Estimating minimum energy requirement for transitioning to a net-zero, developed India in 2070

Rupsha Bhattacharyya, K. K. Singh, R. B. Grover and K. Bhanja*

Determining minimum energy consumption per capita to support high development is a crucial activity for energy planners and policy makers working within resource, environmental and budgetary constraints. A composite metric like the human development index (HDI) of a nation is positively correlated with its energy consumption. The present study focuses on the estimation of minimum energy requirement for India to attain net-zero and a HDI value of 0.9 by 2070. The final energy requirement is found to be about 18,900–22,300 TWh/yr, indicating more than three-fold rise from the current consumption. About 30–40% of the final energy may be consumed in the form of hydrogen, whereas the rest will be used directly as electricity. Rapid infrastructure creation for high development and extensive digitalization may require additional 4400–4800 TWh/yr in the initial phases of rapid growth.

Keywords: Decent living standards, greenhouse gases, human development index, minimum energy requirement, net-zero emissions.

ENERGY usage by a country (quantified as energy consumption per capita per year) is a common indicator of its state of development and prosperity[1]. Numerous studies indicate a positive correlation between energy use and gross domestic product (GDP) per capita, or between energy use and composite indicators of national well-being such as the human development index (HDI), which factors in health, economic conditions and state of education of the citizens[2]. Energy use in a country has several determinants, including its population, climatic conditions, the geopolitical situation in the neighbourhood, the extent of urbanization, types of primary energy sources and final energy services used, relative importance and energy intensities of various sectors and industries making up the country's economy, nature and extent of cross-border trade activities, adoption of energy efficiency, conservation and recovery measures as well as socio-economic inequalities related to energy accessibility and affordability[3]. Thus, energy planning is one of the most complex segments of national policy-making. This is particularly true for developing economies and emerging markets where energy remains an important driver for the attainment of higher prosperity levels and inclusive, sustainable growth.

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The task of energy planning for a nation is often carried out through modelling tools having varying levels of sophistication[4]. Most of these tools require significant amounts of data about historic and current energy and economic trends, as well as Government policies with analytic and predictive/forecasting capabilities for performing detailed integrated assessments. Energy planning now compulsorily includes environmental and other sustainability criteria, given that energy use is the most significant cause identified for anthropogenic climate change and other forms of environmental damage[5]. However, even the mathematically simpler techniques implemented on any general calculation platform and providing support to scenario-based analyses can often provide useful directions for the first level of energy planning. The present study illustrates this approach for the case of India, the second-most populous nation and one of the largest and fastest growing developing economies in the world.

The study focuses on assessing the minimum energy needs for India to transition to a developed economy with a decent standard of living (DSL) for all citizens[6]. It assesses India's current energy situation and state of welfare vis-à-vis that of other countries, and estimates the likely energy usage to significantly enhance the state of welfare. It then calculates final energy requirement for different postulated scenarios leading to a low-carbon, energy-secure and developed economy by 2070. The work is expected to provide insights to policy-making organizations regarding the creation of sufficient energy capacity for

India to adequately support these multi-dimensional objectives.

Current energy and emissions scenario in India

Energy generation and usage pattern

India's total primary energy consumption at present is 42.6 EJ and final energy consumption is 26.4 EJ/yr (ref. 7). The corresponding per capita values are 31 and 19 GJ/yr respectively. The current Indian primary energy mix is mainly based on fossil fuels such as coal and petroleum products (Figure 1 *a*)[7,8]. Electricity makes up about 18% of the final energy consumption in the country (industry, agriculture, services and residential sectors) (Figure 1 *b*) and more than 70% of this electricity is now sourced from coal-fired thermal power plants (Figure 1 *c*). The rural residential sector extensively uses non-commercial forms of energy such as biomass for applications in cooking and domestic water heating. India does not yet have a formal carbon tax though there is a nominal coal cess (currently equivalent to US$ 4 per tonne of carbon dioxide at the point of production) imposed on coal for power generation[9]. Additionally, Indian Railways explicitly overprices coal transport via railways to subsidize passenger services, and this increases the cost of electricity generation[10].

The transportation sector is mainly dependent on imported petroleum products (of which 90% is petrol and diesel, and 10% is aviation turbine fuel) as well as natural gas. This constitutes more than 30% of India's final energy usage[8]. Railway transport is largely electrified. The Indian Government is encouraging enhanced blending of bioethanol and biodiesel in transportation fuels to reduce import dependence and associated expenses, from 5% to 20% by 2025 (ref. 11). The share of renewables, including solar photovoltaic (PV), wind and hydroelectricity in the electricity sector is about 38% (installed capacity) at present and it is growing rapidly, given India's commitments to climate action and decarbonization of energy and industrial sectors for net-zero by 2070.

Installed nuclear electrical capacity is currently about 7.5 GW (ref. 12) and it is expected to triple by the mid-2030s. In line with India's growing economy, national energy demand is expected to grow at the rate of 6% per annum. On the World Energy Trilemma Index, 2020, India, with an overall score of 56.2 and rating of B–C–D stands at overall position 86 out of 128 participating countries, which indicates that the current energy situation of the country on metrics like energy security, equity and sustainability is average or below average[13].

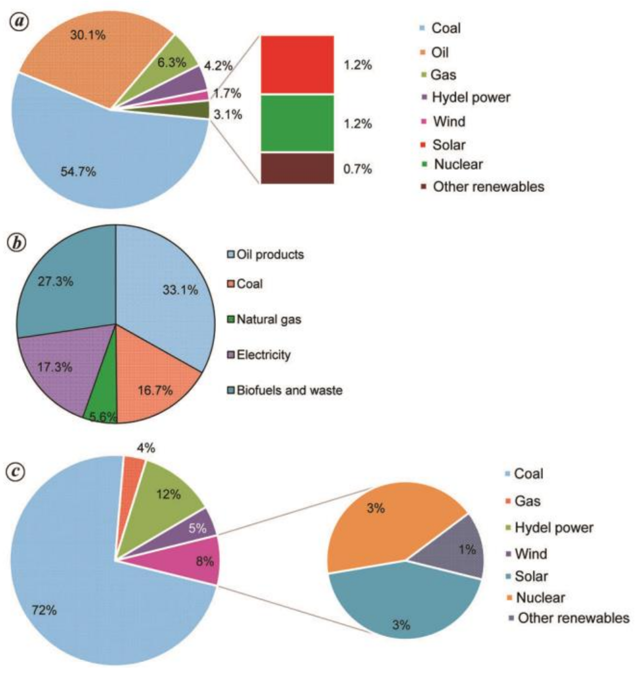

Figure 1. ***a***, Primary energy consumption (%) by source in India in 2019 (refs 7, 8). ***b***, Forms of final energy consumption in India in 2019 (refs 7, 8). ***c***, India's electricity generation mix (%) by source in 2019 (refs 7, 8).

Greenhouse gas emissions

Despite the lower per capita energy consumption and carbon emissions (1.8 tonnes CO_2/capita/yr) compared to global averages (4.8 tonnes CO_2/capita/yr), India accounts for about 7% of total global greenhouse gas (GHG) emissions at present, occupying the third place behind China and USA[14]. GHG emissions originate from electricity production using coal, industrial activities (production of iron and steel, cement, ammonia, petrochemicals, etc.), transportation (liquid and gaseous hydrocarbon use) and from the agriculture sector (Figure 2). Fossil-fuel usage also causes high levels of air pollution and significant health impacts in the country. India's commitment according to the Paris Agreement, 2015 is 33–35% lower carbon intensity of GDP by 2030, primarily by the deployment of 450 GW(e) renewables and by enhancing forest cover by 2030 (ref. 15). India has also declared 2070 as the year by which it will attain net-zero emissions. Thus, an enormous extent of decarbonization is required in the energy and other carbon-intense sectors of the economy to achieve net-zero emissions within the declared timeframe.

India has begun to make significant and concrete commitments on the use of green hydrogen for decarbonization of sectors like fertilizers and petroleum refining/petrochemicals, with the first phase of an Indian hydrogen energy roadmap/strategy announced recently[16]. Indigenous green hydrogen production and use has been strongly emphasized in developing this mission. According to some perspectives, reaching net-zero requires drastic emissions reduction before banking on CO_2 removal technologies

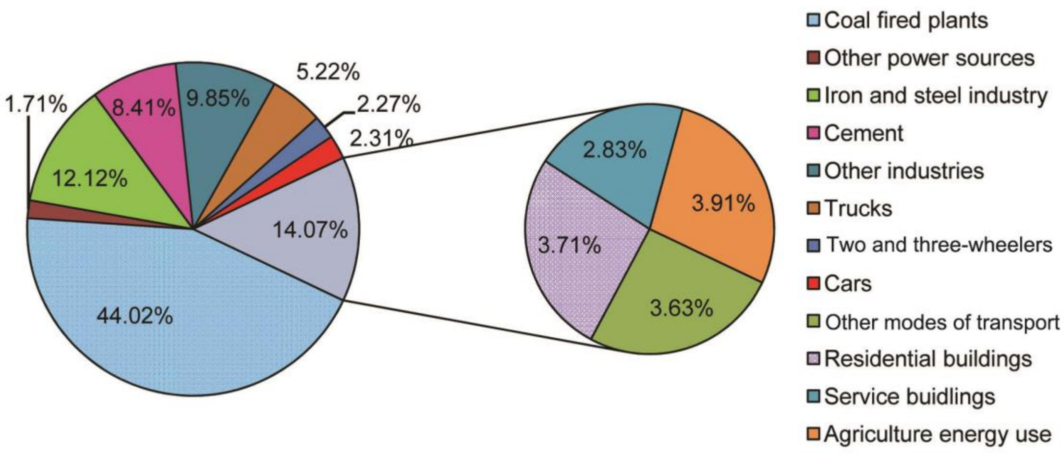

Figure 2. Sectoral contributions to energy-related GHG emissions of India in 2019 (refs 7, 8).

and offsets for residual emissions[17]. For India, shifting from fossil fuels to low-carbon technologies is important for climate change mitigation efforts, reduced dependence on imported fossil fuels, lower energy import bills and attainment of long-term energy security.

Approaches to minimum energy requirement estimation

A fundamental task in India is energy planning is to estimate the minimum energy requirement to support a 'decent living standard' for all its citizens. The definition of a decent living standard is generally based on consumption of a set of goods and services, both publicly and privately provided, that lead to a general level of human welfare[6]. Since energy and quality of life are strongly interrelated, determining the minimum energy requirement sets the basis for economy-wide planning in the short and long term. A top-down (i.e. looking at aggregate energy use in a nation across the various sectors in its economy vis-à-vis its state of development), or a bottom-up approach (looking at individual-level energy use for a certain standard of life) or a combination of both can be used to determine this minimum energy requirement[18]. Table A1 summarizes key findings and conclusions from several such studies (refer to Supplementary Materials, Appendix 1, Table A1).

The estimates of minimum energy consumption per capita in previous studies are found to be spread over a broad range (30–100 GJ/capita/yr) depending on the geographic scope of the study, methodology of assessment and its underlying assumptions. A global minimum energy target is useful only as a generic indicator as the actual requirement is likely to vary significantly from country to country and with time as the nature of the economy, consumption patterns and energy mixes change. The bottom-up or inventory-based approach is based on many assumptions about variables concerning individual behaviour and lifestyle preferences, which are unlikely to be universally applicable across the entire population. These predictions often tend to be on the lower end. Aggregate data used for the top-down approach on the other hand, imbibe such heterogeneity in consumption patterns across the population to a large extent and are therefore more accurate representations of the nation's characteristics. Thus, a top-down approach specifically looking at Indian requirement for different scenarios to high development and a net-zero emissions economy has been adopted in this study.

Application of top-down approach for assessment of India's energy requirement

Examination of current energy and development trends data

For the top-down approach, aggregate trends such as per capita energy consumption and HDI data of 63 nations with low, medium and high per capita income for 2019 were obtained from IEA[7], UN DESA[19] and UNDP[20] (Figure 3 *a*–*c*). Taken together, these countries represent over 90% of the global population today and also a wide range of economic conditions, lifestyles and climate-related factors which determine energy requirement.

It is observed from Figure 3 *a* that no country has achieved HDI equal to or above 0.9 with less than 146 GJ/capita/yr of primary energy consumption. In terms of total final energy, no country has attained HDI of 0.9 with less than 75 GJ/capita/yr (as shown by red markers in Figure 3 *b*), with the exception of Hong Kong, which has a predominantly service-based economy and a high degree (~48%) of electrification of final energy consumption. Thus, one can take 75 GJ/capita/yr as the minimum total final energy requirement for a highly developed India as well.

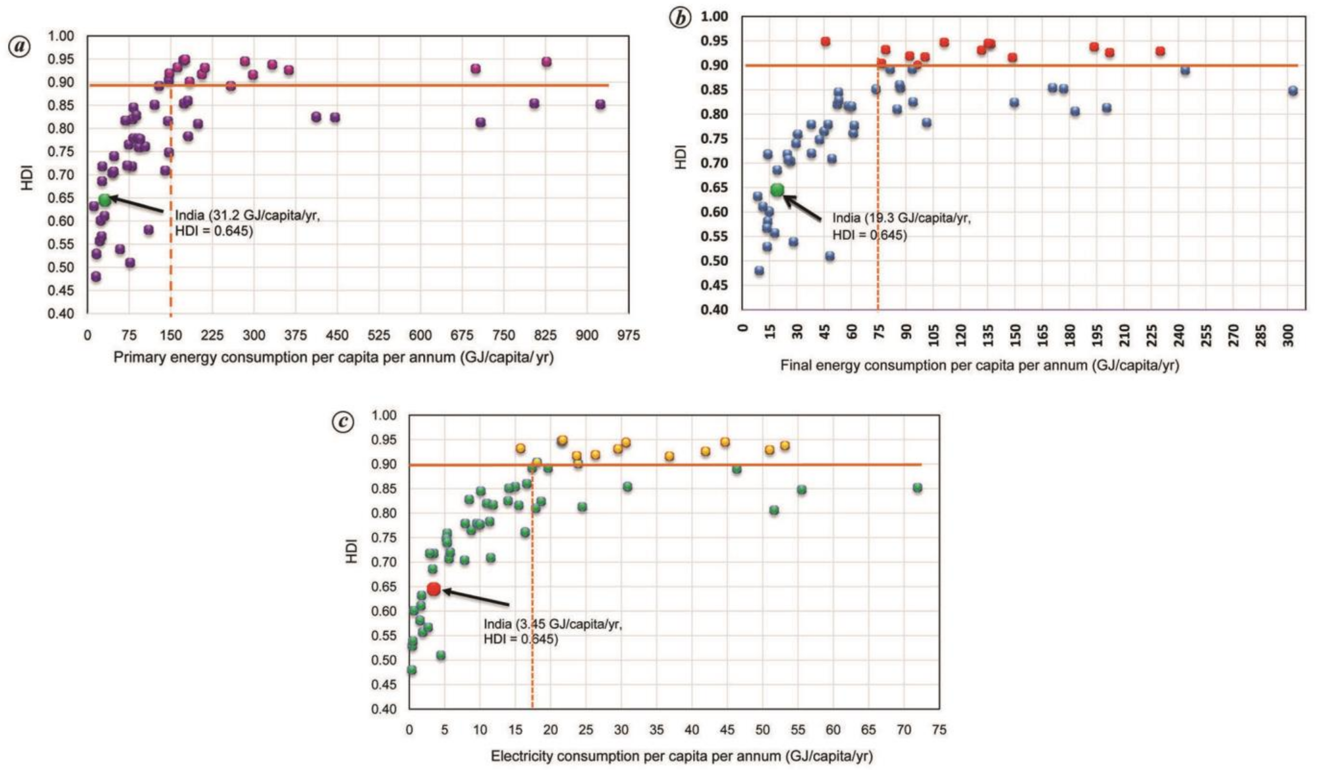

Figure 3. ***a***, Human development index (HDI) as a function of primary energy use in different countries in 2019 (refs 7, 19, 20). ***b***, HDI as a function of final energy use in different countries in 2019 (refs 7, 19, 20). ***c***, HDI as a function of electricity consumption in various countries in 2019 (refs 7, 19, 20).

The final energy consumption is more meaningful than per capita primary energy consumption, as this is what a consumer utilizes and pays for to obtain the energy services required to support a certain lifestyle. It is therefore taken as a starting point for estimating the true energy needs of the nation as a whole. The share of electricity is different in the final energy consumption of various nations, varying widely between 2% and 48% of total final energy consumption in the countries considered in Figure 3 (the current global average being about 20% (ref. 7)). However, electricity consumption per capita (Figure 3 *c*), while not a complete indicator of national energy requirement, will become an increasingly important metric as more and more sectors are electrified as part of decarbonization efforts.

For the specific case of India, historic data in Figure 4 *a* and *b* clearly indicate the strong positive correlation between increasing values of HDI and final energy consumption or electricity consumption per capita per annum for the years 2010–2019. Over this time-frame, the compounded annual improvement in HDI has been 0.5% per annum, with compounded growth rate in per capita final energy consumption of 1.1% per annum and compounded annual growth rate of electricity consumption of 2.7%. The value of HDI as function of energy consumption has not yet reached a plateau (which typically occurs at values of HDI above 0.8 in developed economies; for example, in the case of Turkey (Figure 4 *c* and *d*)). This indicates that for achieving a very high HDI, energy availability has to be significantly enhanced first. Further, considering a wide variation in energy availability for different sections of the population, India has to provide energy at an affordable prices so that it becomes accessible to all.

Developing scenarios for energy requirement estimation in India

Along with increasing the energy supply to support development, it is also necessary to balance carbon emissions and air pollution associated with fossil-fuel usage in India to decouple economic prosperity and environmental degradation. The interlinkages between these factors are commonly expressed by the Kaya identity which decomposes CO_2 emissions of a nation into contributions from population, activities contributing to GDP growth, the energy intensity of economic activities and carbon intensity of the energy system[21]. It is therefore written as

$$\mathrm{CO_2\ emssions} = \mathrm{Population} \times \left(\frac{\mathrm{GDP}}{\mathrm{Population}}\right)$$

$$\times \left(\frac{\mathrm{Energy\ consumption}}{\mathrm{GDP}}\right) \times \left(\frac{\mathrm{CO_2\ emssions}}{\mathrm{Energy\ consumption}}\right). \quad (1)$$

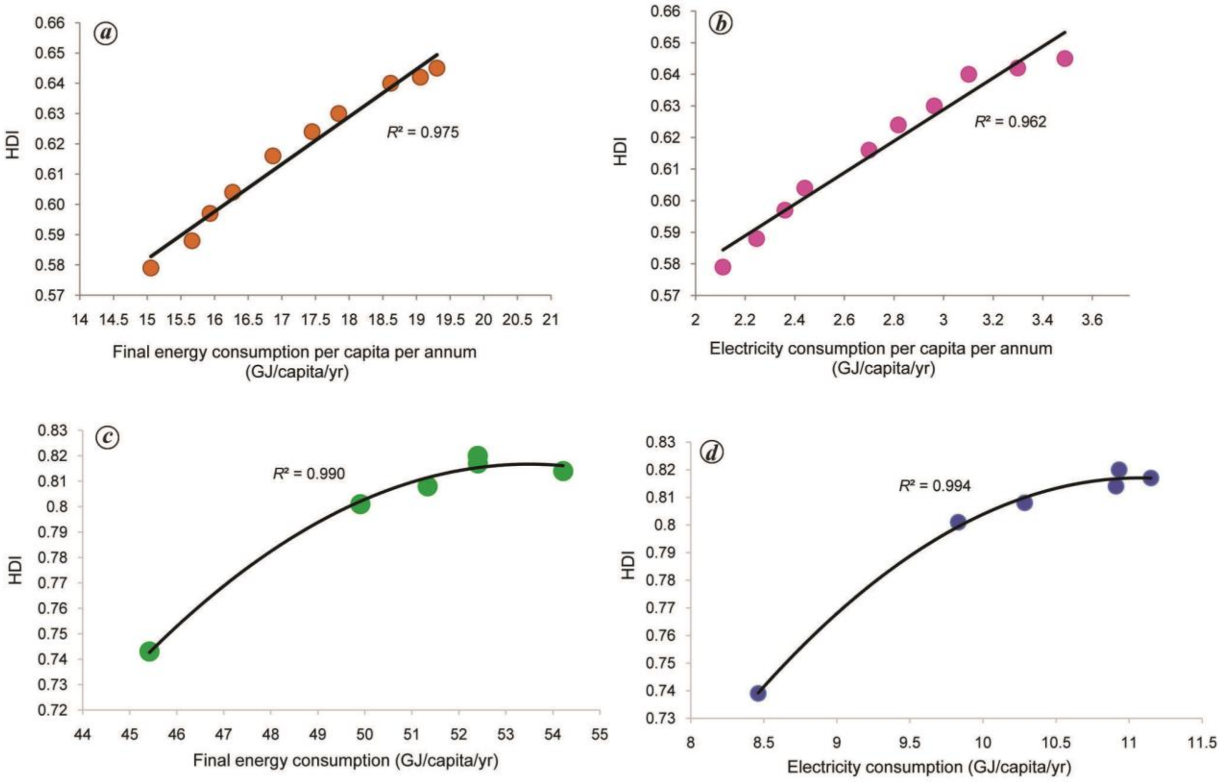

Figure 4. ***a***, Impact of final energy consumption on changes in HDI for India (2010–2019)[7,19,20]. ***b***, Impact of electricity consumption on changes in HDI for India (2010–2019)[7,19,20]. ***c***, Impact of final energy consumption on changes in HDI for Turkey (2010–2019)[7,19,20]. ***d***, Impact of electricity consumption on changes in HDI for Turkey (2010–2019)[7,19,20].

For India, population growth is expected to continue till it peaks in 2048 and then gradually decreases[22]. GDP growth is one of the necessary conditions for improving HDI. Energy consumption will also rise substantially before it is decoupled from further economic growth. Thus, the most important consideration for India is to shift to low carbon intensity energy forms (as energy use-related emissions make up more than 70% of India's total GHG emissions at present), adopt carbon abatement technologies, and implement energy conservation and efficiency improvement measures to support its economic activities with lower energy intensity. These considerations enable development of scenarios for energy planning and forecasting in the country.

Each of the scenarios represents a different end state of India's energy and industry sectors, decarbonized to a large extent but by different technology combinations. Thus, the final energy consumption also varies accordingly. Scenario S0 represents the current state of low energy consumption, low development and high dependence on fossil fuels. Scenario S1 represents high energy consumption with the current energy mix to support economic growth along 'business as usual' conditions. Scenario S2 assumes significant energy efficiency improvements in a graded manner with initial rates of improvement being high and then gradually slower rates, as has been observed globally in the case of primary energy consumption patterns of developed countries[23]. Scenarios S3–S7 add shifts in energy vectors, carbon offsets by forestry and other natural mechanisms, carbon capture technologies and altered consumption patterns to reach net-zero. The assumptions involved in creating these high-development, net-zero scenarios are mentioned below and each of them is analysed in the subsequent sections.

- Decarbonized energy system is based on a very high degree of electrification through all forms of low-carbon energy (e.g. solar PV, wind turbines, hydroelectricity and nuclear power).
- High-temperature heat demand is met by low-carbon heat sources such as high-temperature nuclear reactors, concentrating solar power or hydrogen combustion in the absence of other heat sources.
- For secondary energy vectors such as hydrogen substituting primary energy forms such as natural gas or coal, the estimated energy generation requirement includes the electricity-to-hydrogen conversion efficiencies of devices such as water electrolysers as well as those of re-conversion technologies producing heat (e.g. furnaces for industrial heat application) or work (e.g. fuel cells for transport applications). A detailed discussion is provided in the Supplementary Appendix II.

- Mobile sources of emission such as the transport sector are decarbonized by moving to either clean electricity or carbon-free energy carriers (like hydrogen in fuel cells or internal combustion engine-based vehicles), or a mix of these forms.
- Stationary sources of emissions such as fossil-fired power plants (till the time they can be phased out), metallurgical industries using coal, cement and petrochemical industries adopt a mix of clean energy vectors with carbon capture technologies for the hard-to-avoid emissions arising from the process chemistry itself.
- Sectors requiring green hydrogen for decarbonizing their operations make use primarily of water electrolysers working on low-carbon heat and electricity to meet the demand.
- Extensive and deliberate use of biomass and bioenergy (particularly in the highly processed forms of bioethanol/biodiesel as drop-in substitutes/blending options of fossil fuels in the transport sector) is not considered since emissions from their use will be widely distributed and difficult to capture. Thus, they may not necessarily lead to net-zero emissions. They generally have low energy return on investment (EROI) (recent estimates point to values between 0.68 and 3.12 (refs 24, 25)) and require extensive land and water resources to be harnessed, which could cause potential land-use conflict. Agricultural waste and residues, which will inevitably be generated, may be processed further and used as secondary fuels/carbon sources in fossil-fuel applications (e.g. cement or steel production) with carbon-capture processes.

Extrapolation from scenario S0 to business-as-usual scenario S1

Based on the trends identified in the case of India, final energy consumption per capita would need to rise from 19.3 GJ/yr (baseline scenario S0) to at least 75 GJ/yr (i.e. scenario S1 with 3.89 times the current consumption rate) for it to progress to a high development level (HDI ≥ 0.9) under business-as-usual conditions in the next five decades (i.e. the nature of the economy as well as the energy vectors used to support it are assumed to remain similar to current conditions). India's current population is 1.38 billion and it is expected to peak at 1.61 billion by 2048 (ref. 22). Assuming a population of 1.5 billion in 2070, under scenario S1, total final energy consumption in India would have to be a minimum of 31,275 TWh/yr for high human development (taking 1 GJ ~ 278 TWh).

Energy efficiency improvements in India – scenario S2

Energy requirement forecasts for India presented above are based on the current level of energy efficiency and composition of the economy. Consideration of factors such as adoption of energy conservation measures and energy efficiency improvements will lead to a lower predicted energy requirement for an identical HDI value and identical nature of economy under scenario S2. While reduction in primary energy consumption is the basis for most discussions on energy efficiency improvements and reduction rates as high as 2.6% per annum up to 2030 are considered necessary from a sustainable energy system perspective[23], on the final consumption side, improvement rates will be lower than this value. Thus more conservative estimates, based on trends observed in the decline of energy intensity of advanced economies such as USA, are used in the present study[26].

Assuming implementation of energy conservation, energy integrated operations and efficiency improvement policies on the demand side across all sectors that lead to a phase-wise reduction of energy intensity by 1% per year from 2020 to 2029 (based on significant upgrades in energy technologies), 0.5% per annum from 2030 to 2049, and 0.25% per annum from 2050 to 2070 (ref. 27), a maximum reduction in per capita energy consumption by a factor of 1.286 from the 2019 level is possible. Thus, instead of a minimum of 75 GJ/capita/yr, energy requirement can be reduced to about 58.3 GJ/capita/yr for the same level of development (~23% reduction). The carbon intensity of the economy would decrease proportionately even when low-carbon technologies are not adopted widely. Total final energy consumption for a population of 1.5 billion under this scenario would therefore be at least 24,310 TWh.

Shifts in energy vectors and consumption patterns to approach net-zero energy-related emissions – scenarios S3 to S7

With the announcement of India's net-zero emissions target by 2070, energy planning must take into account the need to shift the energy and material forms used in many sectors to achieve deep decarbonization. On the demand side, a much larger (i.e. greater than the current 18%) share of this energy requirement would have to be provided in the form of low-carbon electricity as India tries to electrify sectors such as cooking and transportation, and also because the nature of its economy may gradually shift more towards services from manufacturing. In addition, electricity would be required to produce low-carbon hydrogen which will be required as a supply-side measure for decarbonization of sectors like chemicals synthesis, metallurgy and others. That overall economic growth in India is well-correlated to electricity consumption has been established by several econometric studies which estimate that from 1970s to about 2018, the elasticity of electricity consumption with respect to growth in GDP has been about 0.77–0.86 in India[28–30]. Some published studies such

Table 1. Description of interventions employed in long-term low-carbon energy scenarios for India in 2070

S3	S4	S5	S6	S7
All oil products replaced completely by low-carbon electricity (nuclear, renewables and hydroelectricity)	All oil products replaced by electrification (50% by direct electrification, 50% by hydrogen)	All oil products replaced by electrification (25% by direct electrification, 75% by hydrogen)	Same as S4	Same as S5
All currently electrified sectors achieve graded energy efficiency improvement from 2019 till 2070 as described in this article	Same as S3	Same as S3	Same as S3	Same as S3
Coal and natural gas used in industry as feedstock, heating application and/or reducing agent are completely replaced by hydrogen	50% of coal and natural gas replaced by hydrogen; the rest is coal and natural gas use abated by natural mechanisms/offsets	25% of coal and natural gas replaced by hydrogen; the rest is coal and natural gas use abated by natural mechanisms/offsets	Carbon capture is available with coal and natural gas usage	Carbon capture is available with coal and natural gas usage
Use of biomass and waste (for domestic cooking/heating) is fully substituted by directly electrified cooking system	Same as in S3	Same as in S3	Same as S3	Same as S3

Table 2. Summary of final energy requirement forecasts for India in 2070 under different scenarios

Scenario	Per capita final energy requirement and human development index (HDI)	Forms of final energy consumption	Remarks
S0	19.3 GJ/capita/yr at HDI of 0.645	17.3% electricity, 33.1% oil products, 16.7% coal, 5.6% natural gas, 27.2% biomass and waste	Derived from 2019 data
S1	75 GJ/capita/yr at HDI 0.9	Same as S0	Calculation based on recent trends between energy consumption and human development
S2	58.3 GJ/capita/yr at HDI 0.9	Same as S0	Adoption of energy efficiency improvement across all sectors till 2070
S3	45.9 GJ/capita/yr at HDI 0.9	59.3% low carbon electricity, 40.7% hydrogen	Energy efficiency improvement accompanied by increased need for electricity to run electrolysers for green hydrogen
S4	47.3 GJ/capita/yr at HDI 0.9	67.3% low carbon electricity, 32.7% hydrogen	Energy efficiency improvement needs more electricity to be generated even as the share diverted to hydrogen production is reduced (compared to S3)
S5	47.0 GJ/capita/yr at HDI 0.9	71.2% low carbon electricity, 28.8% hydrogen	Energy efficiency improvement increases electricity requirement further
S6	48.6 GJ/capita/yr at HDI 0.9	62.7% low carbon electricity, 37.3% hydrogen	Additional energy needed for supporting carbon abatement/capture technologies
S7	45.7 GJ/capita/yr at HDI 0.9	68.7% low carbon electricity, 31.3% hydrogen	Additional energy required for carbon abatement technologies

as those by IEA have come up with forecasts which indicate a very low value of elasticity, which is not realistic[31].

With this premise, a broad sector-by-sector analysis is performed, by considering at the prevailing energy mix used in major Indian industries and its potential transition to cleaner energy forms. The following scenarios, numbered S3–S7 and described in Table 1 are envisaged and corresponding assumptions are made to estimate changed energy requirement in each sector. The methodology is described in the Supplementary Appendix III. Table 2 indicates the quantitative data used for the scenario analysis (see also Supplementary Materials, Appendix III, Table A2).

Under high-development, low-carbon emissions scenario, the minimum energy requirement per capita lies between 46 and 49 GJ/yr. This is because the energy saved through improved electrification in some sectors is offset by a greater amount of electricity required for electrolytic hydrogen production to substitute coal and natural gas. Table 2 summarizes the results from the scenario analysis.

Sensitivity studies for scenarios S3 to S7

For scenarios S3–S7, decarbonization options include technologies that are under development and/or have the

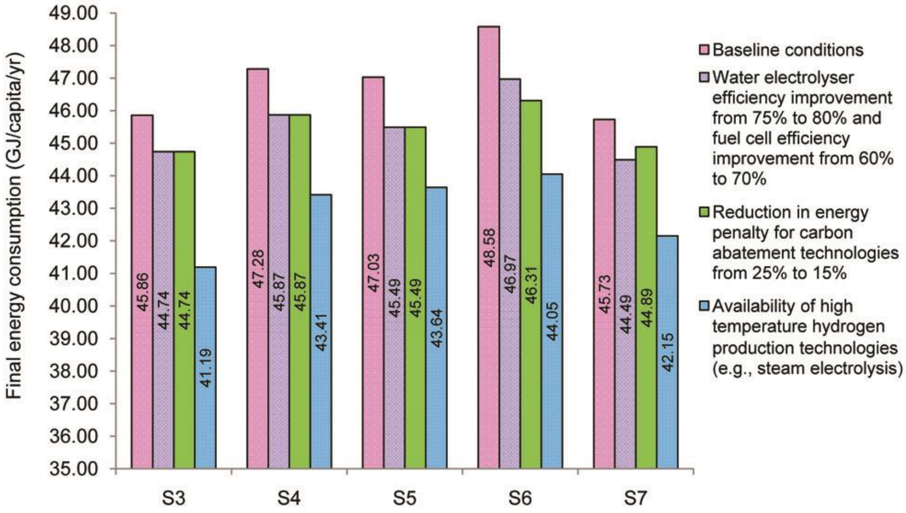

Figure 5. Sensitivity studies on minimum energy requirement for a net-zero India by 2070.

potential for further improvement in their energy consumption characteristics. These include large-scale water electrolysers, hydrogen fuel cells and carbon capture technologies as well as changes in established industrial processes such as steel production, ammonia synthesis, etc. Thus, relevant parameters such as electrolyser efficiency, fuel-cell efficiency and energy requirement in carbon capture (Supplementary Materials, Appendix III, Table A2) vary about their baseline values and changes in the final energy requirement under scenarios S3–S7 are estimated to account for these potential variations. Figure 5 shows the results.

Scenarios S3–S5 which are based on hydrogen utilization but do not include carbon capture technologies, show a 2.5–3.1% reduction in per capita final energy consumption when efficiencies of water electrolysis and hydrogen fuel cells improve from 75% to 80% and 60% to 70% respectively. Additionally, reduction in energy consumption of carbon capture processes under scenarios S6 and S7 from 25% to 15% can reduce overall final energy consumption by 2.3% to 4.8%. With the availability of advanced technologies such as high-temperature electrolysers, a further 10% reduction in final energy requirement is possible as energy requirement for hydrogen production reduces (Supplementary Appendix II).

Estimates for total final energy requirement in India

Based on the inferences from the previous sections and data in Figure 5, the minimum final energy consumption of India in 2070 is expected to lie between 41.2 and 48.6 GJ/capita/yr (i.e. 11,454 to 13,511 kWh/capita/yr). The lower end of the energy requirement spectrum will be adequate for India's development needs only if there is commercial availability and widespread use of efficient and advanced technologies such as high-temperature nuclear reactors, concentrating solar power plants, high-temperature steam electrolysers, etc. Assuming India's population to be 1.5 billion by 2070, the total available final energy (using mostly low-carbon energy forms with abatement technologies for residual emissions) for the country must be between 17,180 and 20,266 TWh. Considering additional 10% energy required for transmission and distribution of electricity and hydrogen to end-users[31], the minimum amount of electricity to be generated is about 18,900–22,300 TWh. This is in line with the range of values from a recent projection by Chaturvedi and Malyan[32], which indicates that electricity generation in India has to rise to about 18,000–24,000 TWh/yr by 2100, depending on specific technology combinations and pathways adopted for net-zero emissions in different sectors. Therefore, this study establishes that a minimum compounded annual growth rate of 2.3% per annum of the total final energy consumption till 2070 will be required from the 2019 value of about 7330 TWh. Considering electricity consumption, a minimum compounded growth rate of 5% per annum is required from the 2019 baseline consumption.

Additional energy requirement estimation

Several factors other than those considered in the previous sections will affect the energy needs of India. The most important among them are quantified below.

Infrastructure development: A high level of human development in India will require rapid infrastructure development (e.g. roadways, transportation, buildings, irrigation systems, clean energy and power generation and distribution networks, communication systems, healthcare services, financial services, education, etc.). This will be accompanied by increased levels of urbanization, supported by

Table 3. Energy needs for rapid infrastructure development in India by 2070 (refs 33, 34)

Material	India's consumption rate (kg/capita/yr)	World average consumption rate (kg/capita/yr)	Embodied energy (MJ/kg)	Additional energy requirement (TWh/yr)
Steel	75	225	35	2190
Cement	195	500	8	1018
Glass	2.5	9	15	41
Aluminium	2.5	11	200	709
Copper	0.6	10	71	278

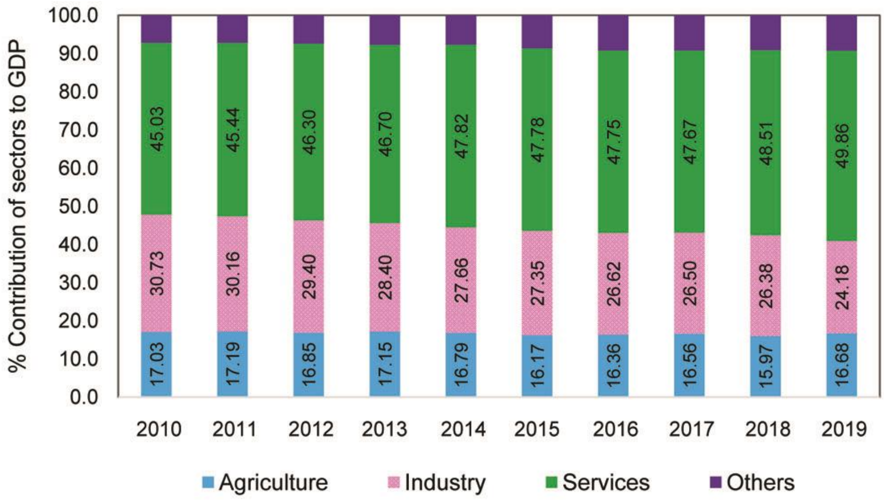

Figure 6. Composition of the Indian economy from 2010 to 2019 (ref. 37).

significant growth of the built environment. There will be much greater consumption of raw materials such as steel, cement, glass, etc. When decarbonization and extensive electrification targets are to be concurrently achieved, much greater demand will be placed on materials such as copper, aluminium, silicon, lithium, cobalt and rare earths. There is additional energy consumption associated with mining, processing and utilization of these materials. Some estimates are provided in Table 3 based on closing the gap between the current consumption rate of the most significant infrastructure-related materials in India and the global average, and the embodied energy or specific energy consumption in their manufacturing and processing by 2070.

Table 3 shows that the additional energy needs may be as high as 4235 TWh per annum in the industrial sector to scale up manufacture of some of the most critical infrastructure-related materials and low carbon energy technologies, particularly during initial phases of rapid development, where most of the upfront investments and material requirements are concentrated[33–35]. This number can be brought down substantially by industrial energy efficiency measures (which will reduce the embodied energy of the materials), material recycling (e.g. scrap steel recycling in electric furnaces) and reuse. The requirement will also taper-off to a lower value when the pace of development attains a plateau.

Digitalization of services: The development of the services sector in India can be expected to be accompanied by high levels of digitalization, particularly in information-technology (IT), communications, financial services and the education sector. This will lead to additional final energy requirement, specifically electricity for data-centre operations. It is estimated that globally about 1–2% electricity consumption today is by data centres[36]. Thus for a Digital India in 2070, an additional 200–500 TWh electricity consumption can be taken as a conservative estimate.

Changing nature of the Indian economy: Considering data of the composition of the Indian economy (expressed by per cent contributions X_1, X_2, X_3 and X_4 respectively, of agriculture, industry, services and other sectors to GDP) (Figure 6)[37] and per capita final energy (PCFE) consumption between the years 2010 and 2019, the multi-variable regression equation eq. (2), (with $R^2 = 0.98$) provides a simplified mathematical representation. The parity plot is shown in the Supplementary Materials, Appendix IV, Figure A3.

$$\ln(\text{PCFE}) = 7.364 - 0.6025\ln(X_1) - 0.8165\ln(X_2) - 0.1335\ln(X_3) + 0.189\ln(X_4). \quad (2)$$

For an assumed long-term scenario where the Indian economy is primarily service-driven and has the composition

$X_1 = 10$, $X_2 = 25$, $X_3 = 55$, $X_4 = 10$, the per capita energy consumption at the current HDI = 0.645 is estimated to be 25.8 GJ/capita/yr from eq. (2), which is 33.5% greater than the current value of 19.3 GJ/capita/yr. Thus, extrapolating to HDI of 0.9 in 2070 with the same composition of economy, the per capita final energy consumption can be expected to lie between 57 and 65 GJ/yr, depending on the advances made in the electrification of end-use sectors, and development of advanced technologies for electricity generation and energy use. Structural changes in the economy will also generate new feedback mechanisms that will further affect energy consumption, which may not entirely be captured by correlations (such as eq. (2)) based on historic data.

Concluding remarks

The following are the results and insights from this study:

- India's energy transition and future energy mix must enable decarbonization through electrification across most sectors. Low-carbon, high-temperature heat sources in the industry will include hydrogen combustion, nuclear power and concentrating solar power systems.
- Final energy consumption may be as high as 31,275 TWh/yr by 2070 for development along a business-as-usual trajectory, which could be reduced to about 18,900–22,300 TWh/yr by electrification of the end-use sectors, adoption of advanced electricity generation technologies, improvement in energy efficiency and implementation of policies aimed at energy conservation.
- About 30–40% of final electrical energy consumption would be used to produce hydrogen by electrolysis (production rates ranging from 113 to 178 million metric tonnes H_2 per year), while the rest would be used to directly electrify and decarbonize specific sectors.
- Infrastructure growth to support high development and decarbonization may require additional 4235 TWh energy per annum (for materials such as steel, cement, etc.), particularly for initial phases of rapid development. Enhanced digitalization of the economy will require another 200–500 TWh of electricity to support digital infrastructure. Overall final energy consumption therefore will lie between 23,335 and 27,035 TWh per annum.
- Electricity consumption would need to increase by at least 5% per annum for the next 50 years. Hydrogen storage, distribution and transportation infrastructure is also required as part of the new energy system.
- Electric power grid modernization and extension along with charging infrastructure development and energy storage technology deployment are crucial to enable energy access by all and support development as most energy use will be in the form of electricity.
- Extensive electrification would also demand greater amount of materials such as copper, aluminium, lithium, cobalt, vanadium, manganese and silicon than are used today. Thus, ensuring a secure supply chain (both domestic and international) of these elements must be part of the long-term energy planning process.
- Energy planning must be linked to other dimensions such as waste management, waste recycling and reuse as feedstock in many industries and waste-to-energy initiatives, which would require additional energy input.

From the analysis, it appears that India needs to generate about 15,560–18,020 kWh/capita/yr for its citizens. Thus, a benchmark value for highly developed India's final energy consumption per capita per year can be taken as 16,000 kWh. Biomass-based energy forms are not considered as due to their low EROI values, they will not materially alter the estimates of the final energy consumption. Moreover, there are uncertainties regarding their carbon neutrality. A part of the final energy will be converted to hydrogen (~4800–6400 kWh/capita/yr) and the remaining (~11,200–9600 kWh/capita/yr) will be used directly as electricity. All processes aimed at power-to-power conversions such as from electricity to hydrogen and hydrogen to electricity have less than 100% efficiencies. Therefore, direct use of electricity for final services will require less energy compared to secondary carriers like hydrogen.

Future work has to include further refinement of the estimates and also factor in energy infrastructure to be installed for meeting the final energy demand. Refined estimates could be different, but one conclusion will not change, i.e. India needs a multifold expansion in electricity generation to meet its development aspirations. Unlike the situation in India, developed countries like those in Europe already have a high level of development as well as energy consumption, and they have to only deal with the transition to a net-zero energy system. Still, they have struggled with destructuring, unbundling, adding layers of rules over layers of rules for three decades, and are now struggling with the addition to the cost of energy as against the promise of free energy from the wind and the sun[38]. India needs to exercise utmost caution in its approach to achieve net-zero and base estimate of energy requirement only on credible improvements in available technologies. The estimate should also include energy inputs for harnessing technologies, for example, manufacturing solar cells in India, and their life-cycle impacts. As new technologies achieve technical and commercial maturity, a continuous update of the estimate has to be made. Estimation based on technologies that have not matured can lead to the formulation of policies that are not tenable.

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