SUPPLEMENTARY MATERIAL

Source influence on emission pathways and ambient $PM_{2.5}$ pollution over India (2015-2050)

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S1. Present day emissions at state-level and sectoral uncertainties in emissions

Table S1. Emissions for 2015 by state (MT/yr)

States	PM2.5	BC	OC	SO2	NOX	NMVOC
Andaman and Nicobar	0.124	0.001	0.003	0.426	0.460	0.032
Arunachal Pradesh	0.006	0.001	0.002	0.000	0.002	0.010
Assam	0.144	0.031	0.048	0.067	0.096	0.266
Bihar	0.747	0.117	0.245	0.331	0.338	1.754
Chandigarh	0.067	0.012	0.029	0.008	0.011	0.122
Chhattisgarh	0.327	0.020	0.024	0.643	0.704	0.124
Dadra & Nagar Haveli	0.002	0.000	0.000	0.003	0.003	0.006
Diu and Daman	0.001	0.000	0.000	0.000	0.002	0.002
Goa	0.008	0.002	0.001	0.009	0.011	0.013
Gujarat	0.505	0.073	0.089	0.904	0.701	0.881
Haryana	0.305	0.041	0.084	0.216	0.322	0.530
Himachal Pradesh	0.030	0.007	0.009	0.004	0.023	0.048
Jammu and Kashmir	0.058	0.011	0.019	0.007	0.026	0.101
Jharkhand	0.230	0.043	0.069	0.186	0.181	0.404
Karnataka	0.439	0.065	0.109	0.338	0.432	0.702
Kerala	0.142	0.029	0.034	0.107	0.133	0.271
Lakshadweep	0.002	0.001	0.001	0.000	0.004	0.005
Madhya pradesh	0.498	0.074	0.107	0.532	0.678	0.706
Maharashtra	0.437	0.070	0.073	0.570	0.709	0.917
Manipur	0.013	0.003	0.005	0.001	0.022	0.023
Meghalaya	0.009	0.002	0.002	0.002	0.008	0.010
Mizoram	0.195	0.029	0.082	0.011	0.022	0.372
Nagaland	0.017	0.003	0.004	0.002	0.014	0.027
NCT Delhi	0.060	0.011	0.009	0.057	0.097	0.132
Orissa	0.372	0.050	0.077	0.489	0.319	0.472
Puducherry	0.004	0.001	0.001	0.003	0.006	0.008
Punjab	0.450	0.050	0.133	0.189	0.405	0.768
Rajasthan	0.515	0.078	0.131	0.680	0.536	0.681
Seemandhra	0.323	0.051	0.082	0.220	0.265	0.572
Sikkim	0.003	0.001	0.001	0.000	0.001	0.004
Tamilnadu	0.441	0.065	0.089	0.461	0.576	0.685
Telangana	0.232	0.036	0.059	0.158	0.190	0.410
Tripura	0.019	0.003	0.007	0.001	0.008	0.033
Uttar pradesh	1.676	0.231	0.508	0.915	1.510	3.579
Uttarakhand	0.043	0.010	0.014	0.006	0.048	0.090
West Bengal	0.656	0.098	0.186	0.544	0.637	1.078
India	**9.101**	**1.320**	**2.337**	**8.091**	**9.498**	**15.839**

Table S2. Uncertainty Bounds (95% Confidence Levels) for Indian Emissions of Individual Pollutants by Sector

Sector	**NO_X**	**SO_2**	**$PM_{2.5}$**	**NMVOC**
Industry	[-85%, +256%]	[-22%, +26%]	[-81%, +217%]	[-80%, +209%]
Transport	[-63%, +122%]	[-71%, +157%]	[-54%, +91%]	[-59%, +107%]
Residential	--	[-59%, +107%]	[-61%, +113%]	[-66%, +133%]
Agricultural	[-60%, +111%]	[-58%, +105%]	[-46%, +70%]	[-63%, +121%]
Informal industry	[-85%, +260%]	[-10%, +11%]	[-74%, +173%]	[-79%, +204%]
Total Emissions	**[-65%, +125%]**	**[-20%, +24%]**	**[-49%, +78%]**	**[-44%, +66%]**

S2. Future emission pathways

S2.1. Methodology

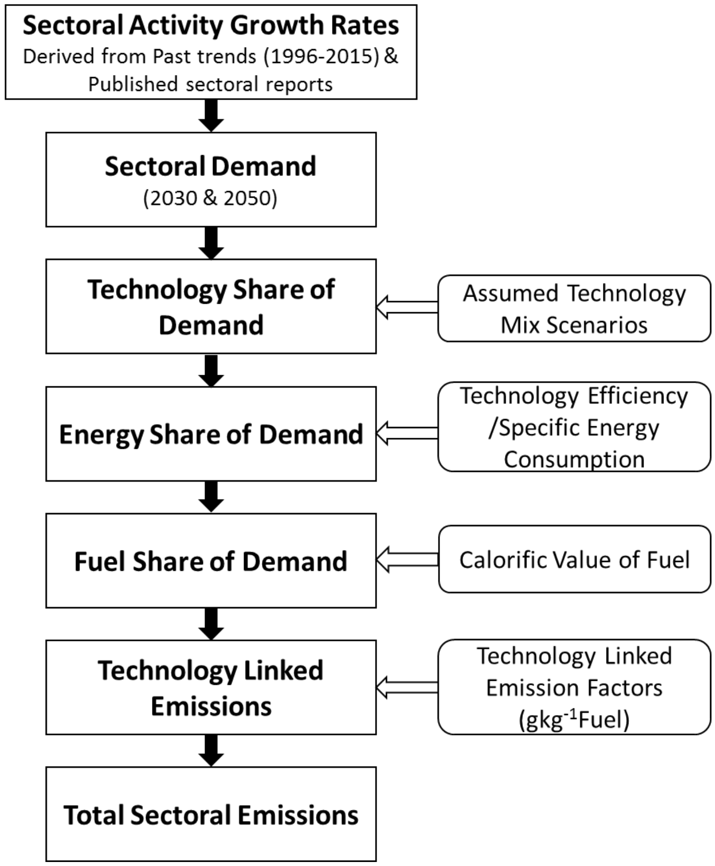

Figure S1. Methodology for estimation of future sectoral activity, apportionment to technology mix and related scenario based emissions.

S2.2. Evolution of sectoral demand

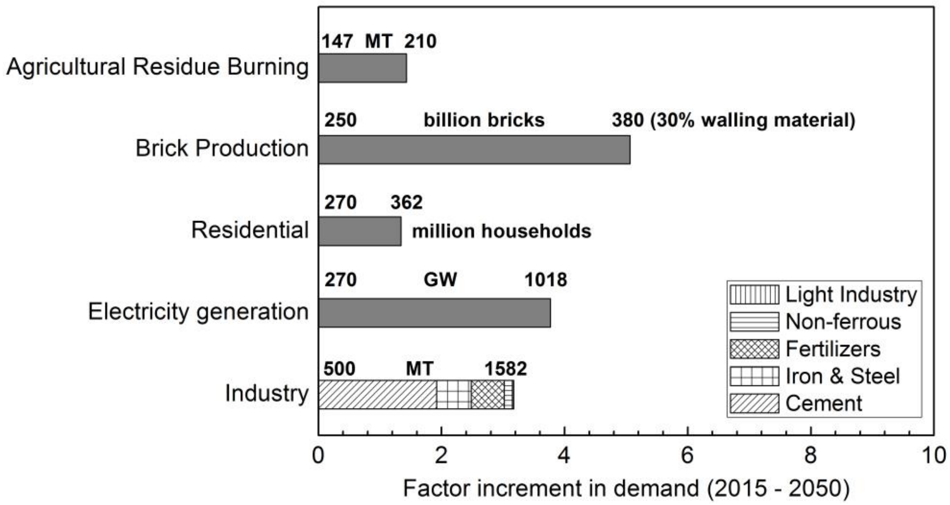

Figure S2. Sectoral Growth between 2015- 2050. Growth rates were computed based on analysis of existing data and reviewed literature.

Table S3. Sectoral growth rates for 2015-2030 and 2030-2050

Sectors	**Activity Name**	**Activity**	**Growth rates in % per year**						
		2015		**2015 - 2030**			**2030 - 2050**		
			Growth rate from 2000-2015 data	**IESS[a] Growth Rate**	**Published growth rate**	**This Study**	**IESS[a] Growth Rate**	**Published growth rate**	**This Study**
Electricity generation	Installed capacity (GW)	270	6.89	6.31	6.7[b]	**6.63**	1.84	NIL	**1.84**
Industry	Production (MT)								
	Cement	215	5.06	5.63	7.08[c]	**6.07**	2.86	NIL	**3.1**
	Iron and steel	88	4.49	8.03	3.26[d]	**4.5**	2.93	NIL	**2.5**
	Fertilizer	190	1.77	1.04	2.86[e]	**2.32**	0.02	NIL	**0.04**
	Non-ferrous	4	6.65	9.74	11.3[f]	**11.3**	6.77	NIL	**6.23**
Brick production	Number of bricks (in billion) (similar to construction growth)	250	NIL	NIL	6.6[g]	**6.6**	NIL	NIL	**3.37**
Transport	Passenger-kilometre (in billion)	9997	6.54*	5.02	NIL	**5.78**	2.42	NIL	**2.89**
	Freight-kilometre (in billion)	2564	3.61	-	NIL	**3.61**	-	NIL	**1.8**
Residential	Household number (in million) (similar to population growth)	270	1.39	1.88	1.1[h]	**1.25**	1.57	0.47[h]	**0.53**
Agriculture	Crop production (KT)	578	1.02	NIL	~ 1 to 1.1[i]	**1.02**	NIL	NIL	**1.02**

	(i.e. cereal produced)								

* Growth rate calculated for data from 1996 - 2015

Sources: [Short forms in brackets]

a) India Energy Security Scenarios 2047, NITI Aayog, Govt. of India, 2015 [NITI Aayog 2015]
b) Data from the Ministry of Environment, Forest and Climate Change (MoEFCC) analysed by the Prayas Energy Group, 2011 [MoEFCC, 2011]
c) International Energy Agency, 2009 [IEA, 2009]
d) Dr.A.S.Firoz, Economic Research Unit, 2014 [Firoz, 2014]
e) Industry Group for Petroleum & Natural Gas Regulatory Board, 2013 [PNGRB, 2013]
f) Prof. K.S.S. Murthy, Gen. Secretary, Aluminium Association of India, 2014 [Murthy, 2014]
g) Maithelet. al., Study report prepared by Green Knowledge Solutions, New Delhi, 2012 [Maithel et al., 2012]
h) Shukla, P. R., et al. "Low Carbon Society Vision 2050. India. Indian Institute of Management Ahmedabad." National Institute for Environmental Studies, Kyoto University and Mizuho Information & Research Institute,2009 [Shukla et al., 2009]
i) Ray, D.K., Mueller, N.D., West, P.C. and Foley, J.A., 2013. Yield trends are insufficient to double global crop production by 2050. PloS one, 8(6), p.e66428. [Ray et. al., 2013]

S2.3 Evolution of technology mix

In 2015, power generation was almost entirely from subcritical pressure thermal power plants with an average gross efficiency of 30.5% (IEP, 2006; IESS, NITI Aayog 2015). A switch to more efficient technologies such as supercritical (SC), ultra-supercritical (USC), and integrated gasification combined cycle (IGCC) is expected in future. For 2030 and 2050, respectively, the non-fossil shares were assumed to be 30% and 40% in BAU, 40% and 60% in S2, and 75% and 80% in S3. The assumed technology mix in S2 follows the NDC's proposed non-fossil share of 2030. In S3, it is consistent with high efficiency-low carbon growth cases in earlier studies (Anandarajah and Gambhir 2014; Shukla and Chaturvedi 2012; Level 4, IESS, Niti Aayog, 2015). The transition of thermal power plants sub-critical boiler technology to more efficient technologies like super-critical, ultra-super-critical and integrated gasification combined cycle (IGCC) is based on published scenarios (IEP, 2006; IESS, Niti Aayog, 2015).

In the transport sector, current technology shares are 81% private vehicles (two-wheeler, three-wheeler and cars) and 19% public vehicles (buses and taxis) (Pandey and Venkataraman, 2014). The share of private vehicles is projected to increase in a business as usual scenario till 2030, especially for two-wheelers and cars (NTDPC, 2013; Guttikunda and Mohan, 2014). However, beyond 2030, as GDP stabilizes, no further increase in private vehicle share is assumed, with a greater demand for public transport. Therefore, in the S2 scenario, private vehicle share is assumed as 75% and 70% in 2030 and 2050, respectively. For S3 private vehicle share is assumed to decrease rapidly to 60% in 2030 and 40% in 2050 in consistent with Level 2 of IESS (NITI Aayog, 2015) (Table S4). For future emissions, Auto Fuel Policy (Auto Fuel Policy Vision 2025, 2014) recommendations were applied, wherein 2/3-wheelers were proposed to have Bharat Stage (BS)-IV standards from 1st April 2015, light and heavy duty diesel vehicles to have BS-Va and BS-Vb. There is a recent proposal to leapfrog directly to BS-VI for all on-road vehicle categories by 2020 (MoRTH, 2016). However, scenarios used here, do not reflect such a quick change, keeping the share of BS-VI at modest levels owing to expected delays in availability of BS-VI compliant fuels and/or difficulties in making the technologies adaptive to Indian road conditions as well as cost-effective (ICRA, 2016), along with the use of non-BS-VI compliant vehicles in peri-urban and rural areas. In the transport sector, engine efficiency improvements are not foreseen to have significant increases across technologies (e.g. across BS-III to BS-VI) as these standards primarily govern the control of emissions of air pollutants. Until 2015 there were no fuel economy standards for India. However, energy efficiency improvement are assumed over the years in the S3 scenario keeping in mind the recently proposed fuel economy targets (MoP, 2015)

In the brick sector, currently 76% of total bricks are produced by Bull's trench kilns (BTK) and 21% by clamp kilns. Clamp kilns are highly polluting, with sun-dried bricks, stacked alternately with layers of powdered fuel, allowed to smolder until the bricks are baked. The demand for non-fired-brick walling materials is currently negligible, but expected to rise (10-25% in BAU, 30-45% in S2 and 40-75% in S3 for 2030-2050), from increased availability of hollow-block technology and the governmental incentives for fly-ash bricks (UNDP, 2009). For fired bricks, cleaner technologies include a retrofit to existing Bull's trench kilns, called zig-zag firing, or significantly more capital intensive, vertical shaft brick kilns (VSBK) which have increased efficiency. For small clamp kilns, it is believed that regulation may not be effective, so a constant activity level, but a decreasing share was assumed in future, with new cleaner technologies filling growing demand (personal communication, Maithel, 2015).

Evolution of technologies in informal industry from say traditional wood furnaces, presently supplying all energy requirements, to gasifier and LPG based technologies is assumed to increase in 2030 and 2050 respectively, to 20% and 35% in S2 and 65% and 80% in S3 (Table S4).

India's rural population largely depends on biomass fuels for cooking and lighting (Venkataraman et al. 2010). Although India has introduced improved biomass cook-stoves to improve fuel efficiency and to reduce smoke exposure using chimneys or combustion improvements, further technological improvements or alternatives are required to reach LPG-like emission levels to reduce disease risk due to household biomass burning. The BAU scenario assumes an increasing penetration rate of liquefied petroleum gas (LPG) and piped natural gas (PNG) typical of 1995–2015 (Pandey et al. 2014). In the S2 and S3 scenarios, assumed future switch in residential energy to use of LPG/PNG or low-emission biomass gasifier stoves and biogas, is consistent with energy efficiency increases proposed in Levels 2 and 4 of the IESS (NITI Aayog 2015). We use lower rates of clean technology adoption in the residential sector in both the BAU and S2 scenarios, because no current legislation or standards target this sector, but a complete switch away from traditional biomass fuels in S3. In case of lighting, 37% usage is of highly polluting kerosene wick lamps and lanterns, which emit large amounts of black carbon (Lam et al. 2012), while the balance is of electricity, with less than 1% solar lamps. Residential lighting is assumed to shift from a modest present-day dependence on kerosene to a complete switch to electricity and solar lamps in 2030 and 2050 (National Solar Mission 2010), a change expected with a national promotion of renewable energy.

In the agricultural sector it is assumed, based on satellite active fire cycles in agricultural land-use areas(Venkataraman et al., 2006), that residues of cereal and sugarcane are burned in field. Gupta (2014) indicated greater mechanization of agriculture, with decrease in amounts of residue, but increase in incidence of field burning, needed to clear the rubble consisting of 6-12 inch stalks, before sowing. Mulching technology was reported to allow sowing even through rubble and loosely spread residue, thus avoiding burning for field clearing. The present work applies different levels of mulching, replacing field burning, in future years (Table S4).

Table S4. Technology fraction for major emissions emitting sectors

Sector	Source Categories	TechMix		BAU		S2		S3	
			2015	2030	2050	2030	2050	2030	2050
Thermal power	Thermal power	Fossil-fuel energy	0.70	0.70	0.60	0.60	0.40	0.25	0.2
		Coal fraction	0.61	0.59	0.48	0.48	0.24	0.20	0.12
		Gas fraction	0.09	0.11	0.12	0.12	0.16	0.05	0.08
		Non-carbon energy	0.30	0.30	0.40	0.40	0.60	0.75	0.80
		Sub-critical	1.00	0.90	0.70	0.65	0.55	0.40	0.30
		Super-critical	0.00	0.10	0.15	0.15	0.20	0.15	0.15
		Ultra super critical	0.00	0.00	0.10	0.12	0.15	0.20	0.20
		IGCC	0.00	0.00	0.05	0.08	0.10	0.25	0.35
Heavy Industry	Cement	PAT	0.72	0.72	0.72	0.77	0.83	0.90	1.00
		Non-PAT	0.28	0.28	0.28	0.23	0.17	0.10	0.00
	Iron and steel	PAT	0.56	0.58	0.60	0.62	0.69	0.85	1.00
		Non-PAT	0.44	0.42	0.40	0.38	0.31	0.15	0.00
	Fertilizer	PAT	0.75	0.75	0.75	0.79	0.84	0.95	1.00
		Non-PAT	0.25	0.25	0.25	0.21	0.16	0.05	0.00
	Non-ferrous	PAT	0.69	0.69	0.70	0.76	0.83	0.90	1.00
		Non-PAT	0.31	0.31	0.30	0.24	0.17	0.10	0.00

Light Industry		PAT	0.30	0.35	0.40	0.50	0.70	0.85	1.00
		Non-PAT	0.70	0.65	0.60	0.50	0.30	0.15	0.00
Brick and informal industry	Brick Production	BTK	0.76	0.50	0.35	0.40	0.20	0.20	0.00
		Clamps	0.21	0.20	0.05	0.15	0.05	0.05	0.00
		Zig-zag firing	0.02	0.15	0.15	0.10	0.10	0.20	0.10
		Hollow	0.01	0.05	0.20	0.05	0.20	0.15	0.20
		Non-fired bricks	0.00	0.10	0.25	0.30	0.45	0.40	0.70
	Informal industry	Trad. Biofuel	1.00	0.90	0.75	0.80	0.65	0.35	0.20
		Gasifier	0.00	0.10	0.25	0.20	0.35	0.65	0.80
Transport	Passenger - Private	Private Vehicles	0.81	0.81	0.81	0.75	0.70	0.60	0.40
		Gasoline	0.97	0.94	0.87	0.88	0.70	0.62	0.30
		BS III	1.00	0.39	0.00	0.08	0.00	0.00	0.00
		BS IV	0.00	0.39	0.00	0.30	0.00	0.30	0.00
		BS V	0.00	0.22	0.71	0.47	0.41	0.30	0.25
		BS VI	0.00	0.00	0.29	0.15	0.59	0.40	0.75
		CNG	0.03	0.05	0.10	0.08	0.20	0.13	0.20
		Electric	0.00	0.01	0.03	0.04	0.10	0.25	0.50
	Passenger - Public	Public Vehicles	0.19	0.19	0.19	0.25	0.30	0.40	0.60
		Diesel	0.98	0.90	0.90	0.82	0.70	0.60	0.40
		BS III	1.00	0.58	0.00	0.15	0.00	0.00	0.00
		BS IV	0.00	0.24	0.00	0.25	0.00	0.12	0.00
		BS V	0.00	0.18	0.59	0.35	0.29	0.38	0.21
		BS VI	0.00	0.00	0.41	0.25	0.71	0.50	0.79
		CNG	0.02	0.05	0.05	0.10	0.20	0.20	0.30
		Electric	0.00	0.05	0.05	0.08	0.10	0.20	0.30
	Freight	Diesel (BS-III)	0.58	0.30	0.00	0.25	0.00	0.20	0.00
		(BS-IV)	0.00	0.23	0.12	0.20	0.02	0.15	0.00
		(BS-V)	0.00	0.05	0.35	0.10	0.40	0.15	0.15
		(BS-VI)	0.00	0.00	0.08	0.00	0.08	0.00	0.30
Residential	Cooking	Trad. Biofuel	0.68	0.61	0.55	0.45	0.30	0.10	0.01
		Gasifier	0.00	0.03	0.05	0.13	0.20	0.35	0.20
		Kerosene	0.03	0.00	0.00	0.00	0.00	0.00	0.00
		LPG	0.29	0.35	0.38	0.37	0.42	0.45	0.61
		Electricity	0.00	0.01	0.02	0.05	0.08	0.10	0.18
	Lighting	Kerosene	0.42	0.34	0.26	0.10	0.05	0.00	0.00
		Electricity and solar	0.58	0.66	0.74	0.90	0.95	1.00	1.00
	Space heating	Wood	1.00	0.95	0.85	0.90	0.80	0.85	0.70
		Electric & solar	0.00	0.05	0.15	0.10	0.20	0.15	0.30
	diesel genset	Diesel	1.00	0.95	0.85	0.90	0.80	0.85	0.75
		Electric & solar	0.00	0.05	0.15	0.10	0.20	0.15	0.25
Agriculture	Agr.res.burn	Open Residue Burning	1.00	1.00	1.00	1.00	1.00	0.65	0.00
		Deep sowing mulching tech	0.00	0.00	0.00	0.00	0.00	0.35	1.00
	Agr. Pumps	Diesel	0.32	0.27	0.20	0.10	0.05	0.05	0.00
		Electric & solar	0.68	0.73	0.80	0.90	0.95	0.95	1.00
	Agr. Tractors	Diesel	1.00	1.00	1.00	1.00	1.00	1.00	1.00

S2.4. Evolution of specific energy and total energy consumption

Different technologies are matched with corresponding specific energy per unit activity (Table S5), related to each technology type. In technology evolution, a given technology may improve in efficiency with time or may be replaced with higher efficiency- lower emissions technology at greater rates with time. Both these possibilities are captured in the assumptions, with no efficiency improvement with time characterizing BAU, but with increasing efficiency improvements with time (in 2030 and 2050) characterizing S2 and S3 scenarios (Table S5). Thus in scenarios with high-efficiency energy technologies, there is a reduction of total energy consumption despite increase in activity.

In thermal power sector, the shift in energy efficiency is seen across the technologies from sub-critical plants being the least efficient to plants using integrated gasified combined cycle having the highest efficiency. Under BAU scenario, the individual technologies are not assumed to undergo any improvement in their energy utilization. For S2 and S3, each technology is assumed to have better energy efficiency by 10% in 2030 and 15% in 2050. This evolution of energy efficiency in power plants is governed by the Perform, Achieve and Trade (PAT) scheme. To nurture energy efficiency in industries, Bureau of Energy Efficiency (BEE) under Ministry of Power launched the 'Perform, Achieve and Trade' (PAT) scheme under the National Mission on Enhanced Energy Efficiency (NMEEE) since July, 2012 (MoP, 2012; IESS, NITI Aayog, 2015). Under this scheme, every industry (includes power plants and heavy industries, referred to as "designated consumers" in the scheme) must meet a certain energy efficiency target by implementing appropriate and timely technological reforms. Thus, for industries also, the specific energy per unit activity is representative of the level of penetration of the PAT scheme across different industries over time under each scenario.

Table S5. Specific energy per unit activity for each technology (PJ/activity)

Sector	Source Categories	TechMix	Acitivity		BAU		S2		S3	
			(units)	2015	2030	2050	2030	2050	2030	2050
Thermal power	Thermal power	Sub-critical-coal	GW	68.24	68.24	68.24	61.41	58.00	61.41	58.00
		Super-critical-coal	GW	60.79	60.79	60.79	54.71	51.67	54.71	51.67
		Ultra super critical-coal	GW	54.05	54.05	54.05	48.65	45.94	48.65	45.94
		IGCC-coal	GW	52.01	52.01	52.01	46.81	44.21	46.81	44.21
		Sub-critical-gas	GW	39.00	39.00	39.00	35.10	33.15	35.10	33.15
		Super-critical-gas	GW	34.75	34.75	34.75	31.27	29.53	31.27	29.53
		Ultra super critical-gas	GW	30.89	30.89	30.89	27.81	26.26	27.81	26.26
		IGCC-gas	GW	29.73	29.73	29.73	26.75	25.27	26.75	25.27
Heavy Industry	Cement	PAT	Million Ton	4.47	4.47	4.47	4.02	3.80	4.02	3.80
		Non-PAT	Million Ton	4.56	4.56	4.56	4.10	3.88	4.10	3.88
	Iron and steel	PAT	Million Ton	25.62	25.62	25.62	23.06	21.78	23.06	21.78
		Non-PAT	Million Ton	34.83	34.83	34.83	31.35	29.61	31.35	29.61
	Fertilizer	PAT	Million Ton	1.30	1.30	1.30	1.17	1.10	1.17	1.10
		Non-PAT	Million Ton	1.39	1.39	1.39	1.25	1.18	1.25	1.18
	Non-ferrous	PAT	Million Ton	189.27	189.27	189.27	170.35	160.88	170.35	160.88
		Non-PAT	Million Ton	280.24	280.24	280.24	252.21	238.20	252.21	238.20
Light Industry[1]		PAT		n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
		Non-PAT		n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	Brick Production	BTK	Billion Bricks	3.75	3.75	3.75	3.00	2.81	3.00	2.81

Brick and informal industry		Clamps	Billion Bricks	7.91	7.91	7.91	6.33	5.93	6.33	5.93
		Zig-zag firing	Billion Bricks	2.25	2.25	2.25	1.80	1.68	1.80	1.68
		Hollow	Billion Bricks	1.67	1.67	1.67	1.34	1.25	1.34	1.25
		Non-fired bricks	Billion Bricks	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Informal industry	Trad. Biofuel	Million Ton	14.65	14.65	14.65	11.72	10.98	11.72	10.98
		Gasifier	Million Ton	8.79	8.79	8.79	7.03	6.59	7.03	6.59
	Passenger - Private	Gasoline -BS III	Billion Pass. Km	0.08	0.08	0.08	0.08	0.08	0.07	0.06
		BS IV	Billion Pass. Km	0.08	0.08	0.08	0.08	0.08	0.07	0.06
		BS V	Billion Pass. Km	0.08	0.08	0.08	0.08	0.08	0.07	0.06
		BS VI	Billion Pass. Km	0.08	0.08	0.08	0.08	0.08	0.07	0.06
		CNG	Billion Pass. Km	0.14	0.14	0.14	0.14	0.14	0.13	0.11
		Electric	Billion Pass. Km	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Passenger - Public	Diesel-BS III	Billion Pass. Km	0.51	0.51	0.51	0.51	0.51	0.46	0.38
		BS IV	Billion Pass. Km	0.51	0.51	0.51	0.51	0.51	0.46	0.38
		BS V	Billion Pass. Km	0.51	0.51	0.51	0.51	0.51	0.46	0.38
		BS VI	Billion Pass. Km	0.51	0.51	0.51	0.51	0.51	0.46	0.38
		CNG	Billion Pass. Km	0.62	0.62	0.62	0.62	0.62	0.56	0.47
		Electric	Billion Pass. Km	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Freight	Diesel (BS-III)	Billion Ton Km	1.19	1.19	1.19	1.19	1.19	1.07	0.89
		(BS-IV)	Billion Ton Km	1.19	1.19	1.19	1.19	1.19	1.07	0.89
		(BS-V)	Billion Ton Km	1.19	1.19	1.19	1.19	1.19	1.07	0.89
		(BS-VI)	Billion Ton Km	1.19	1.19	1.19	1.19	1.19	1.07	0.89
Residential	Cooking	Trad. Biofuel	Million HH	36.28	36.28	36.28	36.28	36.28	7.26	5.44
		Gasifier	Million HH	21.77	21.77	21.77	21.77	21.77	4.35	3.27
		Kerosene	Million HH	15.78	15.78	15.78	15.78	15.78	14.20	12.62
		LPG	Million HH	8.04	8.04	8.04	8.04	8.04	7.23	6.43
		Electricity	Million HH	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Lighting	Kerosene	Million HH	0.92	0.92	0.92	0.92	0.92	0.83	0.74
		Electricity and solar	Million HH	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Space heating	Wood	Million Ton	14.90	14.90	14.90	14.90	14.90	2.98	2.24
		Electric & solar	Million Ton	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	diesel genset	Diesel	kTon	0.04	0.04	0.04	0.04	0.04	0.04	0.03
		Electric & solar	kTon	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Agriculture	Agr.res.burn	Open Residue Burning	Million Ton	14.90	14.90	14.90	14.90	14.90	14.15	13.41
		Deep sowing mulching tech	Million Ton	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Agr. Pumps	Diesel	Million no.	67.57	67.57	67.57	67.57	67.57	60.81	50.68
		Electric & solar	Million no.	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Agr. Tractors	Diesel	Million no.	33.31	33.31	33.31	33.31	33.31	29.98	24.99

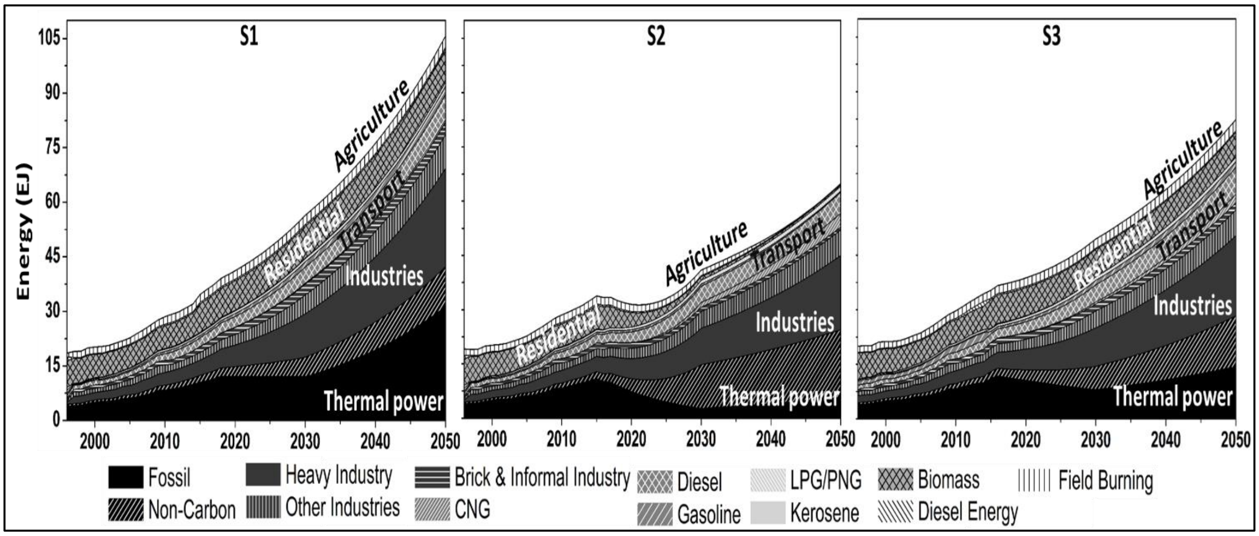

Figure S3. Energy Evolution in Scenarios BAU, S2 and S3

Much of the energy demand in S1 is from electricity generation which is majorly fossil fueled, industry (coal and biomass fueled), in residential biomass is dominantly used as fuel. In scenarios S2 and S3 use of energy efficient technologies like Non-carbon fuel use thermal power, PAT implementation in industries and cleaner technologies in brick production, LPG use in residential and energy efficient standards in transport can help to lower the energy demand.

Table S6. Energy demand for each technology (EJ/year)

			Energy demand (EJ)					
Sector	Source Categories	TechMix	BAU		S2		S3	
			2030	2050	2030	2050	2030	2050
Electricity generation	Electricity generation	Non-carbon energy	5.35	10.92	6.42	13.92	12.04	18.56
		Sub-critical-coal	8.76	23.35	4.65	7.80	1.19	2.13
		Super-critical-coal	0.37	4.46	0.41	1.09	0.17	0.41
		Ultra super critical-coal	0.00	2.64	0.37	0.92	0.26	0.61
		IGCC-coal	0.00	1.27	0.26	0.64	0.34	1.12
		Sub-critical-gas	2.78	3.34	1.94	2.97	0.50	0.81
		Super-critical-gas	0.12	0.64	0.17	0.42	0.07	0.16
		Ultra super critical-gas	0.00	0.38	0.15	0.35	0.11	0.23
		IGCC-gas	0.00	0.18	0.11	0.24	0.14	0.43
Heavy Industry	Cement	PAT	1.67	3.08	1.61	3.02	1.88	3.64
		Non-PAT	0.66	1.22	0.49	0.63	0.21	0.00
	Iron and steel	PAT	2.54	4.31	2.45	4.21	3.35	6.10
		Non-PAT	2.50	3.91	2.04	2.57	0.80	0.00
	Fertilizer	PAT	0.26	0.26	0.25	0.25	0.30	0.30
		Non-PAT	0.09	0.09	0.07	0.05	0.02	0.00
	Non-ferrous	PAT	2.54	8.62	2.51	8.69	2.98	10.47
		Non-PAT	1.69	5.47	1.18	2.63	0.49	0.00
Light Industry		PAT	1.81	3.70	2.58	6.48	3.95	7.08

		Non-PAT	3.35	5.56	2.58	2.78	0.70	0.00
Brick and informal industry	Brick Production	BTK	1.22	1.66	0.78	0.71	0.39	0.00
		Clamps	1.03	0.50	0.62	0.38	0.21	0.00
		Zig-zag firing	0.22	0.43	0.12	0.21	0.23	0.21
		Hollow	0.05	0.42	0.04	0.32	0.13	0.32
		Non-fired bricks	0.00	0.00	0.00	0.00	0.00	0.00
	Informal industry	Trad. Biofuel	0.44	0.45	0.31	0.29	0.14	0.09
		Gasifier	0.03	0.09	0.05	0.09	0.15	0.21
	Passenger - Private	Gasoline -BS III	0.56	0.00	0.09	0.00	0.00	0.00
		BS IV	0.56	0.00	0.37	0.00	0.18	0.00
		BS V	0.30	1.64	0.58	0.66	0.18	0.07
		BS VI	0.00	0.66	0.19	0.95	0.25	0.22
		CNG	0.13	0.51	0.20	0.82	0.24	0.35
		Electric	0.00	0.00	0.00	0.00	0.00	0.00
	Passenger - Public	Diesel-BS III	1.19	0.00	0.36	0.00	0.00	0.00
		BS IV	0.48	0.00	0.59	0.00	0.32	0.00
		BS V	0.36	2.10	0.83	1.26	0.96	0.79
		BS VI	0.00	1.47	0.59	3.15	1.28	2.99
		CNG	0.14	0.24	0.36	1.54	1.04	3.46
		Electric	0.00	0.00	0.00	0.00	0.00	0.00
	Freight	Diesel (BS-III)	1.26	0.00	1.05	0.00	0.76	0.00
		(BS-IV)	0.97	0.72	0.84	0.12	0.57	0.00
		(BS-V)	0.21	2.10	0.42	2.41	0.57	0.68
		(BS-VI)	0.00	0.48	0.00	0.48	0.00	1.35
Residential	Cooking	Trad. Biofuel	7.21	7.22	5.32	3.94	0.24	0.02
		Gasifier	0.21	0.39	0.92	1.58	0.50	0.24
		Kerosene	0.00	0.00	0.00	0.00	0.00	0.00
		LPG	0.92	1.11	0.97	1.22	1.06	1.42
		Electricity	0.00	0.00	0.00	0.00	0.00	0.00
	Lighting	Kerosene	0.10	0.09	0.03	0.02	0.00	0.00
		Electricity and solar	0.00	0.00	0.00	0.00	0.00	0.00
	Space heating	Wood	1.36	1.35	1.29	1.27	0.24	0.17
		Electric & solar	0.00	0.00	0.00	0.00	0.00	0.00
	diesel genset	Diesel	0.21	0.21	0.20	0.20	0.17	0.14
		Electric & solar	0.00	0.00	0.00	0.00	0.00	0.00
Agriculture	Agr.res.burn	Open Residue Burning	2.55	3.12	2.55	3.12	1.58	0.00
		Deep sowing mulching tech	0.00	0.00	0.00	0.00	0.00	0.00
	Agr. Pumps	Diesel	0.19	0.18	0.07	0.04	0.03	0.00
		Electric & solar	0.00	0.00	0.00	0.00	0.00	0.00
	Agr. Tractors	Diesel	0.25	0.30	0.25	0.30	0.22	0.23
		Total	**56.64**	**110.84**	**50.23**	**84.75**	**41.14**	**65.00**

S2.5. Technology linked emission factors

For thermal power, emission factors (Table S7) assumed a mean 38% ash content coal, typical of India, with electrostatic precipitators (ESP) working at 99.98% while more efficient supercritical, ultra-super critical and IGCC technologies, had emission reductions in proportion with increased energy efficiency. In December 2015, the Indian Ministry of Environment and Forests issued new norms for thermal plants with emission standards for SO2 and NOx (MoEFCC,2015). Reported barriers to quick adoption of desulphurization and de-NOx technologies (CSE, 2016), lead to assumptions here of low rates of flue gas desulphurization technology adoption. Preliminary surveys show little progress in the implementation of new standards, mainly due to insufficient knowledge in advanced pollution control technologies and lack of i) space for installation, ii) storage for raw materials and iii) clarity on cost recovery (CSE, 2016). Similarly, in heavy industries like cement, iron and steel, fertilizer and non-ferrous, 90% (S1 and S2) and 100% (S3) operation of existing controls are considered while emission factors for PAT technologies were reduced below non-PAT values using their increase in efficiency (Table S7).

It was assumed that non-fired brick production, which uses cement, involves no use of fuel for firing or drying purposes, hence produces no emissions at the stage of brick production, to avoid double-counting of emissions related to feedstock, which are accounted in cement production. In informal industry, the use of traditional biomass technologies for major thermal and drying operations was assumed shift to cleaner gasifier or LPG technologies, hence, emission factors similar to those for residential cooking were considered. In the residential sector, available measurements (reviewed in Pandey et al. 2014) were used to derive emission factors for wood, dung-cake, crop residue combustion in cook stoves, as also for kerosene and LPG cook stoves, which are also used for biomass fired water-heating and space-heating. Diesel generator sets, for residential use and for mobile towers have been included, whose emission factors are set similar to measured factors for agricultural diesel pumps.

In the agriculture sector, emissions from field burning of cereal straw and sugarcane residue were included. Here, emission factors (Table S7) for cereal and sugarcane burning were used, with zero emissions allocated, in cases of future shifts to deep sowing-mulching technology (Gupta, 2014). The distributed diesel category included diesel use in agricultural tractors and pumps, and in diesel generator sets used for non-grid electricity supply. Emission factors for distributed diesel sources are used, with zero emission allocation for a shift to electric or solar technologies.

Table S7. Emission factors of SLCP's, fine particulate matter and CO_2 (g/kg of fuel used)

Sector	Source Categories	TechMix	SO_2	NO_x	NMVOC	CH_4	CO	$PM_{2.5}$	BC	OC	CO_2
Thermal power	TPP - coal	Sub-critical	7.3	4.5	0.0	0.0	1.5	1.8	0.0	0.0	1766.0
		Super-critical	6.5	4.0	0.0	0.0	1.3	1.6	0.0	0.0	1571.7
		Ultra super critical	5.7	3.5	0.0	0.0	1.2	1.4	0.0	0.0	1377.5
		IGCC	4.9	3.0	0.0	0.0	1.0	1.2	0.0	0.0	1183.2
	TPP - oil & gas	Sub-critical	0.0	3.8	0.0	0.2	0.7	0.0	0.0	0.0	3120.0
		Super-critical	0.0	3.4	0.0	0.2	0.6	0.0	0.0	0.0	2776.8
		Ultra super critical	0.0	2.9	0.0	0.1	0.6	0.0	0.0	0.0	2433.6
		IGCC	0.0	2.3	0.0	0.1	0.4	0.0	0.0	0.0	1860.5
Heavy Industry	Cement	PAT	1.2	2.1	0.1	0.0	1.5	2.3	0.0	0.1	770.0
		Non-PAT	1.2	2.1	0.1	0.0	1.5	2.4	0.0	0.1	786.0
	Iron and steel	PAT	5.2	1.9	0.4	0.1	92.7	1.2	0.3	0.2	1283.0
		Non-PAT	8.6	3.0	0.7	0.1	59.5	1.9	0.4	0.3	2004.0
	Fertilizer	PAT	2.7	1.1	3.7	0.0	7.1	0.3	0.1	0.0	1593.0
		Non-PAT	2.7	1.1	3.8	0.0	6.9	0.3	0.1	0.0	1625.0
	Non-ferrous	PAT	2.7	1.1	3.7	0.0	0.0	0.3	0.1	0.0	1593.0
		Non-PAT	2.7	1.1	3.8	0.0	0.0	0.3	0.1	0.0	1625.0
Light Industry		PAT	15.6	2.9	0.0	0.1	0.6	0.0	0.0	0.0	3149.2

		Non-PAT	13.5	7.0	0.6	0.1	3.6	2.4	0.5	0.1	2087.1
Brick and Informal industry	Brick Production	BTK	9.8	3.8	0.2	0.1	40.4	3.6	3.1	0.1	1714.1
		Clamps	9.8	3.8	0.2	0.1	110.5	4.2	1.6	0.6	1714.1
		Zig-zag firing	9.8	3.8	0.2	0.1	21.1	2.0	0.3	0.2	1714.1
		VSBK	9.8	3.8	0.2	0.1	72.4	2.3	0.0	1.0	1714.1
		Non-fired bricks	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Informal industry	Trad. Biofuel	0.4	0.7	11.2	5.3	70.6	5.6	0.7	2.2	13.1
		Gasifier	0.3	0.7	4.3	0.9	17.7	0.8	0.1	0.3	13.1
Transport	Passenger - Private	Gasoline BS III	0.2	32.4	98.4	6.6	537.2	4.4	0.2	3.5	2810.3
		Gasoline BS IV	0.2	22.7	68.9	4.6	376.1	0.9	0.0	0.7	2810.3
		Gasoline BS V	0.2	13.0	68.9	4.6	214.9	0.9	0.0	0.7	2810.3
		Gasoline BS VI	0.2	2.6	19.7	1.3	43.0	0.4	0.0	0.3	2810.3
		CNG	0.0	10.8	1.8	1.8	20.1	0.0	0.0	0.0	2781.0
		Electric	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Passenger - Public	DieselBS III	0.5	39.2	6.0	0.1	31.5	6.8	1.2	0.4	2365.9
		DieselBS IV	0.4	27.5	4.2	0.1	22.0	1.4	0.2	0.1	2365.9
		DieselBS V	0.4	15.7	4.2	0.1	12.6	1.4	0.2	0.1	2365.9
		DieselBS VI	0.4	3.1	1.2	0.0	2.5	0.7	0.1	0.0	2365.9
		CNG	0.0	17.4	0.0	0.4	20.1	0.0	0.0	0.0	3884.6
		Electric	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Freight	DieselBS III	0.7	44.9	10.1	0.2	35.8	6.8	4.4	1.4	2590.4
		DieselBS IV	0.6	31.5	7.1	0.1	25.1	1.4	0.9	0.3	2590.4
		DieselBS V	0.6	18.0	7.1	0.1	14.3	1.4	0.9	0.3	2590.4
		DieselBS VI	0.6	3.6	2.0	0.0	2.9	0.7	0.4	0.1	2590.4
Residential	Cooking	Trad. Biofuel	0.4	0.7	11.2	5.3	70.6	5.6	0.7	2.2	13.1
		Gasifier	0.3	0.7	4.3	0.9	17.7	0.8	0.1	0.3	13.1
		Kerosene	0.0	0.0	17.0	0.7	39.9	0.6	0.2	0.3	2985.0
		LPG	0.3	0.0	18.8	0.1	14.9	0.3	0.0	0.1	3085.0
		Electricity	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Lighting	Kerosene	0.0	0.0	0.0	0.0	11.0	93.0	90.0	0.4	2770.0
		Electricity and solar	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Space heating	Wood	0.1	0.0	6.9	4.9	76.4	4.1	0.7	1.9	135.8
		Electric & solar	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Diesel genset	Diesel	0.7	97.2	7.7	0.1	20.9	6.9	4.6	1.5	3186.1
		Electric & solar	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Agriculture	Agr.res.burn	Open Residue Burning	0.5	2.9	13.4	3.1	83.8	6.1	0.6	2.2	0.0
		Deep sowing mulching tech	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Agr. Pumps	Diesel	0.7	97.2	7.7	0.1	20.9	6.9	4.6	1.5	3186.1
		Electric & solar	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Agr. Tractors	Diesel	0.7	126.0	1.1	0.0	3.6	17.0	11.0	4.0	3186.0

S2.6. Evaluation of future emissions

Evaluation with ECLIPSE V5a and GAINS-WEO2016

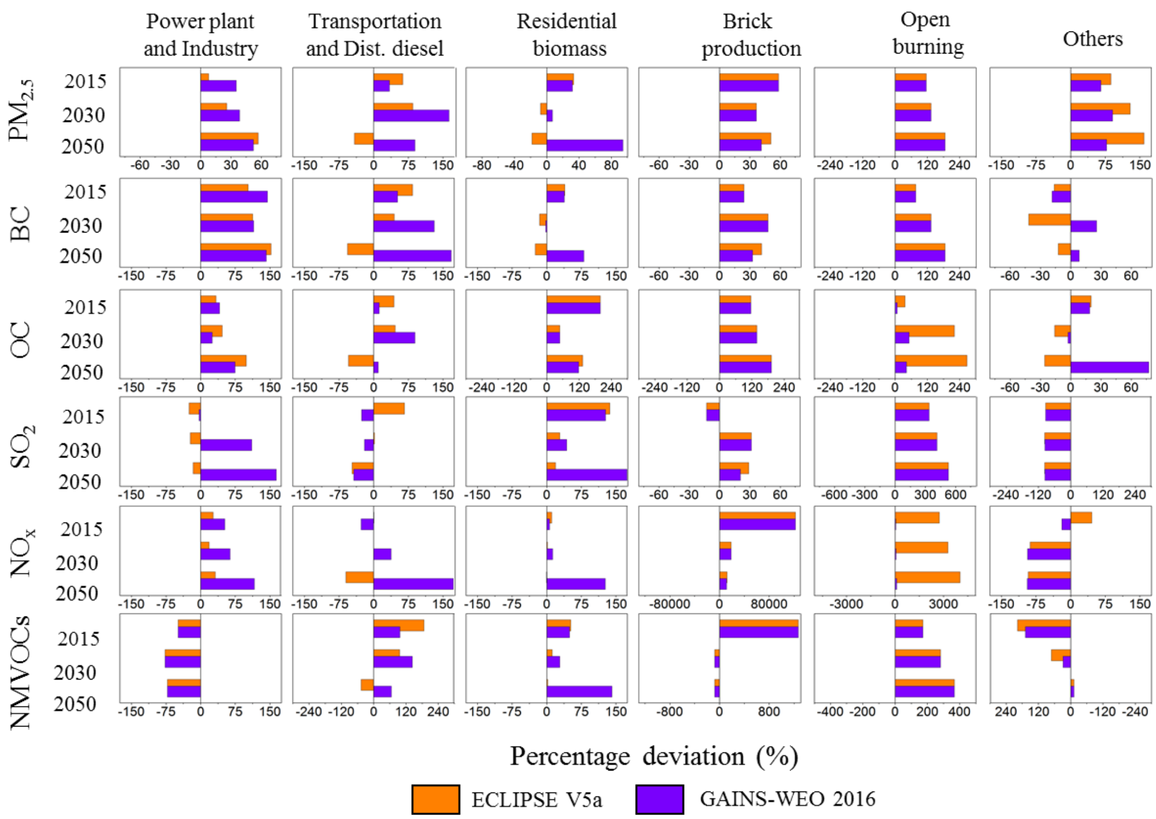

Figure S4. Percentage deviation in emissions of ECLIPSE V5a and GAINS-WEO2016 from emissions of this study by sector.
(Percentage deviation is calculated as (IITB S2 – ECLIPSE V5a) / ECLIPSE V5a and (IITB S2 – GAINS WEO2016) / GAINS WEO2016).

Evaluation with RCP scenarios

RCP2.6 assumes net negative CO2 emissions after around 2070. RCP4.5 and RCP6.0 aim for a smooth stabilization of concentrations by 2150 and RCP8.5 stabilizes concentrations only by 2250. However, RCP scenarios are not tied to any specific socio-economic and technology evolution pathway, making difficult any direct comparison of underlying assumptions, while permitting a comparison of gross emission magnitudes.

Estimated Indian emissions from the RCP scenarios, of SO2, NOx, and NMVOCs, and for BC and OC, for 2005-2050 at 50×50 km resolution, were used for the evaluation. (http://tntcat.iiasa.ac.at/RcpDb/dsd?Action=htmlpage&page=download). The sectors used corresponding to ones in this study, included Energy (Power Plants, Energy Conversion, Extraction, and Distribution), Domestic (Residential and Commercial), Industry (combustion & processing), Surface Transportation and Agriculture waste burning in fields. Gridded emissions in kg m-2 s-1 are summed over the Indian landmass and converted to million tonnes y-1 (Table S8). The present estimates do not include emissions from soils and animal rearing or from shipping and aviation, rather they focus on energy use and solvent based activities. Therefore, corresponding sectors in the RCP database were excluded from the evaluation.

Across RCP scenarios, SO_2 emissions from India are well bounded: 4–9.5 MT/yr in 2030 and 3–7.5 MT/yr in 2050. Emissions of SO_2 estimated here for the highest-control scenario, S3, agreed with those from RCP 4.5 in 2030 and RCP 8.5 in 2050, due to similar assumptions of over 80% non-coal electricity generation. However, the S2 and BAU scenarios estimated much larger emissions, respectively, exceeding RCP8.5 by 1.5 to 2 times in 2030 and 3 to 5 times in 2050. This results from our assumption of low levels (max 25%) of deployment of flue gas desulphurization, as only four coal-fired TPPs in India operate flue gas desulphurization (FGD) units and among those to be commissioned through 2030, only 7 TPPs are listed to have FGD (CAT and Urban Emissions, 2014, Prayas Energy Group, 2011), which differs from assumptions of greater SO_2 emission control in the RCP scenarios. These assumptions would reflect in higher secondary sulphate contribution to $PM_{2.5}$ concentrations from thermal and total coal sectors under the BAU and S2 scenarios, in 2030 and 2050.

For NO_x emissions as well, there is similar agreement of the S3 scenario here with RCP4.5 in both 2030 and 2050, but significantly larger emissions estimated in the S2 and BAU scenarios. The emissions shares are dominated by thermal power and transport sector and grow with sectoral growth under the first two scenarios. Under the S3 scenario, shifts to tighter emission standards for vehicles and a greater share of CNG in public transport, and to non-fossil power generation, reduce NO_x emissions. A non-negligible ~20% share is from residential, agricultural field burning and brick production sectors, which is reduced in magnitude by the adoption of mitigation based largely on cleaner combustion technologies. Similar to emissions of SO_2, those of NO_x in S1 and S2 grow well beyond magnitudes in the RCP database for future years, while those in S3 agree with RCP emission magnitudes, consistent with differences in assumptions in the thermal power sector.

For NMVOC, there is close agreement of S3 scenario emissions with those of RCP6.0 and of S2 scenario emissions lying between those of RCP4.5 and RCP8.5, both in 2030 and 2050. The BAU scenario, which assumes negligible shifts away from residential biomass fuel use and agricultural field burning, calculates somewhat larger NMVOC emissions. Present day NMVOC emissions are dominated by residential energy use, largely from traditional biomass fuel stoves, followed by fugitive emissions from energy extraction (coal mining and oil exploration), and open burning of agricultural residues in fields.

Emissions of BC in the S3 scenario agreed best with RCP6.0 in 2030 and RCP8.5 in 2050, while BAU and S2 scenario BC emissions exceeded those of the RCP8.5 by factors of 1.5 to 3, from inclusion of new sources like residential lighting (with kerosene wick lamps) and water and space heating (with biomass fuels). Emissions of OC in the S2 scenario closely matched those in RCP4.5, while those in BAU matched RCP8.5, in both 2030 and 2050; however, those in S3 were a factor of 3 lower than the lowest RCP6.0 emissions.

Table S8. Representative Concentration Pathways (RCP) scenarios values over India

Scenario	Years	Emissions in MTy^{-1}					
		$PM_{2.5}$	**BC**	**OC**	**SO2**	**NOx**	**NMVOC**
BAU	**2020**	9.8	1.4	2.4	10.3	11.5	15.0
	2030	12.0	1.6	2.6	17.8	18.2	14.8
	2040	14.5	1.6	2.7	26.8	23.3	15.5
	2050	18.5	1.6	2.9	41.4	31.7	16.3
S2	**2020**	9.1	1.2	2.2	9.4	10.5	14.1
	2030	9.5	1.1	2.2	12.7	13.7	12.5
	2040	10.3	1.1	2.2	16.2	15.7	12.4
	2050	11.6	1.0	2.2	20.7	18.4	12.4
S3	**2020**	6.0	0.9	1.4	6.4	8.6	9.9
	2030	3.8	0.5	1.0	6.0	8.6	5.8
	2040	3.0	0.3	0.7	6.6	9.2	4.0
	2050	3.0	0.3	0.7	7.5	10.5	3.8
RCP 2.6	**2020**		0.6	1.9	8.2	4.4	9.9
	2030		0.5	1.9	7.1	4.5	10.3
	2040		0.4	1.8	4.8	4.8	10.3
	2050		0.4	1.5	4.0	5.4	8.5
RCP 4.5	**2020**		0.6	1.7	7.9	4.8	12.4
	2030		0.7	1.8	8.8	6.0	14.3
	2040		0.7	1.8	8.4	6.5	15.8
	2050		0.7	1.6	6.8	6.3	16.8
RCP 6.0	**2020**		0.4	1.3	5.4	3.1	6.7
	2030		0.4	1.3	4.1	2.7	6.1
	2040		0.4	1.3	5.3	3.1	5.9
	2050		0.4	1.3	5.4	3.3	5.9
RCP 8.5	**2020**		0.6	2.0	8.5	5.6	11.0
	2030		0.6	2.1	8.8	6.2	12.5
	2040		0.7	2.3	9.2	6.1	14.1
	2050		0.7	2.5	7.6	4.9	13.2

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