Referee #1

Overall comments Overall, this is a useful and important paper, and of high scientific quality and policy importance.

It would be good to include a table with sources and hyperlinks if consistent with the journal policy.

Yes, good idea.

- Changes made: I have added a table to the Supplement, "India activity data sources."

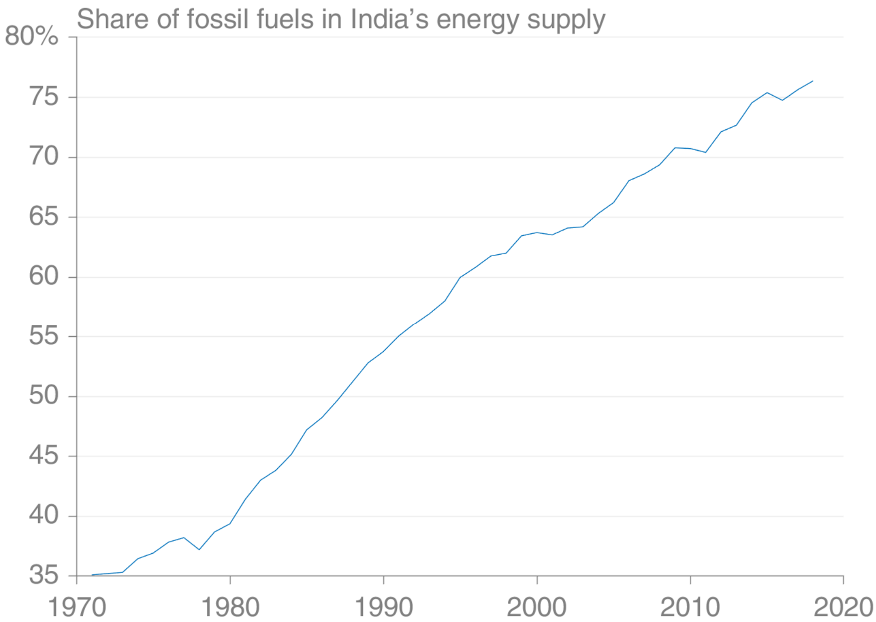
From a policy-making point of view, I believe it would be useful for the paper to make a few observations on the ways in which India's data presentation could be best improved. Frustration with the disparate sources and poor presentation are widespread among the policy community and providing guidance on improvement would be valuable.

- Changes made: Added paragraph to the Conclusions: "India publishes more energy data than many other developing countries, providing a wealth of information for management, policy analysis and scientific research. Nevertheless, there remains significant room for improvement in the quality of these publications. Possible avenues for such improvement include: (i) Publishing more data in machine-readable formats, rather than just as tables in PDF documents or in web-page tables, (ii) Providing a way for the public and researchers to ask questions about or report errors in data, establishing direct contact with those responsible for the data, to facilitate crowd-sourcing of quality assurance, (iii) Encouraging collaboration in data preparation and presentation across ministries to prevent errors creeping into reports, (iv) providing more documentation of reported data, (v) Reducing use of manual copy-pasting and typing, and automating as much as possible with both automatic and manual quality assurance, (vi) Standardising the use of important terms (e.g. 'consumption') across reports from different departments to prevent confusion, (vii) Making available older, non-electronic reports (e.g. Monthly Abstract of Statistics), online through use of digitisation."

Page 1, Lines 24-27: It is worth mentioning here that India's carbon intensity of energy supply has also increased over the last 10-15 years, as the share of hydro electricity has declined, the share of coal increased, biomass transition in the residential sector has progressed, and emissions intensive fuels in industrial final energy consumption has increased.

- Changes made: I have added a clause to the end of this sentence.
  "…including the transition from biomass to petroleum fuels, continuing the long-term increase in the share of India's energy supplied from fossil fuels (see SI Fig 41)"

where the new figure in the Supplement is as below



Page 1, Line 28: Better not to say "small renewables" as India has some of the largest utility scale solar parks in the world.

- Changes made: Changed "small renewables" to "variable renewables".

Page 1, Line 40: this list of references should include the India GHG Platform initiative: http://www.ghgplatformindia.org/

- Changes made: added a reference to the GHG Platform India.

Page 3, Line 25-27: it may be possible to get naptha consumption for production of durable commodities in the Annual Survey of Industries macro-data, and apply this ratio to monthly naptha consumption data.

I don't have access to this, so I've simply suggested it as a possibility.

- Changes made: Added text ", but may be discoverable using data from the Annual Survey of Industries (MOSPI, no date)"

Page 3, Line 37-40: It is known that the calorific value of Indian coal varies greatly between different coal grades, and is generally understood to be declining over time as the quality of domestic mined coal declines. Some discussion of improved estimates of the calorific value of Indian coal should be made.

I have tried to keep most of the detail of the methods in the Supplement, since they're so extensive. I have added the following text and figure to the Supplement.

- Changes made: Added to Supplement:

  Focusing on hard coal, Figure 17 compares a number of different datasets, demonstrating wide divergence in reported coal quality. It seems clear that coal quality overall has declined in the last 50 years, partly as a result of the significant increase in the share of lower-cost production from open-cast mines (77% in 1998/99 to 94% in 2018/19, according to the Coal

Directories), but the IEA's figures in the 1970s and 1980s are markedly different from those reported in all but the most recent Energy Statistics yearbooks.

It is unclear how the Energy Statistics derives average coal quality, but it appears that the IEA has used the annual data on production by coal grade, combined with average energy contents for each grade. This supposition is based on the author doing exactly that with the data provided by the Coal Directories: from 2013, estimates made this way match very closely to those of the IEA. Before 2013, India used a less-detailed grading system. The author's estimates for that earlier period assume that the average energy content did not jump dramatically upwards from 2012 to 2013, something that seems unlikely, and this leads to a difference with the IEA's estimates in that period.

In 2016, Coal India introduced quality assurance routines, sending samples to third-party laboratories for assessment of energy content, a scheme called 'Unlocking Transparency by Third Party Assessment of Mined Coal' (UTTAM). This scheme was introduced after repeated complaints by power station operators that received coal was of lower than the declared (and paid-for) energy content. With 51% sampling coverage in the 2017-18 year, UTTAM results showed that the average analysed energy content was 6% lower than the average declared energy content. Back-calculation of energy content from hard coal production in both energy and mass terms suggests that the Energy Statistics report has subsequently simply used this much lower average for the entire period reported (2006-07 through 2018-19 in the 2020 edition).

The UN Statistics Division's Energy Yearbooks report much higher energy contents in 2012 and 2013, with these numbers having been reported to them by Indian officials; subsequent values are taken from IEA reports (pers. comm., Leonardo Rocha Souza, 16 July 2020). This sharp drop in the UN data for India's energy content translates directly into a sharp drop in production from 2012-13 to 2013-14, which propagates directly to CDIAC's estimates of emissions from solid fuels for India.

Given the insufficient sampling until the introduction of the UTTAM scheme in 2016, it is impossible to say with any uncertainty what the energy content of India's hard coal was before then, but it is unlikely that the constant low value used by the Energy Statistics yearbook is correct.

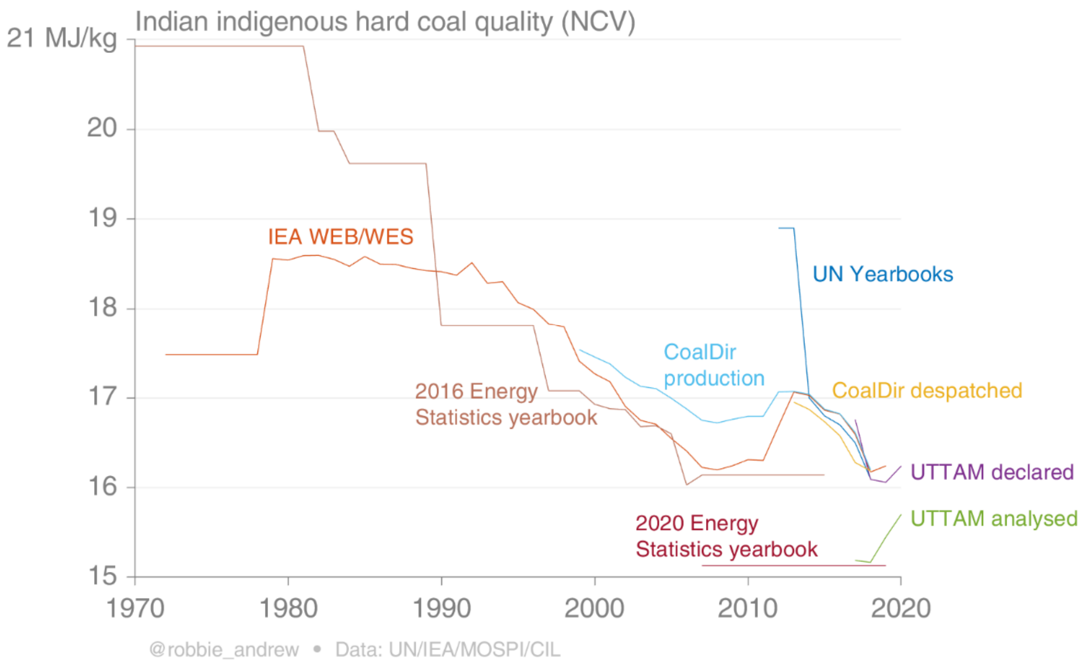


Figure 17: Comparison of energy content of Indian hard coal from various datasets. Data plotted for the Coal Directory ('CoalDir') are the author's estimates derived from data on production by grade. IEA WEB/WES is the World Energy Balances (energy units) and World Energy Statistics (mass units).

Page 4, Lines 23-26, and Page 5, Line 1: it is worth noting that the observed monsoonal seasonality for coal, cement and oil is due in part to the same reason: economic activity in industry and construction declines during monsoon, implying reduced power demand and transport requirement. In additional residential electricity consumption declines as the temperature drops.

Yes, good point, although I don't see a reduction in total electricity demand during the monsoon season. In 2015–2018 it wasn't until October or November that demand dropped as winter temperatures arrived. A drop in residential consumption because of reduced AC use is presumably offset by increases in other sectors' demand. See the figure towards the end of the Supplement.

- Changes made: Added the following sentences: "These emissions patterns largely result from the effects of the monsoon's heavy rains, driving a decline in industrial, construction and transportation activities. Coal emissions are also driven down by the displacing effect of higher power generation from both hydropower and wind during the monsoon season."

Page 7: Lines 11-18: It would be good to discuss in a little detail, which errors may have cancelled. In addition, it would be good to explore the BUR to look at what emissions factors have been used for Indian coal, and how these compare with those used in this paper.

With regard to error cancellation, I already had the following text "it is known that the emissions estimates generated here exclude some carbonate sources" and add a further clause for some additional information.

- Changes made: Added clause "while emissions from naphtha oxidation here might be overestimated"

As for the BUR, I have added the following paragraph to the section in the Supplement that discusses energy contents.

- Changes made: Added paragraph to Supplement:

  Emissions from coal in India's Second Biennial Update Report (BUR) are derived using country-specific energy contents and emission factors (GOI, 2018). The Report is unclear as to whether these factors, reported in tables 2.3 and 2.4, are only used for domestic coal, or whether they are averages for total coal supply, including imports. Imported coal is of higher quality than India's domestic coal, and this likely explains why the energy contents provided in table 2.3 for coking and non-coking coal (23.66 and 18.26 MJ/kg, respectively) are somewhat higher than those reported by the IEA for domestic coal (20.50 and 16.69 MJ/kg). The BUR's reported energy content of lignite, which is entirely domestic, is 9.80 MJ/kg, very similar to the IEA's 9.55 MJ/kg, and somewhat lower than the Energy Statistics' value of 11.37 MJ/kg.

Page 8: Lines 6 -16: This paragraph confused headwinds and tailwinds to coal supply with headwinds and tailwinds to coal demand. "difficulty in acquiring land and environmental permits, local protests, difficulty obtaining finance" relates to coal supply, while "large economic shocks such as 2016's demonetisation, 2017's GST introduction and 2020's COVID-19 pandemic" relate to coal demand through channel of general macroeconomic growth. I believe the latter is much more important to understanding the deviation from forecast demand. In this regard, the paper could cite briefly some of the macroeconomic literature explaining India's growth slowdown (for example: https://www.hks.harvard.edu/centers/cid/publications/facultyworking-papers/india-great-slowdown)

I do agree that this paragraph discusses headwinds and tailwinds of both supply and demand, but that was in fact intentional. However, since the previous paragraph is very specifically about demand, this transition was not made clear to the reader.

- Changes made:
  Added "in both demand and supply of coal" to the first sentence of the paragraph.
  Added "the shadow bank crisis starting in 2018 (Subramanian and Felman, 2019)"

Page 10, Lines 23-26: As discussed above, calorific value and emissions factor estimates for Indian coal may lead to significant uncertainties and are worth reviewing here.

- Changes made: Added text: "This is perhaps the largest source of uncertainty, particularly the energy content of domestic hard coal, for which data have been scarce and inconsistent, and broad sampling efforts in recent years pointing to significant errors, with data from 2016-17 suggesting declared average coal quality was 10% higher than the true value (see Supplementary section: Coal energy content). More work is required to generate a more reliable time series of coal quality in India, but in the absence of additional historical sampling of coming to light, estimates will have to be made."

Referee #2

General comments: The paper addresses an extremely important aspect of the timeliness of India's GHG inventory reporting. Several data limitations and inconsistencies are rightly identified and an effort has been made to solve these, e.g. the differences in reporting intervals of coal production. The dataset provided here is extremely useful not just as activity data for CO2 emissions but also for other GHGs. Overall, the author has put in a great deal of effort into the paper and the supplement, which must be appreciated.

Specific comments: Attending to some of the concerns below, to the extent possible, might further enhance the usability of this dataset:

1. Page 1, Lines 27-31 note the role of renewable growth towards the stabilizing trend in CO2 emissions. It is also useful to point out here the opinion of some experts from the literature that the shortage in coal production has taken due to a combination of complicated factors (land rights, political issues etc.). The following case study makes an excellent assessment of this, and I recommend 1-2 lines on such factors:

Carl, J. (2015). 4 The causes and implications of India's coal production shortfall. The Global Coal Market: Supplying the Major Fuel for Emerging Economies, 123-163.

I believe the point the reviewer suggests I make is largely already made later, in the section "Deviation from forecasts", where I say "But these faced an array of headwinds constraining growth, including difficulty in acquiring land and environmental permits, local protests, difficulty obtaining finance (CEA, 2019), rail under-capacity, debt, subdued demand, unpredictable monsoon rains, "Coalgate" (illegal government coal block allocations; Gilbert and Chatterjee, 2020), the dramatic fall in renewables prices, and large economic shocks such as 2016's demonetisation, 2017's GST introduction, the shadow bank crisis starting in 2018, and 2020's COVID-19 pandemic."

Nevertheless, I agree that the point is usefully made already in the introduction.

- Changes made: Added sentence "In addition, the difficulty India has faced in ramping up domestic coal production has probably also restrained emissions growth (Carl, 2015)."

2. In Page 1, Lines 38-40, it might be useful to point out (if applicable), that the thirdparty reporting through agencies by IEA might not be open-access and that adds to the utility of this dataset.

- Changes made: Added text ", and not all of these are freely available"

3. Page 3, Lines 3-9: I appreciate the explicitness in mentioning the difference in accounting only for combustion based emissions and overall oxidation. In the same vein, a line could be added here (or later) that future inventories could add additional emissions such as CO2 emissions due to spontaneous emissions from coal mines; see following the reference and the recent 2019 IPCC Refinements:

Carras, J. N., Day, S. J., Saghafi, A., & Williams, D. J. (2009). Greenhouse gas emissions from low-temperature oxidation and spontaneous combustion at open-cut coal mines in Australia. International Journal of Coal Geology, 78(2), 161-168.

Singh, A. K. (2019). Better accounting of greenhouse gas emissions from Indian coal mining activities: A field perspective. Environmental Practice, 21(1), 36-40.

This is very interesting. Certainly, future official inventories should attempt to include estimates of emissions from both low-temperature oxidation and any resulting spontaneous combustion of coal. The Australian paper the reviewer cites concludes that CO_2 emissions from spontaneous combustion in the open-cast mines sampled ranged between 0.01% and 1.34% of the amount of CO_2 from eventual combustion of the mines' produced coal. These are very small amounts.

The IPCC 2019 Refinements provide several default factors. Using the average factor for surface mining, 0.44 m^3CO_2/tonne of coal produced, would result in emissions that are 0.03% of India's total CO_2 emissions. The paper the reviewer cites by Singh reports a higher value, from sampling three Indian mines, but this would still result in emissions less than 0.5% of India's total.

Given the very small magnitude of these emissions sources, it's unlikely that I would include these in future revisions of this dataset, when there are much larger sources of uncertainty in this analysis. But I will add this to the section on uncertainty in the estimates.

- Changes made: Added a sentence in the discussion of sources of uncertainty: "A further missing source is that of low-temperature oxidation and spontaneous combustion of coal at mines, but available evidence suggests these would be significantly less than 1% of India's CO_2 emissions (Day et al., 2010; IPCC, 2019; Singh, 2019)"

4. Page 3, Line 41 of main manuscript and section 6 of the Supplement: The authors note using the 2006 IPCC Guidelines default emission factors. However, Indian experts have developed national emission factors which have been vetted and included in the IPCC Emission Factor Database. I recommend using these emission factors either directly or at least for a sensitivity analysis to look at the difference between default and country-specific emission factor.

Indeed, India's reporting to the UNFCCC is based on national coal energy contents and emission factors. However, the information provided in the BUR is insufficient to make use of these, and there has been considerable change over time, not reported in the BUR, which is only for a single year. For now, I will retain the factors I have used, but these can readily be changed in future revisions of this dataset. I have added some discussion of these factors, in addition to significantly extending the discussion of coal energy content in the Supplement.

- Changes made: Added paragraph to Supplement:

  Emissions from coal in India's Second Biennial Update Report (BUR) are derived using country-specific energy contents and emission factors (GOI, 2018). The Report is unclear as to whether these factors, reported in tables 2.3 and 2.4, are only used for domestic coal, or whether they are averages for total coal supply, including imports. Imported coal is of higher quality than India's domestic coal, and this likely explains why the energy contents provided in table 2.3 for coking and non-coking coal (23.66 and 18.26 MJ/kg, respectively) are somewhat higher than those reported by the IEA for domestic coal (20.50 and 16.69 MJ/kg). The BUR's reported energy content of lignite, which is entirely domestic, is 9.80 MJ/kg, very similar to the IEA's 9.55 MJ/kg, and somewhat lower than the Energy Statistics' value of 11.37 MJ/kg.

5. With respect to Figures 12-14 of the supplement, is it possible to decompose the coal production further into surface- and underground-mined coal (either directly or through % estimates from other sources)? That would make the dataset immediately usable for other applications such as methane estimation studies or life-cycle GHG studies.

Yes, that would be useful. Unfortunately, I've found no data that show this split on a sub-annual basis. The *Coal Directory* has data on the share of open-cast and underground production, available from fiscal year 1999, but I have found no monthly breakdown of these. One could make some assumptions, but I have no information on, for example, whether underground mines are less or more affected by the monsoon than open-cast mines. I note that the IEA in its 2020 energy data edition has introduced a fugitive dataset, including methane emissions from coal mining, reaching 1435 kt in 2018.

- Changes made: none.

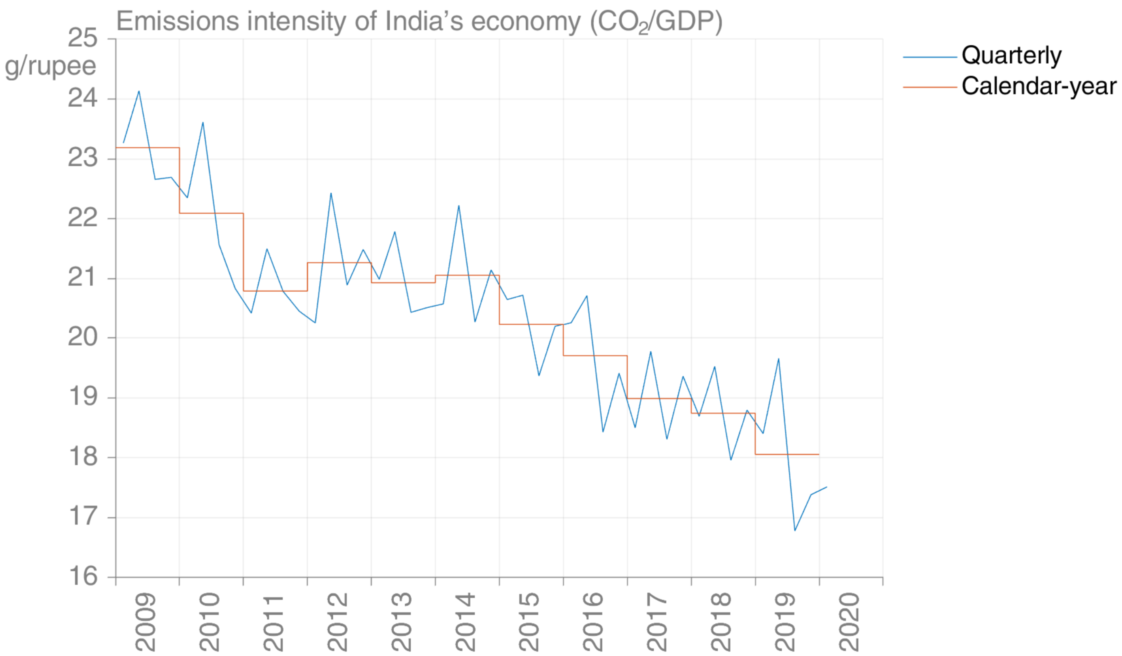
6. In Page 5, line 4: Why does the author apportion the peaking of natural gas emission rise to use as peaking plants? I understand that the use of word “perhaps” conveys uncertainty but I welcome the author to convey the reason for their speculation.

I’m glad you questioned this. Spurred by this comment, I have looked more closely. The monthly data available since 2014 show no indication of any consistent seasonal cycle in natural gas usage for power consumption, so this suggestion of peaking plants was mistaken. However, fertiliser production, which accounts for about a third of natural gas consumption, does exhibit a distinct seasonal cycle, peaking in monsoon months, presumably in response to agricultural demand. I have reworded the text as follows:

- Changes made: Replaced “perhaps being used as peaking plants” with “apparently driven by increased fertilizer production during these months”

7. Page 5, Lines 10-14 make important observations about variation of CO2 emissions per year. The Government of India’s INDC mentions its target as reduction of the GHG intensity (or GHG/GDP) by 33-35%. Therefore, in addition to comparing the GHG emissions, it might be useful to compare the CO2 emissions per unit GDP as well to gauge consistency with the above goal.

- Changes made:
  Added the following figure to the Supplement:



  Added a sentence to the manuscript: “Over the same period, the CO_2-emissions intensity of India’s GDP has declined from 23.2 g/rupee to 18.1 g/rupee, about 2.2%/yr (Supplement Figure 40).”

8. Page 7, Lines 1-2 note the local peak due to KG-D6 basin. Additionally, do the authors have reason to believe that some emissions in the gas sector might have been due to the increase in coalbed methane production as well?

Data from the Ministry of Petroleum and Natural Gas’s Indian Petroleum & Natural Gas Statistics 2018-19 provide CBM production since 2008, and while production has increased from 13 MMSCM to a high so far of 735 MMSCM in 2017/18, the peak proportion of CBM in total natural gas production was only 2.3%, smallest (<0.5%) during the years of growth in offshore production. So no, CBM is not significant here.

- Changes made: none.

9. Page 7, Lines 3-4 mention stranded assets and it might also be useful to mention additional literature discussing potential stranded assets as climate restrictions come into force:

Malik, A., Bertram, C., Després, J., Emmerling, J., Fujimori, S., Garg, A., ... & Shekhar, S. (2020). Reducing stranded assets through early action in the Indian power sector. Environmental Research Letters, https://doi.org/10.1088/1748-9326/ab8033.

This looks like an interesting article, thank you. When I raise the point about stranded assets, it is as a sort of footnote in the context of the substantial rise and fall of natural gas production. The issue of stranded power station assets in general is much larger, and not something I think I should go into in this paper. Unfortunately, Malik et al don't mention the stranding of natural gas fired power stations, otherwise it would have been logical to add this reference.

- Changes made: none.

10. In Page 9, Lines 12-21 where authors point out the COVID-19 effects, it could also be mentioned that this dataset could be used as a correlation to the top-down effects on air pollution reported for Indian studies. This, in my view, further enforces the need for such a dataset.

Yes, I agree.

- Changes made: Added sentence "Furthermore, given the close links between emissions of CO_2 and other air pollutants, studies on changes in air pollution due to India's lockdowns, could be cross-validated with the monthly CO_2 estimates reported here (e.g., Sharma et al., 2020; Mahato et al., 2020)."

11. Page 10, Lines 2-4 make an interesting point about imported urea use. Is it fair to assume that this is another reason why the emissions data in the paper track with the government data as it is also the case for the UNFCCC data reporting practices?

Yes, in this paper I'm trying to include all significant sources of CO_2 emissions in India. In India's reporting to the UNFCCC they are required to do this, and the IPCC Guidelines for inventory construction include such details as calculating emissions from use of urea. The IPCC approach to emissions from use of urea in agriculture is agnostic to where the urea is made, and instead calculates emissions from all urea purchased by agriculture.

- Changes made: none.

Referee #3

This paper is a timely consideration of a significant issue: the status, quality, timeliness and implications of India's greenhouse emissions data, with a very useful summary of the compoinent contributions and recent trends. It makes a valuable contribution and underscores the importance of making data available in a regular manner with sufficient detail to ensure its accuracy and reliability.

Specific comments:

Page 1 line 28: Given the size of some of the utility-scale PV plants, the term "small renewables" should be re-considered.

- Changes made: Changed "small renewables" to "variable renewables".

Page 1 lines 29-30: It might be worth including India's reverse auctions and innovations such as round-the-clock tenders in the list of contributory factors in renewables growth.

I'll avoid reference to round-the-clock tenders, since there's some indication that the implementation of these does not reflect the name: https://economictimes.indiatimes.com/industry/energy/power/round-the-clock-renewable-energy-tenders-worry-developers/articleshow/76012308.cms

- Changes made: Added sentence "Development of variable renewables has been further assisted by the introduction of reverse auctions and the creation of solar parks, among other measures (Bose and Sarkar, 2019)."

Page 1 lines 32-33: In addition to the limitations of the available data listed, it could be noted that official documents are maintained by different ministries and departments, which can also lead to outright inconsistencies between different official sources, such as disagreement between the CEA and the MOSPI Energy Statistics publication concerning the quantity of coal consumed for electricity generation in the three most recent years.

I've taken some time to look at this specific inconsistency. MoSPI's Energy Statistics for coal consumption by the electricity sector (table 6.4 in the 2020 edition) are taken from the Ministry of Coal, and, since 2010, are identical to the numbers in the Coal Directories (table 4.20 in the 2018-19 edition), except for the final year, which comes from the Provisional Coal Statistics. These data represent *despatches of domestic coal to both utility and captive power generators*, not consumption at all, despite the title of both the chapter and table. It seems imported coal used by power stations is included in the 'Others plus import non-coking' column, partly explaining why this column has such large values. The supply data they use do not allow disaggregation of non-coking coal imports by using sector. Nor does this table account for stock changes at power stations. Meanwhile, the CEA data only include utility generation, not captive. So to reconcile the data in these tables one must take the utility despatch data from the Coal Directory (or PCS) and the total coal receipts less imports from CEA. These two are approximately the same, with some residual as is common with comparison of supply and use data from different sources.

The annual Energy Statistics from MoSPI is severely lacking in descriptive text, making it very difficult to determine what the data really mean.

- Changes made: Added a section to the Supplement describing this specific point on coal consumption, and referred to this section in the Introduction as "Furthermore, explanations for data are often lacking in detail, and can conflict across different datasets for reasons that are not immediately apparent (see Supplement: Coal 'consumption')"

Page 3 line 3: The first statement should be qualified to acknowledge that monthly coal consumption figures for power generation are provided by the CEA.

- Changes made: Reworded to "While monthly coal consumption by utility power stations is reported (CEA, various years-b), India does not report sub-annual total coal consumption, and apparent consumption must therefore be calculated using data…"

Page 4 line 22 to page 5 line 7: The discussion of the seasonality of emissions is very important as it is such a strong factor in India's data. Accordingly, some extension of the discussion might be worthwhile, for example, to consider how monsoonal weather affects a) production and supply, hindered by weather affecting logistics, b) demand and consumption, for example decreased construction activity or abrupt decreases in air conditioning load as rains relieve extreme heat conditions that normally occur in May. In addition, the substantial increase in hydroelectric and wind generation that accompanies the monsoon and suppresses coal consumption could be noted here as well as on page 9. The benefit of an extended discussion is that it would guide readers who may wish to analyse seasonal changes in emissions in terms of other economic and meteorological data.

I agree. I've added some of these ideas to the discussion here.

- Changes made: Added the following sentences: "These emissions patterns largely result from the effects of the monsoon's heavy rains, driving a decline in industrial, construction and transportation activities. Coal emissions are also driven down by the displacing effect of higher power generation from both hydropower and wind during the monsoon season."

Page 6 lines 16-18: The apparent omission of power plant coal stockpile changes in the Energy Statistics publication might also be mentioned.

- Changes made: Added sentence: "Furthermore, IEA's data exclude changes of stocks at power stations, which exhibit large swings (SI Fig 10)."

Page 10 lines 12-22: This paragraph considers data revisions and errors. Although it is correctly stated that coal statistics from CIL and SCCL undergo only minor corrections, it might be noted that data from captive power plants and other users are much more sporadic and provided only in summary form. Capturing total coal consumption could benefit from more systematic and timely data on non-CIL and non-SCCL data.

While I would readily have agreed with this statement at the time it was made, I have since discovered that the Ministry of Coal has recently started reporting provisional year-to-date production and offtake explicitly including both captive and other mines at https://coal.nic.in/content/production-and-supplies. I have added a module to my code to check this page and calculate the differences to give monthly production, and will include these in my published dataset. The Internet Archive provided the website in May 2020, allowing the estimation of June's production by difference. I hope the publication of these year-to-date data will continue, but there's never any guarantee.

Moreover, there is also the Monthly Summary to Cabinet (https://coal.nic.in/content/monthly-summary-cabinet), which has included a statement on the production of captive mines since the September 2017 edition. I have added these to my published dataset.

The more general point about having to fill in gaps in available data is made in the preceding paragraph.

- Changes made: none.

Page 11, lines 1-12. The Conclusions are entirely appropriate and relevant. Given the importance of timely and accurate data, and the multiple shortcomings noted in the body of the paper, a useful addition to this section could be a brief set of key recommendations that could guide efforts to better coordinate, accelerate and improve India's collation and publication of energy and related statistics.

- Changes made: Added paragraph to the Conclusions: "India publishes more energy data than many other developing countries, providing a wealth of information for management, policy analysis and scientific research. Nevertheless, there remains significant room for improvement in the quality of these publications. Possible avenues for such improvement include: (i) Publishing more data in machine-readable formats, rather than just as tables in PDF documents or in web-page tables, (ii) Providing a way for the public and researchers to ask questions about or report errors in data, establishing direct contact with those responsible for the data, to facilitate crowd-sourcing of quality assurance, (iii) Encouraging collaboration in data preparation and presentation across ministries to prevent errors creeping into reports, (iv) providing more documentation of reported data, (v) Reducing use of manual copy-pasting and typing, and automating as much as possible with both automatic and manual quality assurance, (vi) Standardising the use of important terms (e.g. 'consumption') across reports from different departments to prevent confusion, (vii) Making available older, non-electronic reports (e.g. Monthly Abstract of Statistics), online through use of digitisation."

Timely estimates of India's annual and monthly fossil CO_2 emissions

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Abstract

India is the world's third-largest emitter of carbon dioxide and is developing rapidly. While India has pledged an emissions-intensity reduction as its contribution to the Paris Agreement, the country does not regularly report emissions statistics, making tracking progress difficult. Moreover, all ~~global~~ estimates of India's emissions in global datasets represent~~are for~~ its financial year, not aligned to the calendar year used by almost all other countries. Here I compile monthly energy and industrial activity data allowing the ~~production of~~ estimation~~es~~ of India's CO_2 emissions by month and calendar year with a short lag. Emissions show clear seasonal patterns, and the series allows the investigation of short-lived but highly significant events, such as the near-record monsoon in 2019 and the COVID-19 crisis in 2020. Data are available at https://doi.org/10.5281/zenodo.3894394 (Andrew, 2020a).

Keywords: India, CO_2 emissions, Covid-19, seasonality

Introduction

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

According to available estimates, India's CO_2 emissions have grown by about ~~4.9~~5%/yr over 2010–2018 (Crippa et al., 2019). This growth has mainly been driven by expansion of the economy as, among other things, the country's labour pool grows and much-needed energy supply is increased (Karstensen et al., 2020), and much of this energy is supplied by coal and petroleum products, including the transition from biomass to petroleum fuels, continuing the long-term increase in ~~.~~the share of India's energy supplied from fossil fuels (see Supplement Figure 42). Countering these upward pressures on CO_2 emissions, India's recent development of ~~small~~ variable renewables, particularly solar and wind, has exerted a downward pressure on emissions growth, assisted by a sharp decline in prices for these technologies and ambitious goals for renewables growth that have ~~been~~ repeatedly been strengthened (Khanna, 2010; MNRE, 2015; Varadhan, 2019). Development of variable renewables has been further assisted by the introduction of reverse auctions and the creation of solar parks, among other measures (Bose and Sarkar, 2019). In addition, the difficulty India has faced in ramping up domestic coal production has probably also restrained emissions growth (Carl, 2015).

India does publish a great deal of energy data, but it is scattered across many documents, often not in machine-readable form, occasionally containing errors, and generally without much documentation. The country's official estimates of CO_2 emissions are infrequent and never for more than a single year (GOI, 2004, 2012, 2015, 2018). Moreover, these reported emissions are for India's financial year, running from April to March, so that they do not align with the calendar-year estimates provided by almost every other country (Andrew, 2020b). This gap in official reporting has been filled by third parties estimating emissions largely based on available financial-year publications, whether directly or via intermediate sources (e.g., IEA, 2019c; Gilfillan et al., 2019; EIA, 2020; Hoesly et al., 2018; GHG Platform India, no date), and not all of these are freely available.

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

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

The International Energy Agency in 2020 stated that the "Government of India should … Improve the collection, consistency, transparency and availability of energy data across the energy system at central and state government levels" (IEA, 2020a, p. 18). While government ministries responsible for publishing these data are making moves to improve the availability of more recent data, there are still obvious examples of copy-and-paste errors in spreadsheets, random misspellings, filename glitches, and even incorrect units given in the Energy Statistics ~~Y~~yearbook. During the Covid-19 lockdown in India, the Central Electricity Authority~~CEA~~ stopped publishing daily generation reports for four weeks. Clearly much data work is still manual, and further automation will significantly improve India's ability to produce robust and timely estimates of fossil CO_2 emissions.

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

Here I present a new dataset collating available information on India's monthly energy production and consumption, as well as cement production, and use this dataset directly to estimate India's monthly and calendar-year CO_2 emissions. In contrast to downsampling techniques, the method used here provides accurate estimates of monthly CO_2 emissions in India.

Materials and Methods

Fossil CO_2 emissions can be divided into four main source categories: coal, oil, natural gas, and carbonates (Friedlingstein et al., 2019). For the fossil fuels, estimates of monthly consumption are required, while for carbonates, production statistics are needed. In all cases, apparent energy consumption approximates true consumption, omitting some minor changes in stocks. For example, reported consumption of petroleum products is most likely supply to the market, with stocks at petrol stations and in vehicles not accounted for. A summary of the methodology is presented here, while full details are provided in the Supplement~~ary Information~~, including a table of individual data sources.

While monthly coal consumption by utility power stations is reported (CEA, various years-a), ~~Since~~ India does not report sub-annual total coal consumption, and apparent consumption must therefore be calculated using data on production, imports, exports, and stock changes. While these data are incomplete, they are sufficient to produce a reasonable estimate of monthly coal consumption. Importantly, the goal of this analysis is an estimate of CO_2 emissions from all oxidation of solid fossil fuels, rather than the more limited emissions from combustion for energy purposes, and this means it is unnecessary to separate out, for example, coking coal used in steel manufacture, which is oxidised rather than combusted.

The energy data sources used include revised, historical data from the Indian Bureau of Mines (2019), Ministry of Coal (various years-a), UN Statistics Division (2020); provisional and revised data from CIL (various years), SCCL (various years), Ministry of Coal (various years-b, various years-c), and Ministry of Mines (Ministry of Mines, various years); power station stocks from CEA (various years-b, various years-a); and international trade from DGCIS (2020) and DOC (2020), supplemented by recent provisional estimates reported by the media. While these data sources combined allow a good estimate of production and stock changes of hard coal with a lag of less than one month, lignite production data has a slightly longer lag, and simple extrapolation is used to complete the picture for the most recent month or two (Supplement~~I~~ Figure 15). It is assumed that the share of consumed coal that is not oxidised is negligible.

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

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

For carbonates, monthly data on clinker production are not available, so monthly cement production statistics are combined with a time-varying estimate of the clinker ratio to produce an estimate of monthly clinker production. Data on production of lime, glass, and ceramics were not available, and emissions from these carbonate sources are therefore omitted; India's second Biennial Update Report indicates these emissions combined contributed 1.9% of fossil CO_2 emissions in 2013-14 (GOI, 2018).

Once monthly energy consumption and clinker production estimates are available, these are converted to estimates of CO_2 emissions. For fossil fuels this requires first converting the consumption in physical units to energy units using information from IEA for coal and petroleum products (IEA, 2019b, a) and PPAC (no date) for natural gas, and then applying emission factors from the IPCC's 2006 guidelines (Gómez et al., 2006). For clinker production, the method of Andrew (2019) is followed to estimate emissions from physical production in tonnes.

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

Results and Discussion

Following the described methods, I have assembled monthly CO_2 emissions estimates for coal, oil, natural gas, and cement for India (Figure 1). The available data and methodology allow estimation of emissions from coal from ~~January 2009~~September 2008, oil from April 1998, natural gas from ~~April~~ January 2009, and cement from April 2001~~4~~.

Emissions from oxidation of coal form the largest share of the total, rising from about 61% in 2010 to 66% in 2014, before levelling off to about 65% in 2019. Peak monthly emissions to date were in ~~May~~ March 2019 with 157 Mt CO_2 in the month. While emissions from coal grew at an average rate of 6.2~~5.5~~%/yr over 2009–2018, in 2019 they ~~grew only 0.3%~~stalled, as electricity demand dropped dramatically (Supplement~~I~~ Figure 41~~39~~).

Emissions from oxidation of oil (petroleum products) are the next-largest source with about 25% of the total, reaching 50–60 Mt CO_2 per month in recent years. Emissions from natural gas and cement production are both about 5% of the total.

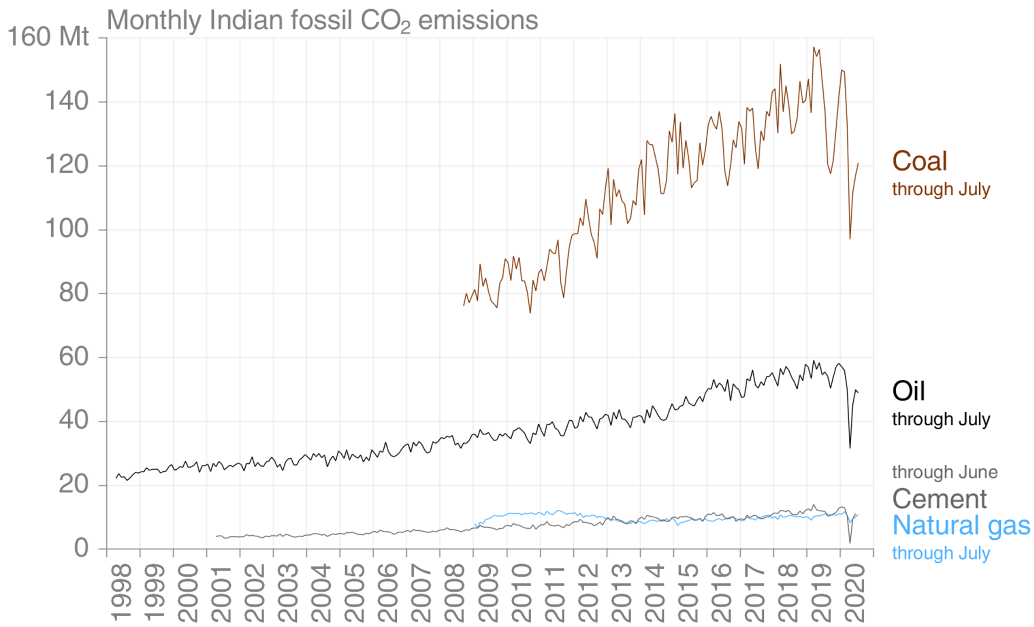

Figure 1: Final monthly CO_2 emissions by category. Source: Own calculations.

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

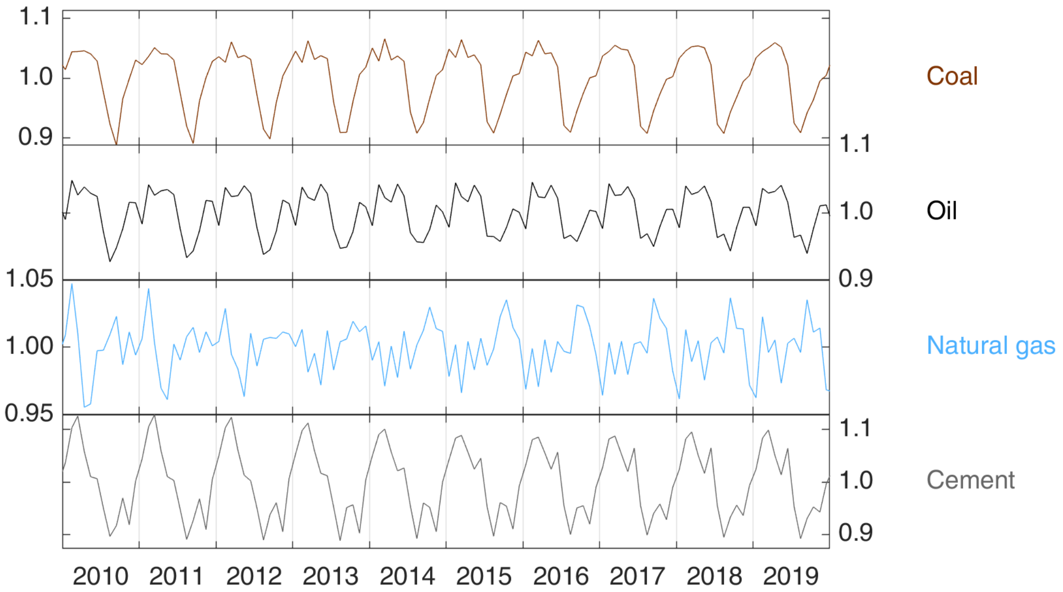

Figure 2: Seasonality of the four emissions categories, derived using the X-11 method. Emissions in 2020 have been excluded from the analysis because of their strong deviations from historical patterns.

Turning to calendar-year emissions, Table 1 summarises emissions by category and total CO_2 emissions for India from 2009 to 2019. Each category has grown by 3%–5%~~about 4%~~ per year over the last five years, although growth from year to year has not been smooth, with coal emissions stable ~~growing only 0.3%~~ in 2019. Total CO_2 emissions in India have grown from 1.6~~7~~ Gt in 2009~~11~~ to 2.6 Gt in 2019, at an annual growth rate of 3.9~~4.2~~%. (An equivalent table for financial-year emissions is presented in the Supplement.) Over the same period, the CO_2-emissions intensity of India's GDP has declined from 23.2 g/rupee to 18.1 g/rupee, about 2.2%/yr (Supplement Figure 40).

Table 1: Calendar-year CO_2 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%

* Continuous compounding and adjusted for leap years.

The monthly Indian fossil CO_2 emissions dataset produced here includes all but about 2% of anthropogenic fossil sources in the country, excluding emissions from decomposition of fossil carbonates in the production of lime, glass and ceramics. The time lags of the emissions estimates are at most two months, and under one month for coal, the most important emissions source.

Comparison with existing emissions estimates

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

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

For oil there are two series: combustion and oxidation (Figure 3b). The combustion series lies very close to that of the IEA – which specifically includes only energy uses of oil products – over the entire period. Oxidation emissions are on average about 50 Mt CO_2/yr higher throughout the period, largely reflecting emissions from oxidised naphtha and petroleum coke. CDIAC's series exhibits quite a different trend.

The natural gas emissions series includes three estimates: combustion, oxidation, and full oxidation (Figure 3c). The last of these assumes that all natural gas is oxidised, merely to present a bounding case. The combustion series agrees well with IEA's estimates, but again the CDIAC series exhibits a very different trend, diverging sharply from 2013–~~-~~14. The oxidation series is significantly higher, largely reflecting the emissions from production and use of nitrogen-based fertilisers. Emissions show a very prominent peak in 2010–2012, a result of the rapid development of offshore gas field KG D6, but while this led to the construction of a number of gas-fired power stations, production from this field dropped substantially leading to ~~substantially~~ greatly reduced domestic supplies and stranded power assets (MoP, 2019)(Supplement~~l~~ Figure 32~~1~~).

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

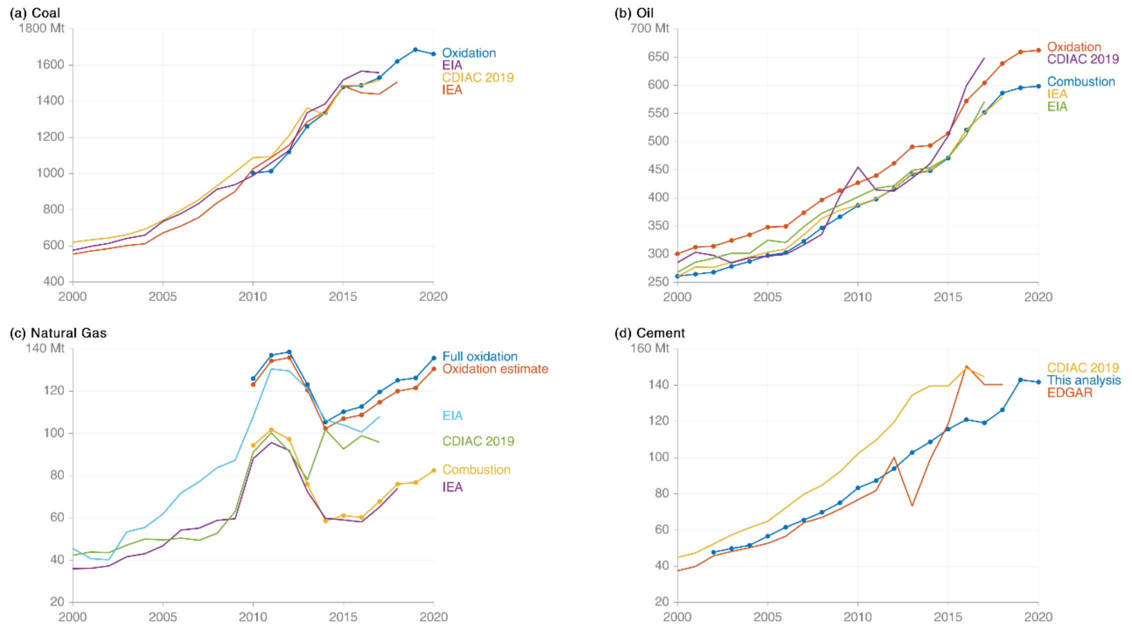

Figure 3: Comparison of financial-year emissions estimates with other datasets, (a) coal, (b) oil, (c) natural gas, (d) cement.
Sources: (Gilfillan et al., 2019; IEA, 2019c; Crippa et al., 2019; EIA, 2020), own calculations.

The most recent Indian official estimate of total CO_2 emissions was presented in India's second biennial update report to the UNFCCC, with 1.998 Gt in the financial year 2013~~–~~-14 (GOI, 2018). In the analysis here, total CO_2 emissions in India in 2013~~–~~-14 are estimated to be 2.04~~00~~ Gt ~~(coincidentally almost exactly 2 Gt)~~. While this is strikingly close, this is not a true measure of the accuracy of the method since some errors have cancelled: it is known that the emissions estimates generated here exclude some carbonate sources, while emissions from naphtha oxidation here might be overestimated, and there are other assumptions in various factors used here that introduce uncertainty. Nevertheless, this match with the official total is encouraging.

Deviations from forecasts

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

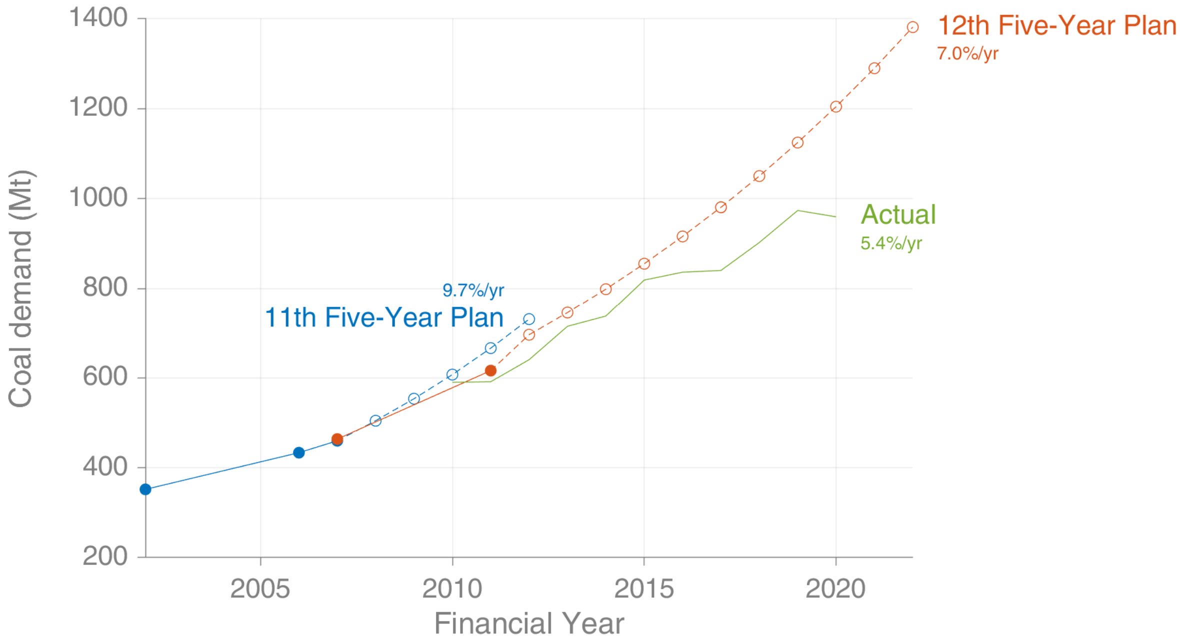

Figure 4: India's hard coal demand. Filled circles and hollow circles show reported and projected demand in two five-year plans, while the green line shows actual demand, and annual growth rates are indicated. Demand does not equal consumption because of changes of stocks at power stations and industry.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

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

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

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

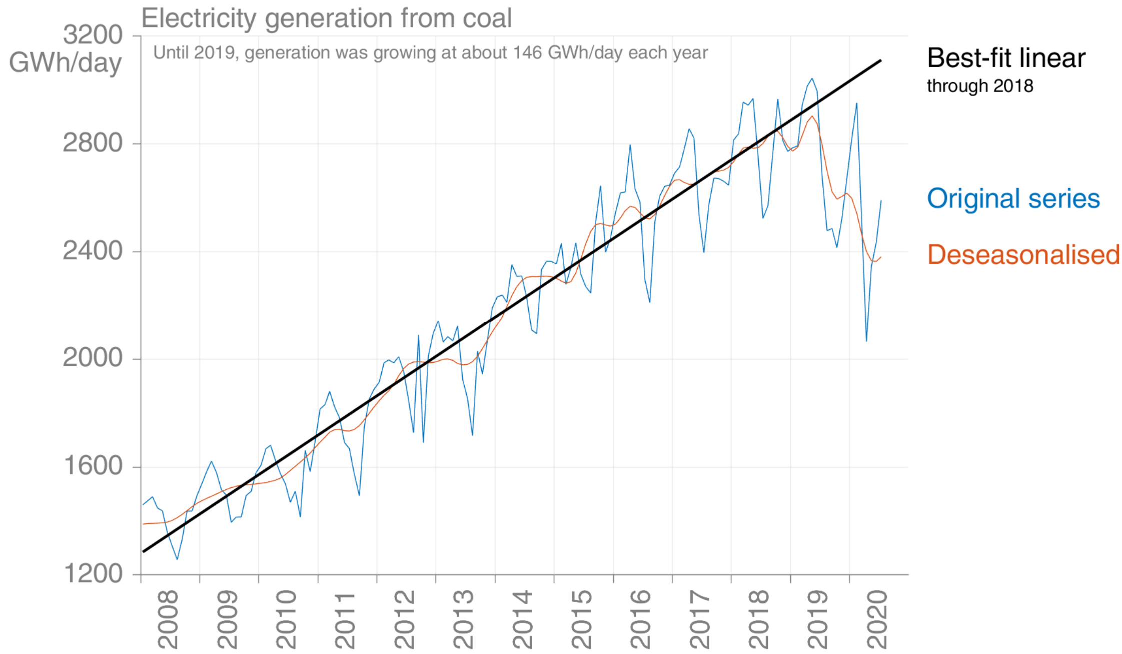

Figure 5: Average daily electricity generation from coal by month, divided by month length, deseasonalised, and a best-fit linear regression. Source: CEA, own calculations.

The seasonal patterns of emissions generally follow the monsoon, particularly with less electricity generation from coal. Rather than being due to decreased demand or difficulty producing electricity from coal during the monsoon, the reason for this is higher generation from both hydro and wind, both of which peak during the monsoon season. In fact, electricity demand is highest through summer and lowest in winter (Supplement~~I~~ Figure 41~~39~~), with energy required in India for summer cooling substantially higher than energy required for winter heating (Gaur et al., 2016).

COVID-19 effects

March would usually be one of the months of the year with the highest coal emissions ~~months of the year~~ (Figure 2), but in 2020 this was affected by Covid-19 measures. India introduced a nationwide lockdown (curfew) on March 25th, although some areas introduced lockdowns in the days before (Roy and Phartiyal, 2020; Varadhan, 2020). Initially the lockdown was to be for three weeks, but was repeatedly extended ~~in April to at least~~ until the end of May (The Tribune, 2020), and thereafter followed by a phased 'unlocking' (The Hindu, 2020)~~ 3rd (Miglani and Jain, 2020)~~. Largely as a result of substantially reduced activity, and despite the lockdown only affecting about one-third of the month, CO_2 emissions from coal in March 2020 were ~~over~~ 15~~8~~% lower than in March 2019 (Figure 6). But April saw the largest drops in emissions, with the lockdown having very substantial effects on almost all areas of economic activity: total CO_2 emissions were down 40% compared to April 2019, with cement production dropping by 85%. Already in May emissions started to rise again as constraints on activity were reduced, but the recovery is far from complete, with July's consumption of oil products declining again compared to June.~~This drop is likely to be even~~

more significant in April, since the entire month will be affected by lockdown, and early data show a sharp decline in the consumption of petroleum products (Reuters, 2020).

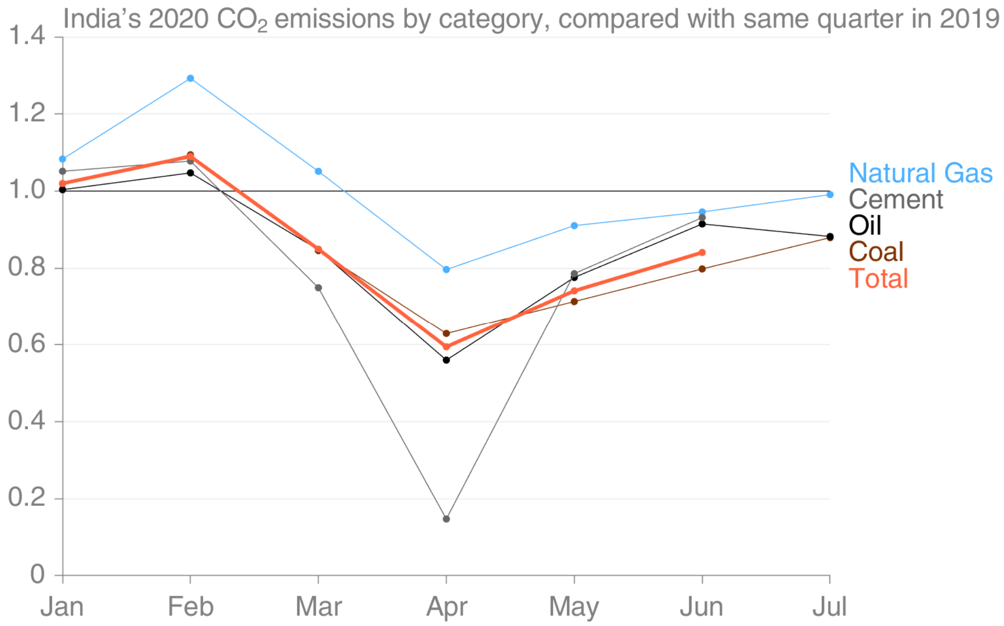

Figure 6: Quarter-on-quarter changes of CO_2 emissions by category during the first months of 2020.

New approaches have recently been used to estimate the effect of the world's pandemic responses on global CO_2 emissions, based on collation of partial activity data for use as proxies, such as electricity generation data or travel indices (Le Quéré et al., 2020; IEA, 2020b; Liu et al., 2020). Such methods are suitable and useful for estimation of global effects in near real-time when more accurate and detailed data are not available, and the monthly estimates reported in the present work may be used to validate these alternative estimates of India's CO_2 emissions. Furthermore, given the close links between emissions of CO_2 and other air pollutants, studies on changes in air pollution due to India's lockdowns, could be cross-validated with the monthly CO_2 estimates reported here (e.g., Sharma et al., 2020; Mahato et al., 2020).

Sources of uncertainty

There are several sources of uncertainty in these emissions estimates, which can be divided into four categories. First is the omission of some emissions sources. This analysis has excluded emissions from some carbonates, estimated to be equivalent to less than 2% of India's total CO_2 emissions. Further, some imported non-energy goods containing fossil carbon are excluded. While the case of Iceland shows clearly that imports of carbon anodes used in aluminium manufacture can be important (Andrew, 2020b), these are not imported by India (DGCIS, 2020). India does import urea from China, and the approach used here will not capture emissions from its use in agriculture; however, the amount is likely to be below 2 Mt/yr (see SI). A further missing source is that of low-temperature oxidation and spontaneous combustion of coal at mines, but available evidence suggests these would be significantly less than 1% of India's CO_2 emissions (Day et al., 2010; IPCC, 2019; Singh, 2019).

Second is use of provisional data and extrapolation before revised data are available. Revisions of coal, the most important emissions source, are in general relatively minor, and use of provisional data along with the methods used here to fill gaps are unlikely to introduce significant error (see SI). Lignite production is relatively small and stable, so its extrapolation is not expected to introduce significant uncertainty. Moreover, if monthly press releases of mineral production have indeed recommenced, the lignite uncertainty will be largely removed in future, except for the most recent month(s).

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

The final category of uncertainty is in the emission factors, energy contents, and oxidised fractions used. This is perhaps the largest source of uncertainty, particularly the energy content of domestic hard coal, for which data have been scarce and inconsistent, and broad sampling efforts in recent years pointing to significant errors, with data from 2016-17 suggesting declared average coal quality was 10% higher than the true value (see Supplementary section: Coal energy content). More work is required to generate a more reliable time series of coal quality in India, but in the absence of additional historical sampling of coming to light, estimates will have to be made. A further source of uncertainty in this category is~~The largest of these may be~~ the assumption that all naphtha is oxidised, which potentially leads to an overestimate in the order of 1–2 $MtCO_2$/month.

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

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

Conclusions

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

The monthly, short-lag estimates of India's CO_2 emissions produced here will likely prove useful for tracking the country's progress against its nationally determined contribution under the Paris Agreement, but will also be useful for analysis of the drivers of India's emissions both historically and in future. Calendar-year estimates derived from these are also better aligned to the global datasets into which India's emissions are incorporated.

The future pathway of India's CO_2 emissions is highly uncertain. But India is developing rapidly in a world that – largely because of emissions in other countries – is carbon constrained. As India's population grows, as roads, railways and houses are built, as both vehicles and houses are electrified, as solar panels and wind turbines are installed, and as new coal mines are opened, tracking CO_2 emissions monthly will allow a closer observation on the consequences of these changes.

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Data Availability

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

~~Code Availability~~

~~Scripts to reproduce the figures in this article are included in the Supplementary Information, while other scripts used in this study are available from the corresponding author upon reasonable request.~~

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Supplementary Information

Timely estimates of India's annual and monthly fossil CO_2 emissions

Contents

1. Coal production

The landscape for Indian activity data is composed of historical data sources, stable ongoing data sources, and unstable sources for low-lag data. National, revised monthly coal production data are reported by the Indian Bureau of Mines with a lag of more than six months, ~~and at time of writing over 12 months~~ (Indian Bureau of Mines, 2019). Provisional national coal and lignite production data were published with a lag of less than two months via press release by the Ministry of Mines until mid-2017 (Ministry of Mines, 2017), but these were not released for about 18 months, reappearing in March 2020 with provisional data for January 2020, although these data are of low precision, and their publication remains unreliable (Ministry of Mines, 2020). The Ministry of Coal has recently begun publishing total provisional fiscal-year-to-date national hard coal production, broken down by CIL, SCCL, Captive, and Other (Ministry of Coal, no date), and with regular access, these can be converted to monthly production values. The Coal Controller's Organisation (CCO) at the Ministry of Coal produces an annual report called Provisional Coal Statistics (PCS) that include monthly national coal production, with a lag of about 7-9 months (Ministry of Coal, various years-c). The CCO also publishes revised statistics in the Coal Directory, with a lag of about 12-16 months (Ministry of Coal, various years-b). ~~Lastly, t~~The United Nations Statistics Division's 'Monthly Bulletin of Statistics Online' also includes monthly coal production for India (UN Statistics Division, 2020). Lastly, the now-discontinued Monthly Abstract of Statistics was published by the Central Statistics Organisation (now Ministry of Statistics and Programme Implementation) (CSO/MoSPI, various years). This last dataset appears to be available for earlier years going back several decades, but the author has not been able to obtain access to these editions. These ~~five~~ datasets are compared and their availability by month shown in Figure 1 (the datasets are so similar that mostly they lie atop one another in the figure). While all figures here are for hard coal, all five of the data sources also report lignite production.

While national coal production data are lacking in recent months, the two largest coal mining companies, Coal India Limited (CIL) and Singareni Collieries Company Limited (SCCL), release their provisional monthly production and offtake data in the first days of the following month (CIL, various years; SCCL, various years). These two companies represent about 90% of Indian coal production. Reporting of data on provisional production at captive mines has recently been introduced in the Ministry of Coal's Monthly Summary to Cabinet (Ministry of Coal, various years-a) and also on the Ministry's website as year-to-date data, which also reports the provisional small production from other mines (Ministry of Coal, no date). In the two months for which all data are available (Sep 2017 and Jan 2020), the sum of provisional production data from CIL, SCCL and captive mines is within 2% of the provisional national production figure, demonstrating that this sum is suitable to fill the gap in provisional national production when production from other mines is not available.

Revised coal production data are available from CIL both in their provisional production reports, which compare to the same (revised) month in the previous year, and in their more recent quarterly reports. In the available data, CIL's revisions are generally within 0.25% of provisional statistics, except for one anomalous data point in 2016 that was revised by 0.7% (Figure 2). For SCCL, available data show that revisions are also within 0.25% of provisional data (Figure 3). No revised data for captive production are available. When the sum of provisional data from CIL, SCCL and captive mines are compared with revised national production, the latter is always higher in the period where data are available, although always less than 2.5% higher (Figure 4), representing the production of a small number of other mines~~suggesting either that captive mine production is always revised~~

upwards, or that some minor production is missing. This could for example be from small mines, or an estimate for theft.

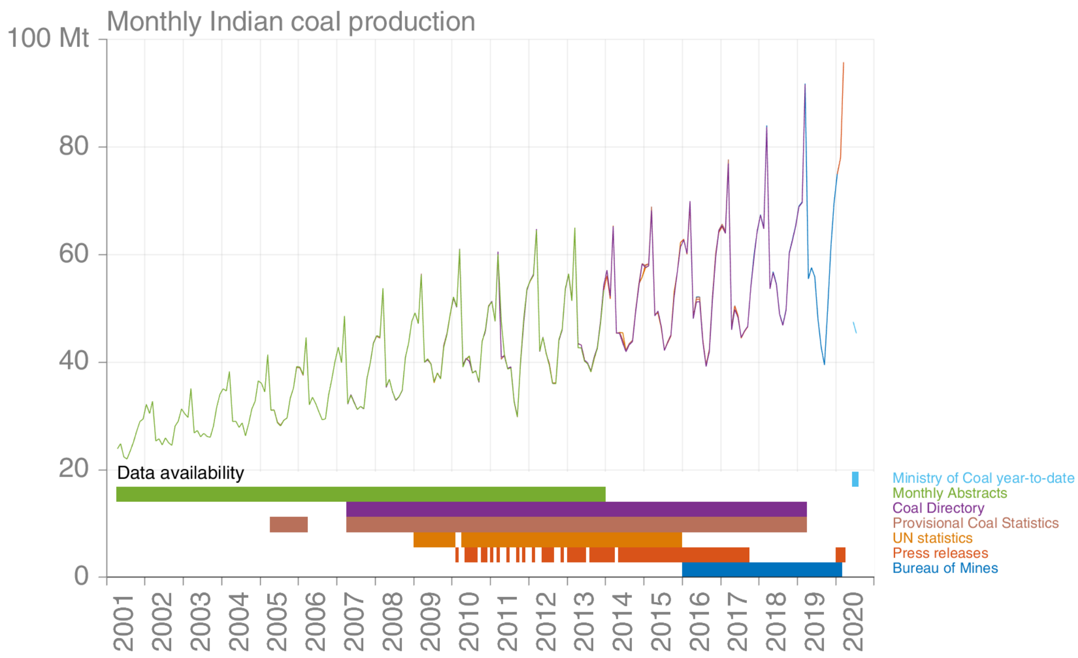

Figure 1: Comparison and availability of the four datasets of India's monthly national coal production. Sources: Monthly Abstracts of Statistics, Coal Directories, Provisional Coal Statistics (PCS), UN Statistics, Ministry of Mines press releases, Indian Bureau of Mines, Ministry of Coal.

In this analysis revised data are always used where available. To close the gap between provisional and revised national coal production statistics, which exhibits no trend (Figure 4), I use the average of this residual, about 1.6% of national production and apply this when revised data are not available.

When looking at each dataset for which both provisional and revised data are available, there are no apparent biases across the full periods, although production of raw coal has mostly been revised downwards in the last five years (Figure 6).

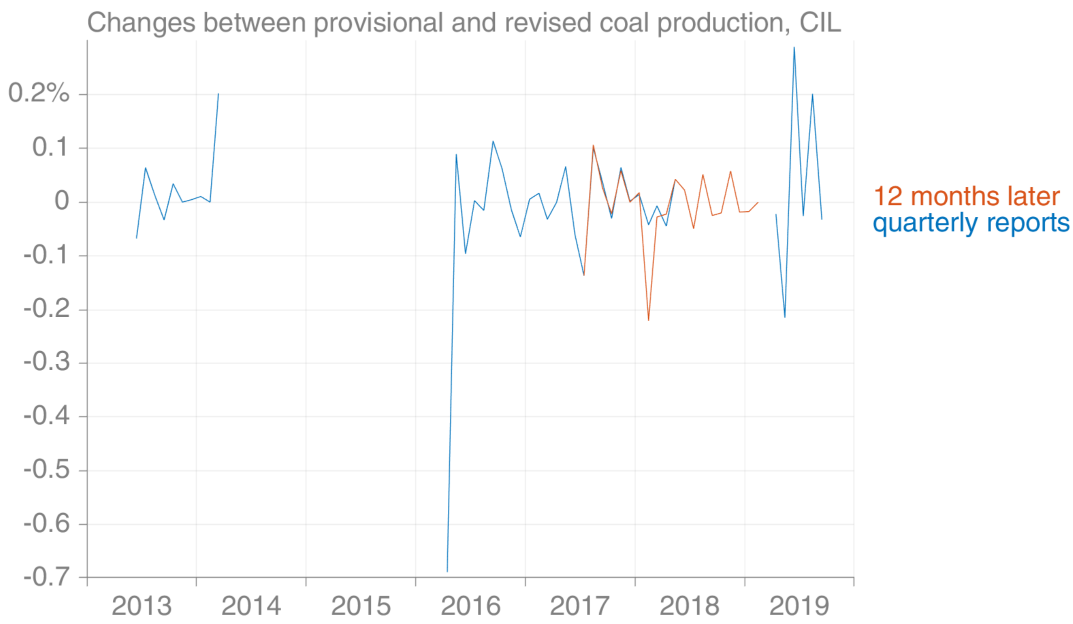

Figure 2: Relative magnitude of revisions reported by CIL to provisional monthly coal production data. Source: CIL.

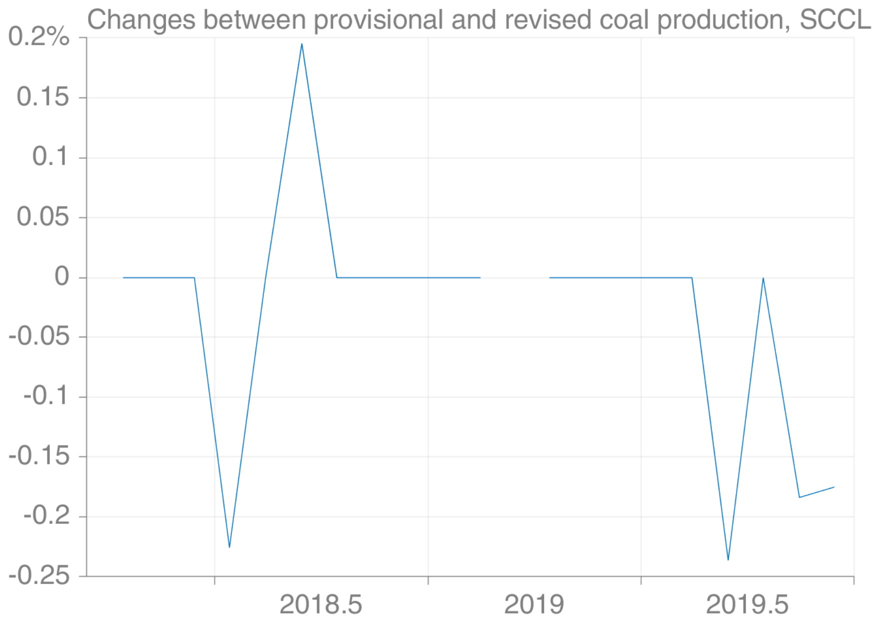

Figure 3: Relative magnitude of revisions reported by SCCL to provisional monthly coal production data. Source: SCCL.

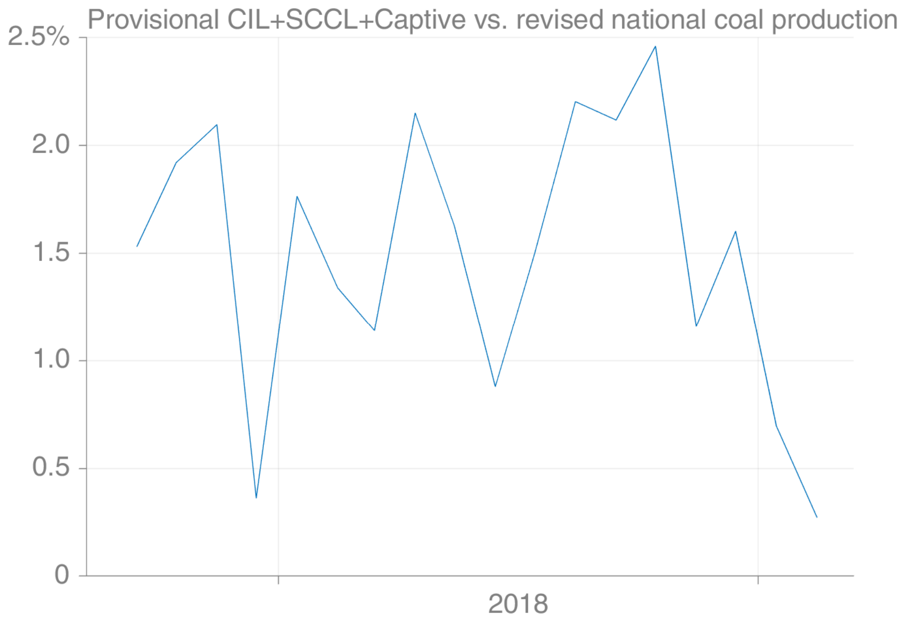

Figure 4: Relative magnitude of revised monthly national coal production and provisional production data from CIL, SCCL, and Captive mines. Source: CIL, SCCL, Ministry of Mines, Indian Bureau of Mines.

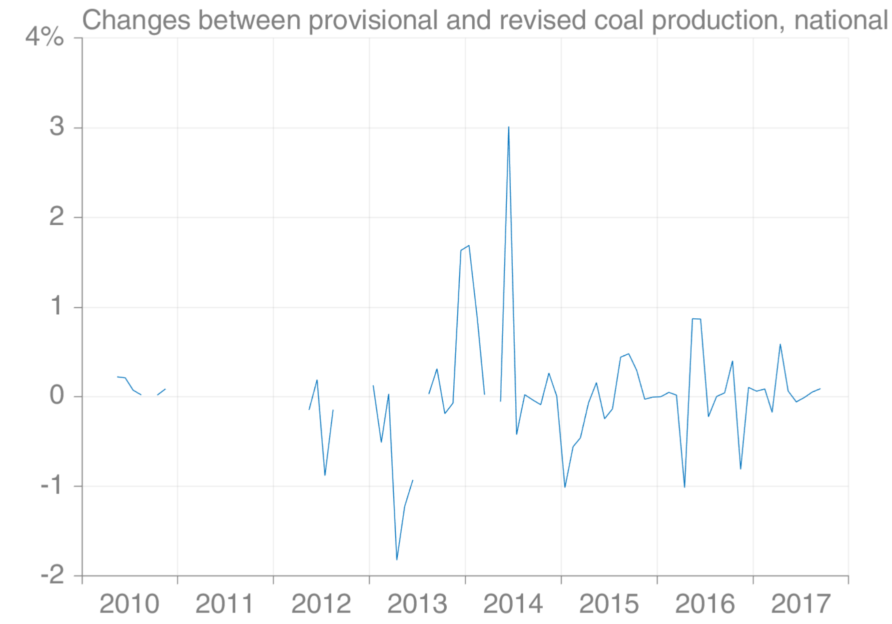

Figure 5: Relative magnitude of revisions. Source: Ministry of Mines, Indian Bureau of Mines, UN Statistics.

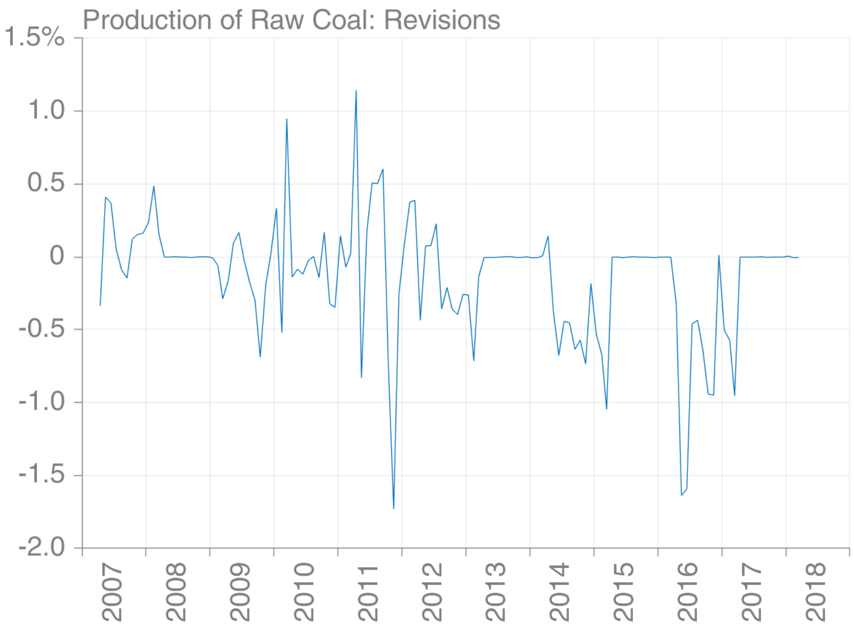

Figure 6: Magnitude of revisions to monthly raw coal production statistics between the Provisional Coal Statistics and Coal Directory reports from the Ministry of Coal.

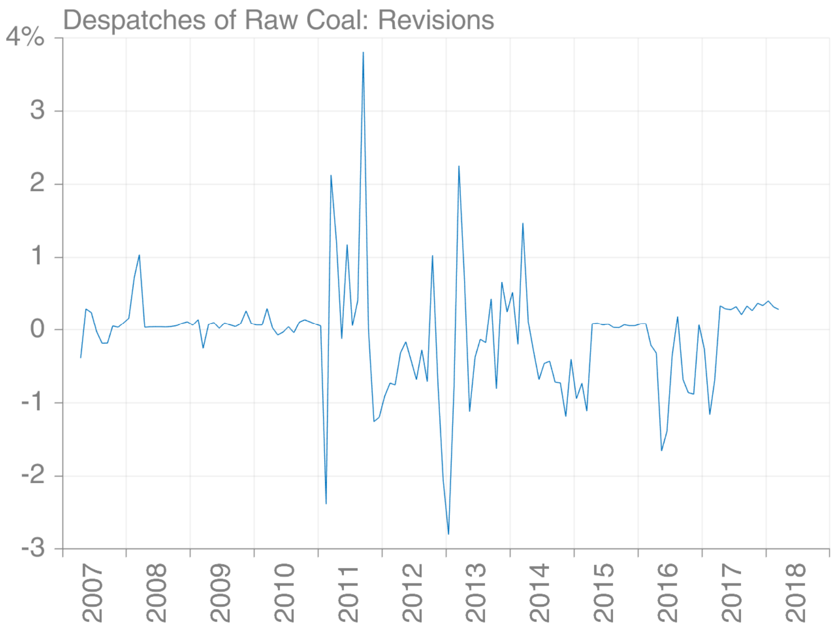

Figure 7: Magnitude of revisions to monthly raw coal despatch statistics between the Provisional Coal Statistics and Coal Directory reports from the Ministry of Coal.

2. Coal stocks

Stocks information are available at mines and power stations, but are unavailable for other users of coal such as steel and cement manufacturers, non-grid power generators, and also at ports. Their omission here amounts to assuming there are no changes of stocks in these categories. Stocks levels follow a strongly seasonal pattern due largely to the monsoon season, where stocks are built up before the heavy rains make both mining and transport of coal significantly more difficult.

Coal mines

Changes in coal stocks are available for CIL and SCCL, calculated as the difference between monthly production and deliveries (SCCL, various years; CIL, various years). The sum of stock changes from the two mining companies matches very closely the monthly data reported in the annual Coal Directory and Provisional Coal Statistics reports (Figure 8), except for a period in 2016-17 that appears to be incorrect in the official estimates, suggesting an unlikely build-up of stocks during the monsoon period. To avoid this anomaly, I use mine companies' data in preference, with Coal Directory and Provisional Coal Statistics data for earlier periods.

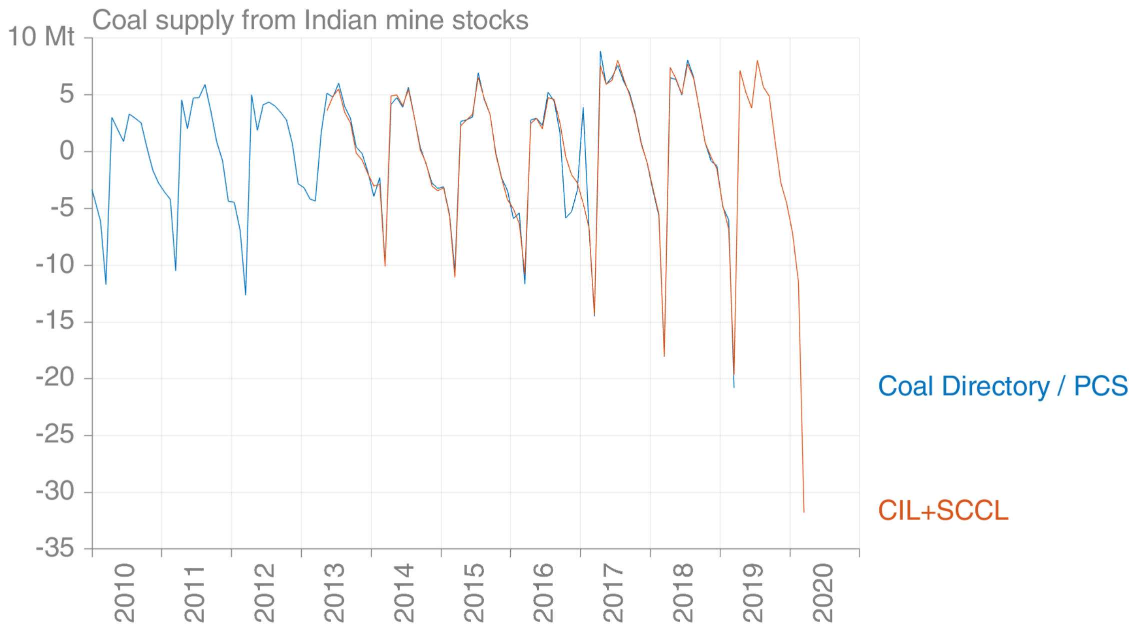

Figure 8: Comparison of reported 'stock changes' in the Coal Directories and Provisional Coal Statistics (PCS) with the sum of stock changes at CIL and SCCL mines. Source: Ministry of Coal, CIL, SCCL.

Power stations

Daily data for coal stocks at so-called 'linkage' power stations are available from the CEA (various years-a). Linkage stations are those that are enrolled in the government's linkage scheme whereby assistance is provided to ensure sufficient supply of coal, and as part of that there are specific data requirements. Some of these data have been made public since 2008.

The earliest data are in CSV format, the middle period in PDF, and the later data (from mid-2018) in Excel format, with some temporal overlap between these three formats. These data were read in and assembled to a single data file.

These raw data show many gaps, especially weekends during 2014–2017, and a number of significant one- or two-day spikes that appear to be spurious (Figure 9); the data improve markedly from 2018. To process these data, I have first removed data prior to 31 July 2008, which are extremely noisy. Then spurious spikes are removed by comparing the signal to a median-filtered (window size 9 days) version and using a threshold (300 kt) to identify significant deviations from the smoothed signal, with these deviations removed from the data. Then the resulting signal is interpolated using a shape-preserving piecewise cubic interpolation without extrapolation. The resulting processed dataset (Figure 10) permits the extraction of reliable estimates of month-end stocks and thence stock changes.

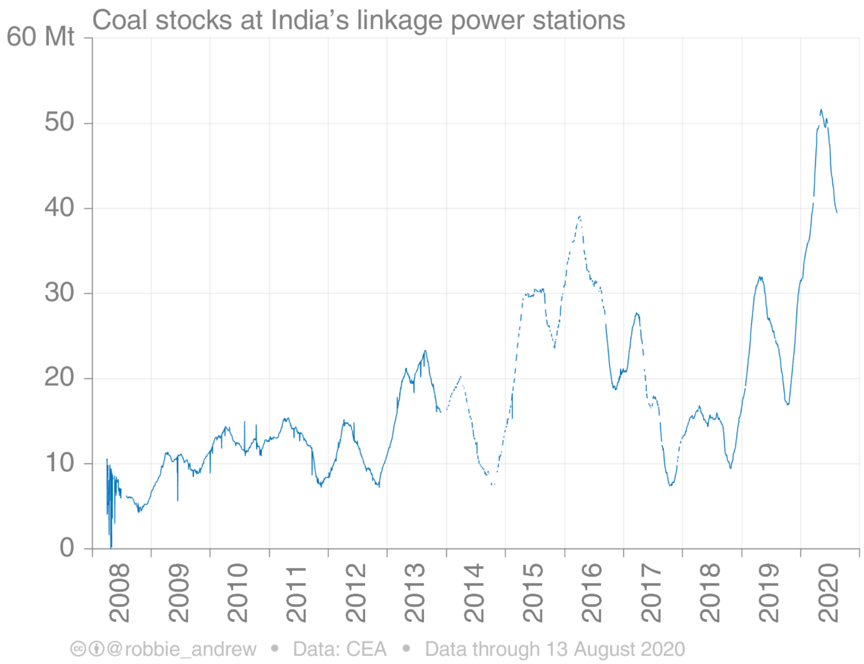

Figure 9: Raw linkage power station coal stocks data collated from CEA.

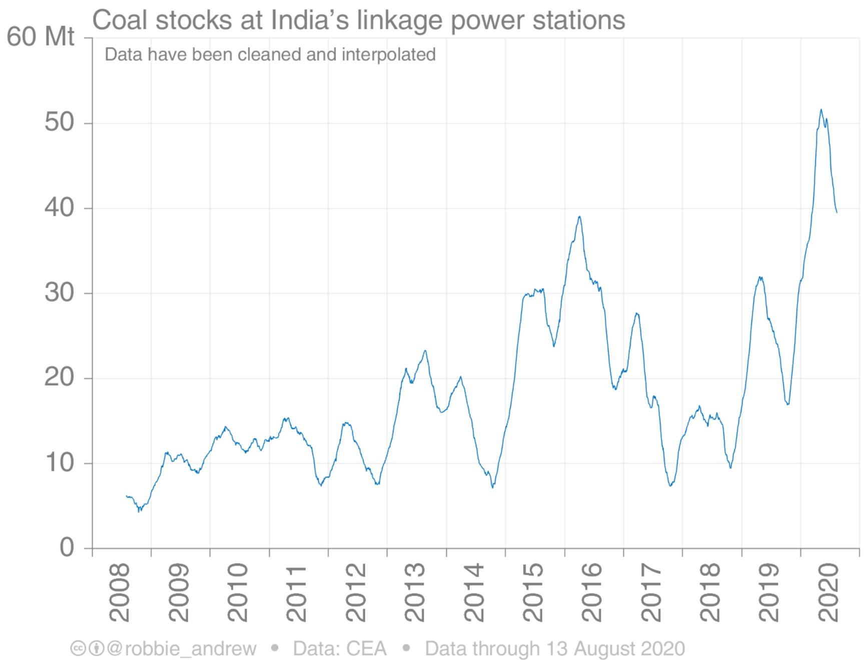

Figure 10: Processed linkage power station coal stocks data.

Because of the unreliability of coal supply in India, most utility power stations are linkage stations, but not all. Monthly data of coal stocks at all stations are also available, but only beginning in April 2014, and generally with a slight greater lag than linkage station stocks data (CEA, various years-b). Here I have used a simple approach of using linear regression to determine a simple, time-independent relationship between the two series, and using this to extrapolate the all-station data to fill the entire period (Figure 11). This method obviously assumes the relationship holds outside of the period where both data are available, and in particular the share of linkage stations to all stations might have been different in earlier years. However, because the goal is stock changes month to month, and the major swings in the linkage station data are clearly reflected in the all-station data, it is expected that the stock changes (a first-order differential) are less affected by this assumption.

Note that coal stocks at captive power stations are not included in these data.

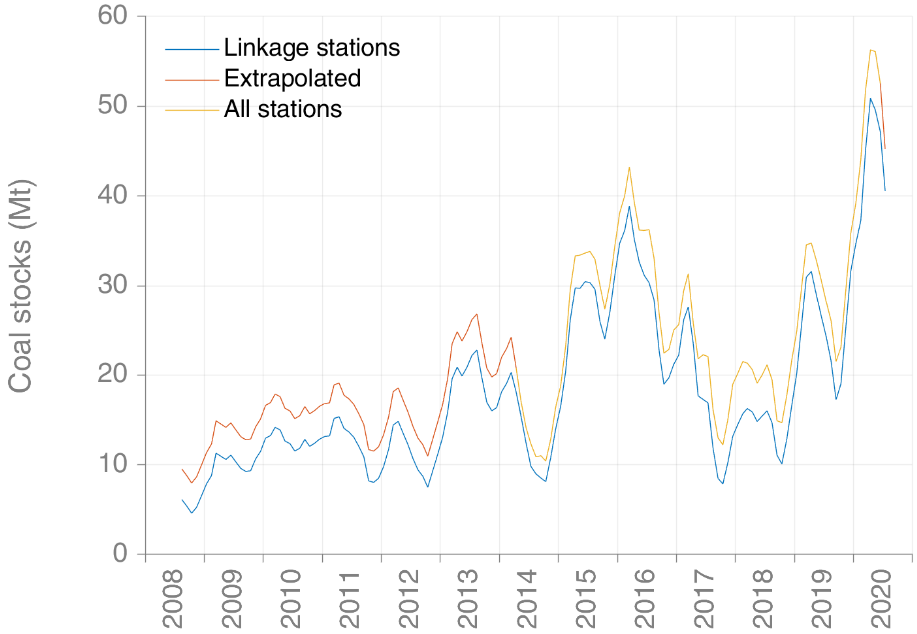

Figure 11: Monthly coal stocks at linkage power stations, all power stations, and the simple extrapolated series for all power stations based on the relationship between the two.

Comparison with IEA data

The IEA derives annual raw coal stock changes from the closing stocks presented in Table 5.2 of the Coal Directory (pers. comm., IEA, April 2020). Figure 12 compares stock changes reported by IEA in the World Energy Statistics 2019 edition with the data presented in two editions of the Coal Directory and with the most recent Provisional Coal Statistics report. Monthly data are estimated from production and despatches from these same Indian reports and should be lower than annual stock changes because they exclude use of collieries. There are four points to make here.

First, the IEA is using a figure for closing stocks for non-coking coal in 2008-09 that has been revised since the 2016-17 Coal Directory, and this results in a difference in calculated stock changes for 2009-10. Approximate stock changes derived from both the monthly and annual data reported in the 2009-10 Coal Directory appear to agree with the later estimate for stock changes of non-coking coal in that year. It seems likely that an error in reported stocks in Table 5.2 in the 2009-10 coal directory was propagated for several years, and finally corrected in the 2016-17 Coal Directory.

Second, the IEA reports exactly zero stock changes for non-coking coal in 2017-18, contrary to the almost 10 Mt stock change reported in the Coal Directory 2017-18. At the time the IEA collated these data, no figure for non-coking coal stock changes in that year were available (pers. comm., IEA, April 2020).

Third, the IEA reports stock changes for both coking and non-coking coal that are at significant variance with those reported in the Provisional Coal Statistics 2018-19, the latter matching provisional production and despatch statistics. While the IEA statistics report a build-up of stocks of non-coking coal of over 20 Mt in 2018-19 (based on information from CIL; pers. comm., IEA, April 2020), the PCS reports a draw down from stocks of about 2 Mt.

Fourth, the IEA's reported stock changes only include stocks at mines, and exclude power stations, ports, and other industrial facilities.

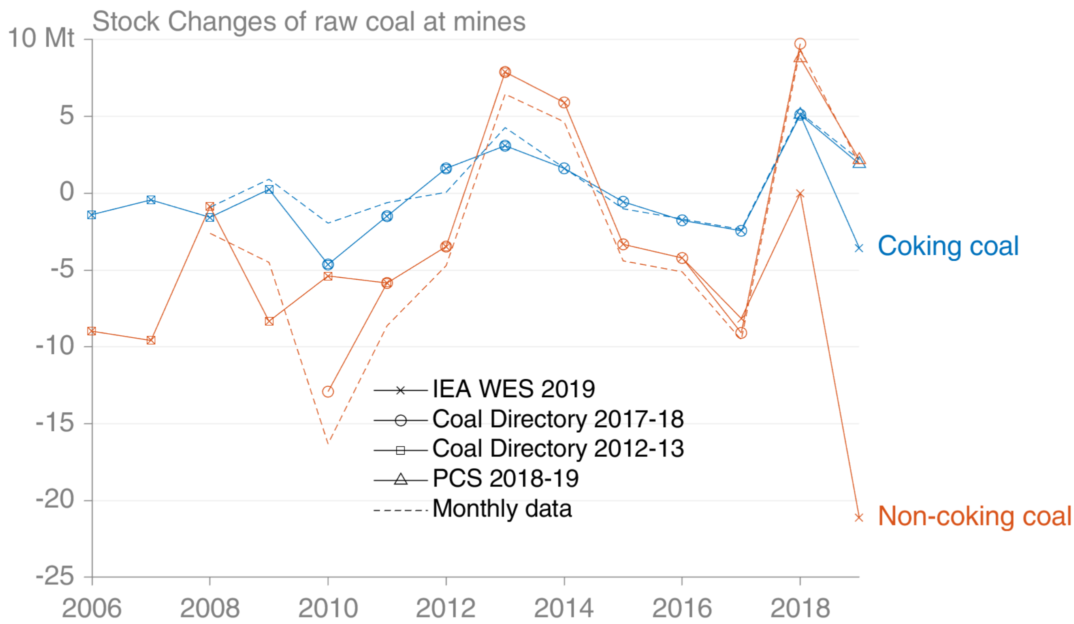

Figure 12: Comparison of raw coal stock changes at mines. Source: IEA, CCO, own calculations.

3. Coal trade

International coal trade data are readily available from the Directorate General of Commercial Intelligence and Statistics (DGCIS) from June 2015 onwards for the principal commodity category 'Coal, coke and briquittes [sic] etc', with a lag of up to two months (DGCIS, 2020). This category includes more than just coal, but the other products, which are very minor in quantity, are derivatives of coal and will also be oxidized when used.

Because of the lag in official reporting, the most recent 1–2 months of coal imports are taken from media reports based on information from mjunction, a company that tracks ships' movements. Given the wide interest in this information, these are regularly reported by a number of media outlets.

More detailed trade data, with a breakdown by coal types, are available from the Department of Commerce (DOC, 2020), but while the lag has recently reduced somewhat, these still become available at least a month later than those from DGCIS.

Coal exports are minor, peaking in the available data at 2.0% of imports in February 2017, and I report net imports henceforth. Monthly imports amount to between 20% and 40% of domestic hard coal production.

The IEA states that India's reported imports of coal until and including the year 2014-15 are significantly below the reports of the same trade from countries exporting to India, and use exporters' data in preference in this period (IEA, 2019b). Here I use IEA's annual import data to scale up the monthly data from DGCIS in that period; in later years IEA data match very closely the data reported by DGCIS, and no adjustment is required (Figure 13).

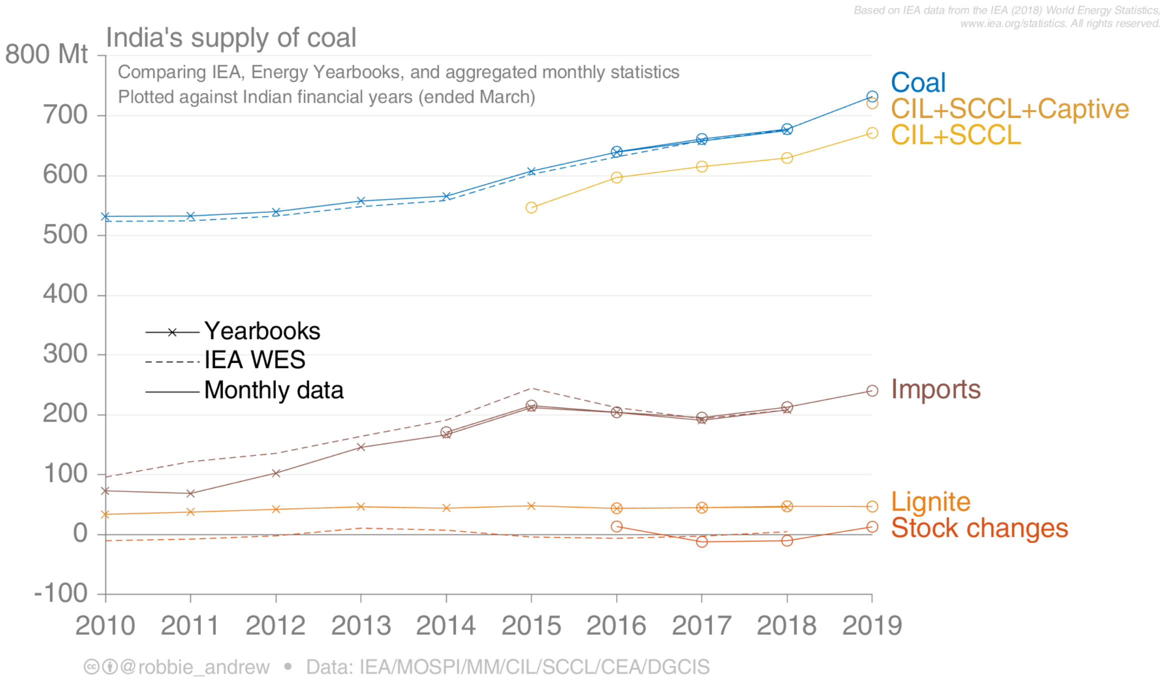

Figure 13: India's supply of coal. Source: IEA, MoSPI Yearbooks, monthly data assembled herein.

For some countries, imports of coal-derived non-energy products such as carbon anodes used in aluminium smelting are significant (Andrew, 2020), but no data was found to suggest this in India.

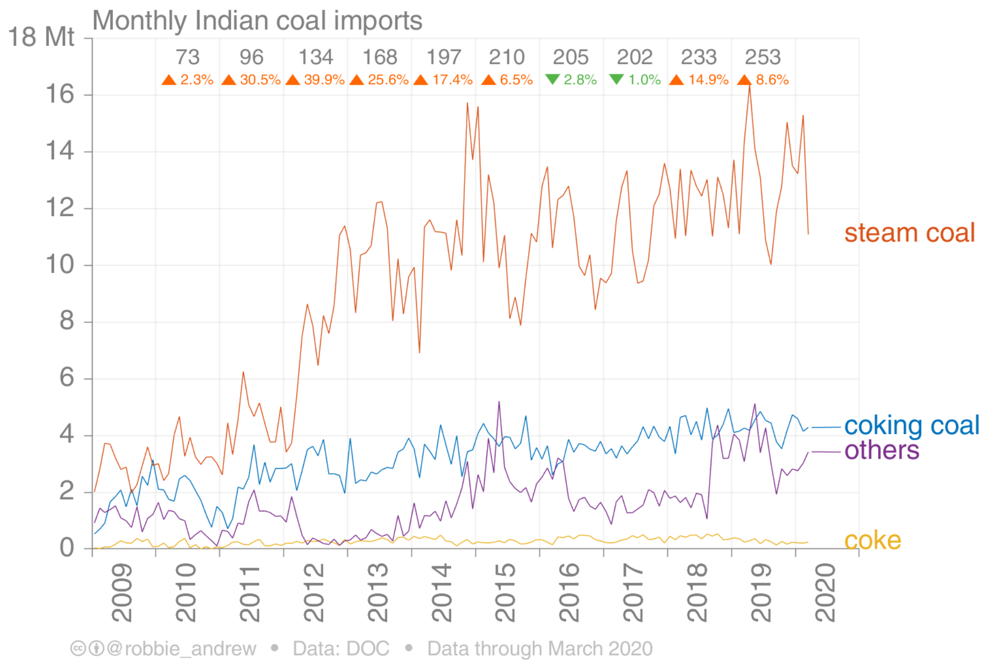

Figure 14: Monthly imports of coal by type. Source: Department of Commerce

4. Extrapolation

Lignite production data lag behind data on production of hard coal and must be extrapolated.

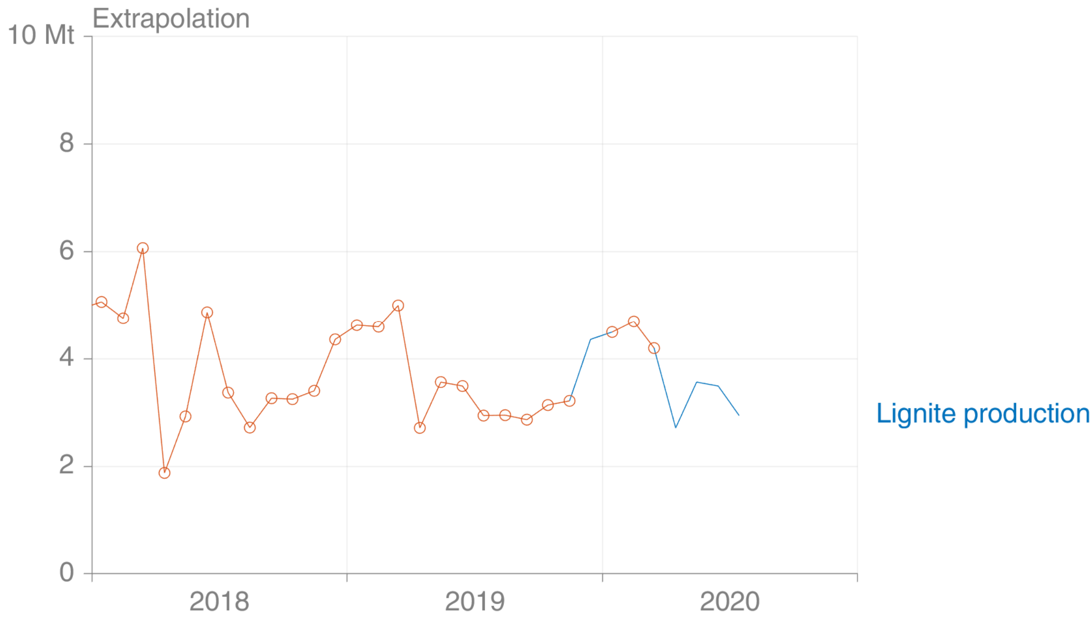

Figure 15: Extrapolation of lignite production. Line with circle markers shows reported values, while line without markers shows interpolation/extrapolation.

5. Coal energy content

The Indian Government introduced quality sampling of coal from 2016 (ETEnergyWorld, 2016), but while these data are collected throughout the year, they are only available on a cumulative basis. India's Energy Yearbook provides tables of annual production and imports in both physical and energy units, but these deviate significantly from those used by the IEA (Figure 16). Here I choose to use the energy contents from the IEA (2019c, 2019d), assuming its information is more reliable, particularly for earlier years.

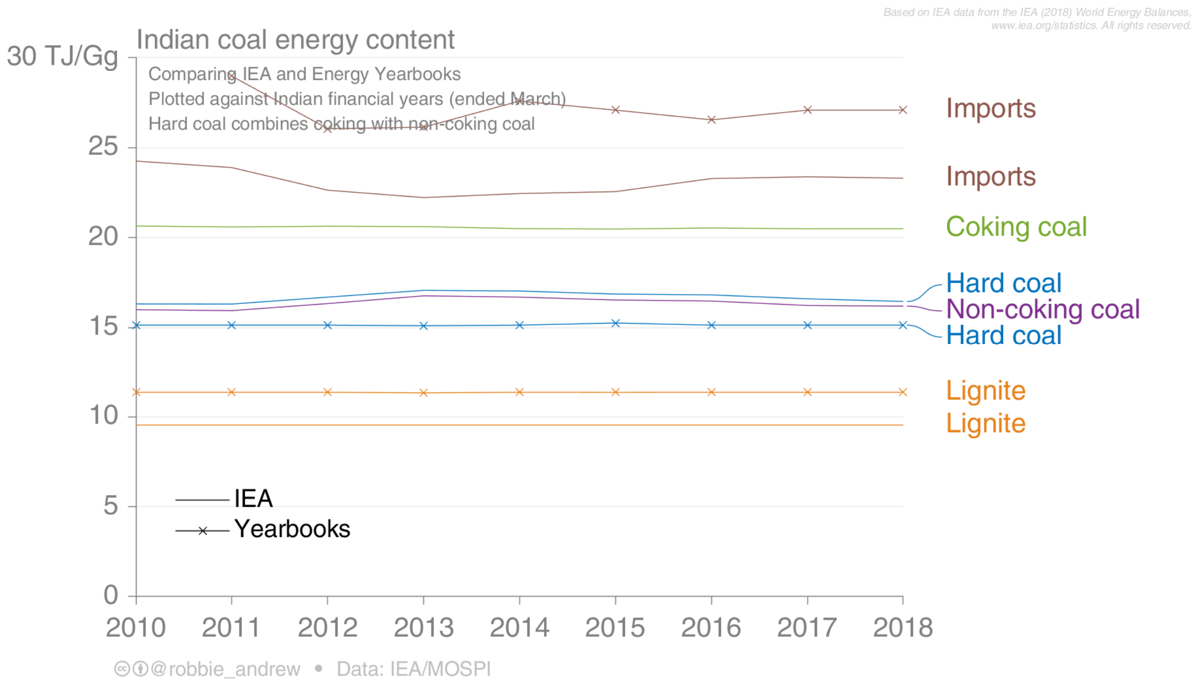

Figure 16: Comparison of energy content of coal from IEA (2019c, 2019d) and India's Energy Yearbooks (MOSPI, various years).

Focusing on hard coal, Figure 17 compares a number of different datasets, demonstrating wide divergence in reported coal quality. It seems clear that coal quality overall has declined in the last 50 years, partly as a result of the significant increase in the share of lower-cost production from open-cast mines (77% in 1998/99 to 94% in 2018/19, according to the Coal Directories), but the IEA's figures in the 1970s and 1980s are markedly different from those reported in all but the most recent Energy Statistics yearbooks.

It is unclear how the Energy Statistics derives average coal quality, but it appears that the IEA has used the annual data on production by coal grade, combined with average energy contents for each grade. This supposition is based on the author doing exactly that with the data provided by the Coal Directories: from 2013, estimates made this way match very closely to those of the IEA. Before 2013, India used a less-detailed grading system. The author's estimates for that earlier period assume that the average energy content did not jump dramatically upwards from 2012 to 2013, something that seems unlikely, and this leads to a difference with the IEA's estimates in that period.

In 2016, Coal India introduced quality assurance routines, sending samples to third-party laboratories for assessment of energy content, a scheme called 'Unlocking Transparency by Third Party Assessment of Mined Coal' (UTTAM). This scheme was introduced after repeated complaints by power station operators that received coal was of lower than the declared (and paid-for) energy content. With 51% sampling coverage in the 2017-18 year, UTTAM results showed that the average analysed energy content was 6% lower than the average declared energy content. Back-calculation of energy content from hard coal production in both energy and mass terms suggests that the Energy Statistics report has subsequently simply used this much lower average for the entire period reported (2006-07 through 2018-19 in the 2020 edition).

The UN Statistics Division's Energy Yearbooks report much higher energy contents in 2012 and 2013, with these numbers having been reported to them by Indian officials; subsequent values are taken from IEA reports (pers. comm., Leonardo Rocha Souza, 16 July 2020). This sharp drop in the UN data for India's energy content translates directly into a sharp drop in production from 2012-13 to 2013-14, which propagates directly to CDIAC's estimates of emissions from solid fuels for India.

Given the insufficient sampling until the introduction of the UTTAM scheme in 2016, it is impossible to say with any uncertainty what the energy content of India's hard coal was before then, but it is unlikely that the constant low value used by the Energy Statistics yearbook is correct.

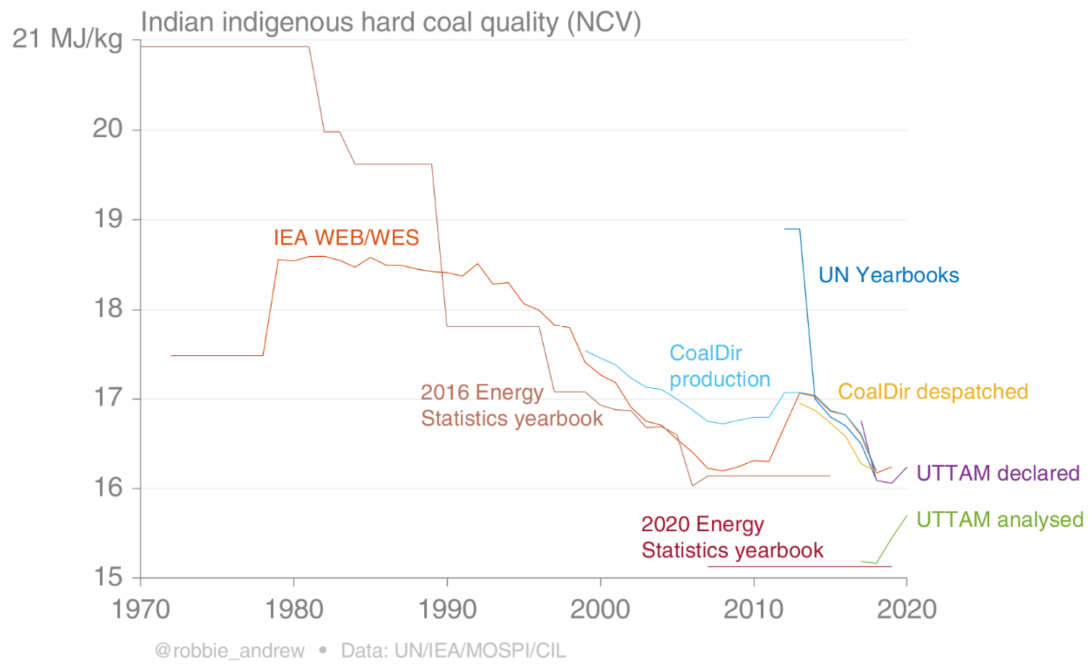

Figure 17: Comparison of energy content of Indian hard coal from various datasets. Data plotted for the Coal Directory ('CoalDir') are the author's estimates derived from data on production by grade. IEA WEB/WES is the World Energy Balances (energy units) and World Energy Statistics (mass units).

Emissions from coal in India's Second Biennial Update Report (BUR) are derived using country-specific energy contents and emission factors (GOI, 2018). The Report is unclear as to whether these factors, reported in tables 2.3 and 2.4, are only used for domestic coal, or whether they are averages for total coal supply, including imports. Imported coal is of higher quality than India's domestic coal, and this likely explains why the energy contents provided in table 2.3 for coking and non-coking coal (23.66 and 18.26 MJ/kg, respectively) are somewhat higher than those reported by the IEA for domestic coal (20.50 and 16.69 MJ/kg). The BUR's reported energy content of lignite, which is entirely domestic, is 9.80 MJ/kg, very similar to the IEA's 9.55 MJ/kg, and somewhat lower than the Energy Statistics' value of 11.37 MJ/kg.

6. Coal CO_2 emissions

I calculate apparent hard coal and lignite consumption in energy terms separately as production + net imports + net withdrawal from stocks. These are then converted to CO_2 emissions using default factors from the IPCC's guidelines (Gómez et al., 2006). Resulting monthly emissions estimates are shown in Figure 18.

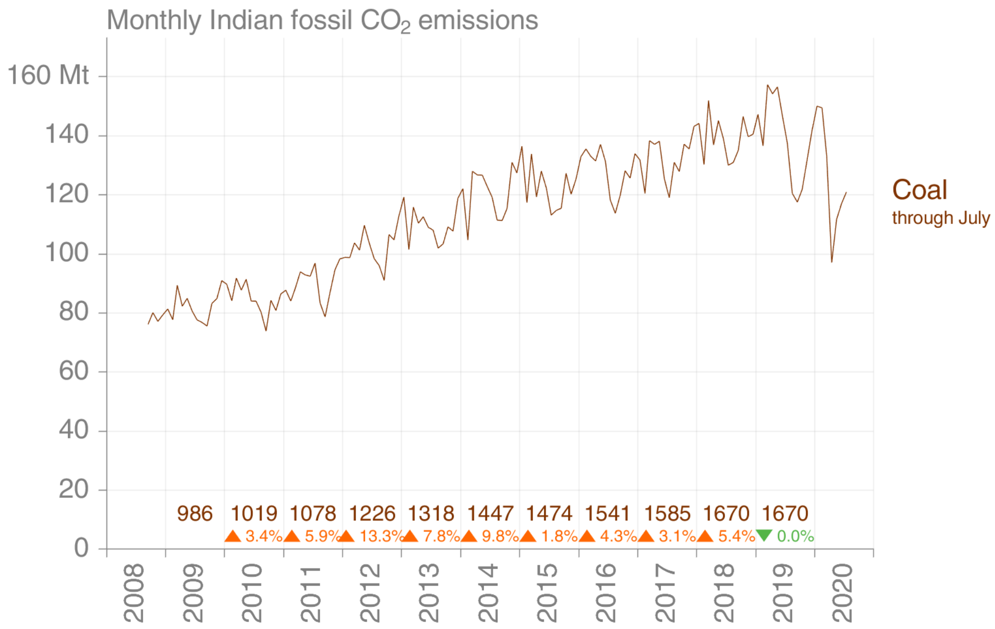

Figure 18: Final monthly estimates of CO_2 emissions from oxidation of coal in India.

7. Coal 'consumption'

Two official Indian reports provide data on coal consumption by the electricity sector. But the numbers they report disagree significantly. The problem is the absence of any definition of 'consumption' in the *Energy Statistics*.

MoSPI's *Energy Statistics* publication presents coal consumption by the electricity sector (table 6.4 in the 2020 edition), with a footnote indicating the source is "Office of the Coal Controller, Ministry of Coal). Since 2010, these data are identical to the numbers in the Coal Controller's *Coal Directory* reports (table 4.20 in the 2018-19 edition), except for the final year, which comes from the *Provisional Coal Statistics*. Importantly, these data represent despatches of domestic coal to both utility and captive power generators, not consumption at all, despite the title of both the chapter and table in *Energy Statistics*. It seems imported coal used by power stations is included in the 'Others plus import non-coking' column, partly explaining why this column has such large values. The supply data they use from the Coal Controller do not allow disaggregation of non-coking coal imports by using sector. Nor does this table account for stock changes at power stations. Meanwhile, the Central Electricity Authority's monthly *Coal Statements* only include consumption by utility generation, not captive generation. Therefore, to reconcile the data in these tables one must take the utility despatch data from the *Coal Directory* (or *PCS*) and the total coal receipts less imports from the *Coal Statements*. These two are approximately the same, with some residual as is common with comparison of supply and use data from different sources.

~~7.~~8. Petroleum production and consumption

Consumption data by mass are available for 12 different petroleum products including non-energy uses such as bitumen, starting in April 1998 (Figure 19)(PPAC, various years-a). These data are most likely in fact sales data rather than actual consumption, a distinction that gains more significance when looking at monthly as opposed to annual data.

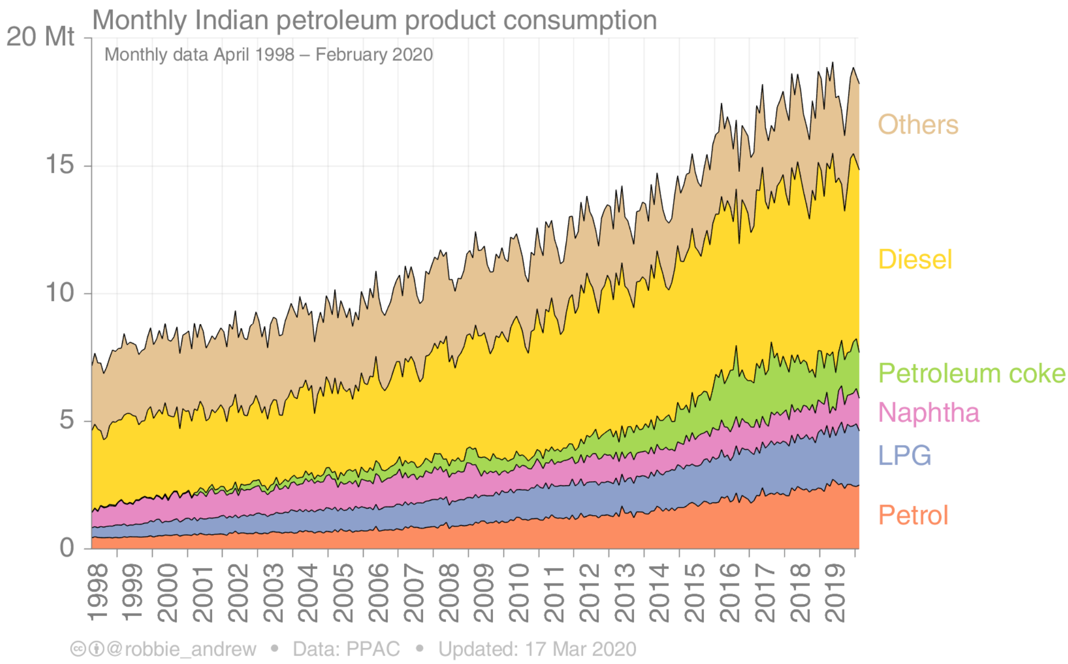

Figure 19: Consumption of petroleum products from April 1998 in physical units. Source: PPAC.

To convert to units of energy I ~~again~~ use factors from the IEA (2018b), which are similar but not identical to the IPCC default factors (Gómez et al., 2006).

Since this analysis focusses on India's domestic emissions, fuel consumption by international aviation and navigation (i.e. bunkers) are excluded. The consumption data from PPAC exclude marine bunker fuels but include aviation bunker fuels, the same convention used by the IEA in its Oil Demand tables (IEA, 2019a). I use the annual ratio of bunker to non-bunker consumption from IEA (2018a) to estimate and remove monthly aviation bunker fuels. This effectively assumes, for example, that the proportion of jet kerosene supplying international flights is constant through the year.

The resulting consumption data in energy units are shown in Figure 20.

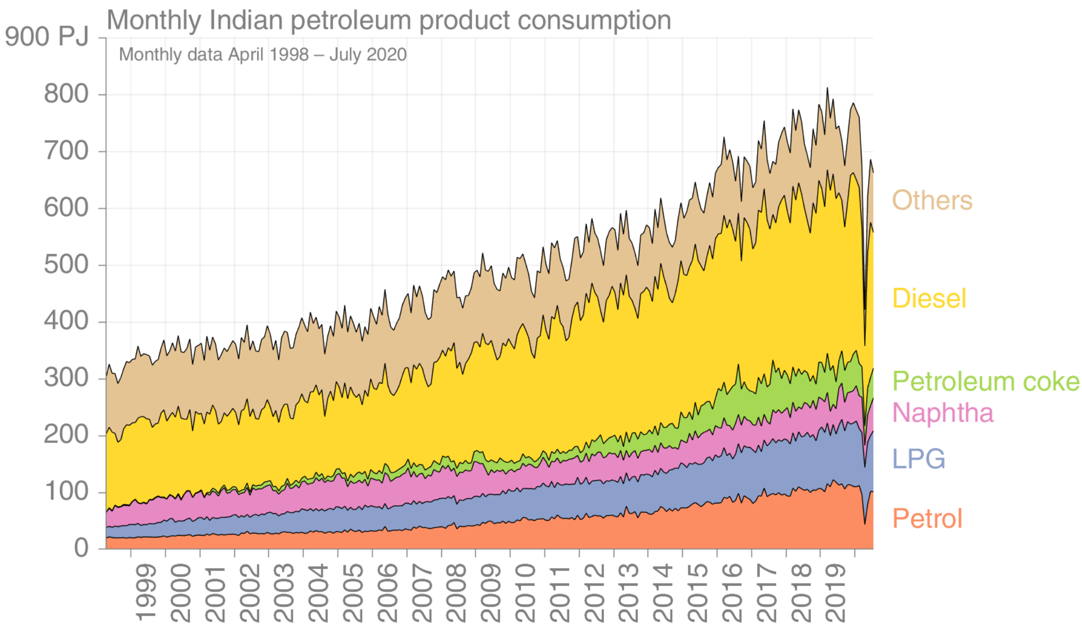

Figure 20: Consumption of petroleum production from April 1998 in energy units. Source: Own calculations.

To determine combustion emissions, non-energy uses of petroleum products must be removed. IEA data also indicate non-energy use by fuel type; these vary gradually over time, and I assume the fractions in the final year of the IEA data also apply for the years immediately following. For oxidation, I assume that both bitumen and lubricants are never oxidised, but that all other fuels are. This is likely to be a small overestimate because some naphtha and other petroleum products are used as feedstocks to produce commodities that might never oxidise. The resulting energy dataset is converted to CO_2 emissions using default IPCC factors (Gómez et al., 2006).

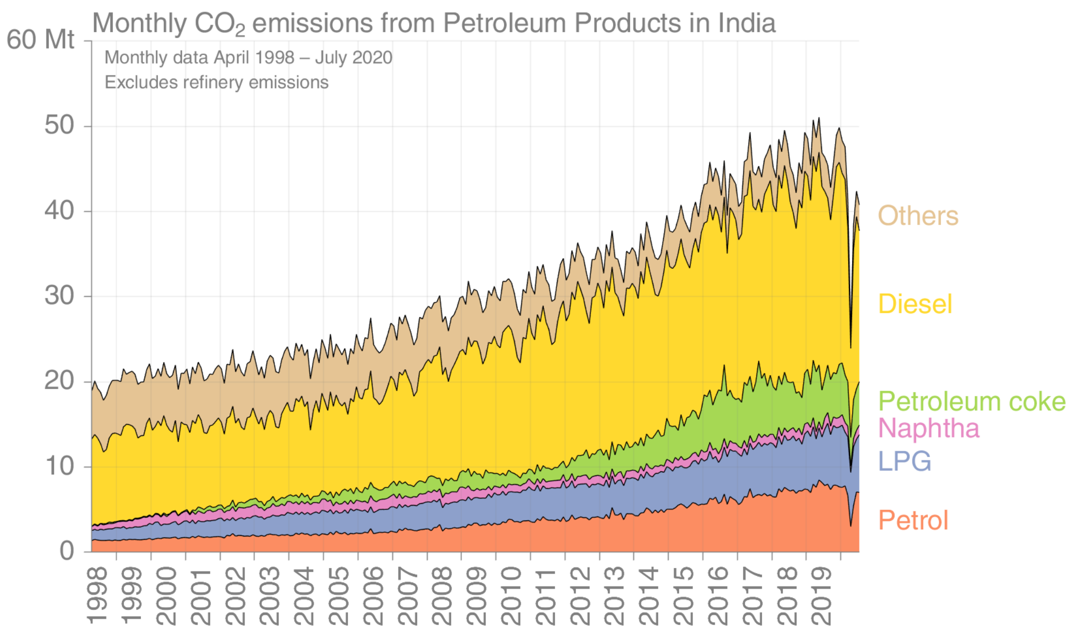

Figure 21: Emissions from combustion of petroleum products, excluding refinery emissions. Source: Own calculations.

Lastly, emissions from refineries' own use of energy are added by scaling annual refinery energy use in the form of petroleum products from IEA (2018a) to monthly production data available from April 2010 (PPAC, various years-b). The IEA indicate that energy use from petroleum products by refineries is entirely refinery gas (IEA, 2019c), and emissions are therefore determined using the default IPCC emission factor for refinery gas (Gómez et al., 2006). Where monthly production data are not available, annual production data are used to estimate refinery emissions. This assumption introduces a small month-to-month error, but refinery emissions are small compared to total petroleum emissions.

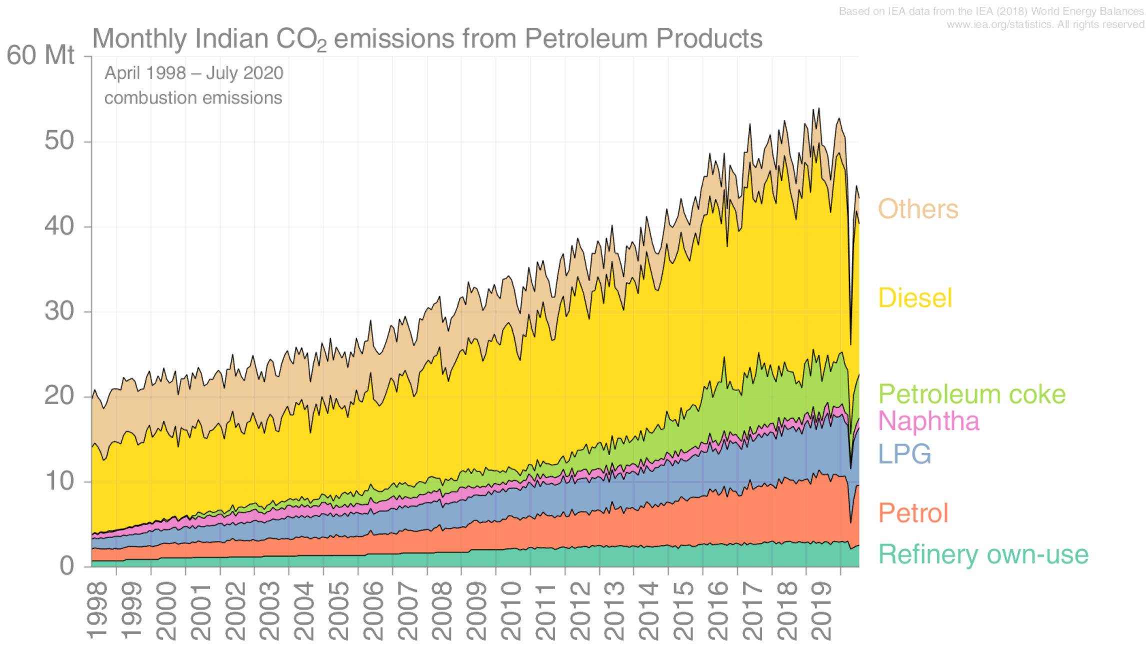

Figure 22: Emissions from combusted petroleum products: Source: Own calculations.

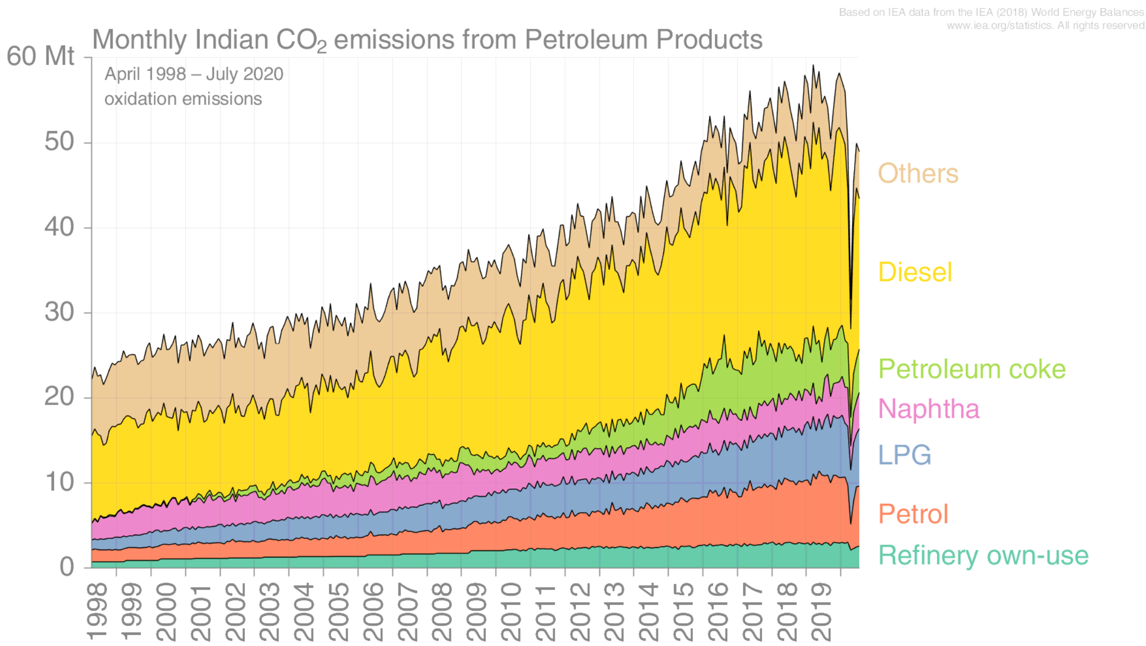

Figure 23: Emissions from oxidised petroleum products: Source: Own calculations.

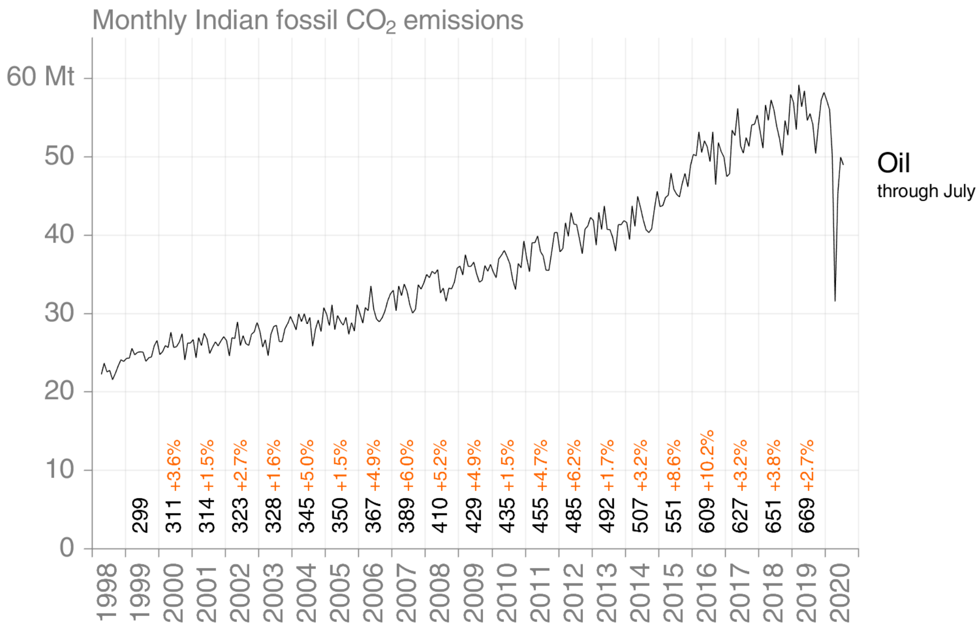

Figure 24: Final monthly estimates of CO_2 emissions from oxidation of oil and oil products in India.

The Joint Organisations Data Initiative (JODI) publishes monthly data on oil and gas production and consumption for a large number of countries, but when comparing India's total oil demand with the official, revised data series from PPAC, some considerable deviations are evident (Figure 25).

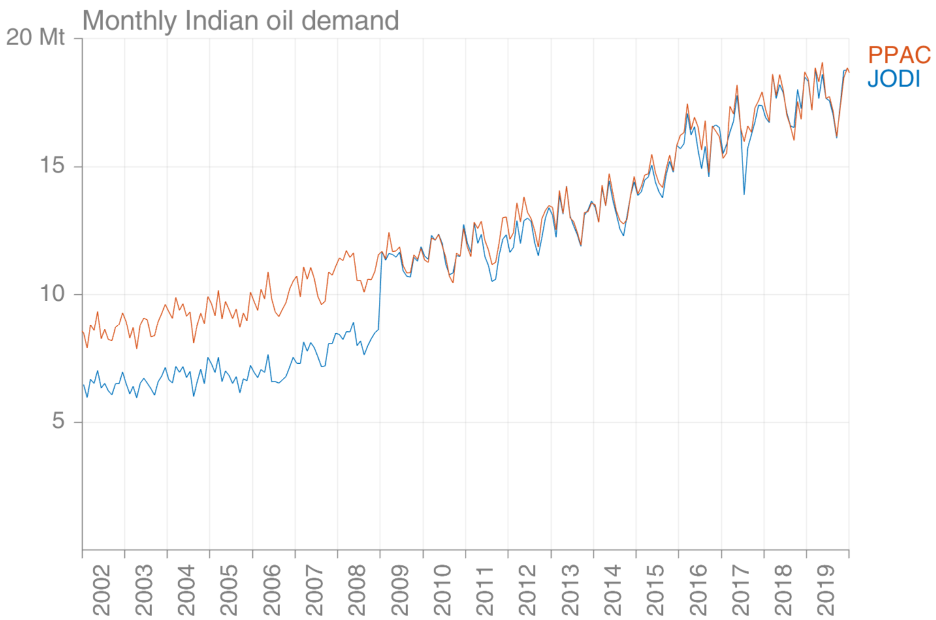

Figure 25: Comparison of monthly oil demand from PPAC and JODI.

Comparison with IEA annual consumption data

The following figures demonstrate that the monthly consumption data as used match very closely the annual data provided by the IEA.

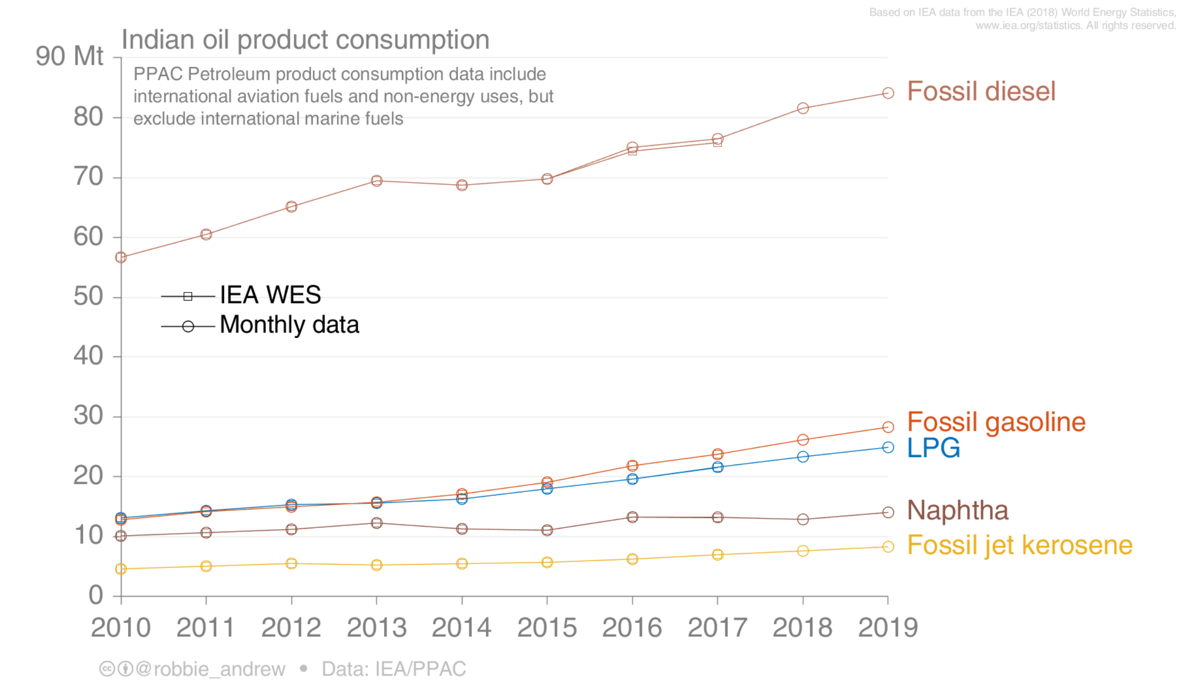

Figure 26: Comparison of consumption of diesel, gasoline, LPG, naphtha, and jet kerosene in physical units between aggregated monthly data from PPAC and annual data from IEA.

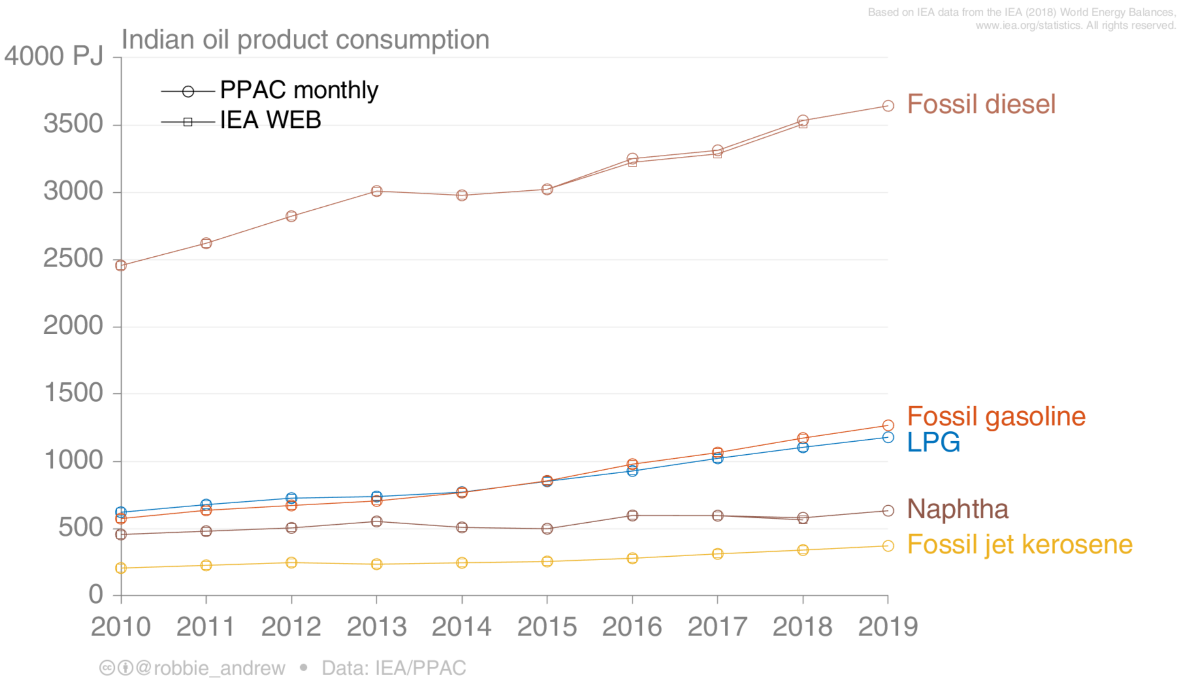

Figure 27: Comparison of consumption of diesel, gasoline, LPG, naphtha, and jet kerosene in energy units between aggregated monthly data from PPAC and annual data from IEA.

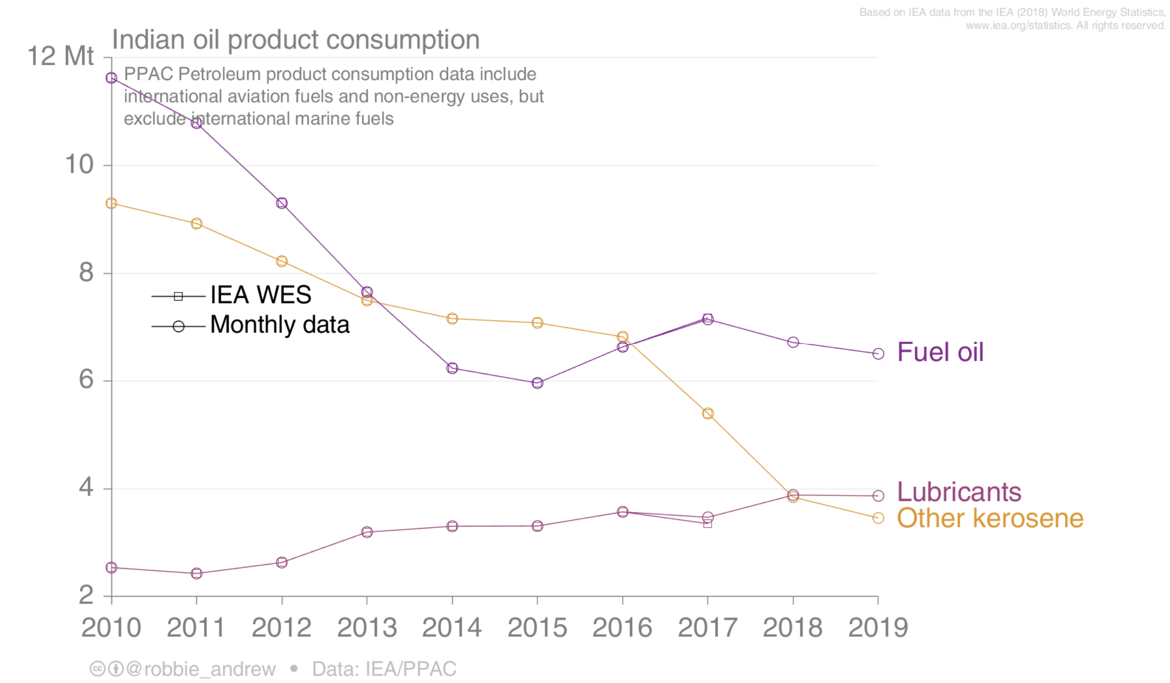

Figure 28: Comparison of consumption of fuel oil, lubricants, and other kerosene in physical units between aggregated monthly data from PPAC and annual data from IEA.

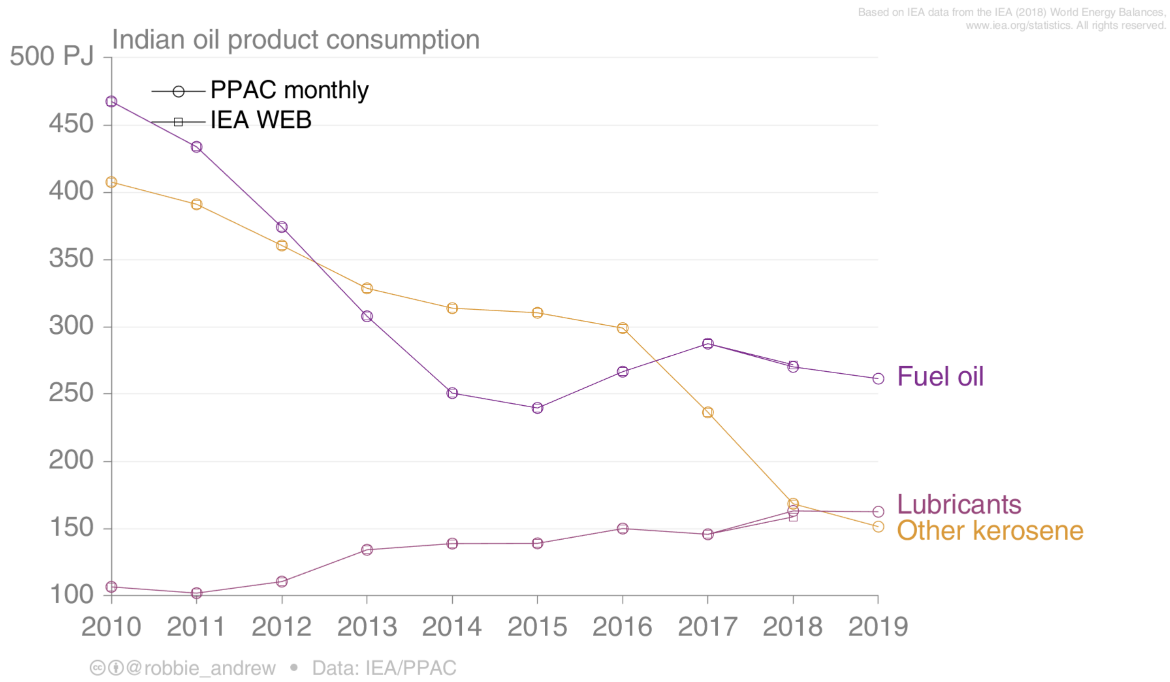

Figure 29: Comparison of consumption of fuel oil, lubricants, and other kerosene in energy units between aggregated monthly data from PPAC and annual data from IEA.

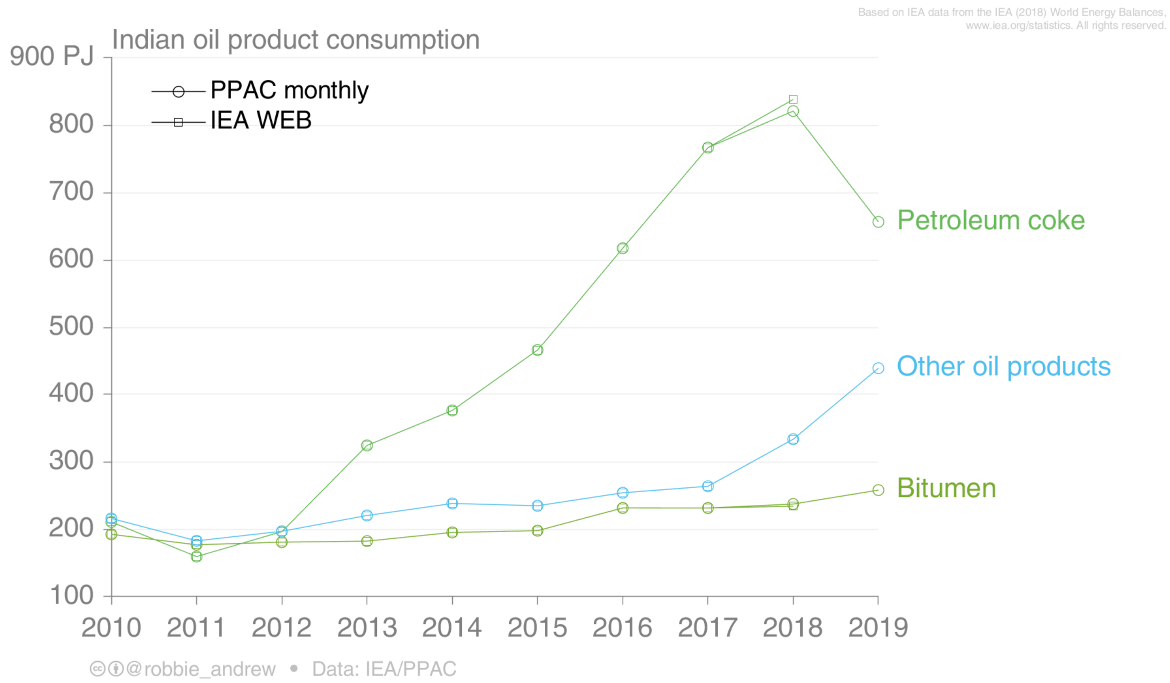

Figure 30: Comparison of consumption of petroleum coke, bitumen, and other oil products in physical units between aggregated monthly data from PPAC and annual data from IEA.

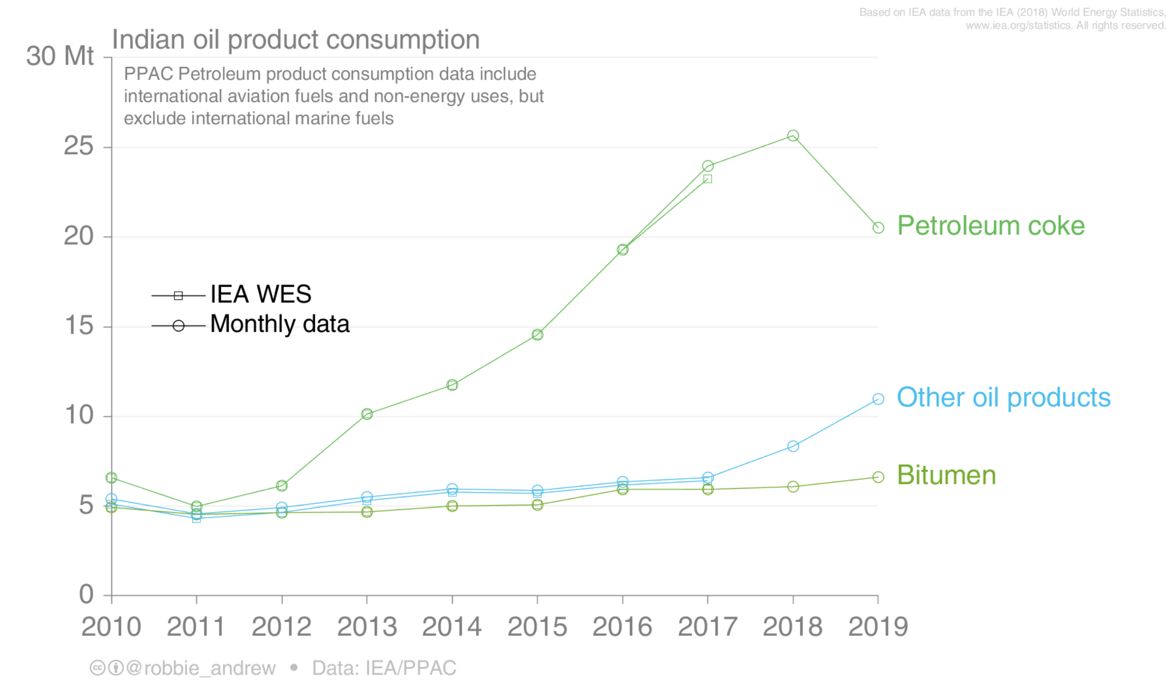

Figure 31: Comparison of consumption of petroleum coke, bitumen, and other oil products in energy units between aggregated monthly data from PPAC and annual data from IEA.

~~8.~~9. Natural Gas

Monthly data for natural gas are available from the Petroleum Planning & Analysis Cell (PPAC) of the Ministry of Petroleum & Natural Gas in four separate reports, all available from the PPAC website: www.ppac.gov.in. Table 1 shows the format and lag between the end of the month for which data are available and the publication of the report.

Table 1: Publication lags of reports that provide data on natural gas production and consumption in India.

Report	Format	Lag
Snapshot of India's Oil & Gas data (Abridged Ready Reckoner)	PDF	~3 weeks
Monthly report on Natural Gas Production, Availability and Consumption	PDF	~5 weeks
Gas Consumption Current	Excel	~5 weeks
Gas Production Current	Excel	~5 weeks

PPAC reports total extracted natural gas as 'Gross production', and variously 'Net availability' or 'Net production' when flaring and losses are removed, noting that the Yearbook indicates that reported losses are very minor. None of the monthly reports explicitly report internal consumption by the gas industry itself, but once this is removed the resulting amount is referred to as 'Net production for sale'. Total supply to the market consists of this net production from domestic production plus LNG imports, and the resulting total supply is called 'Total consumption', noting that this excludes both flaring/losses and internal use by the gas industry. Table 2 shows which reports include each term, and what they are called. India does not export natural gas.

Table 2: Use of natural gas terms across reports on natural gas.

Energy Yearbook (annual data)	Snapshot	Monthly report	Gas Consumption Current	Gas Production Current
Gross production	Gross production	Gross production		Gross production
Flared				
Losses				
Net availability *and* Net Production (for consumption)[1]	Net production		Net production	Net production
Internal use/Consumption				
Net production (sales)		Net production for sale		
LNG imports	LNG imports	LNG imports	LNG imports	
	Total consumption		Total consumption	

[1] Two different terms are used in the Yearbook in different tables.

Data from these sources are available back to April 2012, with some spot data for gross production before that. The UN Statistics Monthly Bulletin of Statistics Online reports monthly production back to January 2009, and these match exactly the net production values from PPAC in the overlapping period until 2016, from which point they match exactly the gross production values from PPAC (except for the very final data point). The assembled data from these sources are shown in Figure 32, For the purposes of a continuous series, the two-month data gap in domestic production in early 2010 is filled with simple linear interpolation.

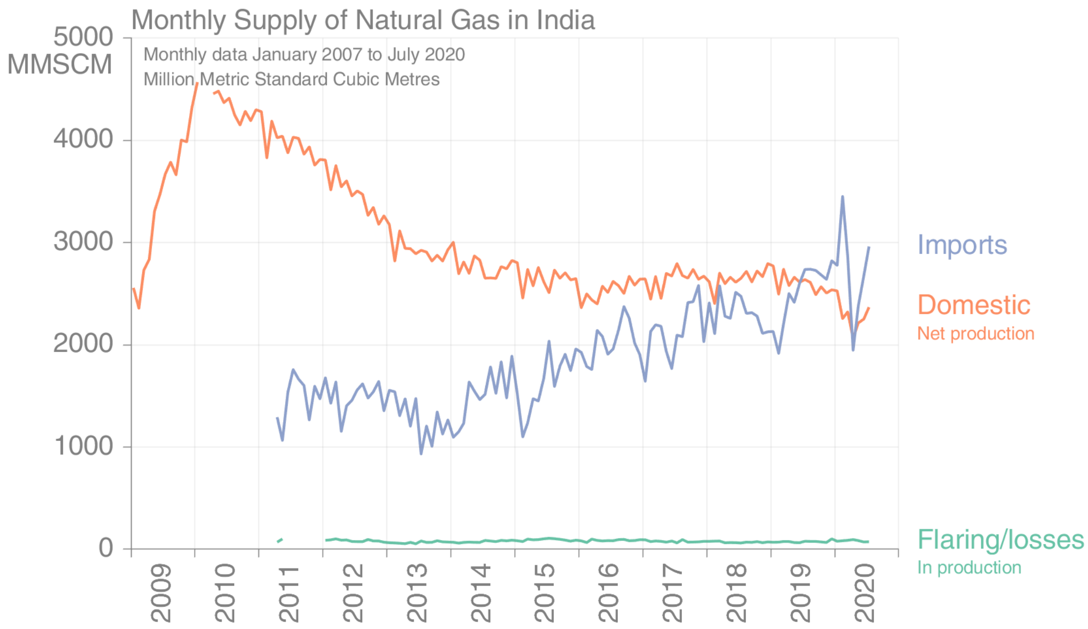

Figure 32: Monthly supply of natural gas in India. Source: PPAC, UN Statistics.

Imports are also available directly from the Department of Commerce (DOC), from January 2007. These data are in units of kilotonnes, and do not match particularly well the data from PPAC when converted using PPAC's conversion factor of 1325 MMSCM (million metric standard cubic metres) per MMT (million metric tonnes), as shown in Figure 33. However, the variation of DOC data does approximately follow that of the PPAC data, and I therefore use the annual totals from the Energy Yearbook spread across months using the DOC dataset to extend monthly imports back to April 2007. Because the period of overlap between domestic production and use of DOC imports data coincides with the lowest proportion of imports in supply in the entire series, the error introduced by this approach is relatively small.

The large spike in imports of natural gas in February 2020 resulted from low international prices because the Covid-19 situation in China reduced demand.

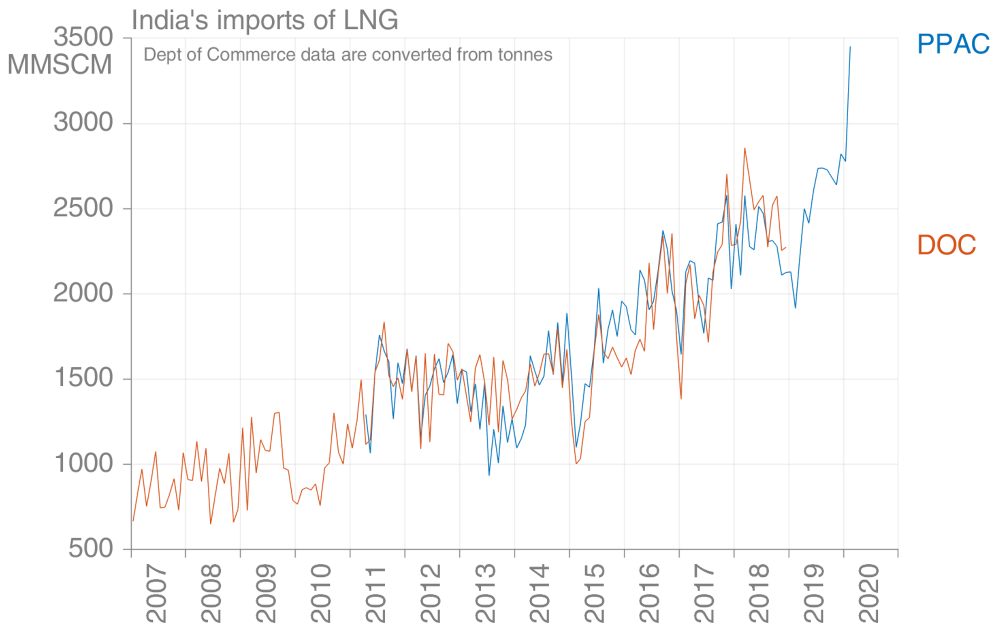

Figure 33: Comparison of LNG import statistics: Source: Petroleum Planning & Analysis Cell (PPAC) of the Ministry of Petroleum and Natural Gas and the Department of Commerce (DOC).

No information is available on stock changes, but there is a considerable supply shortage of natural gas in India, evidenced by gas-fired power stations averaging 20% utilisation factor, so an assumption of zero stock changes is not likely to be far from the truth.

For the purposes of estimating CO_2 emissions from oxidation of natural gas, flaring and internal use should be included in the total, I have used Gross production plus LNG imports, and adjusted that total for an estimated share that is oxidised.

Note that own use in extraction has been mislabelled as 'reinjection' in some editions of the yearbook. The 2013 Yearbook gives very low values for reinjected natural gas, and zero from 1995/96 (Table 3.6 in that book), while the values labelled as reinjection in the 2016 edition (Table 3.5) are identical to those labelled 'internal consumption' in the 2019 edition (Table 3.5).

The "Monthly report" also includes a breakdown of sales by sector (Figure 34). This time series is relatively short, and the 'Others' category includes both oxidised and non-oxidised uses of natural gas, such that this series is not very helpful for determining the share of oxidised gas over time.

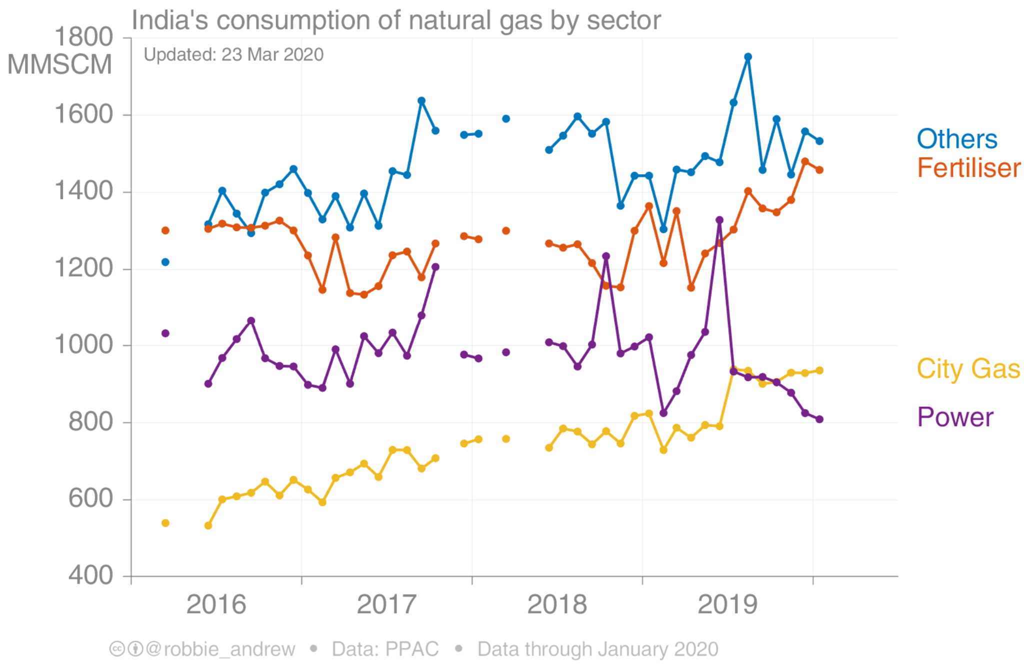

Figure 34: Consumption of natural gas by sector. Reports for missing months were probably produced but have not been located for this analysis. Source: PPAC.

Combustion emissions can be estimated using non-energy use shares either from IEA or India's Energy Yearbooks (MOSPI, various years), and these show considerably lower emissions than if all natural gas were oxidised.

Using information in the Yearbooks on sectoral consumption it is possible to approximate actual oxidation by adding to energy use the non-energy use by the fertiliser and sponge iron industries, along with gas 'shrinkage' (evaporative losses from liquified gas). Some of the natural gas used in the petrochemical industry will also be oxidised, when products are later incinerated, but no data were found from which estimate this fraction. The share of the petrochemical industry grew from about 3% in 2011-12 to about 8% in 2015-16, but has been relatively stable since, and the 2017-18 value is used for later periods until the next yearbook is published.

To convert from physical units to energy units I use the conversion factors provided by PPAC, with 0.90 NCV/GCV and 10000 Kcal/GCV (PPAC, no date). CO_2 emissions factors are taken from the IPCC guidelines (Gómez et al., 2006), resulting in the monthly emissions shown in Figure 35.

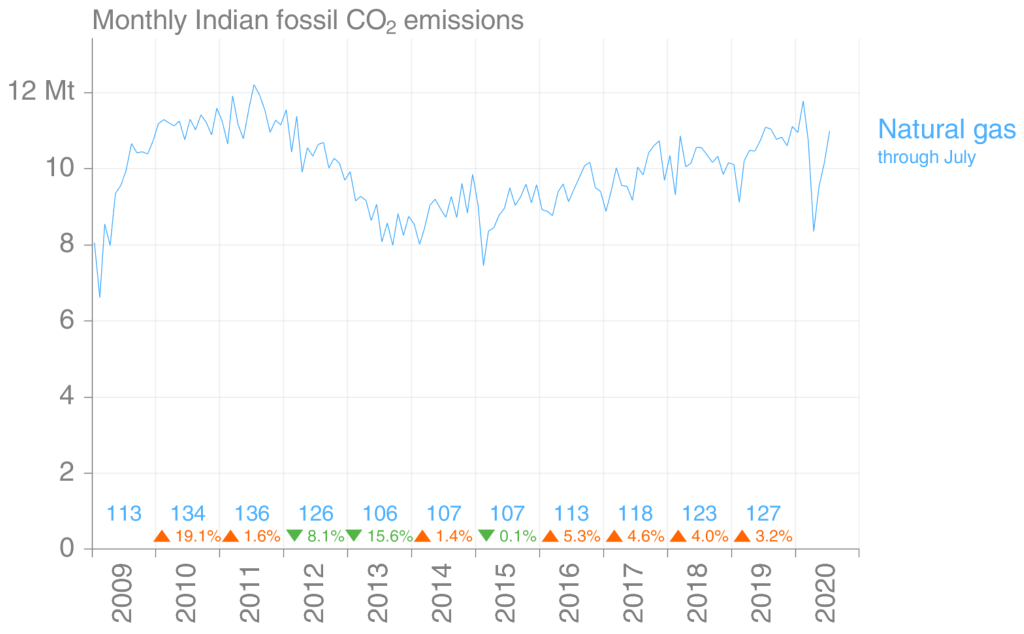

Figure 35: Final monthly estimates of CO_2 emissions from oxidation of natural gas in India.

~~9.~~10. Cement production

Cement production has two major sources of emissions. The first is the use of fossil energy for heating, largely coal, and this is already covered in the estimates of total emissions by fuel category. The second is the chemical reaction that decomposes calcium carbonate into calcium oxide and CO_2 (Andrew, 2019). To accurately estimate these process emissions requires clinker production data, but these have not been published in India since 2012 as a result of a court case against the industry (CCI, 2016). Monthly cement production data are available from the Office of the Economic Advisor (OEA, 2019), and these are used to update the emissions ~~are~~ calculated by Andrew (2019).

I extrapolate the annual clinker data from Andrew (2019) by replicating the final data point forward one to two years, and clinker ratio is calculated from these data and the annualised cement production data from OEA. Then the annual clinker ratio series is interpolated to give a monthly series by placing each annual clinker ratio at the midpoint in each year, and interpolating with a shape-preserving piecewise cubic interpolation, which is then passed through a 36-month moving average filter to reduce potentially spurious volatility (Figure 36). This clinker ratio series is then applied to the entire OEA cement production series to give estimated monthly clinker production, and this is in turn multiplied by the emissions factors used by Andrew (2019) to give monthly process emissions (Figure 37).

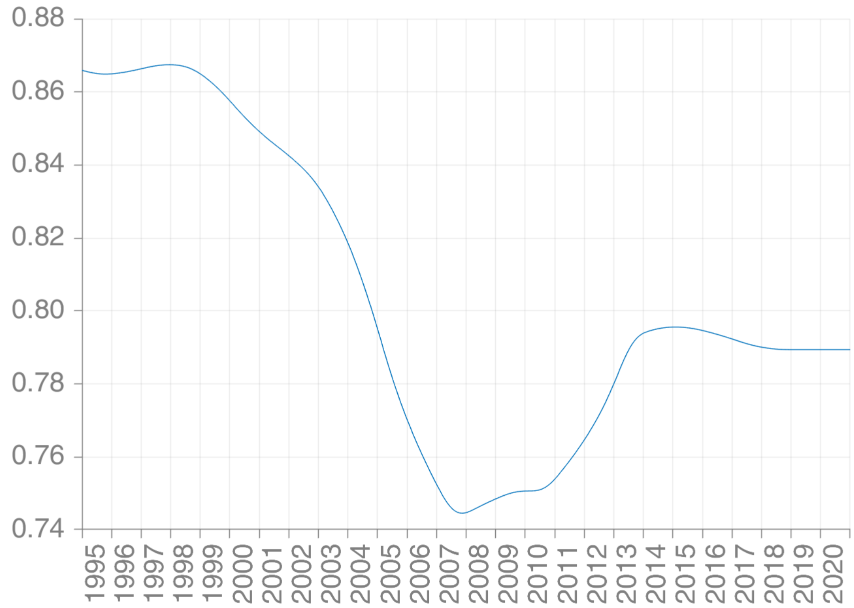

Figure 36: Interpolated/extrapolated monthly Indian clinker-cement ratio.

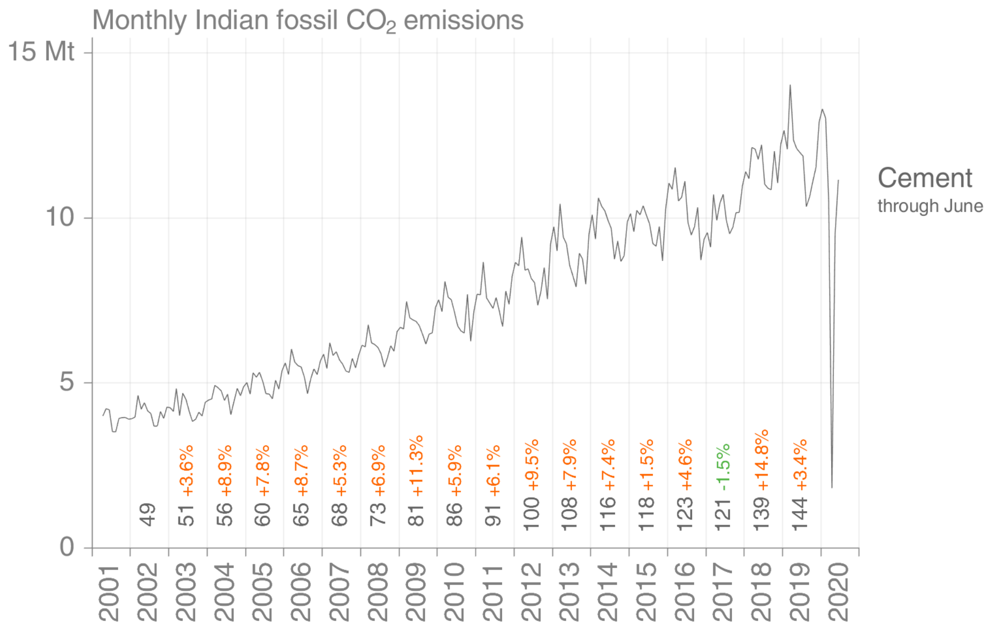

Figure 37: Final monthly estimates of CO2 process emissions from cement production in India.

11. Financial-year CO_2 emissions

Table 3: Financial-year CO_2 emissions in India by category, million tonnes.

Year	Coal	Oil	Natural gas	Cement	Total
2010	1003	427	123	83	1636
2011	1013	440	134	87	1675
2012	1120	462	136	94	1811
2013	1261	491	121	103	1975
2014	1336	493	102	109	2040
2015	1480	515	107	116	2217
2016	1487	572	109	121	2290
2017	1530	604	115	119	2369
2018	1621	639	120	126	2507
2019	1685	659	122	143	2609
2020	1661	662	131	142	2596
CAGR 2016-20*	2.9%	5.0%	3.9%	4.5%	3.5%

* Continuous compounding and adjusted for leap years.

~~10.~~12. Electricity generation capacity

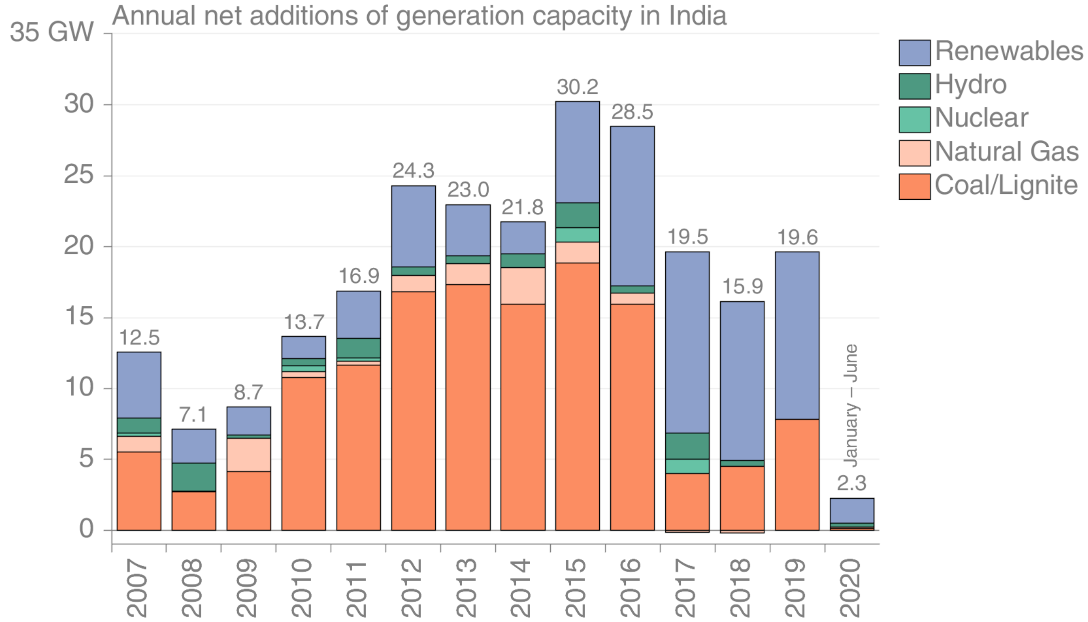

Figure 38: Annual net additions of electricity generation capacity in India. Source: CEA.

~~11.~~13. Quarterly GDP growth

Figure 39 shows official estimates of India's quarterly growth in gross domestic product from 2012, the values published in March 2020 shown in red. This ~~version~~ release reveals substantial revisions compared to the previous ~~version~~ release from December 2019, resulting from changed estimates of the "informal" sector, largely operating with cash and therefore less visible to data collection efforts.

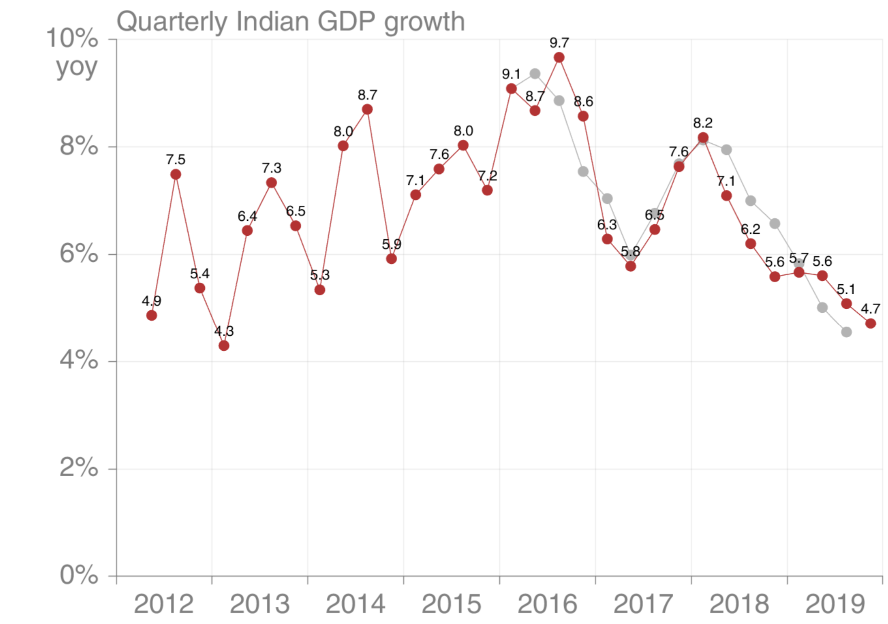

Figure 39: India's Quarterly GDP growth. Latest revision in red, estimates from December 2019 in grey. Source: MOSPI.

14. Emissions intensity of economic production

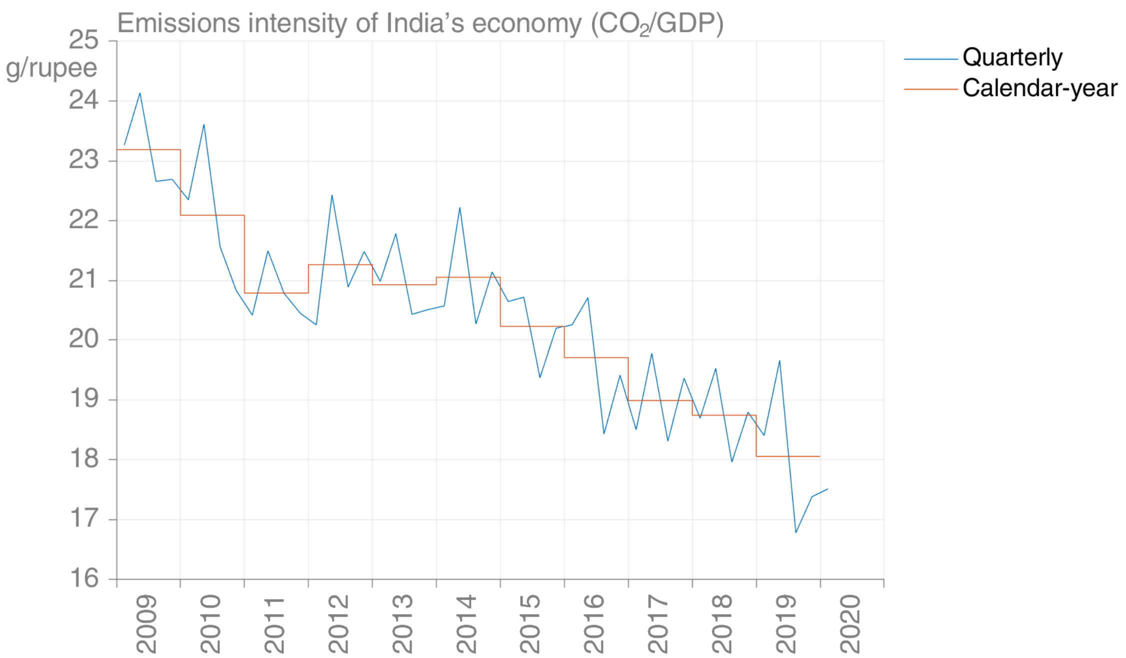

Figure 40: CO2-emissions intensity of India's GDP, measured in constant 2011-12 prices.

~~12.~~15. Total monthly electricity demand

Total electricity demand exhibits summer peaks and winter troughs, reflecting the higher demand for cooling than for heating in India.

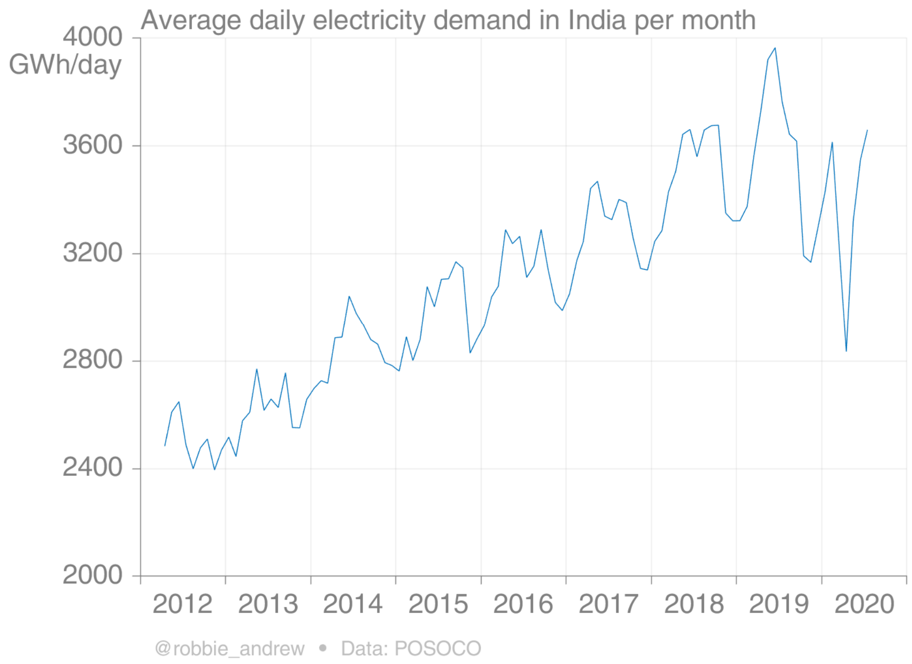

Figure 41: Monthly total electricity demand in India, adjusted for the number of days in the month. Source: POSOCO (2020).

16. Share of fossil fuels in India's energy supply

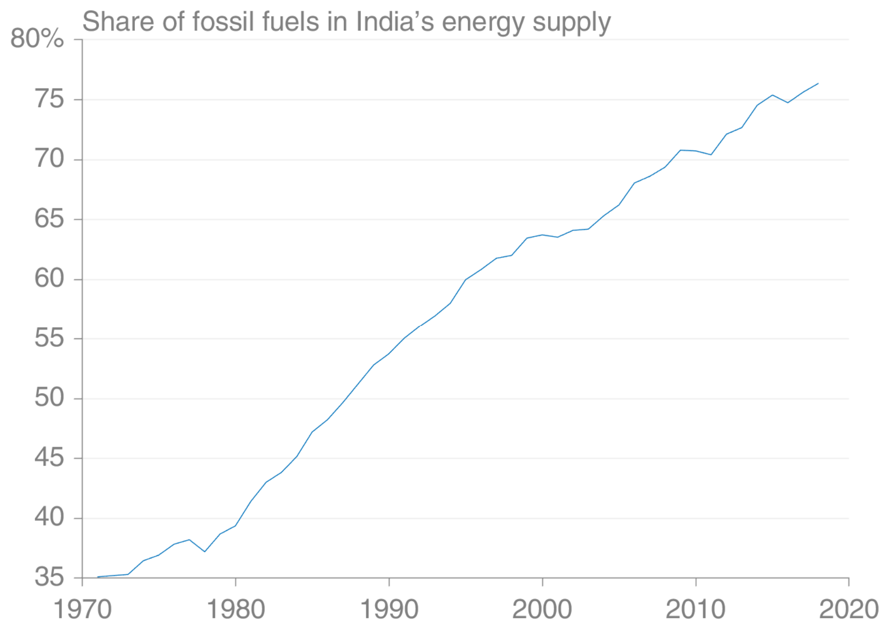

Figure 42: Share of India's energy supplied from fossil fuels, source: (IEA, 2020).

17. COVID-19

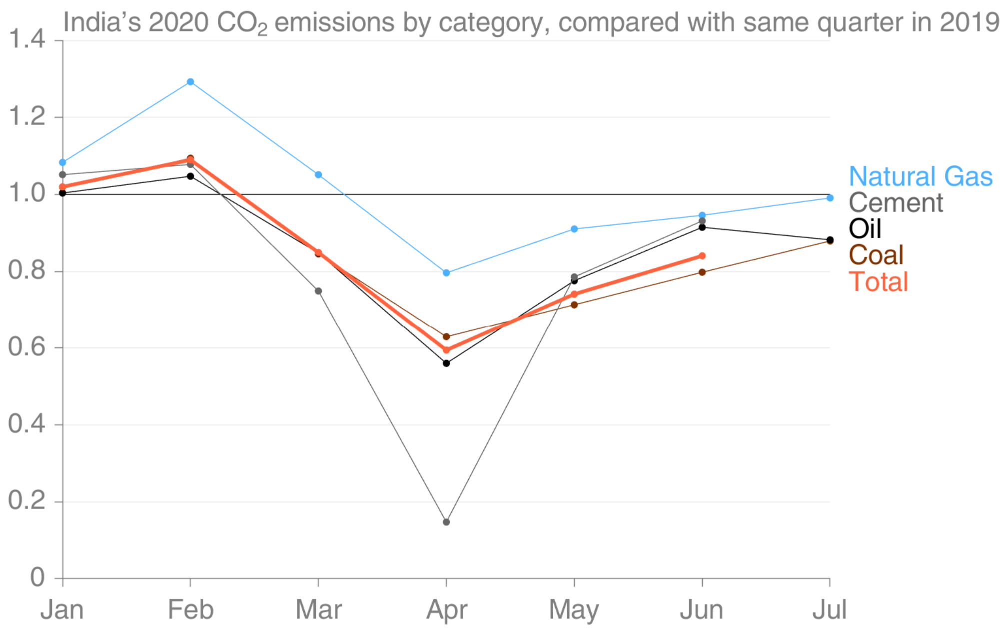

Figure 43: Quarter-on-quarter changes of CO_2 emissions by category during the first months of 2020.

~~13.~~18. Summary of X-11 deseasonalisation method

The following is a brief summary of the method (Eurostat, 2013):

1. Derive an initial estimate of the trend-cycle by applying a moving average to the raw data
2. Subtract this estimate from the raw data to obtain an initial estimate of the seasonal-irregular (SI) and apply a moving average to the SIs for each type of period (month) separately to obtain initial estimates of the seasonal component
3. Subtract the initial seasonal factors from the raw data to obtain an initial estimate of the seasonally adjusted series (i.e. the trend-cycle/irregular) and apply a Henderson moving average to obtain a second estimate of the trend-cycle
4. Subtract the second estimate of the trend-cycle from the raw data to obtain a second estimate of the SIs, and apply a moving average for each type of quarter separately to obtain final estimates of the seasonal component
5. Subtract the seasonal factors from the raw data to obtain a final estimate of the seasonally adjusted series and apply a Henderson moving average to obtain a final estimate of the trend-cycle

~~14.~~19. Imports of urea from China

India imported 2.4 Mt of urea from China in 2019 (Roache, 2020). The IPCC's default factor is 0.20 tonnes of carbon emitter per tonne of urea (De Klein et al., 2006), or 0.73 tCO_2 per tonne. These imports would then lead to emissions of 1.76 Mt CO_2 when used in Indian agriculture.

20. India activity data sources

Category	Organisation	Report	URL
Coal	Ministry of Coal	Monthly Summary to Cabinet	https://coal.nic.in/content/monthly-summary-cabinet
Coal	Coal Controller	Provisional Coal Statistics	http://www.coalcontroller.gov.in/pages/display/20-provisional-coal-statistics
Coal	Coal Controller	Coal Directory	http://www.coalcontroller.gov.in/pages/display/16-coal-directory
Coal	National Power Portal	Daily Coal Reports	https://npp.gov.in/dailyCoalReports
Coal	Central Electricity Authority	Coal Statement	http://cea.nic.in/monthlycoal.html
Coal	Directorate General of Commercial Intelligence and Statistics	Foreign Trade Data	http://14.98.253.4/
Coal	Department of Commerce	System on India's Monthly Trade	https://commerce-app.gov.in/meidb/Default.asp
Coal	Ministry of Coal	Production and Supplies	https://coal.nic.in/content/production-and-supplies
Coal	Coal India	UTTAM	http://uttam.coalindia.in/
Coal	Indian Bureau of Mines	Monthly Statistics of Mineral Production	https://ibm.gov.in/index.php?c=pages&m=index&id=497
Coal	United Nations	Monthly Bulletin of Statistics Online	https://unstats.un.org/unsd/mbs/app/DataSearchTable.aspx
Coal	Coal India	Physical Performance	https://www.coalindia.in/en-us/performance/physical.aspx
Coal	Singareni Collieries Company Ltd	Production	https://scclmines.com/scclnew/performance_production.asp
Oil	Petroleum Planning & Analysis Cell	Consumption of Petroleum Products	https://www.ppac.gov.in/content/147_1_ConsumptionPetroleum.aspx
Oil	Petroleum Planning & Analysis Cell	Production of Petroleum Products	https://www.ppac.gov.in/content/146_1_ProductionPetroleum.aspx
Natural Gas	Petroleum Planning & Analysis Cell	Consumption of Natural Gas	https://www.ppac.gov.in/content/147_1_ConsumptionPetroleum.aspx
Natural Gas	Petroleum Planning & Analysis Cell	Production of Natural Gas	https://www.ppac.gov.in/content/151_1_ProductionNaturalGas.aspx
Natural Gas	Petroleum Planning & Analysis Cell	Snapshot of India's Oil & Gas Data	https://www.ppac.gov.in/View_All_Reports.aspx
Natural Gas	Petroleum Planning & Analysis Cell	Monthly Report on Natural Gas	https://www.ppac.gov.in/View_All_Reports.aspx
Cement	Office of the Economic Adviser	Eight Core Industries	https://eaindustry.nic.in/
Electricity	Power System Operation Corporation Ltd	Daily Reports	https://posoco.in/reports/daily-reports/
Energy	Ministry of Statistics and Programme Implementation	Energy Statistics	http://www.mospi.gov.in/recent-reports

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