SUSTAINABLE ALTERNATIVE FUTURES FOR INDIA

SAFARI

CSTEP
CENTER FOR STUDY OF SCIENCE, TECHNOLOGY & POLICY

Energy and Emissions Implications for a Desired Quality of Life in India

Part 2: Demand Estimation

Methodology and Sample Results from SAFARI

Center for Study of Science, Technology and Policy (CSTEP)

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Disclaimer

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Executive Summary

Developing countries face the unenviable challenge of balancing their developmental goals and climate targets. This project aims to understand the synergies and trade-offs involved in doing so, in the Indian context. Working towards these objectives, the research team at the Center for Study of Science, Technology and Policy (CSTEP) has developed the Sustainable Alternative Futures for India (SAFARI) model. It is a system dynamics simulation model that can help policymakers visualise various long-term low-carbon development trajectories for India, based on technology and policy intervention scenarios of their interest. One of the key imperatives has been to capture as many inter-sectoral interlinkages as possible, in a bottom-up manner.

Defining Developmental Goals

In the previous phase of this project, we defined select developmental goals inspired by India's national priorities as well as the Sustainable Development Goals (SDGs) laid out by the United Nations. The goals include food, housing, healthcare, education, transport, water, and power for all. 'Food for All' refers to achieving food security in India by producing a sufficient amount of foodgrains to satisfy a target per capita requirement. The 'Housing for All' goal involves filling the dynamic urban and rural housing shortage, which we computed based on homelessness, dilapidation, and congestion. 'Healthcare for All' looks at providing adequate healthcare facilities based on government norms, while 'Education for All' targets the construction of an adequate number of schools and colleges to improve gross enrolment ratios (GER). While the GER for primary schools is already close to 100%, the demand for schools in urban areas is likely to increase because of rapid urbanisation. 'Sustainable Transport for All' explores possibilities of lowering emissions (both greenhouse gases and other pollutants) from the emissions-intensive transport sector in India. While we have not set a target for the 'Water for All' and 'Power for All' goals, the model will provide us with estimates of the annual water and electricity requirements. Apart from their emphasis on fulfilling fundamental human needs, the goals were chosen for their bearing on energy demand and emissions.

The goals translate into two kinds of demands—annual operational energy demand and infrastructure build-out demand. In the current phase of the project, we estimated the materials, energy, water, and land demands arising from the goals. Based on population and per capita targets for various goals, we have modelled the total demand for food, housing, healthcare centres, schools, and transport fuels using system dynamics concepts.

Modelling Logic and System Dynamics

In SAFARI, the demands from the goals drive growth in the agriculture, residential, commercial, industry, and transport sectors. Sectoral growth is suitably adjusted by constraints in the availability of water, land, and materials. System dynamics allows us to capture the physical impact of these resource constraints and interdependencies among the demand sectors. For example, meeting the infrastructure goals of housing, healthcare, and education gives rise to an increased cement demand. In SAFARI's cement module, production increases correspondingly until maximum capacity utilisation is reached. When there is a gap between cement demand and supply, the cement shortage feeds back and constrains the number of houses, hospitals, and schools that can be constructed that year. Additionally, the gap informs cement capacity addition to increase production in subsequent years. This way, the housing, healthcare, education, and cement industry sectors dynamically grow, interacting with each other.

Another important feedback in our model comes from water availability. For instance, in the agriculture sector, the 'Food for All' goal drives foodgrain cultivation. This, in turn, gives rise to water demand based on irrigation coverage and type. Considering that there is a finite amount of renewable groundwater and useable surface water, and fierce competition for water from other sectors, water availability dictates how much land can be successfully cultivated. In this manner, we have dynamically modelled growth in sectors of interest based on demands and constraints. To ensure comprehensive estimates for the country's energy demand, the model also considers other subsectors (such as office buildings, retail stores, and other industries) exogenously.

Key Insights

Currently, India produces sufficient foodgrains but at the cost of grave environmental damage (groundwater over-exploitation, diminishing soil health due to fertiliser overuse, and greenhouse gas emissions). As the population grows and other sectors compete for water and land, it is inevitable that India will face a challenge in maintaining food security. In the SAFARI business-as-usual (BAU) case, India's foodgrain shortage in 2050 could amount to almost 70 million tonnes (Mt) if the Central Water Commission's estimate for total annual utilisable water in the country is considered. While regional variations in water availability and agricultural productivity could change the exact estimate for shortage, the overall shortage estimates are unlikely to reduce significantly. Especially with urbanisation-led arable land constraints, competition for fresh water from other sectors, and the increasing population, a combination of interventions is required to achieve food security. In the results section of the report, we explore some of these possibilities—such as dietary shifts from rice to less water-intensive coarse cereals, increased area under microirrigation, and reduced area under sugarcane cultivation—and the respective trade-offs.

For urban and rural healthcare infrastructure, 98% (total built-up area of 318 million square metres) of the BAU target construction can be achieved by 2050. When a more ambitious target is assumed (Ambitious scenario), only 83% can be achieved by 2050. The built-up area of educational buildings will likely rise to over 550 million square metres in 2050, with tertiary education institutes contributing to most of this growth. Health and Education contribute to a small fraction of the total construction materials demand, which is predominantly from the Housing sector.

The 'Housing for All' goal cannot be met in the 2050 time frame if current housing sanction rates continue to persist. To meet the *dynamic* housing shortage by 2030, the annual sanction rate must increase to 6.3 million for urban houses and 8 million for rural houses (SDG scenario as detailed in the report). As a result, the total cement production capacity in the country must increase to around 850 Mt by 2030. Using alternative building materials could reduce this demand.

In the transport sector, we found that the 'Ideal Modal Share' scenario has the maximum impact on reducing GHG emissions. While electrification and biofuels are also important, their individual contributions to mitigation are much lower than that of strategic modal shifts (such as shifting more towards public transport and rail-based freight). Combined electrification and modal shifts will likely see India's transport-sector emissions peaking at 550 Mt CO_2e in 2045.

Limitations and Future Work

One of the main limitations of SAFARI Version 1 is that all estimates are at a national level, which results in a lack of spatial variations across the country. This is particularly important in the water and agriculture sectors. We plan to include regional granularity in Version 2 of the model. In addition, the model currently looks only at the energy demand-side story. In the next phase of this project, we will use the demand estimates from this model to arrive at an ideal energy-supply mix using an optimisation algorithm. This will help us explore the extent to which our demands can be met through fossil-free sources. We will also include financial constraints, which are currently not present in the model. In the final phase of the project, we will integrate SAFARI into CSTEP's in-house decision-support system called Decision Analysis for Research and Planning (DARPAN). This visualisation tool will help achieve our objective of aiding policymakers in planning India's developmental pathways.

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List of Abbreviations

BAU	Business As Usual
BUA	Built-Up Area
CAGR	Compounded Annual Growth Rate
CEA	Clinical Establishment Act
CFL	Compact Fluorescent Lamp
CHC	Community Health Centre
CLD	Causal Loop Diagram
CUF	Capacity Utilisation Factor
DQoL	Desired Quality of Life
EWS	Economically Weaker Section
FAL-G	Fly Ash Lime Gypsum
FSI	Floor Space Index
GDP	Gross Domestic Product
GER	Gross Enrolment Ratio
HIG	High Income Group
HP	Horse Power
ICCT	International Council on Clean Transportation
IESS	India Energy Security Scenarios
IPHS	Indian Public Health Standards
kWh	kilowatt-hour
LBNL	Lawrence Berkeley National Laboratory
LED	Light Emitting Diode
LIG	Low Income Group

MIG	Middle Income Group
MoHFW	Ministry of Health and Family Welfare
NSSO	National Sample Survey Office
NTDPC	National Transport Development Policy Committee
NUHM	National Urban Health Mission
OECD	Organisation for Economic Cooperation and Development
ORGI	Office of the Registrar General & Census Commissioner, India
PHC	Primary Health Centre
pkm	Passenger kilometre
SAFARI	Sustainable Alternative Futures for India
SC	Sub-Centre
SDH	Sub-District Hospital
SEC	Specific Energy Consumption
TOD	Transit-Oriented Development
Toe	Tonne oil equivalent
UNEP-DTU	United Nations Environment Programme – Denmark Technological University
URDPFI	Urban and Regional Development Plans Formulation and Implementation
WSA	Wilbur Smith Associates

1. Premise

The World Economic Outlook reported that India is the seventh fastest growing economy in the world [1]. However, the country is poorly ranked (130 out of 189 countries) in the 2018 Human Development Index [2]. A significant section of the population does not have access to basic necessities such as food, housing, clean water and air, electricity, and healthcare. Furthermore, India's population is expected to rise and peak at about 1.7 billion by 2060, and urbanisation[1] is poised to go up to more than 50% by 2050 [3]. The sheer magnitude of this growth and the consequent efforts to overcome the developmental challenges imply a rapid increase in infrastructure and energy needs.

India is among the countries that have ratified the Paris Agreement. As per Article 4.19 of the Paris Agreement, India needs to formulate and communicate long-term development strategies based on lowering greenhouse gas emissions. The Government of India pledged to achieve its developmental agenda via low-carbon pathways in its Nationally Determined Contributions (NDCs).

Given this backdrop, the overall objective of this study is to develop a simulation model that can help policymakers visualise various long-term low-carbon development trajectories for India, based on technology and policy intervention scenarios of their interest. Considering that India scores poorly in many developmental indicators, we decided to primarily model long-term trajectories in which all people achieve a 'desired quality of life' (DQoL). Working towards these objectives, we conceptualised the study in four phases:

Phase 1: Defining DQoL in terms of select developmental goals

Phase 2: Estimating the annual demand for materials and energy to achieve DQoL

Phase 3: Optimising energy-supply options to meet the demands estimated in Phase 2

Phase 4: Integrating the energy demand and supply models into CSTEP's in-house decision-support system—DARPAN (Decision Analysis for Research and Planning)

1.1. Brief Summary of Phase 1

In the first phase [4] of this project, we defined DQoL in terms of basic developmental goals that contribute to overall human well-being. The selected goals include *food*, *housing*, *healthcare*, *education*, *sustainable transport*, *water*, and *power for all*, as summarised in Table 1. Apart from their emphasis on fulfilling fundamental human needs, the goals were chosen for their bearing on energy demand and emissions, and their connection to the Sustainable Development Goals (SDGs).

Table 1: Summary of selected goals

Goal	Description
Food for All	Achieving food security by producing a sufficient quantity of rice, wheat, coarse cereals, and pulses to satisfy a target requirement of 2,500–3,000 calories per capita per day (foodgrains contribute to around 65% of calorie intake in India)

[1] As of 2018, around 33% of India's population lives in urban areas.

Housing for All	Providing housing to all by constructing required houses and bridging India's housing shortage, computed annually based on homelessness (530,000 urban EWS-LIG people), dilapidation, and congestion
Healthcare for All	Providing sufficient healthcare infrastructure to meet demands by constructing required units (target 2.45 beds per 1000 people by 2050; today's number is 1.34)
Education for All	Providing adequate schools and colleges to improve gross enrolment ratio (100% GER for elementary, secondary, and senior secondary schools, and 60% GER for tertiary education)
Sustainable Transport	Exploring possibilities for reduced emissions (both greenhouse gases and pollutants)
Water for All	Ensuring adequate supply of clean water for all requirements, including direct human consumption, agriculture, construction, and industries
Power for All	Providing access to ample electricity and clean fuels to satisfy the energy demands of the country

The targets for 'Water for All' and 'Power for All' are derived from the annual demands from other sectors. Essentially, they become prerequisites to the achievement of other goals. We will explore electricity supply options, and the potential to achieve 'Power for All', in phase 3 of the project. The model user can modify all the goal targets by using sliders provided on the interface.

1.2. Objective for Phase 2

The objective for phase 2 was to estimate the materials and energy demands arising from the goals mentioned above, in a bottom-up manner. Each of the goals has its own requirements and constraints. Some (such as 'Food for All') have a year-on-year materials and energy demand. Others (such as 'Housing or Healthcare for All') have a one-time infrastructure construction demand, but there will be a recurring need based on population growth and dilapidation of buildings. Considering that it is possible to draw links between most of our goals, the objective was also to capture these interdependencies between goals and sectors. In the following sections, we will first explain the overall modelling approach and then delve into goal-specific details.

2. Approach

We have used system dynamics modelling to estimate the demands arising from the DQoL goals, as well as from other sectors, and their interlinkages. Considering the finite amount of land, water, and other materials, achieving DQoL or SDGs would mean competition for common resources. There would be a dynamic interplay between the goals and the main energy demand sectors (such as agriculture, industry, residential, commercial, and transport), and feedback structures will begin to emerge. For instance, to meet the food demand, more land must be cultivated with foodgrains. This, in turn, would increase water consumption. As more land and water keep getting used up, the resource constraints would eventually end up curtailing foodgrain production. Some of the feedback effects become evident in the model with a time delay. We wanted to understand the trade-offs and co-benefits between the goals and sectors. It is to capture such interactions and feedback that we chose to use system dynamics. We call our model Sustainable Alternative Futures for India or SAFARI.

Causal Loop Diagrams

Causal loop diagrams (CLDs) are an integral part of systems thinking and system dynamics modelling. They consist of dependent and independent variables connected to one another by arrows denoting the causal relationships among them. In Figure 1, we show the most quoted example of causal loops and polarities, where population depends on births and deaths [5]. As the number of *births* increases, *population* increases, and as *population* increases, the number of *births* in turn increases. This is called a reinforcing loop, denoted by R. Reinforcing loops commonly lead to behaviours like exponential growth or exponential decay. On the other hand, as *population* increases, the number of *deaths* increases, but as the number of *deaths* increases, *population* decreases. This is called a balancing loop, denoted by B. Balancing loops often show goal-seeking behaviour, leading to S-shaped curves (upon reaching saturating values or goals) or oscillations.

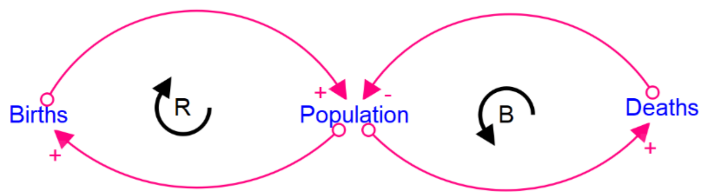

Figure 1: Example of a causal loop diagram (adapted from [5])

In this example, population is typically modelled as a 'stock' with an 'inflow' as number of births and 'outflow' as number of deaths. Stock and flow structures allow us to model systems that constantly change over time, under the influence of many variables. Most dynamic systems have multiple feedback loops, variables, and time delays. The most dominant loops usually determine the behaviour of the system over time. Figure 2 shows an overview of our modelling logic via a CLD. In the figure, the 'endogenous sectors' refer to sectors in the economy that are directly affected by our DQoL goals. The gap between our goals and the existing state of affairs will drive growth in these sectors, but the growth will be constrained by total land and water availability. Two main balancing loops exist in this system: one between gap and endogenous sectors, and the other between resources and endogenous sectors. Therefore, the model will dynamically move towards reducing the gap and reaching the goals. This will give us a more normative projection for how these sectors *should* grow to meet the DQoL standards for all.

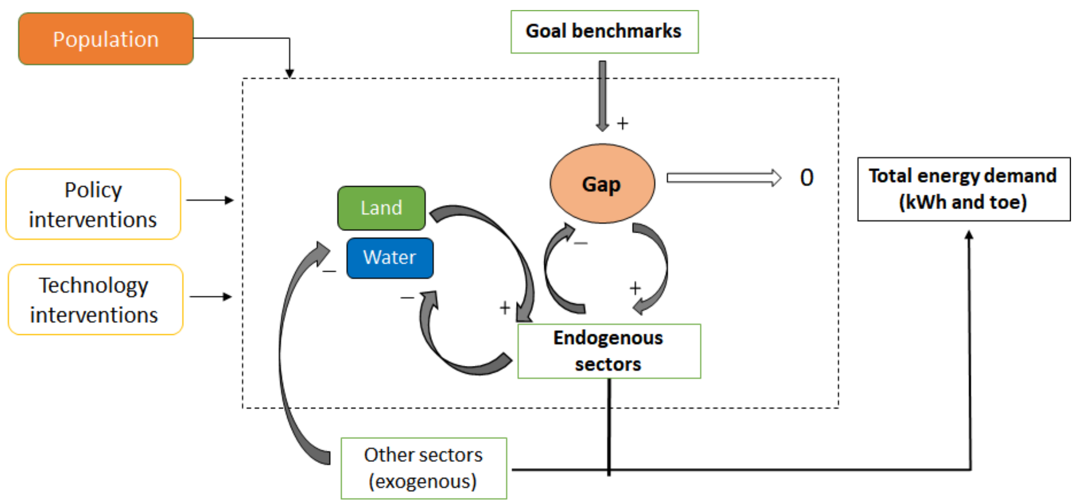

Figure 2: Key modelling logic in SAFARI

Other sectors not directly impacted by our goals that still compete for the common resources are assumed to grow at a business-as-usual (BAU) rate exogenously (mostly based on IESS trajectory 2). Finally, we added up the year-on-year energy demands from both endogenous and exogenous sectors to arrive at the total energy demand of the country. Sectors involved in electricity supply were not taken into account at this point in this study. We will estimate the optimal energy supply mix as part of the next phase of this project. While Figure 3 and Figure 4 provide an overview of the scope as well as sectors considered endogenous, we have explicitly detailed out the endogenous, exogenous, and out-of-scope sectors in the Appendix (Table 10).

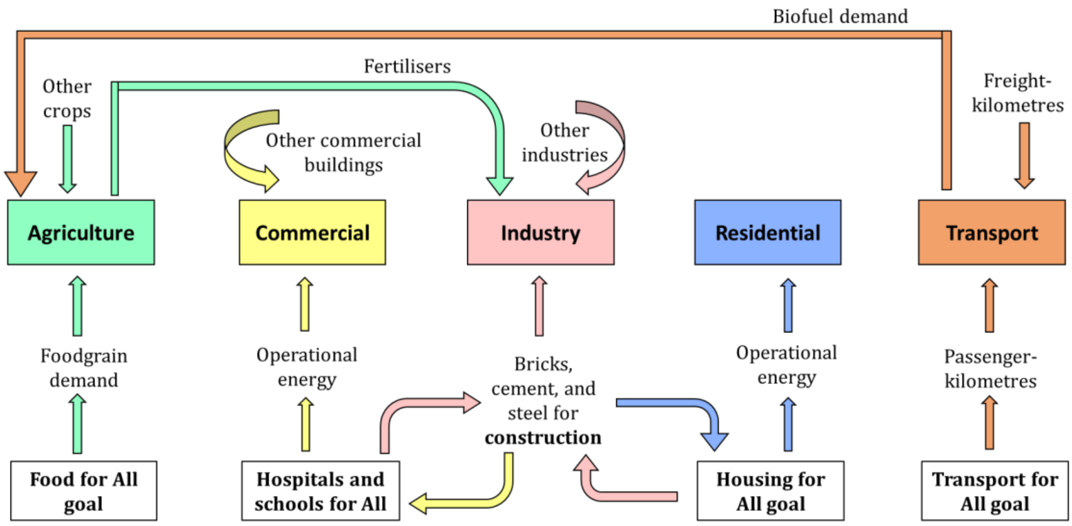

Figure 3: Demand-estimation modelling framework in SAFARI

Figure 3 depicts the demand-estimation framework. The year-on-year demands arising from the goals in a bottom-up manner merge with the BAU sectoral growths estimated in a top-down manner within the major demand sectors of the economy—agriculture, commercial, industry, residential, and transport. For instance, area under foodgrain cultivation is determined in a bottom-up manner from the 'Food for All' demands, while area under other crops grows at BAU rates. Cultivation of both foodgrains and other crops is subject to arable land and water constraints.

Figure 4 shows a simplified version of the integrated causal loop with all the goals and sectors interlinked. This is to provide an overview of the scope, before elaborating the sectoral details. The 'Food for All' goal drives foodgrain production via area under cultivation, which in turn drives fertiliser demand and production. Similarly, the Housing, Healthcare, and Education goals drive the construction industry in their respective sectors by increasing the demand for cement, steel, and other construction materials. Passenger and freight transport also contribute to the overall energy demand and link to agriculture via biofuel demand. Essentially, the energy demands from agriculture, residential, commercial, industries, and transport add up to give us the total annual demand for achieving DQoL. In addition to providing insights on sectoral demands and growth, this framework allows us to see how water or arable land constraints affect India's ability to reach DQoL. It also helps us address the trade-offs that might become necessary and determine the best way to prioritise the goals.

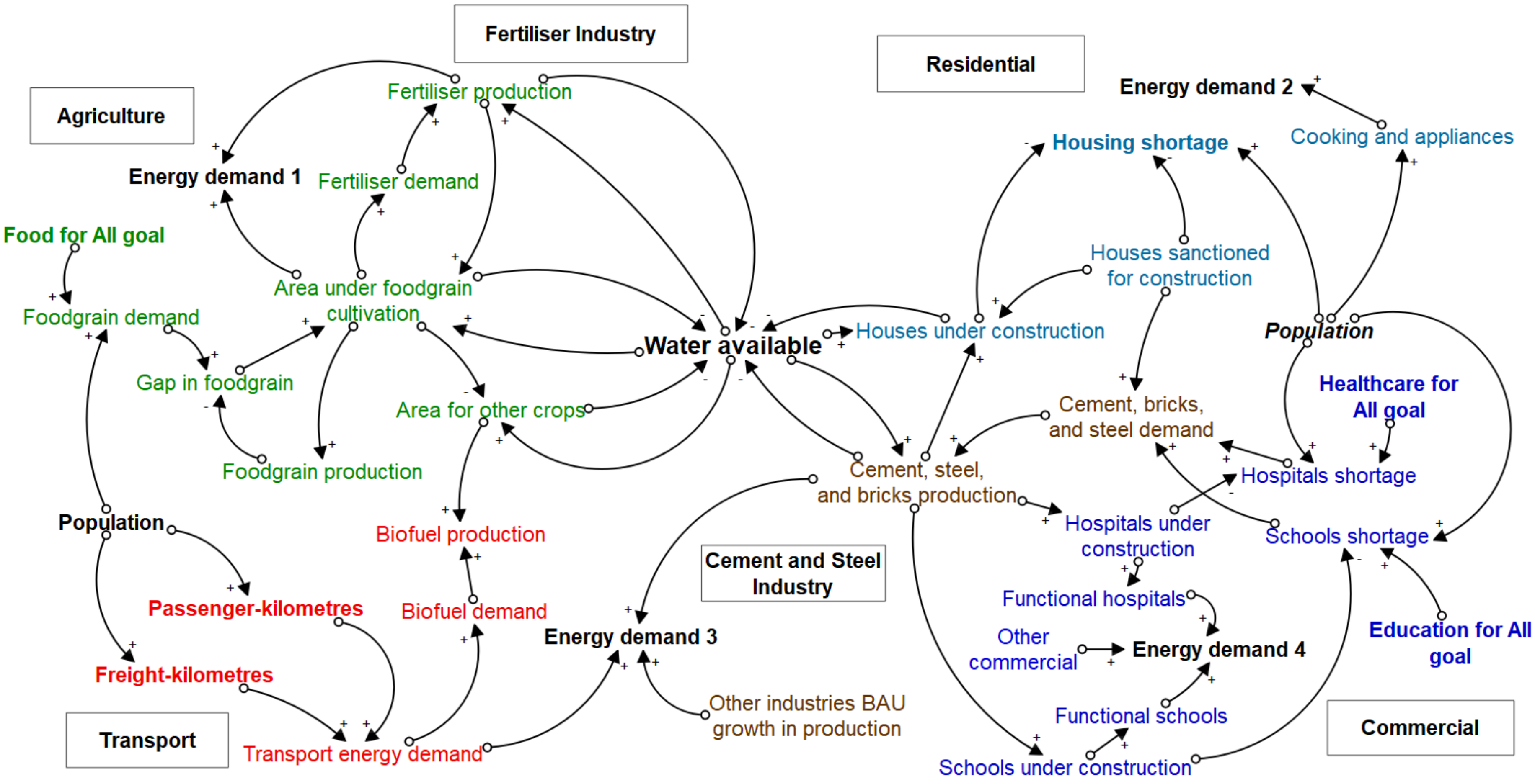

Figure 4: Simplified causal loop diagram for SAFARI

2.1. Water Sector

Water is one of our main resources and constrains growth in sectors that depend on it. We have modelled water availability as a stock with a steady inflow of 1,123 billion cubic metres (BCM) per year for the business-as-usual case, based on estimates of 'annual utilisable water' in India [6]. As shown in Figure 5, apart from the **BAU** scenario, we looked at three more scenarios based on other estimates [7], [8] and assumptions:

- **1151 BCM:** The annual inflow is assumed to be 1,151 BCM.
- **Excess water:** We assumed the total inflow of utilisable water to be 1,350 BCM[2], which seems to be sufficient—no negative feedback on sectoral growths (especially agriculture). This allows us to see what the actual demand would have been if water availability were not an issue. These estimates match that of other studies that follow a linear (non–feedback-based) approach for demand estimation.
- **Water shortage:** The total utilisable water inflow reduces to 60% of BAU by 2050 in a linear manner. This is to capture the effect of overall water scarcity.

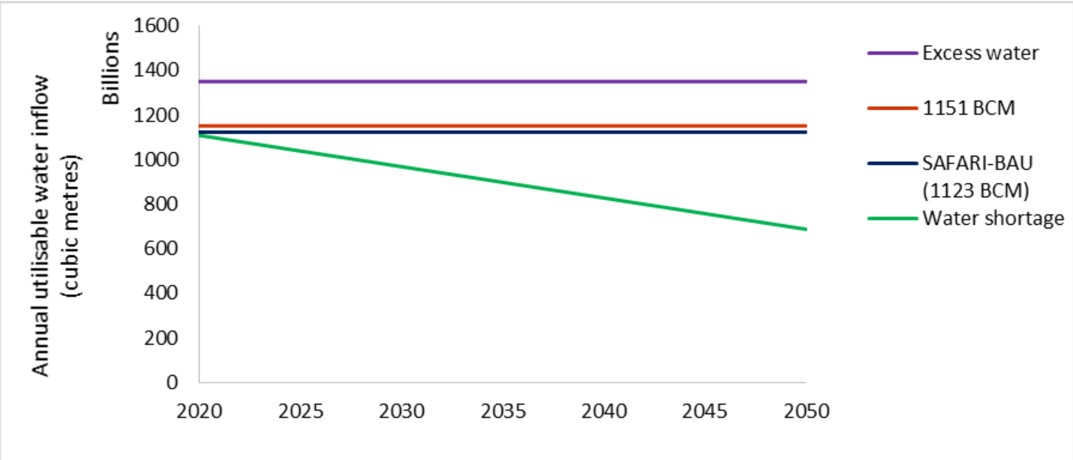

Figure 5 Total utilisable water in India in 4 scenarios

There are many outflows from this stock of water, which are defined as:

$$Sectoral\ water\ consumption = MIN\left(\frac{water\ available}{DT}, sectoral\ water\ demand\right)$$

This means that when there is no water shortage, all sectors will be able to draw out as much water as they need. Water will get distributed across sectors equally until it gets fully drained out, after which the impact of water shortage will feed back into all sectors in proportion to their demand.

In addition to the water inflow scenarios, we also included scenarios for domestic and industrial water recycling. In the domestic recycling scenario, 90% of all non-potable water is sourced via recycling by 2050. Meanwhile, in the industry recycling scenario, 70% of industrial water use comes from recycled water by 2050. These percentages are levers in the model that can be altered.

[2] Chosen based on the minimum water required to meet all demands in India

2.2. Food for All (and Agriculture Sector)

As described in Phase 1, the 'Food for All' goal is to achieve food security in India by producing a sufficient quantity of foodgrains[3]. We are considering all types of foodgrains—rice, wheat, coarse cereals, and pulses, and the total per capita requirement target is set to be 186 kg/year [9].

Figure 6 shows the CLD for the agriculture sector, and Figure 7 highlights the key feedback loops driving the sector. In the model, the presence of a gap between foodgrain production and foodgrain demand implies that the area under cultivation and crop yield are not sufficient to meet the goal. We have programmed the model to increase the area under foodgrain cultivation (subject to land and water constraints) to continuously strive to meet the goal every year. When there is a water shortage, the balancing loop B2 dominates the system. When there are no constraints, B1 dominates and the 'Food for All' goal will be consistently met. The area under cultivation and share of irrigation are used to calculate the annual irrigation water demand, and consequent energy demand for pumping. We also estimated methane emissions from livestock and rice cultivation [10].

The following section provides the assumptions and approach for our agriculture sector model, which includes foodgrains, other crops, fertilisers, livestock, and energy for pumping and tractors.

Foodgrains

- Foodgrains comprise rice, wheat, coarse cereals, and pulses.

- Foodgrain production is the product of *the area under cultivation* and *yield*. Yield for rain-fed crops is typically lower than that of irrigated crops [11]. The overall yield has been calculated as:
  $Overall\ yield_i = (Rainfed\ yield_i \times Rainfed\ area_i) + (Irrigated\ \ yield_i \times Irrigated\ area_i)$
  Where *i* represents each type of foodgrain. In SAFARI, yield is dependent on area under irrigation, type of irrigation, and use of high-yielding crop varieties (as a scenario switch).

- The area under cultivation is endogenously computed in the model to achieve the 'Food for All' goal every year. The main constraints towards expanding the area under cultivation are the availability of arable land, water, irrigation potential, and fertilisers.

    - **Land:** We use maximum arable land estimates from the land use statistics. Based on consistent historical behaviour of the ratio of land under foodgrain cultivation and that under all other crops, we apportioned the maximum arable land for foodgrains (65%) and all other crops (35%) [12]. We have also accounted for cropping intensity.

    - **Water:** Fraction of area under irrigation is increasing based on historical trends and agriculture policy, resulting in better yields over time. We set up checks for the area under irrigation (for both surface and ground) based on the ultimate irrigation

[3] Foodgrains constitute 65% of total calories and 71% proteins consumed in the average Indian diet and occupy 65% of the gross cultivated and 75% of the gross irrigated area.

potential [13]. Using data on crop water requirement [14], average irrigation efficiency of 60%, area under foodgrains, and the share of area under irrigation, we obtained the water demand from the 'Food for All' goal. We captured the effect of a water shortage on achieving the goal through a feedback loop. When there is a water shortage, the area under cultivation will proportionally reduce

For example, the formula to capture the impact of water shortage on the area under cultivation is:

Area change due to water shortage = IF water demand > water consumed THEN
$$\frac{-(water\ demand - water\ consumed)}{crop\ water\ requirement}\ ELSE\ 0$$

- **Fertilisers:** Availability of fertilisers pose constraints on foodgrain production. Further details have been provided on *page 9.*

Other Crops

- To estimate the energy and water requirement from the entire agriculture sector, we need to include non-foodgrain crops (henceforth referred to as 'other crops') as well. Because we have no goal drivers for other crops, we used growth trends, based on historical data, to estimate the cultivated area under other crops.

- The area under other crops is assumed to be growing at 1.2% compound annual growth rate[4] (CAGR), constrained by the maximum arable land. The fraction of area under irrigation for other crops is also assumed to be increasing over time, based on historical trends[5] [12].
- Using data on crop water requirements [14] and the irrigated area under the major crops [12], we computed the weighted average crop water requirements of other crops. Using this weighted average, irrigation efficiency, and irrigated area under cultivation, we get the annual water demand for other crops.

We have a water-shortage and fertiliser-based impact on the area under other crops as well, using the same logic as in the foodgrains sub-sector.

[4] Based on data from 1990-2016 from land-use statistics

[5] *Ibid.*

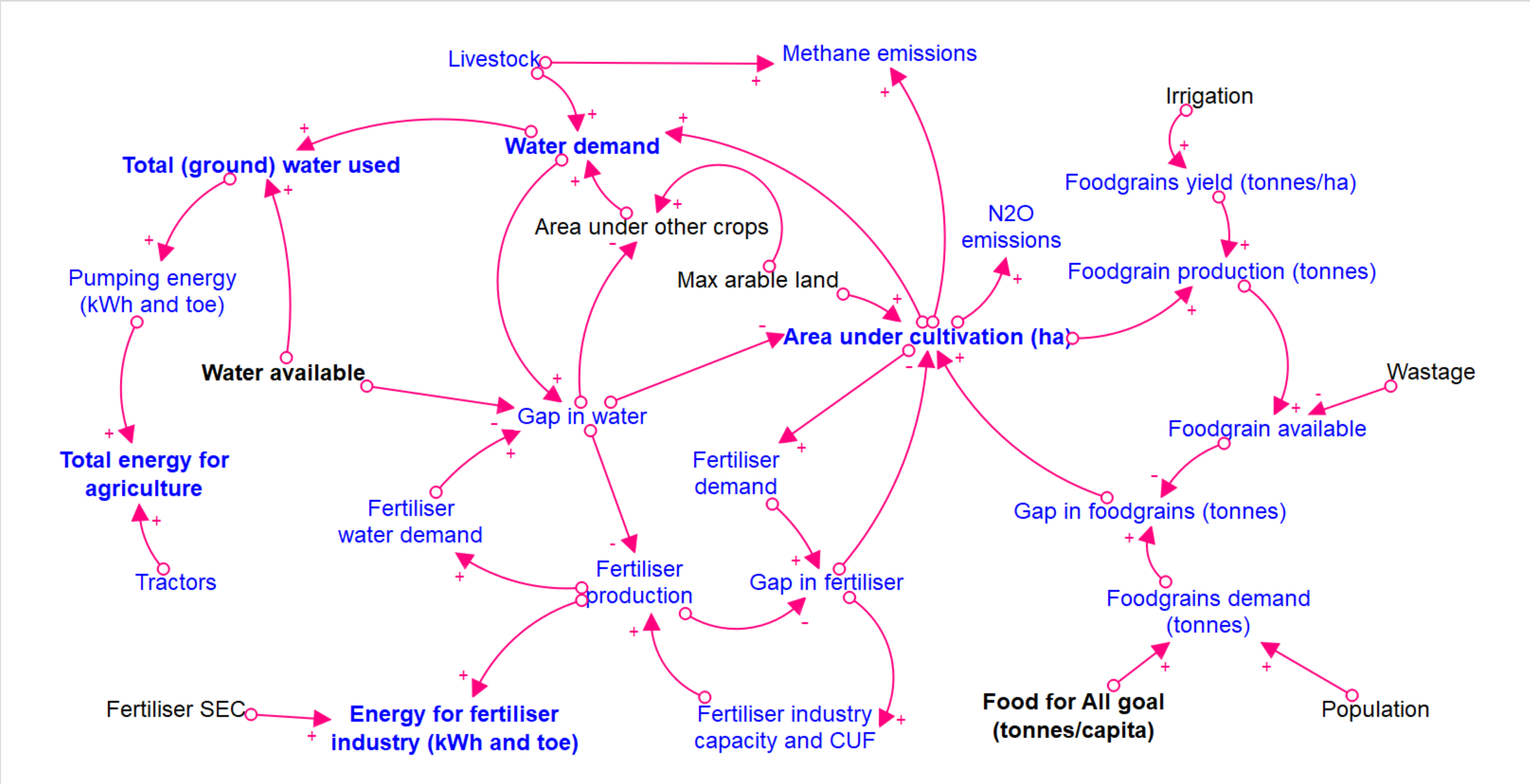

Figure 6: Food and agriculture causal loop diagram

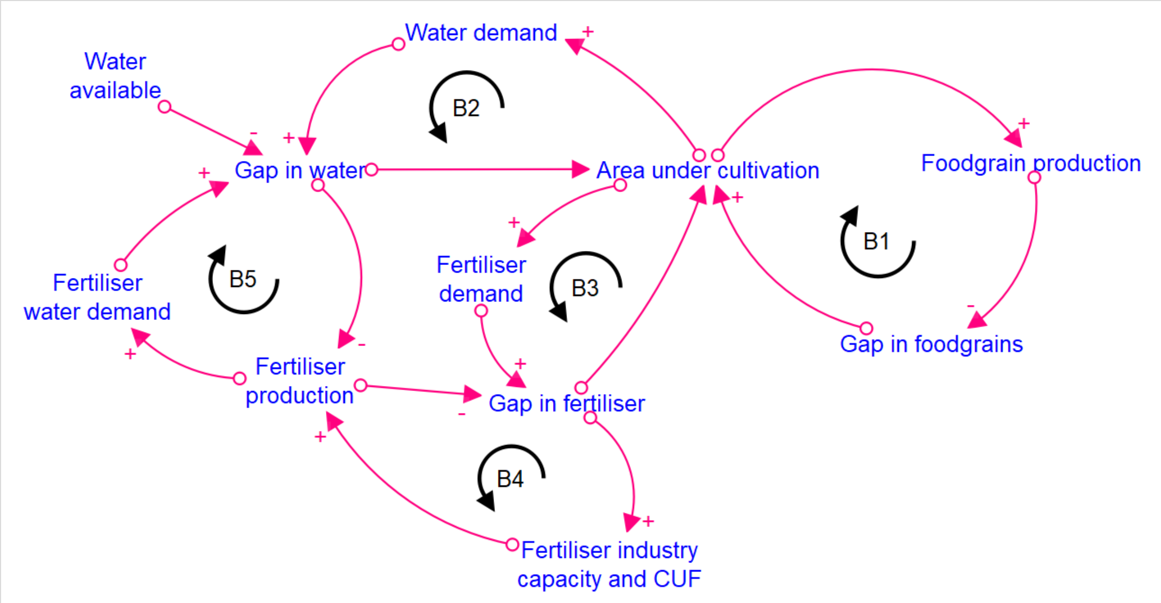

Figure 7 Key feedback loops in the agriculture sector

Fertilisers

- We computed the annual fertiliser demand for the agriculture sector using World Bank data on average fertiliser use per hectare [15] and the area under cultivation. Based on historical data, we assumed a growth trend such that the fertiliser use will potentially increase to 300 kg per hectare by 2050.

- This demand informs the model's fertiliser industry sector. In the fertiliser industry module, with information of the base year installed capacity and capacity utilisation factor (CUF) of the industry, the model checks whether the resultant fertiliser production (Installed capacity × CUF) meets the annual demand. If the demand is not met, as the first step, the CUF is increased to maximum CUF (100%)[6]; if the demand has still not been met, as the second step, the installed capacity is increased.

- India has been importing fertilisers to supplement its installed capacity. 20%–25% of the overall fertiliser demand is imported, as of now. We need to consider imports in addition to the domestic production so as to not overestimate fertiliser shortage and, therefore, impact on foodgrain production. Hence, imports have been included in the model to meet the gap. There is a user input possibility to determine the installed capacity required to meet the demand, with and without imports for future years [17].

[6] Fertiliser industry has recorded >100% capacity utilisation in the years 2008-2011 attributed to debottlenecking in this sector according to the Planning Commission's report on fertiliser industry [16].

Pumping Energy

- We assumed that the pumping energy requirement for irrigation is met entirely from groundwater pumping. Surface water irrigation is mainly gravity-driven via canals and other distribution systems, where no pumping is required.

- We estimated the pumping energy by looking at the total groundwater demand from foodgrains and other crops. We assumed the average pump size to increase from 5 HP to 6 HP by 2030, and 7 HP by 2050, considering the increasing irrigation water demand and depleting water levels. To calculate the average discharge rate, we used the formula [18]:

$$Brake\ horse\ power = \frac{discharge\ rate\ \times average\ dynamic\ head}{3960\ \times efficiency}$$

  where the discharge rate is in gallons per minute and the average dynamic head is in feet.

Tractor Fuel Use

- The average tractor use in 2011-12 was 20 tractors per 1,000 hectares [19]. We assume that it will go up to 40 tractors per 1,000 hectares by 2050. Other assumptions such as the average use per year and tractors' diesel consumption have been based on the IESS methodology [20].

Greenhouse Gas (GHG) Emissions

- We estimated methane emissions from rice cultivation, and nitrous oxide (N_2O) emissions from urea application, using GHG Platform India's emission factors [21]. Fuel emissions for pumping and tractors have also been considered in the agriculture sector.

Livestock

Water demand and methane emissions

We looked into the historical trends[7] of birth rate and average slaughter age from the Livestock Census to arrive at the number of livestock animals every year [22]. The average water requirement per animal is 0.5 litres per day for poultry, and 30 litres per day for all bigger animals [23].

We also estimated methane emissions from ruminants (based on methane emissions per animal of each type) using data from literature [24].

Energy for meat and milk

Based on the birth rate and slaughter age of livestock animals and the average quantity of meat per animal, we estimated the annual meat production. Based on the average meat consumption per capita, meat imports and exports were estimated. Relying on an the average slaughterhouse capacity, water requirement, and energy requirements, we also determined the annual water and energy requirements for the meat industry [25], [26].

[7] Livestock census – (1972-2012)

We projected the annual milk production using historical trends[8] on average in-milk bovine ratio and average yields per animal [27]. Consequently, the energy for milk production was estimated using data on specific energy consumption (SEC) per tonne of milk produced [28].

Scenarios and User Input Possibilities

- **Sustainable diet scenario (SD):** In this scenario, one can examine the land, water, and energy consequences if there is a significant dietary shift[9] in cereal consumption from rice to less water-intensive coarse cereals by 2030. Coarse cereals have a low glycaemic index [29] compared with rice and offer several health benefits including reduced insulin levels. In the BAU scenario, coarse cereals are mainly rain-fed (15% under irrigation currently, which increases to 25% by 2050). However in a scenario where coarse cereals replace rice, it is likely that more area will be brought under irrigation. In this scenario, therefore, area under irrigation under coarse cereals increases to 35% by 2050.
- **Microirrigation scenario:** In this scenario, irrigation technology shifts to microirrigation, with an irrigation application efficiency[10] of 90%. The target percentage area to be under microirrigation by 2050 can be set up by the user to check the sensitivity on land, water, and energy requirements.
- **Yield-based scenarios:** The **potential yield scenario** is a hypothetical scenario which involves India achieving full potential yields[11] (irrigated and rain-fed) of foodgrains by 2050. The **high yield scenario** is a moderate version of the potential yield scenario where yields improve only as much as required for the gap to reduce from BAU. Foodgrain-wise yields and scenario details are available in the Appendix (Table 11).
- **High-efficiency pumping scenario:** Pump set efficiency improves to 75% by 2050[12] from 50% in the base year in this scenario.
- **Natural farming scenario:** The user can examine how the fertiliser industry will be affected by regular farming switching to natural farming. The target percentage of cultivated area to be under natural farming can be set up by the user.

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[8] 2003-2012

[9] Current cereal consumption pattern in India (BAU) is 42% rice, 42% wheat and 16% coarse cereals. We examine a scenario if the consumption pattern changed to 15% rice, 40% wheat and 45% coarse cereals (calorific content of rice and coarse cereals is comparable per kg)

[10] Irrigation efficiency here means the ratio of amount of water required at the point of use to the amount of water to be drawn to deliver it.

[11] "Yield potential or potential yield (Yp) is defined as the yield of a crop cultivar when grown with water and nutrients non-limiting and biotic stress effectively controlled" [11]. In our model, the potential yields may not be achieved at the BAU settings, so we wanted to explore a hypothetical scenario if the potential yields were achieved what the implications would be on land, water and energy.

[12] In the BAU, pump set efficiency improves to 60% by 2050 from 50% in base year.

- **Solar pump scenario:** This scenario is to understand the impact of adopting solar pumps on the agriculture sector electricity demand. The user can set the target for 2050 for the penetration of solar pumps.
- **Foodgrain imports:** This scenario allows the user to check the impact of importing foodgrains on land, water, and energy requirements.
- **Fraction of area under groundwater irrigation:** The BAU scenario revealed that maintaining the current share of groundwater use for irrigation will lead to overexploitation of the renewable/replenish-able groundwater resources. With this lever, one can examine the optimal fraction to be irrigated by groundwater, and thus, get an idea of the corresponding investments required in the surface water irrigation infrastructure.

Limitations of Scope and Challenges

- We have considered the water demand only from the point of view of irrigation. We have not modelled rainfall, and therefore, the impact of rainfall shortage on rain-fed areas under cultivation has not been captured.
- Regional variations in water availability and demand have not been explicitly captured in this version of SAFARI.
- We have not analysed changes in farmers' incomes and the associated impacts.

2.3. Housing for All (and Residential Sector)

The 'Housing for All' goal focuses on the material and energy implications of meeting India's housing shortage. Our primary objective is to meet this shortage in the urban economically weaker section (EWS) housing, urban lower income group (LIG) housing, and rural housing categories. The SAFARI model also examines BAU shortage-filling and reconstruction for the rest of the housing sector (middle-and-high-income groups, or MIG and HIG). In this sense, it models the needs of almost the entire residential sector at the national level.

The scenarios in this segment of the model focus on reducing the operational energy (in terms of appliance use) and embodied energy (in terms of material choice) of the residential sector. The transit-oriented development scenario ties the SAFARI model's housing segment with its transport segment. The residential segment also impacts other model sectors, in particular the industry sector (through demands for steel, cement, etc.) and the water sector.

Approach and Assumptions

Shortage

Categories:

- Urban (EWS, LIG)
- Urban (MIG, HIG)
- Rural

Using expenditure data from the National Sample Survey Office's 66th round[13] [31], we categorised the urban population broadly into the four income groups[14] established by the Ministry of Housing and Urban Affairs [32]. We further clubbed these groups into two categories: EWS & LIG, and MIG & HIG. We then obtained the ratio of EWS & LIG to MIG & HIG population[15] and applied it to our urban population figures from 2011 onwards.

Components of shortage

The factors we considered while computing housing shortage are listed below. These factors, along with the broad methodology for calculating shortage, are based on the approach followed by the erstwhile Ministry of Housing and Urban Poverty Alleviation (MOHUPA) in its 2012 report on urban housing shortage [33].

a) Obsolescence/Dilapidation (houses that are structurally too old or unfit for habitation): The model considers both obsolescence from the existing housing stock (as of 2011) and new housing stock (that might be constructed to bridge the housing gap).

   We extrapolated the results of the NSS 65th round on Housing Condition [34] to 2011 Census data to estimate the age and condition of the existing housing stock. The Report of the Technical Group on Urban Housing Shortage (TG-12) [25] considers as obsolescent houses the following:
   - All houses more than 80 years old
   - All houses reported as being structurally 'bad' between the ages of 40 and 80 years

   The extrapolation was necessary because India's 2011 Census did not collect data on the condition and age of houses. Starting with this data, we built an ageing chain for urban and rural houses. The categories used are described in Table 2.

Table 2: Categories considered in ageing chain for housing obsolescence

Factor	Categories
Ageing chain categories for obsolescence (existing housing stock)	▪ Condition: good, satisfactory, bad ▪ Age: <1, 1 to 5, 5 to 10, 10 to 20, 20 to 40, 40 to 50, 50 to 60, 60 to 80, 80+ years

[13] These numbers were cross referenced with expenditure data from the Global Consumption and Income Project [30]

[14] EWS (economically weaker section), LIG (low income group), MIG (middle income group), and HIG (high income group)

[15] The current ratio of middle/high income population to lower income population is about 1:3. In reality, this is likely to change over time as incomes increase and households migrate across income categories. The Government of India's definition for affordable housing encompasses a variety of affordability considerations, owing to which ascertaining how different income classes for housing will be categorised in the future remains beyond the scope of the present study. At the same time, it is possible to make informed assumptions for possible future categorisations, and generate further scenarios with the model for meeting the housing shortage. The scenarios described in the results section of this report assume a ratio of 1:3 up to 2030, and 1:1 from 2030 to 2051. The latter is based on an assumption that government-initiated 'affordable housing' may exist for at least the lower five income deciles at any point of time.

Ageing chain categories for obsolescence (new stock built by model to fill shortage)	▪ Condition: all assumed to be constructed in 'good' condition ▪ Age: 0 to 30, 30 to 50 years

Once these houses pass through the ageing chain, they move into the category of dilapidated houses, and are then counted under the housing shortage. In the model, shortage due to obsolescence of existing housing stock (as of 2011) has been further subdivided into:

- Obsolescent houses as of 2011, which are all houses above 80 years of age, and 'bad' houses between 40 and 80 years of age
- Obsolescing houses from the 2011 housing stock with the passage of time (all houses 60-80 years of age in 2011, when they cross the age of 80; all other houses 0 to 60 years of age, once they cross the age of 80)
- Newly constructed houses, once they cross the age of 50 years (beyond the timeframe considered in the model)

b) Congestion: 18.42% (urban, EWS and LIG) [33] and 6.5% (rural) [35]
c) Homelessness: 530,000 (urban, EWS and LIG) and 0 (rural) [33]
d) Type of building construction:
   - Unserviceable *kutcha* houses (included under shortage)
   - *Pucca*, semi-*pucca*, and serviceable *kutcha* houses (considered habitable houses and excluded from shortage)
e) Others:
   - Voluntary reconstruction by MIG/HIG households (user input)
   - Percentage of housing stock reconstructed annually due to natural disasters (user input)

Shortage Filling

The sanction rate of houses for construction is a user input in the model (starting from 2019) that functions as a policy and decision-making tool. Depending on how soon users want to meet the housing shortage, they can enter the sanction rate at five-year intervals in one of two ways:

- As a percentage of the shortage that needs to be met
- As an absolute number of houses that needs to be constructed

Materials and Construction

Land - There are no land constraints in absolute terms. However, to avoid excessive urban sprawl and assume feasible home-to-work distances for EWS-LIG housing, we assumed that densifying within the existing urban space might be a requirement. Land made available through demolition (when obsolescent houses need to be reconstructed) feeds back into the land requirement computed for construction, and reduces the pressure on land. Some of the key area-related assumptions we took into consideration have been provided in Table 3, Table 4 and Table 5.

Table 3: Built-area assumptions

Type	Category	Average area (m^2)	References
Built area	Urban (EWS-LIG)	40	[33], [36]–[39], and expert consultation
	Urban (MIG-HIG)	150	
	Rural	50	

Table 4: Open space assumptions

Type	Category	Scenario	% of built area	References
Open space	Urban (EWS-LIG)	Large	50	Expert consultation
		BAU	25	
	Urban (MIG-HIG)	Large	50	
		BAU	25	
	Rural	None	50	

Table 5: Floor space index assumptions

Type	Category	Scenario	FSI	References
Floor space index (FSI)	Urban (EWS-LIG)	High	4	Expert consultation
		Medium	2.5	
		BAU	1.5	
	Urban (MIG-HIG)	High	4	
		Medium	2.5	
		BAU	1.5	
	Rural	None	1	

Materials

- In terms of materials for construction, we considered burnt clay brick masonry (BAU), hollow and solid concrete blocks, autoclaved aerated concrete blocks, fly ash-lime-gypsum (FaL-G) blocks, stabilised earth blocks, and regular fly ash blocks. We then assumed percentage shares of use for each of the construction technologies used and calculated material (cement, steel, sand, aggregate, brick/block) demand for each category of housing [40]–[42].

Water:

- For construction: $2m^3/m^2$ constructed plinth area [43]
- Domestic consumption target: 135 litres/capita per day [38]

Energy

Embodied energy

- For materials not considered under the industries module (sand, aggregate, etc.), we used embodied energy values from studies published in peer-reviewed journals [40]–[42].

Operational energy:

- We considered changing efficiencies of appliances (under four scenarios) and changing growth rates of appliance ownership (with user input possible to change the default 'high growth' scenario), alongside increasing rates of penetration in urban and rural areas.

Table 6: Operational energy considerations

Category	Types considered	References
Lighting	Incandescent, LED[16], CFL[17], tube lights	[44], [44]–[46]
Other appliances	Television sets, refrigerators	
Space cooling	Fans, air conditioners	
Water heating	N/A	
Cooking	Biomass, liquefied petroleum gas (LPG), renewable energy (RE), others (fossil fuel based)	

Residential Sector Scenarios

- Meeting 'Housing for All' policy targets (with user inputs for sanction rate, and three sub-scenarios of interest highlighted in this report)
- Construction technologies (shares of materials used for housing construction), circular economy with construction and demolition waste inputs, etc.
- Transit-oriented development (with transport sector)—high levels of non-motorised transport use, high-density construction
- Appliance penetration and efficiency (four levels)

Limitations of Scope and Challenges

- Economic factors (not considered here) could affect actual construction rates; this model simply indicates what is possible based on energy and resource constraints

[16] Light Emitting Diode

[17] Compact Fluorescent Lamp

- We have not explicitly considered how factors such as migration and ownership of multiple houses could affect the housing shortage, though these are largely implicitly accounted for through changing urbanisation rates and overall obsolescence rates
- The housing shortage and numbers are based on Census 2011 data, which is the most recent available; these numbers are the basis for governmental estimates as well, but might change if data for this sector is collected more frequently and in greater detail
- Because this is a national-level estimation, it was beyond the scope of the modelling exercise to capture regional variations in factors like floor space index and material use

Energy for the actual process of construction is variable and depends on labour, and has been omitted from energy calculations here.

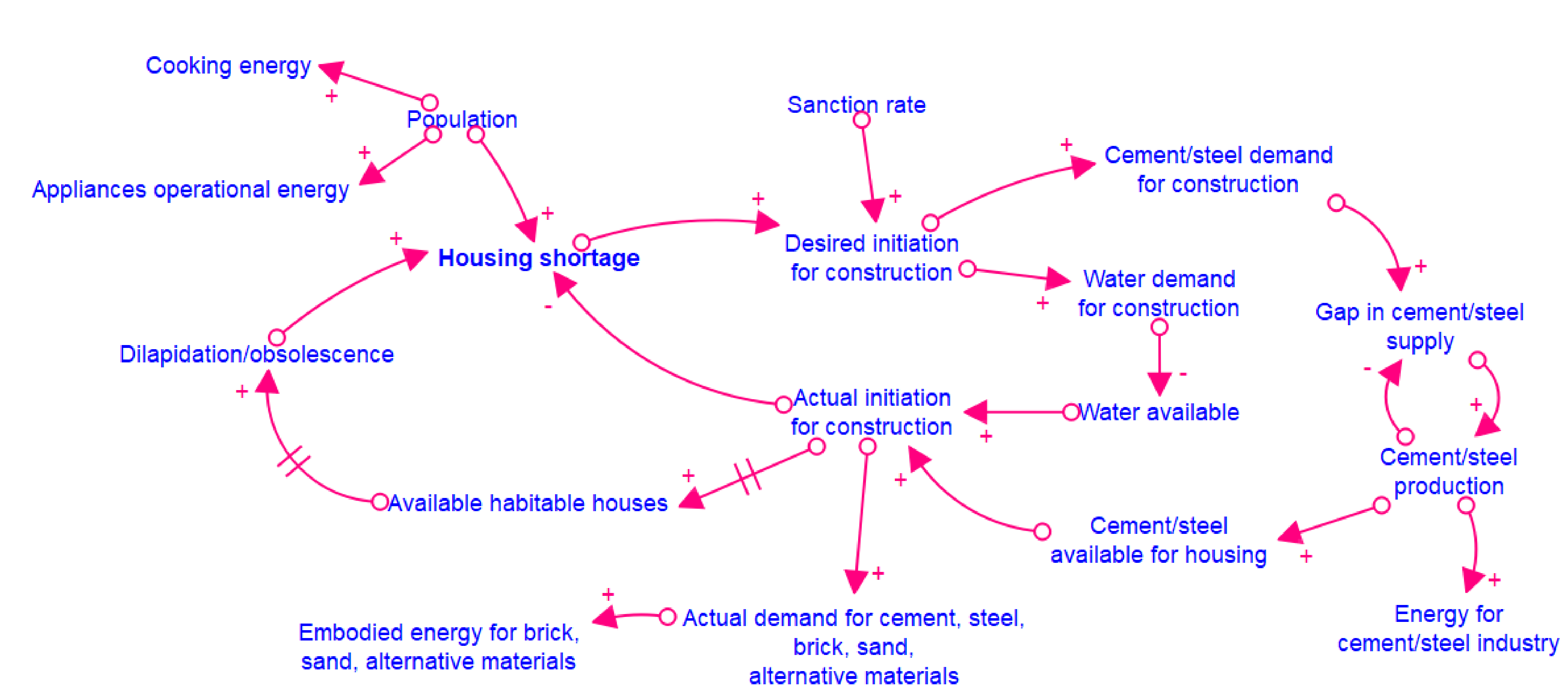

Figure 8: Housing causal loop diagram

2.4. Healthcare for All

In this sector, we assess the materials and energy demand for constructing the required healthcare facilities across urban and rural India. As described in Figure 9, shortage in healthcare units is the difference between healthcare units to be constructed and the actual number of units that get constructed (because of cement, steel, or water constraints). We have programmed the model to bridge the gap at the shortest possible time frame, given the constraints of material and water.

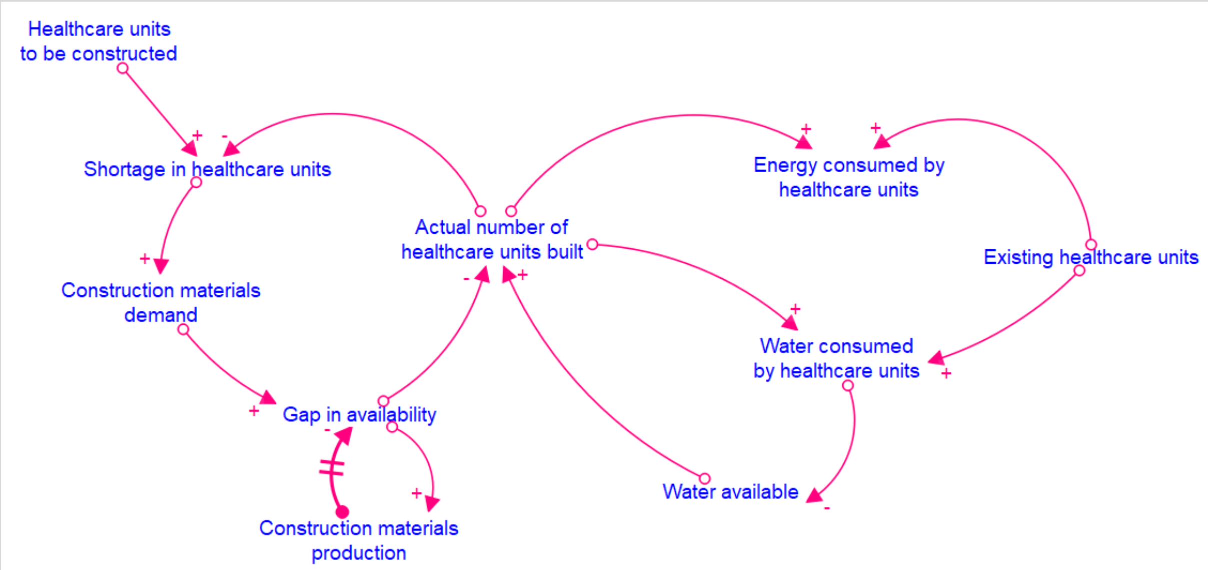

Figure 9: Causal loop diagram for healthcare sector

Assumptions and Approach

- The types of healthcare centres we have considered include sub-centres (SC), primary health centres (PHC), community health centres (CHC), sub-district hospitals (SDH), and district hospitals (DH). We have used data on the number of beds (based on metrics like beds per 1000 people and m^2 per bed) to account for other healthcare units such as government district hospitals and medical colleges, corporate hospitals and private medical colleges, and nursing homes and private economy hospitals. Table 7 lists targets to be achieved in the **BAU and ambitious scenarios**.

Table 7: BAU and ambitious scenario targets for healthcare units

Metrics for healthcare targets	2017	BAU 2050	Ambitious 2050
Beds per 1,000 people	1.3	2.45	3.41
Number of beds (million)	1.61	3.86	5.38
Average number of people per sub-centre (SC)[18]	5,400 (156,231 units)	4,700 (194,751 units)	3000 (304,578 units)

[18] One sub-centre (SC) in rural areas serves 5,000 people in plain and 3,000 people in tribal and hilly areas.

Average number of people per primary health centre (PHC)[19]	33,100 (25,650 units)	27,600 (33,128 units)	19,600 (46,594 units)
Average number of people per community health centre (CHC)[20]	152,000 (5,624 units)	114,000 (8,010 units)	90,000 (10,196 units)
Number of sub-district hospitals (SDH)	1,096	1,943	4,653
Number of district hospitals (DH)	780	1,216	1,638

BAU targets: [47]
Ambitious targets [48]; [49] [50], [51]

- We projected the number of hospitals to be built annually until 2050, respecting current trends in the near term, government targets in the medium term, and comparability with developed countries in the long term.
- The implicit assumption in the BAU scenario is that the country will continue to spend 1.15% of its GDP on healthcare [51], [52].
- In the ambitious scenario, based on the National Health Policy 2017, India is assumed to increase its public health spending to 2.5% of its GDP. We estimate that India may have 2 hospital beds per 1,000 population by 2025 [52].
- Rural and urban population and migration projection factors (by World Bank and ORGI) were considered to project demand for different kinds of healthcare units [53], [54].
- We used the Rural Health Infrastructure time series data (from MoHFW) for primary (SC, PHC, CHC) and secondary healthcare units (sub-district and district hospitals) [55].
- We used information about medical colleges and hospitals (both government and private) from the Medical Council of India (MCI) [56] [57]. Private healthcare facilities have also been taken into account in this study. The projections are based on data from NSSO, the trend of their share of the healthcare market (approximately 70%), and other relevant data from literature surveys [58].
- The built-up area of healthcare units is based on the norms on space per bed, defined in IPHS and CEA [59], [60]. For corporate hospitals, we based the built-up area on L&T Construction – Hospital infrastructure [61].
- Based on projections for built-up area under each healthcare unit type, we calculated the demand for land, water, electricity [62], cement, steel, and bricks. Details on construction materials have been provided in the Appendix.

[19] One primary health centre (PHC) in rural areas serves 30,000 people in plain and 20,000 people in tribal and hilly areas.

[20] One community health centre (CHC) in rural areas serves 120,000 people in plain and 90,000 people in tribal and hilly areas.

- Water demand data has been incorporated from the Code of Basic Requirements for Water Supply, Drainage and Sanitation (450 litres per head for hospitals with more than 100 beds; 340 litres per head if beds are fewer than 100) [63].
- The share of government hospital beds is kept constant in projections, as the Indian government relies on the services of private hospitals to fulfil the health insurance coverage to the poorest of the population under the Ayushman Bharat scheme [50] [64].
- We assumed that nursing homes and economy hospitals will see major growth, as metro cities like Delhi and Mumbai are already quite close to WHO standards for the number of beds per thousand people. Tier-2 and tier-3 cities and rural areas will see a spurt in economy hospitals (up to 100 beds) and nursing homes (up to 40 beds) [65].
- We have not taken into account ambulatory care (day surgery) in our study. Unlike other developed countries that have witnessed a decrease in beds per capita driven by progress in medical technology, India will only add beds as it has just 1.3 beds per thousand people, which is much below the world average of 2.7 in 2011 [66].
- We considered a demolition rate of 1% to factor in renovation and reconstruction due to ageing of buildings, which implies a 100-year lifetime for each building [67]

Limitations of Scope and Challenges

- The water-requirement projection has been based on water-allocation norms. However, some hospitals are reportedly drawing 4 to 10 times the allocated water [58] and the actual water use data is unavailable.
- Actual BUA (varying widely) per bed for DH and SDH is not available as these hospitals do not strictly follow the IPHS norms. Extra beds are often added to cater to the growing population. We have not considered small private clinics with no beds for admission facility.
- We have not considered the National Urban Health Mission (NUHM) in this study because it is still at a nascent stage [59] [60].
- The financial aspects of constructing and maintaining a hospital are out of scope for this phase of the project.
- Because we considered national averages for all parameters, variations across different states have not been captured. An in-depth, state-wise study can be targeted to determine infrastructural requirements/investments to enable better policymaking [70].

2.5. Education for All

In 'Education for All', we set targets for gross enrolment ratio (GER) to improve over time, as listed in Table 8. We have then projected the total built-up area of schools and higher educational institutes that have to be constructed such that there are adequate educational facilities. Similar to healthcare, construction of educational buildings is constrained by the availability of materials and water, as described in Figure 10.

Table 8: GER targets under BAU and ambitious scenarios

Levels of Education	Current GER %	BAU targets %			Ambitious targets %		
	2017	2025	2035	2050	2025	2035	2050
Elementary (I-VIII)	100	100	100	100	100	100	100
Secondary (IX-X)	82	95	98	100	95	99	100
Senior secondary (XI-XII)	57	68	80	100	79	99	100
Tertiary (higher education)	27	33	42	61	37	51	78

Ambitious targets assumptions [71], [72], [66]

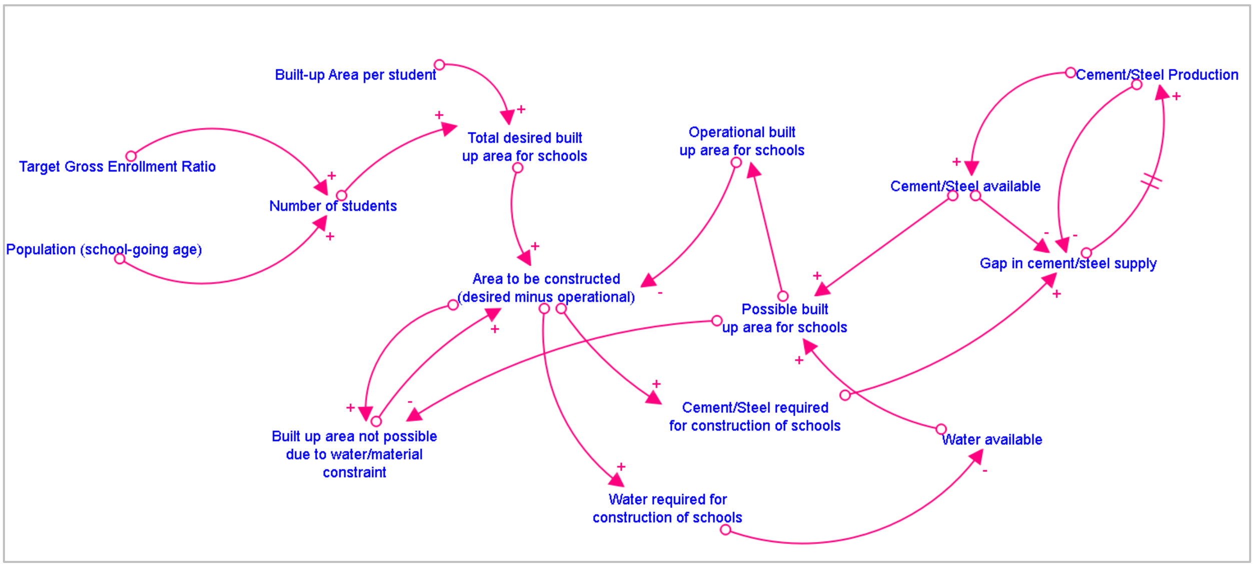

Figure 10: Causal loop diagram for education sector

Assumptions and Approach

- Schools (both government and private) are of three levels:
  - Elementary
  - Secondary
  - Higher secondary

  Colleges, universities, stand-alone institutes, and Institutes of National Importance are bundled into tertiary education.

- In the BAU case, the implicit assumption is that India will continue its public expenditure in education at the historical trend of around 3% [73]. Meanwhile, in the ambitious scenario, we assume that India will increase its public expenditure in education to 6% of GDP as against 2.7% in 2017-18 [71].

- The following norms have been used to calculate and project the built-up area (Table 9):
  - GER in each level of education
  - Instructional space norm per student in a classroom (1 to 1.26 m^2) [74]
  - Classroom size norms (66 m^2, minimum size to be at least 50 m^2) [75]

- Built-up area norm per student for educational institutes [74]

Table 9: Built-up area assumptions for educational buildings

Built-up area (on all floors) per student place	Primary schools	Secondary and higher secondary schools	Primary, secondary, and higher secondary schools
For a school having four sections per class	1.8 m^2	3.4 m^2	2.6 m^2
For a school having two sections per class	1.8 m^2	4.6 m^2	3.2 m^2
For tertiary education, built-up area of 4 m^2 per student and minimum classroom size of 66 m^2 are assumed.			

- Based on our projections for built-up area under each educational level till 2050, we have calculated the demand for land, water, electricity, cement, steel, and bricks.
- For water demand, data has been incorporated from the Code of Basic Requirements for Water Supply, Drainage and Sanitation (45 litres per person in day school and 135 litres in boarding schools) [63].
- We assume that all schools will be electrified (BAU as well as ambitious scenario) in the near future (as against 58%, 88%, and 60% schools electrified in rural areas, in urban areas, and in total, respectively) [76], [77], [78]. Electricity requirements have been estimated from 'Transforming the Energy Services Sector in India' [79].
- For calculating cement, steel, and brick demand, we used a methodology similar to that used in the healthcare sector [80]–[83]. We considered a renovation factor of 1% [67], and more details on construction materials, which have been provided in the Appendix.
- Birth rates are already declining in India, and elementary school-going population has a negative growth rate [53], [54]. Moreover, GER in elementary schools has reached 100% (in urban as well as rural areas). However, due to urbanisation, the demand for elementary schools will increase in urban areas. Consequently, some of the school buildings in rural areas will need to be abandoned, and new ones will have to be constructed in urban areas [84].

Limitations of Scope and Challenges

- Because we have considered national averages for all parameters, variations across different states have not been captured in detail. A more in-depth, state-wise study can be targeted to determine infrastructural requirements/investments to enable better policymaking.
- The quality of education and teachers and the cost aspects of setting up a school have not been considered in this study.
- Due to inadequate availability of data on the existing built-up area of educational institutions, our 2017 values were estimated using the same assumptions as for projections.

2.6. Transport Sector

As described in the Phase 1 report [4], 'transport for all' is slightly different from the other DQoL goals—there is no quantified target for it. The aim of the transport model is to have scenarios that will help plan the lowering of air pollution levels in urban areas, reduce overall GHG emissions, and decrease India's dependence on crude oil imports.

Passenger Transport

Figure 11 shows the causal loop diagram for passenger transport, with key variables that have been explained in the following points:

- We used historical trends in passenger-kilometre per capita (pkm/capita) to get a growth rate and assumed 20,000 km (flexible, can be modified by model user) as the saturation level, to arrive at an S-shaped trajectory for pkm/capita [85]. This is based on the observation from various countries that there exists a maximum distance (or time) that people would travel despite increase in disposable income.

- Consequently, the total passenger transport demand for India is calculated as:

$$Total\ pkm = \frac{pkm}{capita} \times total\ population$$

- To distribute the total pkm between urban and non-urban areas, we first divided India's cities into two categories—urban 1 (>5 million population) and urban 2 (<5 million population), and used their transport data [86] to compute:

$$Annual\ urban\ pkm = \frac{trips}{day} \times \frac{trip\ length}{trip} \times population \times 365$$

$$Annual\ nonurban\ pkm = total\ pkm - annual\ urban\ pkm$$

- The data for urban pkm (like the number of trips per day per person and trip length per trip) was collated by UNEP-DTU [86] from various sources, such as the Planning Commission's study on traffic flows [87], the Ministry of Urban Development's study with WSA on urban transport [88], and other studies in Indian cities.

- From the annual non-urban pkm, we assume 2% to be rural (which is currently assumed to be a mix of non-motorised and two-wheelers) and the rest to be intercity.

- Modes for intercity pkm include air, rail, and road (bus or car).

- Modes for urban pkm include public (bus, suburban rail), private (cars, two-wheelers, three-wheelers), and non-motorised, based on current trends and literature, including India Energy Security Scenarios (IESS) and the National Transport Development Policy Committee (NTDPC) [46], [89].

- Fuels in consideration include petrol, diesel, electricity, compressed natural gas (CNG), ethanol, biodiesel, and bio-jet fuel. All modal shares and fuel shares used in the model can be found in Table 12 and Table 13, respectively, in the Appendix.

- For urban areas, we computed local air pollution in terms of emissions of particulate matter (PM), volatile organic compounds (VOCs), nitrogen oxides (NO_x), and carbon monoxide (CO).
- At a national level, we also estimated the total GHG emissions from the transport sector (CO_2, N_2O, and CH_4) based on fuel efficiency and emission factors.

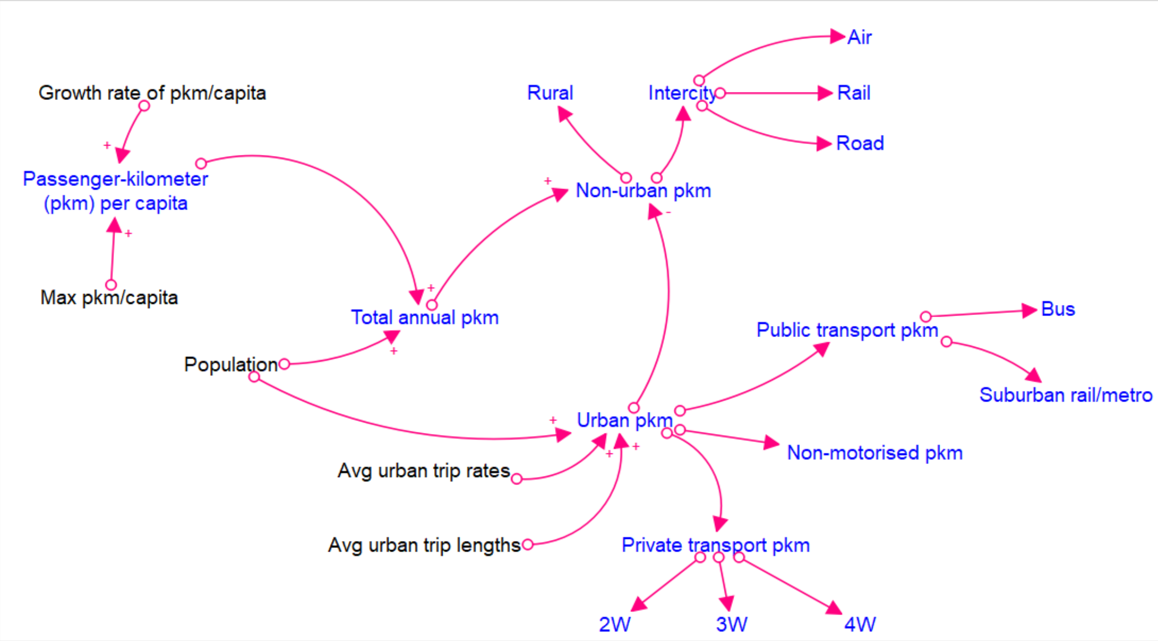

Figure 11: Passenger transport causal loop diagram

Freight Transport

- In freight transport or tonne-kilometres (tkm), we have not distinguished between urban and intercity. We used historical growth rates for tkm/capita to project for the future [85], [86].
- Historical and base year data are from NTDPC, Indian Railways Yearbook 2016-17, Directorate General of Civil Aviation statistics, IESS-2047, and OECD statistics [89], [90].
- Freight transport gets distributed between road, rail, air, and waterways.
- Road freight, or truck-based transport, is one of the hard-to-abate[21] sectors that run on diesel today. The model will look at alternative scenarios such as biodiesel and modal shifts to electrified railways. Details of modal shares and fuel shares used in freight transport have been provided in Table 14 and Table 15 in the Appendix.

[21] Freight transport via road is heavily dependent on diesel, and decarbonising has been a challenge worldwide.

- We included fuel-efficiency standards for heavy vehicles as provided by the Ministry of Power in consultation with the Bureau of Energy Efficiency and the study by LBNL and ICCT (for heavy vehicles less than 12 tonnes) [91], [92].

Scenarios for Transport

- **Ideal modal share (IMS):** Passenger transport shifts towards more public than private vehicles; freight transport shifts towards railways and water, rather than being road-heavy. This scenario is based on guidelines and plans laid out by the government, like the URDPFI Guidelines, and the National Transit Oriented Development Policy [93] (Table 12, Table 14)
- **Transit-oriented development (TOD):** This scenario considers densification of urban areas with an emphasis on public and non-motorised transport. Urban trip rates and trip lengths change to reduce the overall urban pkm and the modal shares follow IMS. Furthermore, this is linked to the high FSI scenario in the housing sector.
- **Clean fuels (CF):** The model considers moving towards electric mobility and biofuels, as mandated by the Indian government, and allows for user input of the ideal fuel share mix in 2050. In the CF scenario, we assumed 100% electrification of railways by 2030, and of 2-wheelers, 3-wheelers, cars, and buses by 2050. (Table 13, Table 15)
- **High fuel efficiency (HFE):** We assumed fuel-efficiency improvements coupled with shared mobility. In the BAU scenario, fuel-efficiency improvements are masked by reduced occupancy because of changes in people's preferences occurring due to an increase in disposable income. So, even if litres/vkm reduce, litres/pkm remain approximately constant. In the HFE scenario, we assume that occupancies will remain high, as we promote carpooling/shared mobility.
- **2G ethanol viability:** Second generation ethanol becomes viable from 2025 onwards, relieving the stress on agriculture to produce enough sugarcane.

Interlinkage with Agriculture Sector

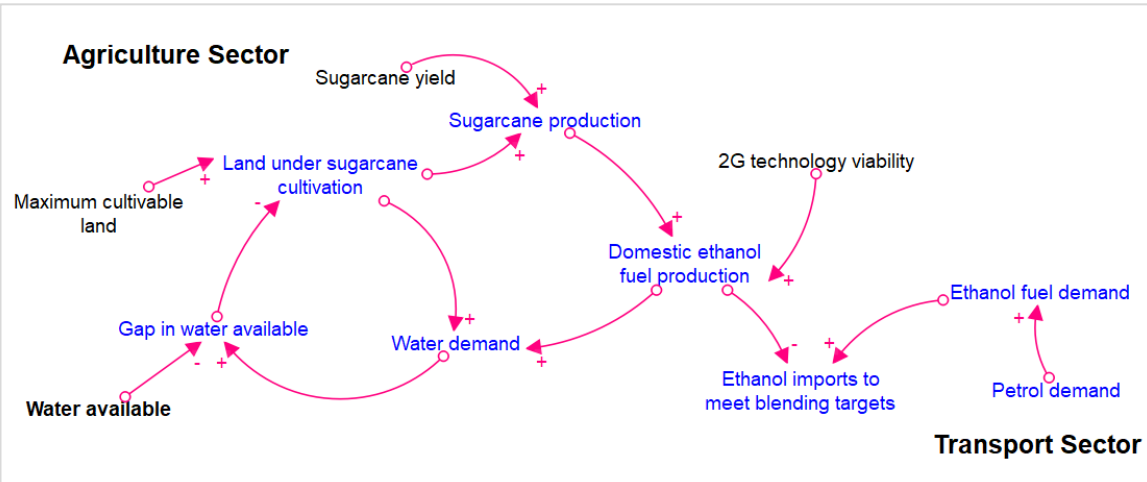

Figure 12: Interlinkage of transport and agriculture

The transport sector is linked to agriculture via ethanol demand. The National Policy on Biofuels 2018 has set a target of 20% ethanol blending in petrol by 2030. Figure 12 shows the feedback structures that emerge between ethanol demand, ethanol production, and sugarcane cultivation, to meet blending targets. As land under sugarcane cultivation increases, sugarcane production increases, causing more domestic ethanol production and reduced imports to meet India's blending targets. However, considering that sugarcane is a water-intensive crop, an increase in land under sugarcane cultivation decreases the water availability, which eventually poses a constraint on the cultivation itself. This approach (i.e., incorporating interlinkages) allows us to estimate the maximum quantity of domestic ethanol that we can produce accounting for the constraints of water as well as arable land (coming from the Food for All goal). If 2G ethanol technology becomes viable, some of these constraints will be eased.

Limitations of Scope and Challenges

- As with all sectors, we did not perform a cost-based analysis in transport, and therefore, modal shifts have not been directly analysed based on the cost of travel.
- Material and energy requirements for automobile manufacturing is out of scope.
- We have not considered bottom-up estimates for infrastructure requirements such as construction of airports, railway stations, bus stops, and roads. However, these are included in a top-down manner in the commercial sector as 'other commercial'.

2.7. Industries

The primary objective of this sector, in our project, was to examine the additional capacity required (if any) to meet the developmental goals for each sector. We have focused on three major industries that connect directly to our goals: fertilisers, cement, and steel.

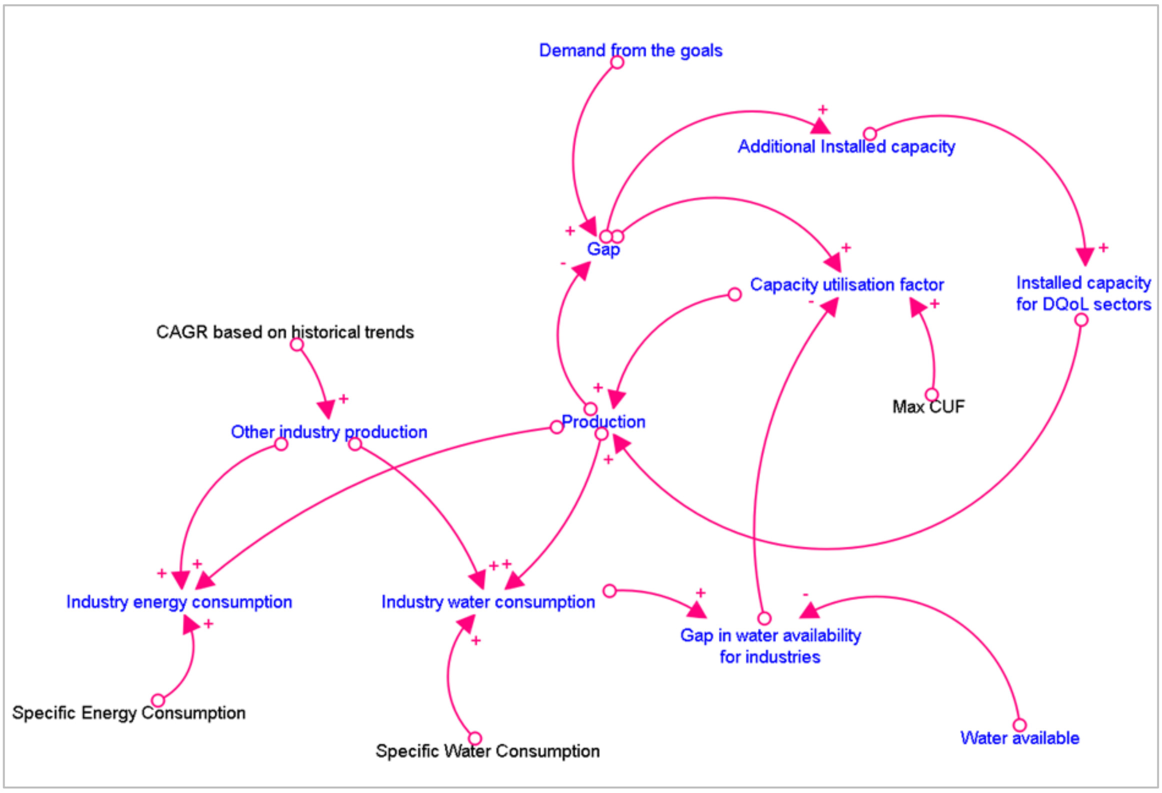

Figure 13: Causal loop diagram for industries module

The overall logic for the industries sector is captured in the causal loop diagram in Figure 13. The demand from the goals informs the respective industry sector of the model. Given the existing installed capacity and CUF of the industry, the model runs to check whether the resultant production (installed capacity * CUF) meets the demand annually. If the demand is not met, the CUF is increased to maximum CUF, as the first step; if the demand is still not met, the installed capacity is increased, as the second step.

Water shortage-based feedback has also been modelled in this sector. The water module (common for all goals and sectors) has been set up in such a way that each sector will be able to draw the minimum of *what is available* and *what the demand is from the sector*. So, in a shortage year, when the consumption is lower than the demand, production is reduced through CUF, thus leading to a demand–supply gap.

Fertiliser Industry

- Because the fertiliser produced is used entirely for the agriculture sector (which is included in the model), we have considered the entire installed capacity of the base year as the start point. Moreover, we have accounted for imports in addition to domestic production considering that India has been importing fertilisers to meet the demand. We have also provided for user-input scenarios to see the additional capacity required to meet the demand with full, reduced, and zero imports.

- We estimated the energy and water consumption of the fertiliser industry based on energy and water consumed per unit produced. There is also user-input provision for choosing the fuel mix—naphtha-based, natural-gas based, or fuel-oil based—for fertiliser production [94].

- The impact of fertiliser demand–supply gap has been explained in the agriculture model.

Cement and Steel Industry

- The demand for cement and steel comes from our infrastructural goals—Housing for All, Healthcare for All, and Education for All. However, the cement and steel industry caters to a wide variety of end uses, in addition to the demand from the developmental goals we have considered. To account for that, we took into consideration a fraction of the base year installed capacity dedicated to meeting our goals. Because the base year for our goals is 2011 and the demand numbers are from real data[22], we assumed the initial values of the installed capacity for cement and steel to be equal to the respective demands from the goals. Thereon, the model endogenously computes the capacity and production based on the causal loop diagram (CLD) logic described above.

- The rest of the production has been assumed to grow at BAU rates.

- Based on the specific energy and water consumption of each technology type, the energy and water consumption of the entire cement and steel industry is estimated annually. User-input options for examining the impact of energy-efficiency interventions, technology changes, and fuel mix for the cement and steel industry have also been provided [94], [95].

[22] This refers to the demand from the hospitals, schools, and houses that actually got constructed in 2011.

- The demand–supply gap in the cement and steel industry affects the housing, healthcare, and educational goals in proportion to their demands. The number of houses, schools, and hospitals built will be lower than the goals according to the annual gap, and the building shortage will accumulate year-on-year.

Other Industries – BAU

- For comprehensive estimates of the energy and water demand from the industry sector, we included industries that are not endogenously modelled.

- Based on historical trends[23] of energy consumption (thermal and electricity) for industries, we projected the demand from other industries.

- To estimate the water demand, we identified the most water-intensive industries; using specific water-consumption and production trends, we assessed the water requirements for other industries.[24]

[23] Energy Statistics 2019 (data from 2006 to 2015)

[24] Because thermal power plants are responsible for 87% of the total water consumption by industries currently, the estimates will change depending on our supply-mix possibilities, which will be explored in Phase 3 of the project.

3. Key Results

It is important to remember that *sustainably* achieving India's developmental goals is the guiding principle behind SAFARI. To ensure sustainable development, growth in all sectors will be constrained by the availability of water, land, and material resources. Moreover, we built SAFARI to be a flexible and user-friendly model, which works as a test-bed to explore policy interventions. It allows users to modify hundreds of variables using levers on the intuitive interface, and visualise the effects by running the simulation immediately. Many scenarios or combinations of scenarios can be visualised in each sector, based on user inputs. We provide **some** examples of such results here.

To reiterate, the broad questions that we are trying to answer are:

- By when can India meet its developmental goals, factoring in various constraints?
- What policy or technology interventions can help achieve the developmental goals quicker and more sustainably?
- What are the implications of achieving developmental goals on energy demands and GHG emissions?

3.1. Water Module

The SAFARI-Water module, as described in Section 2.1, is designed such that there is an inflow of 'total utilisable water' into the stock of available water every year. From this stock, various sectors withdraw water, based on their demands.

The scenarios explored in Figure 14 and Figure 15 are BAU (1,123 BCM per year), 1,151 BCM per year, excess water scenario (1,350 BCM per year), and water shortage scenario (reduces to 60% of 1,123 by 2050). Despite its limitation of being a national-level estimate, this model gives us an idea of the impact of water availability or constraint. SAFARI Version 2 (currently being developed) will explore the regional differences in water availability and demand, thereby providing a more granular view of the interactions and feedback. Here, we provide national estimates as a starting point to understand sustainable use of water resources. The water module can be used to build diverse context-specific scenarios in order to better understand the impact of water shortages on individual sectors. It can also help design better water-apportionment strategies and policies to adapt to and mitigate the adverse impacts of water shortage.

Due to our assumption in the modelling logic that the impact of water shortage is felt in proportion to the demand, we found that the agriculture sector takes the biggest hit when water demand exceeds the water available. As is evident from Figure 14, the gap in the foodgrain supply increases the most under the water-shortage scenario. Even under BAU, there exists a gap of around 25 Mt by 2030 and 70 Mt in 2050 (explained further in section 3.2). Figure 15 shows sectoral water consumption under the four scenarios. The agriculture sector seems to be the most sensitive to water shortage, in our model. Residential and industrial water demands are met even in the BAU case.

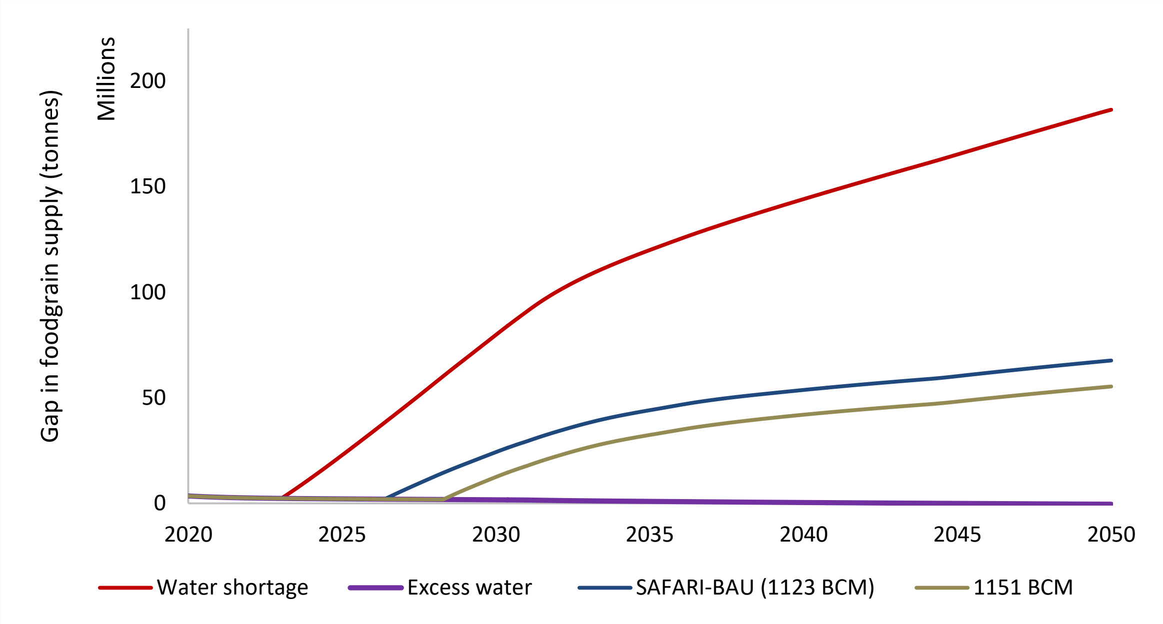

Figure 14 Gap in foodgrain supply under different water scenarios

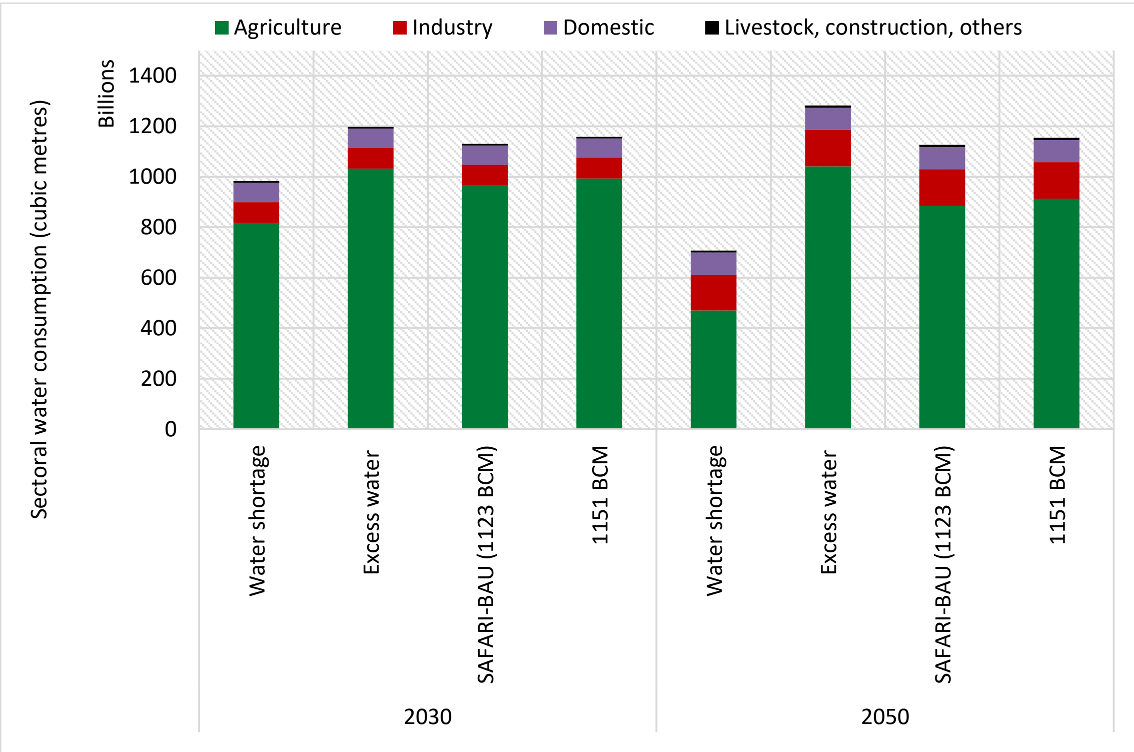

Figure 15: Sector-wise water consumption scenarios

3.2. Food for All and Agriculture

In the food and agriculture sector, achieving food security without over-extraction of groundwater (or unsustainable use of other water resources) is the primary goal. Currently, India produces a sufficient amount of foodgrains to feed its population. However, there is significant wastage, inefficient distribution, and over-extraction of groundwater resources. Challenges to achieving sufficient food production will also arise as the population grows while the arable land remains the same (or even reduces due to rapid urbanisation). In SAFARI's Agriculture module, we developed sustainable alternative scenarios to understand the challenges on the path to achieving food security.

Figure 16 shows the demand for rice, wheat, coarse cereals, and pulses in India to achieve the 'Food for All' goal, as defined previously. This demand does not include foodgrains for non-consumption purposes (like feed and seed preparations) and wastage, which are accounted for while calculating the gap in supply.

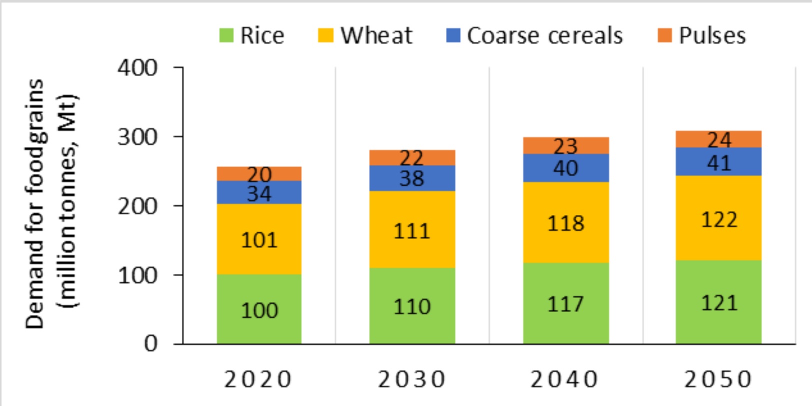

Figure 16 Annual demand for foodgrains in India

In a situation where there are no land or water constraints, foodgrain production in the country will be enough to meet the demand, that is, the gap will tend to zero. This is the 'excess water' scenario[25] represented in Figure 17, where the gap remains low and reaches 0 by 2045. Figure 18 shows that the irrigation water requirements (based on area under irrigation assumptions) for this scenario almost reaches the total 'utilisable' water in the country, leaving little for other sectors. Following a linear approach to estimate foodgrain production, without considering feedback of water availability, has the potential to arrive at such a result.

The SAFARI BAU scenario has a feedback structure based on water availability, which involves reduction of the area under cultivation, causing water demand to also simultaneously reduce (as described in the methodology section). The gap in BAU increases to around 25 Mt by 2030 and 70 Mt in 2050. This is an important result—the 'Food for All' goal cannot be achieved *sustainably* if the current diets, irrigation practices, and yields continue. We will now explore unique scenarios and some potentially sustainable combinations of scenarios.

In the 'sustainable diet' (SD) scenario (consumption of rice goes down and coarse cereals increases), predictably, the irrigation water demand goes down since coarse cereals require much less water than rice. The gap is less than BAU, at around 16 Mt in 2030 and 3 Mt in 2050. However, it does not reach zero because coarse cereals have a lower yield per hectare when compared with

[25] In BAU, the gap in foodgrain supply is due to water shortage (not land constraints), so we have chosen 'excess water scenario' as a proxy for a 'no constraints scenario'.

rice, and therefore require more land to achieve the same production quantity. So, in the SD scenario, while water is not a problem, land is.

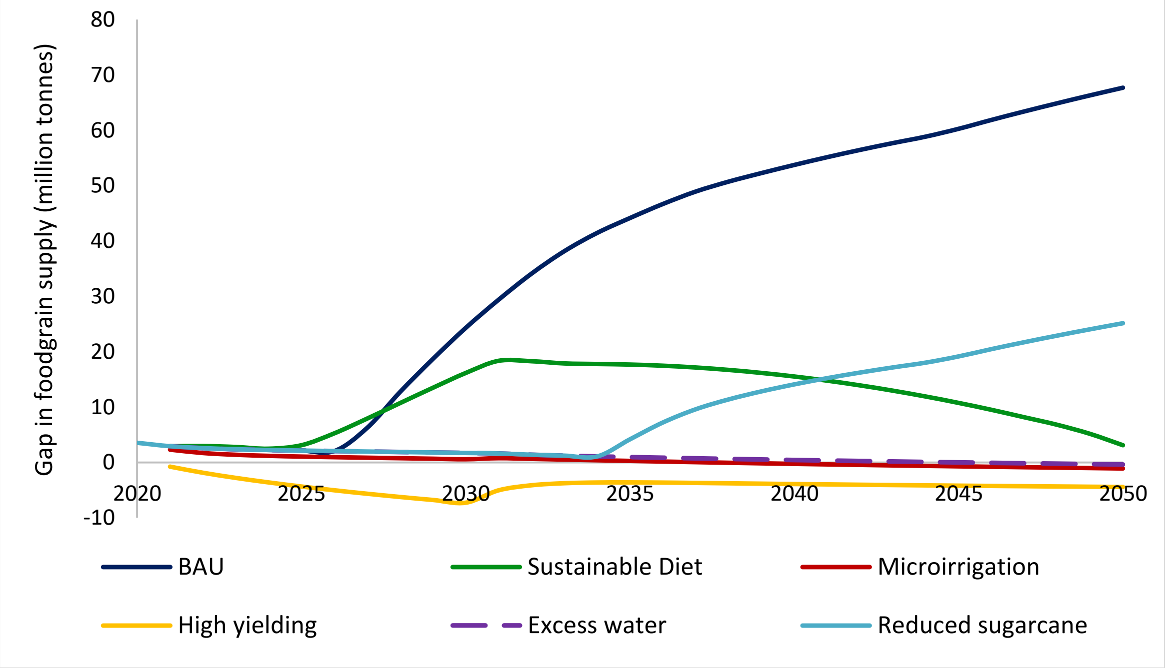

Figure 17 Gap in foodgrain supply to meet the 'Food for All' goal

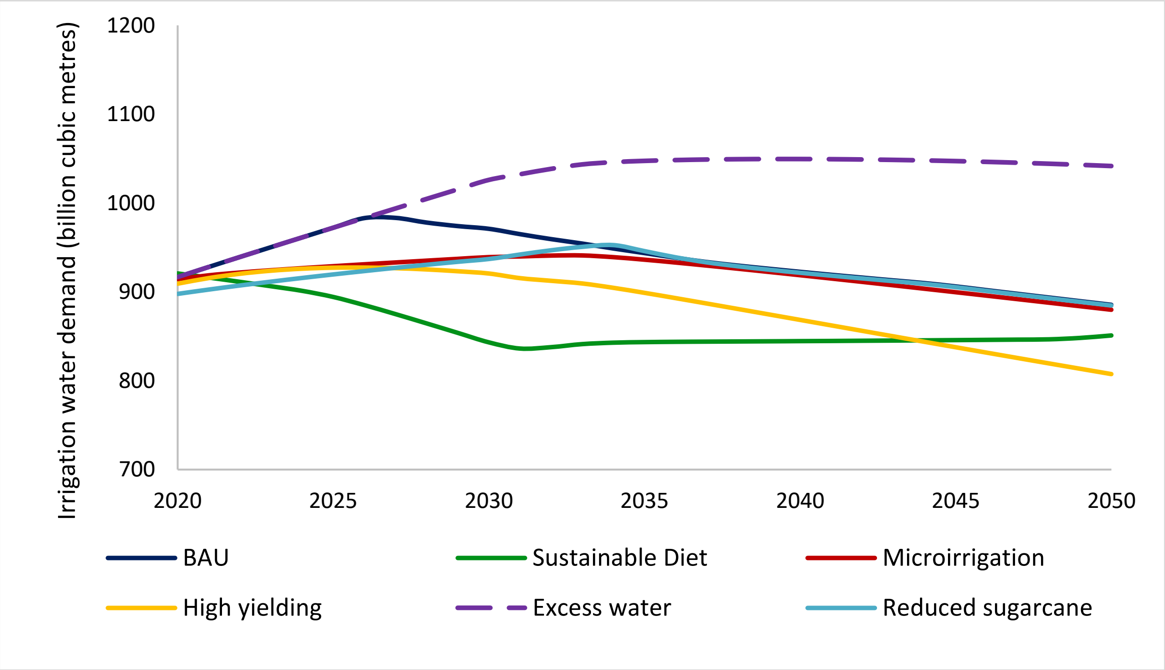

Figure 18 Irrigation water demand for cultivation of foodgrains and other crops

An aggressive microirrigation (MI) scenario (30% by 2030 and 60% by 2050) brings down the gap to zero. This is because water demand is comparatively lower than in BAU and the impact of water shortage is avoided, in addition to crop yield improvements associated with efficient irrigation. Reducing area under sugarcane cultivation from 5 Mha (current area) to 2.8 Mha by 2030 and 2.2 Mha by 2050 (in BAU, it would have increased to 9 Mha) brings down the gap to 25 Mt in 2050.

High-yield scenario (HY) consistently meets the foodgrain goals till 2050 with marginal surplus. This scenario provides a sense for the grain yield improvements necessary (through improved farming practices, scientific breakthroughs, etc.) to achieve food security. These scenarios so far look at one unique way each to reduce water consumption and subsequently try to meet the foodgrain gap.

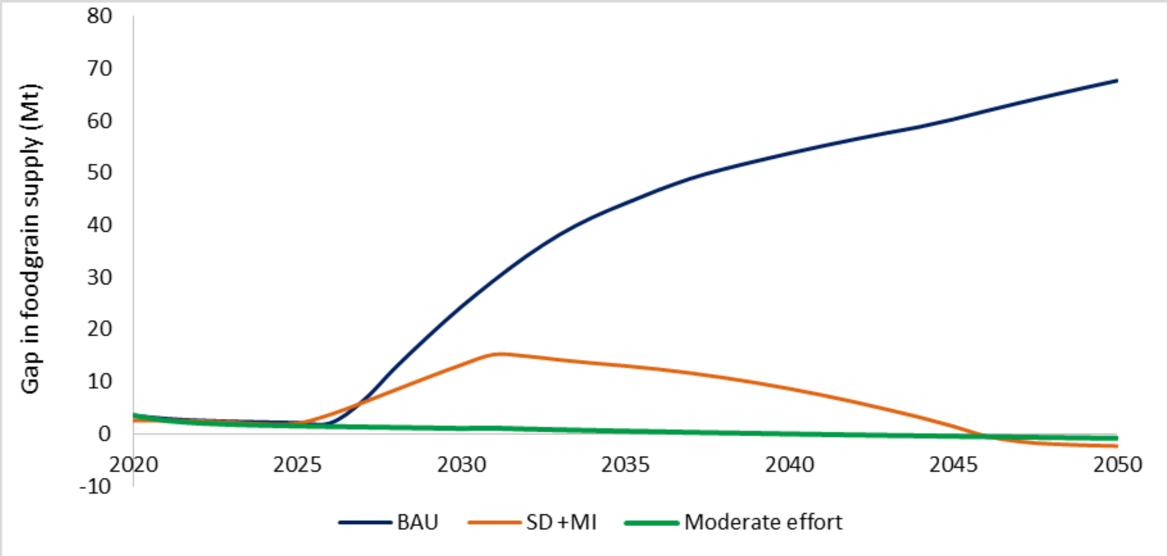

Figure 19 Gap in foodgrain supply in various combinations of scenarios

In Figure 19, we present a couple of examples of scenario combinations that reduce the gap. The SD + MI refers to a sustainable diet along with a 20% microirrigation by 2030 and 40% by 2050 scenario[26]. We also tried to combine some not-so-aggressive interventions under a 'moderate effort' scenario, where the gap is insignificant and reaches 0 by 2035 and onwards.

The moderate-effort scenario includes:

- Moderate microirrigation targets—20% by 2030 and 40% by 2050
- Water recycling in the domestic and industry sectors—50% and 60% by 2050 respectively[27]
- Reduced area under sugarcane cultivation—2.9 Mha by 2050

Similarly, SAFARI allows users to develop their own scenarios by using the levers for various interventions.

To explore the implications of the aforementioned interventions, we considered the following GHG emissions from the agriculture sector in SAFARI:

- methane from rice cultivation
- methane from enteric fermentation in livestock
- direct N_2O emissions from chemical fertiliser application

[26] A net area of ~35 Million Ha. India's microirrigation potential is [70 Million Ha](#).

[27] In BAU, 15% of industrial water needs are assumed to be met with recycled water

- CO_2 emissions from fertiliser production (industrial processes)
- CO_2 emissions from energy use—tractor and irrigation pumping energy (diesel and electricity[28])

In the SAFARI-BAU scenario, the total agriculture sector emissions increase to around 600 Mt in 2050. To understand the impact of achieving food security on GHG emissions, we will focus on emissions relating to crop cultivation alone (i.e., excluding livestock). In Figure 20, we plot agriculture sector GHG emissions (excluding methane from livestock) for various scenarios, as well as the emission intensity in 2030 and 2050.

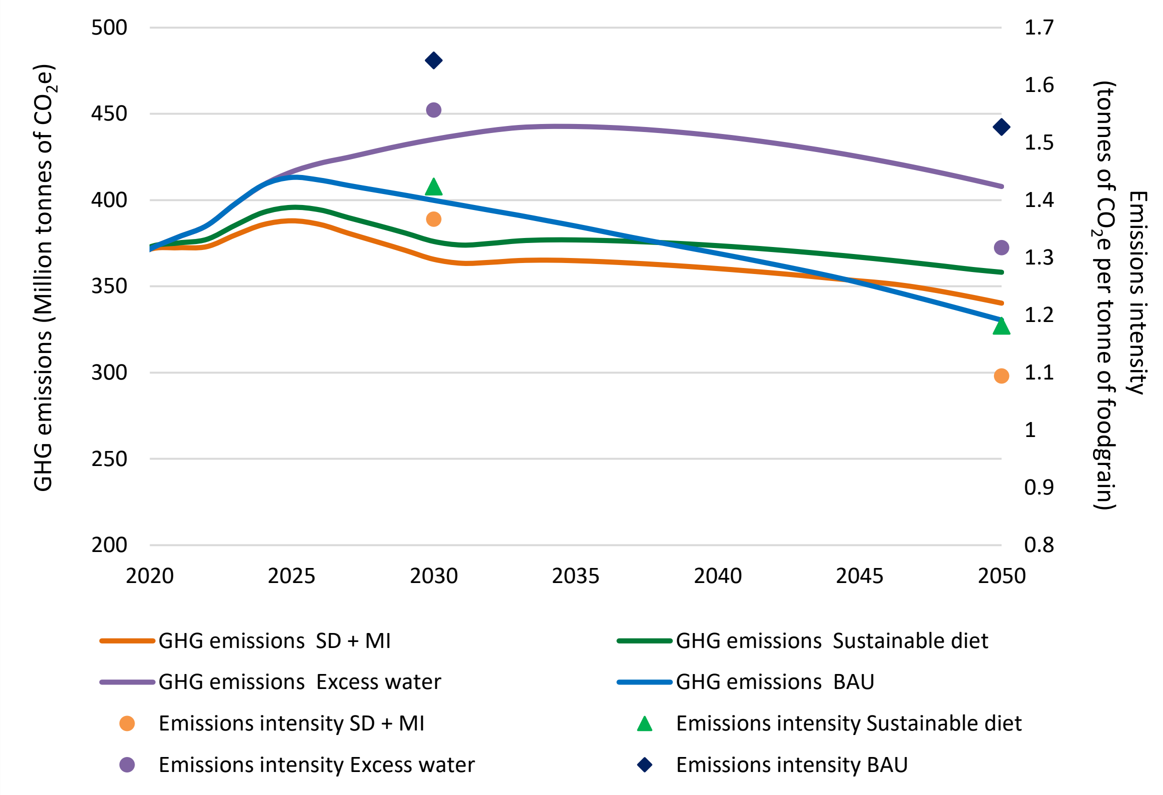

Figure 20 Agriculture sector GHG emissions (excluding methane from livestock) and emissions intensity

In BAU, emissions reduce from 2025 onwards because of the reduction in cultivated area (based on feedback from water shortage). The emission reduction is not based on any sustainability intervention, as evidenced by the high emission intensity (insufficient production). In the sustainable diet scenario, as we transition from rice to coarse cereals, the emissions are lower than in BAU up to 2037, mainly because of the reduction in rice methane emissions. However, it increases thereafter beyond BAU levels, because coarse cereals have lower yields resulting in more land and thus more fertiliser-based emissions. In the SD+MI combination scenario, due to better yields and efficient water consumption, emissions are lower. As discussed previously, the excess-water scenario considers growth without any constraints. Emission intensities reduce over time

[28] Since we have not yet modelled the electricity supply side, we have assumed the grid emission factor to reduce to 0.3 kg CO_2e/kWh by 2050 in a linear fashion.

because of the reducing grid emission factor assumption as well as yield improvements due to irrigation.

In Figure 21, we present the electricity demand for pumping in 2030 and 2050, under various scenarios of interest. In the SAFARI-BAU scenario, electricity demand from irrigation rises to 345 TWh in 2030 (from ~200 TWh as of today) and 389 TWh in 2050.

Some of the other variables in SAFARI that could be considered while making decisions in this sector include groundwater share in irrigation, cropping intensity, and solar-pump penetration.

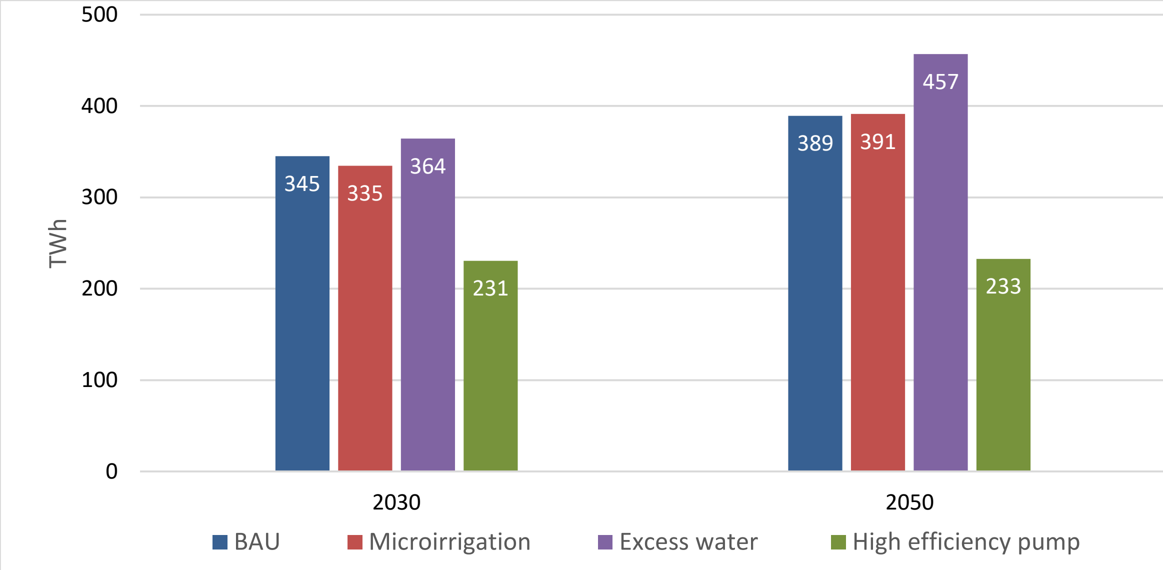

Figure 21 Projections for agriculture electricity demand

3.3. Healthcare for All

In the 'Healthcare for All' goal, we looked at four main scenarios. In the BAU (no constraints) scenario, we estimate annual construction based on a linear approach to reach BAU 2050 targets, without any feedback from materials or water availability. In the BAU (with constraints) scenario, we estimate how much can actually be constructed annually if feedback from cement and steel industries is considered. Similarly, the 'Ambitious 2050' targets are analysed with and without constraints.

In Figure 22, we present the total built-up area of different types of healthcare units in India, in 2025 and 2050, under the scenarios described. In the BAU case, material constraints do not play a major role in restricting construction. Up to 98% of the desired construction is able to be achieved by 2050. In the Ambitious scenario, 70% in 2025 and 83% in 2050 can be achieved. Figure 23 shows the built-up area of each type of healthcare unit in the BAU and Ambitious case in 2050, while considering constraints from the cement and steel industries.

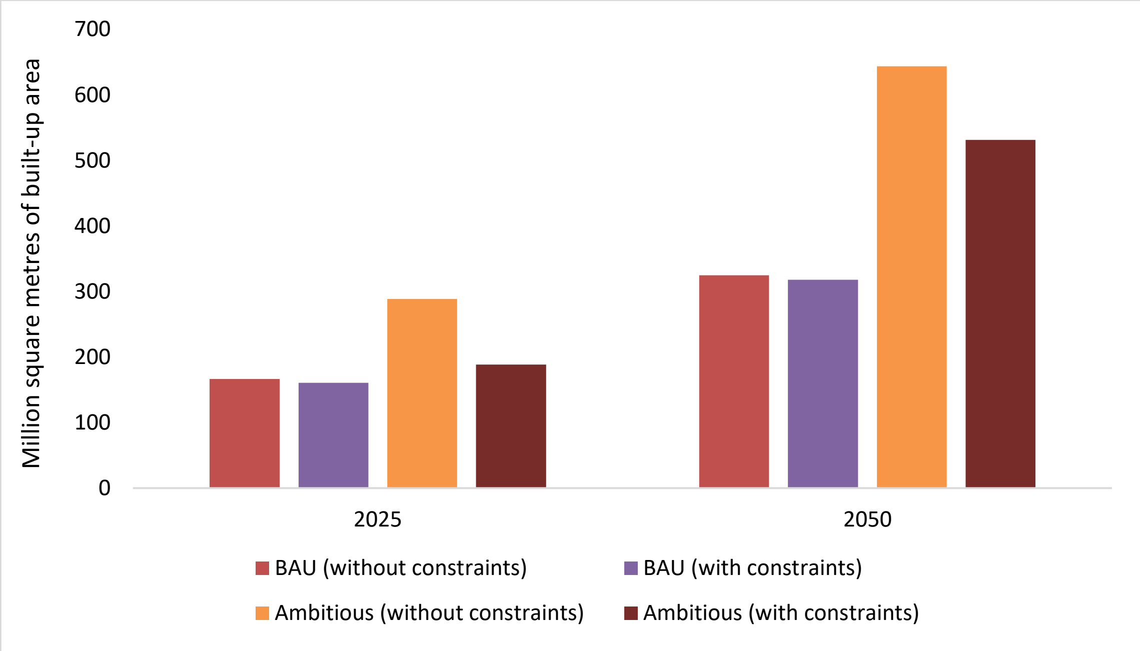

Figure 22 Cumulative built-up area of healthcare buildings in India

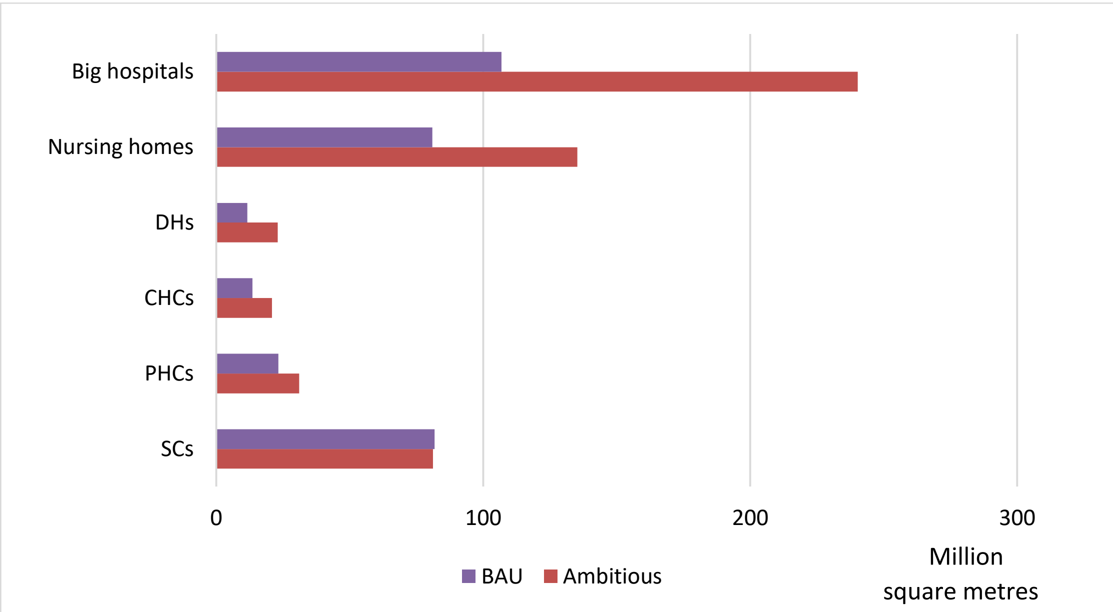

Figure 23 Cumulative built-up area of healthcare units constructed by 2050

The current built-up area, in million square metres, is 40.8 for sub-centres, 11.3 for primary health centres, 5.3 for community health centres, 4.4 for district hospitals, 23.8 for nursing homes, and 42.4 for big hospitals. In BAU, SCs, PHCs, and CHCs are expected to double in terms of their total built-up area by 2050, while DHs, nursing homes, and big hospitals are expected to grow to almost three times by 2050.

3.4. Education for All

There are two major scenarios under the ‘Education (infrastructure) for All’ goal: BAU growth and Ambitious growth. Figure 24 shows the difference in million square meters of area (cumulative) that would be possible to be constructed by 2030 and 2050 under both of these scenarios. Both scenarios have been considered under constrained conditions (with material and resource constraints) and unconstrained conditions (without any constraints).

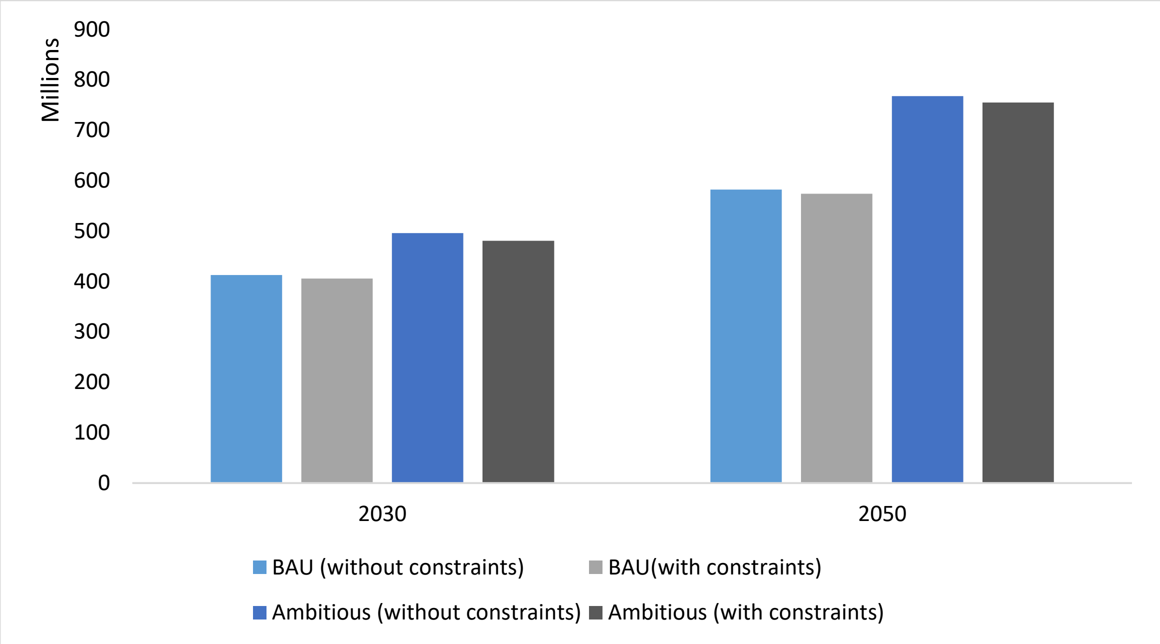

Figure 24 BAU and ambitious construction scenarios with and without material constraints

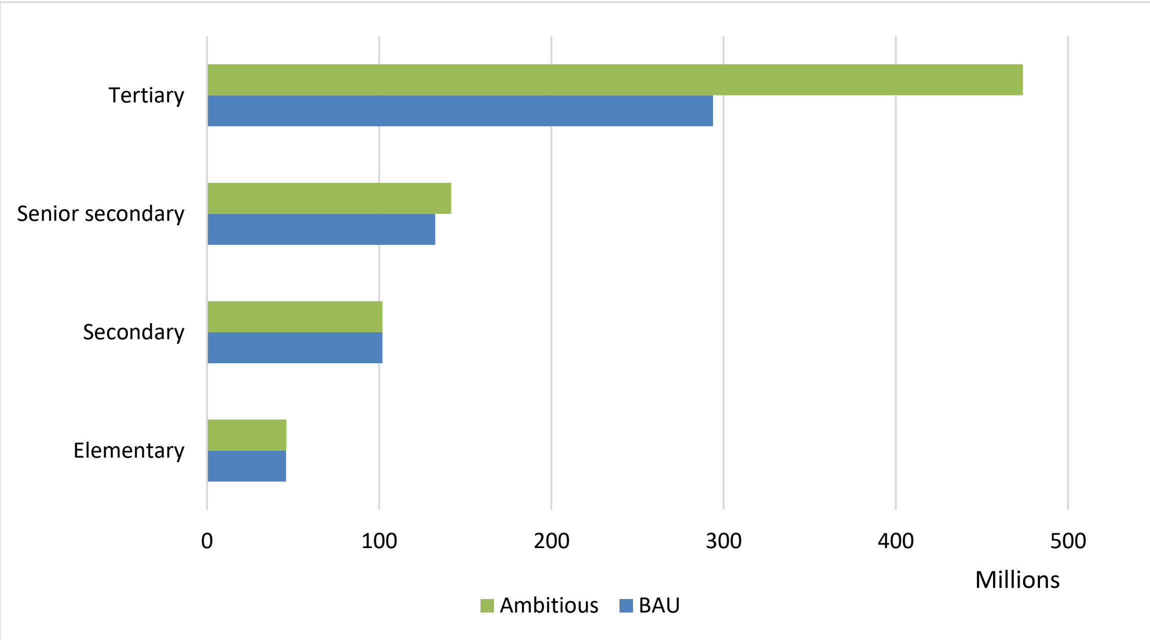

Figure 25 Cumulative built-up area of educational buildings constructed by 2050 (with constraints)

Figure 25 offers a break-up of the area constructed under different types of educational institutes under the BAU and Ambitious growth scenarios, respectively. These are elementary, secondary, senior secondary, and tertiary institutes, while considering material and resource constraint feedbacks. The key difference between these scenarios is the boost in area under tertiary educational institutes in the Ambitious growth scenario.

3.5. Housing for All

The following section examines select housing scenarios against the targets of the PMAY (urban) scheme, which aims to meet an affordable housing target of 11.5 million houses by 2022. The three scenarios presented here are: *current sanction rate*; *ambitious scenario*[29]; and *SDG scenario*. Each explores the effect of different average annual sanction rates for housing on the country's ability to meet the urban affordable housing shortage. The sanction rate, shown in Figure 26, is a measure of approval for construction.

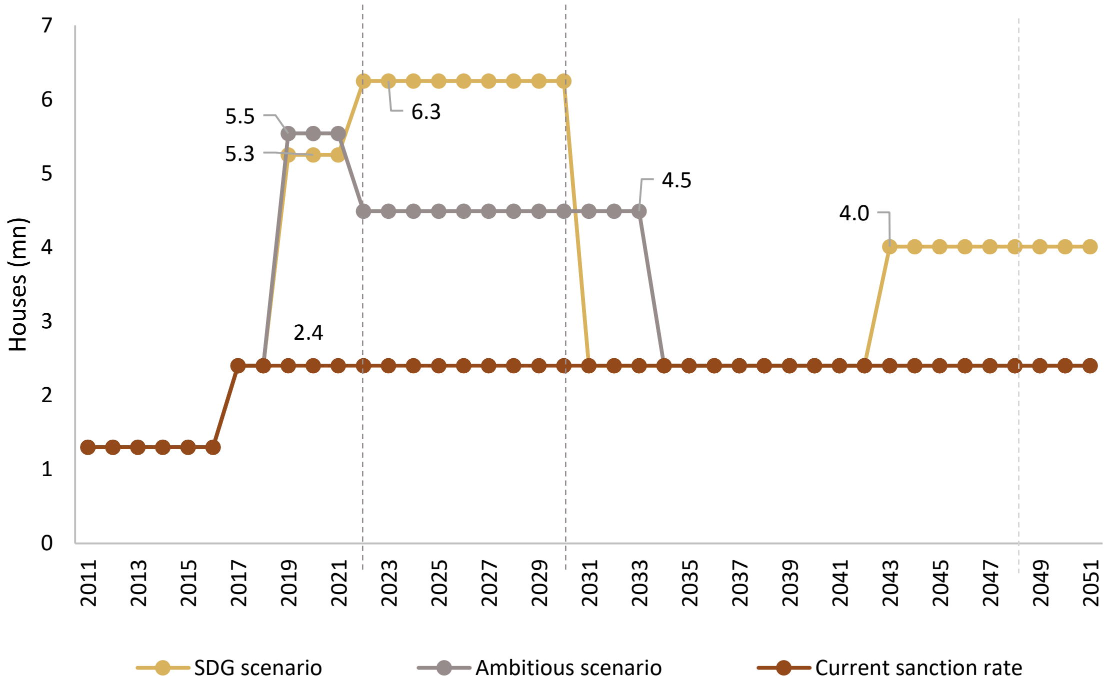

Figure 26 Urban housing sanction rates under various scenarios

The average sanction rate for urban housing was about 2.4 million houses per year between 2016 and 2018. This is depicted in the *current sanction rate* scenario as a constant sanction rate until 2050, and in the *ambitious scenario* until 2019. The *ambitious scenario* collates estimates from various reports with affordable housing projections until 2025 or 2030, and uses intuited sanction rates to try to keep the housing shortage at zero until 2050. The *SDG scenario* adopts sanction rates of 5.3 million and 6.3 million until 2030 to bring the shortage to zero by 2030.

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[29] Sanction rates up to 2030 adapted from https://www.brookings.edu/wp-content/uploads/2018/10/The-future-of-Indian-electricity-demand.pdf

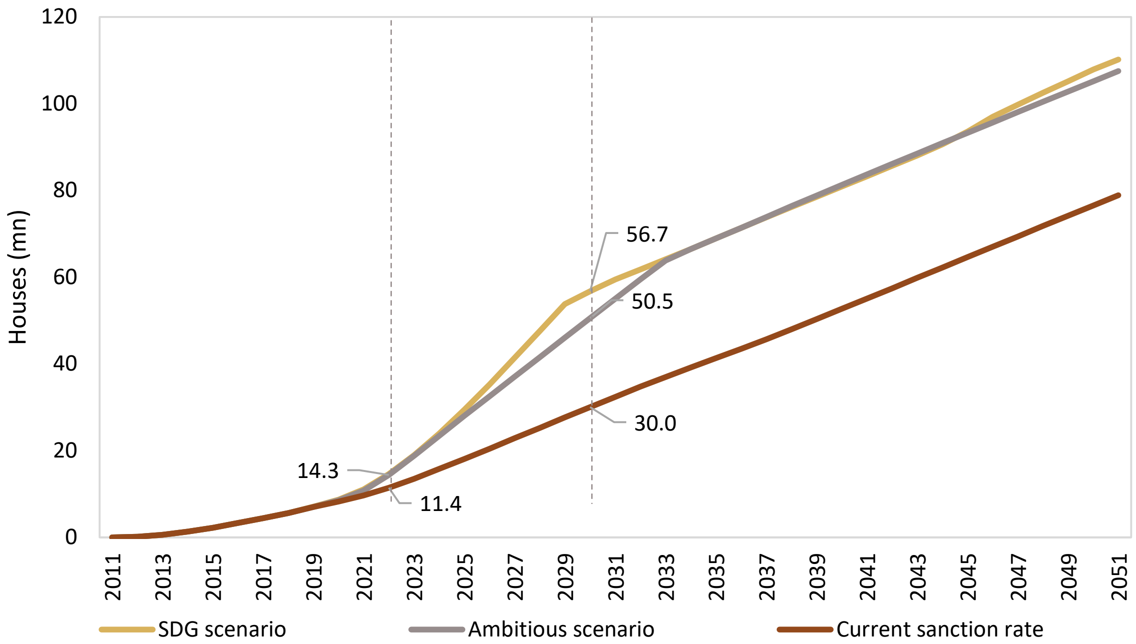

Figure 27 Cumulative number of urban houses constructed (mn)

2022: Figure 27 illustrates the cumulative number of houses that have been constructed each year as a result of the sanction rates in Figure 26, while Figure 28 represents the residual annual housing shortage under the four scenarios. In the *current sanction rate* scenario, with a sanction rate of about 2.4 million houses per year, the housing shortage will never be met if we take into account a dynamically growing shortage (due to population growth and dilapidation).

2030–2050: By 2030, we see that only the *SDG scenario*, with its continued high sanction rate, is able to completely eliminate the housing shortage. The *ambitious scenario* comes close, but is not able to quite catch up with the additional number of households needing housing each year. Under the *current sanction rate* scenario, we manage to stabilise but never quite begin to reduce the dynamic housing shortage.

It is important to note that other factors could also affect our ability to execute the intended sanction rates. These include cement, steel, and water availability, and construction rates (and consequently, material demand) from rural and MIG/HIG housing. Furthermore, by this period, the current income-group classification will have likely been adjusted to reflect rising incomes. The resulting increase in ownership of multiple houses, which is currently reflected in the MIG/HIG category of this model, could conceivably contribute to pressure on resource availability.

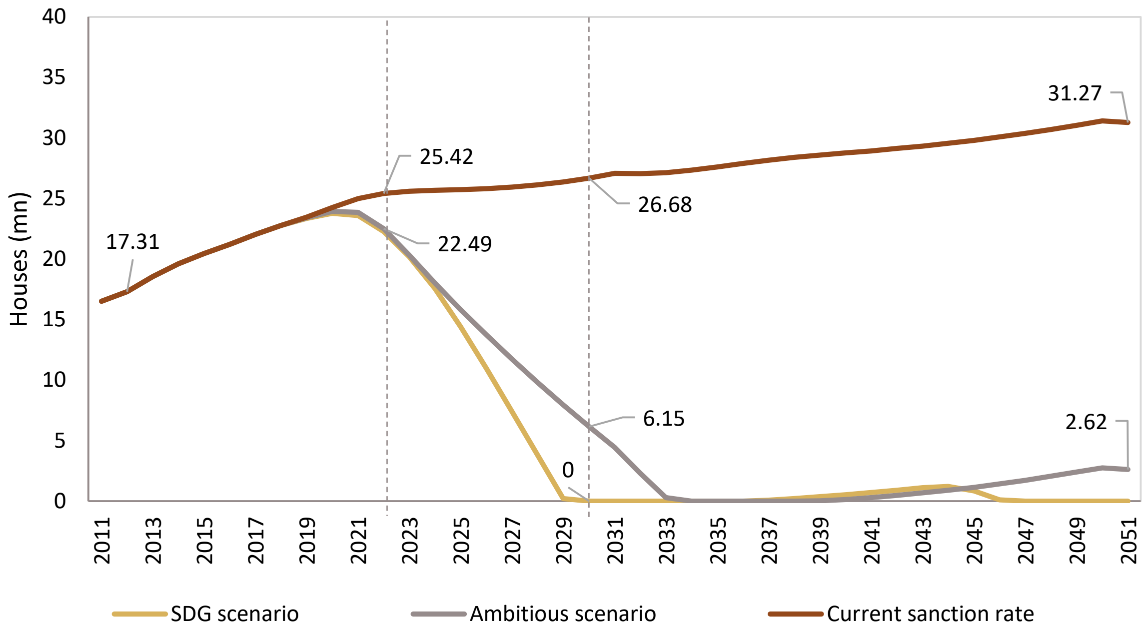

Figure 28 Dynamic urban housing shortage under various scenarios

Rural housing shortage is similarly shown below, in terms of sanction rate (Figure 29), construction (Figure 30), and shortage (Figure 31) under various scenarios. Although the SDG Goal 11 target focuses on urban affordable housing, a similar target of zero shortage by 2030 has been explored for rural housing as well in the *SDG scenario*. The *ambitious 2030 scenario* for rural housing explores reducing dynamic shortage significantly by 2030. It also achieves the Government of India's 2019-2022 target for rural housing (19.5 million houses). The *current sanction rate* scenario assumes a historical average sanction rate of 2.8 million houses per year, until 2051. All three scenarios achieve zero housing shortage between 2027 and 2035, in part due to the anticipated increase in urbanisation.

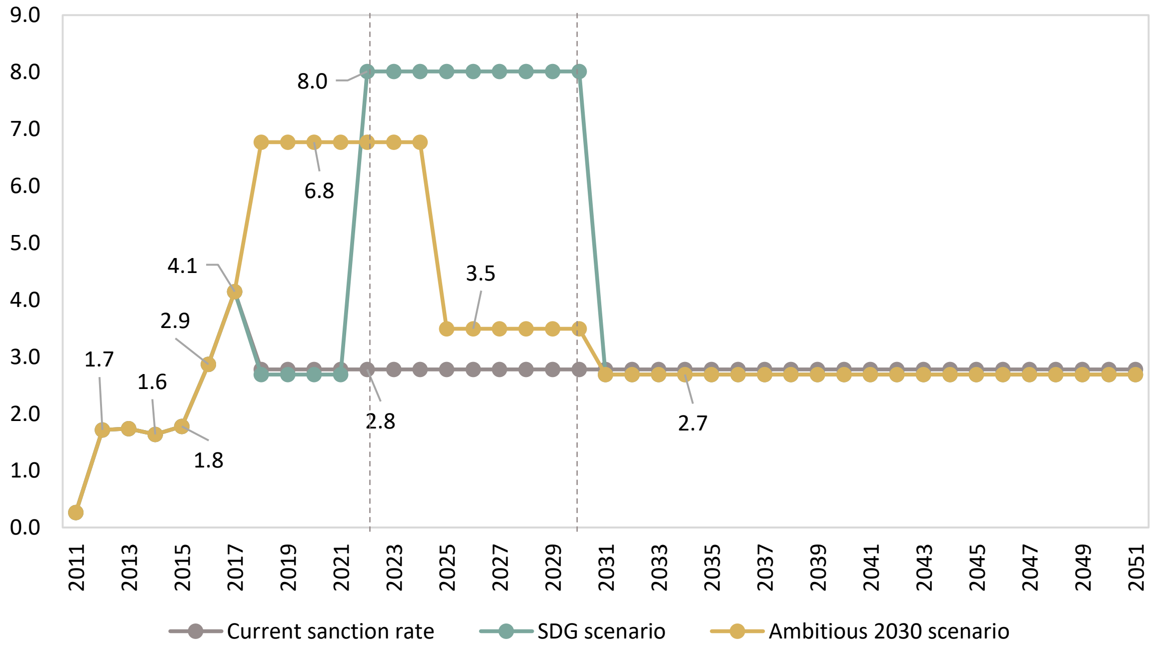

Figure 29 Rural housing sanction rates under various scenarios

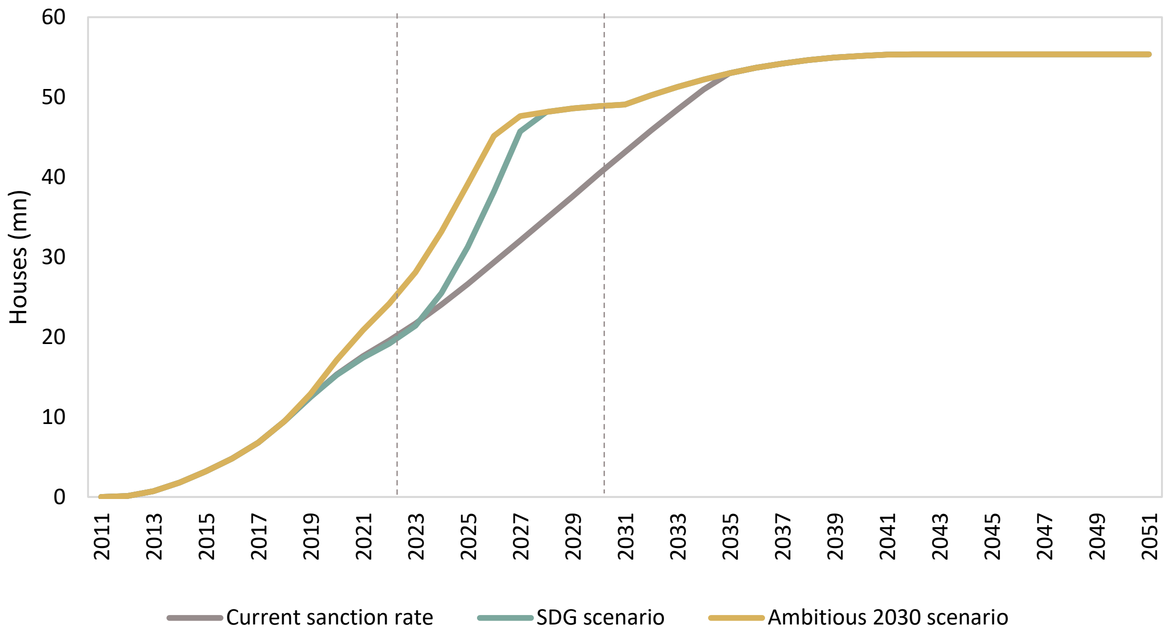

Figure 30 Cumulative number of rural houses constructed (mn)

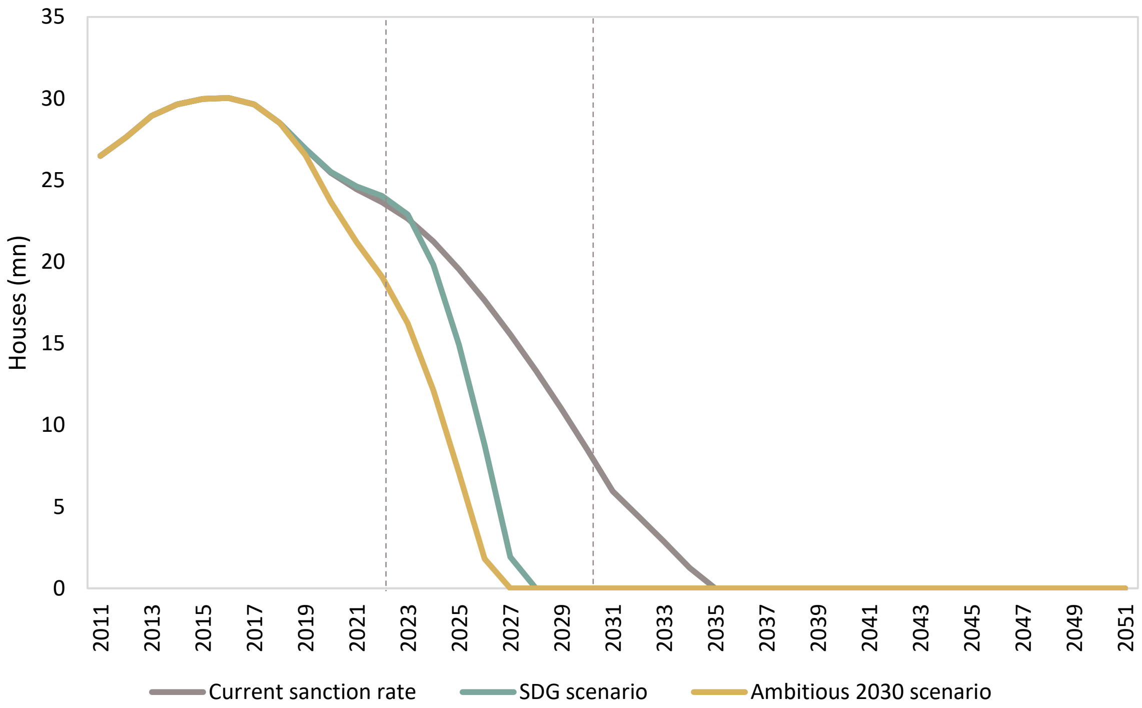

Figure 31 Dynamic rural housing shortage under various scenarios (mn)

Materials and Embodied Energy

It is possible to vary the embodied energy from housing construction by using different combinations of the building materials discussed in the methodology section (cement, steel, sand, aggregate, and different types of bricks/blocks). Figure 32 provides examples of how the **annual** embodied energy from housing construction might vary with different combinations of materials. It uses sanction rates from the *SDG scenario* for housing as its basis.

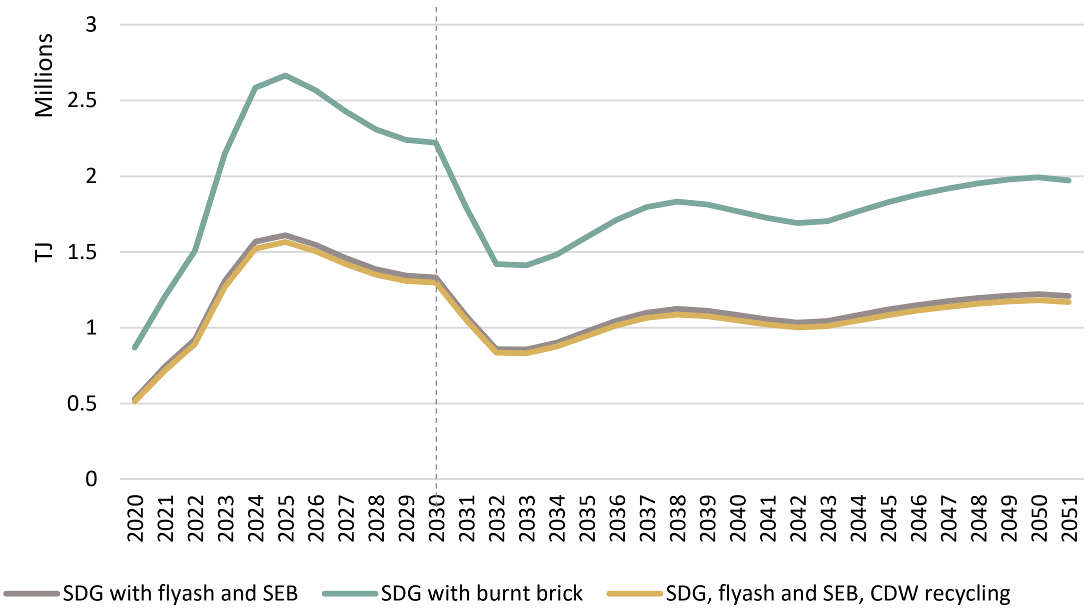

Figure 32 Annual embodied energy from housing construction under various construction material combinations

In the *SDG with burnt brick* scenario, all houses between 2020 and 2050 are assumed to be constructed with cement mortar and burnt brick. In the year 2030, this implies a **cumulative** embodied energy of 22.7 million TJ. By comparison, the *SDG with flyash and SEB* scenario assumes that all houses constructed each year between 2020 and 2050 are split between flyash blocks, F-alG blocks and stabilised earth blocks. In effect, no heavy consumers of cement are involved. This results in a **cumulative** embodied energy of 13.7 million TJ in 2030. The embodied energy can be marginally reduced by assuming different fractions of construction and demolition waste (CDW) being recycled (this example assumed 25%). The resulting **cumulative** embodied energy in 2030 is 13.36 million TJ. More importantly, utilising CDW can reduce environmental pressures resulting from sand and aggregate mining.

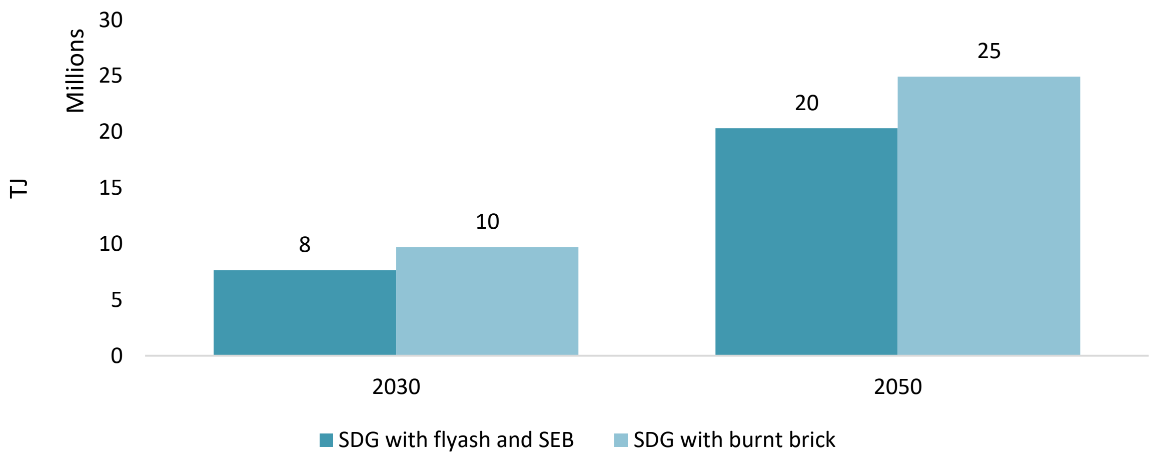

Figure 33 The cumulative embodied energy of cement used in construction under various scenarios

Figure 33 shows the cumulative embodied energy from cement, for the *SDG with flyash and SEB,* and *SDG with burnt brick* scenarios, in 2030 and 2050. By using different building material technologies to construct the same number of houses, it is possible to lower the embodied energy contributed by cement from 9.6 million TJ to 7.6 million TJ in 2030. This is due to the fact that, of the seven building material technologies used in this model, combinations of reinforced cement concrete and burnt brick, hollow concrete block, or solid concrete block are among the most cement-intensive. Less cement is used per unit when stabilised earth block (SEB) and flyash/F-alG blocks are used instead.

3.6. Cement Demand and Adequacy

Examples of the cement sector's response to changing demands in the housing sector have been captured in Figure 34 and Figure 35. We have focussed on the cement sector here because it is more sensitive to changes in demand than the steel and water sectors. Both graphs show how the total cement demand and cement adequacy[30] vary over time for all of the infrastructure sectors together—housing, along with healthcare and education. These variations in demand and adequacy have been plotted using the housing construction rates that were used for the SDG scenario and the Ambitious scenario (urban and rural combined). The purpose of showcasing these scenarios was that sanction rates in these scenarios are considerably higher than in the others, and are therefore more likely to affect cement adequacy.

In Figure 34, high cement demands from high sanction rates in the years leading up to 2023 result in temporary shortages in cement availability. The cumulative urban and rural affordable housing sanction rate (SDG scenario), for instance, is 14.3 million houses in 2022 alone. However, having increased cement capacity to meet these high demands, the cement sector is then almost always able to adequately cover cement demand for the remaining years, up to 2051. In Figure 35, it is apparent that there is a sizeable gap between cement requirement and cement availability between 2018 and 2020. This could be attributed to the high sanction rates in urban and rural housing, particularly the latter (6.8 million houses), between 2019 and 2022. In this scenario, by 2020, cement production catches up with the high demand and manages to meet it until 2051.

[30] In our model, cement adequacy is the sufficiency of cement being produced to meet the demand for cement.

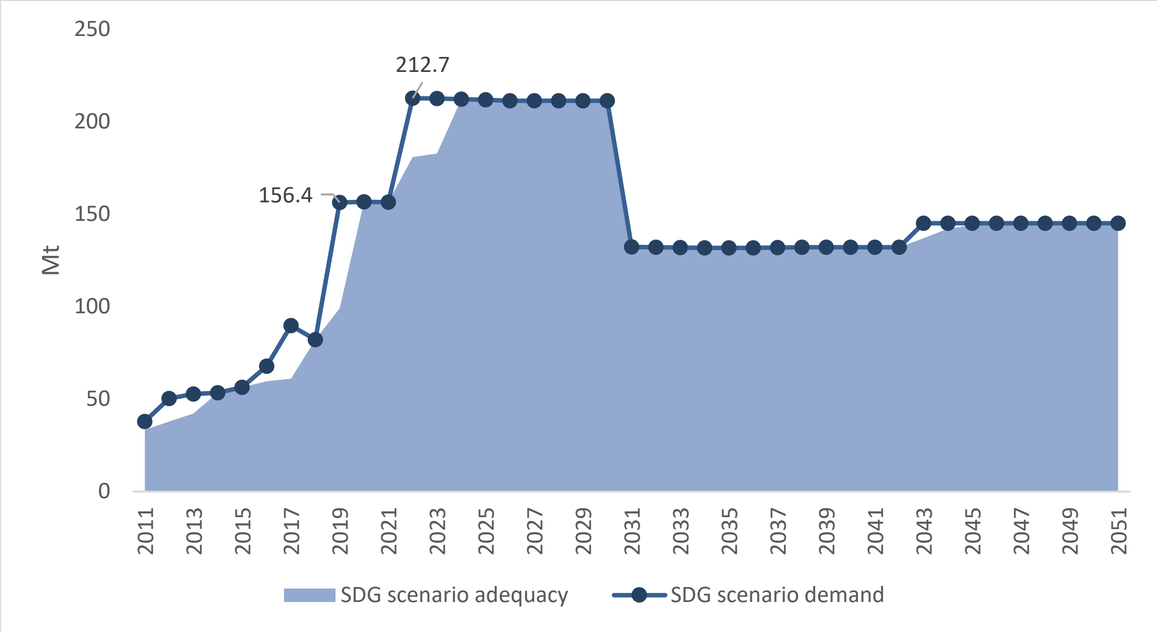

Figure 34 Combined cement demand and adequacy (all infrastructure sectors) under the housing sector's SDG scenario

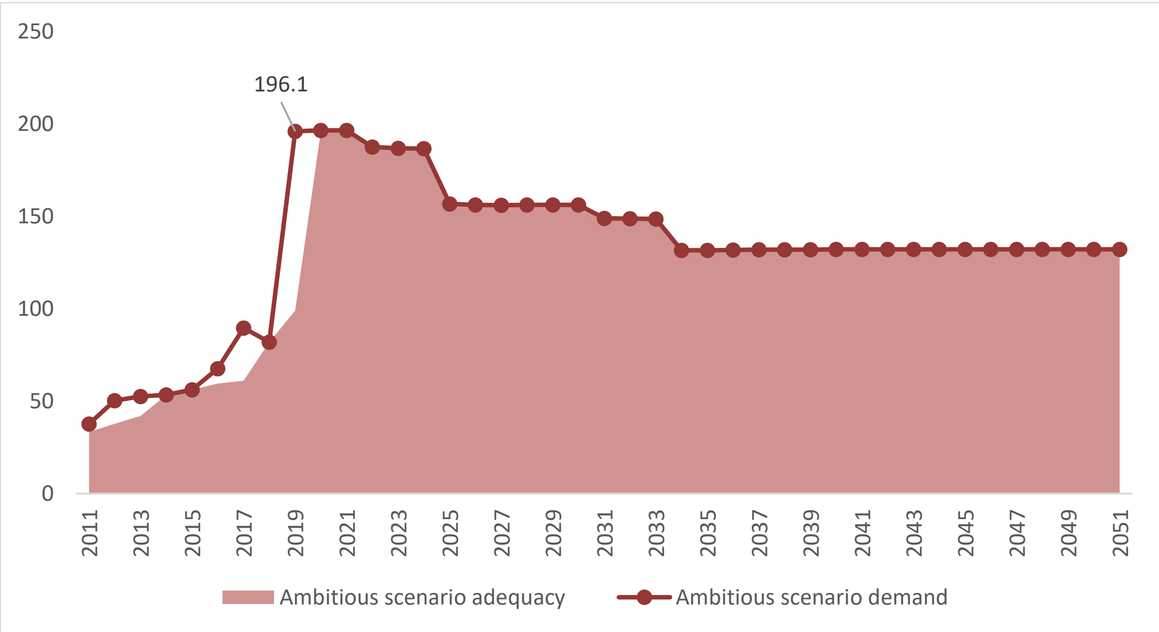

Figure 35 Combined cement demand and adequacy (all infrastructure sectors) under the housing sector's ambitious scenario

3.7. Transport Sector

Based on the methodology, assumptions, and scenarios described in Section 2.6, SAFARI-Transport provides us with projections for India's transport sector growth up to 2050. To start with a common reference point, we first report the total transport demands in terms of passenger-kilometres and tonne-kilometres for the country.

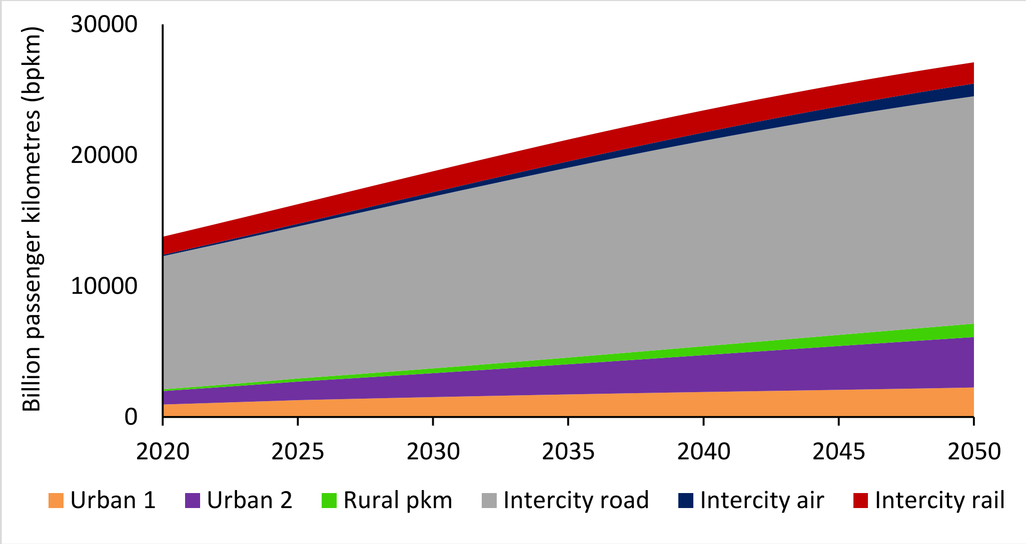

Figure 36 BAU passenger transport demand in India

According to the model, in the BAU scenario, passenger transport demand increases to 27,000 bpkm in 2050 as shown in Figure 36. The share of urban transport demand increases from 14% of the total demand as of today, to 22% in 2050. The maximum demand is from the intercity segment, which is mostly covered by road. As for freight transport, the total demand increases to around 13,000 btkm in 2050, as shown in Figure 37. Based on BAU trends, road-based freight is expected to retain the largest share in total btkm, but it is also one of the hard-to-abate sectors because of the fact that electrification of trucks is technologically challenging. Alternative fuels and modes to replace road-freight are imperative for transport-sector decarbonisation.

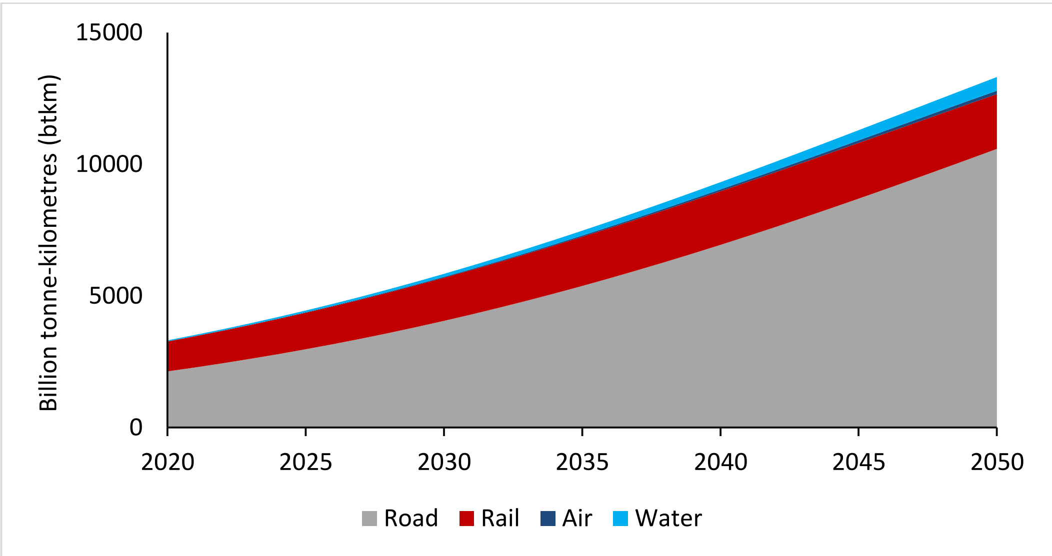

Figure 37 BAU freight transport demand in India

Having provided the overall context for demand, we now explore the impact of key scenarios. In the clean-fuel scenario (CF), as described earlier, we assumed 100% electrification of railways by 2030, and of buses, cars, two-wheelers, and three-wheelers by 2050. In addition, we assumed 20% ethanol blending in petrol by 2030, 10% bio-jet fuels in ATF by 2050, and 40% biodiesel in trucks by 2050 (details in Table 13 and Table 15). We assume that these targets are reached in a linearly increasing fashion. In the ideal modal-share scenario (IMS), passenger transport in urban areas moves more towards non-motorised and public modes, and the share of rail in intercity passenger increases to 25%, and in freight transport increases to 50% (IMS details in Table 12 and Table 14). In terms of energy demand, the transport sector requires liquid fuels and electricity. Liquid fuels considered in the SAFARI-Transport sector include petrol, diesel, CNG, ethanol, biodiesel, aviation fuel, and bio-jet fuel.

Figure 38 shows a comparison of the scenarios with respect to GHG emissions (CO_2, CH_4, and N_2O in terms of CO_2 equivalents). Since we have not yet modelled the energy-supply sectors, we assume the grid emission factor to decline linearly from 0.73 $kgCO_2/kWh$ to reach 0.3 $kgCO_2/kWh$ in 2050 (in the model, it is a lever that can be adjusted to view results, based on varying emission factors for 2050).

In the BAU case, India's transport sector emissions are likely to reach more than 1 billion tonnes of CO_2e by 2050. With sustained electrification and biofuel-blending, we can reduce this by around 10%. However, along with IMS (in CF+IMS scenario), India's emissions can peak at about 550 million tonnes before 2050. This suggests that electrification of transport supplemented with strategic shifts towards sustainable modal shares as well as efforts to decarbonise the electricity grid could be an effective mitigation plan.

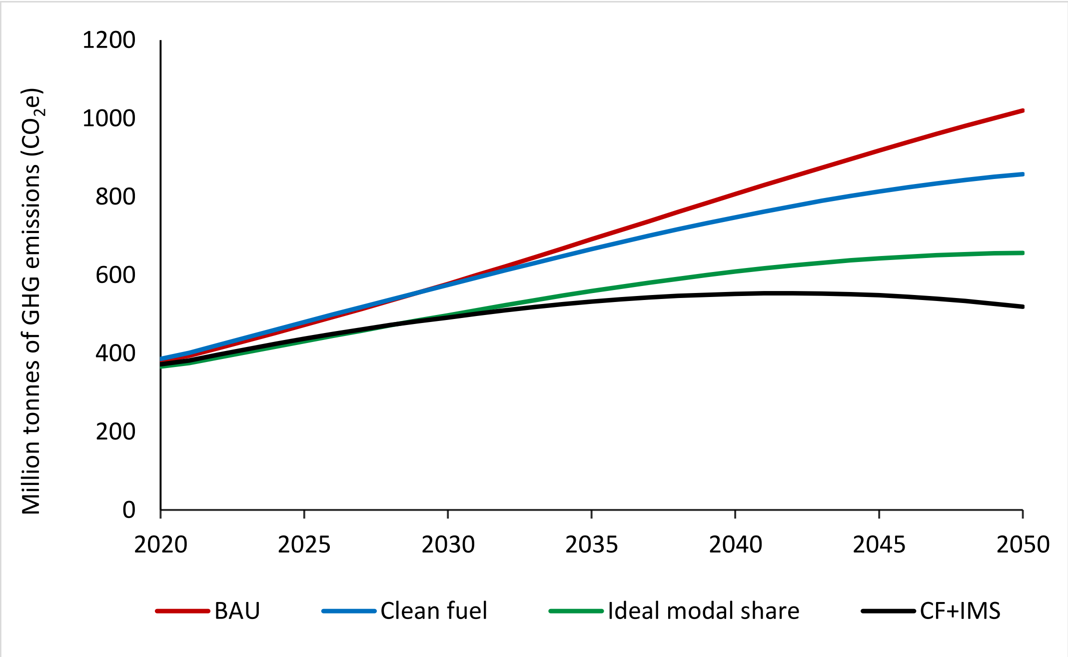

Figure 38 Transport sector GHG emissions under key scenarios

While these are some of the key results and scenarios, many more specific scenarios can be easily generated using SAFARI. For example, the user can explore the impact of changing modal shares as well as fuel shares for various modes (for 2030 and/or 2050) through a pie-chart input graph. To understand the capacity for domestic ethanol production, the user can change the percentage of area under sugarcane cultivation, and switch on '2G ethanol viability by 2025' scenario. Similarly, other technology interventions at a future time can be tested, including transit-oriented development for urban areas.

3.8. Total Electricity Demand

According to SAFARI, the total electricity demand for India, from the sectors modelled, increases from around 1,260 billion units (TWh) in 2020 to 3,760 TWh in 2050 (Figure 39)[31].

The industry sector contributes to 45% of this demand as of today, followed by the residential sector, which is responsible for 26%. With rapid urbanisation and increase in disposable income, the electricity demand from India's residential sector will increase from around 330 (today) to 1,400 TWh by 2050 (37% of total). Close to 60% of this demand is expected to be from air conditioner use in 2050. As for the agriculture sector, in the SAFARI-BAU case, the area under cultivation and consequently the electricity demand for pumping are unable to increase at the rate required to meet 'Food for All' goal, as described earlier. This is due to land constraints and feedback of water shortages.

In the next phase of the project, we will find an optimal supply mix to meet the electricity demand estimated. We will then be able to provide better GHG emission estimates to achieve India's developmental goals.

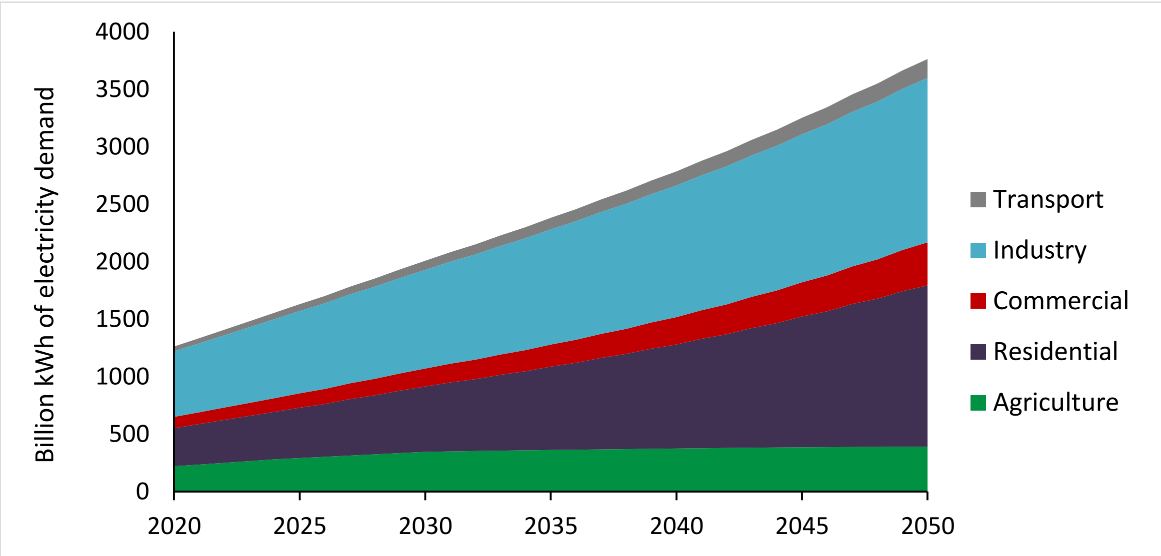

Figure 39 India's sectoral electricity demand up to 2050

4. Conclusions and the Way Forward

In this report, we outlined the modelling logic, methodology, and sectoral assumptions that lie at the core of SAFARI. Our model will enable users to explore policy and technology interventions in the sectors of interest. Furthermore, the simulation interface allows easy visualisation of the complex dynamics of the interdependent variables. Some of the key insights from SAFARI are summarised below:

[31] A comparison with other studies is provided in the Appendix.

- The ‘Food for All’ goal cannot be achieved *sustainably* if the current diets, irrigation practices, wastage, and yields continue. The foodgrain supply–demand gap in BAU increases to around 25 Mt by 2030 and 70 Mt in 2050, due to water shortage. Some moderate-effort scenarios that can decrease the gap to 0 are:
    - SD + MI: ‘Sustainable diet’, where consumption of coarse cereals increases and that of rice decreases over time, along with increasing area under microirrigation (reaching 40% of total cultivated land by 2050). Moving away from rice to coarse cereals reduces methane emissions associated with rice cultivation, but increases emissions associated with fertiliser use (due to lower yields of coarse cereals and subsequent increase in cultivated area). Therefore, it is imperative to couple this dietary shift with a yield-improving scenario like microirrigation.
    - A combination of three moderate scenarios: 1) increasing area under microirrigation to 40% of the total cultivated land by 2050, 2) reducing area under sugarcane cultivation from 5 Mha (today) to 2.9 Mha by 2050, and 3) increasing use of recycled water in domestic (50% of non-potable water demand by 2050) and industrial (60% by 2050)
- The ‘Housing for All’ goal aims at meeting housing shortage, which is computed dynamically in SAFARI based on population, dilapidation of houses, congestion, existing condition of houses and homelessness. Urban EWS-LIG housing shortage, when considered dynamically instead of as a static one-time number, cannot be met with the current sanction rate of 2.4 million houses per year.
    - In the SDG scenario, the urban EWS-LIG shortage can reduce to 0 by 2030 if sanction rates of 5.3 million in the period 2019-21 and 6.3 million from 2022-2030 are maintained.
    - The rural housing shortage can be met by 2035 under the current sanction rate of 2.8 million houses per year. At higher construction rates, the achievement of the goal can be expedited.
    - It is possible to vary the embodied energy (and therefore, emissions) for construction by using different combinations of building materials. We found that there is a 20% reduction in total embodied energy in the material combination with stabilised earth block and flyash compared to burnt bricks and cement-heavy building materials.
- The healthcare and education sectors have two levels of goals. The first is BAU, which is the infrastructure requirement based on government targets and policies. The second is Ambitious, which is based on international standards and averages of indicators such as the number of beds per 1,000 people for healthcare and gross enrolment ratio (GER) for education.
    - As for healthcare, 98% of the BAU targets can be met by 2050. In the Ambitious scenario, 70% and 83% of the targets can be achieved in 2030 and 2050 respectively.

    - In the case of education, we found that about 98% of targets could be met.

- In the transport sector, the 'Ideal Modal Share' scenario, with increased uptake of public in place of private passenger transport and rail-based in place of road-based freight, has the maximum potential for reducing GHG emissions. While electrification and biofuels are also important, their individual contributions to mitigation are much lower than that of modal shifts. Combined electrification and modal shifts will likely see India's transport-sector emissions peak at about 550 Mt CO_2e in 2045, compared with 920 Mt CO_2e in BAU.
- SAFARI is largely a bottom-up model. The energy, emissions, and resource requirements of sectors that are directly associated with the goals considered are estimated bottom-up. We integrated the other sectors top-down mainly to get comprehensive results on electricity. In our BAU case, the total electricity demand for India increases from around 1,260 billion units (TWh) in 2020 to 3,760 TWh in 2050.

This phase of the project focused on estimating energy and material demands for a desired quality of life in India. However, does India have the capacity and resources to meet these demands? If so, do we have the capacity to do so without compromising on global climate targets? Will meeting these demands necessarily entail massive increase in greenhouse gas emissions, or are there ways to avoid this? What are the different ways to avoid this? What timelines would we be looking at?

Such questions will form the basis for the next phase of this project, in which we will explore supply options to meet these energy and material demands.

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Appendix

Table 10 Endogenous, exogenous, and sectors out of scope

<table>
<tr><th>Endogenous Sectors</th><th>Exogenous Sectors</th><th>Out of Scope</th></tr>
<tr><td><u>Agriculture and allied</u>
Rice, wheat, coarse cereals, and pulses production
Livestock</td><td><u>Agriculture and allied</u>
Other crops clubbed together (sugarcane, cotton, oilseeds vegetables, fruits)</td><td><u>Agriculture and allied</u>
Fisheries</td></tr>
<tr><td><u>Commercial</u>
Healthcare centres construction and operation (sub-centres, primary health centres, community health centres, district hospitals, nursing homes, corporate hospitals)
Schools and colleges construction and operation</td><td><u>Commercial</u>
Other commercial operation (hotels, office buildings, transit, retail)</td><td><u>Commercial</u>
Street lights
Construction of ‘other commercial’</td></tr>
<tr><td><u>Industry</u>
Fertilisers
Cement
Iron and steel</td><td><u>Industry</u>
Other industries</td><td><u>Industry</u>
Power plants</td></tr>
<tr><td><u>Residential</u>
Housing construction and operation
Cooking
Appliances – ACs, fans, television sets, water heaters, refrigerators, and lighting</td><td><u>Residential</u>
Other miscellaneous appliances</td><td><u>Residential</u></td></tr>
<tr><td><u>Transport</u>
Road, rail, air passenger transport
Road, rail, water, air freight transport</td><td><u>Transport</u>
Growth rates and modal shares</td><td><u>Transport</u>
Electric vehicle charging infrastructure</td></tr>
</table>

Table 11: Foodgrain yields in tonnes/hectare

Year	Foodgrains	BAU	Potential yield scenario	High yield scenario
2020	Rice	2.82	3.33	2.86
	Wheat	3.33	3.61	3.36
	CC	1.23	2.38	1.34
	Pulses	0.742	1.46	0.81
2030	Rice	2.82	4.92	3.52
	Wheat	3.37	4.36	3.69
	CC	1.28	3.33	1.95
	Pulses	0.748	2.93	1.47
2040	Rice	2.83	6.51	4.12
	Wheat	3.4	5.1	4
	CC	1.38	4.27	2.4
	Pulses	0.754	4.39	2.03
2050	Rice	2.84	8.1	4.79
	Wheat	3.44	5.85	4.33
	CC	1.51	5.21	2.88
	Pulses	0.759	5.85	2.64

Table 12: Modal shares for passenger transport

	Base Year 2011	BAU 2050	IMS Scenario 2050
Intercity pkm			
1. Air	0.75%	5%	3%
2. Rail	13%	8%	25%
3. Road Bus Car	87% 90% 10%	87% 90% 10%	72% 90% 10%
Urban 1 pkm			
1. Public Bus Rail/Metro	60% 30% 70%	60% 30% 70%	70% 30% 70%

2. Private	30%	30%	5%
Cars	28%	28%	28%
2W	52%	52%	52%
3W	20%	20%	20%
3. NMT/Walk	10%	10%	25%
Urban 2 pkm			
1. Public	35%	35%	50%
Bus	60%	60%	60%
Rail/Metro	40%	40%	40%
2. Private	60%	60%	30%
Cars	19%	44%	44%
2W	65%	40%	40%
3W	16%	16%	16%
3. NMT/Walk	5%	5%	20%

Table 13: Fuel shares for passenger transport

	Base Year	**BAU 2050**	**CF Scenario 2050**
Intercity air pkm			
Aviation fuel (ATF)	100%	100%	90%
Bio-jet fuels	0%	0%	10% (linearly from 2025)
Intercity rail pkm			
Diesel	49%	0%	0% by 2030
Electric	51%	100%	100% by 2030
Total bus pkm			
Diesel	90%	70%	0%
Electric	0%	15%	100%
CNG	10%	15%	0%
Total car pkm			
Petrol	70%	50%	0%
Diesel	27%	20%	0%
CNG	3%	10%	0%
Electric	0%	20%	100%
Total 2W pkm			

Petrol	100%	0%	0% by 2030
Electric	0%	100%	100% by 2030
Total 3W pkm			
Petrol	43%	43%	0%
Diesel	40%	20%	0%
CNG	17%	22%	0%
Electric	0%	18%	100%

Table 14: Modal shares for freight transport

	Base Year	BAU 2050	IMS 2050
Air	0.1%	1%	0.1%
Rail	40%	15%	50%
Road	60%	80%	40%
Water	0.18%	4%	9.9%

Table 15: Fuel shares for freight transport

	Fuel Shares		
	Base Year	**BAU 2050**	**CF 2050**
Air freight			
Aviation fuel	100%	90%	-
Bio-jet fuel	0%	10%	-
Railways			
Diesel	34%	29%	0% by 2030
Electric	66%	71%	100% by 2030
Road freight (HDVs)			
Diesel	90%	90%	70%
Biodiesel	0%	0%	25%
CNG	10%	10%	10%
Waterways			
LDO	100%	-	-

Building Material Calculations for Healthcare and Education

Concrete frame structures and shallow individual footing foundations have been considered for calculations for all types of buildings.

Layout

We have taken into consideration the layout provided by the Government of India, under IPHS 2012 for SH and PHC units [59]. For other units, there is no fixed layout. So, we drew out a general layout for each one.

- Determined the total volume of all walls to calculate the fly-ash brick requirement
- Calculated the volume of RCC (reinforced concrete cement) slab for ceiling, columns, and beams to calculate the cement and steel requirement
- For foundations, determined the volume of rectangular concrete pads for each column, beam, and RCC slab to calculate the cement and steel requirement

Material Specifications

- Fly-ash brick: 2.5 kg per brick of 20 cm x 10 cm x 10 cm dimensions [96]
- Masonry work: 1:6 cement mortar is used for masonry work with fly-ash bricks (FAB).
- RCC ceiling slabs: As a thumb rule, the minimum steel consumption for a slab is 70 kg/ m^3, and we have used 80 kg/m^3 in our calculations.
- For beams and columns in building structure and foundation, we have used M25 (1:1:2) grade of concrete; in this, the cement content per cubic metre is about 448 kg/m^3; we have used steel content of about 145 kg/m^3 [80].

We have validated our results with other studies from CSTEP [97], [98] as well as our peer organisations [99]–[101].

Table 16: Electricity demand (TWh) in industry sector - validation with other studies

	SAFARI	IESS (2)	TERI	CSTEP NDC	CSTEP QoL
2011	353		349		
2012	366	336		381.26	
2017	469	396			
2021	601		582		
2022	630	494			
2027	773	617			
2030	859			981.86	1400
2031	887		721		
2032	916	759			
2037	1059	946			
2041	1174		1128		
2042	1203	1169			
2047	1346	1363			

2050	1432				
2051	1461		1524		

Table 17: Electricity demand (TWh) in agriculture sector - validation with other studies

	SAFARI_BAU	SAFARI_excess water	IESS (Trajectory 2B)	TERI (REF)	Energy Statistics 2019	CSTEP NDC	Brookings
2011	144.0	144.0		139	132		
2012	148.8	148.8	136		141		
2017	187.8	187.8	183		191		
2021	235.3	235.3	220	290			
2022	250.1	250.1	245				
2027	313.6	330.0	300				
2030	346.5	382.3	329			347.2	358
2031	349.9	391.7	340	429			
2032	353.3	400.9	360				
2037	367.2	437.3	409				
2041	377.5	460.6	453	545			
2042	379.8	465.9	464				
2047	388.0	489.3	501				
2051	391.4	504.3		580			

Table 18: Electricity demand (TWh) in residential sector - validation with other studies

	SAFARI	IESS (2)	TERI	CSTEP NDC	CSTEP QoL	Brookings
2011	169.7		174.5			
2012	183.5	152.5		200	170.3	
2017	269.5	246.4				
2021	352.7		418.7			
2022	374.4	409.4				
2027	491.1	598.0				
2030	568.3			636	700	669
2031	600.4		837.4			

2032	625.3	867.7				
2037	796.6	1141.5				
2041	952.1		1372.3			
2042	989.2	1386.8				
2047	1244.8	1564.5				
2050	1402.9					
2051	1468.7		1872.4			

Table 19: Electricity demand (TWh) in commercial sector - validation with other studies

	Model	**IESS (2)**	**TERI (REF)**	**CSTEP NDC**	**CSTEP QoL**	**Brookings**
2011	65.9		116.3			
2012	68.5	86.1		81	100.0	
2017	85.8	104.7				
2021	102.1		279.1			
2022	107.1	134.3				
2027	137.4	181.4				
2030	156.0			241	900	348
2031	162.7		639.7			
2032	169.5	261.2				
2037	208.4	400.2				
2041	248.3		1407.2			
2042	259.6	573.6				
2047	325.9	767.9				
2050	374.8					
2051	392.9		2698.2			

Table 20: Billion passenger kilometres - validation with other studies

	IESS-2	**SAFARI**
2010	7285.73	9728.44
2015	9838.95	11870.25
2020	13179.94	14268.02

2025	16840.93	16771.87
2030	20692.85	19277.30
2035	24299.45	21669.80
2040	27979.32	23852.06

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