Sustainable Alternative Futures for India

Phase 3 & Phase 4

CSTEP
CENTER FOR STUDY OF
SCIENCE, TECHNOLOGY & POLICY

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

Center for Study of Science, Technology and Policy

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Designed and edited by CSTEP

Disclaimer

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Executive Summary

India has to overcome several developmental challenges in the coming decades. Bridging the housing shortage; improving healthcare and education infrastructure; providing 24/7 electricity, clean water, and clean cooking fuels to all; and maintaining food security are some of the challenging goals for India that are in line with the UN's Sustainable Development Goals (SDGs). The Government of India has also emphasised its commitment to climate action by ratifying the Paris Agreement and formulating Nationally Determined Contribution (NDC) targets. Many developed countries have announced net-zero emissions targets and submitted their mid-century long-term strategies to the United Nations Framework Convention on Climate Change (UNFCCC). India, however, has to prioritise its developmental aspirations while also doing its bit to mitigate global warming. Balancing development with climate action requires a good understanding of the interactions between sectors, natural resource systems, and environmental externalities. This modelling study aims to provide such an understanding and help create scenarios for low-carbon development by using an interactive simulation tool—named Sustainable Alternative Futures for India (SAFARI).

Objectives and Approach

The overall objective of this project is to provide an analytical framework that helps **identify sustainable long-term development strategies for India**.

In the first phase of the project, we selected and defined key development goals that fulfil fundamental human needs. The chosen goals include food security, bridging the housing shortage, constructing sufficient infrastructure for healthcare and education, meeting transport demand, achieving cooking needs through clean fuels, and ensuring adequate power and water supply for various sectors.

In the second phase, we assessed the energy and resource footprints to meet the defined goals. In our model, development goals and socio-economic parameters are the key drivers of growth in demand. One of the objectives was to examine interlinkages and interdependencies between sectors and various systems—energy, economy, land, water, and material resources.

In the third phase, we built SAFARI's power supply module (driven by the electricity demand estimated in Phase 2), included inputs from a computable general equilibrium (CGE) model to maintain macroeconomic consistency, and developed integrated scenarios—cohesive sectoral narratives that enable the examination of development ambitions and their implications.

In the fourth and final phase, we integrated the SAFARI model into a decision support system (DSS) that can help policymakers visualise various long-term development trajectories for India based on technology and policy interventions of their interest.

Thus, SAFARI is a user-interactive system dynamics simulation model of India's energy demand and supply up to 2050. Figure A shows the overall model structure and the various interactions. The year 2011 has been selected as the base year. Wherever possible, model projections have been validated and calibrated against goal- and sector-specific information as reported by the Government until 2019.

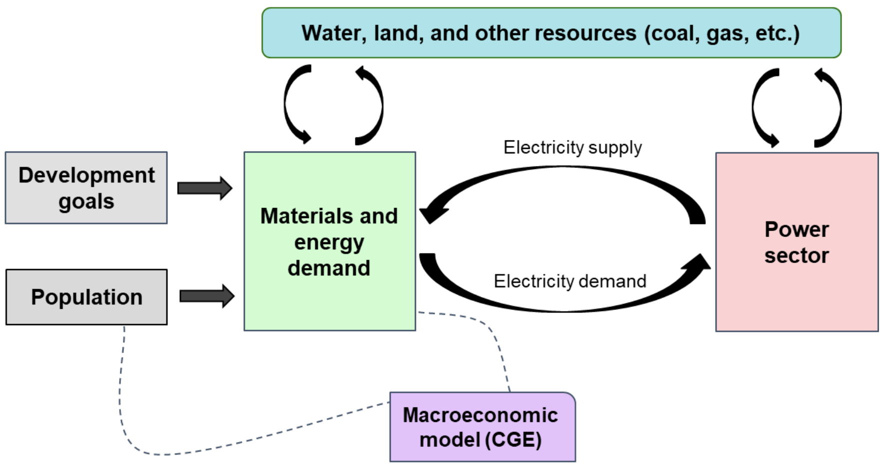

Figure A: SAFARI model overview

Scenario Development

SAFARI can be used to build long-term development scenarios for India. To demonstrate its ability to do so, we have developed a few scenarios that focus on key integrated policy choices the country may want to pursue, considering its developmental objectives, global commitments, and resource constraints. Our integrated scenarios are based on the following assumptions and storylines (users of the tool can similarly create their own scenarios):

1. **Business-as-usual (BAU):** In this scenario, historical trends and implementation of current policies are assumed to continue, but in the short run, the economic slowdown due to COVID is accounted for.

2. **Development Goals (DG)**: The basic development goals are assumed to be met by 2030 through a boost in investments post-COVID. Also, not much effort is made towards sustainability or low-carbon development.

3. **Sustainable Development 1 (SDa)**: In this scenario, the development goals are assumed to be met by 2030, and in addition, relatively easy-to-achieve sustainability interventions (through technological and efficiency improvements) are implemented, for example, moderate penetration of electric mobility, use of efficient appliances, increased energy efficiency in industries, increased precise irrigation, and energy-efficient pumps.

4. **Sustainable Development 2 (SDb)**: Climate and development are given equal priority in this scenario. Interventions that require medium to high effort to realise are considered, for example, a behavioural shift towards eating more millets than rice, use of more public transport for urban and intercity travel, shared mobility, better planned and compact cities, and no 'new' coal power plants after 2025. Efficiency improvements continue similar to or higher than those in SDa.

5. **Overconsumption (OC)**: In this scenario, the aspiration is towards international (based on the Organisation for Economic Co-operation and Development [OECD] countries) standards of living and consumption.

Key Findings

The BAU trajectory neither meets the goals nor is sustainable. The average annual gross domestic product (GDP) growth rate is ~5.3% (2020–2050), and the development goals are only partially met. For instance, even though around 22 million affordable housing units are built by 2030, it only bridges 50% of the shortage. GDP/capita of USD 5,000 (2012 prices) is reached in 2045. Compared to 2020, by 2050, electricity demand increases by four times, final and primary energy demands increase by around 2.5–3 times, and greenhouse gas (GHG) emissions more than double. Issues such as groundwater depletion, urban congestion, air pollution, and import dependence worsen.

The energy and emissions footprint of achieving development goals (DG scenario) is not considerably higher than that in the BAU scenario. Increased investments in healthcare, housing, education, and agriculture result in the development goals being met by 2030 and an increased GDP growth rate of ~6% (annual average for 2020–2050). GDP/capita of USD 5,000 (2012 prices) is reached a little earlier than BAU, around 2041. Since the goals are partially met even in BAU, the incremental increase in energy and emissions in the DG scenario is only around 5%–10% annually (detailed in Table A). However, both BAU and DG scenarios are resource-intensive, unsustainable, and not fossil fuel–free.

The developmental goal benchmarks could be achieved in a more sustainable manner. We explored two sustainable development scenarios (SDa and SDb) using SAFARI on the basis of ease of achievement and the policy effort required. Figure B shows the implications of the various sectoral interventions on GHG emissions.

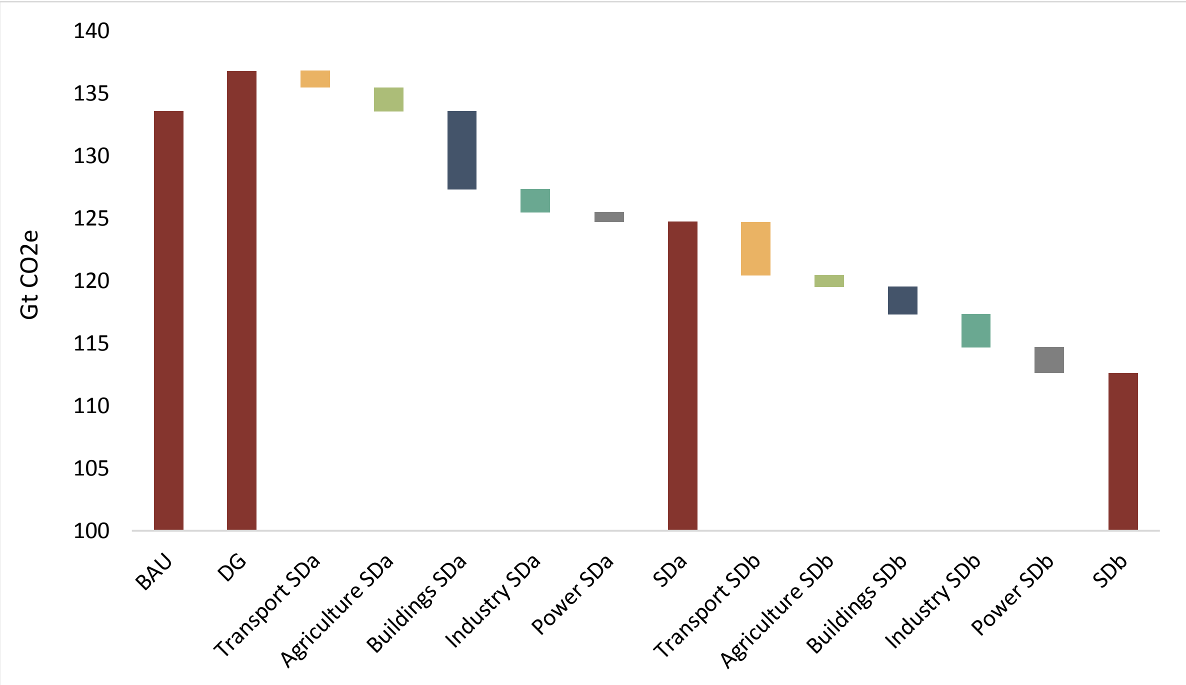

Figure B: Cumulative GHG emissions (2020–2050) in BAU, DG, SDa, and SDb scenarios[1]

[1] Please note that the y-axis starts at 100 instead of 0. This has been done to clearly show the relative contributions of sectoral interventions to GHG savings. Figure 26 shows the accurately scaled graph.

In the SDa scenario, 12 Gt CO_2e can be saved cumulatively by 2050 when compared with the DG scenario (Figure B and Table A). The three most effective interventions in this scenario in terms of carbon mitigation are as follows:

- Increased adoption of best practices (energy efficiency) in the cement and steel industries
- Use of alternative construction blocks, such as autoclaved aerated concrete (AAC), which have lower embodied emissions and better thermal properties (reduced space cooling demand)
- Improved water-use efficiency through increased precise irrigation coverage (reducing groundwater use) and use of energy-efficient irrigation pumps in the agriculture sector

In the SDb scenario, 24 Gt CO_2e can be saved cumulatively by 2050 when compared with DG (Figure B and Table A). The three most effective interventions in this scenario in terms of carbon mitigation are as follows:

- An increase in the share of railways in total freight transport to 35% by 2050 and growth in shared mobility (increased occupancy) across passenger transport modes
- A no 'new' coal power plant policy along with the reduced demands in this scenario results in GHG emissions from the power sector peaking around 2035.
- Increased diffusion of best practices in the cement and steel industries and increased use of Portland Slag and scrap steel in cement and steel production, respectively

In SDb, India's total GHG emissions plateau in the 2040s and slowly decline post-2046. Reaching net zero, however, would require implementation of technologies such as carbon capture, green hydrogen, and electric trucks.

Table A: Comparison of key variables in 2050 and cumulative GHG emissions for 2020–2050

Variable	BAU	DG	SDa	SDb	OC
Water withdrawal (BCM) in 2050	1,219	1,225	1,110	983	1,250
Electricity demand (TWh) in 2050	4,500	5,000	3,910	3,328	6,825
Final energy demand (EJ) in 2050	58	60	53	44	88
Coal-based generation (TWh) in 2050	1,773	1,955	1,240	632	2,458
Total coal demand (EJ) in 2050	34	36	27	19	50
Primary energy demand (EJ) in 2050	74	77	65	50	104
GHG emissions (Gt CO_2e) in 2050	6.1	6.3	5.3	4	9.5
Cumulative GHG emissions 2020–2050 (Gt CO_2e)	134	137	125	112	200
GDP growth rate (2020–2050)	5.3%	6%	-	-	-

Striving for international standards of consumption will not be a feasible developmental strategy for India, given the limited resources and huge population. In the Overconsumption (OC) scenario, where living standards in the OECD countries are used as benchmarks to drive demands in India, our analysis shows that the GHG emissions footprint is ~50% higher than that in the DG scenario, and severe water scarcity (due to increased demands and competing users) will have cascading effects on food and energy security. In fact, this scenario may result in India not being able to meet certain development goals owing to resource constraints. Sustainable development is the only effective way forward for India.

One of the benefits of the SAFARI tool is that within a scenario, one can analyse policy trade-offs between interlinked sectors. Here, we present some sectoral scenarios and describe how the tool was used to develop strategies to minimise trade-offs through alternatives.

- **Densification instead of sprawl in urban areas reduces the transport sector demand (and emissions) but could have other trade-offs in residential energy.** Densely constructed communities tend to experience the 'urban heat island' effect, which causes increased cooling demands. Also, taller buildings (typical in densification or vertical development scenarios) require 10%–20% more energy-intensive construction materials such as steel. A mild sprawl scenario with increased public transport or a densification scenario with alternative construction materials that reduce cooling demands could be two potential options for sustainable urbanisation.

- **A dietary shift away from water-intensive crops such as rice towards coarse cereals such as millets could significantly alleviate the water scarcity issue in the country but will require more land (because of millets' lower yields compared to rice's).** Improving the yields of coarse cereals, through research and development, will become necessary to avoid the trade-off. Every year, around 300 BCM of water, and close to 50 Mt of CO_2e through the avoided rice-methane emissions, can be saved through this intervention.

Limiting sugarcane cultivation is a good strategy to avoid freshwater depletion (and consequently ensuring food security); however, that could prevent India from achieving its ethanol blending policy. To ensure both food security and biofuels production, alternative strategies need to be developed to either boost ethanol production (through non-sugarcane crops) or reduce ethanol demand (through increased electric mobility or other fuels). Such integrated strategies that take into account cross-sectoral demands and constraints can be efficiently developed using the SAFARI tool.

Next Steps

Through stakeholder engagement, we will further refine the scenarios for India's future and define the contours of the most important and relevant pathways. By highlighting system linkages and policy trade-offs, we hope to shed light on the potentially unintended consequences of policy choices and thus the need for integrated strategy formulation. We hope that the tool can act as an effective test bed for policy evaluation, assisting in the development of Paris Agreement–compatible long-term strategies for India and providing a platform for cross-sectoral dialogues on sustainable development. In the future, we would like to extend SAFARI's modelling horizon to 2100 and include carbon sinks to be able to evaluate various net-zero emission pathways. We would also like to explore more regional implications of achieving India's development goals and resource constraints to further enhance national-level analyses.

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Abbreviations

BAU	Business-as-usual scenario
CGE	Computable general equilibrium
CO_2e	Carbon dioxide equivalent
COVID	Coronavirus disease (refers to the ongoing pandemic)
CUF	Capacity utilisation factor
DQoL	Desired quality of life
DG	Development goals scenario
DSS	Decision support system
GDP	Gross domestic product
GHG	Greenhouse gas emissions
Gt	Giga tonnes (equivalent to billion tonnes)
GW	Gigawatt
IPPU	Industrial process and product use
kWh	Kilowatt-hour
LCOE	Levelised cost of electricity
LTS	Long-term strategy
Mha	Million hectares
Mt	Million tonnes
NDC	Nationally determined contributions
OC	Overconsumption scenario
OECD	Organisation for Economic Cooperation and Development
PLF	Plant load factor
PV	Photovoltaic
RE	Renewable energy
SAFARI	Sustainable Alternative Futures for India
SDa	Sustainable Development scenario 1
SDb	Sustainable Development scenario 2
SDGs	Sustainable Development Goals
SEC	Specific energy consumption
T&D	Transmission and distribution
TWh	Terawatt-hour (equivalent to billion kWh)
UNFCCC	United Nations Framework Convention on Climate Change

PHASE 1

Define desired quality of life (DQoL) in terms of developmental goals

Set goal benchmarks for food, housing, healthcare, education, and water

PHASE 2

Estimate the demand for materials and energy to meet the developmental goals

Capture sectoral interlinkages; and water, materials, and land constraints

PHASE 3

Include sectoral growth inputs from a macroeconomic model to complement the goals-driven growth

Develop the electricity-supply-side model and preliminary integrated scenarios

PHASE 4

Encode the integrated model into a user-interactive DSS interface

Hold stakeholder consultations to finalise scenarios using DSS

1. Introduction

1.1. Premise

How can India achieve its developmental goals while reducing its greenhouse gas emissions? This is one of the most important questions we are faced with today. Developing countries such as India face the challenge of balancing their developmental goals and climate action imperatives, which are often assumed to be in conflict. However, research has found that this is not the full picture. In fact, there are more synergies between climate action and other Sustainable Development Goals (SDGs) than trade-offs, especially when planned in tandem (Fuso Nerini et al., 2019). The importance of capturing interlinkages and interdependencies in modelling exercises cannot be overemphasised, as it helps policymakers leverage synergies and limit trade-offs between their various goals. In turn, it will help India balance its Nationally Determined Contributions (NDC) targets[2] with its developmental goals.

1.2. Context: Long-Term Strategies and NDCs

The Intergovernmental Panel on Climate Change's (IPCC's) 2018 Special Report (IPCC, 2018) outlines several pathways to limit average global temperature rise to 1.5˚C (compared to pre-industrial levels). According to this report, we will need to reduce our net global CO_2 emissions by 45% by 2030 and then reach net-zero emissions by mid-century to stay within 1.5˚C. All of the 1.5˚C pathways outlined in it require a global transition towards fossil-free energy sources. Furthermore, it establishes that the NDC pledges made ahead of the 2015 Paris Agreement are insufficient to meet the 1.5˚C target. There is a clear need for stronger NDC ambition and developing long-term strategies harmoniously with our NDCs (WRI, 2019). To reach net-zero emissions, we need to rapidly decarbonise emissions-intensive sectors, such as electricity, buildings, transport, and agriculture. For India, one of the key challenges ahead lies in ensuring that its developmental aspirations are achieved in synergy with its climate strategies.

Countries were due to submit revised NDC pledges in 2020 and every 5 years thereafter according to the Paris Agreement (UNFCCC, 2015). They are also urged to develop long-term strategies (LTSs) that extend beyond the NDCs' 2030 timeline to mid-century. Ahead of the 26th UN Climate Change Conference of the Parties (COP26), India must take stock of the progress made on the 2015 NDC and make revisions if needed. The LTSs we develop should facilitate our NDC pledges.

Several countries around the world have already submitted their LTS. The United Kingdom (UK), the European Union (EU), and Canada intend to achieve net-zero carbon emissions by 2050, and quite recently, China announced that it intends to achieve net-zero emissions by 2060. Preliminary analysis suggests that China's LTS could provide significant economic benefits for the country (Pollitt, 2020). As one of the world's biggest GHG emitters and a country

[2] Reduce the emissions intensity of its GDP by 33% –35% from 2005 levels, increase non fossil-fuel based sources of electricity to 40% of the total installed capacity, create carbon sinks of 2.5–3 billion tonnes CO_2e through forest cover, and promote a sustainable development trajectory for the country by 2030.

with developmental aspirations, India is now facing international pressure to rapidly lower emissions, as well as achieve net-zero emissions.

Even the critics of adopting a net-zero target for India favour exploring low-carbon development trajectories, suggesting that this is more pragmatic and equitable. A sizable portion of the Indian population lacks adequate access to food, housing, clean water and air, healthcare, and electricity. It is, thus, imperative to consider ways to fill existing gaps and sustain future needs[3].

Equity is an important consideration in mitigation and decarbonisation efforts. With this in mind, the principle of common but differentiated responsibilities and respective capabilities (CBDR-RC) was formalised in the United Nations Framework Convention for Climate Change (UNFCCC) in 1992. Article 3.1 of the Convention mentions CBDR, stating that Parties should protect climate systems 'on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities' (UNFCCC, 1992). The CBDR principle also features in the 2015 Paris Agreement (UNFCCC, 2015). The Paris Agreement encourages developed countries to provide financial assistance to developing countries for implementing the UNFCCC objectives via low-carbon development strategies.

1.3. The SAFARI Model: Background

The Sustainable Alternative Futures for India (SAFARI) model developed at CSTEP is different from conventional models because it does not use GDP as the primary metric of development and welfare. Instead, SAFARI, a system dynamics simulation model, uses a more bottom-up approach where demands arising from achieving various development goals—food, housing, healthcare, education, power, water, and transport—are the main drivers of growth (CSTEP, 2020b). On the other hand, conventional models use GDP as an exogenous socio-economic driver for sectoral demand alongside population and energy intensity.

Simulation modelling allows stakeholders to explore "possible worlds" and understand how they function, which can inform policy decisions by providing insights into how the real world works (Desai, 2012). Simulation models, including system dynamics models, have the potential to serve multiple functions. They help with planning, forecasting, and moderating competing resource needs (Zhong et al., 2012). The simulation process allows users to learn through experiences of their decisions in a simulated environment. In this sense, the iterative storytelling possibilities make simulation models useful decision support systems (DSS). Using DSSs in policymaking could, therefore, help detect the 'unintended consequences' of policies that arise from a limited understanding of synergies and trade-offs. It is vital to make this process participatory, as "simulation is not a spectator sport" (Desai, 2012). System dynamics models have proved to be well suited for participatory policymaking. They help provide a good platform for stakeholders to come together and prioritise developmental objectives through collaborative policy design and planning (Abdullah & Kennedy, 2015).

[3] especially since India's population of 1.35 billion is projected to reach 1.7 billion by 2060

1.4. Project Objectives

One of the objectives of the project is to develop a model to estimate India's materials and energy demands, and the consequent emissions, up to 2050 with a special focus on meeting developmental goals. Another specific objective of the model is to include interlinkages and interdependencies between sectors to capture unintended consequences of policy choices and the trade-offs between achieving different goals. Finally, the goal is to integrate this model into a visualisation platform that will enable policymakers to create and virtually test their strategies.

Phase 1	Define a desired quality of life (DQoL) in terms of developmental goals
	Set goal benchmarks for food, housing, healthcare, education, and water
Phase 2	Estimate the demand for materials and energy to meet the developmental goals
	Capture sectoral interlinkages and water, materials, and land constraints
Phase 3	Include sectoral growth inputs from a macroeconomic model to complement the goals-driven growth
	Develop the electricity-supply-side model and preliminary integrated scenarios
Phase 4	Encode the integrated model into a user-interactive DSS interface
	Hold stakeholder consultations to finalise scenarios using DSS.

Figure 1 Project overview

We conceptualised the project in four phases, as described in Figure 1.

Some of the questions we explored in the model include: what would be the coal power generation share up to 2050 in the various trajectories of interest? What will be the demand for coal across scenarios? Will RE growth in our power generation mix alongside electrification of transport offset increase in GHG emissions on account of growing transport demand? To what extent could behavioural changes help reduce emissions in specific sectors such as agriculture, cooling, and industries? Should our cities develop vertically or continue to sprawl?

2. Approach

2.1 Overall Model Structure

In Figure 2, we present an overview of the SAFARI model structure.

The demand drivers in the SAFARI model are the selected development goals (food, housing, healthcare, education, transport, clean cooking, water, and power) and socio-economic parameters such as population and GDP. GDP is an output from our macroeconomic computable general equilibrium (CGE) model (CSTEP, 2020a), soft-linked to SAFARI. The CGE model is driven by investments, and accounts for the current economic slowdown caused by the pandemic. Details on sectoral investment assumptions and the soft-linking methodology can be found in Section 9.4 (Appendix).

Goals, population growth, and GDP drive materials and energy demand in the agriculture, residential, commercial, industry, and transport sectors. The availability of water, land, and other materials pose constraints on the growth of these sectors. For instance, the foodgrain demand required to meet the food-for-all goal drives increased the area under foodgrain cultivation. However, constraints of arable land and water availability may limit foodgrain production. The causal loop diagrams describing the structure and dynamics of all the goals and demands are described in the Phase 2 report (CSTEP, 2020b), and the agriculture and urbanisation sectors are further elaborated in our recent journal articles (Ashok et al., 2021; Kumar et al., 2021).

The total energy demand estimated (from development goal needs and demand for materials) comprises electric and thermal energy. The electricity demand is then used to drive growth in power sector capacity and generation in the country. We looked at fossil-fuel sources such as coal and natural gas and fossil fuel–free sources of power such as hydro, nuclear, biomass, solar, and wind. Electricity supply is also constrained by the availability of water, land, and resources.

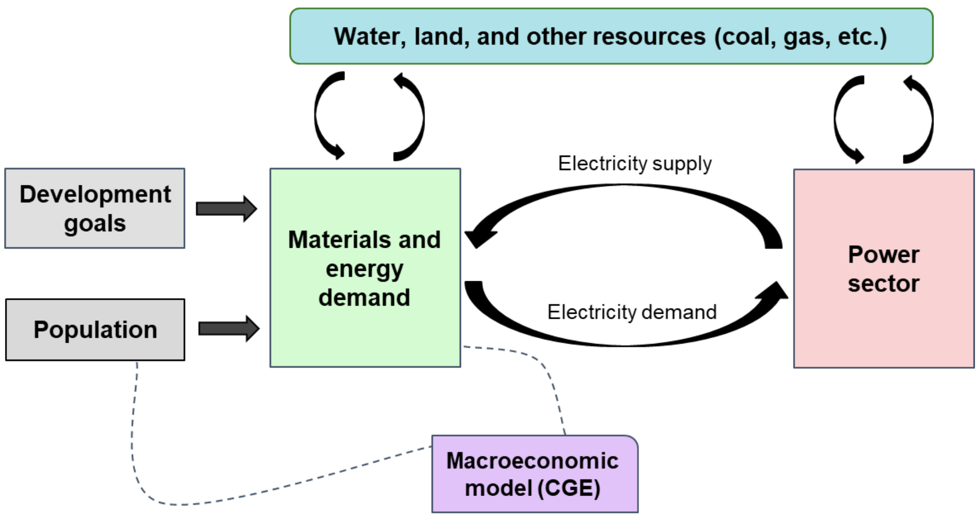


Figure 2 SAFARI model structure

An important output of the SAFARI model is GHG emissions (in CO_2e). It includes emissions from energy use, industry processes and product use (IPPU), and agriculture sectors—covering about 93% of the country's GHG emissions as of 2014. Emissions related to the waste sector and forestry and land use (FOLU) are not covered. Table 13 provides more details.

2.2 Electricity Supply Modelling

System dynamics has had a long history of being used for energy modelling (Fiddaman, 1997; Gallagher et al., 2019; Naill & F, 1977; Naill, 1992; Sterman, 1982). System dynamics modelling focusses on capturing real-world decision-making processes to the extent possible. Similar to other simulation models, decisions are made at each time step recursively, depending on the system's state at that particular time. Decision-making in these models works using the bounded information available in a time step. This is consistent with other dynamic recursive simulation models where the decision-making is based on limited or myopic foresight, which is different from models that assume perfect economically rational behaviour or optimal decision-making (perfect foresight over the whole duration of the run). This makes system dynamics simulation models represent real-world decision-making while reflecting market imperfections or failures (Bolwig et al., 2019; Semertzidis, 2015). Rather than establishing an optimal strategy according to one criterion (objective function), simulation scenarios are compared based on several criteria. Ideally, many relevant considerations need to be taken into account, and their relative importance cannot necessarily be measured by one common denominator. Consequently, simulation models are rooted in the philosophy that alternative routes and end states with dissimilar strengths and weaknesses should be identified and discussed (Lund et al., 2017).

The electricity supply module of SAFARI is built to respond to demand and meet the overall and peak demand for all scenarios. It captures interactions between electricity demand, electricity supply, and other resources. The model architecture is represented in Figure 3. Supply sources being considered include coal, nuclear, natural gas, large hydro, solar PV, wind, biomass, micro-hydro, and grid storage–integrated solar PV. The model considers India as one spatial unit and runs at an annual time step, although it accounts for variations in day, night, and peak, in a broad manner as detailed in the Appendix (Section 9.5).

Feedback Loops in the Electricity Supply Module:

Future planning to meet demand (B1): All capacity additions in the model are based on the projected future electricity demand and the current supply. Additionally, the model also considers the potential generation availability attributable to low plant load factors (PLFs) of coal, nuclear, and hydro while calculating the gap between projected demand and supply. The difference between the two is used to calculate how much capacity needs to be added to meet future electricity demand (after accounting for auxiliary consumption and T&D losses).

Current management (B2): The year-on-year demand–supply equilibrium is maintained by the changing of PLFs, subject to a maximum PLF for each technology.

Future planning for peak load (B3): Additional capacity is added if there is a gap in meeting the future peak electricity demand.

Cost-based changes in supply mix (B4): The model is designed to expand capacities is based on discounted levelised cost of electricity (LCOE). The LCOE for each supply source is calculated every year, based on the respective cost trajectories[4] and dynamic PLFs[5]. Therefore, LCOE is a dynamic variable being endogenously calculated. The decision-making for determining the capacity expansion portfolio is determined by economic attractiveness—lower the LCOE, higher the economic attractiveness and higher the share in the additional capacity mix (subject to a maximum based on ultimate potentials and resource constraints).

The dynamic LCOEs are calculated endogenously in the model at each time step according to the standard formulation:

$$\text{Dynamic LCOE} = \frac{\textit{Discounted total lifetime cost}}{\textit{Discounted total lifetime electricity generation}}$$

This forms a balancing loop where the increase in PLFs would lead to a reduction in LCOE, and a technology with lower LCOE would drive higher capacity expansion (and consequently lower the demand–supply gap, thereby restricting the growth of PLFs).

Energy resource limits (B5): The model is constrained by the ultimate resource availability of each supply source that limits the growth in capacities of the respective sources. For supply sources such as coal and gas, the domestic resource limit is overcome through imports.

Water constraints, supply-side (B6): Water withdrawal for electricity generation based on water footprint for each technology is considered in the model. If there is a water shortage, the corresponding loss of electricity generation is provided as an indicator.

Water constraints, demand-side (B7): If there is water scarcity, it impacts electricity demand and supply.

Policy goals (B8): This is an illustrative loop to explain how the model fits into a DSS. Here, the model user could explore various policy decisions and input them into the model (through switches and levers) to create different demand scenarios. The power supply–side model will respond to the demand changes and would generate a supply mix and subsequent emissions. This way, the model presents an integrated and dynamic approach for testing policies and interventions.

[4] provided in the Appendix

[5] There is an expectation formation built into the calculation, which uses the trend of dynamic PLFs from the last 5 years to form an expectation of the PLF for the next 5 years (using trend-based forecasting, FORCST function in STELLA). Through this, an average expected dynamic PLF is computed, which feeds into the LCOE calculation and subsequently informs the relative share of the new capacity additions.

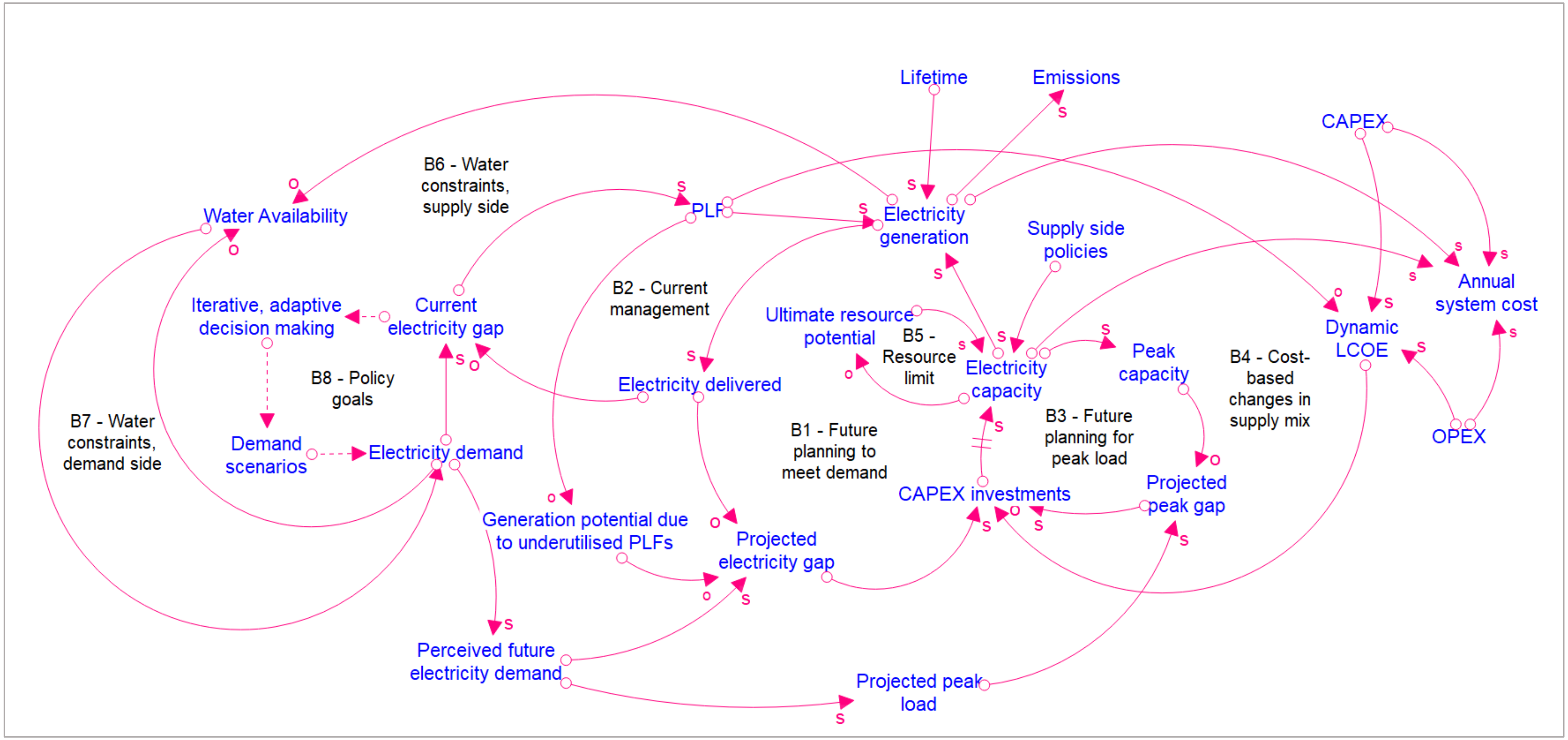


Figure 3 Electricity supply model architecture

2.3 Development of Integrated Scenarios

Scenario development through modelling is typically an iterative exercise involving discussions with stakeholders and sectoral experts. In Figure 4, we outline the process we are following to finalise scenarios using SAFARI.

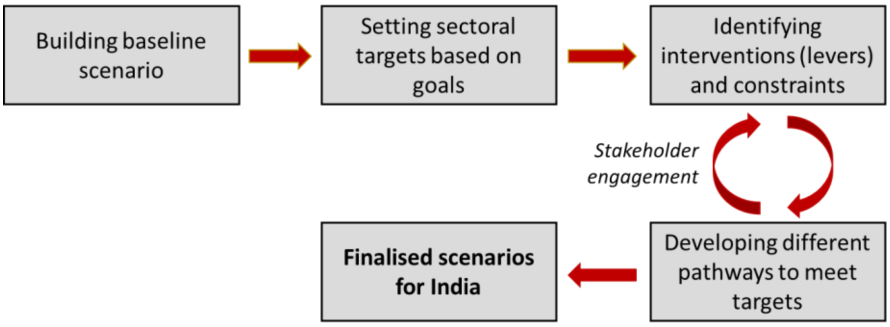


Figure 4 Scenario development approach

The first step is to build the baseline or the business-as-usual (BAU) scenario, which essentially means extrapolating historical trends and identifying the extent to which current policies will be implemented. This allows us to see which SDGs or climate targets could be met without any additional effort.

We then project what achieving the goals would mean in terms of sectoral growth. For instance, how much should the agriculture sector production increase to maintain food security in the country or what is the additional cement capacity required to support the infrastructural goals?

Back-casting from these targets, in the next step, we identify important sectoral interventions and policy levers that could help achieve the goals sustainably. For instance, we identify penetration of micro-irrigation to improve water-use efficiency and crop productivity or the use of alternative construction materials with lower-embodied energy and emissions. We also note the upper bounds, where applicable, for these interventions—such as the ultimate irrigation potential—to avoid overshooting beyond realistic limits. While we have come up with a set of levers (detailed in Table 1), further stakeholder engagement (in the upcoming phase) will help identify other levers and shortlist the most relevant ones. We have provided a comprehensive list of policies and plans covered in the SAFARI model in the Appendix.

The next step is to develop various pathways towards achieving targets using different intervention (or lever) combinations. Stakeholders and sectoral experts can use this tool to explore various scenarios to come up with policy interventions and a range of likely/desirable scenarios. For ease of understanding, we have categorised the key interventions into three buckets based on enabling mechanisms. While these categories are not mutually exclusive and there are overlaps, the intent is to classify based on the most dominant enabler.

1. Policy, regulation, and ambition: interventions that require a more aggressive policy push from the Government to make them feasible.

2. Technology improvement, innovation, and market: interventions that require improvements in technology through research and development and market-driven solutions

3. Behavioural shifts based on personal choices: interventions that require citizens to behave responsibly and make sustainable choices

Table 1 Key interventions and levers in SAFARI

Policy, regulation, and ambition	Technology and markets	Behavioural shifts
Micro-irrigation coverage	High-yielding varieties of crops	A dietary shift to less water-intensive crops
Reducing area under sugarcane cultivation	Reducing foodgrain wastage through better storage technologies	A dietary shift towards less red meat
Solar pumps for irrigation	2G ethanol and other advanced biofuels	Zero-budget natural farming and other natural farming methods
Energy-efficient pumps	Manufacturing of alternative materials for construction	Use of public transport
Water-use policies in industries and recycling	Smart buildings	Reduced travel demand (teleworking)
Incentives for electric vehicles	Improved battery storage technology and manufacturing	Carpooling and shared mobility
Transit-oriented development and urban densification (vs sprawl) based on higher floor space indices (FSIs)	Cement industry blending shares	Appliance usage patterns
Raising the housing-for-all targets to account for the *real* shortage and size-per-house	Increased fuel efficiency	Clean cooking
Guidelines to increase the share of alternative materials	Appliance efficiency	Domestic water recycling
Recycled steel use in the steel industry		
Alternative fuels in industries		
High RE in the power sector		
No 'new' coal power plants		

We describe various scenarios for India's developmental future using a combination of these interventions (Table 1) and the growth drivers described earlier, in the succeeding chapters. We also look at a few sectoral implications and trade-offs in sustainable urbanisation and agriculture.


Housing
Bridge real housing shortage computed considering degradation, congestion, and homelessness
Food
Food security through sustainable agriculture practices (efficient water-use)
Healthcare
Improving infrastructure through adequate healthcare centres with 3.5 beds per 1000 population by 2050
Power
Cleaner electricity supply to meet all demands arising from various developmental goals
Education
Adequate infrastructure with a focus on improving enrolment ratio in higher education
Water
Sufficient water supply for various competing demands including domestic consumption of 135 litres/capita/day
Transport
Sustainably meet transport demands (lower emissions and air pollution)
Clean Cooking
Shift towards cleaner cooking fuels (LPG & electricity)

3. Development Goal Ambitions: Gaps and the Implications of Bridging Them

3.1 Desired Quality of Life Benchmarks and Current Gaps

Figure 5 provides an overview of the goals and their benchmarks considered in this study as important for achieving a desired quality of life (DQoL) in India. Each goal is unique in the way that it is considered here (CSTEP, 2018, 2020b).

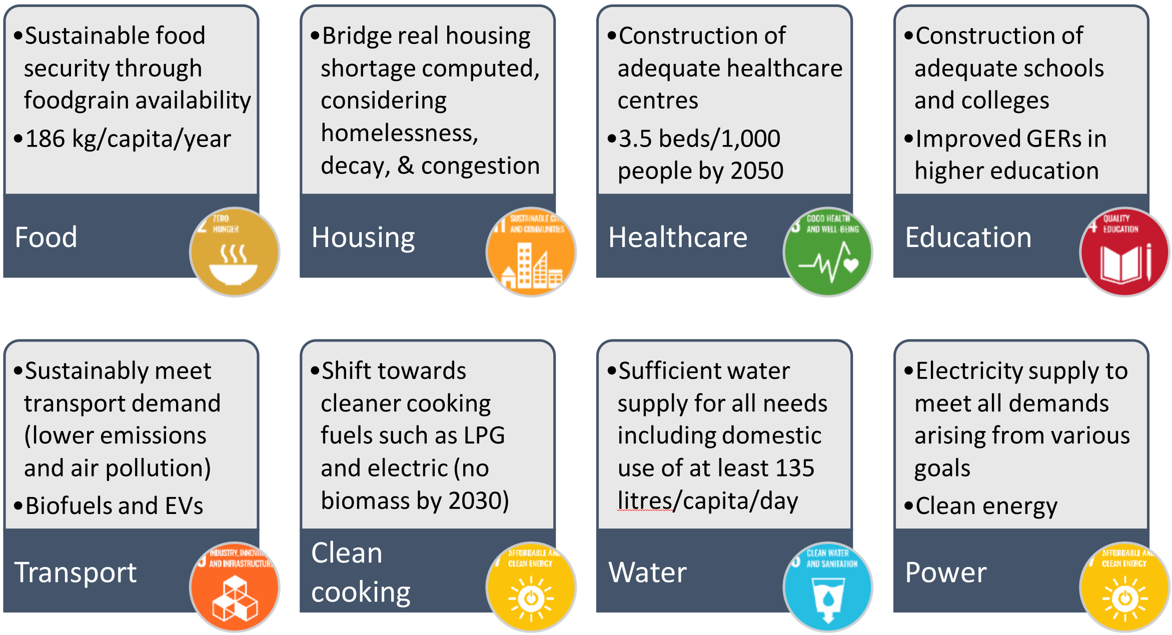


Figure 5 Developmental goals considered in this study, DQoL benchmarks

The food goal looks at producing a sufficient quantity of foodgrains (for human consumption and livestock, based on meat demand) to satisfy the per capita dietary requirements. While India is currently self-sufficient in foodgrain production, maintaining our food security could become a significant challenge as the population grows and competing demands for water and arable land increase (Kumar et al., 2016). Moreover, the agriculture sector has been mainly responsible for groundwater over-exploitation (Dubash, 2007; Rodell et al., 2018) in some regions of the country[6]. Continued over-extraction of groundwater through progressively deeper bore wells (until aquifers are completely dried out) will have disastrous impacts on the environment and achieving food security. Therefore, efficient agricultural practices that reduce water demand through regulated water use policies are vital to maintaining food security.

[6] In the 1960s, the Government of India enacted a series of policies to subsidise various agricultural inputs, including electricity supply, to stimulate production and ensure food security. Along with the Green Revolution, these subsidies certainly played a role in increasing agricultural productivity over the next few decades. However, it is well established that one of the unintended consequences of providing cheap electricity in the long term has been the over-exploitation of groundwater for growing water-intensive crops such as rice and sugarcane. Freshwater depletion and falling aquifer levels have been quite severe in the north-west and eastern parts of the country.

The housing goal examines India's affordable housing shortage along a 2050 timeline. India already has 'Housing-for-All by 2022' policies in place (Pradhan Mantri Awas Yojana [PMAY] Urban and Rural; MOHUPA, 2015), which looks at meeting both urban and rural housing shortage by 2022. PMAY-Urban targets building 11.5 million houses by 2022 while PMAY-Rural aims to build 29.5 million houses by 2022. However, while these policies try to meet a fixed housing target by 2022, SAFARI computes the annual housing shortage based on factors such as the annual dilapidation of existing houses, congestion, population increase, and changes in household size. The average sanction or construction[7] rate for urban housing was about 2.4 million houses per year between 2016, when it started, and 2018. Assuming this to be the BAU construction rate going forward, we see that while it may be possible to meet policy targets, it would not be possible to meet SAFARI's estimated dynamic shortage. In a BAU scenario, where current construction rates continue, the urban housing shortage would increase to 24 million in 2030 and 47 million in 2050. The rural housing shortage can be met by 2035 if current rates of construction continue.

Healthcare and education goals focus on constructing hospitals to meet the required beds per capita and schools to achieve gross enrolment ratio (GER) targets. In BAU, the number of hospital beds per 1,000 people would remain below two even in 2050, and the GER for senior secondary and tertiary education would reach up to ~60%. With a significant increase in health and education infrastructure investments, the DQoL benchmarks can be achieved.

In the transport and cooking goals, sustainability is a part of the goal itself. For the transport sector, increased public transport in urban areas is considered (to reduce air pollution and congestion). In cooking, biomass will be completely phased out by 2030, and there will be a shift towards electric cooking in urban areas. The water and power goals are key development goals but will also include demand arising out of interventions to meet other goals.

[7] While in reality, sanction rate and construction rate are not the same, in this model, it is assumed that once a house is sanctioned, it is immediately possible to construct it, subject only to material availability and resource constraints. Therefore, for this report, sanction rate and construction rate can be considered interchangeably.

3.2 Integrated Scenarios

Business-as-usual (BAU) *'Que Sera Sera'*

Energy consumption and emissions rise as they would in the absence of additional interventions; existing policies are implemented to varying degrees; and developmental gaps remain in our key sectors.

Development Goals (DG) *'The Bare Necessities'*

Developmental gaps are filled as a priority, in contrast to BAU, but this is done without much consideration to environmental indicators, energy, or emissions.

Sustainable Development 1 (SDa) *'Here Comes the Sun'*

Mitigation is a serious consideration, and technological and efficiency improvements by mid-century reduce the resource, emissions, and energy footprints of efforts towards filling the developmental gaps.

Sustainable Development 2 (SDb) *'What a Wonderful World'*

Climate and development are given equal urgency, with behavioural shifts induced through a variety of measures. Technological and efficiency improvements seen in SDa continue, with greater ambition at times.

Overconsumption (OC) *'Comfortably Numb'*

India aspires for living standards and consumption patterns of OECD countries. Without serious thought given to technological and behavioural changes, climate efforts take a backseat and GHG emissions rise considerably.

3.3 BAU and DG: Implications of Meeting Development Goals

The implications of achieving DQoL (DG scenario) in terms of GDP, materials and freshwater demand, and electricity demand and supply, in comparison to BAU, are described below.

GDP

In BAU, where historical trends and practices are assumed to continue and urbanisation reaches over 50% by 2050, most development goal benchmarks (DQoL) are not met. The average annual GDP growth rate for 2020–2050 is around 5.3% based on our CGE model (described in the Appendix, Section 9.4), after including the impact of COVID on economic growth[8].

Aiming for DQoL benchmarks implies increased investments in agriculture, health, education, and construction sectors, especially in the coming decade (investment growth rates are provided in Appendix Section 9.4). In our economic modelling framework (CGE), we find that these investments have ripple effects on several key production sectors (such as cement and steel) and household and institutional consumption, resulting in an increased average annual growth rate of around 6% (2020–2050). The GDP is projected to reach the USD 5 trillion target around 2035 under both these scenarios.

Table 2 shows growth in GDP/capita in BAU and DG by 2050.

Materials and Water

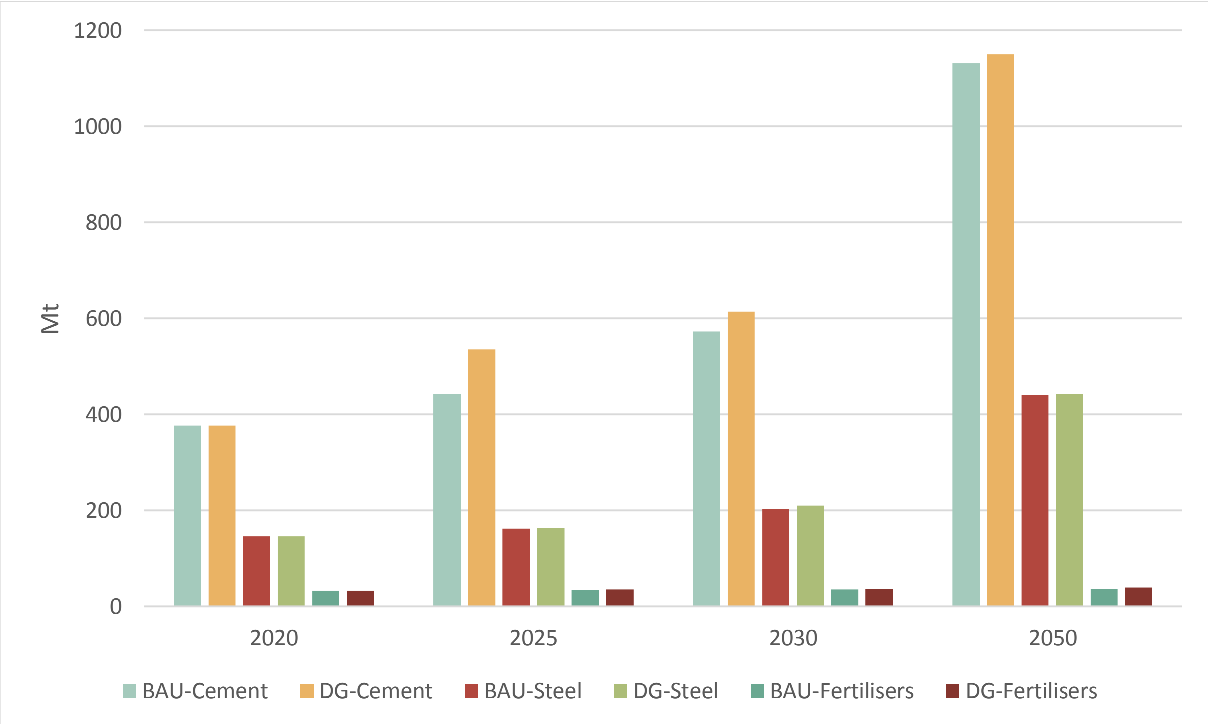


Figure 6 Annual demand for cement, steel, and fertilisers in BAU and DG scenarios

[8] Our pre-pandemic estimate of average annual GDP growth for 2020–2050 was ~6%.

Figure 6 shows the annual industrial demands for fertiliser, cement, and steel in the BAU and DG scenarios. The cement demand in the DG scenario is higher than BAU in the coming decade to meet the housing, education, and healthcare infrastructure goals. Otherwise, the demand for materials in the DG scenario is only marginally higher than BAU. This is because even in BAU, a fraction of the development goals are being achieved.

The total demand for water (withdrawal) reaches around 1,225 billion cubic metres by 2050, of which ~78% is for irrigation. More details on sectoral material demands can be found in our previous report (CSTEP, 2020c).

Energy

Figure 7 and Figure 8 show the sectoral electricity demands for BAU and DG scenarios, respectively. The difference in total electricity demand between BAU and DG is only about 5% in 2030 and 11% in 2050. 70%–80% of the incremental increase in electricity demand over the years in DG, compared to BAU, is from the residential sector. This is due to the increase in the total residential built-up area (driven by SAFARI's housing goal benchmarks) and the subsequent increase in demand for space-cooling and other appliances.

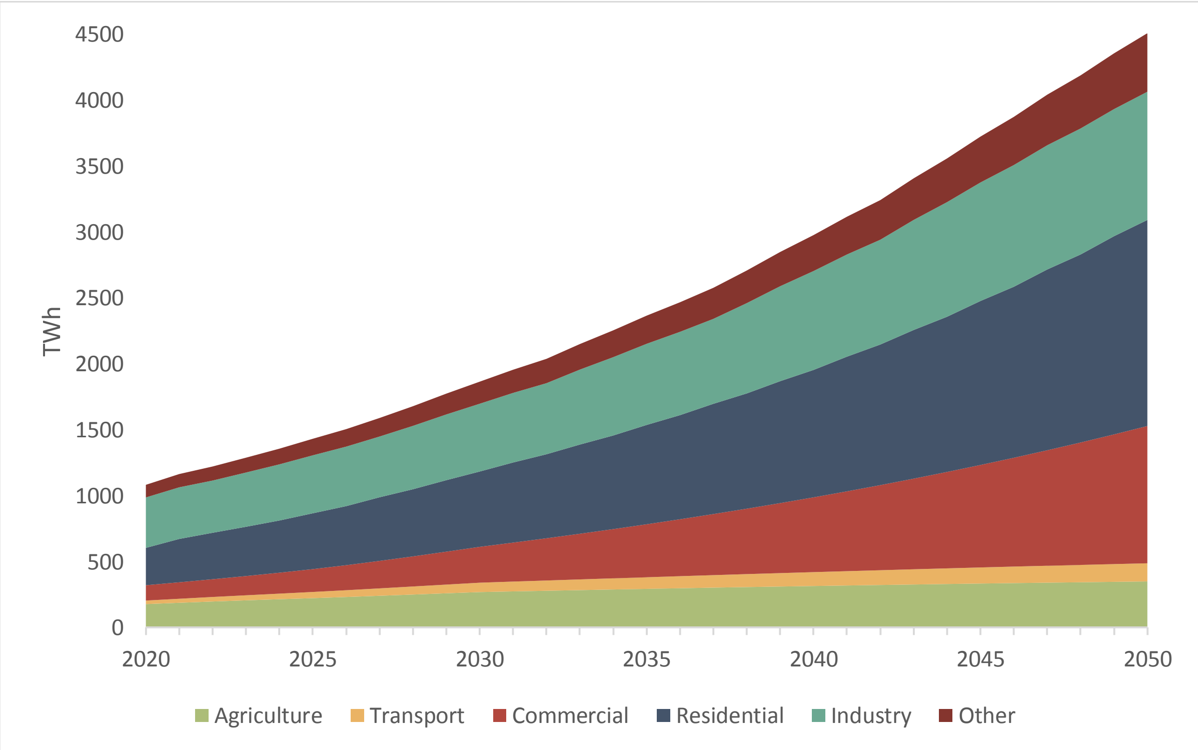


Figure 7 Sectoral electricity demand in BAU

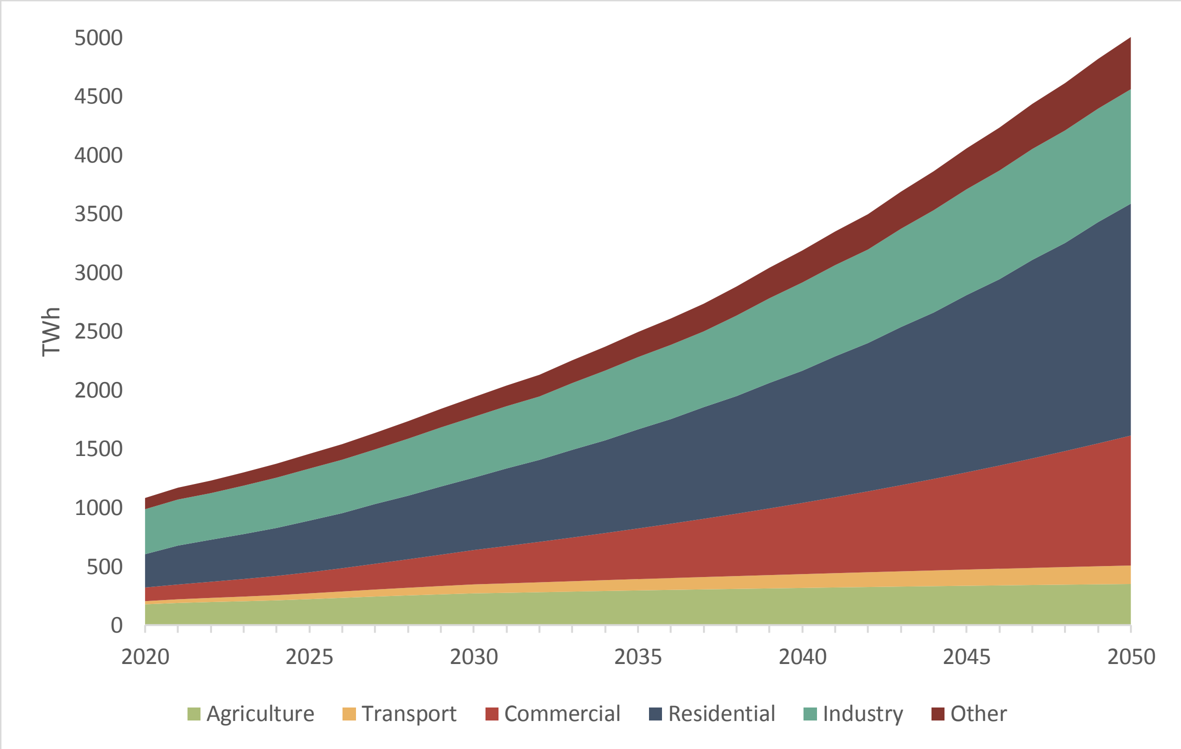


Figure 8 Sectoral electricity demand in the DG scenario

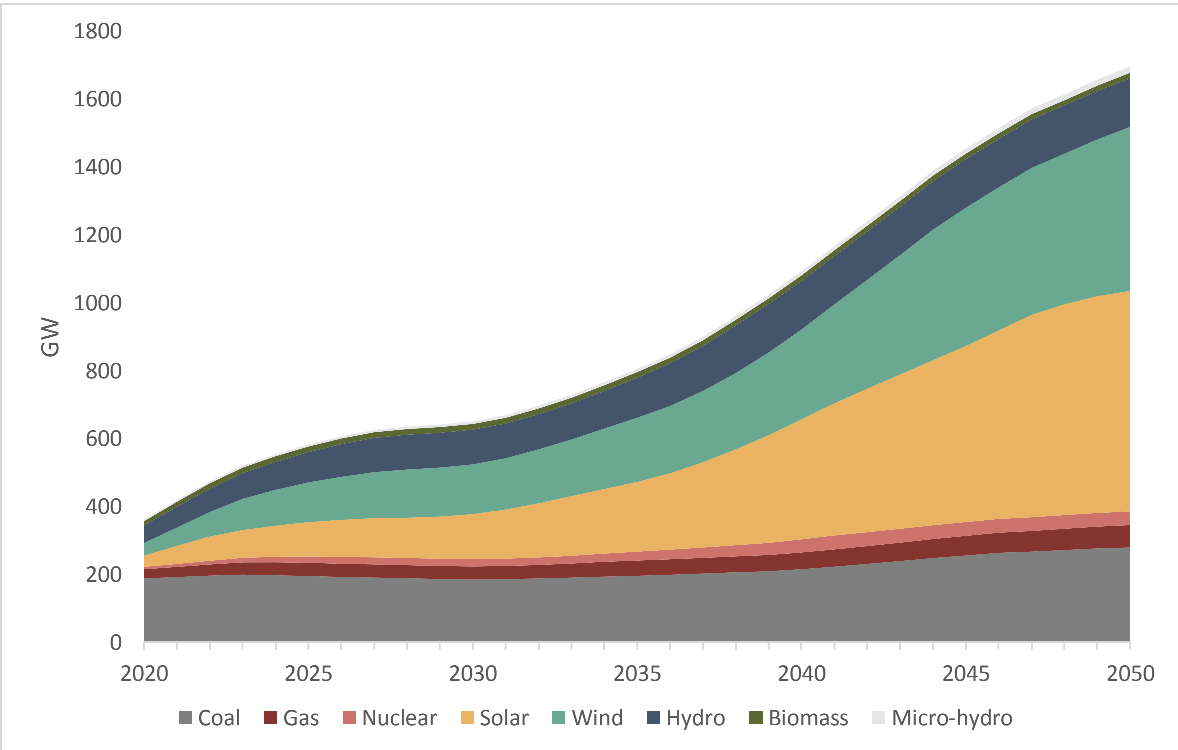


Figure 9 Power sector operating capacities in BAU

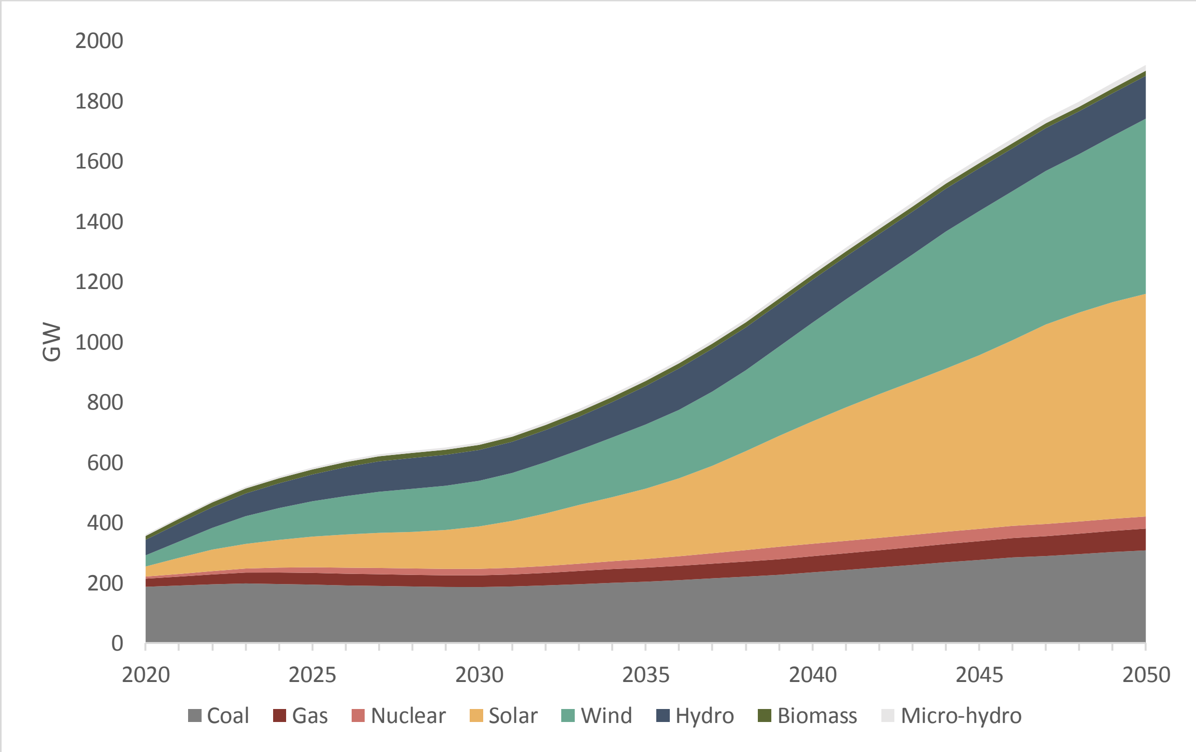


Figure 10 Power sector operating capacities in the DG scenario

In the power sector, as shown in Figure 9 and Figure 10, the total installed capacity almost doubles by 2030. The share of fossil-free capacity is projected to be 64% in 2030, surpassing India's NDC goal of 40%. This is mainly driven by increased penetration of renewables (on account of cost reduction, improvements in generational efficiency, and availability of grid storage). RE penetration can be higher than what is projected in the Central Electricity Authority (CEA)'s National Electricity Plan, 2018, because we considered a more ambitious reduction in costs of renewables, an assumption supported by recent data/developments.

The model indicates that the operating capacity requirement increases almost five times—from around 360 GW in 2020 to between 1,700 GW and 1,920 GW in 2050 under the BAU and DG scenarios, respectively. In both scenarios, due to the cost attractiveness of solar power, the capacity growth rate is higher than the generation growth. The fossil-free share in the total installed capacity in 2050 increases to around 78% under these scenarios.

Although coal and gas power account for only 36% (2030) and 22% (2050) of the total operating capacity, they still contribute to around 54% (2030) and 37% (2050) of generation in both BAU and DG scenarios (Figure 11). Generation shares remain similar between BAU and DG since supply-side parameters such as RE cost reduction or technological advancements in power generation technologies are assumed to be the same across both scenarios.

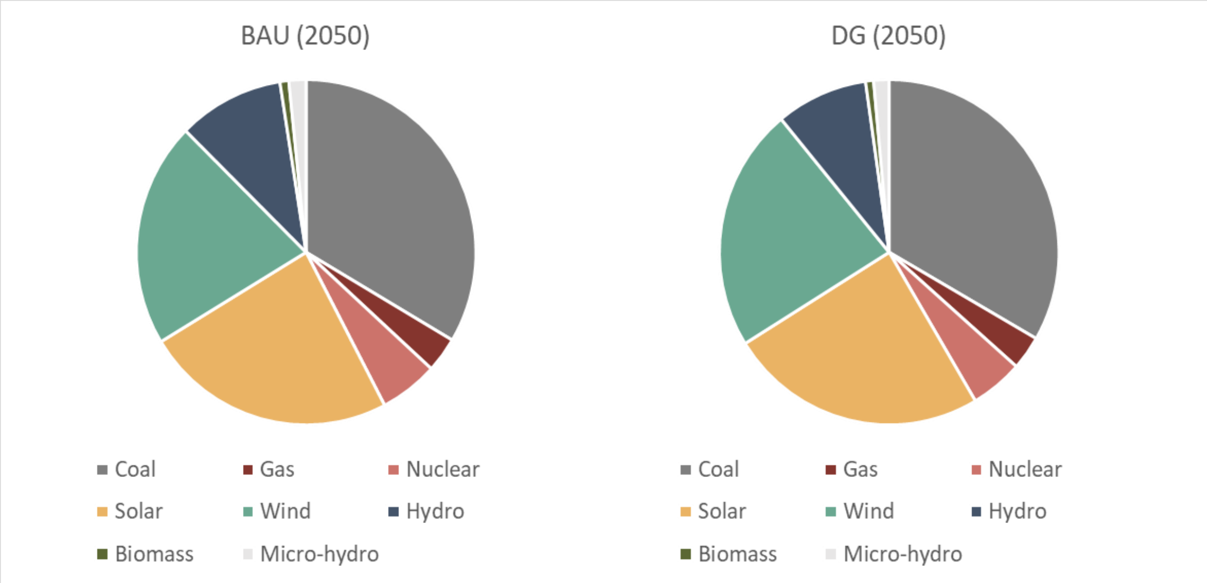


Figure 11 Electricity generation shares in BAU (5,294 TWh generation) and DG (5,867 TWh generation) in 2050

India's final energy demand and primary energy demand are expected to increase by 2.5 to 3 times by 2050 (from 2020 values) in both BAU and DG. The demand for coal and total GHG emissions across scenarios are discussed in Sections 3.7 and 0, respectively. Table 2 summarises the results for water and energy demands and GDP growth rates in the BAU and DG scenarios.

Table 2 Summary of BAU and DG scenarios

Variable	2020	BAU 2050	DG 2050
Water withdrawal, BCM	1,015	1,219	1,225
Electricity demand, TWh (before losses)	1,082	4,500	5,000
Final energy demand, EJ	22	58	60
Power sector operating capacity, GW	360	1,700	1,920
Fossil fuel–free generation share, %	25%	63%	63%
Primary energy demand, EJ	29	74	77
Average annual GDP growth rate (2020–2050)	-	5.3%	6%
GDP/capita (2012 prices)	USD 1,800 (INR 1,02,845)	USD 7,058 (INR 4,02,308)	USD 8,484 (INR 4.83,598)

Our analysis shows that achieving DQoL benchmarks will only marginally increase India's materials or energy demands in the future compared to BAU. However, India is already on a resource-intensive and unsustainable growth trajectory. More groundwater is extracted than is annually replenished, leading to falling aquifer levels. India's cities are congested and have severe air quality issues. There is high dependence on fossil-fuel imports to meet growing energy demands. In the next section, we explore more sustainable pathways for achieving DQoL goals through better resource-use efficiency, technology improvements, and behavioural changes.

3.4 Sustainable Development 1 (SDa scenario): 'Here Comes the Sun'

In the SDa scenario, we imagine a future for India in which all development gaps are filled in food, transport, housing, and other sectors as in the DG scenario but with an eye on relatively easy-to-achieve sustainability targets. These are mostly technological (such as electric mobility and better construction materials) and efficiency-related targets (such as the use of efficient appliances and energy efficiency improvements in industries) and achievable through efficiency improvement policies (IEA, 2019). Furthermore, this scenario explores alternative pathways for meeting the DG scenario goals through more sustainable use of resources (such as increased coverage of precise irrigation) and lower energy and emissions. This scenario assumes that the current trend of groundwater over-extraction stops. Further details are given in Table 3, which lists all the interventions in this scenario. Table 9 in the Appendix provides a comparison of assumptions across scenarios.

The total electricity demand in 2050, in the SDa scenario, is around 13% lower than that in the BAU scenario and around 21% lower than that in the DG scenario (Figure 12). Demand reduction is primarily driven by the residential and agriculture sectors. In the residential sector, greater mixed-use development (medium FSI) and consequently shorter trip lengths in the transport sector compared to the DG scenario can result in lower energy demand. Technological improvements such as higher appliance efficiency and greater electrification of cooking and transport also affect demand. Figure 13 and Figure 14 reveal an increase in the renewable energy share in the power sector by 2050.

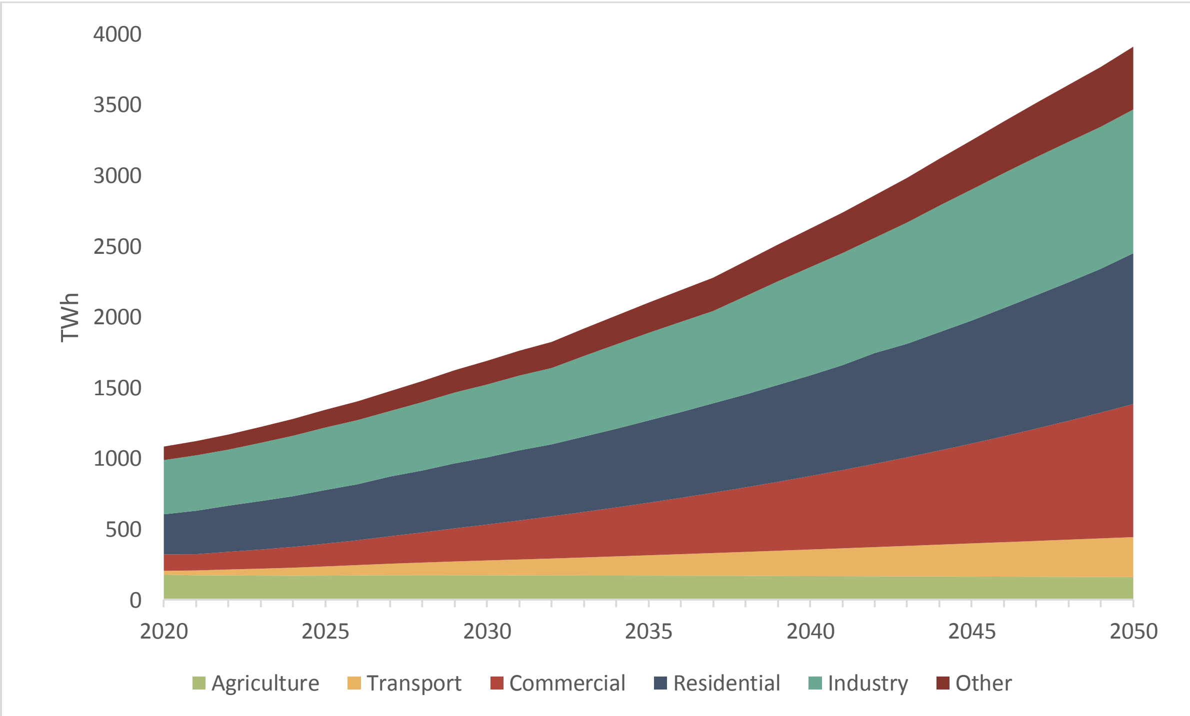


Figure 12 Sectoral electricity demand in the SDa scenario

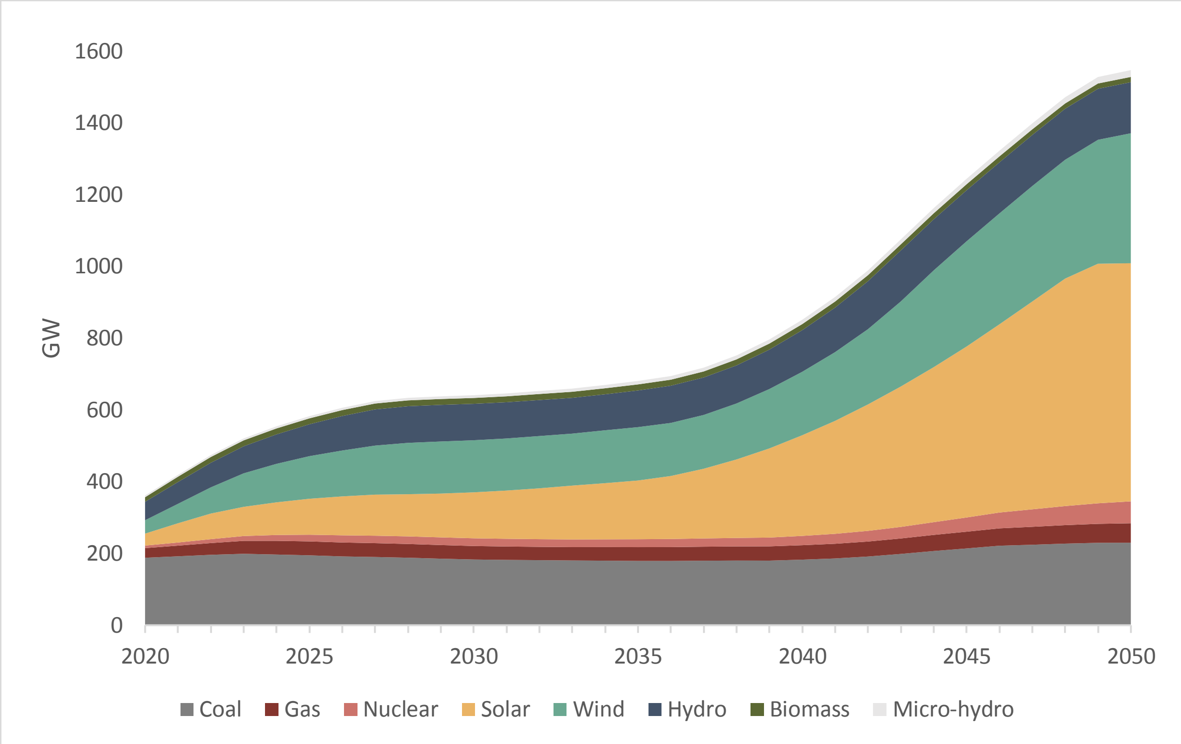


Figure 13 Power sector operating capacities in the SDa scenario

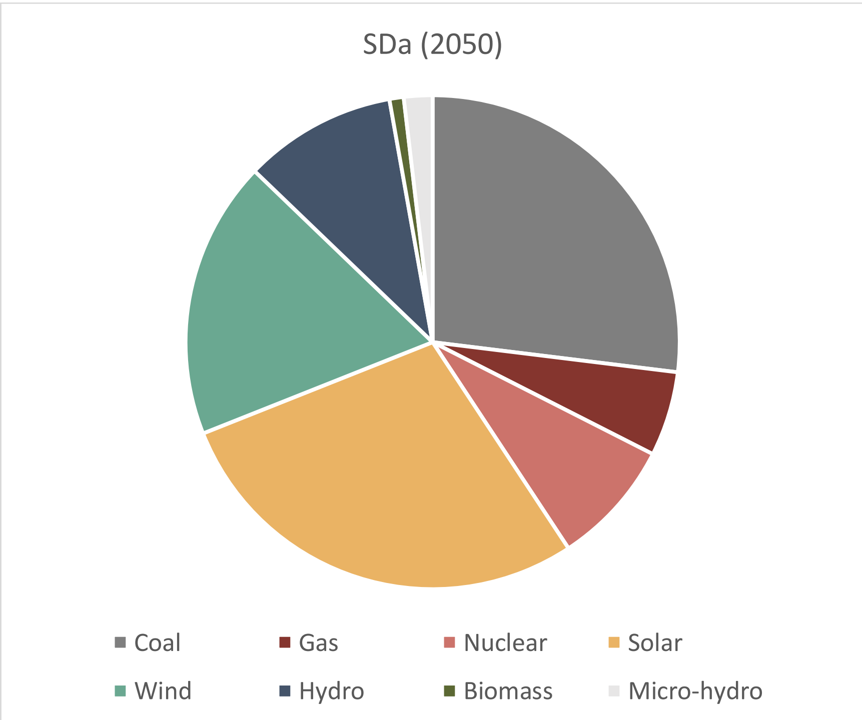


Figure 14 Power generation share in SDa (4,600 TWh generation) in 2050

Table 3 Interventions in SDa 'Here Comes the Sun' compared to BAU

Sector	Interventions in SDa	BAU levels (without interventions)
Agriculture and food	• Improved water-use efficiency—precise irrigation coverage increases to 40% of the irrigated area (~30 Mha) by 2050; no groundwater over-exploitation • Irrigation pump efficiency improves to 75% by 2050	• As of 2020, around 4 Mha (5% of the irrigated area) is under precise irrigation and is assumed to increase to ~8 Mha (10%) by 2050 in BAU • Irrigation pump efficiency improves from 50% in 2020 to 60% by 2050
Residential and housing	• Semi-compact cities (average FSI = 4), moderate open space per capita (12 m^2); the urban heat island effect increases cooling demand by 10%. • Alternative materials (50% of construction blocks are AAC by 2050) for housing construction • 20% recycling of sand and construction and demolition (C&D) waste • Appliance efficiency level: medium • Electric cooking increases to 40% (urban) and 20% (rural) by 2050	• Average FSI of 1.5 (semi-sprawl), open space per capita of 12 m^2; no urban heat island effect • Conventional construction materials used—80% of construction blocks are burnt clay bricks and 1% AAC. • 1% of sand and C&D waste are recycled for reuse. • Appliance efficiency level: low • Share of electric cooking increases from being <1% currently to 15%–20% by 2050.
Commercial, including healthcare and education	• 15%–20% reduction in the energy performance index (EPI)[9] of commercial buildings (from BAU levels) by 2050	-
Transport and mobility	• 25% of bus pkm, 50% of car pkm, 60% of three-wheeler pkm, and 100% of two-wheeler pkm to be electric by 2050, and complete electrification of passenger and freight railways by 2030. • Semi-compact cities, leading to slightly reduced trip lengths in urban areas	• 15% of bus pkm, 10% of car pkm, 20% of three-wheeler pkm, and 50% of two-wheeler pkm to be electric by 2050, and complete electrification of passenger and freight railways by 2030. • Semi-sprawl urban form
Industry	• 50% of cement industries in 2050 use today's best practices (an average specific energy consumption (SEC) improvement of 13%). • The share of alternative fuels in the cement industry increases to 40% by 2050. • Only natural gas is used as feedstock and fuel in the fertiliser industry. • 50% of the steel industry in 2050 uses today's best practices (an average SEC improvement of ~7%).	• 10% of cement industries in 2050 use today's best practices (an average SEC improvement of ~10%). • The share of alternative fuels in the cement industry continues at 15%. • The share of natural gas in the fertiliser industry increases from 80% in 2020 to 90% by 2050. • 40% of the steel industry in 2050 uses today's best practices (average SEC improvement of ~3%).

[9] Energy consumed per metre square of built-up area, on average

Power sector	• The maximum potential for nuclear capacity increases to 60 GW and battery storage reaches 400 GW by 2050. • Solar CAPEX (per GW) reduces by 40%, wind CAPEX by 30%, and battery cost by 80% by 2050. • The average water footprint of coal power plants reduces to 4.38 m^3/GWh by 2030 and beyond.	• Maximum potential for nuclear capacity is 40 GW, and battery storage reaches 250 GW by 2050 in BAU. • Solar CAPEX (per GW) reduces by 30%, wind CAPEX by 10%, and battery cost by 70% by 2050. • The average water footprint of coal power plants reduces from 50 m^3/GWh today to 4.38 m^3/GWh by 2050.

3.5 Sustainable Development 2 (SDb scenario): 'What a Wonderful World'

In the SDb scenario, as in the DG and SDa scenarios, all development gaps are filled in food, transport, housing, and other sectors. However, this scenario features behavioural changes in addition to technological and efficiency improvements similar to those in SDa. Further, as was the case with SDa, SDb explores alternative pathways for meeting the DG scenario goals through the use of more sustainable resources and lower energy and emissions. This scenario represents a serious attempt to harmonise climate, environmental, and developmental goals.

In this scenario, the total electricity demand in 2050 is around 26% lower than that in the BAU scenario and around 34% lower than that in the DG scenario. In the residential sector, particularly in urban areas, densification reduces pressure on land and curtails urban sprawl. SDb further imagines a prioritisation of urban green space for a better quality of life. This, in turn, reduces the heat island effect in urban areas and contributes to a lower active space cooling demand. With high levels of alternative material usage, passive interventions in residential buildings further reduce active cooling demand, thus lowering the overall electricity consumption. In the transport sector, transit-oriented development, shorter trips made increasingly with public and non-motorised transport, and electrification of passenger transport reduce urban passenger transport fuel demand.

In the agriculture sector, as in the SDa scenario, high levels of precise irrigation and reduced competition for water because of lower power sector water demands continue coupled with the cessation of current levels of groundwater over-extraction. Furthermore, sugarcane cultivation, which is highly water-intensive, is limited in this scenario. With greater diffusion of solar pumps, higher levels of natural farming, and a gradual dietary shift towards millet consumption, this scenario envisions high levels of behavioural changes in the food and agriculture sector.

Figure 15 shows sectoral electricity demands, Figure 16 shows power sector operating capacities, and Figure 17 shows electricity generation shares in 2050. With the further addition of non-fossil fuel capacity as well as a 'no new coal' by 2025 policy, the emissions intensity of electricity reduces considerably by 2050. Table 4 describes the interventions used in SDb in detail.

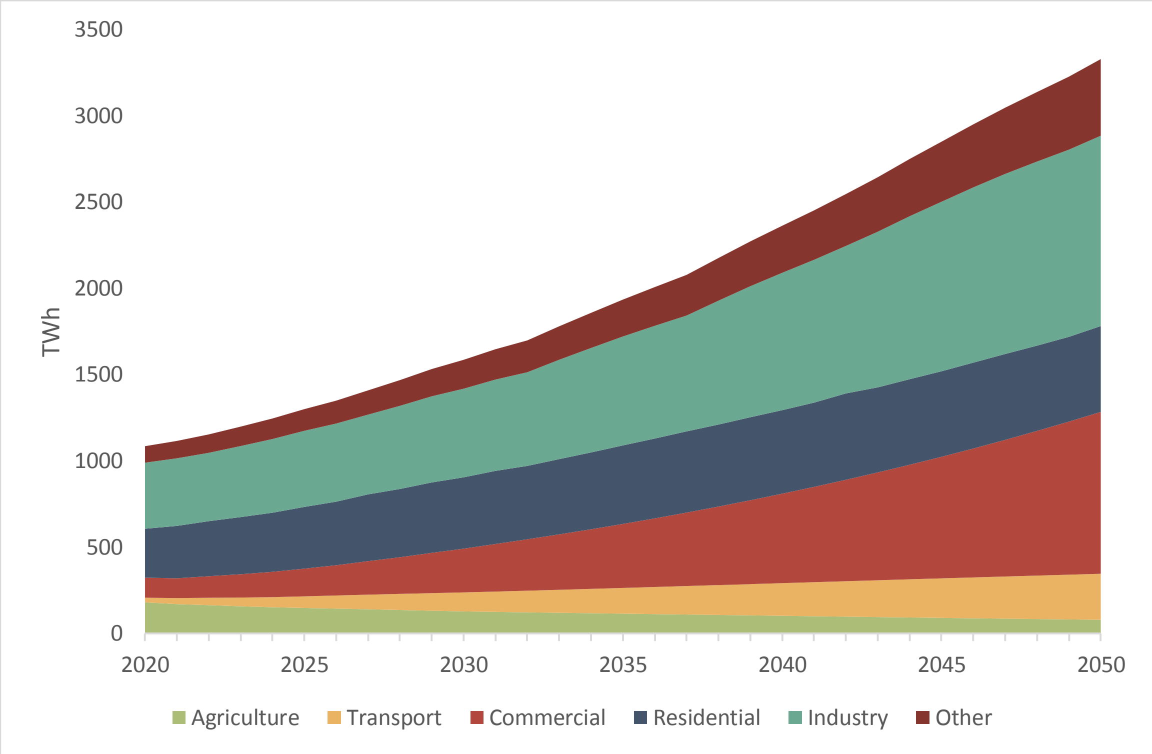


Figure 15 Sectoral electricity demand in the SDb scenario

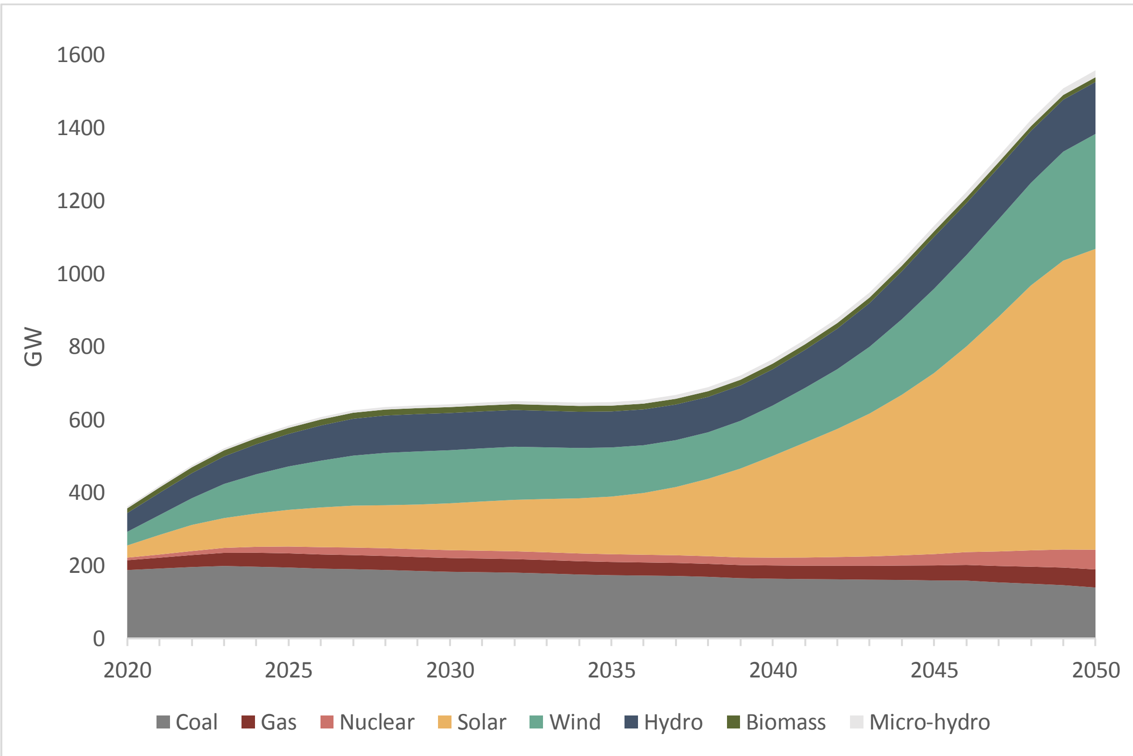


Figure 16 Power sector operating capacities in the SDb scenario

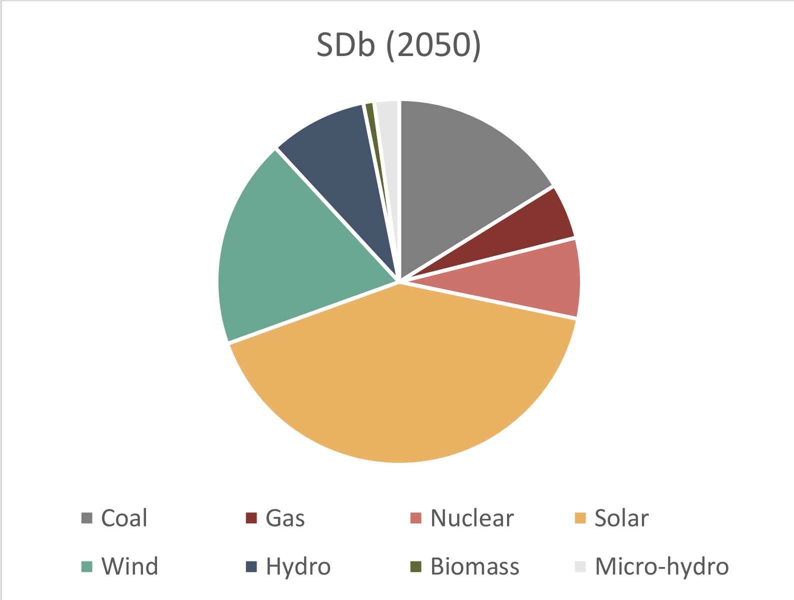


Figure 17 Power generation share in SDb (3,908 TWh generation) in 2050

Table 4 Interventions in SDb: 'What a Wonderful World'

Sector	Interventions in SDb[10]	BAU
Agriculture and food	*Improved water-use efficiency—precise irrigation coverage increases to 40% of irrigated area by 2050 (no groundwater over-exploitation). Irrigation pump efficiency increases to 75%.* • A dietary shift towards coarse cereals—half of all rice is replaced by millets in our diets by 2050. • Area under sugarcane cultivation is limited to 5 Mha • 50% penetration of solar pumps by 2050 • 20% of all cultivated area is under natural farming (such as zero-budget natural farming) by 2050.	• In BAU, our diets remain dominated by rice and wheat. • The area under sugarcane cultivation is currently ~4.5 Mha and increases to ~7.5 Mha by 2050 in BAU. • 10% penetration of solar pumps by 2050 • 5% of the cultivated area is under natural farming by 2050.
Residential and housing	• Compact cities (average FSI = 8) and high open space per capita (30 m²) • The urban heat island (UHI) effect increases the cooling demand by 10%. • Alternative materials (75% of construction blocks are AAC by 2050) for housing construction • 40% recycling of sand and C&D waste • *Appliance efficiency level: medium* • Electric cooking increases to 60% (urban) and 30% (rural) by 2050.	• Average FSI of 1.5 (semi-sprawl), open space per capita of 12 m²; no UHI. • Conventional construction materials used—80% of construction blocks are burnt clay bricks and 1% AAC. • 1% of sand and C&D waste are recycled for reuse. • Appliance efficiency level: low • The share of electric cooking increases from being <1%

[10] The interventions that remain the same as in SDa are in italics.

		currently to 15%–20% by 2050.
Commercial, including healthcare and education	*15%–20% reduction in the EPI of commercial buildings by 2050*	-
Transport and mobility	*Complete electrification of passenger and freight railways by 2030, and 25% of bus pkm, 50% of car pkm, 60% of three-wheeler pkm, and 100% of two-wheeler pkm become electric by 2050.* • An increase in the share of rail in intercity passenger transport to 25% and reduction in the share of air to 3% by 2050 • An increase in the share of rail in freight transport to 35% by 2050; the share of road, water, and air by 2050 will be 55%, 9%, and 1%, respectively. • More shared mobility and, therefore, higher fuel efficiency per pkm • Compact cities result in reduced urban trip lengths by 2050.	• The share of rail is currently 15% and continues to remain so until 2050. • The share of rail in freight transport is currently 35% and reduces to 15% by 2050 in BAU and is replaced by road. • No special emphasis on shared mobility. • Mild sprawl is the BAU urban form.
Industry	*The share of alternative fuels in the cement industry increases to 40% by 2050. Only natural gas is used as feedstock in the fertiliser industry.* • 70% of cement industries in 2050 use today's best practices (an average SEC improvement of ~23%) • 60% of the steel industry in 2050 uses today's best practices (an average SEC improvement of ~16%). • The proportion of Portland Slag–type cement goes up to 85% by 2050, replacing ordinary Portland cement to reduce the clinker to cement ratio. • By 2050, 25% of the steel production occurs via scrap steel recycling and 19% by using an electric arc furnace (12% natural gas–driven iron reduction and 7% coal-driven iron reduction).	• 10% of cement industries in 2050 use today's best practices (an average SEC improvement of ~10%). • 40% of the steel industry in 2050 uses today's best practices (an average SEC improvement of ~3%). • The proportion of Portland Slag–type cement reaches 68% by 2050 (compared to 11% today).
Power sector	• The existing and planned coal plants run their lifetime, but no new coal plants are sanctioned. • Maximum potential for nuclear capacity increases to 80 GW, and battery storage reaches 600 GW by 2050. • Solar CAPEX reduces by 40%, wind CAPEX by 30%, and battery cost by 80% by 2050. *The once-through cooling technology gets phased out by 2030 in coal, nuclear, gas, and biomass power plants to reduce water withdrawal.*	• Coal plants continue to be added based on the least cost • Maximum potential for nuclear capacity is 40 GW, and battery storage reaches 250 GW by 2050 in BAU. • Solar CAPEX (per GW) reduces by 30%, wind CAPEX by 10%, and battery cost by 70% by 2050.

3.6 Overconsumption (OC): 'Comfortably Numb' Scenario

In this section, we describe the Overconsumption scenario where the benchmarks for the goals considered in Section 3.1 are increased to meet international standards (as in the OECD countries)[11]. As detailed in Table 8, the Overconsumption scenario is meant to look at a future where India aspires to be like the West in terms of size of houses, private vehicle use, occupancies, area per student in schools, size of hospitals, and overall increased consumption of goods. This scenario leads to a much higher electricity demand (Figure 18), water demand, operating capacities of power plants, and GHG emissions.

Driven by consumptive lifestyles and the western quality of life benchmarks, the operating capacity of power generation increases considerably under the Overconsumption scenario (Figure 19). Coal-based electricity generation (Figure 20) reaches 2,458 TWh by 2050, which is more than double that of 2019–20 levels.

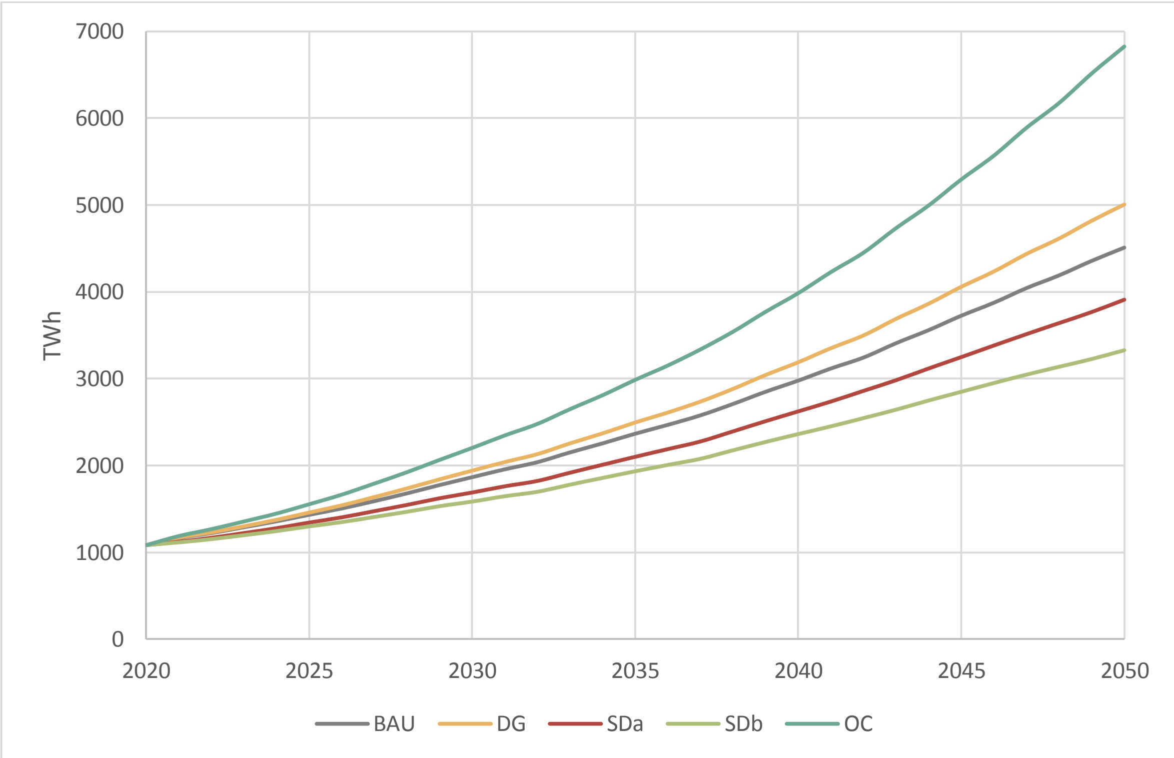


Figure 18 Electricity demand across scenarios

[11] https://stats.oecd.org/

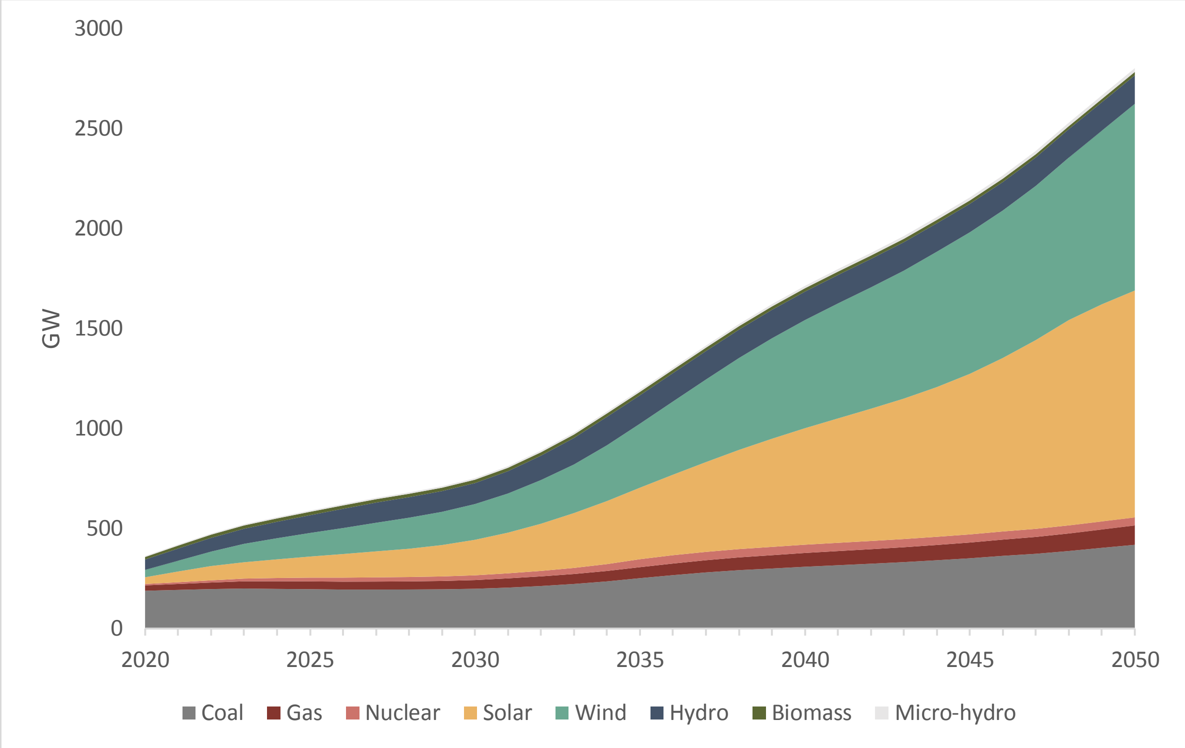


Figure 19 Operating capacities in the Overconsumption scenario

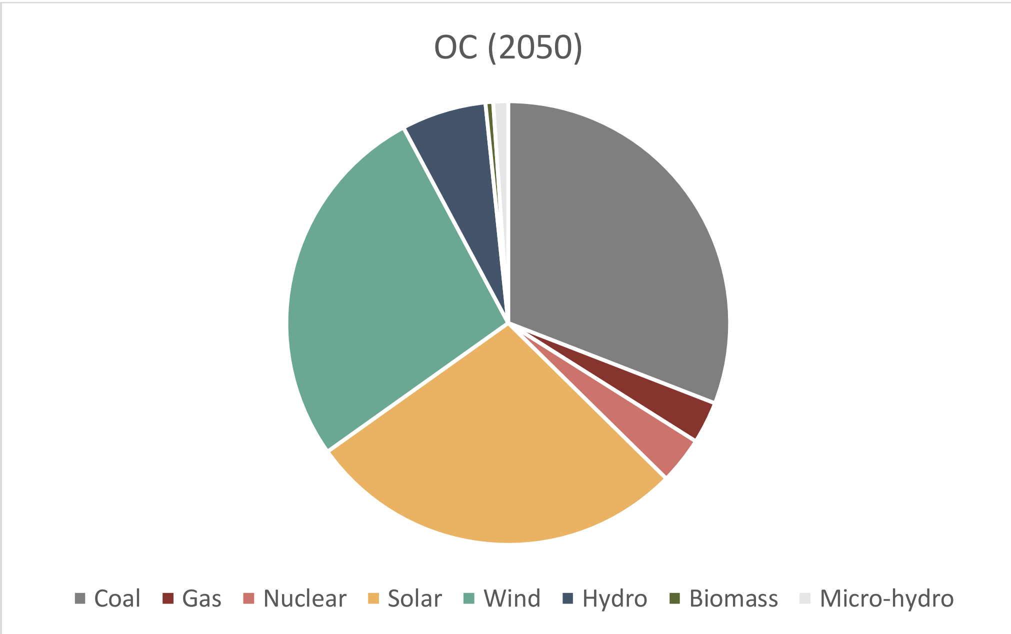


Figure 20 Power generation share in the OC scenario (7,956 TWh generation) in 2050

3.7 Demand for Coal

In this section, we present the demand for coal from the industrial sector (thermal coal for process heating and captive power and coking coal for steel manufacturing) and the power sector (coal-fired power plants).

The power sector coal demands are based on the least-cost power supply mix as described in the previous sections. Figure 21 shows India's total coal demand up to 2050 across integrated scenarios in SAFARI. Our estimates suggest that India's annual coal demand as of 2019 was around 16 EJ (billion GJ), of which 60% was from the power sector. According to the Coal Directory[12] published by the Ministry of Coal, India produced 12.4 EJ of coal in 2018–19. The remaining demand was met via imports, bringing the total annual demand closer to our estimate[13].

The share of imports in meeting the coal demand varies across sectors. For instance, up to 80% of the coking coal demand is met through imports, while for the power sector, the share of imported coal in meeting the demand is only around 11% (as inferred from the Coal Directory and the Provisional Coal Statistics[14]). Estimating the import share for future years is critical in calculating the tonnes of coal required because of the variability in energy content between domestic and imported coal. Therefore, we first present the exajoules (EJ) of coal demand (Figure 21) and then use assumptions for estimating the future share of imports to calculate the coal tonnage.

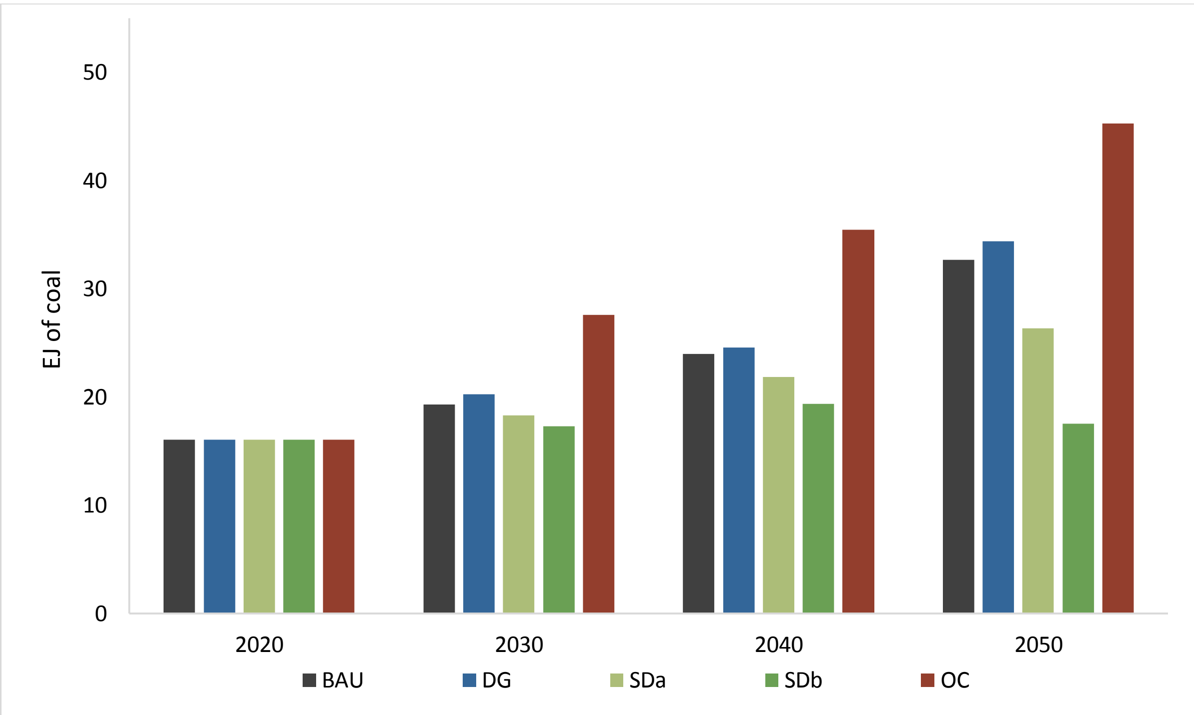


Figure 21 Total coal demand in exajoules (EJ)

[12] The Coal Directory 2018–19

[13] The total EJ demand (domestic + import) is not mentioned in the Coal Directory; however, the ratio of domestic to imported coal for 2018–19 is 76/24 (based on tonnage).

[14] Provisional Coal Statistics 2018–19

In the BAU and DG scenarios, the coal demand doubles by 2050, while in the OC scenario, it increases by almost three times. The annual coal demand increases to almost 35 EJ (~836 Mtoe) in 2050 in the DG scenario. A little over 50% of this demand is from the power sector (at an estimated coal-based electricity generation of 1,955 TWh in 2050), followed by 25% from the steel industry (at an estimated steel production of 440 Mt). Coal demand for the steel industry includes coking coal and thermal coal for heating and captive power requirements. Cement production reaches ~1.15 billion tonnes by 2050 (in the DG scenario) and contributes to 6% of the coal demand. More than 80% of this demand is met through imports today.

To estimate the tonnes of coal required, we assumed that for the power sector, by 2024, all demands are met through domestic coal (based on announcements by the Coal Ministry), while in other sectors, current shares of imports continue.

As shown in Figure 22, the total demand for coal across scenarios is 900–1,380 Mt (in 2030) and 880–2,475 Mt (in 2050). In the SDb scenario, where no new coal power plants are added beyond 2025, the total coal demand in 2050 is about 5% more than today's annual demand (as shown in Figure 22). Even though the SDb scenario projects lower coal demand from the power sector (coal-based electricity generation reduces to ~630 TWh by 2050[15]), the increase in industrial demand will more than offset it.

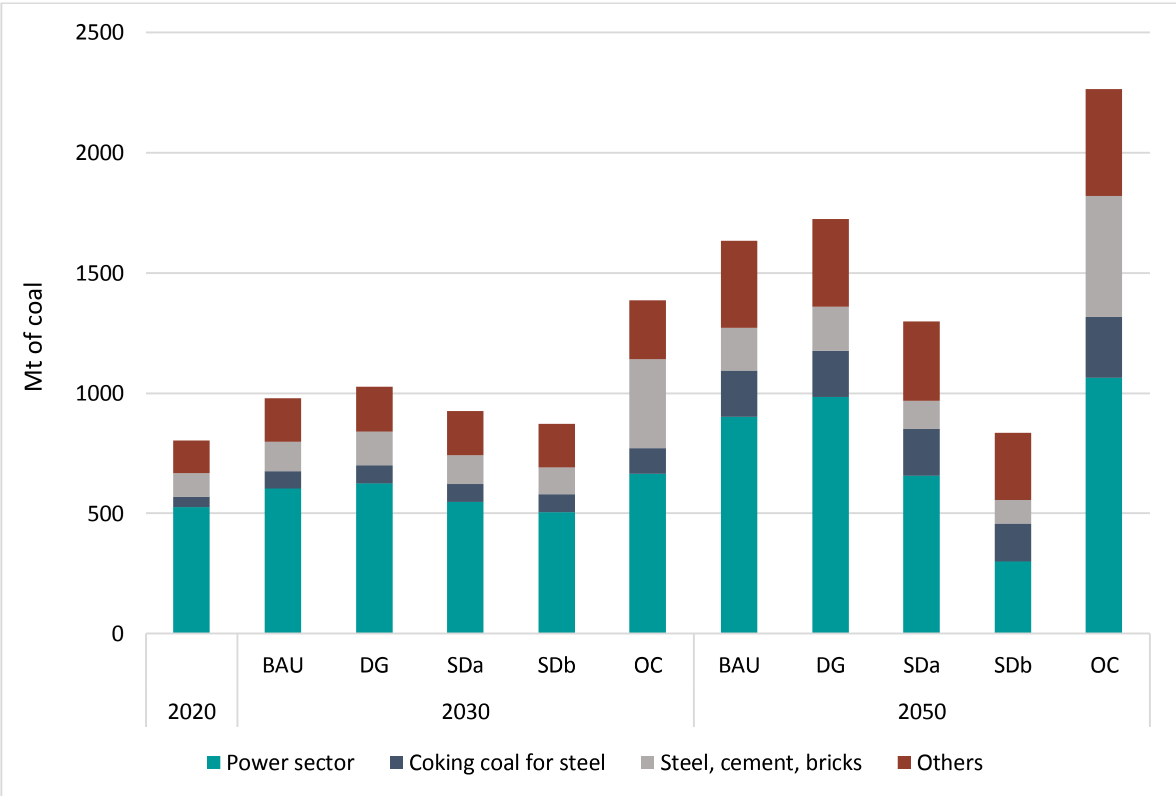


Figure 22 Demand for coal in million tonnes (Mt)

In terms of coal supply, as of 2019–20, India's domestic coal production stood at around 730 Mt, and Coal India Limited plans to add another 400 Mt production capacity in the next 5 years.

[15] Due to the 'no new coal' policy assumed in the SDb scenario

4. GHG Emissions

As of 2019–20, India's per capita GHG emissions were about 1.96 tonnes, less than half of the global average at 4.4 tonnes/capita (according to the International Energy Agency[16]). Figure 23 shows a comparison of India's emissions with other countries in 2019.

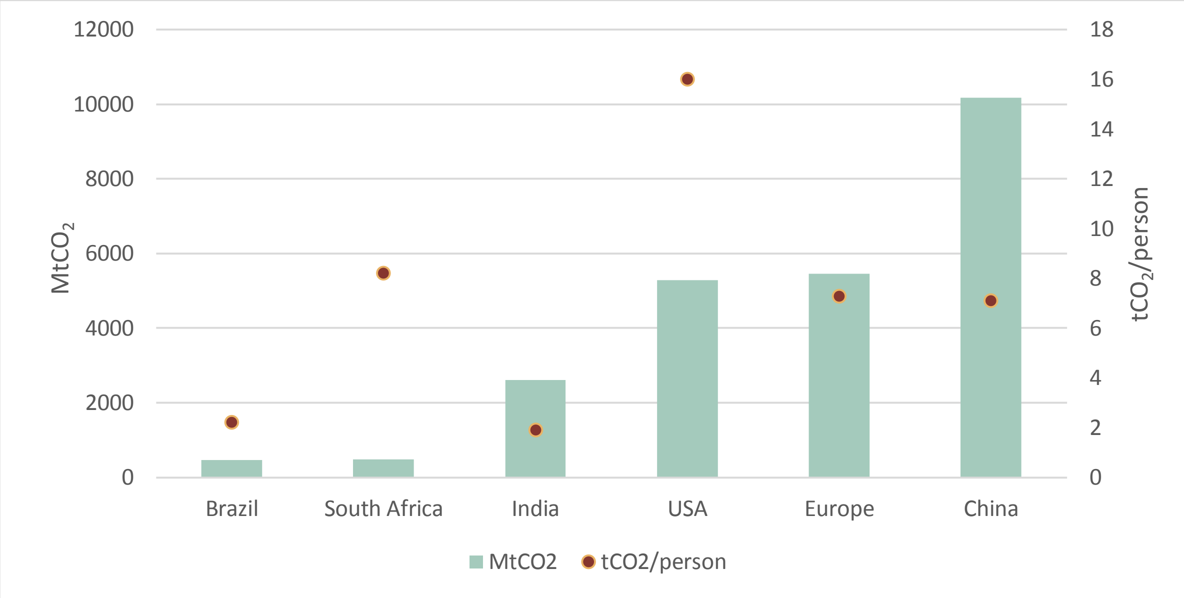


Figure 23 Total and per capita GHG emissions of countries in 2019

The figures below (Figure 24 and Figure 25) show India's GHG emissions (total and per capita) across scenarios considered in this study.

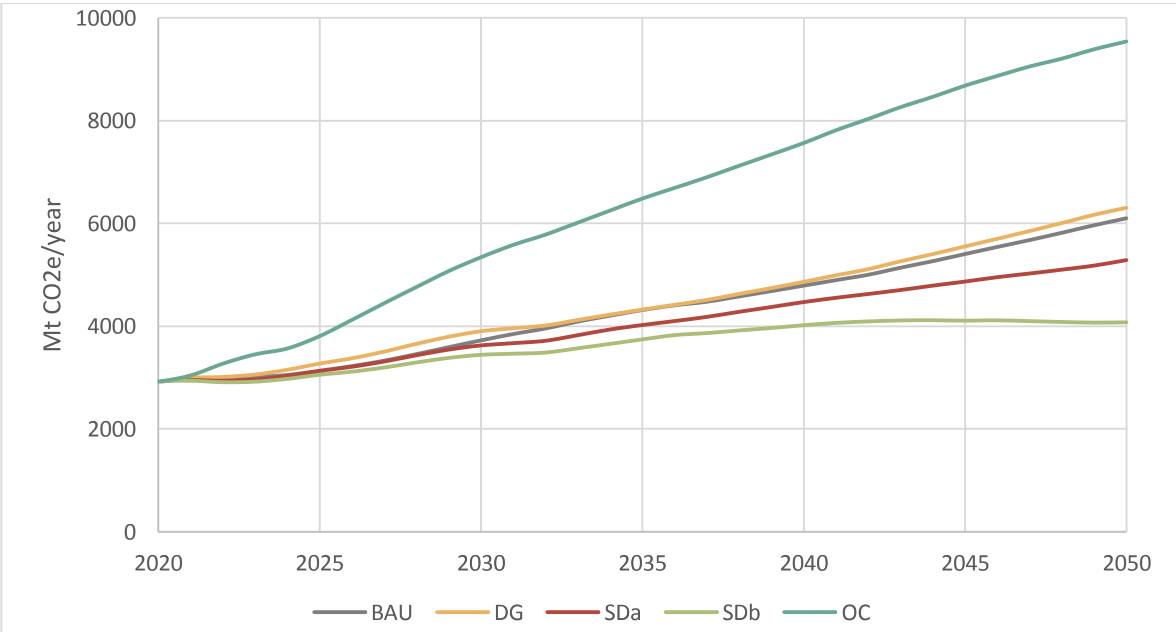


Figure 24 Total annual GHG emissions across scenarios

[16] IEA data and statistics

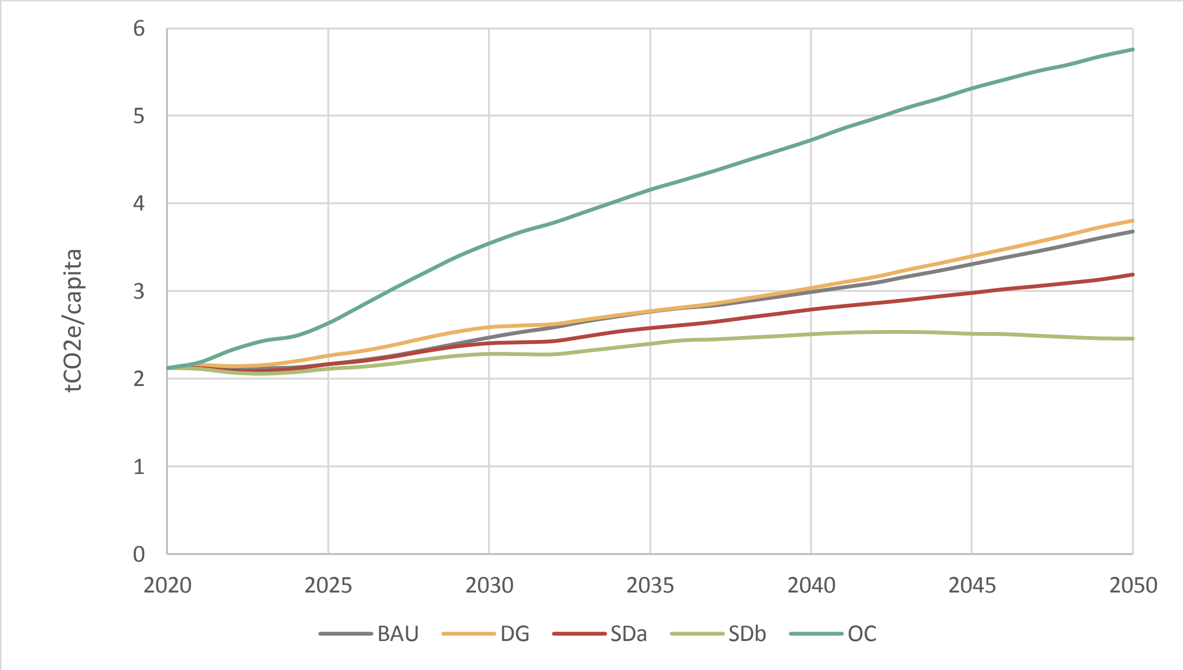


Figure 25 Per capita GHG emissions across scenarios

Like the increase in materials and energy demand, the difference between BAU and DG scenarios in terms of GHG emissions is very small at ~5% annually. Through the implementation of the various interventions (described in Sections 3.4 and 3.5), SDa and SDb scenarios result in lower emissions compared to BAU and DG. In the SDb scenario, India's GHG emissions plateau by 2040 (with a slow rate of decline after 2045). The OC scenario, understandably, results in much higher emissions (around 1.5 times higher than BAU by 2050) and is the only scenario where India's per capita emissions overtake today's global average.

The contribution of various interventions towards reducing the total cumulative GHG emissions (direct and indirect) for the 2020–2050 period in the SDa and SDb scenarios is shown in Figure 26. In moving from DG to SDa, the buildings sector interventions have the largest impact, contributing to cumulative savings of around 6.2 Gt CO_2e. The most effective intervention in the buildings sector is using alternative construction materials with lower carbon footprints (embodied) and better thermal properties resulting in reduced space cooling demand. In the agriculture sector, greater penetration of precise irrigation, reduced groundwater exploitation, and improved pump efficiency results in cumulative emission savings of 1.9 Gt CO_2e. Higher energy efficiency in the cement and steel industries contribute to emission savings of around 1.8 Gt CO_2e, while moderate levels of electrification of passenger (and rail freight) transport reduce cumulative emissions by 1.3 Gt CO_2e.

Going from SDa to SDb, the biggest contributor to the lower emissions (relative to SDa) is the transport sector. Increasing the share of railways in the total freight transport to 35% by 2050, promoting shared mobility (increased occupancy) across modes, and the development of 'compact cities' with reduced trip lengths contribute to emission savings of 4.3 Gt CO_2e. In the industry sector, more effort into energy efficiency (compared to SDa), increased use of Portland Slag in cement production to decrease the clinker to cement ratio, and increased use of scrap steel (25% by 2050) for steel production are key interventions to lower emissions. A 'no new coal' policy where beyond 2025, no new coal power plants are sanctioned results in GHG emissions from the power sector peaking around 2035 and decreasing to 580 Mt CO_2e by 2050. The lower electricity demands in this scenario are also partly responsible for the peaking. In the buildings sector, the use of energy-efficient appliances, electric cooking, better planned compact cities, and the more aggressive (compared to SDa) use of alternative construction materials lead to emissions savings of 2.2 GtCO_2e.

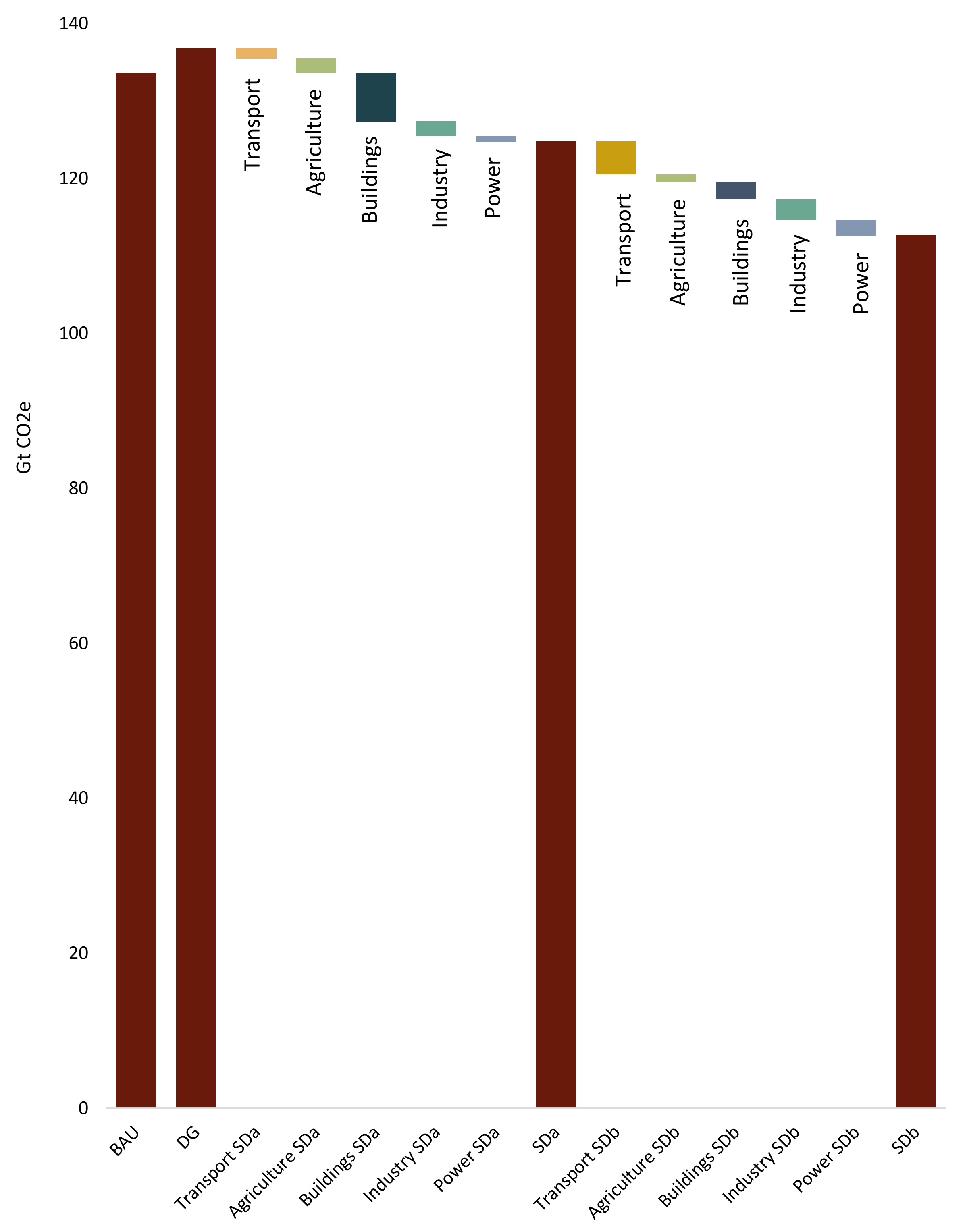


Figure 26 Cumulative (2020–2050) GHG emissions reduction in SDa and SDb scenarios

According to the second biennial update report (BUR II), the energy sector accounts for more than 70% of the total GHG emissions. Electricity production accounts for about 58% of the energy sector's emissions, and the remainder is from the industrial sector (~20%), transport (14%), and other sectors (8%). The power sector, therefore, has a high reduction potential. Our analysis indicates that under the SDb scenario, where no 'new' coal plants are sanctioned, the power sector emissions peak around 2035. To implement more ambitious decarbonisation targets in the power sector, substantial efforts will be needed to aggressively bring down the costs of renewable energy, manage variability using grid-level storage, and strengthen transmission.

Consistency with carbon budgets in the literature:

Table 5 summarises carbon budgets for India reported by various studies. These numbers include only the CO_2 emissions, not all GHG. In SAFARI's SDa and SDb scenarios, the cumulative CO_2 emissions between 2011 and 2050 amount to around 132 $GtCO_2$ and 120 $GtCO_2$, respectively[17]. While these projections are within most of the carbon budgets for India (according to several of the listed studies), compliance with a global 1.5°C temperature rise pathway would require consistent and continued efforts post 2050 to bring emissions to net zero.

Table 5 Carbon budgets for India reported in the literature

Year(s)	Sector/extent	1.5°C budget $GtCO_2$	2°C budget $GtCO_2$	Source
2011–2050	Energy	43	82	(Dhar et al., 2018)
2011–2050	Full	<115	128–136	(Vishwanathan & Garg, 2020)
2011–2050	Full	90–126	-	(Vishwanathan & Garg, 2020)
2011–2050	Full	40–140	-	(Vishwanathan & Garg, 2020)
2011–2050	Full	<115	115–130	(Vishwanathan et al., 2018)
2012–2050	Full	160	-	(Parikh et al., 2018)
2020–2075	Full	-	185	(Mittal et al., 2018)
2050	Full	1.3 t/person		(Gadre & Anandarajah, 2019)
2030	Per capita	-	48/year	(Raupach et al., 2014)
2005–2050	Full	-	162.3	(Shukla et al., 2008)
2005–2050	Full	-	62.6	(Shukla et al., 2008)
2014–2035	Full	133	-	(Gignac & Matthews, 2015)
2014–2050	Full	114	-	(Gignac & Matthews, 2015)

[17] Earlier graph and estimates of cumulative emissions were inclusive of all GHG emissions, expressed in CO_2e, and were for the time period 2020–2050.


Food
Housing
Healthcare
Education
Clean Cooking
Transport
Water
Power

5. Sectoral Insights on Synergies and Trade-offs

While moving towards achieving DQoL benchmarks, there are sectoral trade-offs that begin to emerge. In the following sections, we discuss two of them: urban form (residential and transport) and its implications on land and energy, and sustainable agriculture through a dietary shift. More insights and details on sustainable urbanisation and agriculture using SAFARI can be found in our journal articles (Ashok et al., 2021; Kumar et al., 2021).

5.1 Urban Form, Energy, and Land

SAFARI's urban form module looks at the interplay between the housing, transport, and industry sectors and the consequent implications for land, energy, and GHG emissions. At a BAU housing shortage filling rate, around 2.2 million houses are constructed each year between 2020 and 2030. This is inadequate to meet the housing shortage that SAFARI computes (Figure 27). However, with a construction rate of 4.8 million houses per year until 2030, it is possible to fill the housing shortage by 2030. This scenario is in line with the SDG target of providing affordable housing to all by 2030.

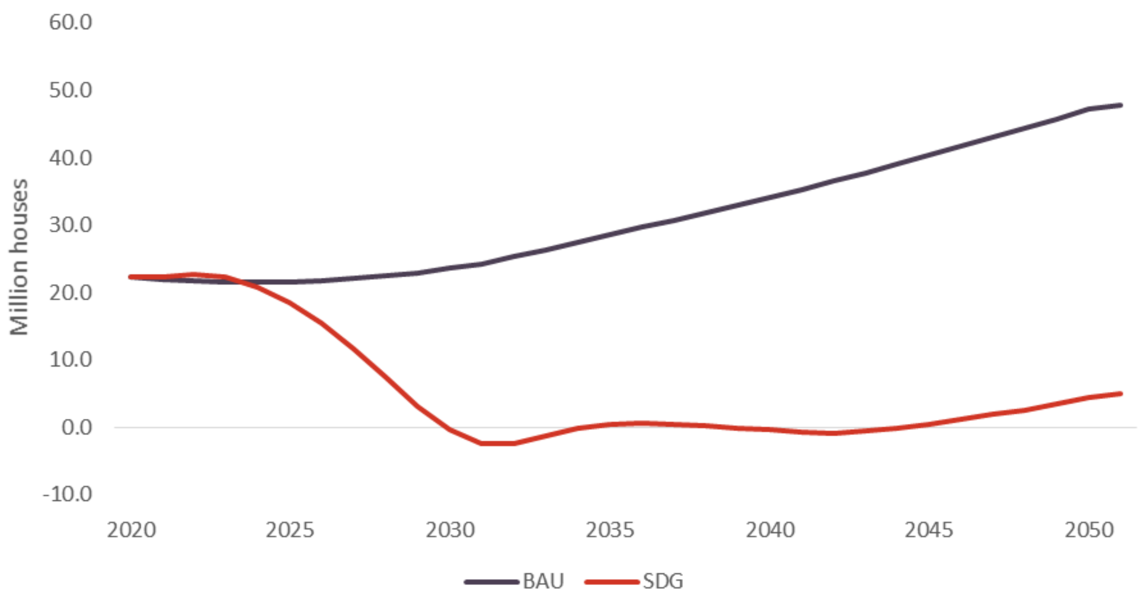


Figure 27 Urban affordable housing shortage

Using the DQoL (or SDG) scenario construction rate of 4.8 million houses per year, we examine the implications of floor areas, floor space indices (FSI), and mobility patterns on land and emissions. We consider three broad FSI storylines: a BAU FSI of about 1.5, a densification FSI of about 8, and a sprawl scenario FSI of about 0.75. Since these are averages at the national level, local FSIs may, in reality, vary. The area of an affordable house is assumed to reach 60 m^2 by 2050 in the BAU and compact construction stories and 75 m^2 in the sprawl story. Similarly, the average area of higher-income housing is set to 150 m^2 by 2050 under BAU and densification and 200 m^2 by 2050 under sprawl.

These scenarios are combined with scenarios in the transport module, which vary in terms of trip length and share of public transport by 2050. Urban transport is further subdivided into two categories: Urban 1, or U1 (cities >5 million population), and Urban 2, or U2 (cities < 5 million population). There are three trip-length scenarios (corresponding to BAU, sprawl, and compact construction). Additionally, two major modal share scenarios are centred around the share of public transport: 60% U1 and 35% U2 and 70% U1 and 50% U2. Combining the housing and transport scenarios, we derive five urban form scenarios, as described in Table 6.

Table 6 Urban form scenarios

Scenario	Average trip-length per trip in 2050	Share of public transport in 2050	FSI	Area of higher income house in 2050 (m^2)	Area of affordable house in 2050 (m^2)
BAU	13 km in Urban 1, 6.8 km in Urban 2	60% in Urban 1, 35% in Urban 2	1.5	150	60
Sprawl	14 km in Urban 1, 9 km in Urban 2	60% in Urban 1, 35% in Urban 2	0.75	200	75
Sprawl + Public	14 km in Urban 1, 9 km in Urban 2	70% in Urban 1, 50% in Urban 2	0.75	200	75
Densification	10 km in Urban 1, 5 km in Urban 2	60% in Urban 1, 35% in Urban 2	8	150	60
Densification + Transit-oriented development	10 km in Urban 1, 5 km in Urban 2	70% in Urban 1, 50% in Urban 2	8	150	60

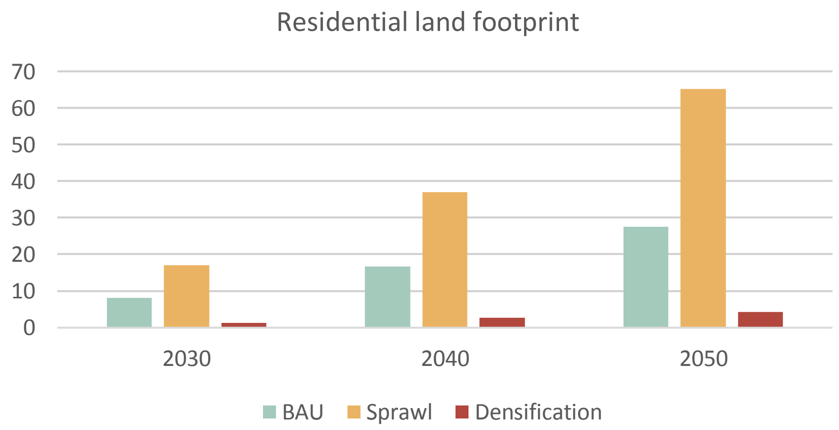


Figure 28 Urban residential land footprint (billion m^2)

Figure 28 illustrates the effect of these scenarios on the residential land footprint. The densification scenario has the lowest land footprint, requiring less than 5 billion m^2 of new land by 2050. The sprawl scenario, on the other hand, calls for nearly 65 billion m^2 of new land by 2050. While there is no absolute land shortage globally and in India, the problem occurs when urban areas expand and cause land-use change and land conversion (also mentioned as a category in the IPCC inventory methodology under LULUCF). This conversion causes agricultural land to be diverted for urban construction, which is problematic. Figure 29 shows the effects of these scenarios on transport sector emissions. Two additional scenarios are included to reflect the impact of increasing the share of electric vehicles in the transport mix—by 2050, all two-wheelers and three-wheelers and 40% of buses and cars are assumed to be electric in urban India.

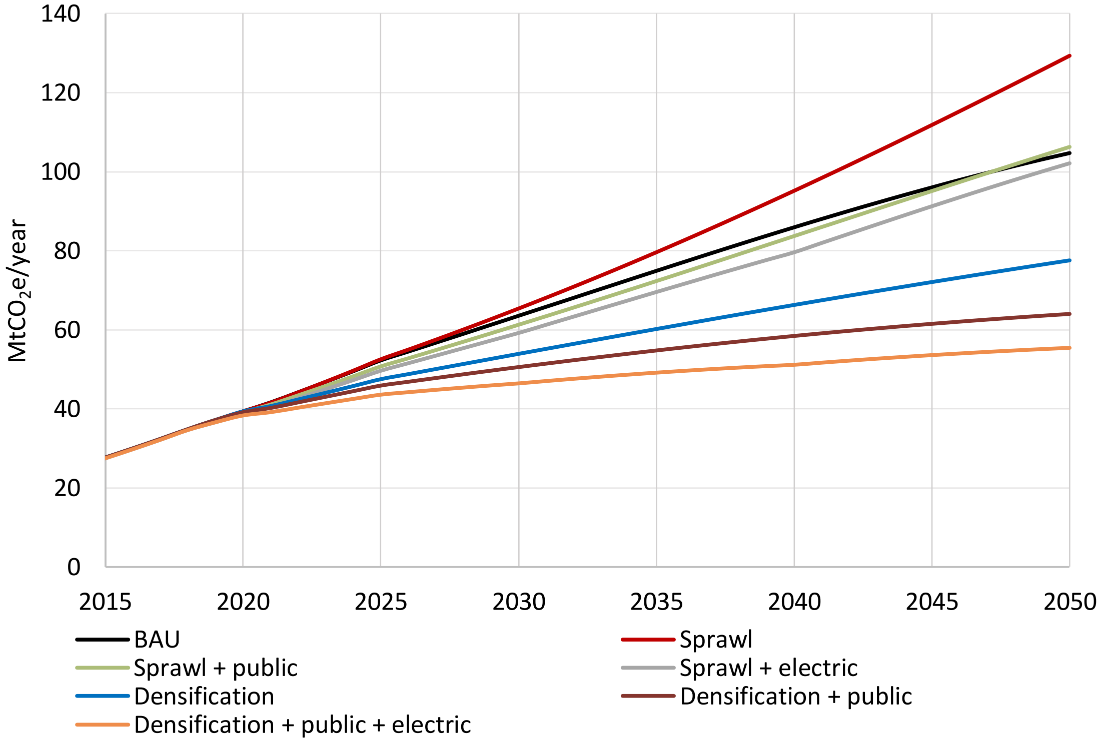


Figure 29 Urban transport emissions

The sprawl scenario is the most emissions-intensive, while the densification + public scenarios have the least GHG emissions. This trend is also true for local pollutant emissions.

In terms of total GHG emissions from urban areas, another factor is considered based on the literature (Guattari et al., 2018; Santamouris et al., 2018; Silva et al., 2018; Zhou et al., 2014): the effect of the urban heat island on cooling demand. As a result, under densification scenarios, cooling demand increases by 10% to 20%, and under sprawl scenarios, it reduces by 10% to 20%. This is highly context-specific and can only be approximated at the national level but is nevertheless important to account for. Assuming an increase in cooling demand due to urban heat island effects, the emission savings from densification and reduced transport demand could be counteracted. Additionally, taller buildings also have a higher demand for steel for construction and increased energy demand for elevators, water pumping, and so forth, which we account for in our calculations.

Using alternative materials balances out the land emissions trade-offs resulting from our urban form scenarios. Our alternative materials scenario (AM2) assumes that burnt clay brick used in housing construction is replaced by aerated autoclaved concrete (AAC), which has better thermal properties. SAFARI estimates suggest that this measure could reduce cooling demand in a residential unit by around 30%.

Figure 30 represents the combined transport and residential operational energy emissions resulting from our scenarios. Our analysis suggests that the *densification + TOD + AM2* scenario is the most favourable scenario for land, emissions, and energy. Despite the increase in cement and steel for greater vertical construction, the high levels of urban green space per capita and consequently reduced urban heat island effects in this scenario result in overall energy savings from reduced space cooling demand.

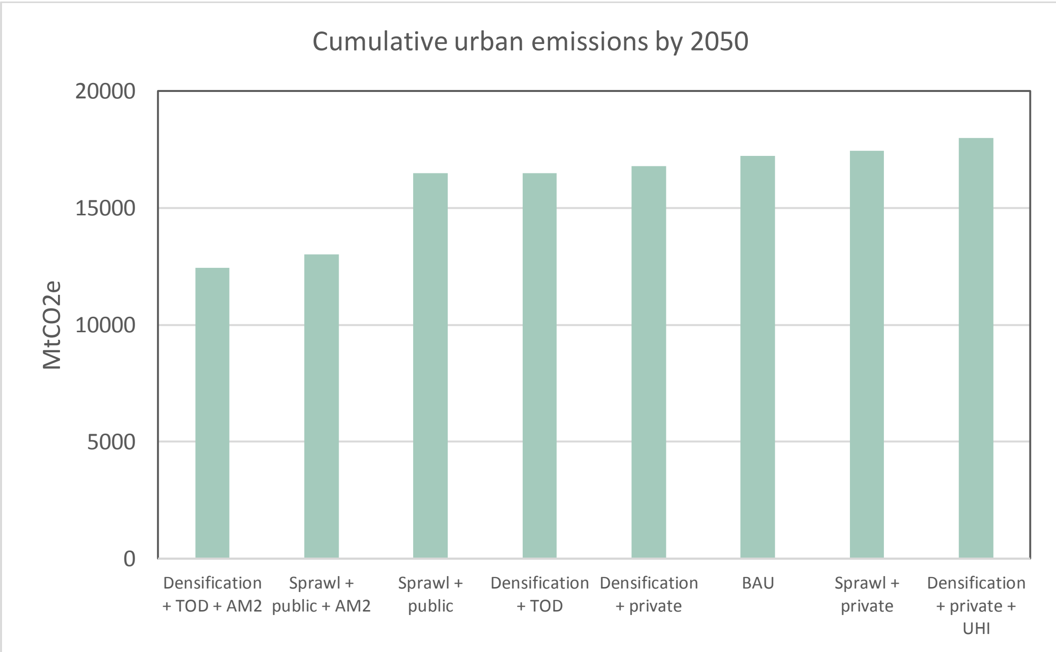


Figure 30 GHG emissions under urban form scenarios assuming urban heat island (UHI) effects

Overall, SAFARI's densification scenarios have benefits in terms of reducing land exploitation and possible drawbacks in terms of emissions from energy use. The potential emissions of land conversion are not accounted for in this study and would likely increase in the sprawl scenarios, as neighbouring land is converted for urbanisation. There is, therefore, a potential trade-off between land and GHG emissions.

5.2 Sustainable Agriculture Through Dietary Shifts

As described earlier, the agriculture sector is the largest withdrawer of water, currently accounting for 90% of the total groundwater extraction. If the current unregulated water extraction scenario prevails in the future, water tables would recede further, in turn, driving the need for substantially more pumping energy to extract the requisite volume of water.

In a water-regulated policy scenario (assuming the average total annual replenishable groundwater availability to be 433 BCM), current patterns of use will create a water shortage and, therefore, food shortage. In this section, we look at an alternative pattern of water use—through dietary shifts to millets—and its ability to meet food security sustainably (Ashok et al., 2021). This course correction that we consider is a slow and linear shift from the current rice- and wheat-intensive diet to a coarse cereals- and wheat-intensive diet by 2050. We examine four scenarios in the 2050 time frame.

- BAU or 'Exploitation as Usual' (EAU): Over-extraction of groundwater continues to meet the demands, and current agricultural practices and dietary patterns continue.
- Regulated Water Use (RWU): Overall average annual groundwater availability is restricted to 433 BCM per year, and current agricultural practices and dietary patterns continue.
- Diet shift: RWU with a dietary shift to coarse cereals from rice linearly by 2050
- Diet shift with micro-irrigation: Diet shift scenario with increased area under micro-irrigation (30 million Ha by 2030 and 44 million Ha by 2050)[18]

As expected, the EAU scenario shows no foodgrain shortage (Figure 31) but at the cost of high energy and emissions and receding water levels. In the RWU scenario, without arranging alternative procurement strategies for water, there will be a foodgrain shortage (almost 100 Mt by 2050). The reduced production is also reflected as high energy intensity (energy per unit production) in Figure 32. The diet shift scenario brings down the foodgrain shortage by over 50% by 2050. The trade-off here is land and productivity—coarse cereals typically have a lower yield than rice and require more land to attain the same production amounts. This is addressed by the Diet shift + micro-irrigation scenario through its impact on improved yields. This scenario brings the foodgrain shortage to zero sustainably—reducing water use, energy intensity, and emissions through higher productivity.

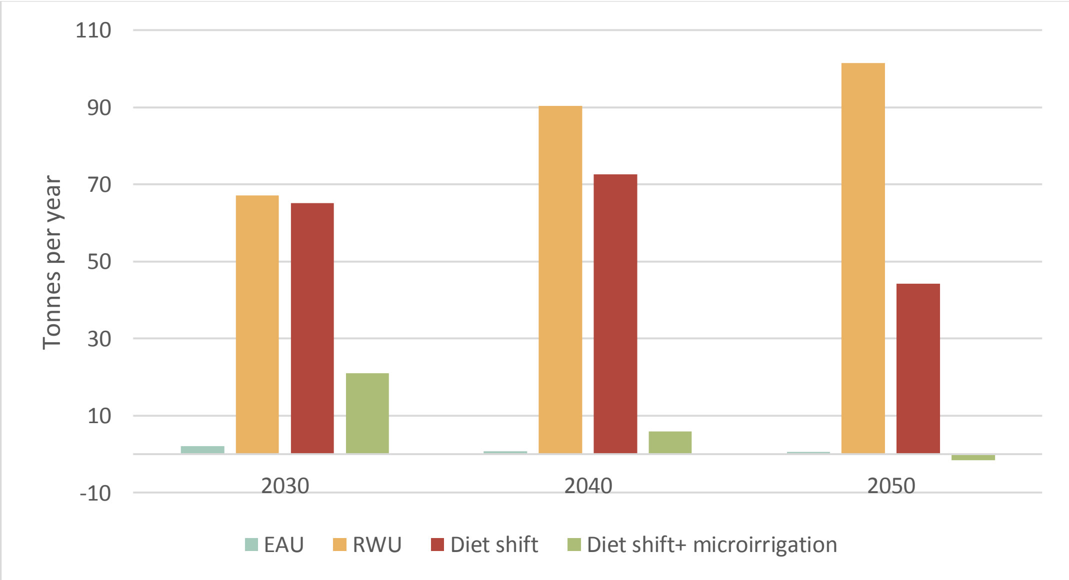


Figure 31 Foodgrain shortage under various scenarios

An interesting trade-off the model can capture is the competition between foodgrain availability for direct human consumption and foodgrain for livestock feed. This is evident in the coarse cereal diet scenario because coarse cereals form the largest feed share among foodgrains. Presently, given the low meat consumption in the country, this is not of immediate concern. In the future, in a scenario of increased meat consumption as a consequence of economic well-being, feed for livestock will put pressure on foodgrain availability per capita. Livestock feed

[18] Micro-irrigation potential is 70 million Ha.

demand for coarse cereals is estimated to be about 32 Mt by 2050 if the meat demand for the country is met domestically. If imports meet the extra requirement for meat, the total foodgrain gap can be reduced by 18%.

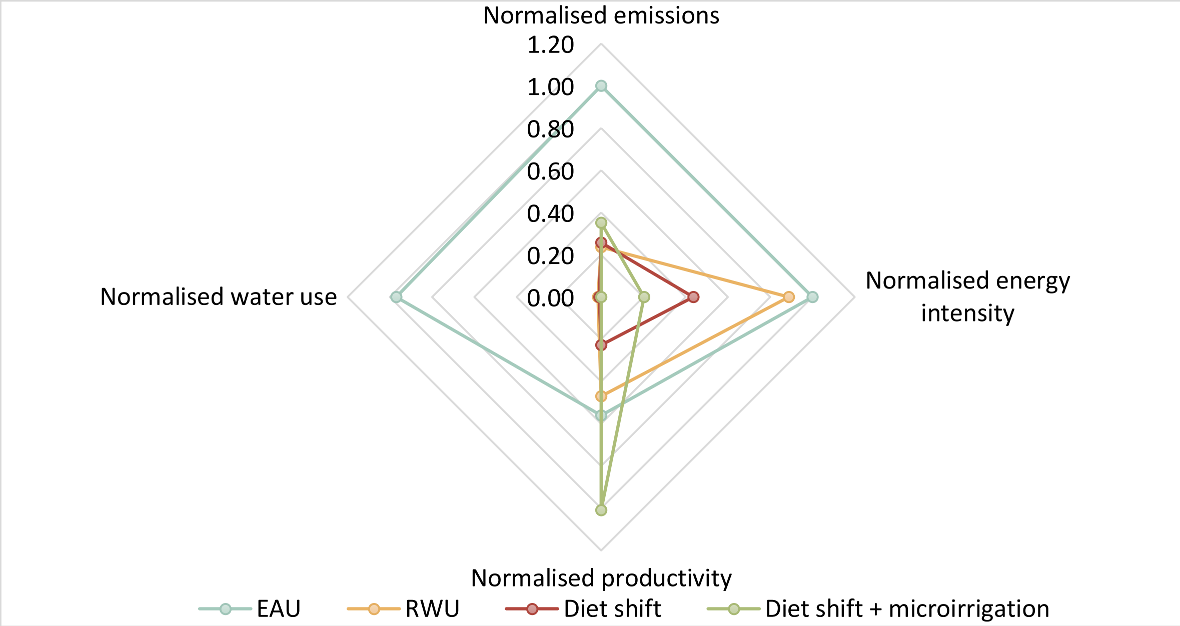


Figure 32 Implications on energy, emissions, water, and productivity

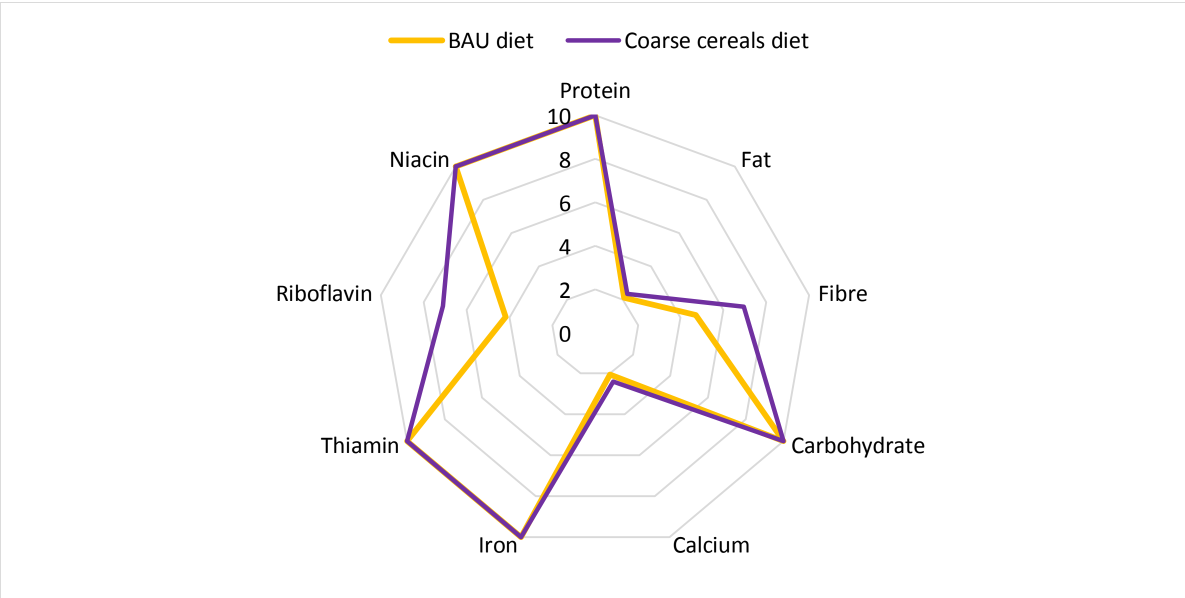


Figure 33 Nutritional implications of BAU and millets diet

There are co-benefits to the diet shift as well. First, millets are more climate-resilient and can tolerate diverse abiotic stresses than conventional rice varieties. Second, methane and nitrous oxide emissions from rice cultivation contribute to around 20% of the agriculture sector GHG emissions in India, which can be reduced by replacing rice with coarse cereals. Third, in terms of nutrition and health, millets have a lower glycemic index and are a healthier alternative to rice (more riboflavin, calcium, fibre, and iron), as shown in Figure 33. Therefore, another option to achieve and maintain sustainable food security (DQoL benchmarks) is via a dietary shift towards coarse cereals, away from the water-intensive rice.

6. Limitations

The SAFARI model, as described in previous chapters, is a novel system dynamics simulation model of India's materials and energy demand and GHG emissions up to 2050. It includes the impact of achieving development goals on India's growth trajectory and allows model users to build scenarios using the various sustainability interventions across sectors. While SAFARI provides an integrated framework to analyse sustainable development pathways for India, the current version of the model does have certain limitations.

The macroeconomic model is currently only *soft-linked* with the system dynamics modules. The impact of achieving development goals in the DG scenario on overall investments and GDP has been considered through soft-linking. However, the implications of sustainability interventions (in the SDa and SDb scenarios) on GDP and the costs of transitioning have not been modelled. To understand the role of investments in sustainability and low-carbon policies and their impacts on jobs, a more detailed and revised CGE model is required. With this, the impact of energy transitions on livelihoods, especially jobs, can be determined.

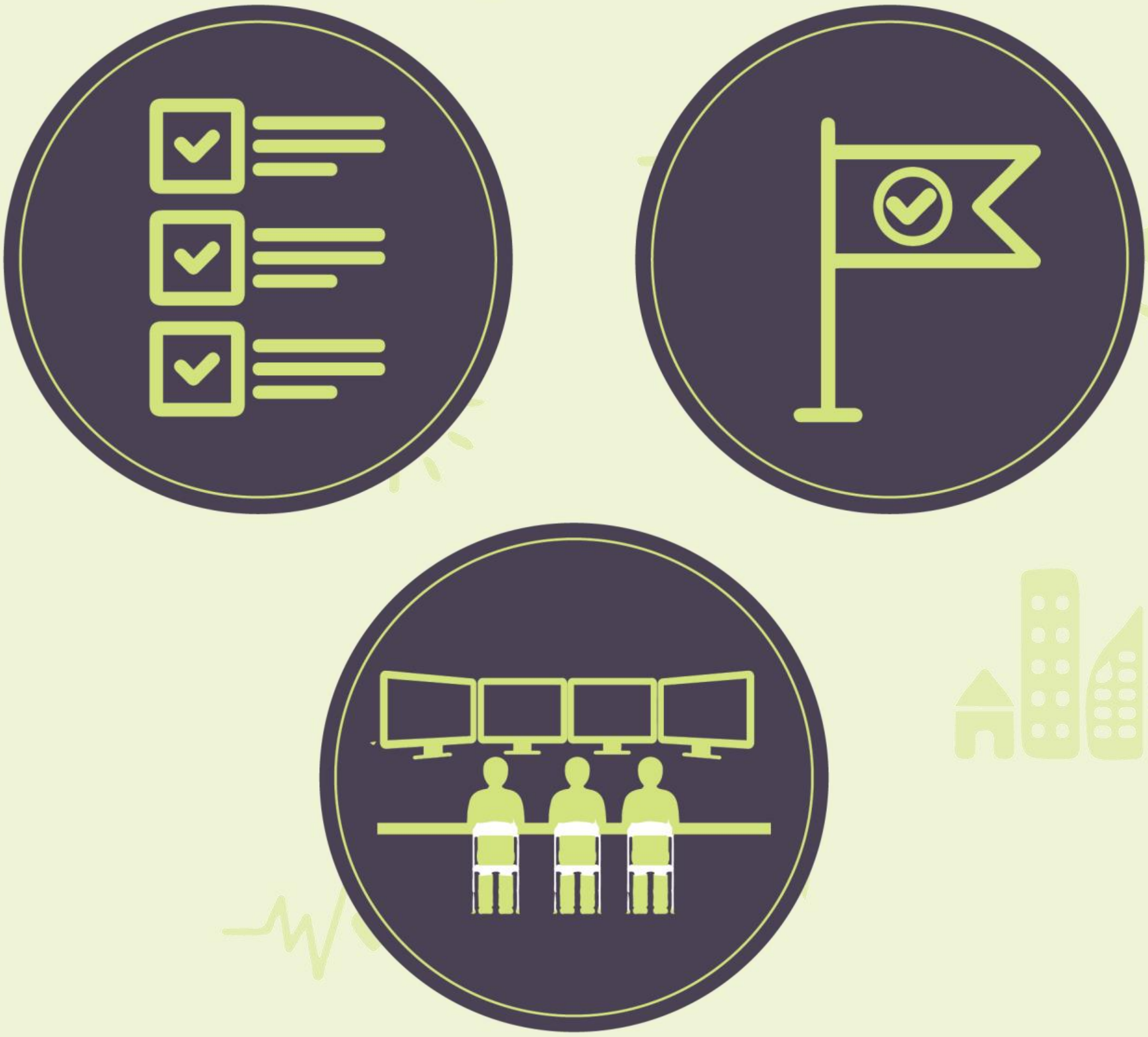
One of the main outputs of the SAFARI model is electricity demand and supply mix estimation. While the power sector module adds capacity based on a least-cost algorithm, SAFARI does not include a full-fledged detailed representation of the electricity markets and grid operation. For instance, it does not look at hourly resolutions of demand—the time step considered in the model is annual. Variations in electricity demand and supply during daytime, night-time, and peak are accounted for based on assumptions, as described in Section 9.6.

Another limitation of the model is that the regional implications of achieving the development goals, in terms of impact on resources and carrying capacities, are not captured. We have started to develop a regionally disaggregated version of the model for the water and agriculture sectors, as described in our journal article (Ashok et al., 2021). In the future, we will extend the regional disaggregation to other sectors such as power as well.

As for the goals considered (described in Section 3.1), we have picked the ones that have a direct bearing on energy, emissions, and resource footprints. Some of the other important development goals such as poverty eradication and gender equality have not been considered.

Finally, 'sinks' have not been included in the model—neither forests nor carbon capture technologies—and, therefore, competition for land between forests and infrastructure has not been considered. Carbon sinks could become crucial while exploring pathways towards net-zero emissions; however, to model net-zero pathways, the modelling horizon must be extended to 2100 and more futuristic technologies must also be included.

In subsequent versions of SAFARI, we will aim to address these limitations.



7. Conclusions and Future Directions

7.1 Conclusions

In this report, we have presented an integrated energy model for India that looks at development, energy, resources, and the environment in totality—Sustainable Alternative Futures for India (SAFARI). The growth drivers in the SAFARI model are development goals and socio-economic parameters such as population and GDP (taken from our macro-economic CGE model). The development goals considered include food, water, housing, healthcare, education, transport, cooking, and power, as described in Section 3.1 and our earlier reports (CSTEP, 2018, 2020). Within SAFARI, over 80 intervention levers can be changed to impact energy, emissions, and resource footprints. Using this framework, we have developed some long-term scenarios as examples.

The development goals are not met in a business-as-usual (BAU) scenario. BAU assumes that historical trends and practices continue up to 2050; however, COVID would have an impact. In the short term, the economy slows down considerably. Beyond 2023, investments pick up and the average annual growth rate of GDP (2020–2050) is around 5.3% (lower than the pre-COVID estimates). In this scenario, the development goals are not completely met by 2030.

More ambitious policies and higher investments in certain sectors are required to achieve the development goals (DG scenario). Post-2023, investments in the construction (for housing, healthcare, and other infrastructure) and agriculture/food processing sectors are assumed to increase more than in the BAU scenario to meet development goals. The average annual growth rate of GDP in this scenario increases to around 6% for 2020–2050. In terms of energy and resources demand and emissions, the DG scenario is only 5%–10% higher than the BAU scenario through 2050. This is because, even in the BAU scenario, material progress is made towards the goals; for instance, around 50% of the affordable housing shortage is met by 2030.

BAU and DG scenarios are unsustainable. By 2050, the demand for energy-intensive materials such as cement and steel is expected to increase by three times, and petroleum imports and coal demand are expected to double in both scenarios. Cumulative GHG emissions during 2020–50 are projected to be around 134 Gt CO_2e in BAU and 137 Gt CO_2e in DG, with no sign of emissions 'peaking'. Without water-use efficiency interventions, India will continue to extract more groundwater than is annually replenished, leading to groundwater depletion. The continued increase in air pollution and congestion will lead to a deteriorating quality of life in urban areas. Therefore, it is essential to explore sustainable alternative futures for India.

SAFARI is meant to be used to generate alternative scenarios based on various objectives and what-ifs. To demonstrate its ability to do so, we have created two Sustainable Development scenarios—SDa and SDb—where the DQoL goal benchmarks are met.

In SDa, we picked policy and technology interventions (Table 3) that are relatively easy to achieve and are already in the pipeline such as moderate levels of electrification of passenger transport, efficient agricultural practices, and improved energy efficiency in industries. In this scenario, when compared to DG, in 2050, water consumption reduces by around 10%, electricity demand by 22%, coal consumption by 25%, and GHG emissions by 16%, as shown in Table 7. Cumulative GHG emissions (2020–2050) reach around 125 Gt CO2e, and there is no peaking before 2050.

In SDb, we assume behavioural changes towards sustainability and increased ambition on the policy and technology interventions from SDa (Table 4) such as shared mobility and the use of public transport, a dietary shift away from water-intensive rice towards coarse cereals, and no 'new' coal in the power sector. In this scenario, when compared with BAU and DG, in 2050, water consumption reduces by 20%, electricity demand by 34%, coal consumption by 47%, and GHG emissions by 37%. Cumulative GHG emissions (2020–2050) reach around 112 Gt CO2e. GHG emissions peak around 2045 and start declining after that and could reach net zero in the latter half of the century through sustained efforts to decarbonise.

In terms of GHG emissions mitigation, the most impactful interventions include

- No 'new' coal-fired power plants to be sanctioned for construction
- The use of alternative construction materials with lower embodied energy and emissions and better thermal properties, leading to reduced space cooling demand
- A modal shift away from road towards rail, especially for freight transport
- Increased energy efficiency in industries

DG, SDa, and SDb trajectories achieve development goals based on India-relevant benchmarks (DQoL). **If India were to aspire for consumption standards of OECD countries, the country would be on an 'overconsumption' (OC) pathway, leading to extremely unsustainable outcomes.** The electricity demand and GHG emissions in 2050 would be 40%–50% higher than those in DG. Groundwater depletion, air pollution, urban congestion, and import dependence would be further exacerbated compared to BAU and DG, making this an overall unsustainable scenario. Table 7 summarises estimates for key variables in the five integrated scenarios developed in this study.

Table 7 Summary of scenarios

Variable	BAU	DG	SDa	SDb	OC
Water withdrawal (BCM) in 2050	1,219	1,225	1,110	983	1,250
Electricity demand (TWh) in 2050	4,500	5,000	3,910	3,328	6,825
Final energy demand (EJ) in 2050	58	60	53	44	88
Coal-based generation (TWh) in 2050	1,773	1,955	1,240	632	2,458
Total coal demand (EJ) in 2050	34	36	27	19	50
Primary energy demand (EJ) in 2050	74	77	65	50	104
GHG emissions (Gt CO_2e) in 2050	6.1	6.3	5.3	4	9.5
Cumulative GHG emissions 2020–2050 (Gt CO_2e)	134	137	125	112	200
GDP growth rate (2020–2050)	5.3%	6%	-	-	-

7.2 Way Forward

The future directions for this project fall into two broad directions: (a) model refinements and expansion to address its limitations and (b) stakeholder engagement to ensure the tool's relevance and usefulness.

In terms of model refinements and expansion, we aim to do the following:

- Capture the impact of sustainable development scenarios on investment requirements, GDP growth, and jobs.
- Extend the modelling horizon until 2100 to model net-zero scenarios.
- Include futuristic technologies in the model such as carbon capture and sequestration, hydrogen fuels, and truck electrification to enable net-zero pathways. We will also include forestry (natural 'sinks') to understand the competition for land.
- Further develop our regional version of SAFARI—named SAFARI-R (Ashok et al., 2021) to include all sectors—to analyse regional implications of development and sustainability.

In terms of stakeholder and policy engagement, we plan to demonstrate the tool's ability to address some pertinent questions for India. These range from sectoral goals and challenges to (that will be of interest to specific government departments) to aggregate nationwide energy needs and emissions. Some examples are as follows: *What is the expected demand for ethanol in 2025 to meet the E20 (20% blending) target under different penetration levels of electric mobility? Can sugarcane production from the agriculture sector meet this demand? What will be the annual shortage in affordable housing up to 2050, considering homelessness, congestion, quality of life, and income classes? Will better urban planning and alternative building blocks help reduce demand for energy-intensive construction materials? How much of the increasing cooling demand should be avoided (or met) through better planning and passive cooling? Do compact cities have trade-offs? What will be the coal demand by 2050 under our best-case scenario? Which sector contributes to the most GHG emissions, and what are the intervention levers of maximum impact?*

By using SAFARI to answer such questions and more, we hope to build sectoral visions as well as integrated long-term scenarios for India, which have minimal policy trade-offs.

8. References

Abdullah, M. A., & Kennedy, S. (2015). *A Simulation Gaming Approach to Micro-grid Design and Planning: Participatory Design and Capacity Building* (pp. 79–88). Springer, Cham. https://doi.org/10.1007/978-3-319-15964-5_7

Ashok, K., Natarajan, R., Kumar, P., Sharma, K., & Mathur, M. (2021). Sustainable Alternative Futures for Agriculture in India—The energy, emissions, and resource implications. *Environmental Research Letters*. https://doi.org/10.1088/1748-9326/abf0cd

Bolwig, S., Bazbauers, G., Klitkou, A., Lund, P. D., Blumberga, A., Gravelsins, A., & Blumberga, D. (2019). Review of modelling energy transitions pathways with application to energy system flexibility. In *Renewable and Sustainable Energy Reviews* (Vol. 101, pp. 440–452). Elsevier Ltd. https://doi.org/10.1016/j.rser.2018.11.019

Bruinsma, J. (2017). *World Agriculture: Towards 2015/2030: An FAO Study*. Routledge.

CSTEP. (2018). *Energy and Emissions Implications for Desired Quality of Life Part 1: Literature and Data Survey*.

CSTEP. (2020a). *Assessing impacts of economic growth trajectories on climate goals: A CGE-TIMES framework for India*.

CSTEP. (2020b). *Energy and emissions implications for a desired quality of life in India, via SAFARI*.

CSTEP. (2020c). *Energy and emissions implications for a desired quality of life in India, via SAFARI*.

Desai, Anand. (2012). *Simulation for policy inquiry*. Springer.

Dhar, S., Pathak, M., & Shukla, P. R. (2018). Transformation of India's transport sector under global warming of 2 °C and 1.5 °C scenario. *Journal of Cleaner Production*, *172*, 417–427. https://doi.org/10.1016/j.jclepro.2017.10.076

Dubash, N. K. (2007). The Electricity-Groundwater Conundrum: Case for a Political Solution to a Political Problem. *Economic and Political Weekly*, *42*(52), 45–55.

Fiddaman, T. (1997). *Feedback complexity in integrated climate-economy models*.

Fuso Nerini, F., Sovacool, B., Hughes, N., Cozzi, L., Cosgrave, E., Howells, M., Tavoni, M., Tomei, J., Zerriffi, H., & Milligan, B. (2019). Connecting climate action with other Sustainable Development Goals. In *Nature Sustainability* (Vol. 2, Issue 8, pp. 674–680). Nature Publishing Group. https://doi.org/10.1038/s41893-019-0334-y

Gadre, R., & Anandarajah, G. (2019). Assessing the evolution of India's power sector to 2050 under different CO2 emissions rights allocation schemes. *Energy for Sustainable Development*, *50*, 126–138. https://doi.org/10.1016/j.esd.2019.04.001

Gallagher, K. S., Zhang, F., Orvis, R., Rissman, J., & Liu, Q. (2019). Assessing the Policy gaps for achieving China's climate targets in the Paris Agreement. *Nature Communications*, *10*(1), 1–10. https://doi.org/10.1038/s41467-019-09159-0

Gignac, R., & Matthews, H. D. (2015). Allocating a 2°C cumulative carbon budget to countries. *Environmental Research Letters*, *10*(7), 075004. https://doi.org/10.1088/1748-9326/10/7/075004

Guattari, C., Evangelisti, L., & Balaras, C. A. (2018). On the assessment of urban heat island phenomenon and its effects on building energy performance: A case study of Rome (Italy). *Energy and Buildings*, *158*, 605–615. https://doi.org/10.1016/j.enbuild.2017.10.050

IEA. (2019). *Energy Efficiency 2019*. IEA, Paris. https://www.iea.org/reports/energy-efficiency-2019

IPCC. (2018). Summary for Policymakers—Global Warming of 1.5 ^{o}C. In *International Govermental Panel for Climate Change*.

Kumar, P., Joshi, P. K., & Mittal, S. (2016). Demand vs Supply of Food in India—Futuristic Projection. *Proceedings of the Indian National Science Academy*, *82*(5), 1579–1586. https://doi.org/10.16943/ptinsa /2016/48889

Kumar, P., Natarajan, R., & Ashok, K. (2021). Sustainable Alternative Futures for urban India: The resource, energy, and emissions implications of urban form scenarios.

Environmental Research: Infrastructure and Sustainability. https://doi.org/10.1088/2634-4505/ac048e

Lund, H., Arler, F., Østergaard, P., Hvelplund, F., Connolly, D., Mathiesen, B., & Karnøe, P. (2017). Simulation versus Optimisation: Theoretical Positions in Energy System Modelling. *Energies*, *10*(7), 840. https://doi.org/10.3390/en10070840

Mittal, S., Liu, J.-Y., Fujimori, S., & Shukla, P. (2018). An Assessment of Near-to-Mid-Term Economic Impacts and Energy Transitions under "2 °C" and "1.5 °C" Scenarios for India. *Energies*, *11*(9), 2213. https://doi.org/10.3390/en11092213

MOHUPA. (2015). *Pradhan Mantri Awas Yojana—Housing for All (Urban)—Scheme Guidelines 2015*. 1–62.

Naill, & F, R. (1977). *Managing the energy transition: A system dynamics search for alternatives to oil and gas. [COAL2 model]*. Ballinger Publishing Co.,Cambridge, MA.

Naill, R. F. (1992). A system dynamics model for national energy policy planning. *System Dynamics Review*, *8*(1), 1–19. https://doi.org/10.1002/sdr.4260080102

National Transport Development Policy Committee. (2014). *India Transport Report: Moving India to 2032*.

Parikh, K. S., Parikh, J. K., & Ghosh, P. P. (2018). Can India grow and live within a 1.5 degree CO2 emissions budget? *Energy Policy*, *120*, 24–37. https://doi.org/10.1016/j.enpol.2018.05.014

Pollitt, H. (2020). Analysis: Going carbon neutral by 2060 'will make China richer.' *Carbon Brief*.

Raupach, M. R., Davis, S. J., Peters, G. P., Andrew, R. M., Canadell, J. G., Ciais, P., Friedlingstein, P., Jotzo, F., Van Vuuren, D. P., & Le Quéré, C. (2014). Sharing a quota on cumulative carbon emissions. In *Nature Climate Change* (Vol. 4, Issue 10, pp. 873–879). Nature Publishing Group. https://doi.org/10.1038/nclimate2384

Ritchie, H., Reay, D., & Higgins, P. (2018). Sustainable food security in India—Domestic production and macronutrient availability. *PLOS ONE*, *13*(3), e0193766. https://doi.org/10.1371/journal.pone.0193766

Rodell, M., Famiglietti, J. S., Wiese, D. N., Reager, J. T., Beaudoing, H. K., Landerer, F. W., & Lo, M. H. (2018). Emerging trends in global freshwater availability. *Nature*, *557*(7707), 651–659. https://doi.org/10.1038/s41586-018-0123-1

Santamouris, M., Haddad, S., Saliari, M., Vasilakopoulou, K., Synnefa, A., Paolini, R., Ulpiani, G., Garshasbi, S., & Fiorito, F. (2018). On the energy impact of urban heat island in Sydney: Climate and energy potential of mitigation technologies. *Energy and Buildings*, *166*, 154–164. https://doi.org/10.1016/j.enbuild.2018.02.007

Semertzidis, T. (2015). Can energy systems models address the resource nexus? *Energy Procedia*, *83*, 279–288. https://doi.org/10.1016/j.egypro.2015.12.182

Shukla, P. R., Dhar, S., & Mahapatra, D. (2008). Low-carbon society scenarios for India. *Climate Policy*, *8*, S156–S176. https://doi.org/10.3763/cpol.2007.0498

Silva, M., Leal, V., Oliveira, V., & Horta, I. M. (2018). A scenario-based approach for assessing the energy performance of urban development pathways. *Sustainable Cities and Society*, *40*(October 2017), 372–382. https://doi.org/10.1016/j.scs.2018.01.028

Sterman, J. (1982). *The energy transition and the economy: A system dynamics approach*.

UNFCCC. (1992). The United Nations Framework Convention on Climate Change. In *Unfccc.int* (Vol. 1, Issue 3). https://doi.org/10.1111/j.1467-9388.1992.tb00046.x

UNFCCC. (2015). Paris Agreement. *Paris Agreement - Pre 2020 Action*.

Vishwanathan, S. S., & Garg, A. (2020). Energy system transformation to meet NDC, 2 °C, and well below 2 °C targets for India. *Climatic Change*, *162*(4), 1877–1891. https://doi.org/10.1007/s10584-019-02616-1

Vishwanathan, S. S., Garg, A., Tiwari, V., & Shukla, P. R. (2018). India in 2 °C and well below 2 °C worlds: Opportunities and challenges. *Carbon Management*, *9*(5), 459–479. https://doi.org/10.1080/17583004.2018.1476588

WRI. (2019). *Climate Action for Today and Tomorrow: The Relationship between NDCs and LTSs Climate Action for Today and Tomorrow: The Relationship between NDCs and LTSs*.

Zhong, W., Lant, T., Jehn, M., & Kim, Y. (2012). Pandemic influenza simulation with public avoidance behavior. In *Simulation for Policy Inquiry* (pp. 181–201). Springer New York. https://doi.org/10.1007/978-1-4614-1665-4_10

Zhou, Y., Clarke, L., Eom, J., Kyle, P., Patel, P., Kim, S. H., Dirks, J., Jensen, E., Liu, Y., Rice, J., Schmidt, L., & Seiple, T. (2014). Modeling the effect of climate change on U.S. state-level buildings energy demands in an integrated assessment framework. *Applied Energy*, *113*, 1077–1088. https://doi.org/10.1016/j.apenergy.2013.08.034

9. Appendix

1. DG vs OC Scenario Benchmarks

The DG scenario benchmarks are based on literature review and national targets, whereas the OC scenario benchmarks are based on consumption levels in OECD countries.

Table 8 DQoL and Overconsumption benchmarks

Goal	DQoL (DG scenario) benchmarks	OECD/Overconsumption benchmarks
Food	• 186 kg/capita/year foodgrains (Kumar et al., 2016) • 18 kg meat/capita/year and associated feed (Ritchie et al., 2018)	• 186 kg/capita/year foodgrains (Kumar et al., 2016) • 25 kg meat/capita/year and associated feed (Bruinsma, 2017)
Housing	• To bridge dynamic housing shortage • Affordable housing: 40 m^2 in 2020 to 60 m^2 per house in 2050 • Higher-income groups: 150 m^2 per house	• To bridge 'dynamic' housing shortage • Affordable housing: 40 m^2 in 2020 to 100 m^2 per house in 2050 • Higher income groups: 300 m^2 per house by 2030, three houses per household
Healthcare	• 2 beds/1,000 people by 2030 (today it is ~1) • 3.5 beds/1,000 people by 2050	• 2.5 beds/1,000 people by 2030, • 5.2 beds/1,000 people by 2050 (based on OECD average)
Education	• GER for primary, secondary, and senior secondary to reach 100% and tertiary to reach 90% by 2050 • Area per student for primary, secondary, senior secondary, and tertiary are 1, 2.5, 2.5, and 4 m^2, respectively.	• GER targets remain the same as DQoL • Area per student for primary, secondary, senior secondary, and tertiary schools increases to 1.5, 3.5, 3.5, and 6 m^2, respectively, by 2030.
Transport	• By 2050, the share of public transport in urban 1 and urban 2 areas will increase to 70% and 50% respectively (National Transport Development Policy Committee, 2014)	• Decreased occupancies to mimic international standards of travel, thereby reducing the efficiency of travel per pkm
Cooking	• No use of biomass by 2030	• 50% electric cooking by 2050 in addition to DQoL targets

Table 9 Key variables in 2050 across scenarios

Variable	BAU	DG	SDa	SDb	OC
Precise irrigation coverage (% of irrigated area)	10%	10%	40%	40%	10%
Natural farming coverage (% of foodgrains area)	5%	5%	5%	20%	5%
Groundwater exploitation	Yes	Yes	No	No	Yes
Irrigation pump efficiency	Low	Low	High	High	Low
Solar pumps penetration	10%	10%	10%	50%	10%
Foodgrains in diet	Rice and wheat dominant	Rice and wheat dominant	Rice and wheat dominant	50% of rice replaced by millets	Rice and wheat dominant
Area under sugarcane cultivation (Mha)	8	7.2	7.2	5	7.2
Average floor space index (FSI) for cities	FSI of 1.5	FSI of 1.5	Semi-compact city (medium FSI of 4)	Compact city (high FSI of 8)	Sprawl (FSI of 0.75)
Recycling of C&D waste	1%	1%	20%	40%	0%
Green open space per capita (m^2)	12	12	12	30	12
Share of rail in freight transport	15%	15%	15%	35%	15%
Railways electrification	100% by 2050	100% by 2050	100% by 2030	100% by 2030	100% by 2050
Road transport electrification	Low	Low	Medium	Medium	Low
Shared mobility	Low	Low	Low	High	Very low
Share of public transport in urban mobility	44%	58%	58%	58%	44%
Fossil-free share of power capacity	78%	78%	80%	87%	80%
Fossil-free share of power generation	63%	63%	69%	83%	67%
Clinker to cement ratio in 2050	0.67	0.67	0.67	0.6	0.67
Share of grid electricity for industries	25%	25%	40%	60%	25%
Share of steel production via scrap steel	10%	10%	10%	25%	10%
Alternative fuels in cement production	15%	15%	40%	40%	15%
Improvement in cement SEC	10%	10%	13%	23%	10%
Improvement in steel SEC	3%	3%	7%	16%	3%
Improvement in fertiliser SEC	3%	3%	6%	6%	3%

2. India's Policies and Plans Covered in SAFARI

Table 10 Policies that can be explored in SAFARI

Policy/Plan	Creating the Desired Policy Scenario in SAFARI
Pradhan Mantri Awas Yojana (Housing for All) by 2022 – Urban/Rural	The housing shortage interface pages allow users to explore different annual construction rates to provide affordable housing for all by 2022 as well as beyond it. It is also possible to explore different building materials, carpet areas, floor space indices, tenures, and occupancy levels for these houses.
India Cooling Action Plan (ICAP)	The ICAP aims to reduce cooling energy requirements by 25% to 40% by 2037–2038 and to reduce cooling demand across sectors by 20% to 25% by 2037–2038. It is possible to explore alternative material scenarios, changes in cooling demand, and improvements in cooling appliance efficiency over time.
Energy Conservation Building Code (ECBC; Eco-Niwas Samhita) 2018	The ECBC provides guidelines for improving the energy efficiency of residential buildings, particularly through the building envelope. SAFARI allows users to modify materials, floor space index, and carpet area of residential buildings and broadly estimate changes to residential cooling demand resulting from these.
Pradhan Mantri Ujjwala Yojana Scheme	The SAFARI model allows users to explore LPG and electric cooking access and penetration over time in both urban and rural populations.
Atal Mission for Rejuvenation and Urban Transformation (AMRUT)	AMRUT emphasises improving urban green space and transport infrastructure. The former can be manually determined in SAFARI on a per capita basis. The latter can be adjusted through modal shares, trip lengths, and fuel shares in the transport and urban form modules of SAFARI.
National Food Security Mission	The mission sets annual production targets for cereals and pulses. SAFARI allows users to set production targets based on a normative approach by setting a per capita foodgrain (cereals + pulses) consumption goal. Users can also set the share of rice, wheat, coarse cereals, and pulses if desired.
Compulsory Food Waste Reduction Act, 2018	This act sets a target to halve food wastage in India by 2025. SAFARI allows users to set a target for aggregate wastage reduction in the supply chain for foodgrains, as well as other food (fruits and vegetables, milk, and meat), by 2050.
Per Drop More Crop (Pradhan Mantri Krishi Sinchayee Yojana)	The policy aims to improve water-use efficiency (reducing water wastage), boost the adoption of precision irrigation, and other water-saving technologies. SAFARI allows users to set sequential targets for the percentage of irrigated land under precision irrigation (with 90% application efficiency) for the years 2030 and 2050. Users can also set 2050 targets for the average efficiency of conventional irrigation and average conveyance efficiency for surface water infrastructure.
Accelerated Irrigation Benefits Programme (AIBP) and *Har Khet Ko Pani* (Pradhan Mantri Krishi Sinchayee Yojana)	These schemes are aimed at the creation and utilisation of irrigation potential. SAFARI allows users to determine the percentage of ultimate irrigation potential utilised (net, surface, and groundwater) for years 2030 and 2050.

Groundwater (Sustainable Management) Bill, 2017	The bill is based on the recognition of the unitary nature of water, the need for decentralised control over groundwater, and the need to protect it at the aquifer level. SAFARI, by default, assumes sustainable groundwater management and, therefore, has a hard 1,123 billion cubic metres (BCM) limit on annual utilisable water resources. However, it allows users to explore the failure of sustainable management with a 'Groundwater Over-extraction' switch.
The NITI Aayog Action Plan (2017–2020) (Item 24.17)	Chapter 24 of the action plan sets specific sustainable water management strategies. It calls for an initiative to be launched to ensure different types of industries meet a certain share of their demand through recycled water. SAFARI allows users to set the targets for the share to be met by recycled water for industries (except power plants) sequentially for 2030 and 2050. It also allows users to set similar targets for meeting non-potable domestic water demand.
Millet Mission (Under the National Food Security Mission)	Under this mission, millets are being promoted through technology dissemination, quality seeds, awareness generation, minimum support price, and inclusion in the public distribution system (PDS). SAFARI allows users to switch on the 'Millets diet' scenario to explore a scenario where millets reach the current share of rice consumption in our diets by 2050.
Green Revolution Krishonnati Yojana	It is an umbrella scheme for many crop development programmes to increase crop productivity and bridge the yield gap. SAFARI allows users to set targets for the percentage of yield gap to be bridged in 2030 and 2050. SAFARI also allows users to set sequential 2030 and 2050 targets for the national average cropping intensity.
Pradhan Mantri Kisan Urja Suraksha Evam Utthaan Mahabhiyan (PM-KUSUM)	Component B of the scheme envisages the installation of 17.50 lakh stand-alone solar-powered agriculture pumps in the country by 2022. SAFARI allows users to set targets for the 2050 diffusion of solar pumps. The number of solar pumps installed in 2022 and the impact of those pumps on energy and emissions can be visualised as well.
Paramparagat Krishi Vikas Yojana (PKVY)	PKVY promotes organic farming through a participatory guarantee system of certification. Its definition of organic comprises all types of chemical-free farming, including zero-budget natural farming (ZBNF). Yield gains and water-saving possibilities, although widely discussed, are not supported by sufficient scientific consensus on a national scale. SAFARI allows users to set the 2050 target coverage of cultivated land under organic/natural farming, and the impact on fertiliser demand, production, and the related energy and emissions can be visualised.
Fair and Remunerative Price (FRP) of Sugarcane	India has structurally become a sugar surplus country because of the FRP fixed by the Government for sugarcane, which leads to 60%–70% higher returns than most crops. On the other hand, it is observed that the increased production is a result of area expansion, with productivity stagnating. SAFARI allows users to set a percentage of area under sugarcane cultivation sequentially for 2030 and 2050 to test scenarios where government support may reduce/continue/strengthen.
National Policy on Biofuels 2018	The policy mandates 20% ethanol blending in petrol by 2030. SAFARI allows users to estimate sugarcane availability for ethanol production and determine the maximum possible blending achievable every year (given the constraints of food, water, and arable land).

Draft National Logistics Policy (2019)	The policy aims to push modal shares of freight transport closer to international benchmarks—decrease road freight from 60% to 30%, increase rail freight from 31% to 50%, and increase water freight from 9% to 20%. The freight transport page of the transport sector in SAFARI allows users to visualise the impact of such modal shifts.
Dedicated Freight Corridor	Increase the share of railways in freight transport using the pie charts on the freight transport page.
Faster Adoption and Manufacturing of Electric Vehicles in India (FAME) and Other Electric Vehicle Incentives	While the financial aspects of electric mobility cannot be explored using SAFARI, users can assess the impact of varying degrees of electrification across modes in combination with varying levels of grid decarbonisation.
National Urban Transport Policy (2006, 2014) and the Smart Cities Mission (2015)	These policies focus on improving air quality in cities, reducing congestion, and creating sustainable transport infrastructure through better public and non-motorised transport. SAFARI's urban transport sector can be used to analyse the impact of such changes on emissions (both greenhouse gas and pollutants) and energy demands.
National Transit Oriented Development Policy	In SAFARI's urban transport sector, trip lengths can be adjusted to recreate a transit-oriented development scenario in combination with a higher floor space index (FSI) scenario in the buildings sector (impacts of a compact city versus sprawl).
Perform, Achieve, and Trade (PAT) Scheme	It is a regulatory mechanism to reduce the specific energy consumption (SEC) of energy-intensive industries. SAFARI allows users to set 2050 targets reduction because of the energy efficiency measures (separately for thermal and electrical SECs) in three energy-intensive industries: cement, steel, and fertilisers.
National Steel Policy, 2017	Sections 4.2.3 and 4.2.4 of the National Steel Policy, 2017, mention the possible production process share[19] for 2030–2031. SAFARI allows users to set the steel production process share in 2050 and visualise the impacts on emissions and energy demand.
Modified New Pricing Scheme (NPS-III), Department of Fertilisers	Under this scheme, all naphtha-based fertiliser plants are to be converted to natural gas. This is subject to pipeline connectivity. Fuel/feedstock share of naphtha and natural gas can be varied in SAFARI to evaluate the impacts.
Intended Nationally Determined Contributions (INDC)	The targets for realising INDC include achieving 40% installed capacity from non-fossil fuels by 2030 and generating 175 GW of renewable energy (RE) by 2022 (including 60 GW of ground-mounted solar under the National Solar Mission). The achievement of these targets can be explored under various scenarios on the SAFARI interface. Climate finance policies including coal cess, capital expenditure, and import duties can be tested using SAFARI.

[19] Exact shares are not specified—it is mentioned as 'under discussion'. https://steel.gov.in/sites/default/files/draft-national-steel-policy-2017.pdf

Energy Storage System Roadmap, 2032, NITI Aayog	The NITI Aayog estimates a total energy storage requirement of 209 GWh in 2032 to meet the RE targets. The SAFARI model has battery energy storage and pumped hydro storage. It allows users to set a maximum possible capacity in the 2050 time frame and adjust cost trajectories for battery storage and pumped hydro storage systems. The impacts on supply mix and, therefore, emissions and total system costs can be visualised.
National Education Policy (NEP), 2020	The NEP 2020 envisages a 100% gross enrolment ratio (GER) for preschool to secondary level by 2030 and 50% GER for higher education by 2035. SAFARI has two preset GER scenarios. In the business-as-usual scenario (BAU), the current trends of expenditure in the education sector continue (98% and 80% GER in secondary and senior secondary school levels and 42% GER in higher education are achieved by 2035). SAFARI's 'Education goal' switch assumes that the NEP targets are achieved (99% GER in secondary and senior secondary school levels and 51% in higher education by 2035). In addition, users can also evaluate the impact of increased average area per student (at par with the average of developed countries) on material and energy demand and emissions with the 'Overconsumption' switch.
National Health Policy, 2017	The policy aims to ensure the availability of two beds per 1,000 people. The DQoL scenario assumes the achievement of this target by 2025 and 3.41 beds per 1,000 people by 2050. Users can also visualise the impacts of a lower target and a higher OECD-standards target.

3. Energy Comparisons With India Energy Outlook 2021

Table 11 Comparison with India Energy Outlook 2021, IEA

		Electricity demand (TWh)	Coal capacity (GW)	Gas capacity (GW)	Nuclear (GW)	Renewables (GW)
2030	IEA-STEPS[20]	1959	269	30	16	436
	IEA-SDS[21]	1922	221	72	17	641
	SAFARI-DG	1940	187	29	22	419
	SAFARI-SDa	1689	185	38	21	399
	SAFARI-SDb	1585	185	38	21	400
2040	IEA-STEPS	3146	260	46	31	1066
	IEA-SDS	2980	144	134	36	1334
	SAFARI-DG	3189	236	54	41	905
	SAFARI-SDa	2623	182	40	26	603
	SAFARI-SDb	2362	164	36	21	544
2050	SAFARI-DG	5005	309	72	40	1499
	SAFARI-SDa	3909	230	54	61	1202
	SAFARI-SDb	3328	140	50	62	1313

[20] STEPS – stated policies scenario
[21] SDS – sustainable development scenario

4. CGE Model Soft-Linking Methodology

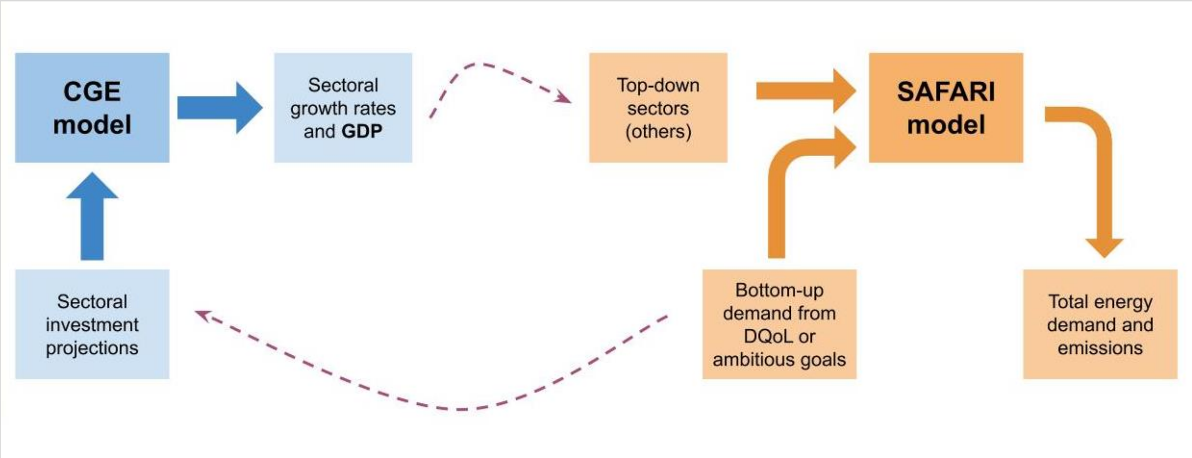


Figure 34 CGE-SAFARI soft-linking

The CGE model's exogenous investment trajectories are based on published historical trends and aligned with the Government's sectoral vision targets as well as policy narratives from the SAFARI framework[22]. We sourced capital stock growth rates and factor productivity data for our sectors from the India KLEMS database version 2020[23], published by the Reserve Bank of India. Table 12 lists the capital stock[24] assumptions for the model's sectors that are aligned with the goals.

Our investment assumptions for the BAU scenario are closely aligned with historical sectoral trends (2010–2015), albeit at lower levels of investment demand across the economy (6% p.a., compared with a historical investment growth of 7%–8% p.a. as per KLEMS 2020 data). The model has also been modified to maintain historical levels of sectoral economic activities in the pre-COVID slowdown (especially in manufacturing sectors).

The impact of dampened consumption and productivity owing to COVID lockdowns and partial economic activity during 2020–2021 was adjusted to indicate an average near-zero growth in the 2 years. In effect, the projections begin from 2023 where a moderate level of investment growth occurs and growth is mainly driven by the service sector. Growth in agriculture and construction (and allied manufacturing sectors) sectors is relatively slower than recent historical trends, in line with post-2010 trends. Therefore, even as service sector investments grow at about 6.5% p.a., the primary agriculture sector investment growth is limited to about

[22] Macroeconomic assumptions in the CGE model are in line with short-term projections by the Government and institutional agencies. The current account balance is retained at rates marginally higher than projected (at 3.5% of GDP), keeping in mind the weak export demand and uncertain global cues resulting from the USA–China trade tariff dispute. In addition, we assume a 3% increase in government transfers to lower-income households in both rural and urban areas.

[23] The India KLEMS database was compiled to support research in the areas of economic growth and policies that support the acceleration of productivity growth in the Indian economy. The database version includes measures of economic growth, employment, capital formation, and productivity. Input measures include capital (K), labour (L), energy (E), materials (M), and services (S).

[24] The capital input is one of the variables in the multi-factor productivity database for 27 industries, annual time series 1980–1981 to 2015–2016. Updated estimates are based on the revised National Accounts Statistics (NAS) with the base year 2011–2012. The capital input comprises growth rates of capital stock, capital services, and capital income share in gross value added (GVA).

3% p.a. (in line with historical trends) and the industrial sector investment grows at about 5% (instead of the historical highs of 8%–9%).[25]

In the DG scenario, we account for a 'boost' over BAU investment levels in sectors, such as construction, housing, health, education, and agriculture, that are required to meet the material and resource needs for achieving the goal benchmarks outlined in Section 3. Even as historical trends for primary agriculture sector investments are considered, productivity is marginally improved. For education and healthcare service sectors, 'operational' requirements are assumed to remain consistent with historical investment trends of about 10%–11% growth p.a., whereas the construction activities to support physical infrastructure needed for these 'goals' are met by doubling investments in construction and allied manufacturing. This corresponds to sectoral construction growth volume for housing, education, and health infrastructure from the SAFARI model[26].

Table 12 Capital stock assumptions in the CGE model (average up to 2050)

Sector	Historical *	BAU scenario	DQoL scenario	
	2000–2017	2023–2050	2023–2040	2040–2050
Agriculture sectors	3.6%	3%	3%	3%
Manufacturing sectors	8.5%	5%	6.5%	4.5%
Agricultural production, processing, and preservation	6%	4%	6%	4%
Service sectors	8.8%	6.5%	6.8%	6.3%
Construction	8.5%	11%	18%	8%

Source: Authors' compilation; historical capital stock growth rates sourced from RBI-KLEMS Database, 2020

*The historical period growth referenced here reflects the post-liberalisation boost in manufacturing and services sectors. Our projections consider a moderate growth trajectory.

[25] In the 66 activity sector IO-SAM matrices set up for long-term low-carbon pathways analysis for use in CSTEP's CGE model (2018–2019), there are four primary agriculture sectors, 35 manufacturing sectors, and 27 service sectors.

[26]The outlay for construction activities under housing schemes (PMAY-Urban and Rural), education (NEM), and health (NHM & PMSSY) was estimated to be about 55% of the construction sector outlays in the 2015–2018 budgets. Assuming the same level of productivity in the construction sector based on historical trends, the SAFARI model's DQoL scenario indicates that during 2020–2030, construction activities will grow about 1.4 times the BAU. Hence, a similar boost is considered under the DQoL scenario in the CGE model.

5. Emissions Inventory

Table 13 provides the list of sectors typically considered in the emissions inventory according to GHG Platform India and India's second biennial update report submitted to the UNFCCC. Since the model's base year is 2011, we have compared the GHG emissions from SAFARI with GHG platform India (GHG-PI) for the year 2014 in this table.

Table 13 GHG emissions covered in SAFARI

Mt CO2e		2014	
		GHG-PI	SAFARI
Energy-use emissions			
1A	**Fuel combustion activities**		
1A1	Energy industries	980	909
1A1a	Main activity electricity and heat production (utility + captive)	980	909
1A1a – public	Utilities	923	812
1A1a – private/CPP	CPP		97
1A1b	Petroleum refining	50	
1A1c	Manufacture of solid fuels and other energy industries	7	
1A2	Manufacturing industries and construction	437	451
1A2a	Iron and steel	216	166
1A2f	Non-metallic minerals, "predominantly cement"	84	56
1A2b,c,d,e,g,h,i,j,k,l,m	"Other industries"	137	229
1A3	Transport	236	256
1A4	Other sectors	150	103.3
1A4ci	Agriculture: diesel pumps + tractors	29	45.2
1A4b	Residential: cooking	107	58.1
1A4a	Commercial: fuel combustion - cooking	9	
1A4cii	Fisheries	5	
1A5	Non-specified		
1B	**Fugitive emissions**	**38**	
IPPU			
2A	**Mineral industry**	**116**	**105**
2A1	Cement production	109	105
2A2,3,4,5,	Other mineral industry	7	
2B	**Chemical industry**	**39**	**25**
2B1	Ammonia production	23	25
2B2,3,4,5,6,7,8,9,10	Other chemical industry	16	
2C	**Metal industry**	**14**	
2C1	Iron and steel	7	
2C2,3,4,5,6,7	Other metal industry	7	
2D	**Non-energy products from fuel and solvent use**	**4**	
2E	**Electronics industry**		

2F	**Product uses as substitutes for O3 depleting substances**		
2G	**Other product manufacture and use**		
2H	**Other**		
AFOLU			
3A	**Livestock**	**225.5**	**197**
3A1	Enteric fermentation	204	197
3A2	Manure management	21.5	
3B	**Land use**	**-117**	
3C	Aggregate sources and non-CO_2 emissions sources on land	126.2	139.8
3C4	Direct N_2O emissions from managed soils	50.5	77.9
3C7	Rice cultivation	69.5	61.9
3C1	Biomass burning	6.2	
	Beyond scope		
	Included in other industries		

6. Power Sector Modelling Methodology

Peak Demand Estimation

Data on past years' (2009–2010 to 2018–2019) peak demand values and electricity demand values were taken from the CEA's Load Generation Balance Reports. A regression analysis was carried out to understand the relationship between peak load and annual electricity requirement. Linear regression was seen to be a good fit, and the obtained regression equation was used in the model to estimate the peak loads of future years based on the electricity demand forecasts. The inherent assumption is that the shape of the demand load profile with respect to peak demand would remain the same in the future, as seen in the past. This information helps the balancing loop B3 (peak load management) to determine dynamically if any additional capacities are required or not to meet peak load in future years and, subsequently, informs capacity additions.

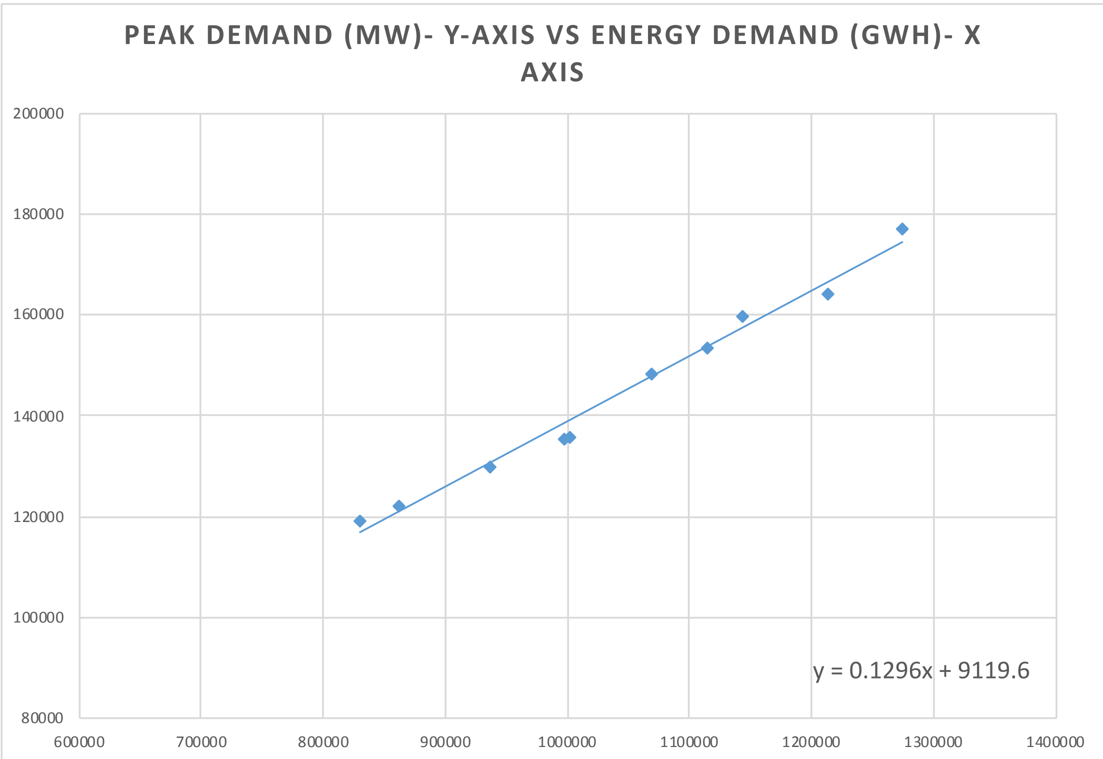


Figure 35 Regression analysis for peak demand and energy demand

The model uses a forecast function to estimate future electricity demand. The time frame for future estimation, from 2020 onwards, is kept at 6 years for both demand and peak demand. This is the smallest forecast time frame found that ensures there is no unmet demand in the model.

Daytime/Night-Time Demand Estimation

The annual demand was broken down into daytime and night-time demand. This was done by analysing the typical representative daily load curve data for different months (POSOCO, 2016). The analysis determined that the average (across typical days from all months) daytime demand, from 7 a.m. to 7 p.m. window, was 47% of the total demand, while the night-time demand, from 7 p.m. to 7 a.m., was 53% of the total. In the model, the daytime demand can be met by a combination of all supply sources (as determined by the cost-based shares), while the night-time demand would need to be met by non-solar sources.

Levelised Cost of Electricity (LCOE)

The equivalent Stella equation in the model is given below:

(CAPEX_per_GW + PV(discount_rate, lifetime, (Fixed_Cost+(OPEX_per_GWh+Var_OM)*Average_Expected_Annual_Functioning_Hours))/PV(discount_rate_coal, lifetime, Average_Expected_Annual_Functioning_Hours)

where Opex per GWh = (Fuel cost*Fuel per year)/Electricity generation per year

Average expected annual functioning Hours = Expectation of functioning hours, made using the trend of dynamic PLFs from the last 5 years to form an expectation of the PLF for the next 5 years and arrive at an average expected functioning hours value.

Coal

Once the model determines the coal capacity addition required, the construction is initiated into the 'Coal capacity under construction' stock. There is a construction delay, after which the plant comes online and is able to produce power. After its lifetime is over, the plant is retired.

The coal operating capacity generates power according to the balancing loop B2 (current management). The PLF of coal determines the annual functioning hours of coal in a year, which gets multiplied by the capacity to give the generation. From the total generation, auxiliary consumption and T&D losses are reduced to get the electricity delivered, which goes to meet the demand.

The model assumes a shift towards efficient coal technologies over time. Thus, the thermal efficiency of the coal fleet increases over time to reflect the shift from a mix of subcritical/supercritical to a 50/50 mix of supercritical/ultra-supercritical by 2051. This also reflects through an increase in the capacity addition costs. Data inputs to the coal sector are given in the table below.

Table 14 Data inputs for coal power module

Parameter	Value	Units
Capex: 2011	45 billion	INR/GW
Capex: 2051	90 billion	INR/GW
Fixed cost	1.14 billion	INR/GW/year
Fuel cost of coal: Domestic	3091	INR/tonne
Fuel cost of coal: Imported	5145	INR/tonne
GCV: Domestic coal	4440	Kcal/kg
GCV: Imported coal	6290	Kcal/kg
Average thermal efficiency: 2011	33%	Unitless
Average thermal efficiency: 2051	40%	Unitless
Coal plant life	40	Years

Percentage of auxiliary consumption	9%	Unitless
Availability factor for peaking	75% till 2030, increasing to 85% by 2051	Unitless
Coal land footprint	277	Ha/GW
Coal water withdrawal (once through cooling technology)	158.5	Cubic metre / MWh
Coal water withdrawal (cooling tower technology)	4.6	Cubic metre / MWh
Ultimate domestic coal reserves for power production	23.59	Billion tonnes

Natural Gas

Natural gas has a stock-flow structure similar to that of coal. Parameter values for the natural gas sector are given below.

Table 15 Data inputs for natural gas power module

Parameter	Value	Units
Capex	47 billion	INR/GW
Fixed cost	420 million	INR/GW/year
Variable O&M cost	60,000	INR/GWh
Fuel cost of gas: Domestic	15	INR/SCM
Fuel cost of gas: Imported	32	INR/SCM
GCV: Domestic gas	37620	KJ/SCM
Gas power plant life	30	Years
Percentage of auxiliary consumption	3%	Unitless
Availability factor for peaking	89%	Unitless
Gas land footprint	40	Ha/GW
Gas water footprint: Once through cooling	96.8	Cubic metre / MWh
Gas water footprint: Low water technology	2.6	Cubic metre / MWh
Domestic Gas reserves (for power production)	780	BCM

Nuclear

Nuclear has a stock-flow structure similar to that of coal and natural gas. One key difference in the structure is that there is a limit imposed on the growth of nuclear. Therefore, the maximum it can grow until 2051 is 40 GW. The limit is not imposed for any particular year. The model has the flexibility to build nuclear at the rate determined through the cost-based shares; however, the ultimate limit is 40 GW. If and when the limit is reached, new capacities will stop being added. Parameter values for nuclear are given below.

Table 16 Data inputs for nuclear power module

Parameter	Value	Units
Capex	140 billion	INR/GW
Fixed cost: 2011	3.5 billion	INR/GW/year

Variable O&M cost	1 million	INR/GWh
Fuel cost	500000	INR/GWh
Nuclear power plant life	40	Years
Percentage of auxiliary consumption	10%	Unitless
Availability factor for peaking	68%	Unitless
Land footprint	2600	Ha/GW
Nuclear water footprint: once cooling technology	193	Cubic metre / MWh
Nuclear water footprint: Low water technology	4.2	Cubic metre / MWh
Ultimate capacity	40	GW
Max annual PLF	0.85	Unitless

Solar PV

Solar PV has been modelled as a renewable resource where, after retirement, the land is again made available for the reinstallation of solar PVs. The model uses the ageing chain structure to capture the time delays at every process point in the system—the time it takes to construct solar capacity and its retirement time. The ultimate potential for solar capacity is the limit for how much solar PV can be installed at a point in time.

Solar power generation happens based on its operating capacity and the functioning hours in a year. Capacity utilisation factor (CUF) determines generation in a year. A learning rate has been assigned to the CUF to account for improvements over time because of improvements in technology, operation, and scale. The model also gives the flexibility for testing policy impact on the growth of solar PV.

Table 17 Data inputs for solar power module

Parameter	Value	Units
Solar module cost: 2015	21 billion	INR/GW
Solar module cost: 2051	14 billion	INR/GW
Import duty (as % of module cost)	15%	Percentage
Fixed cost	500 million	INR/GW/year
Variable O&M cost	0	INR/GWh
Fuel cost	0	INR/tonne
Solar plant life	30	Years
Percentage of auxiliary consumption	0%	Unitless
Solar land footprint	4800	Ha/GW
Solar water footprint	80	Cubic metre / GWh
CUF	18% to 22% by 2051	Unitless
Ultimate potential	2000	GW
Construction time	2.5	Years

Wind

The stock-flow structure of wind is also similar to that of solar PV where the retired capacity again comes on board once the land area is made available for the reinstallation of wind power. Unlike solar, wind does not suffer from supply-side load limitations and can supply electricity throughout the day and night. The wind model structure also has the flexibility to run on policy targets such as solar.

Table 18 Data inputs for wind power module

Parameter	Value	Units
Capex: 2015	66 billion	INR/GW
Capex: 2051	57 billion	INR/GW
Fixed cost	1.05 billion	INR/GW/year
Variable O&M cost	0	INR/GWh
Fuel cost	0	INR/tonne
Wind plant life	25	Years
Wind capacity factor for peaking	0.24	Unitless
Percentage of auxiliary consumption	0%	Unitless
Wind land footprint	12140	Ha/GW
Wind water footprint	0	Cubic metre / GWh
CUF	0.19 to 0.265 by 2051	Unitless
Ultimate potential	1300	GW
Construction time	4	Years

Hydropower

Hydropower resembles the structure of a renewable source of power. As the ultimate source of power (the water availability) is renewing itself, once the infrastructure retires after its lifetime, the head is freed up for another project, which can come on board after a time delay. The ultimate value of hydropower is constrained by the ultimate hydro potential.

Table 19 Data inputs for hydropower module

Parameter	Value	Units
Capex	117 billion	INR/GW
Fixed cost	1 billion	INR/GW/year
Variable O&M cost	0	INR/GWh
Hydro power plant life	55	Years
Percentage of auxiliary consumption	1%	Unitless
Availability factor for peaking	87%	Unitless
Land footprint	780	Ha/GW
Hydro water footprint	17	Cubic metre / MWh
Ultimate reserves	145	GW

Grid Storage

The storage sector is governed by three balancing loops—B1, which is trying to construct storage to meet the storage target (given as an exogenous input); B2, where additional solar capacity comes on board for generating storage power requirements; and B3, where the ultimate potential for constructing solar limits the amount of storage that can be built over time.

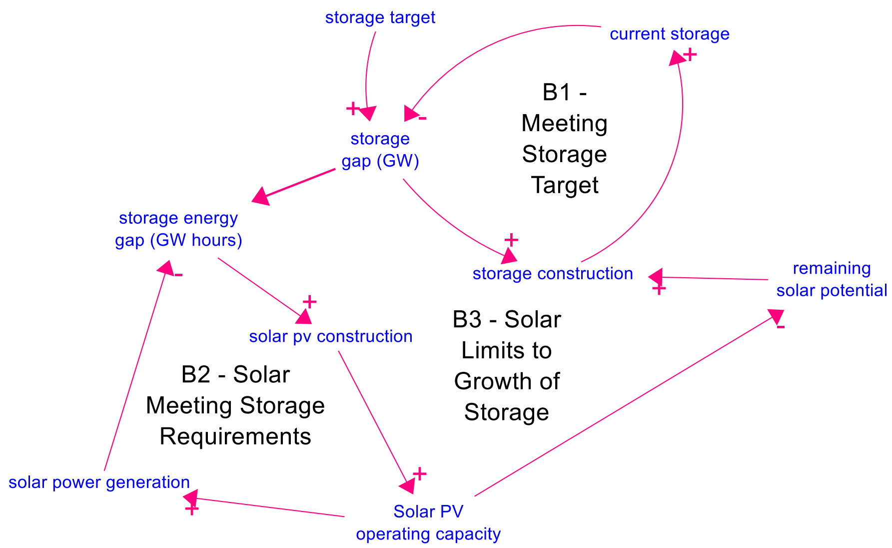


Figure 36 CLD for storage module

Grid-level battery storage is modelled as a closed-loop system similar to the renewable energy structure, where storage retirement again comes back through reinvestment. Ultimate battery storage is the target that is given to the model as an exogenous input. Additional solar capacity is enabled to be built without the day/night time constraints, corresponding to the exogenously driven storage capacity and generation available. The overall solar capacity constrained by the country's ultimate solar power potential.

The annual cost of storage is calculated as the capex per GW (for additional storage and reinvestment) plus the annual fixed cost of storage. The annual cost of additional solar PV for storage is also added to compute the integrated storage and solar PV cost.

Table 20 Data inputs for grid storage

Parameter	Value	Units
Capex: 2015	44 billion	INR/GW
Capex: 2051	11 billion	INR/GW
Fixed cost: 2015	870 million	INR/GW/year
Fixed cost: 2051	230 million	INR/GW/year
Storage target for 2050 (in BAU)	250	GW
Storage energy hours	4	Hours/day
Construction time	3	Years
Efficiency	0.85 going up to 0.92 by 2051	Unitless

Biomass

The stock-flow structure of biomass is also the same as solar PV and wind, where all the retired capacity again comes on board.

Table 21 Data inputs for biomass power module

Parameter	Value	Units
Capex	60 billion	INR/GW
Fixed cost	7 billion	INR/GW/year
Variable O&M cost	47000	INR/GWh
Fuel cost	3.87 million	INR/GWh
Biomass lifetime	20	Years
Percentage of auxiliary consumption	5%	Unitless
Availability factor for peaking	9%	Unitless
Biomass water footprint: once through cooling	152	Cubic metre / MWh
Biomass water footprint: Low water technology	3.3	Cubic metre / MWh
Ultimate biomass potential	17	GW
Biomass construction time	2	Years

Micro-hydro is modelled as a scenario with a maximum of 19 GW of ultimate operating capacity up to 2051.

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