Implications of a net-zero target for India's sectoral energy transitions and climate policy

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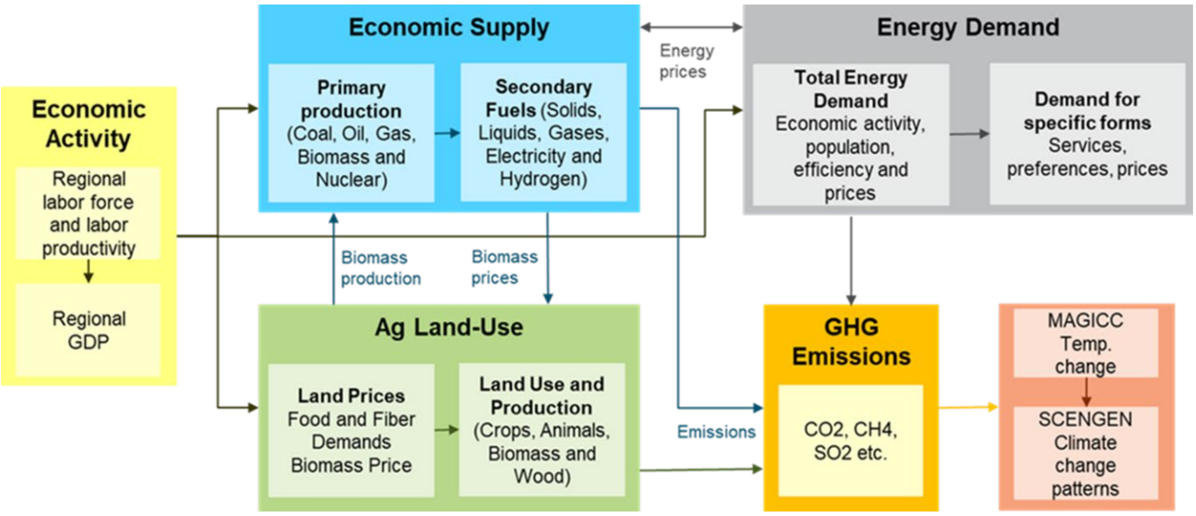
SUPLEMENTARY MATERIAL

Annexure 1: Methodology

M1. Modelling framework – Global Change Analysis Model (GCAM)

We use the modelling framework of GCAM, IIM Ahmedabad version for our analysis. GCAM is a model with a detailed energy sector module and a land use module.

Figure S1: Schematic representation of Global Change Analysis Model (GCAM)



Source: Reproduced from Joint Global Change Research Institute/Pacific Northwest National Laboratory, USA

Figure S1 presents the schematic for GCAM. GCAM is housed at the Joint Global Change Research Institute (USA), and models 32 regions of the world with India as a separate region. GCAM-IIM version was set up at IIM Ahmedabad during 2007–09, and since has been used extensively for India-specific analysis. GCAM-CEEW version is an updated version of GCAM-CEEW, which changes in assumptions related to the transport sector. The electricity generation sector is modelled in detailed within GCAM, as explained in Section 3.2. GCAM-CEEW has a detailed representation of the building and transportation sectors, and an aggregate representation of the industrial sector. Detailed related to modelling end-use sectors in GCAM-CEEW are given in Section 3.3.

GCAM has been an important part of IPCC assessments on modelling related literature, and has been used extensively for national and international exercises since over three decades. Modelling analysis based on GCAM has been extensively published in high impact international journals. GCAM does not model the impact of energy and climate systems on the economic variables like GDP, investments, etc. Currently, GCAM-CEEW is one of in-house models of the CEEW, India. Please refer Shukla and Chaturvedi (2012), Edmonds, et al. (2012), Hejazi, et al. (2013), McJeon, et al. (2014), Iyer, et al. (2015), Kyle and Kim (2015), Chaturvedi and Sharma (2016), Calvin, et al. (2017) among other papers for a detailed overview on the application of GCAM for analysing Indian and global energy and climate policy issues.

The key input variables and parameters across the electricity and end-use sectors are presented in sections below.

M2. Modelling electricity generation growth and technology share

Electricity in GCAM can be generated based on nine fuel types (coal, gas, oil, nuclear, solar, wind, hydro, biomass, combined heat and power), which could be associated with multiple technologies, e.g. photovoltaic (PV) and CSP for solar. The share of any given technology within GCAM is based on its cost relative to the cost of all other technologies, and is modelled based on modified logit formulation (Clarke and Edmonds, 1993). In the electricity sector, the market share of individual fuels is determined endogenously in the model based on the following formulation:

$$S_{i,r,t} = \frac{(SW_{i,r})(P_{i,r,t})^{\lambda}}{\sum_{i}^{n}(SW_{i,r})(P_{i,r,t})^{\lambda}}$$

where SW is the share weight, Pi is the cost of generating power based on a specific fuel i in region r at time t (includes the capital, operation & maintenance, and endogenously determined fuel cost), λ is a cost distribution parameter, and n is the number of fuels competing in the electricity generation sector as stated above. The share weight is a calibration parameter, and the cost distribution parameter regulates the degree to which future price changes will be reflected in fuel shifts. In case of a price levied on emissions (e.g. carbon price), the endogenously determined fuel costs changes for fossil fuels resulting in a different electricity generation mix.

In this formulation, even if a technology has higher average cost than other technologies in the choice set, it will take a small share in the energy mix. This reflects the real world scenario – even if the average cost of a technology is higher, it could still be competitive in some regions due to numerous local factors and constraints. GCAM assumes that the capital cost of existing vintage of stock in any given year is sunk, so these costs do not Figure in the future operating decisions. Production from existing vintage is not subject to competition from new technologies. If in year 2030 total electricity demand is 100 units, 70 units are already generated in 2025[1], and no electricity generation capacity is retied between 2025 and 2030, competition happens between new technologies only for the balance 30 units. Existing vintage plants may be temporarily shut down if input fuel cost is higher than the average revenue from the electricity generated. This could be the case in the event of a high carbon price that increases the generation cost from a coal-based power plant even more than the average revenue, in which case generation from this vintage will be temporarily shut down.

Demand for electricity generation and other forms of energy is determined in the end-use sectors, where the penetration of electricity-based technologies (e.g. air-conditioning) and other-fuel based technologies (e.g. oil-based cars) increases as income increases. Details of modelling demand for electricity and other fuels in the end use sectors are given in separate sections below. Generally speaking, alternative technologies compete with each other for providing energy for any given service in the end-use sectors based on their relative costs and efficiencies e.g. electric cars and oil-based cars compete to provide passenger transportation service in the transportation sector, while LEDs and fluorescent light bulbs compete to provide lighting service in the building sector. As

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[1] GCAM operated in five-year time steps.

demand for electricity grows in the end-use sectors, electricity generation grows to meet this demand.

As India moves towards a higher share of variable renewable energy (VRE), i.e. solar and wind electricity, in the grid, there could be challenges in managing the transition. The current share of VRE in generation is less than 10 per cent. But as this share grows to 15 per cent, 25 per cent, 50 per cent, and even higher in the long-term future, there could be a new set of challenges that the country might face. For addressing intermittency related issues, technical interventions either in form of storage technologies or back up systems like gas based turbines will be required. These technical interventions will have a cost attached to them. We, hence, levy a nominal cost on top of the base solar and wind electricity cost to account for the cost of integration. In the supplementary material, we also present scenario with no integration cost (which simply means that the cost of technical interventions for managing grid integration is borne by the government), and a scenario with a higher integration cost. This sensitivity analysis tells us the criticality of this variable for India's power systems. The assumption related to additional cost of integration levied on solar and wind electricity is given in the supplementary material.

We do not model rooftop solar or decentralised mini-grid based electricity generation and hence in our results the utility related electricity demand might be higher than what is seen in the future if at least some part of demand is met through such off-grid sources. Our results exclude captive generation by industries, which we believe would be a very small fraction of India's total electricity demand in the long run.

M3. Modelling end-use energy sectors

Building sector

GCAM models three end-use energy sectors – buildings, industry, and transportation. In GCAM-CEEW, the buildings sector is disaggregated into commercial buildings, rural residential, and urban residential sectors. Energy service demand is modelled for air-conditioning (high and low efficiency), cooking (biomass, coal, electricity, liquefied petroleum gas (LPG), and natural gas), lighting (fluorescent bulbs, incandescent bulbs, kerosene lamps, and LEDs), refrigeration (high and low efficiency), ventilation (low- and high-efficiency ceiling fans), television, water heaters (electricity, LPG, solar) and 'other appliances' as a category. Demand for each energy service grows in response to income and service prices. Technologies compete on the basis of cost and efficiency to provide a given service. For example, LED, incandescent and fluorescent lighting technologies compete on the basis of cost and efficiencies to provide lighting services. Detailed theoretical formulation for the building sector as modelling in GCAM-CEEW can be found in Chaturvedi et al. (2014). A brief explanation is given below.

The three equations below represent demand per unit floor space for heating, cooling and other services (e.g. cooking, lighting, appliances, etc,).

$$d_H = k_H(HDD\eta r - \lambda_H IG)\left[1 - \exp\left(-\frac{\ln 2}{\mu_H}\frac{i}{P_H}\right)\right]$$

$$d_C = k_C(CDD\eta r + \lambda_C IG)\left[1 - \exp\left(-\frac{\ln 2}{\mu_C}\frac{i}{P_C}\right)\right]$$

$$d_j = k_j\overline{q_j}\left[1 - \exp\left(-\frac{\ln 2}{\mu_j}\frac{i}{P_j}\right)\right]$$

where the first coefficients are the usual calibration parameters, the second aggregate terms represent the "satiated demand" (the maximum level of heating, cooling or other service that a consumer might require), and the third aggregate terms represent the economic adjustment for space heating service, space cooling service, and other services. Regarding the satiated demand term, HDD and CDD are heating and cooling degree days (h ^{0}C), which change over time, Z is thermal conductance (GJ/m^{2} h^{-1} C^{-1}) or building U-value, r is building floor-to-surface area ratio representing the size of building shell exposed to outdoor temperature, IG is the amount of building internal gains (GJ/m^{2}), and are internal-gain scalars accounting for the potential mismatch of the time when space conditioning is required and the time when the internal gains are produced. Thus, with the internal gains, space heating demand decreases, whereas space cooling demand increases. The satiated demands for other services are held fixed. It was also assumed that aggregate cooking service demand responds more consistently to population increase rather than floor space increase. Thus, for this service, satiation level has been assumed to be equal to the per capita cooking service consumed in USA for 2005, though the actual penetration will still depend on the income, service price, and efficiency of cooking technologies. Regarding the economic choice term, i is per capita income, P_j is the price of an energy service, m_j is referred to as saturation impedance of the service. The saturation impedance represents the extent to which the saturation of an energy service is impeded, given the affordability of the service, i/P_j in the process of prioritizing various energy services within the budget. Given the same affordability, the higher the level of saturation impedance for the energy service, the lower the level of the energy service delivered. This relationship captures the two desired characteristics: attenuation in the responsiveness of energy service demand to income and price, and ultimate service demand satiation.

Transport sector

The energy demand in transportation sector is modelled for passenger transport (road, rail and aviation), freight transport (road and rail), and international shipping with the demand for each service being driven by per capita GDP and population. Each type of service demand is met by a range of competing modes. For passenger transport, two-wheelers, three-wheelers, cars, buses, railways, and aviation compete with each other for providing passenger service. Changes in modal shares in future periods depend on the relative costs of the different options, modelled using a logit choice formulation. Costs in the passenger sector include time value of transportation which tends to drive a shift towards faster modes of transport (light duty vehicles, aviation) as incomes increase. In core GCAM (global version available for research community's use) many of the modes (including light duty vehicles) include competition between different vehicle types, which also uses a logit choice mechanism that is calibrated to base-year shares; for example, in GCAM, the passenger car segment comprises four types of cars. In GCAM-CEEW, the structure has been simplified to represent only one type of car with different fuels. For new or emerging technologies (such as electric or hydrogen vehicles), costs also consider infrastructural constraints, non-economic consumer preferences and as such are especially high in the near-term future time periods. No upper limits of battery electric vehicles (BEV) or fuel cell vehicles (FCV) use are implemented. In GCAM-CEEW, population and income (GDP) are the exogenous drivers of passenger service demand expressed in passenger kilometres travelled (PKT). Further, in GCAM-CEEW the passenger service demands by mode are estimated endogenously based on the total travel costs (monetary cost per passenger kilometre travelled, USD/PKT) by mode, fuel, technology and time cost of travel which itself is a function of the average hourly wage rate of the employed population, mode-specific value of travel time (VTT) and travel speed. Freight service demand is based on simple functions of population, GDP, and fuel prices in GCAM-CEEW. Freight trucks (five categories in the global version, while one representative category in GCAM-CEEW version) and railways compete for servicing freight demand in GCAM-CEEW. The rate of efficiency improvement of each represented vehicle technology is exogenous in GCAM-CEEW. Details related to transportation in GCAM can be found in Kyle and Kim (2011) and Mishra et al. (2013). A brief explanation is given below.

The total demand for transportation service (passenger-km or ton-km) in a given year is represented by

$$D_{r,t} = \sigma_r (Y_{r,t})^{\alpha} (P_{r,t})^{\beta} (N_{r,t})$$

where σ represents a base year (2010) calibration parameter, Y is the per-capita GDP, P is the total service price aggregated across all modes, N is the population , and α and β are income and price elasticities, respectively. The service price is represented as the cost per unit of service demand including the value of time in transit (e.g. dollars per passenger kilometer), and is averaged across all modes, such as airplane, train, or LDV. The total cost of any passenger mode (Pi) in region r and time period t is calculated as follows:

$$P_{i,r,t} = \frac{(FP_{i,r,t})(I_{i,r,t}) + NFP_{i,r,t}}{LF_{i,r,t}} + \frac{W_{r,t}}{S_{i,r,t}}$$

where FP is the fuel price, I is the vehicle fuel intensity, NFP is the vehicle non-fuel price, LF is the load factor (persons per vehicle), W is the wage rate, and S is the vehicle speed. Fuel prices are endogenous, and include the impact of any emissions penalties (e.g. carbon price) depending on the scenario. All other variables are exogenously specified for each technology and in each time period. The fuel intensity and non-fuel costs of any single technology in GCAM are exogenous. Future technological improvements and cost declines assumed for any technology may therefore be attributable to a variety of sources that are not disaggregated explicitly in the model. The non-fuel cost includes the capital cost, maintenance costs, insurance and registration, and a variety of other costs, discounted and levelized per vehicle kilometer. The load factor represents the average number of passengers in each vehicle. The wage rate is calculated as the per-capita GDP divided by the number of working hours in the year, and the vehicle speed represents the average door-to-door speed for the mode.

The market share of individual models is determined endogenously in the model based on the following formulation:

$$S_{i,r,t} = \frac{(SW_{i,r})(P_{i,r,t})^{\lambda}}{\sum_i^n (SW_{i,r})(P_{i,r,t})^{\lambda}}$$

where SW is the share weight, Pi is the cost of transport service, λ is a cost distribution parameter, and n is the number of modes in the given sector. The share weight is a calibration parameter, and the cost distribution parameter regulates the degree to which future price changes will be reflected in modal shifts.

Industry sector

The industrial sector in GCAM-CEEW is modelled in an aggregate way, with industrial service demand responding to income growth and fuel prices. Various fuels (biomass, coal, electricity, natural gas and oil) compete on the basis of relative prices for providing energy service for meeting industrial energy demand. Current model version only tracks the energy mix (for energy use and feedstock use) and emissions from an aggregate indusrial sector and includes energy demanded in the agricultural sector.

The total demand for the generic industrial service in a given year is represented by

$$D_{r,t} = \sigma_r (Y_{r,t})^{\alpha} (P_{r,t})^{\beta}$$

where σ represents a base year (2010) calibration parameter, Y is the aggregate GDP, P is the total price aggregated across all fuels, and α and β are income and price elasticities, respectively.

The market share of individual fuels is determined endogenously in the model based on the following formulation:

$$S_{i,r,t} = \frac{(SW_{i,r})(P_{i,r,t})^{\lambda}}{\sum_i^n (SW_{i,r})(P_{i,r,t})^{\lambda}}$$

where SW is the share weight, Pi is the cost of delivering that particular fuel (includes the capital and endogenously determined fuel cost), λ is a cost distribution parameter, and n is the number of fuels in the industrial sector (electricity, coal, natural gas, oil, biomass). The share weight is a calibration parameter, and the cost distribution parameter regulates the degree to which future price changes will be reflected in fuel shifts. GCAM has the capability of detailing industrial module into various industrial sectors like steel, paper, cement, etc (e.g. see Zhou et al., 2013).

As GCAM is a detailed energy sector model, fuel use in one sector impacts its use in other sector through the fuel price. For example, if oil demand in the transport sector reduces due to shifts towards electricity based vehicles, its price will decline, which will lead to increased usage of oil in other sectors.

In GCAM, energy efficiency improvements in the end-use sectors are modelled with the help of exogenous assumptions, as well as endogenous price responses. Sectoral energy efficiency improvements for all the end use sectors in the Reference (Ref) and sensitivity scenarios are presented in Table S3. We also model endogenous price responses at the appliance/technology level which leads to improvements in average efficiencies. E.g. we have a high-efficiency air conditioner (AC) and a low-efficiency AC. If the price of electricity increases due to any intervention, we will see a shift towards ACs with higher efficiency. At the vehicle technology level, energy efficiency impacts the fuel cost of a vehicle. If the cost of fuel of a given technology (say car) increases due to any intervention, the given technology becomes less competitive. In the end-use sectors, shares of technologies/fuels respond to price signals. E.g. if coal becomes expensive in the end-use sectors due to say carbon tax, its share will decline the competing technology will fill the gap.

M4. Modelling energy access

Our model has a detailed representation of energy service demands for the urban and rural residential sectors. Demands are responsive to costs as well as income. As affordability of services increase, the demand for energy services increases both in urban and rural areas. We incorporate energy access related policies in our analysis in the following way:

(i) Urbanisation rate: The rate of urbanisation depends on the rate of economic growth. Higher the economic growth, higher is the transition towards urbanisation. We reflect this experience in our model by assuming different rates of urbanisation under the different growth rate scenarios. We assume that urbanisation rate in 2050 will increase to 50 per cent under the medium economic growth scenario, to 55 per cent under the high economic growth rate scenario, and to 45 per cent under the low economic growth rate scenario to represent the dynamics in a stylised way.

(ii) Urban rural income divide: How energy access will evolve in urban and rural areas will depend on how per capita income grows across urban and rural households, which is linked to the growth rate of the aggregate economy. We assume that a high economic growth rate at the country level will imply that the per capita income disparity between urban and rural areas will decline at a faster rate as compared to the medium economic growth rate, which in turn will be higher than a low economic growth rate. The rate at which this disparity decreases will impact the rate of energy access in rural and urban households. The per capita urban and rural income assumptions across the three economic growth scenarios are presented in supplementary material. Thus, our three economic growth scenarios do not just analyse the impact of the higher level economic growth rate and urbanisation rate, but also of differing levels of energy access in urban and rural areas. As compared to our assumption, data from the past three decades in India will show that even though the average per capita incomes have risen in India with economic growth, income disparity has increased between urban and rural areas (instead of decreasing as we have assumed). This is a failure of Indian economic policy which has been not able to address the growing urban rural divide. Our assumption in a way only reflects the scenario in which Indian policy makers are successful in decreasing the urban rural income gap. Our framework is capable of modelling increasing inequality in incomes as well. As energy access in itself is not the focus of this analysis, we have chosen a stylised representation of this issue, which can be argued as an optimistic assumption of the state of urban rural divide in India's future. There could be alternative ways of modelling energy access. We present one stylised way to incorporate the impact of varying income levels on access. Our approach in a way focuses primarily on the demand side based on the logic that even if electricity is brought to a household (which is a supply side perspective), the level of consumption will largely be determined by the household income.

(iii) Clean cooking access: The Indian government has embarked on an ambitious programme to provide clean fuel, mainly LPG to Indian households. We assume that under the medium growth scenarios, biomass will be entirely replaced by alternative cooking fuels by 2040 in the medium GDP growth scenario, 2030 in the high growth scenario, and 2050 under the low growth scenario.

(iv) Efficient lighting: With a thrust on the LED programme, we assume that the penetration of LEDs increases at a fast pace. Incandescent bulbs will be phased out from Indian households by 2030 across all scenarios. The incandescent bulbs will be replaced by LEDs as well as CFLs. A recent report highlights that LEDs have mostly replaced CFLs in India rather than incandescent bulbs (Chunekar et al., 2017). Our assumption in a way reflects that Indian policy makers undertake strong regulatory steps to stop the sales of inefficient incandescent bulbs, as the LED focused policy in itself might not be successful in replacing incandescent bulbs in India.

Whether the transitions in efficient lighting, clean cooking, or industrial and transportation sector efficiencies will happen as per the timelines that we have assumed is open to debate, as these depend on many factors. Our effort is not to present our assumptions as the 'best' assumptions but reflect policy developments in the Indian energy sector in our modelling analysis. We have chosen a stylised way to do this.

Cost and efficiency assumptions

The capital cost, operations & maintenance cost, and energy efficiency for all technologies across all sectors are critical assumptions in GCAM. The fuel cost is endogenously determined for all fuels across all sectors based on the demand and supply of these. The Ref scenario reflects a particular combination of how the technical and economic assumptions evolve across sectors. The cost and efficiency assumptions of technologies across sectors are based on India specific information taken from secondary literature including company websites, etc. Cost for power generation technologies are based on discussions with sectoral experts from solar and wind power developers, Ministry of New and Renewable Energy (MNRE), and National Thermal Power Corporation (NTPC) as undertaken for a previous research (Chaturvedi et al., 2021), and is presented in Table S2. Assumptions related to energy efficiency improvements in the Ref scenario across end use sectors are presented in Table S3. The rate of GDP growth and urbanisation rate in Ref sc are presented in Table S1. The cost and efficiency assumptions for all technologies across all sectors are same for all net-zero scenarios, excluding the cost of CCS and hydrogen in breakthrough technology scenarios. For breakthrough technology scenarios, different technology costs have been assumed for CCS and hydrogen.

Modelling Timeframe

The timeframe for our analysis is up to 2100, as this is the time frame relevant for our discussion on net-zero scenarios.

GCAM focuses on the long-term pathways and is suited for policies that could influence these pathways. It does not explicitly model grid balancing related aspects as that would require a model with hourly resolution and much finer representation of the grid both on the supply- and demand-side.

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GDP, Population, Technology cost, Energy efficiency, and Land/Water/Job coefficient assumptions

Table S1: Socioeconomic and Demographic Assumptions

	2015	2030	2050	2075	2100	Units
GDP	2118	5375	17143	37028	51820	Billion 2015 USD
GDP CAGR#	6.8%	7.7%	4.7%	2.2%	1.0%	Percentage
Population	1310	1504	1639	1607	1447	Million
Per capita income	1617	3574	10458	23038	35811	2015 USD per capita
Urbanisation Rate	32.7%	39.9%	50.7%	62.5%	74.4%	Percentage
GDP CAGR	2015-50: 6.16%			2050-2100: 2.24%		Percentage
Population CAGR	2015-50: 0.64%			2050-2100: -0.25%		Percentage

Note: The CAGR presented in the table is also a five-year time step variable. For instance, the growth rate shown in the column 2030 is the rate between 2025 and 2030.

Table S2: Generation cost pathways for key electricity generation technologies (INR/kWh)

Generation Technology	2020	2030	2040	2050	2075	2100	Units
Biomass combined cycle	12.35	11.54	11.07	10.78	10.31	9.92	2015INR/KWh
Biomass conventional	8.11	7.87	7.80	7.83	7.76	7.50	
Coal Ultra Super Critical	-	3.68	3.71	3.76	3.82	3.85	
Coal Super Critical	3.52	3.55	3.57	3.6	3.62	3.61	
Gas	6.88	5.08	5.17	5.4	5.66	6.52	
Nuclear	3.84	3.87	3.92	3.99	4.16	4.31	
CSP	6.71	6.86	6.78	6.9	6.61	6.34	
Solar	2.62	2.32	2.06	1.85	1.59	1.3	
Wind	3.53	3.23	3.14	3.04	2.9	2.75	
RE integration cost	-	0.75	0.9	1.1	1.1	1.1	

Note: RE integration cost refers to additional cost on solar and wind due to their variability. This could be due to storage cost, back up gas turbines, curtailment, or any other cost required for their higher penetration.

Table S3: The incremental cost of CCS for electricity generation technologies

Technology	Increment in cost from base tech cost
Biomass combined cycle + CCS	50%
Biomass conventional + CCS	91%
Coal ultra-super critical + CCS	72%
Coal super critical + CCS	72%
Gas + CCS	72%

Table S4: Cost of hydrogen production and end-use

Scenarios	Technology	2020	2030	2040	2050	2060	2070	2080	2090	2100	Units
Hydrogen Breakthrough Sc	Electricity – grid	5.48	4.11	3.65	3.30	3.02	2.78	2.59	2.47	2.35	2015 USD/Kg
	Gas	1.80	1.82	1.84	1.91	1.94	1.94	1.99	2.10	2.23	
	Solar	3.86	2.58	1.52	0.79	0.79	0.79	0.79	0.79	0.79	
	Wind	3.88	3.05	1.83	1.34	1.34	1.34	1.34	1.34	1.34	
Reference Sc	Electricity – grid	5.48	5.48	5.48	5.48	5.48	5.37	5.10	4.86	4.74	
	Gas	1.80	1.82	1.84	1.91	1.94	1.94	1.99	2.09	2.22	
	Solar	3.86	3.86	3.86	3.86	3.86	3.77	3.58	3.41	3.32	
	Wind	3.88	3.88	3.88	3.89	3.89	3.80	3.61	3.44	3.36	
Transportation cost to end-use		2.22	1.93	1.35	0.77	0.77	0.77	0.77	0.77	0.77	

The hydrogen produced using grid electricity is more expensive than the other modes because of the high cost of purchased electricity as compared to electricity generated by any other renewable sources such as solar or wind. Even in hydrogen breakthrough scenario where hydrogen production technologies such as electrolyser because cheaper, the overall cost of production remains high as compared to other costs because of the electricity cost component. The cost of hydrogen production using electricity grid in current year is in line with Hall, et al. (2020). The long-term decline in cost of production is based on the consideration that hydrogen production technologies will reach commercial mtaurity by 2050 and hit the floor cost by then. The optimistic cost of production is in line with the estimates given by Biswas, Yadav and Baskar (2020).

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Table S5: Energy efficiency improvement rates for fuels and technologies in end use sectors

				CAGR		
Sector	**Consumer**	**Technology**	**Fuel**	**2020-2030**	**2030-2050**	**2050-2100**
Buildings	Residential	Air conditioner (hi-eff)	electricity	1.39%	1.10%	0.04%
		Air conditioner (lo-eff)	electricity	1.39%	1.15%	0.05%
		Cooking	electricity	0.00%	0.00%	0.00%
			gas	0.00%	0.00%	0.00%
			refined liquids	0.00%	0.00%	0.00%
		Lighting - bulb	electricity	0.31%	0.08%	0.09%
		Lighting - cfl	electricity	0.31%	0.08%	0.09%
		Lighting - led	electricity	0.26%	0.25%	0.22%
		Other appliances	electricity	0.25%	0.25%	0.25%
		Refrigerator (hi-eff)	electricity	0.27%	0.24%	0.25%
		Refrigerator (hi-eff)	electricity	0.23%	0.26%	0.25%
		Telivision	electricity	0.00%	0.00%	0.00%
		Ceiling fan (hi-eff)	electricity	0.00%	0.00%	0.00%
		Ceiling fan (lo-eff)	electricity	0.00%	0.00%	0.00%
		Electric water heater	electricity	0.00%	0.00%	0.00%
		LPG water heater	gas	0.00%	0.00%	0.00%
	Commericial	Cooking	electricity	0.00%	0.00%	0.00%
		Cooking	gas	2.26%	0.00%	0.00%
		Cooking	refined liquids	2.26%	0.00%	0.00%
		HVAC	electricity	1.34%	1.12%	0.10%
		Lighting	electricity	0.31%	0.08%	0.09%
		Other appliances	electricity	0.25%	0.25%	0.25%
Industry	Aggregate efficiency improvement			1.39%	0.45%	0.22%
Transport	Four-wheeler (Cars)		oil	0.69%	0.66%	0.11%
			gas	0.66%	0.63%	0.10%
			electricity	0.20%	0.20%	0.20%
	Two-wheeler (Cars)		oil	0.30%	0.30%	0.30%
			electricity	0.61%	0.61%	0.61%
	Three-wheeler (Cars)		oil	0.69%	0.66%	0.11%
			gas	0.30%	0.30%	0.30%
			electricity	0.40%	0.40%	0.40%
	Buses		oil	0.81%	0.81%	0.81%
			gas	0.81%	0.81%	0.81%
			electricity	0.92%	0.92%	0.92%
	Trucks		RL	0.16%	0.16%	0.15%
			NG	0.16%	0.16%	0.15%
			Electric	0.16%	0.16%	0.15%
			FCEV	0.34%	0.34%	0.34%
	Freight Rail		oil	0.02%	0.03%	0.02%
			electricity	0.02%	0.03%	0.02%
	Passenger Rail		oil	0.02%	0.03%	0.02%
			electricity	0.02%	0.03%	0.02%
	Domestic Aviation		oil	0.69%	0.48%	0.00%
	International Aviation		oil	0.69%	0.48%	0.00%

Table S6: Land coefficients for the power sector (Acre/MW)

Fuel	Coefficient
Coal	0.54
Solar Rooftop	2.98
Solar PV	5.50
Wind	3.38
Gas	0.18
Nuclear	0.20
CSP	5.09
Biomass	1.54
Hydro	4.59

Source: Authors' compilation based on CEA (2010), NPCIL (2011), NHPC (2015), TSAS (2017), NREL (2021), SECI (undated) and BREDA (undated)

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Table S7: Water consumption coefficients for the power sector (m^3/MWh)

Fuel	Water consumption intensitities
Biomass	4.35
Coal	2.59
Gas	1.17
Nuclear	3.82
Solar	-
Wind	-

Source: Chaturvedi et al. (2020)

Chaturvedi, V, Koti P N, Sugam R, Neog K and Hejazi M. 2020. Cooperation or rivalry? Impact of alternative development pathways on India's long-term electricity generation and associated water demands. Energy

Table S8: Job coefficients for the power sector

Source	Manufacturing	Construction	Operation and Maintenance	Fuel Supply
	(Jobs/MW/Year)	(Jobs/MW/Year)	(Jobs/MW/Year)	(Jobs/GWh)
Coal		0.92	0.63	0.33
Gas		0.92	0.31	
Large Hydro		2.08	0.57	-
Nuclear		2.29	1.39	-
Solar utility	2.6	2.95	0.5	
Solar rooftop	2.6	24.22	0.5	-
Wind	0.86	0.77	0.5	
Small Hydro		13	0.84	-
Biomass		6.96	9.28	1.22

Source: Kuldeep et al. (2019)

Kuldeep N, Koti P N, Dutt A, Bishnoi T, and Dalal A. 2019. Future skills and job creation with renewable energy in India: Assessing the co-benefits of decarbonising the power sector. IASS, TERI, CEEW and SCGJ

Annexure 2: Emissions by sectors across the Reference and Net-Zero scenarios