

1 Timely estimates of India's annual and monthly fossil CO₂ emissions

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4 Abstract

5 India is the world's third-largest emitter of carbon dioxide and is developing rapidly. While
6 India has pledged an emissions-intensity reduction as its contribution to the Paris
7 Agreement, the country does not regularly report emissions statistics, making tracking
8 progress difficult. Moreover, all estimates of India's emissions in global datasets represent
9 its financial year, not aligned to the calendar year used by almost all other countries. Here I
10 compile monthly energy and industrial activity data allowing the estimation of India's CO₂
11 emissions by month and calendar year with a short lag. Emissions show clear seasonal
12 patterns, and the series allows the investigation of short-lived but highly significant events,
13 such as the near-record monsoon in 2019 and the COVID-19 crisis in 2020. Data are available
14 at <https://doi.org/10.5281/zenodo.3894394> (Andrew, 2020a).

15 Keywords: India, CO₂ emissions, Covid-19, seasonality

16 Introduction

17 As the world rapidly approaches the temperature limits set in the Paris Agreement
18 (CONSTRAIN, 2019), timely estimates of greenhouse gas emissions are critical for steering
19 policy and scientific understanding of the global carbon cycle (Le Quéré et al., 2020). India,
20 although having low per-capita emissions, is the world's third-largest emitter of carbon
21 dioxide (Friedlingstein et al., 2019), yet its most recent official report of emissions covers the
22 single year 2014 (GOI, 2018).

23 According to available estimates, India's CO₂ emissions have grown by about 5%/yr over
24 2010–2018 (Crippa et al., 2019). This growth has mainly been driven by expansion of the
25 economy as, among other things, the country's labour pool grows and much-needed energy
26 supply is increased (Karstensen et al., 2020), and much of this energy is supplied by coal and
27 petroleum products, including the transition from biomass to petroleum fuels, continuing
28 the long-term increase in the share of India's energy supplied from fossil fuels (see
29 Supplement Figure 42). Countering these upward pressures on CO₂ emissions, India's recent
30 development of variable renewables, particularly solar and wind, has exerted a downward
31 pressure on emissions growth, assisted by a sharp decline in prices for these technologies
32 and ambitious goals for renewables growth that have repeatedly been strengthened
33 (Khanna, 2010; MNRE, 2015; Varadhan, 2019). Development of variable renewables has
34 been further assisted by the introduction of reverse auctions and the creation of solar parks,
35 among other measures (Bose and Sarkar, 2019). In addition, the difficulty India has faced in
36 ramping up domestic coal production has probably also restrained emissions growth (Carl,
37 2015).

38 India does publish a great deal of energy data, but it is scattered across many documents,
39 often not in machine-readable form, occasionally containing errors, and generally without
40 much documentation. The country's official estimates of CO₂ emissions are infrequent and
41 never for more than a single year (GOI, 2004, 2012, 2015, 2018). Moreover, these reported

1 emissions are for India's financial year, running from April to March, so that they do not align
2 with the calendar-year estimates provided by almost every other country (Andrew, 2020b).
3 This gap in official reporting has been filled by third parties estimating emissions largely
4 based on available financial-year publications, whether directly or via intermediate sources
5 (e.g., IEA, 2019a; Gilfillan et al., 2019; EIA, 2020; Hoesly et al., 2018; GHG Platform India, no
6 date), and not all of these are freely available.

7 Given the rapid pace both of India's development and of the change in global context,
8 emissions estimates at a frequency greater than annual are also of interest. Higher-
9 frequency data open up opportunities to analyse the relationships between emissions and
10 policy shifts, economic cycles, weather, and more. The ability to explain why emissions have
11 changed is critical to developing effective emissions policies.

12 Much of India's energy data is not available in formats that are readily machine-readable. In
13 many cases, tables must be copied from PDF-format reports, either automatically using
14 'scraping' scripts, or by hand. On some occasions, reports posted on official websites are
15 low-quality scans of signed documents, further reducing the availability of these data for
16 analysis. Furthermore, explanations for data are often lacking in detail, and can conflict
17 across different datasets for reasons that are not immediately apparent (see Supplement:
18 Coal 'consumption').

19 The International Energy Agency in 2020 stated that the "Government of India should ...
20 Improve the collection, consistency, transparency and availability of energy data across the
21 energy system at central and state government levels" (IEA, 2020b, p. 18). While
22 government ministries responsible for publishing these data are making moves to improve
23 the availability of more recent data, there are still obvious examples of copy-and-paste
24 errors in spreadsheets, random misspellings, filename glitches, and even incorrect units
25 given in the Energy Statistics yearbook. During the Covid-19 lockdown in India, the Central
26 Electricity Authority stopped publishing daily generation reports for four weeks. Clearly
27 much data work is still manual, and further automation will significantly improve India's
28 ability to produce robust and timely estimates of fossil CO₂ emissions.

29 Monthly emissions estimates are also a core input to atmospheric inversion models (Oda et
30 al., 2018). The standard approach taken in the literature to produce monthly emissions
31 estimates is to use a temporal profile based on partial monthly activity data to temporally
32 downsample annual emissions estimates. Three examples of this downsampling approach in
33 the literature are the very first seasonal estimates made by Rotty (1987), CDIAC's gridded
34 estimates (Andres et al., 2011) and EDGAR's temporal profiles (Crippa et al., 2020). Rotty
35 (1987) and Andres et al. (2011), for example, used coal-fired power generation as a proxy for
36 all coal consumption in India, while Crippa et al. (2020) used a proprietary database of
37 activity data. EDGAR's monthly gridded dataset has no intra-annual variation for India (pers.
38 comm., Matthew Jones, 10 July 2020).

39 Here I present a new dataset collating available information on India's monthly energy
40 production and consumption, as well as cement production, and use this dataset directly to
41 estimate India's monthly and calendar-year CO₂ emissions. In contrast to downsampling

1 techniques, the method used here provides accurate estimates of monthly CO₂ emissions in
2 India.

3 **Materials and Methods**

4 Fossil CO₂ emissions can be divided into four main source categories: coal, oil, natural gas,
5 and carbonates (Friedlingstein et al., 2019). For the fossil fuels, estimates of monthly
6 consumption are required, while for carbonates, production statistics are needed. In all
7 cases, apparent energy consumption approximates true consumption, omitting some minor
8 changes in stocks. For example, reported consumption of petroleum products is most likely
9 supply to the market, with stocks at petrol stations and in vehicles not accounted for. A
10 summary of the methodology is presented here, while full details are provided in the
11 Supplement, including a table of individual data sources.

12 While monthly coal consumption by utility power stations is reported (CEA, various years-b),
13 India does not report sub-annual total coal consumption, and apparent consumption must
14 therefore be calculated using data on production, imports, exports, and stock changes.
15 While these data are incomplete, they are sufficient to produce a reasonable estimate of
16 monthly coal consumption. Importantly, the goal of this analysis is an estimate of CO₂
17 emissions from all oxidation of solid fossil fuels, rather than the more limited emissions from
18 combustion for energy purposes, and this means it is unnecessary to separate out, for
19 example, coking coal used in steel manufacture, which is oxidised rather than combusted.

20 The energy data sources used include revised, historical data from the Indian Bureau of
21 Mines (2019), Ministry of Coal (various years-a), UN Statistics Division (2020); provisional
22 and revised data from Coal India Limited (CIL, various years), Singareni Collieries Company
23 Ltd (SCCL, various years), Ministry of Coal (various years-c, various years-b), and Ministry of
24 Mines (Ministry of Mines, various years); power station stocks from Central Electricity
25 Authority (CEA, various years-a, b); and international trade from the Directorate General of
26 Commercial Intelligence and Statistics (DGCIIS, 2020) and Department of Commerce (DOC,
27 2020), supplemented by recent provisional estimates reported by the media. While these
28 data sources combined allow a good estimate of production and stock changes of hard coal
29 with a lag of less than one month, lignite production data has a slightly longer lag, and
30 simple extrapolation is used to complete the picture for the most recent month or two
31 (Supplement Figure 15). It is assumed that the share of consumed coal that is not oxidised is
32 negligible.

33 Monthly data on production and consumption of petroleum products are available from the
34 Petroleum Planning and Analysis Cell (PPAC) of the Ministry of Petroleum and Natural Gas. In
35 all four categories, revised data are always used when available in preference to provisional
36 data. Since consumption data are available, the apparent consumption approach used for
37 coal is not required for petroleum products. All products except for bitumen and lubricants
38 are assumed to be fully oxidised; while it is known that some naphtha is used for production
39 of durable commodities, this share is not known, but may be discoverable using data from
40 the Annual Survey of Industries (MOSPI, no date).

1 PPAC also publishes monthly data on production, import, and supply of natural gas (PPAC,
2 various years-a, b). Some data on consumption by sector are also published, and these are
3 used to estimate the proportion of natural gas that is oxidised.

4 For carbonates, monthly data on clinker production are not available, so monthly cement
5 production statistics are combined with a time-varying estimate of the clinker ratio to
6 produce an estimate of monthly clinker production. Data on production of lime, glass, and
7 ceramics were not available, and emissions from these carbonate sources are therefore
8 omitted; India's second Biennial Update Report indicates these emissions combined
9 contributed 1.9% of fossil CO₂ emissions in 2013–14 (GOI, 2018).

10 Once monthly energy consumption and clinker production estimates are available, these are
11 converted to estimates of CO₂ emissions. For fossil fuels this requires first converting the
12 consumption in physical units to energy units using information from the International
13 Energy Agency (IEA) for coal and petroleum products (IEA, 2019c, b) and PPAC (no date) for
14 natural gas, and then applying emission factors from the Intergovernmental Panel on
15 Climate Change's 2006 guidelines (Gómez et al., 2006). For clinker production, the method
16 of Andrew (2019) is followed to estimate emissions from physical production in tonnes.

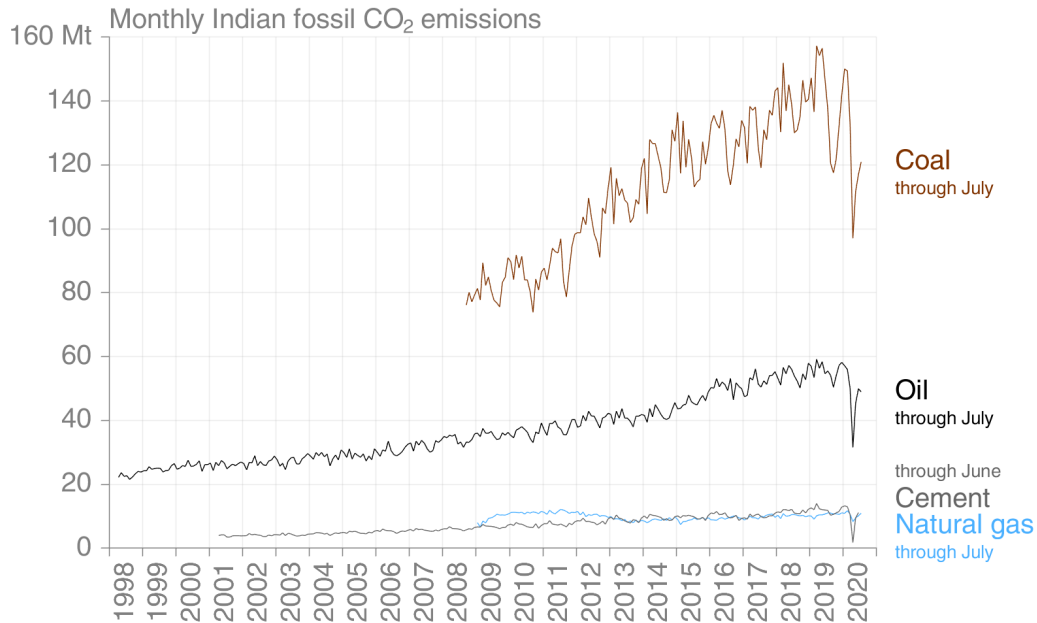
17 For complete details of the methodology, data sources used, comparisons of provisional and
18 revised energy data, comparisons of energy data from different sources, and more, see the
19 Supplement. The monthly energy and cement data collated here are available at
20 <https://doi.org/10.5281/zenodo.3894394> (Andrew, 2020a).

21 Results and Discussion

22 Following the described methods, I have assembled monthly CO₂ emissions estimates for
23 coal, oil, natural gas, and cement for India (Figure 1). The available data and methodology
24 allow estimation of emissions from coal from September 2008, oil from April 1998, natural
25 gas from January 2009, and cement from April 2001.

26 Emissions from oxidation of coal form the largest share of the total, rising from about 61% in
27 2010 to 66% in 2014, before levelling off to about 65% in 2019. Peak monthly emissions to
28 date were in March 2019 with 157 Mt CO₂ in the month. While emissions from coal grew at
29 an average rate of 6.2%/yr over 2009–2018, in 2019 they stalled, as electricity demand
30 dropped dramatically (Supplement Figure 41).

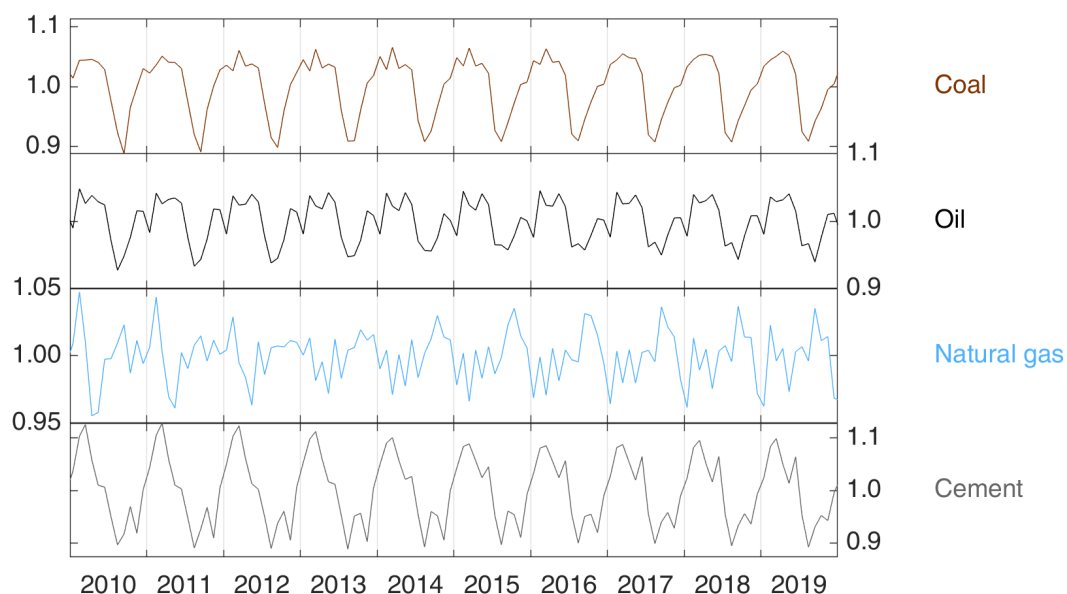
31 Emissions from oxidation of oil (petroleum products) are the next-largest source with about
32 25% of the total, reaching 50–60 Mt CO₂ per month in recent years. Emissions from natural
33 gas and cement production are both about 5% of the total.



1

2 *Figure 1: Final monthly CO₂ emissions by category. Source: Own calculations.*

3 While the monthly emissions series appear quite volatile, X-11 seasonality analysis (Darné et
 4 al., 2018; Shiskin et al., 1967; summarised in the Supplement) reveals strong, underlying
 5 seasonal patterns (Figure 2). Coal emissions reach a peak in March through May, before
 6 declining by up to 10% below the trend line for the typical southwest monsoon months of
 7 June through August and then picking up again towards the end of the year, and emissions
 8 from both oil and cement show similar though somewhat less smooth patterns. These
 9 emissions patterns largely result from the effects of the monsoon’s heavy rains, driving a
 10 decline in industrial, construction and transportation activities. Coal emissions are also
 11 driven down by the displacing effect of higher power generation from both hydropower and
 12 wind during the monsoon season. In addition, oil emissions exhibit a consistent dip in
 13 January and in March–April. Natural gas emissions show a substantially lower amplitude of
 14 seasonality, under $\pm 5\%$, with recent years showing a peak during the monsoon, apparently
 15 driven by increased fertiliser production during these months. The seasonality of natural gas
 16 emissions is also less stable over time, as supply constraints have changed considerably.
 17 Despite relatively clear derived seasonal signals, considerable volatility is superimposed on
 18 this seasonality in all emissions series (Figure 1).



1
 2 *Figure 2: Seasonality of the four emissions categories, derived using the X-11 method. Emissions in 2020 have been excluded*
 3 *from the analysis because of their strong deviations from historical patterns.*

4 Turning to calendar-year emissions, Table 1 summarises emissions by category and total CO₂
 5 emissions for India from 2009 to 2019. Each category has grown by 3%–5% per year over the
 6 last five years, although growth from year to year has not been smooth, with coal emissions
 7 stable in 2019. Total CO₂ emissions in India have grown from 1.6 Gt in 2009 to 2.6 Gt in 2019,
 8 at an annual growth rate of 3.9%. (An equivalent table for financial-year emissions is
 9 presented in the Supplement.) Over the same period, the CO₂-emissions intensity of India’s
 10 GDP has declined from 23.2 g/rupee to 18.1 g/rupee, about 2.2%/yr (Supplement Figure 40).

11 *Table 1: Calendar-year CO₂ emissions in India by category, million tonnes.*

Year	Coal	Oil	Natural gas	Cement	Total
2009	986	429	113	81	1608
2010	1019	435	134	86	1674
2011	1078	455	136	91	1762
2012	1226	485	126	100	1936
2013	1318	492	106	108	2023
2014	1447	507	107	116	2177
2015	1474	551	107	118	2249
2016	1541	609	113	123	2387
2017	1585	627	118	121	2451
2018	1670	651	123	139	2583
2019	1670	669	127	144	2609
CAGR 2015-19*	3.2%	5.5%	3.7%	4.5%	3.9%

12 * Continuous compounding and adjusted for leap years.

13 The monthly Indian fossil CO₂ emissions dataset produced here includes all but about 2% of
 14 anthropogenic fossil sources in the country, excluding emissions from decomposition of

1 fossil carbonates in the production of lime, glass and ceramics. The time lags of the
2 emissions estimates are at most two months, and under one month for coal, the most
3 important emissions source.

4 [Comparison with existing emissions estimates](#)

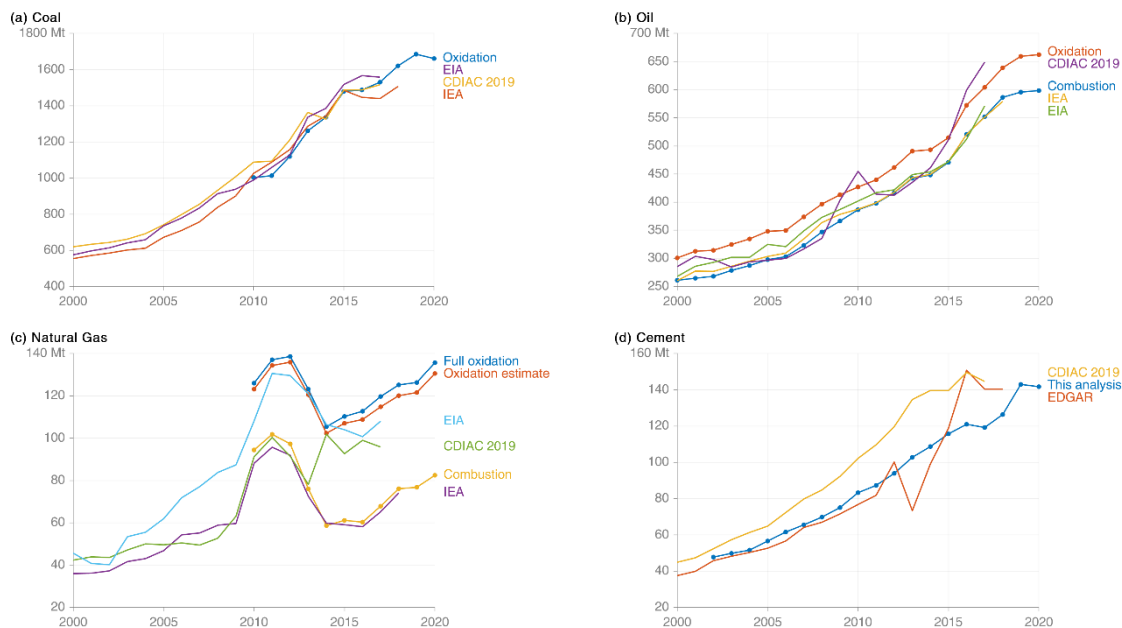
5 To compare the emissions estimates produced here with other datasets, I aggregate
6 monthly emissions to annual emissions against the Indian financial year, April–March. Figure
7 3 compares the emissions estimates produced here with those of the IEA (2019a) and CDIAC
8 (Gilfillan et al., 2019), and also EDGAR (Crippa et al., 2019) for cement, noting that all three
9 of these datasets report emissions in the period April 2017 through March 2018 as 2017
10 emissions.

11 For coal the method produces one series of oxidation emissions, and this is largely similar to
12 the estimates from both IEA and CDIAC (Figure 3a). In the final two years 2017–18 and
13 2018–19, however, IEA has lower estimates. Close investigation has revealed potential
14 errors in IEA’s reported stock changes in both years, amounting to about 30 Mt in 2018-19
15 (detailed in Supplement section 2); IEA’s 2018-19 estimate is indicated as being preliminary.
16 Furthermore, IEA’s data exclude changes of stocks at power stations, which exhibit large
17 swings (Supplement Figure 10). CDIAC’s estimate declines between 2012-13 and 2013-14, in
18 strong contrast to the growths in other series, and this is because of CDIAC’s use of UN
19 energy data, which has a sharp drop in energy content of coal (see Supplement: Coal energy
20 content).

21 For oil there are two series: combustion and oxidation (Figure 3b). The combustion series
22 lies very close to that of the IEA – which specifically includes only energy uses of oil products
23 – over the entire period. Oxidation emissions are on average about 50 Mt CO₂/yr higher
24 throughout the period, largely reflecting emissions from oxidised naphtha and petroleum
25 coke. CDIAC’s series exhibits quite a different trend.

26 The natural gas emissions series includes three estimates: combustion, oxidation, and full
27 oxidation (Figure 3c). The last of these assumes that all natural gas is oxidised, merely to
28 present a bounding case. The combustion series agrees well with IEA’s estimates, but again
29 the CDIAC series exhibits a very different trend, diverging sharply from 2013–14. The
30 oxidation series is significantly higher, largely reflecting the emissions from production and
31 use of nitrogen-based fertilisers. Emissions show a very prominent peak in 2010–2012, a
32 result of the rapid development of offshore gas field KG D6, but while this led to the
33 construction of a number of gas-fired power stations, production from this field dropped
34 substantially leading to greatly reduced domestic supplies and stranded power assets (MoP,
35 2019)(Supplement Figure 32).

36 For cement process emissions, the series is much lower than that of CDIAC, for reasons that
37 have been explained elsewhere (Andrew, 2019). EDGAR’s series appears to be reasonable up
38 until 2010–11, when national clinker production data are readily available, but thereafter
39 the trend appears unrealistic.

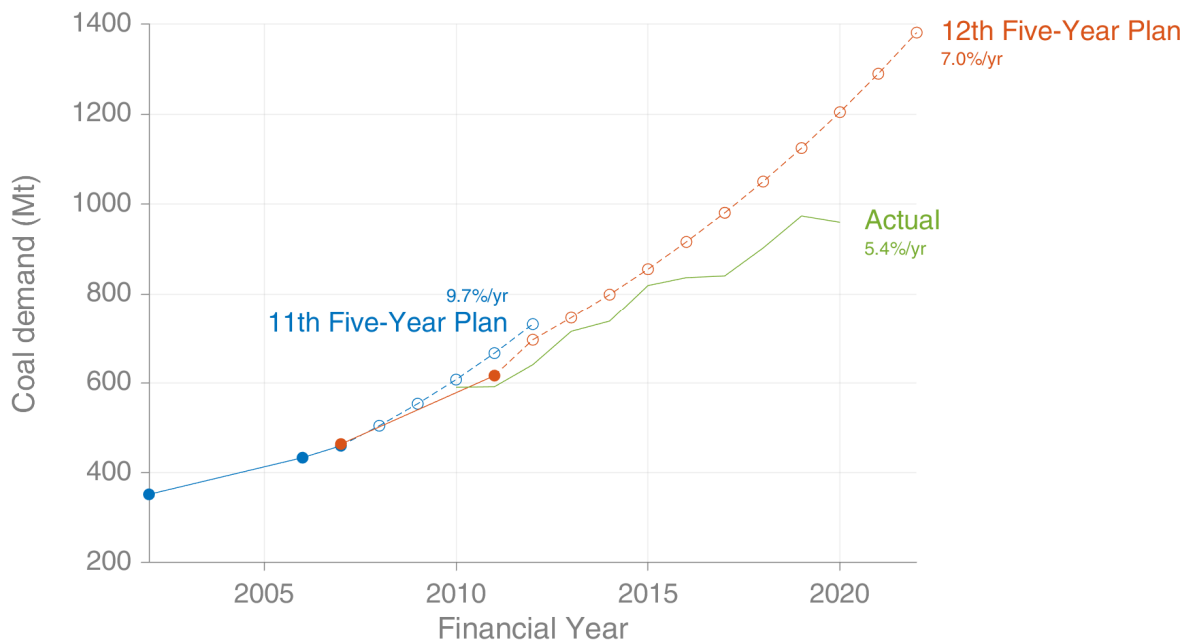


1 *Figure 3: Comparison of financial-year emissions estimates with other datasets, (a) coal, (b) oil, (c) natural gas, (d) cement.*
 2 *Sources: (Gilfillan et al., 2019; IEA, 2019a; Crippa et al., 2019; EIA, 2020), own calculations.*

3 The most recent Indian official estimate of total CO₂ emissions was presented in India's
 4 second biennial update report to the United Nations Framework Convention on Climate
 5 Change (UNFCCC), with 1.998 Gt in the financial year 2013–14 (GOI, 2018). In the analysis
 6 here, total CO₂ emissions in India in 2013–14 are estimated to be 2.04 Gt. While this is
 7 strikingly close, this is not a true measure of the accuracy of the method since some errors
 8 have cancelled: it is known that the emissions estimates generated here exclude some
 9 carbonate sources, while emissions from naphtha oxidation here might be overestimated,
 10 and there are other assumptions in various factors used here that introduce uncertainty.
 11 Nevertheless, this match with the official total is encouraging.

12 [Deviations from forecasts](#)

13 If official forecasts of growth in hard coal demand had played out, demand would have been
 14 more than 20% higher in 2019–20, with consequently higher emissions (Figure 4). These
 15 forecasts were based on assumptions of underlying growth in the economy of as much as
 16 10%/yr (Ministry of Coal, 2011). In fact, the report on coal and lignite for the 12th five-year
 17 plan included a second scenario with much higher demand growth, reaching 1200 Mt
 18 already in 2016–17. While growth in demand followed the projection reasonably closely
 19 until 2014–15, it has since slowed markedly.



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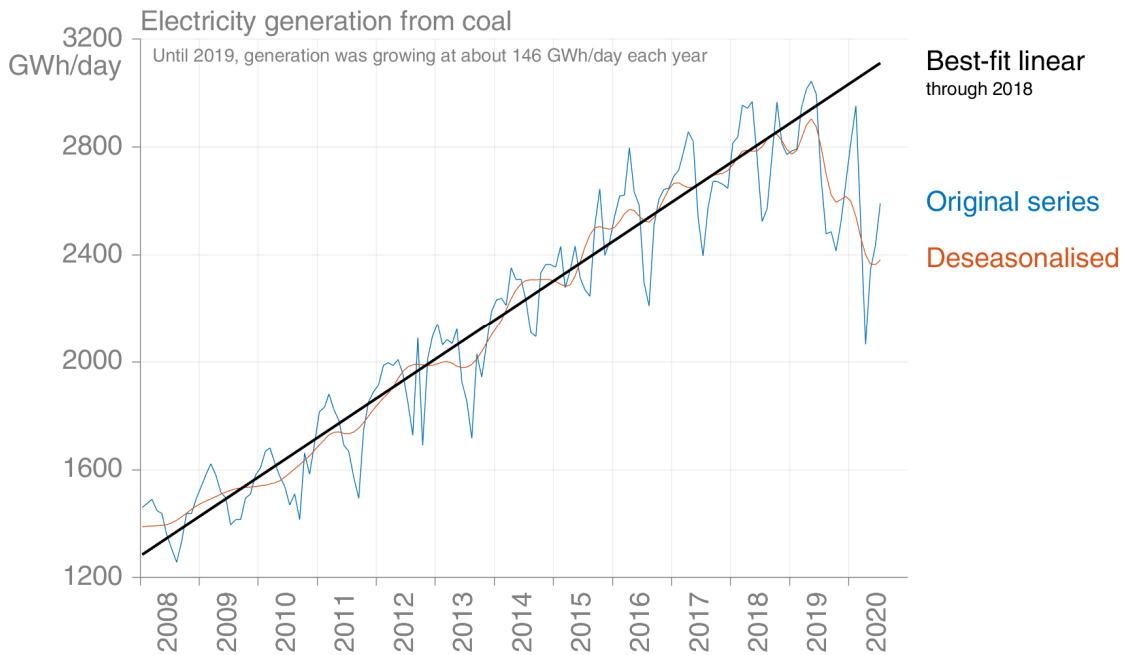
2 *Figure 4: India's hard coal demand. Filled circles and hollow circles show reported and projected demand in two five-year*
 3 *plans, while the green line shows actual demand, and annual growth rates are indicated. Demand does not equal*
 4 *consumption because of changes of stocks at power stations and industry. Source: Ministry of Coal (2006, 2011), own*
 5 *calculations.*

6 There were certainly significant tailwinds in support of high growth in both demand and
 7 supply of coal, such as strong political will, the 25%/yr annual average growth in coal imports
 8 2011–2014, the rapid construction of new coal-fired capacity 2010–2016 (Supplement Figure
 9 38), high targets for coal mining, the opening up of coal mining to competition, and
 10 significant expansion of the labour pool, among others. But these faced an array of
 11 headwinds constraining growth, including difficulty in acquiring land and environmental
 12 permits, local protests, difficulty obtaining finance (CEA, 2019), rail under-capacity, debt,
 13 subdued demand, unpredictable monsoon rains, “Coalgate” (illegal government coal block
 14 allocations; Gilbert and Chatterjee, 2020), the dramatic fall in renewables prices, and large
 15 economic shocks such as 2016’s demonetisation, 2017’s GST introduction, the shadow bank
 16 crisis starting in 2018 (Subramanian and Felman, 2019), and 2020’s COVID-19 pandemic. In
 17 comparison, China’s much larger consumption of coal grew by almost 9%/yr over 2000–2010
 18 (NBS, 2019).

19 As suggested by Figure 5, growth in electricity generation from coal – recently about 75% of
 20 all coal consumption – has been more linear than exponential in the last ten years.

21 Figure 5 also shows how significant the deviation in coal generation was in the latter half of
 22 calendar-year 2019, also clear in Figure 1. From 2008 to 2018, the largest deviation of
 23 monthly electricity generation with seasonality removed from the trend line is 110
 24 GWh/day, while in 2019 it peaked at over 390 GWh/day. Generation from hydropower was
 25 17% higher in 2019 than in 2018, partly a result of a very heavy southwest monsoon (IMD,
 26 2019). But total electricity demand was down by almost 3% in the second half of 2019
 27 compared to the same period in 2018, and more than 13% down in October 2019 (POSOCO,
 28 2020), probably driven by a stalling economy (Subramanian and Felman, 2019), with value-

1 added growth in the manufacturing sector below zero in the period July to December 2019
2 (MOSPI, 2020).

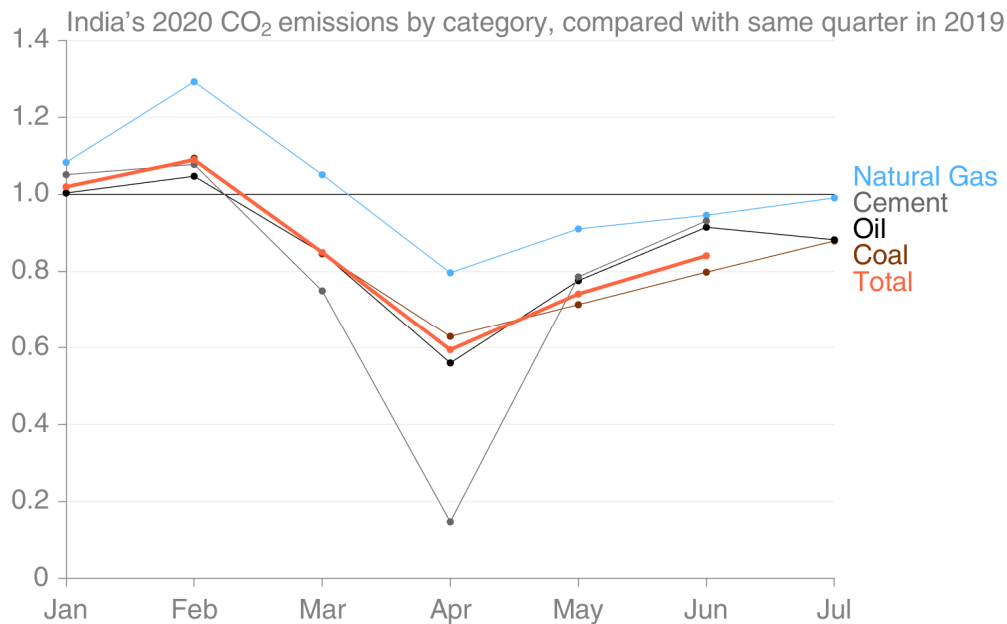


3
4 *Figure 5: Average daily electricity generation from coal by month, divided by month length, deseasonalised, and a best-fit*
5 *linear regression. Source: Central Electricity Authority, own calculations.*

6 The seasonal patterns of emissions generally follow the monsoon, particularly with less
7 electricity generation from coal. Rather than being due to decreased demand or difficulty
8 producing electricity from coal during the monsoon, the reason for this is higher generation
9 from both hydro and wind, both of which peak during the monsoon season. In fact,
10 electricity demand is highest through summer and lowest in winter (Supplement Figure 41),
11 with energy required in India for summer cooling substantially higher than energy required
12 for winter heating (Gaur et al., 2016).

13 COVID-19 effects

14 March would usually be one of the months of the year with the highest coal emissions
15 (Figure 2), but in 2020 this was affected by Covid-19 measures. India introduced a
16 nationwide lockdown (curfew) on March 25th, although some areas introduced lockdowns in
17 the days before (Roy and Phartiyal, 2020; Varadhan, 2020). Initially the lockdown was to be
18 for three weeks, but was repeatedly extended until the end of May (The Tribune, 2020), and
19 thereafter followed by a phased 'unlocking' (The Hindu, 2020). Largely as a result of
20 substantially reduced activity, and despite the lockdown only affecting about one-third of
21 the month, CO₂ emissions from coal in March 2020 were 15% lower than in March 2019
22 (Figure 6). But April saw the largest drops in emissions, with the lockdown having very
23 substantial effects on almost all areas of economic activity: total CO₂ emissions were down
24 40% compared to April 2019, with cement production dropping by 85%. Already in May
25 emissions started to rise again as constraints on activity were reduced, but the recovery is
26 far from complete, with July's consumption of oil products declining again compared to
27 June.



1

2 *Figure 6: Quarter-on-quarter changes of CO₂ emissions by category during the first months of 2020.*

3 New approaches have recently been used to estimate the effect of the world's pandemic
 4 responses on global CO₂ emissions, based on collation of partial activity data for use as
 5 proxies, such as electricity generation data or travel indices (Le Quéré et al., 2020; IEA,
 6 2020a; Liu et al., 2020). Such methods are suitable and useful for estimation of global effects
 7 in near real-time when more accurate and detailed data are not available, and the monthly
 8 estimates reported in the present work may be used to validate these alternative estimates
 9 of India's CO₂ emissions. Furthermore, given the close links between emissions of CO₂ and
 10 other air pollutants, studies on changes in air pollution due to India's lockdowns, could be
 11 cross-validated with the monthly CO₂ estimates reported here (e.g., Sharma et al., 2020;
 12 Mahato et al., 2020).

13 Sources of uncertainty

14 There are several sources of uncertainty in these emissions estimates, which can be divided
 15 into four categories. First is the omission of some emissions sources. This analysis has
 16 excluded emissions from some carbonates, estimated to be equivalent to less than 2% of
 17 India's total CO₂ emissions. Further, some imported non-energy goods containing fossil
 18 carbon are excluded. While the case of Iceland shows clearly that imports of carbon anodes
 19 used in aluminium manufacture can be important (Andrew, 2020b), these are not imported
 20 by India (DGCIS, 2020). India does import urea from China, and the approach used here will
 21 not capture emissions from its use in agriculture; however, the amount is likely to be below
 22 2 Mt/yr (see Supplement). A further missing source is that of low-temperature oxidation and
 23 spontaneous combustion of coal at mines, but available evidence suggests these would be
 24 significantly less than 1% of India's CO₂ emissions (Day et al., 2010; IPCC, 2019; Singh, 2019).

25 Second is use of provisional data and extrapolation before revised data are available.

26 Revisions of coal, the most important emissions source, are in general relatively minor, and
 27 use of provisional data along with the methods used here to fill gaps are unlikely to

1 introduce significant error (see Supplement). Lignite production is relatively small and stable,
2 so its extrapolation is not expected to introduce significant uncertainty. Moreover, if
3 monthly press releases of mineral production have indeed recommenced, the lignite
4 uncertainty will be largely removed in future, except for the most recent month(s).

5 Third is that of the revised data, effectively measurement error. While energy and emissions
6 data in China serve as a cautionary example (Korsbakken et al., 2016), and India's economic
7 production data face heavy revisions (Supplement Figure 39), these issues are not expected
8 to affect India's energy and emissions data. One of the reasons for China's high data
9 uncertainty is the very large number of enterprises involved, but in India energy and cement
10 production are highly concentrated and closely monitored. As examples, two coal-mining
11 companies, both state-owned, account for close to 90% of all coal production, and three
12 state-owned fuel retailers account for about 90% of India's retail fuel sales (Reuters, 2020).
13 While there have recently been claims of official tampering with economic statistics in India
14 (Nadeem, 2019; The Telegraph, 2019), and incorrectly calculated productivity data (Singh,
15 2012), there is as yet no evidence of manipulation of energy or industrial production data.

16 The final category of uncertainty is in the emission factors, energy contents, and oxidised
17 fractions used. This is perhaps the largest source of uncertainty, particularly the energy
18 content of domestic hard coal, for which data have been scarce and inconsistent, and broad
19 sampling efforts in recent years pointing to significant errors, with data from 2016-17
20 suggesting declared average coal quality was 10% higher than the true value (see
21 Supplementary section: Coal energy content). More work is required to generate a more
22 reliable time series of coal quality in India, but in the absence of additional historical
23 sampling of coming to light, estimates will have to be made. A further source of uncertainty
24 in this category is the assumption that all naphtha is oxidised, which potentially leads to an
25 overestimate in the order of 1–2 MtCO₂/month.

26 The combination of data availability and assumptions made mean that coal emissions can be
27 estimated with the shortest lag, within a week of the end of the month. Oil, natural gas, and
28 cement emissions are usually delayed an additional month. There are two main reasons that
29 coal emissions have a short lag. Firstly, coal-fired power stations have faced critical
30 shortages at times and are monitored very closely, and secondly, the two largest mining
31 companies, which report within a day of the month closing, make up the great majority of
32 production. While short-lag emissions estimates require extrapolation of some components
33 (e.g., lignite production), and use provisional data, as reported and revised data become
34 available, these are incorporated into the estimation procedure used here.

35 While there are some identified deficiencies in the emissions estimates here, including the
36 exclusion of emissions from use of limestone apart from in cement clinker production,
37 comparisons with annual estimates from other sources, and in particular India's official
38 reporting to the UNFCCC, suggests relatively good accuracy and therefore a high level of
39 usefulness.

40 Conclusions

41 India publishes more energy data than many other developing countries, providing a wealth
42 of information for management, policy analysis and scientific research. Nevertheless, there

1 remains significant room for improvement in the quality of these publications. Possible
2 avenues for such improvement include: (i) Publishing more data in machine-readable
3 formats, rather than just as tables in PDF documents or in web-page tables, (ii) Providing a
4 way for the public and researchers to ask questions about or report errors in data,
5 establishing direct contact with those responsible for the data, to facilitate crowd-sourcing
6 of quality assurance, (iii) Encouraging collaboration in data preparation and presentation
7 across ministries to prevent errors creeping into reports, (iv) providing more documentation
8 of reported data, (v) Reducing use of manual copy-pasting and typing, and automating as
9 much as possible with both automatic and manual quality assurance, (vi) Standardising the
10 use of important terms (e.g. 'consumption') across reports from different departments to
11 prevent confusion, (vii) Making available older, non-electronic reports (e.g. Monthly Abstract
12 of Statistics), online through use of digitisation.

13 The monthly, short-lag estimates of India's CO₂ emissions produced here will likely prove
14 useful for tracking the country's progress against its nationally determined contribution
15 under the Paris Agreement, but will also be useful for analysis of the drivers of India's
16 emissions both historically and in future. Calendar-year estimates derived from these are
17 also better aligned to the global datasets into which India's emissions are incorporated.

18 The future pathway of India's CO₂ emissions is highly uncertain. But India is developing
19 rapidly in a world that – largely because of emissions in other countries – is carbon
20 constrained. As India's population grows, as roads, railways and houses are built, as both
21 vehicles and houses are electrified, as solar panels and wind turbines are installed, and as
22 new coal mines are opened, tracking CO₂ emissions monthly will allow a closer observation
23 on the consequences of these changes.

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29 Data Availability

30 All monthly input data used in the analysis, in addition to the monthly emissions estimates,
31 seasonality analysis results, and a copy of the Supplement, are available at
32 <https://doi.org/10.5281/zenodo.3894394> (Andrew, 2020a).

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