NO SILVER BULLET

Essays on India's Net-Zero Transition

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Center for Study of Science, Technology and Policy

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Disclaimer

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SAFARI
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Executive Summary

India announced its net-zero target for the year 2070. Long-term projection models are expected to play an important role in developing India's strategies to achieve this target. However, developing such long-term strategies is a very complex and challenging task because of the uncertainties involved in looking at such long-time horizons. If someone back in 1974 were asked to predict the cost of a solar panel today, or any other technology, imagine their chances of getting it right. Similarly, our assumptions and estimates for 2070, however 'correct' the math may be, need to be viewed with cautious optimism. This is particularly true for models that provide a single silver bullet answer, or pathway, to the net-zero puzzle. What is deemed 'not optimal' today could in fact be the most likely scenario 40 years later and, therefore, should not be discarded without deep consideration.

Future uncertainty is not a novel concept; modelling groups have been trying to address it by creating multiple different scenarios for the future. However, merely presenting 'range' scenarios cannot be a proxy for deep uncertainty analysis. The purpose of modelling is to understand causal relationships and enable the careful examination of scenario design to truly highlight key uncertainties. Models can help ask the right questions and be used for more discussions and joint scenario-building rather than merely serving as calculators. For this to happen effectively, models should be made more accessible and transparent to non-modellers so that assumptions, logic, and possible scenarios can be debated. We hope that this report is a useful contribution in this regard. We put forth some of the questions related to net-zero goals and scenarios that came up while updating our model (the Sustainable Alternative Futures for India, or SAFARI) and our attempts at answering them. We also present often under-discussed points for debate and scrutiny.

The Demand Estimation Conundrum

Gross domestic product (GDP) is one of the key drivers of demand in most models. While some models try to estimate the net impact of a scenario on the overall GDP, the 'new' GDP is not used again to compute new demand. For example, studies have shown that a net-zero transition would result in significant GDP gains compared to a business-as-usual (BAU) scenario. Does this mean that consumption or demand would also be correspondingly higher in a net-zero scenario? More importantly, the relationship between GDP and demand can be complex and dynamic. As countries develop, per capita demand for certain materials and services tends to saturate. Transport demand increases with income but is expected to plateau or saturate beyond a certain level. Similarly, per capita demand for cement and steel has saturated at different levels for different countries. India is expected to become a developed nation in the 2050s. Therefore, at what level will India's per capita demand saturate, if at all? Reference scenario (or BAU) emissions can be very different based on assumptions on saturation levels and the rate at which India will reach there. Modelling groups can benefit from a discussion of these assumptions around saturation because the level of ambition needed to reach net zero is dependent on them.

Industrial Decarbonisation

Industrial sector emissions are typically considered hard to abate. In this report, we have examined the contribution (and maximum potential) of various interventions to bringing down cement, steel, and fertiliser industrial emissions. Complete decarbonisation is entirely contingent on the successful commercialisation of technologies such as carbon capture and storage (CCS) and green hydrogen. The use of electricity (directly or via electrolytic hydrogen) is an inefficient way to produce the high temperatures needed in industries, even when technologically feasible. Complete electrification for the sake of industrial decarbonisation would, therefore, significantly increase electricity demand, thereby passing on the challenge of decarbonisation to power generation.

Is the Power Sector Really the 'Low-Hanging Fruit'?

Modelling results show that in a business-as-usual scenario, while India will achieve its 2030 targets (NDCs), fossil-fuel-electricity will continue to play a role until the end of the century. In a net-zero scenario, where electrification rates in all sectors increase, the true burden of decarbonisation shifts to the power sector. While costs of renewable energy (RE) have been falling, there are many issues yet to be resolved—intermittency and cheap storage options, grid stability, import dependence for technology and critical minerals, land acquisition and availability—some of which may in fact increase the costs of RE in later years. Our analysis shows that nuclear power is a crucial piece to this puzzle, and India should follow through on its plans to install 65 GW by 2050 and the 'three-stage atomic energy plan' transitioning towards thorium energy post-2050.

Behavioural Shifts for a Sustainable Environment

India's per capita consumption levels, being a developing country, are well below the world average. To ensure sustainable consumption, we must make sure that we do not aspire for Western standards of overconsumption because that may become too unsustainable for a populous country such as India. However, there are some behavioural shifts that can help in our net-zero transition and overall sustainability to varying degrees. Examples include a partial dietary shift towards millet (from rice), the use of public transport for urban and intercity travel, electric cooking, and the use of energy-efficient appliances, which together can save more than 1GtCO_2e in 2070.

Carbon Pricing

As India gears up to introduce carbon pricing (through an emissions trading scheme to begin with), we discuss potential spillover effects such as exacerbated inequality and potential import dependence (see the feedback loops in Figure 6). If the price on carbon is too low, people (industries, consumers) might find it cheaper to pay the tax than to shift to a (more expensive) low-carbon alternative. However, a very high carbon price could exacerbate inequality as the prices of essentials increase. A careful balance needs to be struck with complementary non-market policies to enable the success of carbon pricing in India at a transformative rather than incremental scale.

Given the complexity of these interdependencies and future uncertainties, long-term models have the power to do more than be mere calculators that attempt to provide a silver bullet solution. There is no correct pathway to net-zero emissions, decades into the future. Modifying the famous quote, we believe that 'all models give the wrong answer, some help ask the right questions'. We hope that the points and questions raised in this report are discussed further as part of India's net-zero modelling and scenario-building efforts.

Contents


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1. Context and Rationale

Many newspaper articles have been published since 2021 on India's net-zero ambition, as countries across the world started to announce net-zero targets with India too making its announcement at COP26. These articles have largely been based on a few studies using models such as GCAM[1], EPS[2], E3ME[3], and MARKAL[4] (V. Agarwal et al., 2021; Ahluwalia & Patel, 2021; Asia Society Policy Institute, 2022; Chaturvedi & Malyan, 2021; Shell & TERI, 2021).

These modelling studies have given us a good starting point for how India's future (the energy system in particular) 'should' look if we were to achieve net-zero emissions. We, at the Center for Study of Science, Technology and Policy (CSTEP), have been analysing net-zero options for India using our Sustainable Alternative Futures for India (SAFARI) model, and this report highlights some of the complex and often overlooked issues.

As countries develop, per capita demands for materials such as cement and steel are expected to saturate beyond a particular income level. For example, it has been observed that at a GDP/capita of USD 12,000, cement/capita levels have saturated between 350 and 720 kg for different countries such as the United Kingdom, the United States, Germany, and Japan. India is expected to cross GDP/capita of USD 12,000 in the 2050s (Bleischwitz et al., 2018; B. J. van Ruijven et al., 2016). At what level will cement consumption per capita saturate for India? The level and timing of emissions peaking in this sector are highly sensitive to the saturation level assumed. Similarly, saturation has been seen in other countries for per capita steel, aluminium, and passenger kilometres; we discuss the complexities of demand estimation in these sectors in Section 2.

Electrification of industry (and transport) is the common assumption in several models to reach net zero. But studies have shown that high-heat industrial processes (temperatures >1000°C) cannot be easily electrified. It is possible of course that in the future, with technological advancements, this becomes more feasible. However, such a blanket assumption on complete electrification prevents any discussion on alternatives to industry decarbonisation. Moreover, process emissions (IPPU) from the cement industry can be completely abated only with a technological breakthrough towards a new production process or through the use of carbon capture and utilisation/storage (CCUS) technologies. Therefore, achieving net zero without CCS/CCUS is questionable and worth pondering over. These aspects of industrial decarbonisation in the context of a net-zero transition are discussed in Section 3.

While the power sector is considered a 'low-hanging fruit' in the net-zero transition discourse (because of the falling costs of renewable energy), there are unresolved issues relating to intermittency, grid stability, and large-scale battery storage availability. We feel that nuclear power, which is often sidelined because of potential safety concerns and public perception,

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[1] The Global Change Assessment Model
[2] The Energy Policy Simulator
[3] The simulation model built by Cambridge Econometrics
[4] The linear programming model of the Indian energy system

should be explored as an option to decarbonise the power sector at a reasonable rate. We elaborate on this idea in Section 4.

The Prime Minister called for a movement called LIFE—Lifestyle for Environment—at COP26 along with announcements on net zero and other targets. Behavioural changes do affect the environment but can be harder to quantify with conventional energy system models that focus on supply-side dynamics. The SAFARI model, on the other hand, can be used to determine the impacts of behavioural shifts in diet, transport, appliance usage, and so on, as the model is driven by quality-of-life indicators and estimates bottom-up demand in key sectors such as agriculture and housing (Ashok et al., 2021; CSTEP, 2021; Kumar et al., 2021). In Section 5, we discuss the impact of behavioural changes on the environment using the SAFARI model.

India is expected to announce a carbon pricing mechanism/platform soon. In Section 6, we discuss the pros and cons of carbon pricing for India and describe the macroeconomic impacts of specific low-carbon policies. This is based on CSTEP's analyses using a social accounting matrix (SAM) multiplier model (CSTEP, 2022b).

The aim of the report is to ignite conversations on complex and promising net-zero pathways. It does not seek to provide any magical answers, such as 'X trillion USD investments will be needed to achieve net zero in India'. However, it does raise pertinent questions that should not be ignored. We will organise workshops and consultation events in the coming months to enable such discussions and contribute to the model development process in India.

2. The Demand Estimation Conundrum

The demand for materials and energy is one of the main drivers of greenhouse gas (GHG) emissions. Most of the models used in India to analyse energy and emissions—the MARKAL model, the Sustainable Alternative Futures for India (SAFARI) model, the Global Change Assessment Model (GCAM), the Energy Policy Simulator (EPS), and so on—use exogenous macroeconomic drivers to varying degrees to project future demands. The assumptions made on the GDP growth trajectory and its relationship with various demands have a big role to play in determining the emissions trajectory, sometimes even more than assumptions on the penetration of low-carbon interventions (Spencer & Dubash, 2022).

While the GDP trajectory is often discussed, we feel that the relationship between GDP and demand is rarely unpacked. Regressions (and other econometric models) to estimate future demand work fine when the relationship between dependent and independent variables remains consistent with historical trends. But when a change in trend is expected in the future, it becomes a bit more challenging. For example, distance travelled per capita, measured as passenger kilometres per capita (pkm/capita), has historically increased with the increase in income but is seen (in developed countries) to saturate beyond a particular level of income (Dhar & Shukla, 2015; Millard-Ball & Schipper, 2011; S. K. Singh, 2006). This is because despite the increase in income, there is a limit to the amount of time that people want to spend commuting (~1.1 hours per day). The level at which pkm/capita saturates depends on various country-specific factors such as demographics, investments in infrastructure, and the design and density of cities. Japan's saturated at 10,000 km, while the United States' reached 27,000 km.

Similarly, for industries, the per capita consumption of materials such as cement, steel, and aluminium reaches a saturation value, as summarised in Table 1 (Bleischwitz et al., 2018; B. J. van Ruijven et al., 2016). As countries develop, there is a change in economic structure, going from agriculture-driven growth towards manufacturing and, finally, services. Through this, a 'long-term dematerialisation' trend has also been observed across countries (B. van Ruijven et al., 2008). In fact, per capita demand for food grains has already saturated in India (Kumar et al., 2009).

Table 1: Per capita demand and saturation levels based on literature

Variable	India's current value	Global average today	Saturation levels seen [5]
Pkm/capita	~7,500 [6]	NA	10,000–27,000
Cement kg/capita	235	520	350–720
Steel kg/capita	75	225	400–850
Aluminium kg/capita	2.85	11	20–25

[5] In developed countries

[6] By calibrating 2019 values to be 6,900 based on stakeholder consultations for IESS version 2

While there is some literature and discussion around saturation levels for pkm/capita, we find little to no mention of industrial saturation. This becomes particularly crucial to consider while modelling post-2050 when India is expected to become a developed economy. Another point to note here is that India's trajectory to become a developed economy could be unlike current benchmarks, all of which have had a very carbon-intensive development pathway. At what rate and level would India's demand saturate? Figure 1, Figure 2, and Figure 3 show emission trajectories for transport, cement, and steel industries, respectively, at different saturation levels according to the SAFARI model. The scenarios presented are 'reference scenarios' where minimal decarbonisation is assumed, so the peaking and reduction in emissions are predominantly due to demand saturation. Given the large variations between these scenarios, the saturation level becomes an important but rarely discussed modelling assumption.

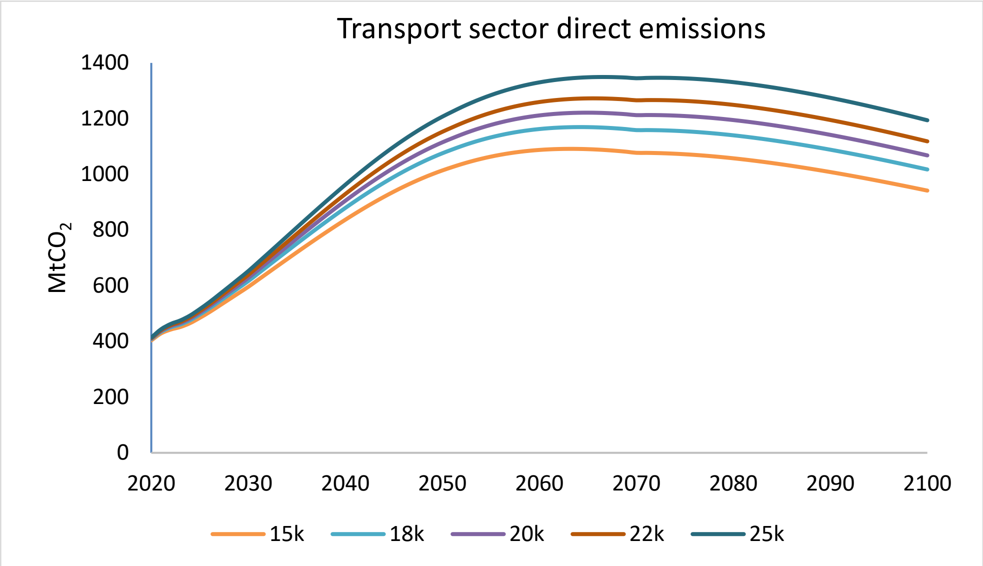


Figure 1: Reference scenarios for the transport sector based on different pkm/capita saturation levels

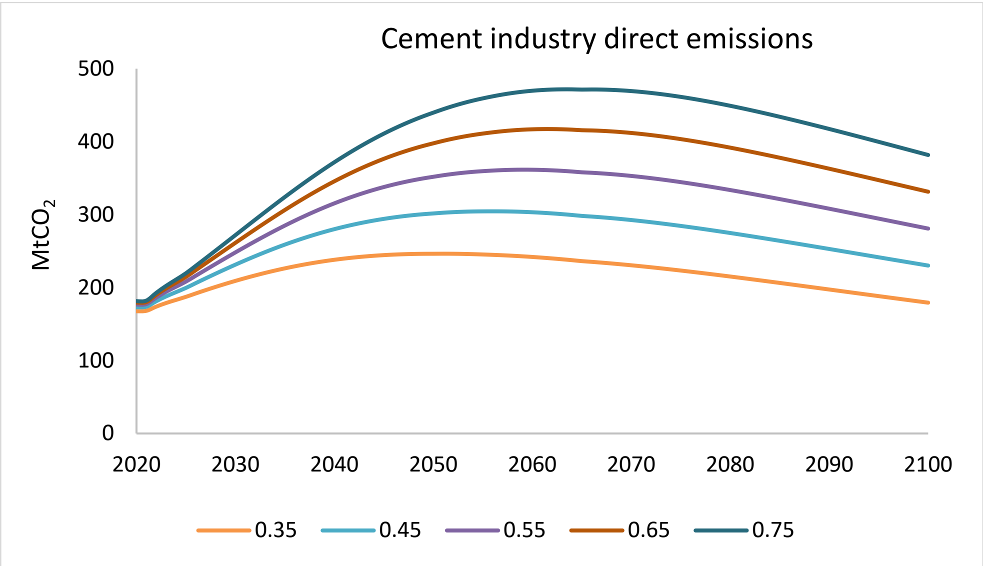


Figure 2: Reference scenarios for the cement industry based on different per capita saturation levels

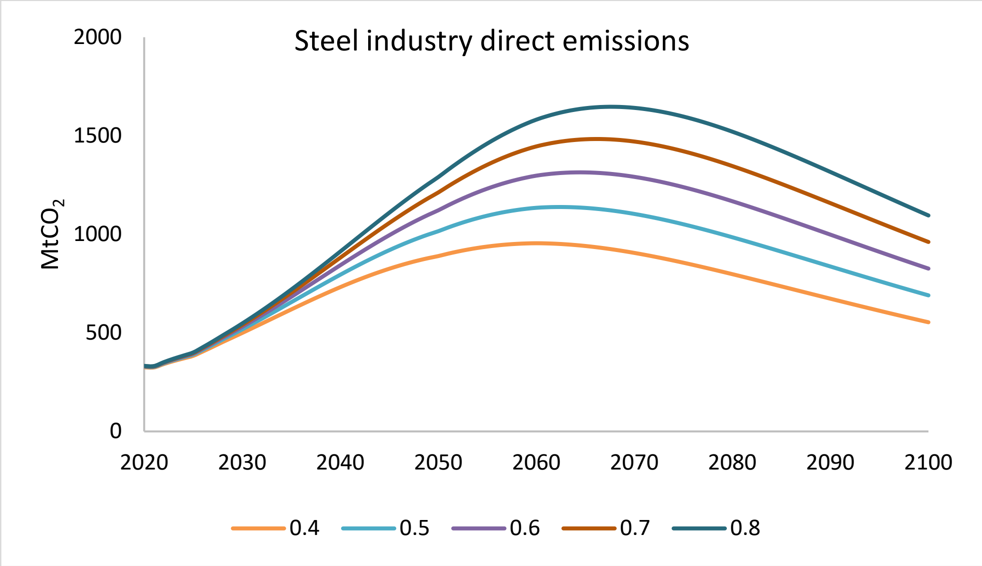
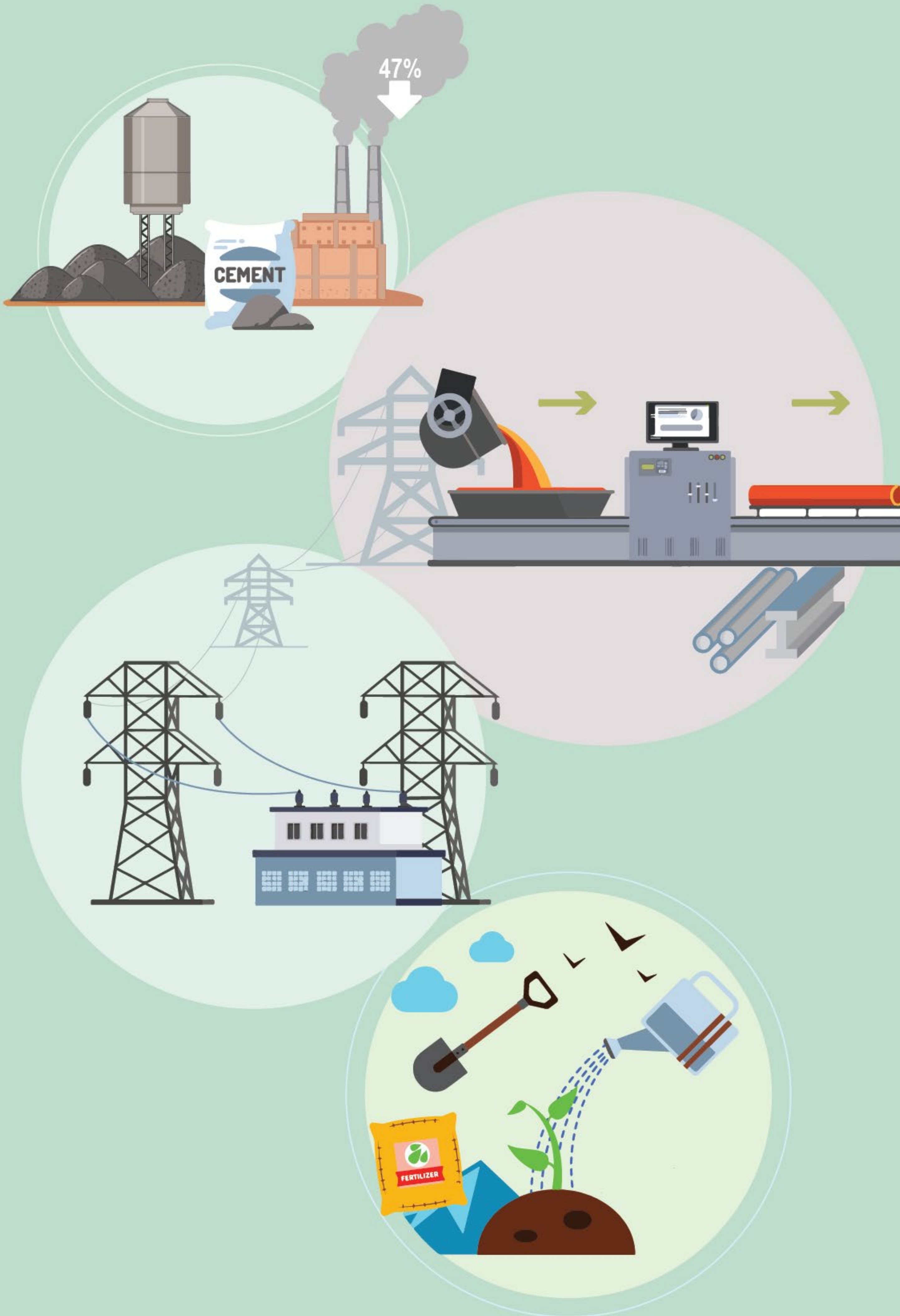


Figure 3: Reference scenarios for the steel industry based on different per capita saturation levels

A bottom-up demand estimation framework would help in determining potential saturation levels; however, there aren't any such models going up to 2050 or beyond for India, covering all sectors. This is because it would be a very challenging thing to do. Important frameworks such as 'decent living standards' (DLS) offer benchmarks of material and energy consumption to achieve a decent quality of life within planetary boundaries (Rao & Min, 2018) and have helped shape the SAFARI model. DLS is, however, based on assumptions of an egalitarian society where everyone's demands are as per household-level and community-level thresholds. As much as we aspire for a world without inequality and driven by sensible consumption, it will not be reflective of the probable reality, especially for a growing country (Millward-Hopkins, 2022). Even in analyses using the DLS framework, estimating energy and emissions in sectors unaffected by DLS benchmarks is done via SSP-based macroeconomic assumptions (Rao et al., 2019). Without a bottom-up demand estimation framework, forecasting a country's demand for decades into the future is as much of an art as a science. However, there are some models that partly do demand-oriented modelling. Rumi projects bottom-up demand up to 2030–31, particularly for the housing sector (Prayas Energy Group, 2021), and the SAFARI model (CSTEP, 2021) projects bottom-up demand arising out of meeting specific development goals such as housing, food, and healthcare. For example, SAFARI estimates annual demand for cement and steel to cater to the construction of houses, hospitals, and schools, but demand from construction of other buildings or infrastructure is assumed to be driven by GDP growth. Using such concepts of bottom-up estimation, we can arrive at potential saturation levels for India in consultation with policymakers and industry experts. This should be one of the important steps in the net-zero modelling process.


47%
CEMENT
FERTILIZER

3. Industrial Decarbonisation

The industry sector currently contributes to around 32% of the country's total emissions according to the SAFARI model. While the power and transport sectors are geared up to decarbonise rapidly in the near term, the same cannot be said about the industry sector. Moreover, the industry sector is set to grow substantially to meet the growing demand of society—owing to increasing population, rising income levels, and urbanisation rates. It is evident that going forward, the role of the industry sector in determining India's net-zero pathway will be critical. In this section, we will take a look at decarbonisation strategies and discuss their potential in key heavy industries.

3.1. Cement

Cement is one of the hardest-to-abate industries, contributing to about 20% of the industrial sector's emissions. Emissions due to energy, that is, fuel burning constitute only about 40% of the cement industry emissions. The remaining is process emissions from the calcination process in the manufacture of clinker (Markewitz et al., 2019). The Indian cement industry has assimilated state-of-the-art technology, and the plants are comparable to the world's best in terms of technology and efficiency. The average thermal energy consumption is 3–3.1 GJ/t of clinker, which is very close to the best available technology performance (2.9–3 GJ/t clinker)(WBSCD, 2018). There is a further reduction potential of about 10%–25% to reach the thermodynamic minimum range (IEA, 2018). Considering that efficiency levels are already high, the final 10%–25% reduction will be more difficult (and expensive) to unlock.

Given the high temperature requirement (1300°C–1500°C) of the cement manufacturing process, waste heat recovery is an effective strategy to reduce the overall energy requirement. Indian cement plants have been increasingly adopting waste heat recovery systems (WHRS). Potential fuel-cost savings, in light of surging coal and electricity prices, make WHRS a lucrative option. The Perform, Achieve, Trade (PAT) scheme has also been instrumental in accelerating the WHRS lever in India. The full potential of waste heat recovery in India is a 27%–30% of reduction in electrical intensity (WBSCD, 2018). The combined abatement potential of improving energy intensity and waste heat recovery is ~11%–12% (65 $MtCO_2e$ in 2070).

The cement industry has been predominantly fuelled by coal and petroleum coke in India. A wide portfolio of low-carbon biomass and waste-derived alternative fuels are also available, which have been successfully adopted by many cement manufacturing units. The thermal substitution rate (TSR) or alternative fuel and raw material utilisation (AFR) in the Indian cement industry reached 4% in 2017 (WBSCD, 2018). Several policies are expected to drive this further: solid waste management rules, 2016, which mandate at least 5% TSR in cement kilns with fuel derived from municipal solid waste (Solid Waste Management Rules, 2016), and guidelines from the Central Pollution Control Board (CPCB, 2017) and the Ministry of Housing and Urban Affairs (MoHUA, 2021), which recommend the use of hazardous, agricultural, and municipal wastes in suitably located cement kilns. The potential TSR in the Indian cement industry is estimated by the CII to be 25% by 2025, out of which 57% is expected to be from municipal solid waste (MSW) and 34% from biomass (CII, 2016). The abatement potential of the TSR lever is 6%–7% (37 $MtCO_2e$ in 2070).

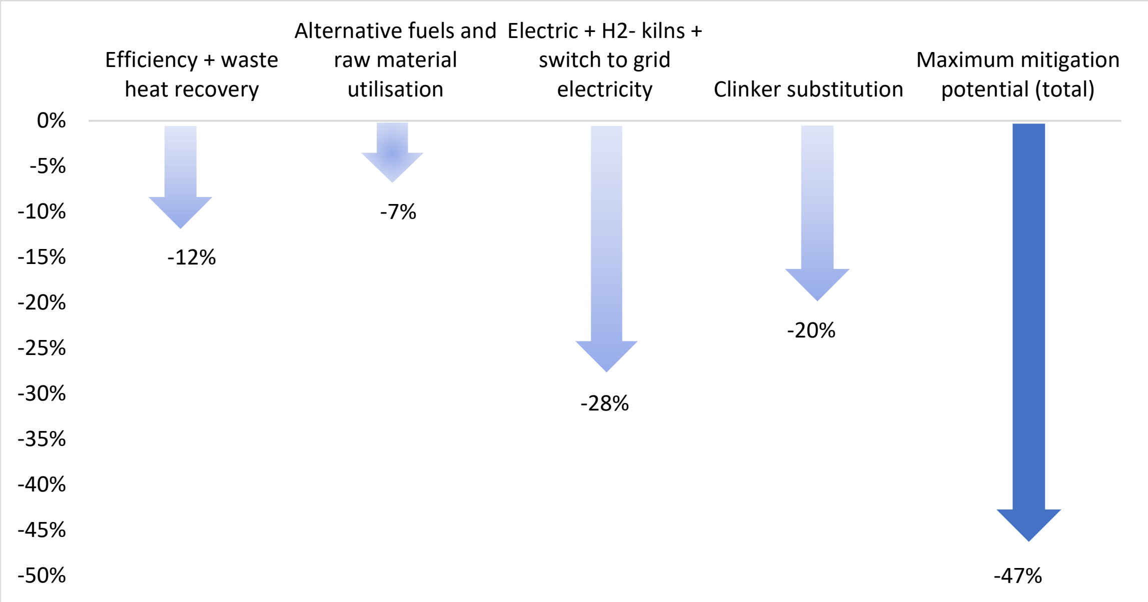


Figure 4: Mitigation potential of different levers in the cement industry (source: authors' analysis)

Electric cement kilns capable of meeting high temperature requirements for cement manufacturing are currently under fairly advanced stages of R&D (International Cement Review, 2022). We find a three-fold increase in electricity consumption if 20% of cement production is to be via electric kilns[7]. Indirect electrification via electrolytic hydrogen-fuelled cement production also results in similar levels of increase in electricity consumption[8]. The electrification route for low-carbon cement will be an energy-intensive one. Therefore, it will not be a good prospect unless via renewable energy (RE) sources. At present, around 20% of the industry's electricity requirement is met by the grid and the remaining is generated in captive power plants—which are primarily running on coal, adding to the emissions. The combined abatement potential of electric and electrolytic hydrogen-fuelled cement kilns (assuming 10% cement production for each route and 25% via alternative fuel) in combination with a complete switch to grid-based electricity is 27%–28% (159 $MtCO_2e$ in 2070).

The maximum mitigation potential for energy emissions from cement manufacturing is ~25%–26% and can go up to 34% if we factor in electrification (direct and via hydrogen).

Process emissions from calcination of limestone in clinker manufacture is the chief hard-to-abate component in cement. At best, commercially established clinker substitutes such as slag and fly ash can only substitute half of the clinker. There are alternative binding materials that can wholly replace conventional limestone-based clinker—belite and calcium sulphoaluminate-based clinker—which offer a significant reduction in process emissions intensity, ranging from 12%–63%. However, their versatility and applicability do not appear to be as universal as conventional cement, and they are in the early stages of R&D (IEA, 2018; International Cement Review, 2020). Therefore, the maximum mitigation potential with

[7] Assuming energy efficiency to be the same as thermal kilns
[8] Assuming 48 MWh/T of H_2

clinker substitution using commercially established substitutes, bringing down the clinker-to-cement ratio to 50% from the present 70% levels, is 20% (114 $MtCO_2e$ in 2070).

Figure 4 summarises the impact of all the strategies discussed[9]. Even considering an early and aggressive implementation, which includes shifting to 100% alternative fuels, the cement industry will still be emitting at least 300 $MtCO_2e$ in 2070 (in comparison to the reference case of 570 $MtCO_2e$).

3.2. Steel

Steel is a critical input for buildings, infrastructure, and machinery and tools, all of which are expected to grow significantly to support the developmental goals of our growing economy. Steel production is an energy- and emissions-intensive process. There are several production processes that are established in India, among which blast furnace-basic oxygen furnace (BF-BOF) constitutes the dominant share followed by Electric Arc Furnace (EAF) and Induction Furnace (IF)(Ministry of Steel, 2017). The scale of the steel industry is rather heterogeneous in India, ranging from large integrated steel plants (ISPs) that produce high-quality steel to small mini-mills that cater to local steel needs. The ISPs typically go the conventional BF-BOF route, while medium- and small-scale units employ EAF and IF (TERI, 2022). Going forward, India's choice of production processes will be the principal determinant of steel industry emissions and, therefore, achieving net zero.

The share of BF-BOF is likely to increase in the near-medium term. The National Steel Policy, 2017, also projects an increase in the share of the BF-BOF process until 2030 (Ministry of Steel, 2017). Historical precedents in developed economies suggest that there will be a shift to EAF-driven steel-making from BF-BOF only when the demand starts to saturate (McKinsey, 2019). At the same time, BF-BOF plants are long-living assets that are hard to decarbonise. Mitigation measures in BF-BOF such as improving average efficiency to the best available technology levels (Krishnan et al., 2013) and adding electrolytic hydrogen as an auxiliary reduction agent to reduce coke consumption (Yilmaz et al., 2017) can mitigate up to a maximum of 50% emissions.

Considering that 35%–40% of steel production is currently via EAF, could India then leapfrog to the EAF stage? EAF is suitable for making steel from iron ore and scrap and can be fully decarbonised with electrolytic hydrogen (Gielen et al., 2020). According to a recent study by TERI, H_2-based EAF is cost-competent in comparison to BF-BOF with CCUS and natural-gas-based EAF and can get cheaper with falling H_2 prices (TERI, 2022). Indeed, this is a route that is extremely electricity intensive and will require significant capacity addition in the power sector. To put this in perspective, 100% steel production via H_2-EAF would require an additional 580 GW (+20%) operating capacity in 2070[10]. A cluster-based approach to EAF would help achieve economies of scale and optimal use of land and raw material for EAF units as planned in the steel policy. It can also help with the deployment of economical

[9] The percentage mitigation potential of individual levers/strategies does not add up to the total mitigation potential. This is because the levers are not independent; they impact each other—for instance, clinker substitution reduces the overall thermal energy requirement, which reduces the mitigation potential of the efficiency lever when in combination with clinker substitution.

[10] Assuming all electricity is provided from a low-carbon grid

decentralised clean energy solutions and hydrogen electrolyser hubs to meet burgeoning demand.

On the other hand, our preliminary analysis shows that if the plan as per the national steel policy is to increase the share of BF-BOF to 65% (from the current share of 55%) until 2035 and then phase out to 0 even by 2070, there will be stranded assets to the tune of 100 MT capacity (capital investments worth USD 64 billion (2019)) of BF-BOF steel plants[11]. Of course, attaching CCUS is an option to avoid operational BF-BOF plants from becoming redundant. Even without considering the storage and/or utilisation challenges of the captured carbon, it may just prove to be a very expensive and energy-intensive Band-Aid measure in the absence of a long-term plan. These aspects highlight the need for a strategic road map for the steel sector that aligns with the net-zero emissions plan.

3.3. Fertiliser

Our analysis shows that nitrogen-based fertiliser demand and production in India saturates at around 45–50 Mt by 2050 (assuming full self-sufficiency). While emissions contributions of this industry are not very significant (<5%), it is a strategic sector worth discussing because it is a critical input for agriculture (and food security). The fertiliser industry is dependent on imported natural gas as its primary fuel and feedstock. It is widely considered the low-hanging fruit to kick-start the hydrogen economy. Electrolytic hydrogen produced from low-carbon grid electricity or captive RE generation can steer the Indian fertiliser sector to net-zero emissions. This is possible with an additional 10 GW operational capacity from the grid[12].

The recently approved exclusive subsidy policy for Talcher Fertilizers Limited for urea production through coal gasification (PIB, 2021) is a strategic decision made to reduce transport subsidy and import dependence on urea and natural gas, targeted at its unit located in East India where there is no other urea manufacturing unit. However, going forward, the decision to incentivise coal gasification in the fertiliser industry should be scrutinised, given the falling prices and mature technology of electrolytic H_2. The carbon pricing approach could be a possible solution to avoid any policy incoherence with net-zero plans. Carbon pricing is discussed in detail in Section 6.

3.4. Electrification of industry: A note on captive generation

Industrial electricity tariffs are higher and used to cross-subsidise other sectors' electricity consumption. Higher tariffs, along with the unavailability of reliable power, over time have resulted in industries, especially large-scale and electricity-intensive ones, to favour captive generation over sourcing from the grid. To illustrate, the average share of grid electricity in aluminium, fertiliser, and cement sectors is 5%, 10%, and 20%, respectively. The remaining electricity is generated in captive power plants, usually co-located and powered by fossil fuels (coal or diesel). The captive plants are typically connected to the grid to sell surplus generation. This, according to experts, has in turn resulted in the increased financial vulnerability of electricity distribution companies (DISCOM)—a combination of loss of possible revenue from industrial consumers and loss from surplus grid-connected capacity,

[11] Assuming a lifetime of 50 years

[12] Assuming all electricity is provided from a low-carbon grid

resulting in low thermal plant load factors (PLFs) and further inefficiencies (Dasgupta, 2020). Since the grid is going to be increasingly powered by renewables because of their falling prices, we find that fully switching to grid-based electricity has an abatement potential of up to 90% for the aluminium industry and 15% for the cement industry. While a complete switch may not be realistic, with a reliable supply of electricity and the rationalisation of industrial electricity tariffs, significant abatement can be achieved in the industry sector with the increasing share met by the grid. For suitably located large-scale plants, RE-based captive generation may also be considered. One possible enabler for reducing the emissions from captive generation could be carbon pricing, which will nudge industries to go either the grid route or the 'RE for captive generation' route.

3.5. Demand-side management

As evident, bringing down emissions in the industry sector is a wicked problem that cannot be solved only at the industry level. The cement and steel industries have complex interlinkages with other sectors—most obviously the buildings sector. Apart from the population and urbanisation drivers, there is also the (arguably the most over-cited) fact that most of the buildings that will exist in 2040 are yet to be built (IEA, 2021b). In other words, India is going to be under construction for the foreseeable future. Demand-side interventions will go a long way in cementing the low-carbon future of cement and steel industries. One such possibility is the widespread adoption of alternative-materials-based masonry that requires 20%–25% less cement for binding compared to burnt clay bricks in the construction sector (Bansal et al., 2014). Material use-efficiency in design such as the use of precast concrete and steel, post-tensioning, and avoidance of over-design could bring in additional mitigation for cement and steel industries. Further, design choices such as enhanced sharing spaces and consolidation of urban utilities for more intensive use of buildings can also potentially reduce material requirements (Watari et al., 2022).

India has a steel and aluminium (non-ferrous metals) scrap recycling framework (Ministry of Mines, 2020; Ministry of Steel, 2019) and a draft resource efficiency policy (MoEFCC, 2019). They signify a clear policy shift towards a 'circular economy,' which is expected to strengthen the recycling and scrap value chains, particularly for high demand and energy-intensive metals such as steel and aluminium. Energy savings of up to 60% are possible when metals are produced from scrap rather than raw ores.

A dynamic material flow analysis bottom-up modelling of key sectors will help get a handle on better evaluating the demand-side measures. For instance, SAFARI is able to estimate the impact of shifting to natural farming on fertiliser demand and consequently emissions as agricultural land and fertilizer inputs are captured to a fair amount of detail. To reiterate the message from the section on demand saturation, bottom-up modelling is necessary to understand emissions drivers and mitigation interventions, which are vital for framing net-zero scenarios. Econometrics, which is dependent on historical shares, may not be able to capture any future disruptions in demand. For example, aluminium demand and scrap availability will behave differently in the future with the explosive growth and domestic manufacturing expected in RE and battery storage, which have a high aluminium intensity (IEA, 2021a).


~2.2 $GtCO_2e$
300 $MtCO_2e$
by 2070
65 GW
by 2050
Saving
5 million
hectares

4. Power Sector

Power is one of the most discussed sectors in the context of mitigation and net zero. Most power sector models used in discussions are driven by a least-cost logic and use similar assumptions on macroeconomic trends and technology costs. No surprises that the results have been similar too. All studies have consistently found that India is well-positioned to achieve its original NDC targets of fossil-free generation and capacity in 2030 (Chaturvedi et al., 2021; CSTEP, 2021; du Can et al., 2019; Thambi et al., 2018). SAFARI projections show that fossil-free and renewable energy (RE) targets as per the enhanced NDC can also be achieved in the base case.

However, in 2070, we find that despite manifold increase in RE capacity (2670 GW), and storage (3280 GWh) owing to falling costs, the power sector will still emit ~2.2 $GtCO_2e$ because of the continued prevalence of gas and coal plants in the base case. In other words, achieving net zero would require significant CCUS installation (which increases auxiliary consumption of electricity in coal and gas plants to an average of 30%–35%) worth USD 620–800 billion (2019) as per our preliminary analysis[13]. How much carbon pricing will be required to justify that in a cost-optimised power system?

RE is in the spotlight of India's power sector policy. Policies such as revamped production-linked incentives (PLI) to boost domestic manufacturing (PIB, 2022), transmission charge waivers (Ministry of Power, 2018), and purchase obligations(Ministry of Power, 2022) among many others have led to record investments in RE (World Economic Forum, 2022). However, RE is not without challenges. The intermittency issues will pose a significant challenge at least until grid-scale battery storage systems are installed with capacity proportionate to RE operational capacity. Solar, wind, and battery technology in particular have high critical mineral intensity (IEA, 2021a) requiring copper, cobalt, and lithium, which could make us largely import-dependent (Ministry of Mines, 2020). Land conflicts are already affecting planned large solar and wind parks, which may exacerbate with more competition from urbanisation and agriculture (M. Agarwal, 2021). While we do not think any of these challenges are unsurmountable, acknowledging them will help with drafting a more robust strategy, which is inclusive of more options such as nuclear energy along with renewables.

India has a robust nuclear power programme that goes all the way back to 1948. India has a 7.48 GW installed capacity of nuclear energy (PIB, 2022), out of which 2 GW is from imported reactors and the remaining is from indigenously designed reactors. If not for the worldwide public and political backlash following the Fukushima incident, nuclear power could arguably have played a more significant role in India. There are plans and proposals at various stages to install around 65 GW of nuclear reactors based on light water technology (imported + domestic) as of today (World Nuclear Energy, 2022). In parallel, the department of atomic energy (DAE) has also been unwaveringly pursuing the 'three-stage' atomic energy plan as chalked out by Dr Homi Bhabha in 1954 to transition to thorium energy in the long term. We have evaluated the three-stage programme in detail and find that upon full implementation,

[13]Assuming CCUS in the power sector (retrofitting and for new plants) starts in 2050 at an annual learning rate of 0.1%

at least 150–200 GW of nuclear energy at very low fuel costs[14] is a possibility by 2100, starting from the 2050s (CSTEP, 2019)[15]. Using the SAFARI model, we ran a scenario to simulate the full implementation of the 65 GW of planned and proposed reactors by 2050 and the three-stage atomic energy plan beyond 2050. Preliminary analysis suggests that a cumulative emissions reduction of 10% is possible from 2020 to 2100—translating to around 300 $MtCO_2e$ reduction in 2070, with insignificant changes in total cumulative system costs[16]. There is also a potential land saving of around 5 million hectares.

Even with grid-scale battery storage systems, the intermittency and seasonality-induced issues of RE may persist. Currently, with ~100 GW of installed RE capacity, coal- and natural gas–based power plants are operated in a flexible mode to manage intermittency. To enable greater integration of intermittent renewables into the grid (necessary to achieve the net-zero 2070 target), low-carbon and flexible sources are necessary. Could nuclear energy play a role in this respect in India? In the conventional merit order, the units with lower operational costs (mostly comprised of fuel costs) are operated at full power (i.e., in baseload) and units with higher operational costs are operated partially loaded, designed to reduce/increase electrical output as required. Nuclear fuel is extremely energy dense and, therefore, cheap, whereas nuclear plant capital costs are high, making nuclear power a traditional baseload supply. Consequently, there is limited global experience of operating nuclear power plants in a load-flexible mode, even though countries such as France and Germany have been doing it for decades. For India, it is obvious that nuclear energy has not reached the scale for it to be considered a dispatchable source. However, we have interesting long-term options to consider to balance a high RE grid.

One such option is the coupling of a nuclear reactor with a heat energy storage system. A portion of the heat generated by the fast reactor will be stored in the thermal energy storage system, which can then be converted to electricity, and flexibly dispatched as per the grid requirement. Such a design potentially offers a solution where nuclear energy can operate flexibly while not compromising on its economic viability (MIT Energy Initiative, 2018). One such prototype design of the Natrium technology is expected to be commercial by the late 2020s—it is a 345 MWe sodium-cooled fast reactor, which can provide up to 500 MWe (+45%) with the storage system for more than 5.5 hours as per requirements (Terrapower, 2022). It has been plugged as a key element in the net-zero plan of the United States. Another possibility is the molten salt breeder reactor (MSBR), an advanced reactor design pursued by the DAE for the last stage of the three-stage programme. There are simulation studies that demonstrate the safe operability of the reactor design in the load-following mode (Chen et al., 2022; V. Singh et al., 2017). Furthermore, a thorium-fuelled MSBR design meets many of the future goals of nuclear energy—improved sustainability, higher efficiency, inherent safety, low-pressure operations that do not require expensive containment, and waste reduction (Elsheikh, 2013).

[14] The idea of the three-stage plan is that the spent fuel of one stage is used as a resource for the subsequent stages based on a closed fuel cycle.

[15] These are conservative estimates, assuming the operational and under-commissioning first-stage reactors and reprocessing capabilities. If more stage 1 (PHWR) reactors and proportionate fuel reprocessing capacity are there to set the ball rolling, the total capacity will be even higher.

[16] Costs of nuclear energy are inclusive of waste management and decommissioning.

Exponentially falling RE prices and conventional merit order based on the lowest marginal costs have been driving the mainstream narrative in energy and modelling spaces in India. At the risk of sounding provocative, this might be a case of seeing only a part of the system, which is akin to the parable of 'blind men and the elephant,' particularly in such a long-time frame. Given the net-zero goal, continued reliance on less expensive fossil-based power sources for baseload and flexible energy could prove to be a huge financial burden as stranded assets in the future. With the increasing integration of RE to the grid, flexible load will become more valuable than baseload, which will need to be reflected in the cost-based logic of models. The RE system costs with rising competition for critical minerals and other resource constraints, such as land, will be more dynamic (Leader et al., 2019). We need a framework and a research agenda in the energy modelling space that take into account these factors.

Electrification is a major decarbonisation strategy in other large sectors such as transport and industry. This means that the role of the power sector is going to be even more crucial in the net-zero emissions plan. Well-established integrated assessment models (IAM) have been and are imperative to inform policy vis-à-vis a cost-optimal power supply system. IAMs are models that typically assume perfect foresight while a strategy to get to net zero in such a long-time frame will be affected by deep uncertainty. We strongly feel that the modelling space should be complemented by dynamic simulation models that enable scenario planning, consider real-world decision-making, and take into account multiple futures to identify robust and adaptive actions in the power sector and other sectors as well. Our ultimate objective with the SAFARI model is to enrich the modelling environment to this effect, and for that, we welcome our peers to come up with tough questions that we can explore together. The pursuit of a net-zero strategy, particularly for the power sector, is indeed a complex problem, the solution to which requires all kinds of perspectives to see the complete picture of the proverbial elephant.

5. LIFE: Lifestyle for Environment

In its updated Nationally Determined Contributions (NDCs) submission, India has committed to promoting sustainable lifestyles based on traditional Indian values of conservation and moderation in consumption (Government of India, 2022). Behaviour and lifestyle certainly impact the environment, and to estimate these impacts, we need a model that looks in detail at the demand side (end-use sectors) of the economy. The Sustainable Alternative Futures for India (SAFARI) model projects demand in agriculture, transport, buildings, and industries, driven by population, GDP, and Sustainable Development Goals (SDGs) targets such as food for all, housing for all, and so on (Ashok et al., 2021; CSTEP, 2021; Kumar et al., 2021). Here we use the SAFARI model to analyse some behavioural shifts and their implications.

As a developing country, India's current per capita consumption levels are below the global average, with 27.9% of the population still considered to be in multidimensional poverty according to the Global Multidimensional Poverty Index 2021. India is ranked 133 out of 190 countries, with a Human Development Index (HDI) score of 0.63. Until at least basic human developmental goals are achieved and a decent quality of life for all is on the horizon, it will not be fair to consider any radical reductions in consumption. Therefore, the behavioural 'shifts' in consumption that we will explore are about ensuring that we as a country do not aspire for overconsumption lifestyles of the West. This is crucial if we are to meet our development goals without exceeding planetary boundaries. Further, behavioural shifts in some sectors can help avoid otherwise costly transitions needed to reach net-zero emissions.

5.1. Diets and agriculture

Dietary choices impact health and the environment. Studies have shown that a shift to a healthier diet most often results in better environmental outcomes too (Clark et al., 2019; Kim et al., 2020). For example, reduced consumption of red meat is shown to reduce both disease risk as well as the GHG footprint. In India, which has one of the lowest per capita levels for meat consumption, the largest dietary contributors to GHG emissions are dairy products, followed by plant-based foods. Crop cultivation can be environmentally unsustainable too as it leads to excessive exploitation of groundwater (Famiglietti, 2014). Food systems, therefore, need to be managed to ensure sufficient nutrition and health while also remaining environmentally sustainable. Here, we explore a few dietary scenarios for India (Table 2), all of which assume that food and nutrition security are not compromised.

Table 2: Dietary choice scenarios simulated using the SAFARI model

	Reference Scenario	**Millets Scenario**	**High Meat Scenario**
Description	Meet food security, continue today's dietary patterns and trends	Meet food security, but half of the rice in our diet gets replaced with coarse cereals by 2050	India's per capita meat consumption increases to reach today's global average by 2050

Consumption of food grains/capita/year	186 kg	186 kg	186 kg
Share of rice in food grains by 2050	40%	20%	40%
Consumption of meat/capita/year by 2050 (excluding seafood)	20 kg	20 kg	60 kg
Implications (compared to the Reference Scenario)	-	Annual savings of ~300 billion cubic metres of water and 50 $MtCO_2e$ as rice methane emissions	Increase in annual livestock methane emissions by almost 300 $MtCO_2e$ and negative impacts on food security because of competition for feed

In the Reference Scenario, we assume that food security is maintained and the share of rice, wheat, coarse cereals, and pulses in the food grains that we consume remains the same as today. In this scenario, groundwater exploitation continues, resulting in increased energy demand (deeper and deeper bore wells) and the eventual possibility of running out of groundwater for irrigation (and other needs such as drinking and industries).

In the Millets Scenario, therefore, we assume a reduction in the share of water-intensive rice from 40% (today) to 20% in 2050, which is replaced by coarse cereals such as millet. This kind of dietary shift is expected to reduce the stress on groundwater extraction, as well as improve nutrition/nourishment. Coarse cereals, however, have a lower yield than rice, so promoting this dietary shift should be accompanied by a push for the production of high-yielding varieties of millet. This scenario is also expected to have lower rice methane emissions.

The High Meat Scenario is modelled as an unlikely doomsday scenario in which we aspire for a fundamentally different dietary pattern. Even reaching today's global average for per capita meat consumption would be highly unsustainable for India, especially assuming we try to meet it domestically. This is because of the competition for food grains from livestock feed. In the High Meat Scenario, the demand for food grains for livestock feed more than doubles, constraining the limited arable land and freshwater available for agriculture. This scenario would also more than double livestock methane emissions. In fact, to reach such high meat production levels, we may even have to switch to more production-intensive livestock-rearing practices, currently pursued by the global North, which will result in much more emissions and land-use change.

5.2. Mobility choices

India's passenger transport sector today is quite efficient. Our overcrowded buses and trains result in reduced fuel consumption (and emissions) on a per passenger kilometre (pkm) basis. Further, India has one of the lowest levels of car ownership in the world, at 22 per 1000 population. However, these aspects of low per capita energy demand and emissions are because of the lack of affordability and access. As India develops and incomes rise, occupancy will decrease and car ownership will increase, but preventing unsustainable consumption should be our focus.

In India's cities today, the mode share for public (not including cabs and three-wheelers) and non-motorised transport (NMT+PT) is between 40% and 60% depending on the size of the city and its demographic characteristics. These shares are expected to reduce over time (in the Reference Scenario) based on historical trends, but even if we are able to just maintain these shares through proper planning and infrastructure, annual emissions savings of around 30 $MtCO_2e$ can be achieved in 2070 according to the SAFARI model (see Figure 5). A recent study on behavioural shifts showed that people are willing to shift to public transport even if it costs up to 20% more as long as travel time and convenience (seamless connectivity) are improved (CSTEP, 2022a).

For intercity passenger travel, the share of railways has been decreasing from around 30% before 2011 to 17% now and is expected to decrease further as people prefer air and road over rail. However, if we can raise the share of rail back to 30% through behavioural nudges, 90–100 $MtCO_2e$ emissions savings can be achieved per year in 2070. This is because train travel is a lot more efficient in terms of fuel consumption and likely to be fully electrified (and net zero) by 2030. This will reduce the need for costly decarbonisation of the aviation sector via inefficient synfuels or biofuels that may impact land use.

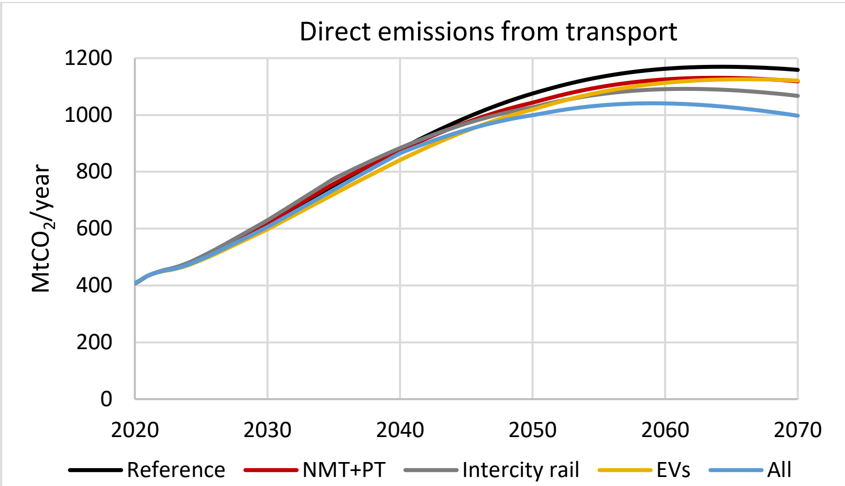


Figure 5: The transport sector emissions under various behavioural shift scenarios

Another behavioural shift useful in the transport sector would be to purchase and use electric vehicles (EVs). While this may be more of a technology shift rather than a behavioural shift, we include it here for comparison nevertheless. If all two-wheelers and 30% of private cars are electric by 2050, annual emissions savings (not including electricity emissions) in 2070 would be around 40 $MtCO_2e$. Purchase price is the biggest determinant of electric vehicle uptake, so via subsidies and other cost reductions over time, this scenario may be achievable. Because we have not included electricity emissions here, the abatement potential of EVs might seem exaggerated. There is quite a bit of uncertainty on how quickly the grid will decarbonise, so the potential for EVs to bring us to net zero will depend on that (Abdul-Manan et al., 2022).

5.3. Housing and appliances

The residential sector contributes to GHG emissions directly via the use of cooking fuels and indirectly via electricity use and construction materials. Direct emissions (from cooking) are only ~2% of India's total GHG emissions. The residential sector contributes to ~30% of India's electricity demand and 50%–60% of the cement demand. Reducing any of these contributions (or at least not further increasing) through behavioural shifts can be beneficial towards achieving our climate goals.

Direct emissions from the residential sector are predominantly from the use of fossil fuels in cooking. Shifting completely to electric cooking by 2070 (in both urban and rural areas) will result in emissions savings (without including electricity emissions) of around 100 $MtCO_2e$ per year. The annual residential electricity demand would increase by more than 300 TWh.

Indirect emissions come from construction (production of cement, steel, etc.) and electricity usage for appliances. If the average size of a house of middle- and high-income groups increases to 200 m^2 (from today's average of <100 m^2), there will be ~40% increase in cement demand for housing and subsequent emissions. Aspiring for larger houses beyond a point (towards Western standards) might not be a sustainable way forward for India, considering the population density and other constraints.

Buying and using energy-efficient appliances can have a significant impact on energy demand and emissions. India already has the successful model of UJALA scheme that achieved massive energy savings and accelerated the growth of the domestic lighting industry. A complete shift to energy-efficient appliances could help save more than 1600 TWh of electricity demand annually in 2070 (compared to a reference scenario), which in turn translates to emissions savings of almost 1 $GtCO_2$ per year (based on a reference scenario power sector grid in 2070, which would be ~80% fossil-free in terms of capacity).

6. Macroeconomics and Carbon Pricing

We have so far discussed various low-carbon interventions and how they can be modelled, as well as their implications on emissions trajectories. In this section, we discuss how market mechanisms such as carbon pricing can enable these interventions and explore their implications on the Indian economy.

A bill recently passed in the Lok Sabha (The Energy Conservation (Amendment) Bill, 2022) mentions the accelerated deployment of non-fossil fuel energy sources (through enforcement mandates to meet a specified part of demand through non-fossil fuels in sectors such as transport, commercial buildings, and industry) and the establishment of a voluntary carbon market. An earlier document (Bureau of Energy Efficiency, 2021) published by the Ministry of Power also discusses a strategy to help the Perform, Achieve, Trade (PAT) scheme (energy savings–based trading scheme to encourage improved energy efficiency in select sectors/industries) transition to a voluntary carbon market, both to encourage faster emissions reduction and help overcome some of the issues faced by the PAT scheme (for example, an oversupply of energy efficiency certificates). In this context, it is important to look at the successes and failures of different explicit and implicit carbon pricing mechanisms in India and abroad and consider how the implementation of a carbon trading scheme and/or explicit carbon tax could pan out in India.

6.1. Causal loop diagram: Carbon pricing

We attempt to address some of the concerns with carbon price implementation and flag certain aspects that should be kept in mind while designing a carbon pricing policy. We look at carbon pricing through a systems lens; Figure 6 is a causal loop diagram, calling attention to the potential impacts of carbon pricing and depicting balancing (negative feedback loops) and reinforcing loops (positive feedback loops)[17].

B1: Putting a price on carbon increases the cost of fossil fuel production, thereby increasing the price of fossil-fuel-intensive commodities such as fossil fuel electricity. This reduces the demand for those commodities and eventually decreases emissions, getting the system closer to target emissions (identified while imposing the carbon price).

B2 and B4 represent basic demand–price dynamics.

[17] Causal loop diagrams are integral to systems thinking and indicate the causal relationships between dependent and independent variables. For example, population, births, and deaths are interrelated. A rise in the number of births increases population, and population in turn increases births. This is a reinforcing loop and usually leads to exponential growth or decay. In contrast, an increase in deaths reduces population, and an increase in population leads to a higher number of deaths. Thus, this is an example of a balancing loop, which often shows goal-seeking behaviour, leading to S-shaped curves (upon reaching saturating values or goals) or oscillations.

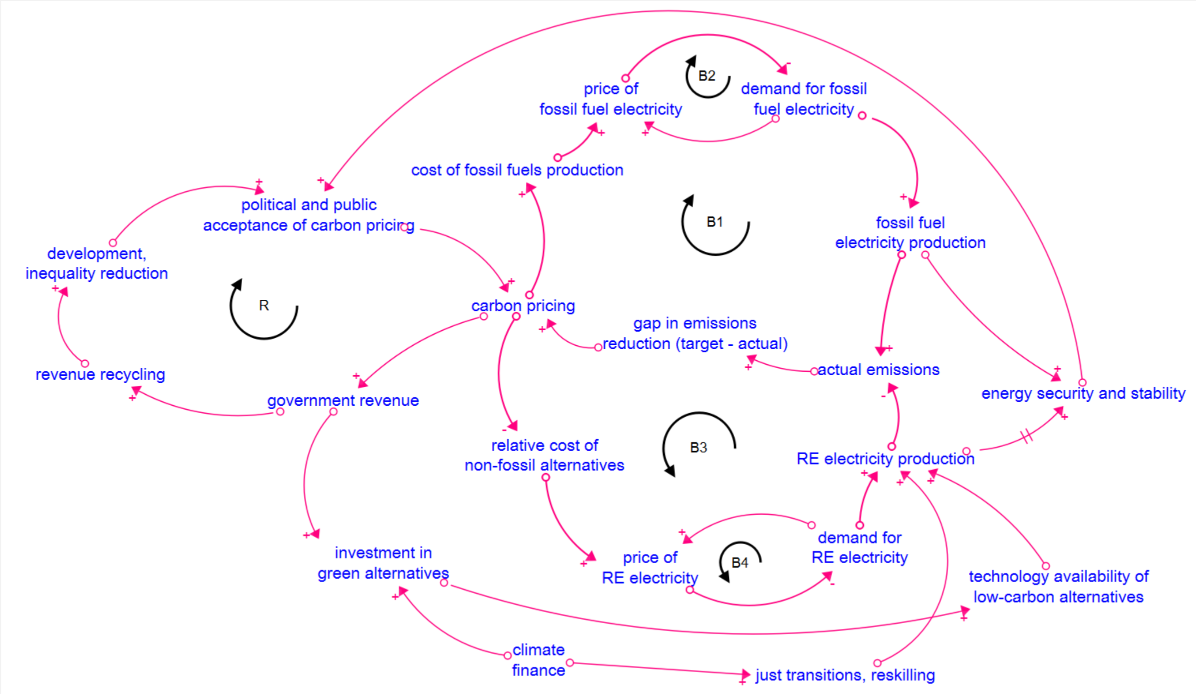


Figure 6: Potential impacts of carbon pricing: A causal loop diagram[18] (source: authors' analysis)

B3: A carbon price would reduce the relative cost of non-fossil alternatives, making them more competitive and thereby decreasing the price of green commodities (such as RE-based electricity). This in turn would increase their demand and production, leading to reduced emissions, once again getting the system closer to target emissions. However, this is contingent on the availability of technologies for the green alternatives, which need investments (either from the government, climate finance, or other avenues).

Once alternatives are available, carbon pricing policies can be much more successful at reducing emissions, as seen in the case of Germany. Carbon pricing was successful in Germany because of the complementary policies that aided the development of solar and wind-based electricity generation capacity (Gugler et al., 2021). CSTEP's modelling study on the economic impacts of low-carbon policies (CSTEP, 2022b) showed that investing in RE such that it accounts for a majority of electricity generation leads to numerous positive economic impacts. The results show that overall GDP could grow an additional 0.16%. Additionally, household income rises, especially in rural areas, which would see an average increase of INR 2,172 in the annual per capita income. So, in addition to making a carbon price more effective, investment in RE and other low-carbon technologies has positive impacts on the whole economy.

R: There is only one reinforcing loop in this system. Carbon pricing would increase government revenue, which can be used to recycle revenue to the more vulnerable sections of society to avoid negative distributional impacts. This would reduce inequalities and improve development, increasing the overall public acceptance of a carbon tax. However, identifying the 'worst-off' sections of society and ensuring they receive appropriate compensation could prove difficult. More robust techniques and associated enforcement

[18] '+' signifies a positive correlation between the connected variables, while '-' signifies an inverse relationship. Balancing (B) and reinforcing (R) loops are labelled.

mechanisms to avoid the disproportional impact on poor households need to be developed when implementing an explicit carbon price. Bolstering the institutions used for the implementation of the public distribution scheme and direct benefit transfers in India must complement the development of a carbon pricing mechanism. Additionally, CSTEP's modelling study (CSTEP, 2022b) found that the imposition of a carbon tax on unrefined fossil fuels would continue to incentivise industries to shift to low-carbon alternatives while protecting poorer households from a higher cost of living.

If the government revenue is not spent on development and inequality reduction and instead used to invest in green alternatives, this would strengthen the B3 loop by making low-carbon technologies available for adoption. Alternatively, climate finance and other sources of domestic and foreign investment will be needed to keep B3 strong.

6.2. Innovation and deep decarbonisation

While carbon prices are expected to incentivise technological innovation and system-wide transformation, carbon pricing policies implemented across the world show little evidence of such innovation taking place (Tvinnereim & Mehling, 2018) when they are not supplemented by other climate policies (Gugler et al., 2021). Instead, they seem to be successful in ensuring the optimal use of established technologies but do not incentivise actions required for deep decarbonisation. For example, the European Union Emissions Trading Scheme (EUETS) managed to encourage significant fuel switching, allowing natural gas to become the dominant fuel in the electricity sector by replacing major coal power plants. However, it has not been able to encourage further innovation and move beyond incremental change. For India, a carbon pricing mechanism that only drives the switch from coal to natural gas would negatively impact our energy security and raise our already high energy import bills tremendously.

In combination with other complementary policies such as targeted support for emerging innovations, restructuring of markets, and strengthening of institutional capacities, carbon pricing can be effective at facilitating transformative change. Carbon prices in Germany worked at increasing the use of RE in the electricity generation sector because RE capacity had already been developed and was available as a result of subsidies.

6.3. Tax versus ETS

Finally, the choice of the carbon pricing tool matters. Theoretically, carbon taxes deliver price stability but compromise on emissions certainty (clarity on the amount of emissions reduction that can actually be secured by the tax). As a country that is still growing and has historically had a relatively smaller contribution to cumulative GHG emissions, India is justified in wanting to focus more on ensuring price stability to enable easier long-term decision-making, particularly for businesses. While that generally points to carbon tax as the better alternative, it may not have to be the only mechanism in place. India already has plans to establish a voluntary carbon market, stemming from the implementation of the successful PAT scheme. A tax in addition to that to ensure revenue generation and price stability and build on the experience gained from administering the coal cess for years could be an option worth exploring to circumvent the need to make a decision between the different carbon pricing tools. For the urgency of climate action required, an emissions trading scheme (ETS) with specific modifications such as a price floor might be more prudent to ensure a balance between price and quantity certainty. India provided INR 14,908 crore in coal subsidies and INR 55,670 crore in oil and gas subsidies in 2020 (Viswanathan et al., 2021). The amount of fossil fuels subsidies has been declining over the 2014–2020 period. Even the complete removal of these subsidies could act as an effective first step towards imposing a carbon tax.

In conclusion,

- There are numerous spillover effects to consider when implementing a carbon pricing policy, especially in India.
- Carbon pricing can play a role in bringing about the required energy systems transformation, provided it is supplemented by other non-market policies, such as investment in cleaner alternatives.
- Additional revenue streams are required to ensure we meet both development and mitigation goals. International climate finance is only one option.
- Energy security concerns should not be ignored, given the incremental nature of carbon pricing's effectiveness.
- Inequality is a major concern for India, and appropriate design options should be considered when imposing a carbon price.
- Picking the right carbon pricing tool or combination of tools is important.
- Fossil fuel subsidies can be completely removed as a first step.

Here are some unanswered questions we would like to highlight for further discussion:

Given the dependence of certain clean technologies (e.g., solar) on key emissions-intensive industries such as iron and steel, could a carbon price actually make clean alternatives more expensive as well? How much of the higher price of iron and steel would affect RE?

Will revenue recycling really work in India? The current range of taxes and duties on petrol and diesel provide significant amounts of revenue to the government. Would a carbon price simply replace these taxes, and if so, would that leave any revenue left to recycle?

Despite the success of the Ujjwala scheme, is there a risk that carbon price would initially encourage people to go back to biomass burning as their primary source of energy as LPG becomes expensive? What about the associated health risks, even in the absence of a significant GHG emissions rise?

7. Conclusions and the Way Forward

In this report, we set out to flag some of the issues around pathways to net-zero emissions for India. Our analyses using different models (SAFARI, SAM multiplier, etc.) have been presented in an attempt to kick-start the dialogue around these often overlooked aspects and provide an initial direction. However, there are questions and concerns that we are still working on to find possible solutions.

Though there is some discourse regarding the saturation of pkm/capita demand in the transport modelling literature, the saturation of demand in key industries such as cement, iron and steel, and aluminium is still a largely unanswered question and remains very difficult to predict using top-down models that tie demand to the projected GDP growth. Instead, we propose a bottom-up approach to estimating demand though that is plagued by issues of data availability and a lack of availability of appropriate models, especially since saturation is dependent on numerous country-specific factors such as demographics, economic structure, expected growth trajectory, and so on.

Determining saturation levels is crucial to determining the extent and types of interventions required as there is, for example, a 250 $MtCO_2e$ difference in emissions between different saturation levels in the transport and cement industries and an almost 700 $MtCO_2e$ difference in the steel industry—in the 'reference scenario' where minimal decarbonisation is assumed.

Industrial decarbonisation is difficult to achieve, and the most discussed option is electrification, both through shifting to grid-based electricity and through the use of RE captive generation plants rather than the currently popular coal-based captive generation plants. However, the risk that this merely redirects the mitigation burden to the power sector, which would then have to simultaneously manage both a large-scale rise in demand from industrial consumers and decarbonisation to actually reduce emissions from a lifecycle perspective, is significant.

The power sector is already facing challenges with respect to decarbonisation. Despite falling RE costs, it is unlikely to help us achieve net zero without CCUS and significantly higher systems costs, that is, without the implementation of carbon prices. The tendency to disregard nuclear energy as a viable option because of public perception is costing us, not least because of the energy security and trade balance implications of relying solely on RE.

Behavioural and lifestyle changes can be a lever to reduce emissions in certain sectors, but there is a dearth of models that look at end-use sectors in detail, thus limiting the analysis of the extent to which behavioural changes can be impactful. However, models such as SAFARI help us to plug this gap and conclude that the evidence of huge environmental and social costs of wasteful overconsumption lifestyles of the West warrant a more cautious, measured approach to achieving development goals and higher standards of living. We observe that, for example, dietary changes have multilevel impacts on emissions, sustainable resource use, and even health outcomes. A recurring theme in net-zero reports is electrification in cooking and transportation, which takes us back to the excessive strain that it could potentially place on the power sector. Behavioural changes in the buildings sector (i.e., the use of more energy-efficient appliances) can reduce the overall rise in energy/electricity demand that is expected as we target net zero.

Market-based mechanisms (i.e., carbon prices) are receiving a lot of attention as potential emissions reduction tools. In Section 6, we discussed the pros and cons of implementing a carbon price in India (whether it is a tax or a trading scheme or the removal of existing fossil fuel subsidies) and the balancing and reinforcing loops that would come into play. However, the answers to some of our questions remain to be worked out. For example, how likely is it that higher prices of iron and steel (as a consequence of being emissions-intensive industries) spill over and make steel-dependent RE technology such as solar electricity generation, for which iron and steel account for almost 60% of production cost, more expensive? Or the potentially regressive consequences of carbon pricing such as the likelihood that it would initially encourage poorer households to shift back to biomass burning and cause health hazards, undoing the success of the Ujjwala scheme as LPG becomes expensive and inaccessible? Would we need to spend even more on subsidies to ensure that LPG remains affordable in the presence of a carbon tax, and do we have the fiscal space for such an expenditure increase? While the argument could be made that carbon pricing revenue could be recycled for this purpose, it is necessary to consider whether it would supplement or simply replace the current range of excise duties and taxes on fossil fuels.

Given the wide range of concerns and questions that need a deeper analysis to deal with the increased uncertainty in many of the net-zero levers, we believe the next step is to engage fellow modellers and policymakers in discussions and workshops (beginning with reviewers of this report) so that India's net-zero strategy is truly well thought out and comprehensive.

8. References

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