be electric. Pump size was assumed as 4 kW throughout the modeling period. The demand for pumping will increase due to a combination of decreasing

Table 3
Drivers for Agriculture.

Drivers	India 2015	China 2015	India 2050
Food grain production (million tonnes)	275	621	
Arable land (million hectares)	141.5	166	141.5
Irrigated arable land (million hectares)	63.6	66	99.1
Number of electric pumps (millions)	26.1	9.3	59.5
Number of farm tractors (millions)	4.1	23.1	16.5

water resources and increasing food demand so we assume pump penetration per hectare to double between now and 2050.

The energy intensity of diesel pumps is assumed to be constant at 3730 kWh per device since the focus of policy interventions is on pump electrification. The energy intensity of electric pumps was assumed to increase from 5987 kWh per device in 2010 to 11,500 kWh per device in 2050. This is because the overall irrigated area is assumed to grow from 40% in 2010 to 70% in 2050 and the duration of irrigation is also expected to grow. Combining these trends with the increase in total pumps drives our assumption that pump energy intensity will increase until 2050.

The tractor stock was projected assuming no energy efficiency improvements or demand side incentives to improve energy efficiency. Also, as the size of the average land holding keeps reducing, the tractor stock will keep increasing and the average energy intensity of each tractor is assumed to remain constant at 263 MWh per tractor.

4.3. Industry

The main driver of energy use in the industrial sector is the level of material produced in each energy intensive industry. Historical trends show that the importance of industry within an economy varies by its stage of economic development. At an early stage of development, the share of the agriculture sector in the economic activity is the largest. With income growth, the share of the industry sector increases to satisfy a growing demand for infrastructure such as roads, railways, buildings, power grids, etc. As development continues, the need for basic infrastructure saturates and consumer demand for services becomes the dominant sector.

Projections of material production in energy intensive industries are described in the Methodology section above. Table 4 provides results of the material production embedded modeling for India in 2050 and compares it with China in 2015. According to the embedded material modeling, production of most material remains below China's levels of today, except for paper and plastic, which are driven by population growth.

Energy intensity data were taken from a large span of literature documentation. India's government, through the Bureau of Energy Efficiency, launched a massive energy efficiency program targeting energy intensive sectors in July 2012. The Perform Achieve Trade (PAT) program assigns specific energy consumption (SEC) reduction targets to

Table 4
Material Production.

Drivers	India 2015 (million tons)	India 2050 (million tons)	China 2015 (million tons)
Steel	95.5	457.6.0	808.4
Cement	283.5	1127.7	2400.1
Aluminum	2.4	13.0	32
Plastics	14	79	65
Ammonia	13.5	19.6	46.0
Paper	14.9	132.7	111.2
Glass	4.7	38.5	64
Copper	0.8	14.6	6.8
Caustic Soda	2.5	5.9	28.5
Soda Ash	2.6	10.2	25.7
Calcium Carbide	0.2	0.1	26.4

Table 5
Selected Energy Intensive Average Energy Intensity.

Branches	India 2015 GJ/t	India 2050 GJ/t
Pulp and Paper	26.4	22.4
Ammonia	13.3	11.1
Ethylene	169.8	155.9
Cement	3.2	2.9
Glass	9.5	9.2
Iron and Steel	27.6	21.3
Aluminum	68.3	49.3

Table 7
Projected Growth in Vehicle Ownership (2015–2050).

Drivers	Unit	India 2015	India 2050
Car ownership	vehicles/1000 people	17	163
Motorcycle ownership	vehicles/1000 people	96	567

industries referred as Designated Consumers (DCs). The first phase (2012–15) covered 478 DCs from six energy intensive sectors—aluminum, cement, chlor-alkali, fertilizer, iron and steel, and paper and pulp—as well as two additional sectors: thermal power plants and textiles. Achievement from the first cycle reached 362 PJ of energy savings which was an overachievement of about 30% in comparison to the original assigned targets. At present, the PAT program is being implemented on a rolling cycle basis and has expanded to cover more DCs that represent about 70% of India's total industrial energy consumption. The development of this program has allowed the collection of detailed data on each sector's structure, the average energy intensity, and other parameters for low carbon development such as the share of recycling material and more. We used the following sources: Krishnan et al. [44] for the iron and steel industry in India, CII [45] for the cement industry with forecast of energy intensities to 2050, Verma et al. [46] for the aluminum industry, Deloitte [47] for the chemical industries, CII [48] for the pulp and paper industries, and [49] for the glass industry. Many of these reports were supported by the Bureau of Energy Efficiency and the Indian Shakti Sustainable Energy Foundation to assist designated consumers in meeting their PAT targets. Data were also taken from Sathaye et al. [50]. These reports provide details on the current energy intensity per type of processing technology and also provide details on current best practices for energy intensity. For example, the iron and steel subsector is further divided in processing technologies: 45% Blast Furnace-Basic Oxygen Furnace (BF-BOF) route, 31% Induction Furnace routes, and 24% Electric Arc Furnace route. Each route has different fuel usage requirements and energy intensities. Average intensity projections for 2050 were based on assuming that the average stock of technology in use will reach current available best practices. Table 5 provides average energy intensity values for selected energy intensive subsectors.

For the non-energy intensive industries, data on fuels consumed by type of fuel for each of the four-digit industry classes were taken from the Annual Survey of Industries [51] and were used to calculate 2015 energy intensity. An annual autonomous energy efficiency improvement of 1% was assumed as a baseline scenario.

4.4. Transport

India is rapidly urbanizing, leading to significant unplanned

development in newly created agglomerations. Since these developments are unplanned they lack a well-established public transit system. This will act as a strong driver for the demand of taxis and rickshaws, particularly those supported by app-based services like Uber and Ola. Passenger transport demand from motorcycles and private cars was estimated using historical vehicle registration and sales data [52]. The demand from buses and rail transport was estimated from GDP projections since prior research has clearly established the strong correlation between GDP and demand for passenger mobility [20]. In addition, existing and upcoming policy targets for vehicle efficiency, such as the fuel efficiency standards for cars and light-duty trucks [19] and public infrastructure spending such as the Smart Cities Mission [53], were also taken into account. As a result of these assumptions the total passenger transport demand of India is expected to rise from 5503 billion passenger kilometers (bpkm) in 2015 to 43,316 bpkm in 2050. A snapshot of these assumptions is documented in Table 6.

As shown in Table 7, vehicle ownership is projected to rise from 17 cars per 1000 people in 2015 to 163 cars per 1000 people in 2050. This is still significantly less than the rate of ownership in countries like the United States (809 cars per 1000 people) and Germany (568 cars per 1000 people). However, motorcycle ownership is expected to rise faster, from 96 motorcycles per 1000 people to 567 motorcycles per 1000 people, due to the relative affordability of motorcycles.

Similarly, GDP and freight transport demand have an almost one-to-one correlation [54]. That, combined with the establishment of dedicated freight corridors (DFC) for rail freight, is expected to drive significant growth in demand for both passenger and freight rail services. Additionally, the ambitious goals of road network expansion from the government will help support steady growth of road freight traffic. As a result, total demand for freight transport is expected to rise from 3568 billion tonne kilometers (btkm) in 2015 to 34,077 btkm in 2050.

4.5. Residential buildings

Given that most of the appliance stock is yet to be purchased in India, a large quantity of incremental electricity demand will occur to 2050 in the residential sector. A recent detailed analysis from Abhyankar et al. [43] was used to model the growth in penetration of electric equipment in the residential sector and to assess the unit energy consumption. The analysis looked at the following electricity-consuming appliances and equipment: air conditioners (ACs), refrigerators, TVs, ceiling fans, lights, and electric water heaters. The analysis assessed the energy performance of the current stock and new sales based on information collected from the Bureau of Energy Efficiency on
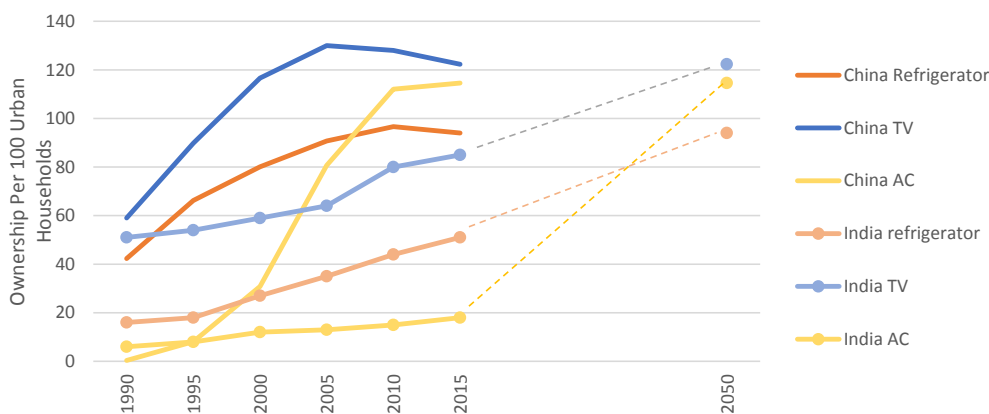
Table 6
Energy Intensity and Penetration Assumptions for the Passenger Transport Sector.

Mode	Unit	India 2015	India 2050
Heavy duty diesel bus (Intracity)	million ton of oil equivalent/vehicle km	138.58	133.81
Diesel taxi	million ton of oil equivalent/vehicle km	82.46	79.62
Gasoline car	million ton of oil equivalent/vehicle km	63.3	45.46
Electric car	million ton of oil equivalent/vehicle km	8.11	7.83
Diesel 3-wheelers	million ton of oil equivalent/vehicle km	29.45	28.4
Gasoline motorcycle	million ton of oil equivalent/vehicle km	20.5	19.8
Electric motorcycle	% of vehicle kilometers	2.4	29
Electric 3-wheelers	% of vehicle kilometers	2.43	19.05
Electric cars	% of vehicle kilometers	1.5	19
Electric taxis	% of vehicle kilometers	1.89	23.8

Fig. 1. Historical and Projections of Urban Household Equipment Penetration in China and India, 1990–2050. Source: Historical data from China yearbook and India NSSO surveys, several years. Projections based on India LBNL DREAM model.

minimum energy performance standards. The India National Sample Survey Organization (NSSO) surveys provide a wealth of information regarding energy consumption in the Indian residential sector based on micro level household data collected across the country. Fig. 1 shows the historical saturation of three major types of household equipment in urban Chinese and Indian households. The figure also shows that assumptions of India ownerships in 2050 match China's 2015 levels.

Minimum energy performance standards in India are mandatory for the following residential equipment: fixed-speed room ACs, refrigerators (frost free and direct cool), fluorescent tube lights, distribution transformers, electric water heaters, and TVs. Standards for variable speed ACs and ceiling fans are under consideration. Beyond BEE's labeling program only a handful of utilities and ESCOs have run appliance efficiency programs and such programs have seen mixed success. One of the most notable programs is the UJALA light-emitting diode (LED) program by the Energy Efficiency Serviced Limited (EESL). Between 2015 and 2018, EESL distributed more than 300 million LED lamps across the country and has built the critical momentum for full market transformation [55]. With demand aggregation and global competitive bidding EESL was also able to reduce the procurement cost of LEDs by over 80% in two years. Currently, EESL is undertaking similar programs for other key appliances such as fluorescent tube lights (FTLs), ceiling fans, super-efficient ACs, and agricultural pumps, albeit at a small or pilot scale. Table 8 summarizes unit energy consumption assumptions of the appliances in India's residential sector for the baseline scenario.

NSSO data collected allow detailed estimations of the quantity of fuel consumption by households in urban and rural areas [56]. Detailed data on quantity of fuels used per capita and per monthly per capita consumption expenditure (MPCE) class was used to determine the quantity of fuel used per household and to project fuel switching as household income increases. Although efforts have been made to assign energy consumption to each category, in many situations they overlap. In the model, water heating was considered to be a single category with cooking, unless an electric appliance is used in which case we included

this use in the Appliance section. As shown in Fig. 2, a substantial difference in final energy use between urban and rural areas arises because rural households use much more inefficient fuels such as fuel wood for cooking. Hence, their requirement to provide energy services equivalent to urban households is much higher. However, rural households consume much lower quantities of modern fuel like liquefied petroleum gas (LPG) and electricity.

4.6. Commercial buildings

The growth of the commercial building sector is forecasted as a result of the significant growth in the service sector in India which contributed 53.8% of the gross value added in 2016 [1]. Existing floor space in use, based on commercial floor space, was estimated using data available from the economic census [23,57]. A recent analysis from Vishwanathan et al. [20] was adapted to develop projections about the growth in the commercial buildings sector. To model commercial building growth buildings were categorized based on their area, type of use, ownership, and number of occupants, as shown in Table 9.

The above categorization was developed based on available data from various governmental and non-governmental sources which were then organized to develop projections. Energy intensity data were sourced from the BEE's Commercial Building Energy BenchmarksBEE [58] and the NITI Aayog's dataset for the 2047 Calculator [18].

4.7. Power

With a total installed capacity of 358 GW (GW) in 2015, India has one of the largest electricity transmission and distribution systems in the world [59]. The model capacity additions were based on the current government target of increasing the total renewable energy installed capacity from about 34 GW in 2015 to 175 GW by 2022, with solar power capacity targeted to increase from 3 GW (2015) to 100 GW (2022), wind power capacity to increase from 23 GW to 60 GW, and small hydro and biomass capacity to increase from 7 GW to 15 GW

Table 8
Residential Equipment Energy Performance Projection in the Baseline Scenario.

Appliance		UEC 2015 (kWh/yr)	UEC 2050 (kWh/yr)
Lamps	Incandescent/CFL moving to LED (~120 lm/watt [W])	72	20
FTLs	T-8 + magnetic choke moving to T5 + electronic choke, LED	95	44
Fans	Single phase induction motor ceiling fan	120	100
Televisions	Old stock is CRT; new sales are mostly LCD/LED	146	80
Water Heaters	Electric geysers	240	146
Refrigerators	Direct cool/frost free; significant efficiency gain through efficient compressors and gaskets	399	200
Air Conditioners	Old stock is fixed speed; moving toward inverter ACs	1992	1269

Note: UEC: Unit Energy Consumption; LCD/LED: liquid crystal display/light-emitting diode; CRT: cathode ray tube; FTL: fluorescent tube lights; AC: air conditioners.
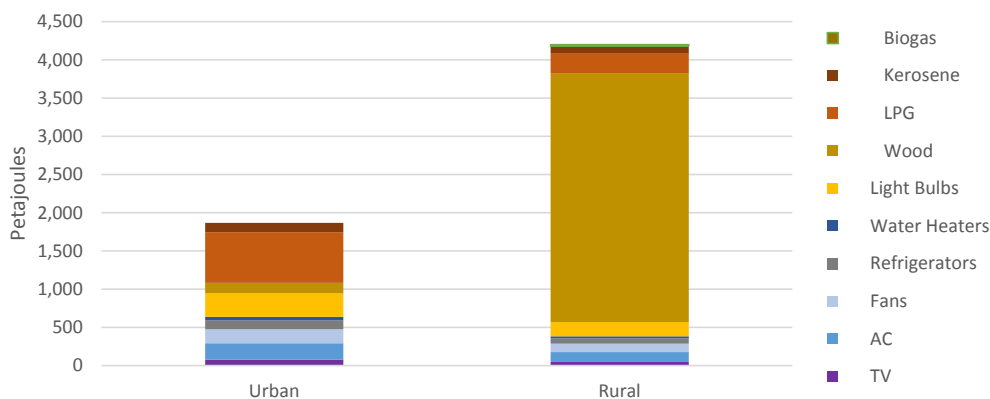
Fig. 2. 2015 Urban and Rural Household Final Energy Consumption in India.

Table 9
Classification of Commercial Buildings.

Building Sector	Key Parameters	Categories
Office buildings	Number of employees	Public, private
Hospitals	Number of beds in public and private hospitals	Government (rural/urban), private
Educational buildings	Number of public and private schools, colleges and universities	Schools, colleges, universities
Retail	Number of stores per 1000 people	Malls, large stores, small stores
Hotels	Number of hotel rooms	1 star to heritage hotels[*]
Places of worship	Number of places of worship	Small to large, based on floor area

* Heritage hotels are hotels operating in palaces/castles/forts/lodges/residence of any size built prior to 1950.

[60]. The projected capacity additions are shown in Fig. 3 and include the NDC objective of 40% of renewable energy by 2030. The model follows a merit order dispatch that prioritizes renewable energy to meet demand.

Until 2010 almost all Indian coal-fired plants used subcritical technology with an average efficiency of around 30%, compared with 36% in China [61]. The first supercritical plant in India was commissioned in 2012 and it is expected that plants using this technology will account for an increasing share of new coal plants being developed. The model therefore assumed an improved efficiency to 40% by 2040 in the Baseline Scenario.

The Power sector represents 97% of the energy use in the transformation sector in India's energy balance [61]. The remaining energy consumption is used to produce coal and petroleum products. In the India DREAM model, coke ovens and blast furnace are accounted in the iron and steel sector and refineries are included in the industry sector under the category "Other".

5. Result insights

5.1. Base year results comparison

Results for 2015 were compared with data from MOSPI and the IEA [62,61] as shown in Fig. 4. For several reasons the breakdown by sector varies significantly across data sources. First, biomass consumption is an estimation of the quantity of wood used by rural and urban households and primary survey results can vary. In our case, we used the NSSO 2001 survey and our estimation of biomass is lower than the IEA by 50% which explains our lower estimate of total energy use for the residential sector. Second, many fuels are sold without any record of the end-user category that ultimately consumes them. For example, this is the case for some petroleum products like LPG, kerosene, and diesel oil. Therefore, the government energy statistics do not provide a detailed sector breakdown and a large quantity is reported in a "non-specified category" included in the industry sector. In these cases, a bottom-up approach is the most effective way to allocate and estimate fuel use by
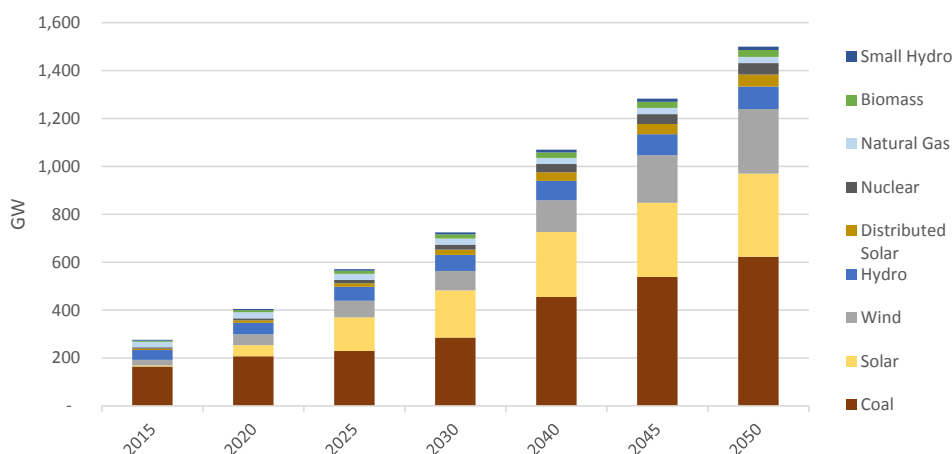

Fig. 3. Projected Capacity Additions in GW in India in the Baseline Scenario, 2015–2050.
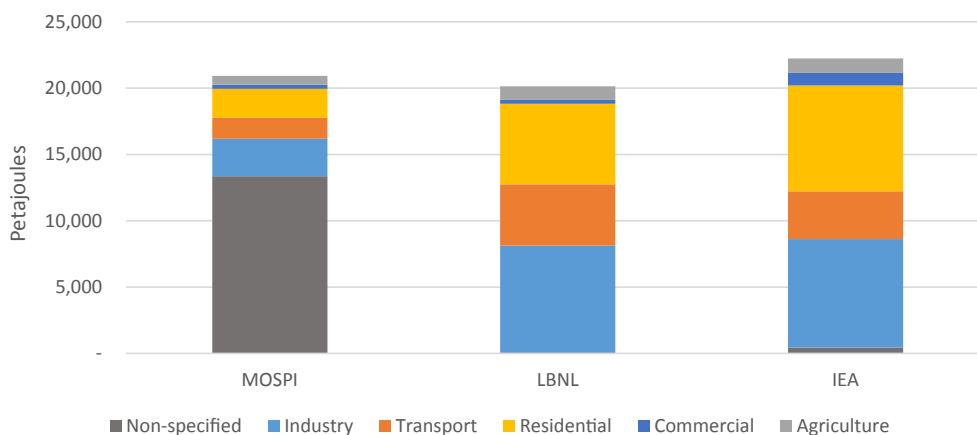
Fig. 4. India 2015 Final End-Use Energy Consumption Base Year (2015) Comparison with MOSPI and IEA.
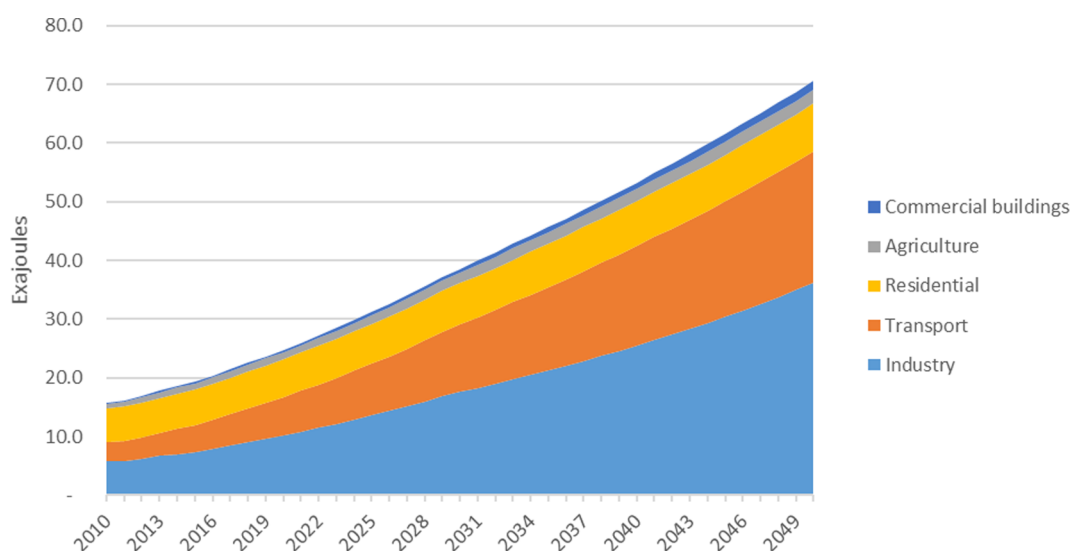

Fig. 5. Final Energy Consumption Projections for India's End-Use Sectors in the Baseline Scenario, 2015–2050.

sector. For the industry sector, we used the industry annual surveys which allowed us to obtain a more granular breakdown of energy use per subsector than reported in the national energy balance statistics.

5.2. Economy-wide results

India's final energy demand is expected to grow significantly between 2015 and 2050, driven mainly by the industry and transport sectors (Fig. 5). The demand for energy service is expected to grow significantly in the residential sector because of the increased penetration of equipment and greater need for useful energy for cooking and water heating. However, the final energy consumption will not grow significantly in this sector because of the transition from biomass to LPG for cooking in the rural sector as well as the expected efficiency gains
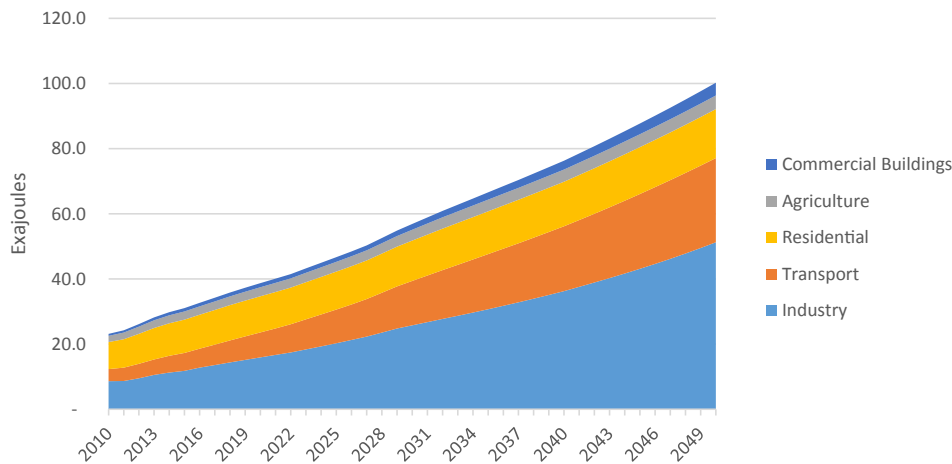
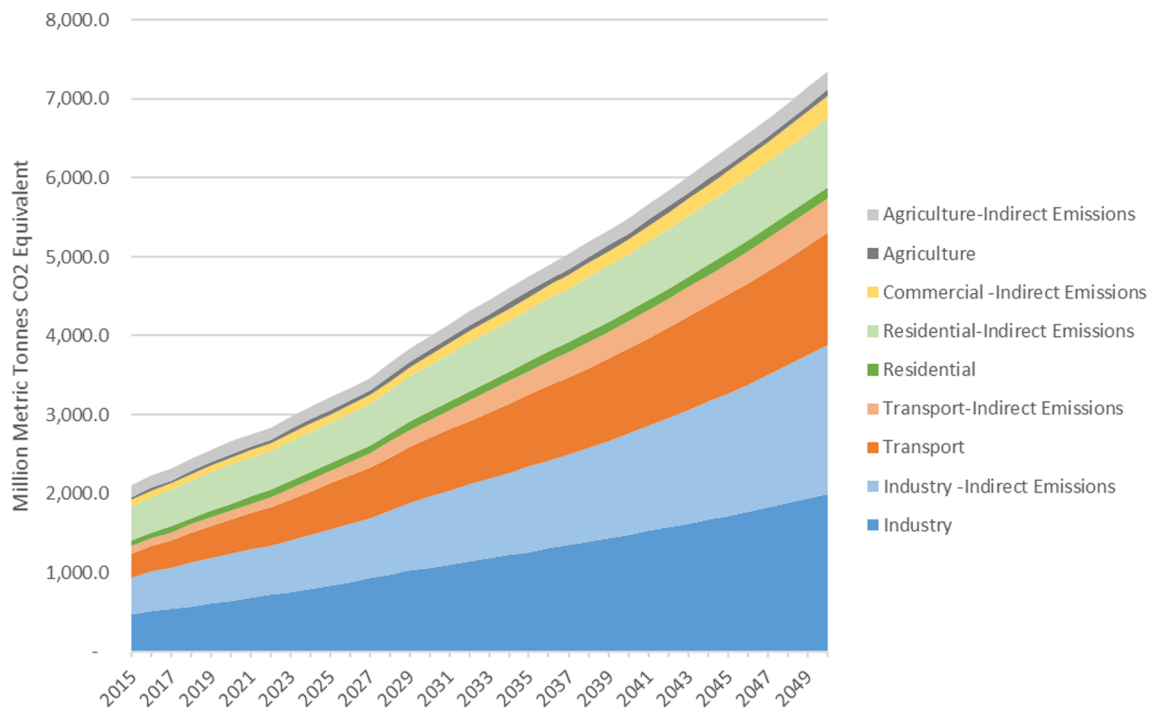**Fig. 6.** Primary Energy Consumption Projections for India's End-Use Sectors in the Baseline Scenario, 2015–2050.

Fig. 7. Projected Direct and Indirect CO_2 Emissions in India in the Baseline Scenario, 2015–2050 from Fuel Combustion.
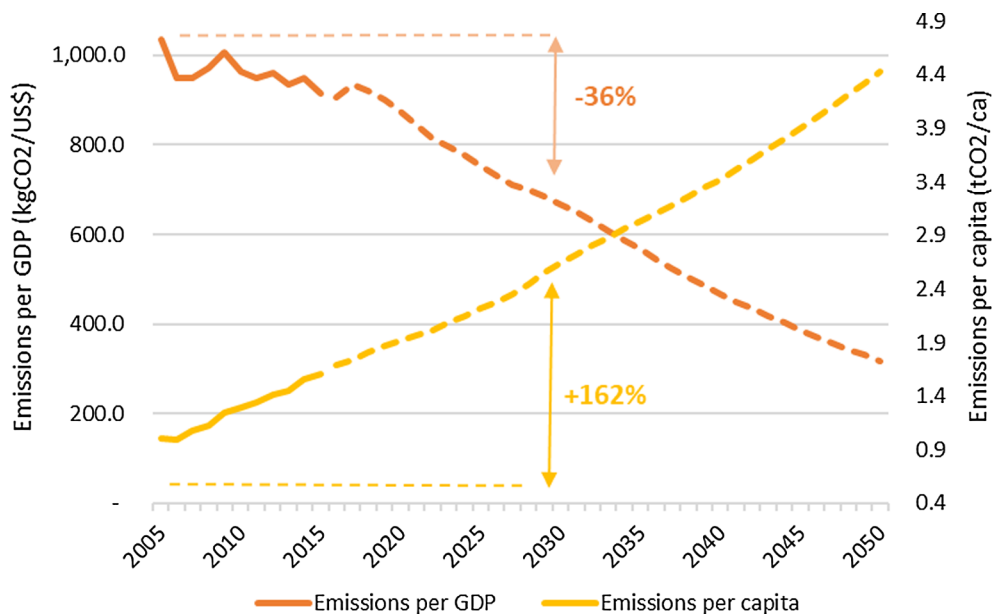

Fig. 8. CO_2 Emissions per Capita and CO_2 Emissions per GDP in India in the Baseline Scenario, 2005–2050.

from lighting and some residential equipment such as TVs and re-frigerators as explained in the Assumptions section and the following Results section on residential buildings.

In the India DREAM model, fuel switch projections result from the growing penetration of more advanced cleaner technologies which can use a different form of energy than conventional technologies. For example, in the transport sector, the share of electric vehicle kilometers traveled increases from almost 2% across all passenger modes in 2015 to 20% in 2050.

Primary energy will grow at a slightly lower rate than final energy. This is due to the fact that the primary energy required to produce 1 unit of electricity will decrease due to the projected increase in re-newable penetration. Primary energy are projected to grow from

31.1EJ in 2015 to 100.2 in 2050 (Fig. 6).

CO_2 emissions from fuel combustion were estimated by applying CO_2 emissions factors to each fuel category based on the IPCC guide-lines for National Greenhouse Gas Inventories [63]. In the case of electricity, indirect emissions were calculated to show emissions at the end-use sectors [64]. Indirect emissions resulted from the power mix as defined in the power sector of the model (see Fig. 7).

The graph in Fig. 6 presents the baseline scenario projected CO_2 emissions from fuel combustion in India from 2015 to 2050. India's emissions are projected to quadruple over these 35 years with a total of 7.4 billion of tons of CO_2 (BtCO$_2$) in 2050, lower than China's level of 9.1 BtCO$_2$ in 2016 [65]. In terms of emissions per capita, India is ex-pected to be well below China's current level and reach 4.4 tCO$_2$ per
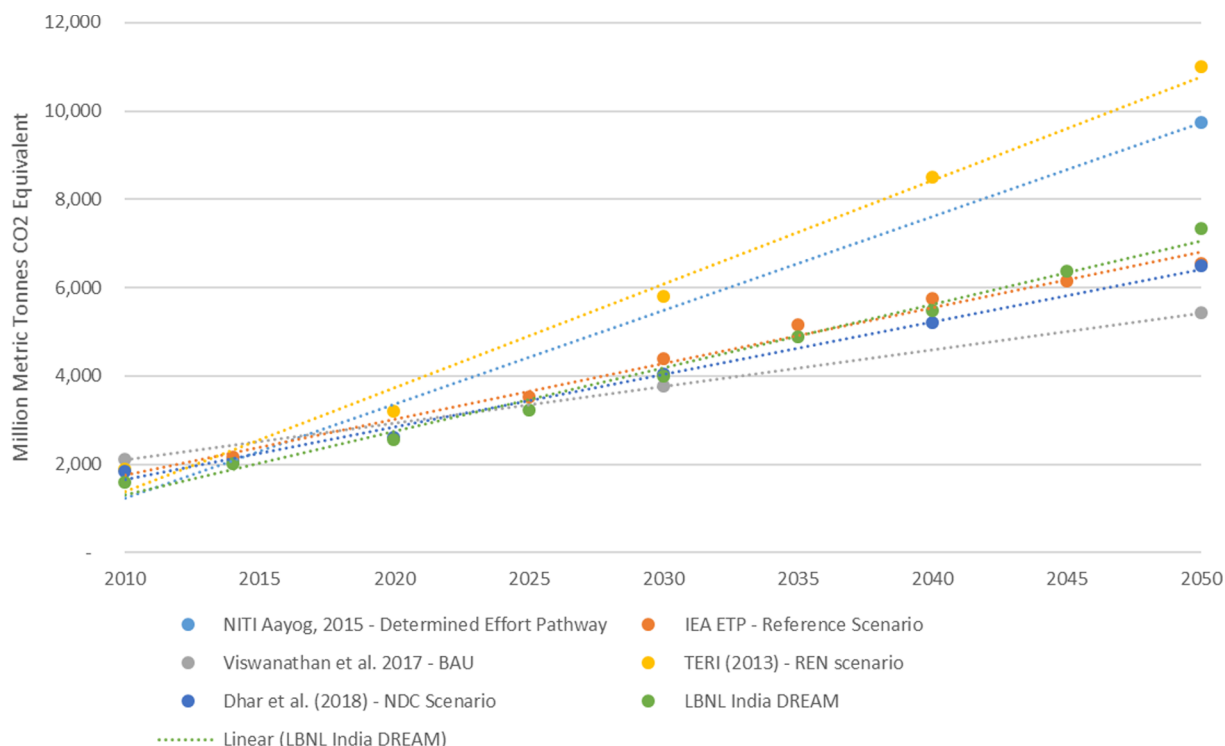
Fig. 9. Model Comparisons of Total CO_2 Emissions in India in Baseline Scenarios, 2010–2050.

capita in 2050 compared to 7.6 tCO_2 per capita in China in 2015. Indirect emissions, i.e. emissions from electricity production reallocated to the end-use sector, will still represent a large share of the total emissions—51% in 2050 compared to 58% in 2015. Indirect emissions are the largest in the industry sector, followed by the residential sector, due to the significant share of electricity use in that sector that powers a large array of appliances and electric equipment. In the industry sector, electricity is used mostly for motor drives.

CO_2 emissions per unit of GDP are expected to decrease significantly which indicates a sizeable decoupling of economic growth and emissions growth (Fig. 8). This also suggests that if India continues its engagement on energy efficiency policies and meets its NDC renewable energy commitment, the country will also most likely meet its NDC emissions intensity reduction target of reducing emissions intensity by 33% from 2005 levels by 2030. In our baseline scenario, India's emissions GDP intensity is projected to decrease by 36% by 2030, while emissions per capita will increase by 162%.

5.3. Comparison with other models

Total sector emissions baseline scenario projections for India were compared with baseline projections from other models. Fig. 9 shows projections from the five models succinctly described in the Literature Review section. Total sector emissions in the LBNL India DREAM baseline scenario are projected to reach 7352 MtCO_2 in 2050. Three other models project baseline emissions to reach a lower level. This is the case of the IEA ETP model, the model described in Dhar et al. [21], and the UNEP model [20] which project emissions to reach 6549 MtCO_2, 6500 MtCO_2, and 5432 MtCO_2, respectively. On the other hand, two models project baseline emissions to reach higher levels. This is the case of the NITI [18] Determined Effort Pathways and the TERI Renewable Scenario which project emissions to reach 9738 MtCO_2 and 11,000 MtCO_2 in 2050, respectively.
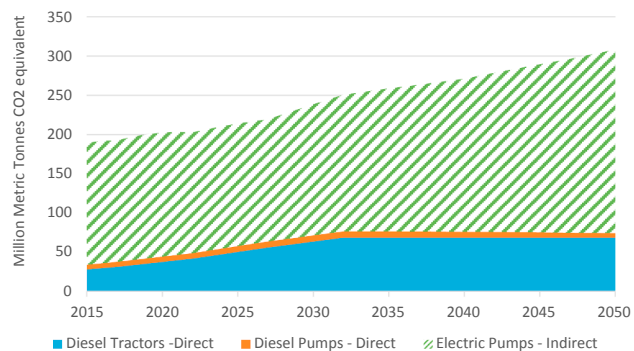

Fig. 10. Direct and Indirect Energy-Related CO_2 Emissions from Agriculture in India in the Baseline Scenario, 2010–2050.

5.4. End-use sector results

5.4.1. Agriculture

While the Indian agriculture sector is key from an economic perspective, its share of the nation's final energy consumption is projected to decline from 5.2% in 2010 to 2.8% in 2050. However, the absolute final energy demand from agriculture will rise from 841 petajoules (PJ) in 2010 to 2,329 PJ in 2050, driven by higher penetration of key technologies like water pumps and tractors. As a result of that growth, total direct and indirect CO_2 emissions from agriculture are expected to rise from 137 million metric tons in 2010 to 311 million metric tons in 2050 (Fig. 10).

5.4.2. Industry

The industry sector in India consumed 7.3 exajoules (EJ) in 2015, representing 38% of India's total final energy consumption. The energy intensive industries represent 75% of all the sector's energy consumption in 2015, while only representing 30% of the total industry value added.
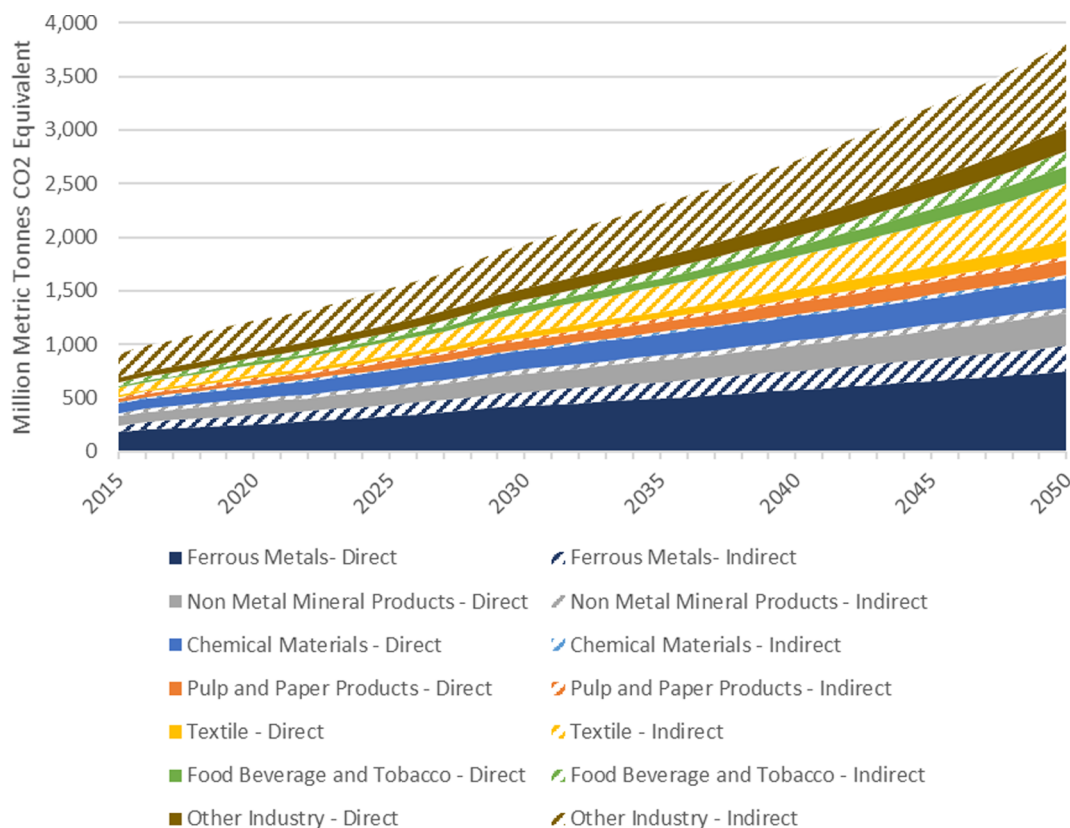
Fig. 11. Direct and Indirect Energy-Related CO_2 Emissions from Industry in India in the Baseline Scenario, 2015–2050.

The industry sector is the largest source of energy-related CO_2 emissions and is expected to remain so due to the important use of fossil fuel, notably in a few energy intensive industries. Iron and steel production are by far the largest source of direct emissions in the industry sector. Growth in this sector is expected to be significant as steel is a major input to infrastructure development. Moreover, the sector is very coal intensive and there is little incentive for the sector to transition to lower carbon fuels.

Fig. 11 shows projected direct and indirect CO_2 emissions from fuel combustion in India's industry subsectors in the baseline scenario. Total emissions are projected to more than quadruple from 2015 to 2050, from 932 $MtCO_2$ in 2015 to 3883 $MtCO_2$ in 2050. In 2050, direct emissions are projected to represent 50% of total emissions in the industry sector, close to the level of 51% in 2015. Direct emissions from the ferrous metals subsector, which is composed of 98% of iron and steel making emissions, are projected to represent 38% of total direct CO_2 emissions from the sector. The production of non-metal mineral products, chemical materials, and pulp and paper products will represent 15%, 14% and 7% of India's total industry sector direct CO_2 emissions, respectively. Therefore, these four subsectors will represent 74% of total direct CO_2 emissions in 2050 in the baseline scenario. Indirect CO_2 emissions display a very different breakdown across sectors. The textile industry represents the largest subsector share of indirect CO_2 emissions, with 29% in 2050, followed by ferrous metals with 13%, and beverage and food with 8% of the total indirect CO_2 emissions from the sector. The remaining indirect CO_2 emissions result from electricity demand in the non-energy intensive industries.

5.4.3. Transport

Transport demand in the baseline scenario is projected to grow in both the passenger and freight segments with the total final energy demand from transport going from 3179 PJ (20% of total final energy consumption) in 2010 to 22,348 PJ (27% of the total final energy consumption) in 2050.
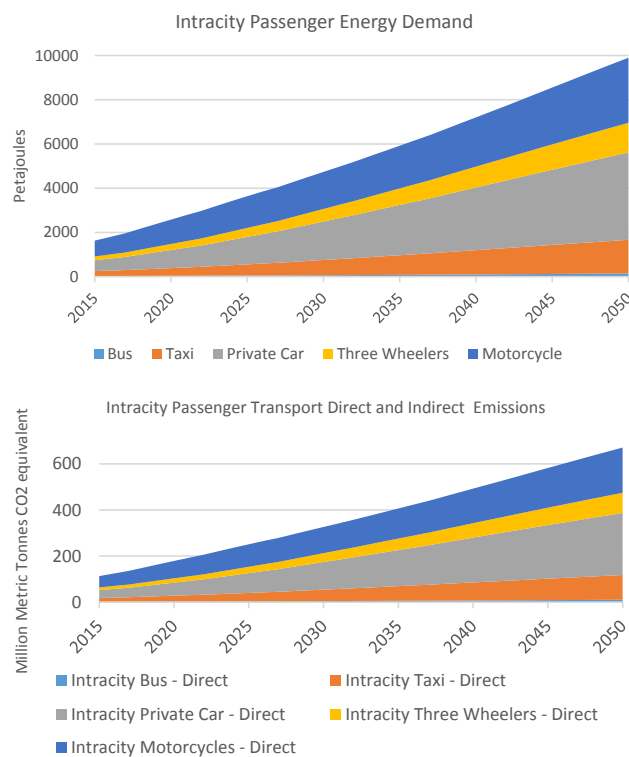

Fig. 12. Final Energy Demand and Direct and Indirect CO_2 Emissions from Intracity Passenger Transport in India in the Baseline Scenario, 2015–2050.

Based on the baseline scenario projections, passenger transport will be a key driver in the intracity transport segment, growing from 85.7% of all intracity energy demand in 2010 to 94.6% of all intracity
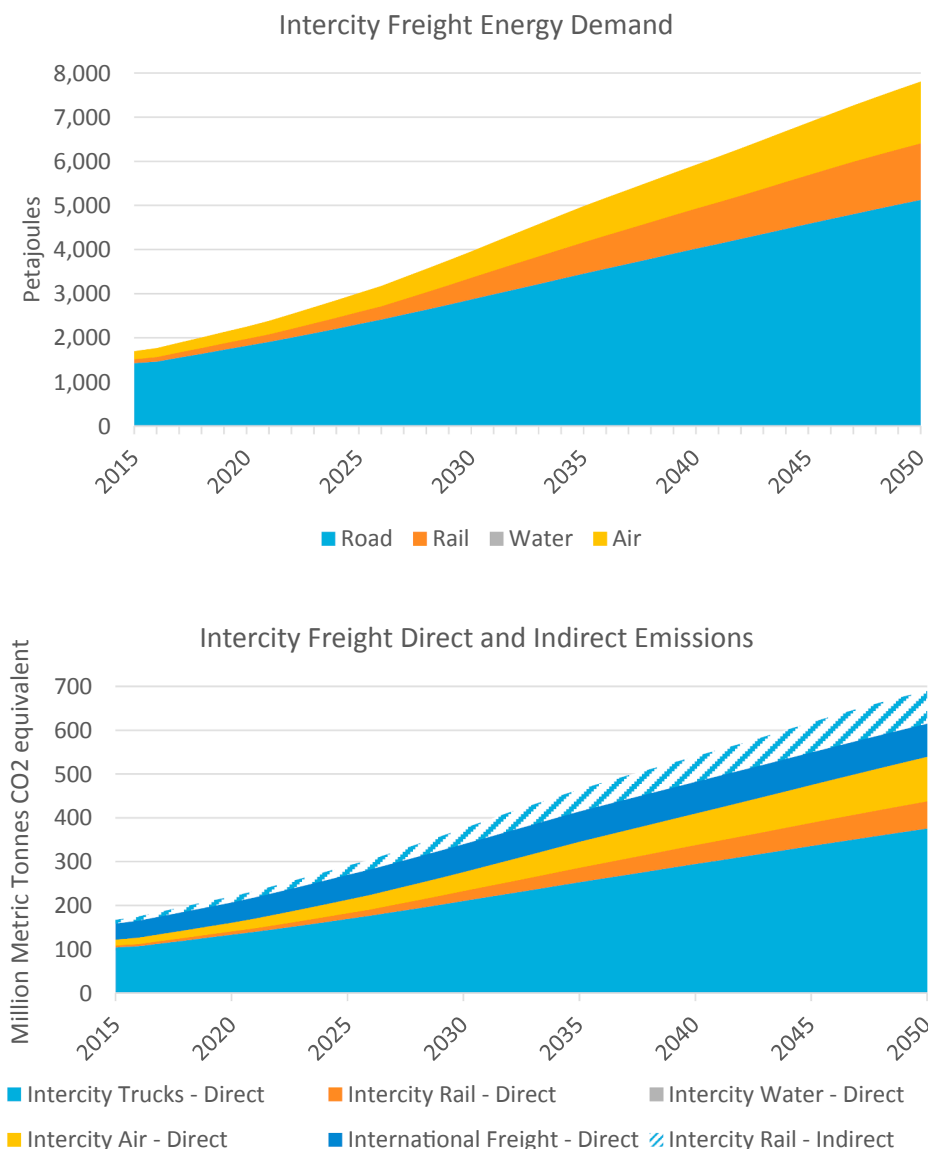
Intercity Freight Energy Demand

Intercity Freight Direct and Indirect Emissions

Fig. 13. Final Energy Demand and Direct and Indirect CO_2 Emissions from Intercity Freight Transport in India in the Baseline Scenario, 2015–2050.

transport energy demand in 2050. Road transport demand dominates energy use in the intracity transport sector, with private cars growing from 23.8% of total sectoral energy demand in 2010 to 37.7% in 2050. In addition, private cars will also contribute the most to the overall growth in CO_2 emissions, from 27.6% in 2010 to 40.8% in 2050. Fig. 12 shows energy demand and CO_2 emissions from intracity passenger transport and Fig. 13 shows energy demand and CO_2 emissions from intercity freight transport.

Similarly, freight road transport will continue to be the key driver in the intercity transport segment, making up 72% of the total energy demand in that segment throughout the model period from 2010 to 2050.

5.4.4. Residential

Dividing Indian households into rural and urban locales enables a better understanding of the different energy consumption patterns in these locations (Fig. 14). Within the locales, end uses were divided into air conditioning, appliances, cooking and water heating, lighting, and a residual category.

A large quantity of incremental electricity demand in India will come from the residential sector. As incomes grow, AC penetration will increase significantly due to India's very warm climate. Air conditioners

are very energy intensive, and when used, they account for a major share of a household's electricity bills. Penetration of ACs will increase much more rapidly in urban areas than in rural areas. For example, the penetration of ACs is 127% in Chinese cities; whereas, it is 25% in rural areas [42]. As income increases, AC ownership increases in all classes because ACs improve comfort, just as space heating does in countries with cold climates.

In terms of CO_2 emissions, only liquid petroleum gas (LPG) used for cooking results in direct emissions (Fig. 15). However, indirect emissions from the use of electricity for powering appliances and equipment represent the largest source of residential CO_2 emissions. Expected efficiency gains in lighting, refrigeration, TVs, and fans will help compensate for some of the growth in penetration of this equipment. However, growth in AC energy use will lead to significant growth in indirect CO_2 emissions unless the electricity sector is completely decarbonized.

5.4.5. Commercial

Commercial buildings are a small but growing segment of India's total energy demand, increasing from 195 PJ in 2010 to 1622 PJ in 2050. Within the commercial buildings sector, retail and offices will be the two biggest growing subsectors, both in terms of energy demand
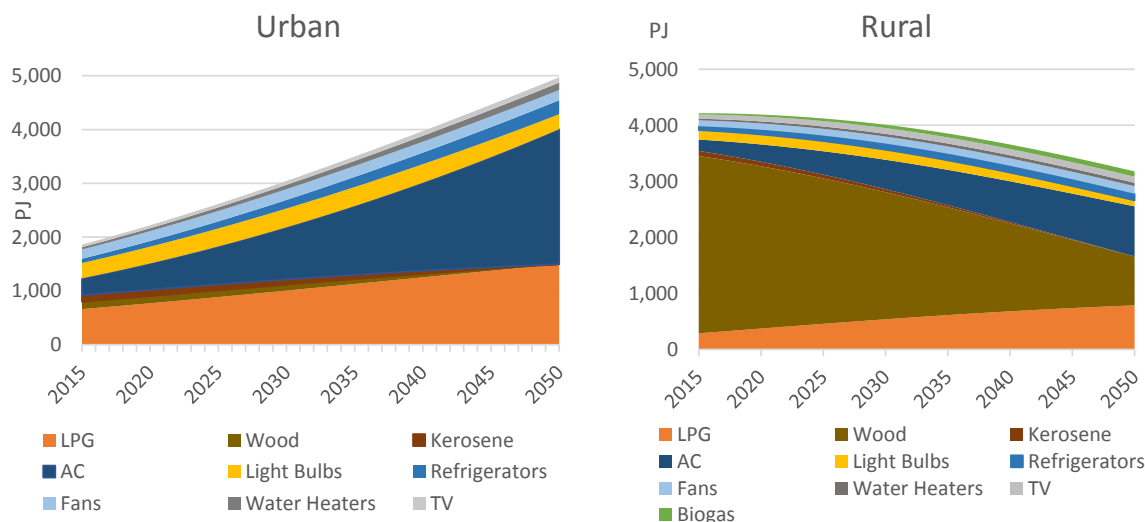
Fig. 14. Residential Final Energy Use Projection in India in the Baseline Scenario, 2015–2050.

and CO_2 emissions between 2010 and 2050, as shown in Fig. 16.

As shown in Fig. 16, energy consumption in offices grows from 85 PJ of the final energy demand in 2010 to 502 PJ in 2050, while retail energy demand grows from 103 PJ in 2010 to 598 PJ in 2050. Since most of construction of these two building types is forecasted for the future, it provides a unique opportunity to incorporate energy efficient practices from the very beginning.

All the emissions in the commercial building sector are indirect emissions as shown in Fig. 16 because all of the energy use is electricity driven. Since a significant portion of the commercial building stock is yet to be built, there is a significant opportunity to reduce the forecasted growth in emissions through energy efficiency measures particularly in space cooling.

6. Conclusion

India's current programs and policies to reduce energy-related CO_2 emissions are ambitious in terms of renewable energy and energy efficiency deployment. These current efforts will enable India to pursue a much lower CO_2 intensive pathway than China's relative experience and to reach its Paris Agreement NDC commitment. India can benefit from new, more efficient, and cleaner technologies that are now cost competitive. Moreover, the urgency of climate change, pollution, and energy security has driven strong commitments from the India government to move to a low carbon pathway. However, India is bound to develop and energy demand for growing its economy, building its

infrastructure, and improving its lifestyle will still need to be met with a large quantity of fossil fuels—especially as India's population will surpass China's in 2022 according to UN projections and reach 1.66 billion persons in 2050.

Our analysis shows that India can achieve its Paris Agreement NDC target with currently implemented policies. It provides detailed end use energy intensity targets that can be used by policy makers to reach India's NDC commitment and go beyond to contribute to the 1.5 degree commitment. Our baseline scenario projects the share of non-fossil power generation capacity to reach 47% in 2030, corresponding to a 32% share of electricity generation due to the low availability factor of renewable energy. India's CO_2 emissions intensity in 2030 will be 34% below 2005 levels. Thus, under current policies, India is likely to achieve both its 40% non-fossil and 33% emissions intensity NDC targets. According to a new IPCC Special report, median estimates of current NDC commitments range from 50 to 58 $BtCO_2$ per year in 2030, far from the range of 25 to 30 $BtCO_2$ per year in 2030 needed to limit global warming to 1.5 °C [66]. Increased action is needed to achieve net zero CO_2 emissions in less than 15 years. Our analysis estimates that India will reach 4.0 $BtCO_2$ per year in 2030 and 7.4 $BtCO_2$ in 2050 in a baseline scenario that is in line with its current NDC commitment. More research and policy commitments are needed to achieve a lower carbon pathway that aim at limiting global warming to 1.5 °C require GHG emissions.

The intent of this modeling exercise is to provide a reasonable baseline scenario of growth in energy use and related CO_2 emissions
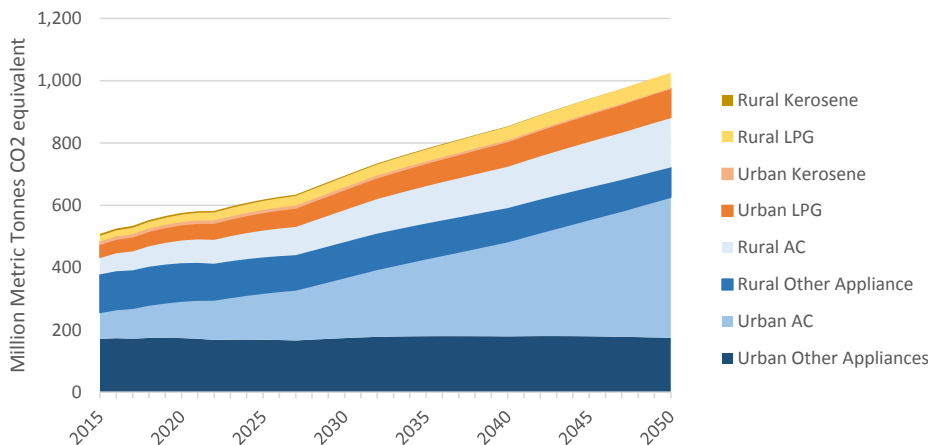

Fig. 15. Residential Direct and Indirect CO_2 Emissions in India in the Baseline Scenario, 2015–2050.
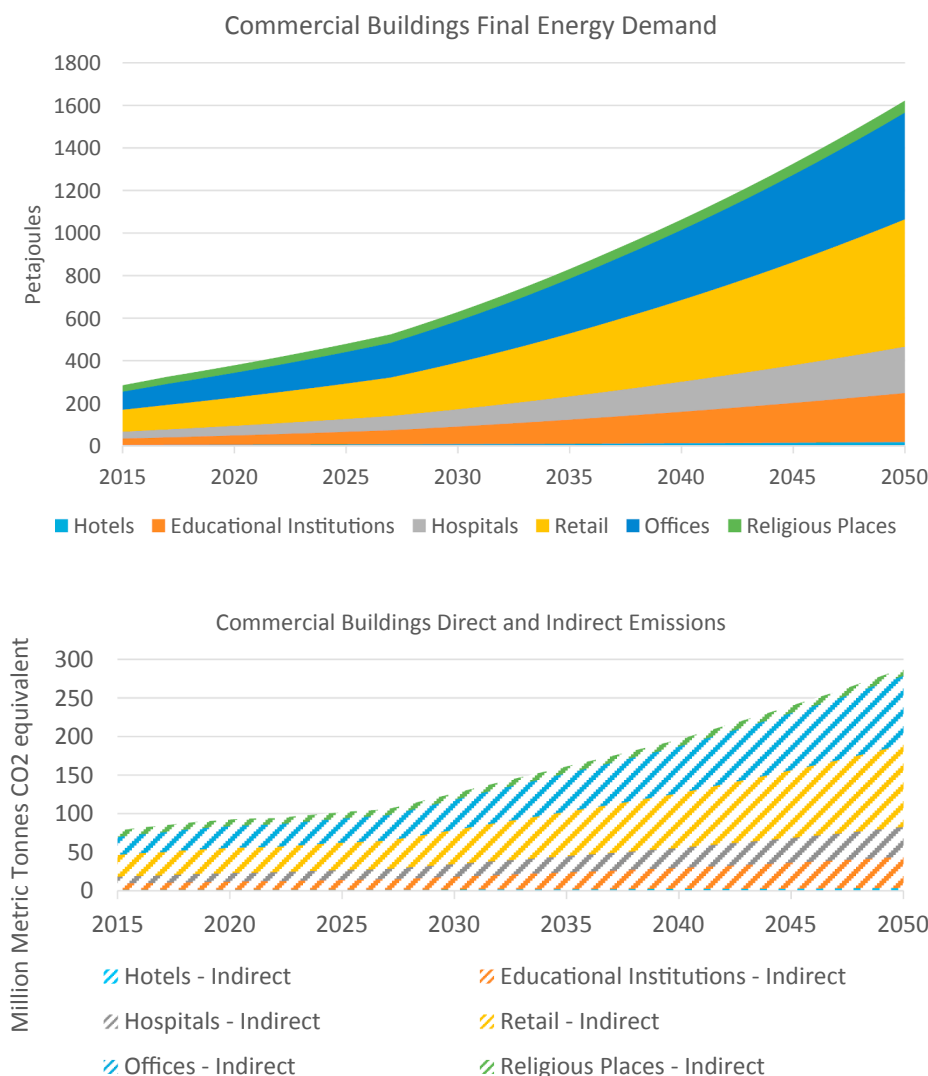
Fig. 16. Commercial Buildings Final Energy Demand in India in the Baseline Scenario, 2015–2050.

considering India's current policy commitments and global technology trends. The baseline scenario developed in this paper could then be used for future development of alternative scenarios for modelling India's economic and energy demand growth using different technology and policy interventions.

The goal of this model is also to provide insights on end-use energy consumption and to identify priority sectors and subsectors where low carbon solutions need to be encouraged. From this analysis, the industry sector represents a considerable challenge to be decarbonized. Among energy intensive subsectors, the iron and steel, cement, and chemicals sectors should be considered a priority, even more so as large investment will be made in these sectors to sustain India's current economic development. Direct CO_2 emissions from the ferrous metal, non-metal mineral products, chemical materials, and pulp and paper subsectors are projected to represent 74% of total direct emissions in 2050 in the baseline scenario. These sectors are hard to decarbonize, as low carbon technology solutions are nascent and consist of a combination of solutions that include expanding renewable energy for heat use, increasing energy efficiency, and encouraging material efficiency.

As we described in the literature review, several technology models recently have been developed in India and these contribute to the research effort of constructing a realistic baseline scenario that represents the mostly likely pathway if no breakthrough technology comes to market. More work is needed to compare assumptions to better

understand differences in results and to demonstrate the most economic low carbon pathways that can achieve 2 or 1.5 °C scenarios. Policy makers need access to the detailed underlying assumptions to offer information for targeted policy interventions.

India's huge pending demand for energy between now and 2050 constitutes a unique opportunity for the Indian government, the private sector, and the international community to demonstrate how low carbon technologies can contribute to economic development and strengthen developing economies' mid-century low carbon strategies.

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