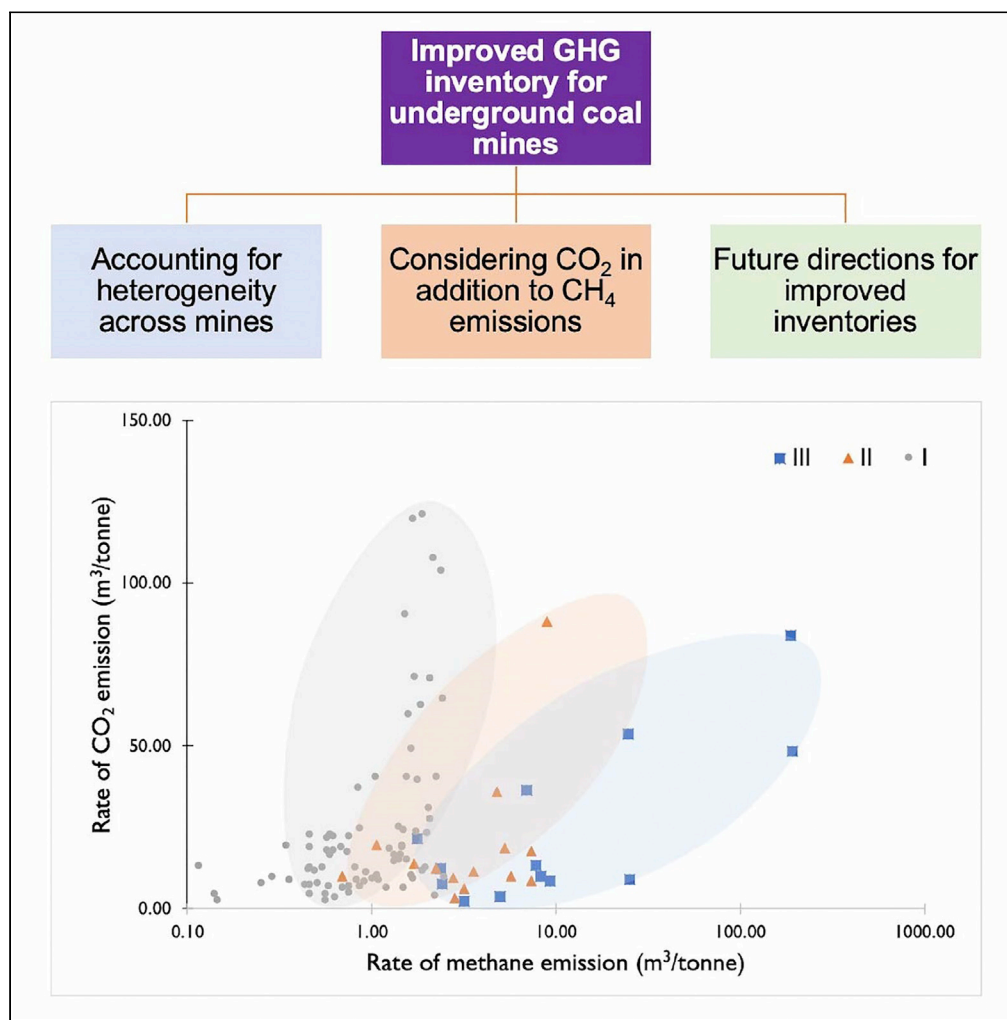


Article

Updated greenhouse gas inventory estimates for Indian underground coal mining based on the 2019 IPCC refinements



Ajay K. Singh,
Udayan Singh,
Durga C.
Panigrahi, Jayant
Singh

udayan.singh@northwestern.
edu

Highlights

GHG inventory estimates are presented for Indian underground coal mining

CO₂ – in addition to CH₄ – may be significant in terms of fugitive emissions

Overall emissions have reduced because of a declining trend in underground mining

Generalizable approaches to improve estimates are discussed

Singh et al., iScience 25,
104946
September 16, 2022 © 2022
The Author(s).
[https://doi.org/10.1016/
j.isci.2022.104946](https://doi.org/10.1016/j.isci.2022.104946)

Article

Updated greenhouse gas inventory estimates for Indian underground coal mining based on the 2019 IPCC refinements

Ajay K. Singh,^{1,4} Udayan Singh,^{2,4,5,*} Durga C. Panigrahi,¹ and Jayant Singh³

SUMMARY

Underground coal mining has been known as a significant source of fugitive greenhouse gas emissions. Past analyses of these emissions in India used deterministic emission factors and predominantly focused on methane emissions with reporting of CO₂ emissions remaining limited to a few sites. This study addresses these gaps via field measurements on 108 underground mines (out of a total 338) to evolve greenhouse gas reporting in this sector. Results show large heterogeneity across “degrees” of mines as categorized by the Indian government. In addition, CO₂ emissions are found to be significant in shallower mines of lower gassiness. Overall, the emissions from underground mining have reduced from 2.6 to 8.3 Mt-CO₂e to 1.3–3.6 Mt-CO₂e during 1980–2019. These emissions might remain significant by 2050 under a 2–2.5°C constraint or may decline below 100,000 t-CO₂e under a 1.5°C constraint. We also discuss several generalizable outcomes and approaches to make inventories in this sector more robust.

INTRODUCTION

Coal production in India has increased from 112 Mt in 1980 to 773 Mt in 2019, with a compounded average growth rate of 5.1% (Ministry of Coal, 2021). Although the Government of India’s climate efforts are directed toward renewable energy expansion, they do not explicitly aim at a coal phase-out (Roy and Schaffartzik, 2021; Shukla et al., 2017). Accordingly, even in several stringent climate pathways, there is a substantial presence of coal albeit with strong mitigation measures such as CO₂ capture and storage (CCS) (Vishwanathan and Garg, 2020). The key thrust of reduction of greenhouse gas emissions (GHG) in India is that from coal combustion which contributes to two-thirds of CO₂ emissions in India (Andrew, 2020). That said, fugitive emissions during coal mining activities are also a substantial contributor to global GHG emissions. Worldwide methane emissions from coal mining were around 957.3 Mt-CO₂e in 2020 and might further increase without key mitigation efforts (GMI, 2022). Top-down modeling results suggest that even under a strong 2°C transition pathway, these emissions would remain significant at around 300 Mt-CO₂e until the end of the century (Kholod et al., 2020). Therefore, appropriate bottom-up quantification and understanding of mitigation measures is an important activity as part of GHG inventory preparation for India, which is now the second largest coal producer after China.

India’s coal production has largely been dominated by surface mining and the share of underground mining has steadily gone down to 6% during this decade (Ministry of Coal, 2021). This decline in underground mining has been because of multiple reasons – lower economic productivity, increased safety concerns, and low-cost extraction opportunities from shallow deposits (Tripathy and Ala, 2018). That said, there is a consensus among industry leaders and other stakeholders that if Coal India’s targets of 1 billion tonnes production by 2024 are to be realized, it can be only through an increase in underground mining (Garg et al., 2021; Tongia, 2016; US EPA, 2019). This thinking stems from the reasoning that production from low-hanging, shallow coal deposits has now plateaued. This means that increasing production from the current ~750 million tonnes to the 1 billion tonnes target would entail an increase in underground production by 100 million tonnes in the very short term (The Economic Times, 2022). Although the socio-technical and regulatory challenges of such an increase are manifold, this article focuses on the GHG implications of underground coal mining in India.

¹PMRC Private Limited, Dhanbad 826004, India

²Institute for Sustainability and Energy at Northwestern, Northwestern University, Evanston, IL 60208, USA

³Department of Environmental Engineering Sciences, University of Florida, Gainesville, FL 32611, USA

⁴These authors contributed equally

⁵Lead contact

*Correspondence: udayan.singh@northwestern.edu

<https://doi.org/10.1016/j.isci.2022.104946>



There are several considerations associated with GHG inventories of underground coal mining. First, the magnitude of the rate of emissions is significantly higher than surface mining. The amount of methane content in coal increases directly with the depth and, accordingly, deeper deposits emit 1–2 orders of magnitude more methane when mined out (IPCC, 2006). Second, the variability in the rate of emissions from such mines is also higher. Thus, if Tier 1 default emission factors are used for such mines, they tend to exhibit much larger deviation compared to surface mines (Singh, 2019). Third, although the emissions are higher, underground mining activities also present a significant mitigation opportunity in the form of pre-mining drainage of methane (or coal mine methane [CMM] recovery) (Karacan et al., 2011). This could bridge some of India's scarce natural gas reserves while also reducing safety hazards during underground mining. In China, these efforts have already resulted in significant emission reduction and health co-benefits (Zhang et al., 2020; Zhou et al., 2016). Finally, the most recent update to the Intergovernmental Panel on Climate Change (IPCC) methodology for fugitive methane estimations i.e., the 2019 IPCC Refinements indicates there may be a significant scope of emissions in the form of CO₂ from the ventilation air (IPCC, 2019). These emissions result from slow oxidation of the exposed coal surface and their genesis is, accordingly, distinct from methane emissions.

In view of these considerations, an update to India's underground mining activities is deemed necessary for accurate GHG reporting. Prior estimates for methane emission factors considered a single-point, averaged methane emission factor which did not account for regional variability (Singh and Kumar, 2016). These emission factors, which have featured in the IPCC Emission Factor Database and used for India's national communications to the UNFCCC, could benefit from regional specificity, which could also be matched with coalfield-level mitigation opportunities. Moreover, because reporting of CO₂ emissions from coal mining activities has been recommended by the IPCC guidelines only as recently as 2019, such published inventory does not exist to our knowledge.

To bridge the data gaps mentioned above, this article seeks to present the distributions of underground mining emission factors associated with different categories and coalfields in India. These are combined with the time-series data on coal production to estimate the overall GHG emissions from such activities. Finally, a discussion of projected future inventory is presented to understand the extent to which these emissions may be reduced. The key novelty in this article is to improve the understanding of heterogeneity in emissions from coal mining, while also accounting for CO₂ emissions from spontaneous combustion that have been neglected in the past. Although the paper discusses mining with respect to India, the discussion section also provides several generalizable outcomes to improve inventory activities globally.

Description of study sites

Coal in India occurs primarily in two formations – the Gondwana formations and the Tertiary formations. The Gondwana formation accounts for >99% coal reserves in the country and are found in the south-eastern quadrant of the country. They span ten states spread over 64,000 km². The coals in this formation range from sub-bituminous to bituminous grade coal, including some prime coking coal in the Jharia coalfield (Singh et al., 2018). Tertiary coal deposits are found in the northern, southern and western part of the country, as well as in the northeastern states of Meghalaya, Nagaland, Assam, and Arunachal Pradesh. Gondwana coals range from high rank in the Damodar Basin to low rank. Tertiary coals are generally low-to-moderate rank and some lignites (Singh, 2022).

The names of the coal mines, their daily coal production, and company names are noted in the [supplemental information](#). Here, we discuss the reasons for selecting these mines as being representative of national coal production data. The mines evaluated here included 81 degree-I mines, 14 degree-II mines and 13 degree-III mines. These mines represented 31, 20, and ~100% of all the active coal mines in the respective categories, based on the most recent compiled statistics of underground coal mines in India (Singh, 2022).

From a coalfield-level perspective, our analysis included measurements at the 12 largest coalfields in terms of production (Raniganj, Jharia, East-Bokaro, Mand-Raigarh, Makum, Pranhita Godavari, Sohagpur, Ib Valley, Pench-Kannan, Bisrampur, Johilla, and Hasdeo). It may be noted that coalfields of higher gassiness (degrees II and III) are mostly present in limited coalfields – Raniganj, Jharia, and East Bokaro in the Gondwana coal basin, and Makum coalfield in the Tertiary basins. This also covers >95% of the coal production from underground mines out of the 16 coalfields in India (Vishal et al., 2013).

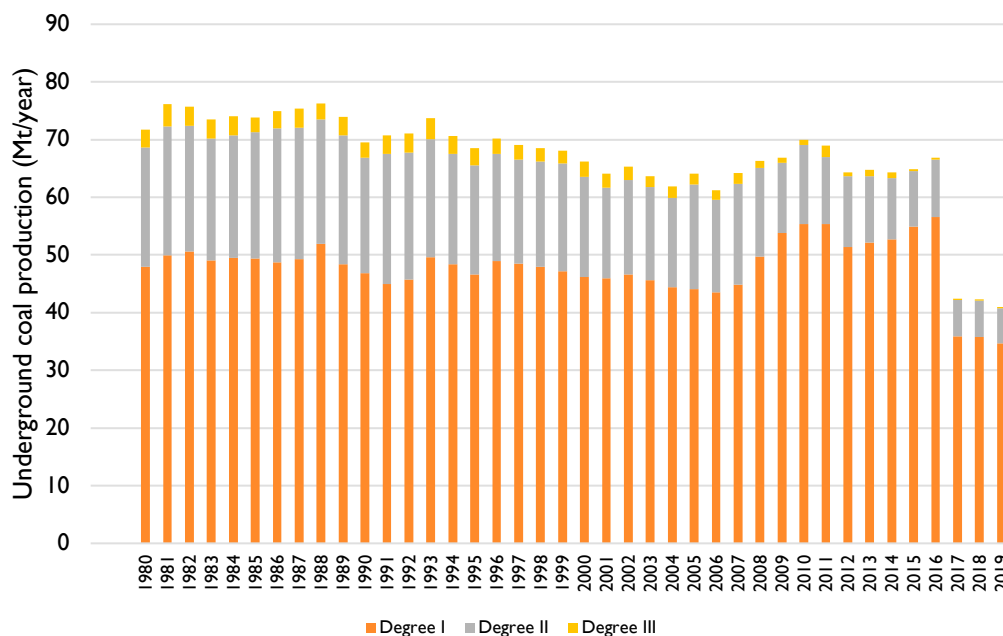


Figure 1. Coal production from underground mines in India

Data source: Statistics of Mines in India Vol. I (Coal), (Various years), Directorate General of Mines Safety, Ministry of Labour and Employment, Government of India. Authors' illustration.

Emissions are also determined by the type of mining: Longwall versus board and pillar, with longwall mining producing higher emissions. Around 98% of production in India occurs via the board and pillar method, and the rest are mined through the longwall method (Nayak and Dalai, 2010). As such, most mines evaluated in our study are ones which are mined via the board and pillar method. That said, some prominent longwall mines (Moonidih, Kottadih, Kargali, Jhanjra, and Chasnalla) are included in this study. The depth cover of the Moonidih is over 600 m, and it is one of the deepest coal mines in India (Mishra et al., 2018). It also produces high-quality coking coal, whereas most of the degree-I mines studied here produce higher-ash coal.

The coal production data was collected from the statistics of the Directorate General of Mines Safety (DGMS), Government of India. These publications provide year-wise data for coal production in different categories of mines. In the context of underground mining activities, these entail the following degrees of gassiness:

- Degree-I: The percentage of methane in the general body of air does not exceed 0.1 and the rate of emission of methane does not exceed one cubic meter per tonne of coal produced.
- Degree-II: The percentage of methane in the general body of air is more than 0.1 or the rate of emission of methane is one cubic meter per tonne or more but less than 10 cubic meter per tonne of coal produced.
- Degree-III: The rate of emission of methane per tonne of coal produced exceeds 10 cubic meters or more per tonne of coal mined.

Although this classification was done to implement safety regulations, our prior work (Singh and Kumar, 2016) has utilized these datasets for calculation of the fugitive methane emission inventory as well. The summarized coal production from Indian underground mines is shown in Figure 1.

RESULTS

Magnitude and variability of GHG emissions

The first major point of discussion is the rate of CH₄ and CO₂ emissions with respect to the degree of mines. As pointed out earlier, the DGMS categorizes mines as degree-I, II or III based on whether the rate of

Table 1. Summary of estimates for CH₄ and CO₂ emission factors across Indian underground coal mines (n = 108), and comparison to the prior estimate

m ³ /tonne-coal	CH ₄			CO ₂		
	Degree-III	Degree-II	Degree-I	Degree-III	Degree-II	Degree-I
5	2.11	0.92	0.29	3.06	4.67	3.80
25	3.17	2.08	0.58	7.80	9.16	8.32
50	7.77	3.36	1.03	12.03	11.75	15.88
75	24.36	6.07	1.66	42.16	18.60	23.98
95	188.40	7.82	2.22	65.67	54.22	90.13
Weighted average	14.12	4.46	0.86	17.65	7.83	13.76
Previous estimate	23.68	13.08	2.91	Not estimated		

nominal emission is <1, 1–10 or >10 m³/tonne of coal produced. Although this classification was initially made from the standpoint of mines safety, these have been routinely used for GHG inventories as well. Using our field measurements, we first calculated the emission factors for both CH₄ and CO₂ – as reported in Table 1. It is evident that even the emissions within single degree of mining exhibit as much as two orders of magnitude when the 90% confidence interval (CI) is observed. It is essential that some outlier measurements are not considered here (discussed later). As such, we have used the interquartile range of the 50% CI as our default means of reporting uncertainty, unless specified otherwise. Another important observation is that CO₂ emission factor per tonne of coal mined is non-trivial and incorporating it provides enhanced robustness in GHG inventory practice. Also, because of fewer field measurements in the earlier studies, some higher-emitting mines skewed the emission factor. In fact, the CH₄ emission factors from the previous study are close to the 75th percentile of the rate of emissions in this analysis.

While Table 1 summarizes the key emission factor trends, Figure 2 shows the rate of CH₄ and CO₂ emission from the 108 individual mines surveyed in this study (Data S1). Several interesting trends are visible from Table 1 and Figure 2.

First, our analysis provides an important refinement to the magnitude and the quantified range of the emission factors. Results show considerable variability in the rate of CH₄ emissions not only across degrees of gassiness but also within each degree of classification as well. For instance, the rate of CH₄ emission (50% [CI]) for degree-III mines is in the range 3–25 m³/t-coal, thus showing an order of magnitude of variance. This variation is somewhat less pronounced in mines of less gassiness with the 50% CI for degree-II mines being 2–6 m³/t-coal and that for degree-I mines being 1–2 m³/t-coal. This large variation, particularly within degree-III mines, makes an important case for the tier-3 IPCC methodology followed in this study. Earlier work that was also reflected in India's national communications to the UNFCCC did not take into account these uncertainties and instead relied on a single point, deterministic emission factor calculated by taking the weighted average of rate of emissions across mines (Singh, 2022). Based on the lower number of mines considered in those measurements, they reflected a considerably higher emission factor than ones calculated in this paper. Thus, the emission factor calculated in our earlier work (Singh and Kumar, 2016) calculated the emission factor for degree-III mines as 24 m³/t-coal. In contrast, the weighted average for such mines calculated in this broader exercise is 14 m³/t-coal. This difference is present in lower degree mines as well although the margin of deviation is less. Our estimation for degree-II mines is 4.5 m³/t-coal and 0.86 m³/t-coal, with corresponding emission factors from the previous work being much higher, i.e., 13 m³/t-coal and 3 m³/t-coal respectively. Accordingly, we conclude that a larger number of field measurements refine not only the variability but also the magnitude of emission factors by diversifying the types of mines surveyed for GHG measurement.

An additional point worth noting for CH₄ emissions in Figure 2 is some critical outliers that depict emission rate much greater than the 50% CI. For instance, the Tirap mine in Assam shows a rate of CH₄ emission ~190 m³/t-coal. These outliers are included in the weighted average presented in the previous paragraph. However, they do not considerably influence the overall emission factor or the 50% CI because the amount of coal produced for such mines is lower than 100 t-coal/day (Saikia et al., 2016). Thus, the large magnitude of the rate of emissions from these mines do not overly skew the overall metrics for CH₄ emission factor in this study and corresponding inventory calculation carried out later.

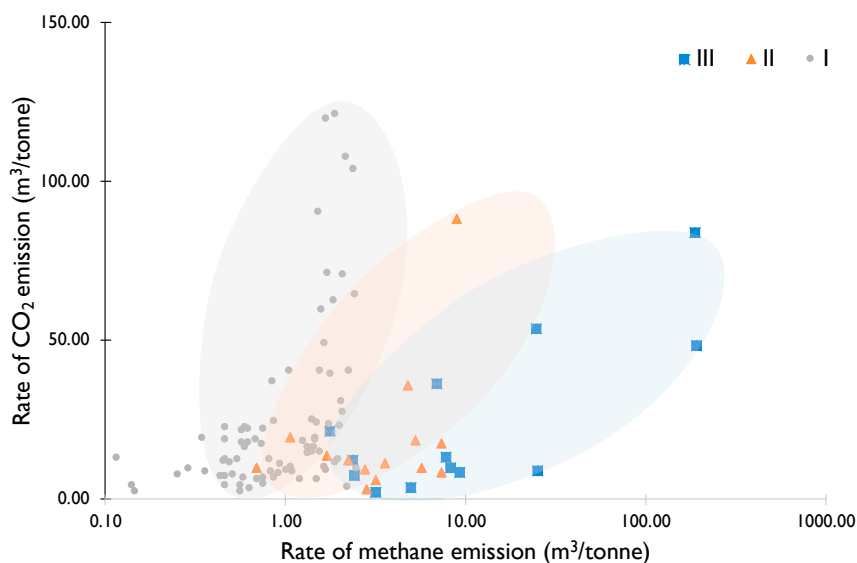


Figure 2. Indicative range of the rate of CH₄ and CO₂ emissions from mines of different degrees of gassiness

The second novel feature of Figure 2 is the reporting of CO₂ emissions for >100 underground mines. To our knowledge, the only previous work produced for this for Indian mines was from our group wherein only three mines were surveyed from a single coalfield (Singh, 2019). Although these measurements were used as a basis for framing the default emission factors in the IPCC 2019 refinements, they were calculated at three underground mines within a single coalfield. Accordingly, the dataset here is statistically more robust and diversified. We find that even though the global warming potential in several mines is primarily induced by CH₄ emissions, the magnitude of CO₂ emissions is significant. Thus, the 50% CI for the rate of CO₂ emissions is 8–42 m³/t-coal for degree-III mines, 11–18 m³/t-coal for degree-II mines and 8–24 m³/t-coal for degree-I mines.

It should be noted that whereas higher degree mines show higher emissions, the rate of emissions is comparable across degree. This contrasts with the trend for CH₄ emissions where the inter-degree difference is quite significant and varies by almost an order of magnitude. We posit that this difference in the rate of CH₄ and CO₂ emissions occurs because of the difference in the genesis of the two GHGs in underground mines. CH₄ is produced during the coalification process itself and, therefore, higher-rank coal mines often have higher CH₄ emissions. This is illustrative of a larger maturity for the coal. On the other hand, CO₂ is produced through spontaneous oxidation of the coal surface due to passage of ventilation air. As such, the rate of CO₂ emission is primarily affected by the quantity of air itself (Singh, 2019). But the maturity of coal could also affect the oxidation kinetics. Coal with lower maturity tends to get oxidized faster and accordingly, could be associated with high rates of CO₂ emissions. As illustrated in Figure 2, several degree-I mines are associated with CO₂ emission rate greater than 50 m³/t-coal.

Based on the contrasting trends in CH₄ and CO₂ across degree of mines, it is worth estimating the proportion of each GHG to the overall inventory of the mining activity. Using a global warming potential of 28 for methane, we find that the share of methane emissions is predominantly high in degree-III mines and is higher than 90% in some mines with large production such as the Chasnalla colliery of the Steel Authority of India Limited (SAIL). As per our hypothesis, this mine is among the few in India producing prime-quality coking coal and is accordingly associated with a high share of methane emissions. Several degree-II mines also show similar trends with the share of methane emissions being >80%. Some mines with lower production rate do show about one-third of GHG emissions arising due to CO₂. The share of CO₂ becomes progressively higher in degree-I mines with the share of CO₂ emitted from an average mine being 80% by volume. This is not skewed by the outliers in Figure 2 and is rather characteristic of some of the larger mines. For instance, the Rajendra mine in the Sohagpur colliery produces 1300 t-coal/day and nearly 90% of the GHG emissions (by volume) from this mine are CO₂ emissions due to spontaneous oxidation.

These measurements are similar to a study carried out in Brazil on two mines. In that study, these mines have methane emission rates comparable to an average degree-II and degree-I mine respectively. Their

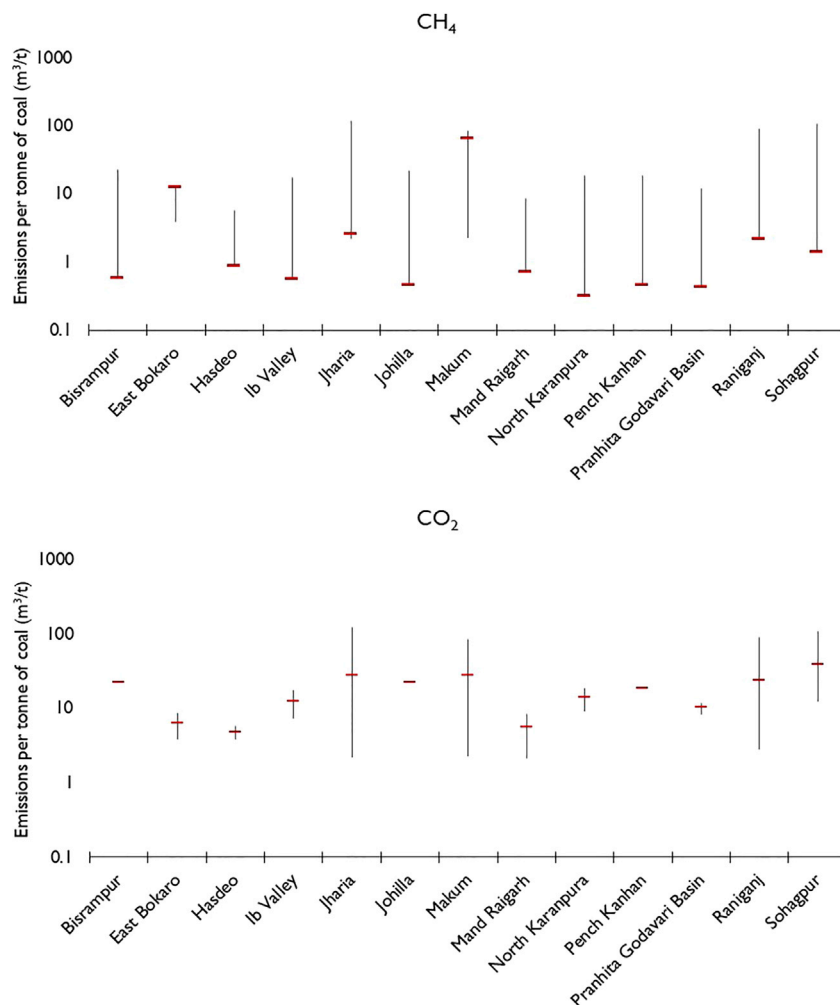


Figure 3. Coalfield-wise rate of emissions of CH₄ and CO₂ per tonne of coal mined

The whiskers in the plot reflect the 95% confidence interval for each coalfield (2.5–97.5 percentile), while the marker reflects the median.

study shows that the share of CO₂ emission in the former is 33% while that in the latter is 77%. This forms the basis for an important conclusion from this article. Earlier inventory estimates based on the 2006 IPCC Guidelines and reported in most countries' communications to the UNFCCC do not report CO₂ emissions. Because our measurements and those from Bonetti et al. (2019) show a high share of CO₂ emissions, it is imperative that governments include these emissions in their reporting to the UNFCCC. The share of CO₂ emissions compared to CH₄ is also important to understand mitigation opportunities. Although CH₄ emissions may be directly reduced using pre-mining drainage or concentrating methane in the ventilation air, CO₂ emissions may not directly be reduced and may require other offsets.

Coalfield-level trends in GHG emissions

Although degree-level assessments are useful in making comparisons to prior inventory estimates, it is also an objective of this paper to assess the regional variability in GHG emissions. Figure 3 shows the average, along with the maximum and minimum rate of CH₄ and CO₂ emissions for each coalfield considered in this study.

The average rate of methane emission for most coalfields is below 3 m³/t-coal. This is because more than 95% of the operational underground mines in each coalfield are degree-I or degree-II mines which have lower methane emissions. Although the number of degree-III mines was higher before 2000, they have continued to be retired because of complexity in handling the safety operations of the mines. Methane

(firedamp) explosion in several of the mines with high methane content has led to 53% of the coal mining casualties in India so far. Two prominent exceptions are noted here. The first exception is the East Bokaro coalfield where a majority of the underground coal is mined out from the Sawang colliery. This was among the initial contenders for degasification with an early project started in the 1980s (Hummel et al., 2018). However, even with drilling of 2m, large influx of methane and water was noted. Shortly thereafter, knowledge gaps led to the shutting down of the project. During five years of this project (1981–1985), 480,000 m³ methane was produced. Apart from the methane content itself, the rate of production was also considerably high. Thus, the East Bokaro coalfield is an important repository of methane, especially when considered along with the adjoining Asnapani block (Singh and Hajra, 2018). Another exception is the Makum coalfield where the average rate of methane emission is 83 m³/t-coal. As discussed in the previous subsection, this is because of the low coal production and complex geo-mining conditions which involve a disproportionately high amount of ventilation air.

Although the average values are useful in delineating overarching trends, it is also important to note the maximum value of rate of emissions in several of these coalfields. Coalfields with high rate of methane emissions could translate to commercial opportunities for coal mine methane recovery and utilization. Apart from the East Bokaro coalfield which has already been discussed, we see comparably high values for the Raniganj, Jharia, and Sohagpur coalfields, which could prospectively be treated as mitigation opportunities. These coalfields are also characterized by suitable thickness, high saturation and appropriate permeability for gas extraction to be technically feasible.

The rate of CO₂ emission shows similar trends as noted previously, wherein they do not necessarily follow the trend of CH₄ emissions due to different sources of genesis. We find that the average rate of most coalfields is close to 10 m³/t-coal. The CO₂ emissions are accompanied with significantly less variability across coalfields. We also note that coalfields producing high-rank coal derive most of their GHG emissions from methane. Accordingly, both Raniganj and Jharia coalfields have >70% share of methane in overall GHG emissions while it is as high as 98% for East Bokaro coalfield. For most other coalfields, the average share of methane and CO₂ is equal in their overall GHG inventory. Thus, we reiterate the need for combined CH₄ and CO₂ field measurements during national inventory preparations. Significant variability in methane emissions also point to the need for region-specific measurements.

Historic and future emission inventory estimates

The emission factors from Table 1 and the activity data from Figure 1 are combined to estimate the overall GHG emissions from underground coal mining activities (Figure 4). We find that the GWP-100 value was 2.6–8.3 Mt-CO₂e in 1980 and this decreased to 1.3–3.6 Mt-CO₂e in 2019. The reduction in the GWP-20 value is from 5.7 to 18.9 Mt-CO₂e in 1980 to 2.5–7.4 Mt-CO₂ in 2019. Thus, the emissions attributable to such mines has more than halved in less than four decades irrespective of the time-horizon followed. This reduction in emissions is because of shift in mining operations from underground to lower-cost surface mining. In 1980, underground mining contributed to about 65% of the total 112 Mt coal production, which has now reduced to less than 6%. Even so, the total methane emissions from both the categories of mines are still comparable because of a much higher emission factor for underground mines.

Because the upper-bound – or the 75th percentile – of the new emission factors is close to the deterministic emission factor of the prior analysis (Table 1), we find that the overall emissions are also comparable. The deviation between these two estimates remains between –4 and 8%. As discussed before, this shows the importance of increasing the number of field measurements when calculating the emission factors. The use of prior emission factors was concentrated in mines with a higher rate of emissions and in fewer coalfields. This likely led to an over-reporting of CH₄ emissions. It may be noted here that the prior estimate was a 100% CH₄ as CO₂ emission factors were considered insignificant. In our newer estimates, CH₄ emissions are close to 60% of total emissions (when reported in the form of GWP-100), with the rest being in the form of CO₂ emissions. It is imperative to put these emission results in context. India's methane emissions rank fourth in the world, and totaling about 400 Mt-CO₂e. This represents 15% of the overall GHG emissions. Although these emissions are dominated by the livestock and agriculture sectors, the coal mining sector provides a low-cost opportunity for point-source mitigation. The emissions from agriculture and livestock are more dispersed, which reduces the potential of mitigation in these sectors (Harmsen et al., 2019). On the other hand, a substantial portion of emissions from underground coal mining may be mitigated in degree-II and degree-III mines at net profits.

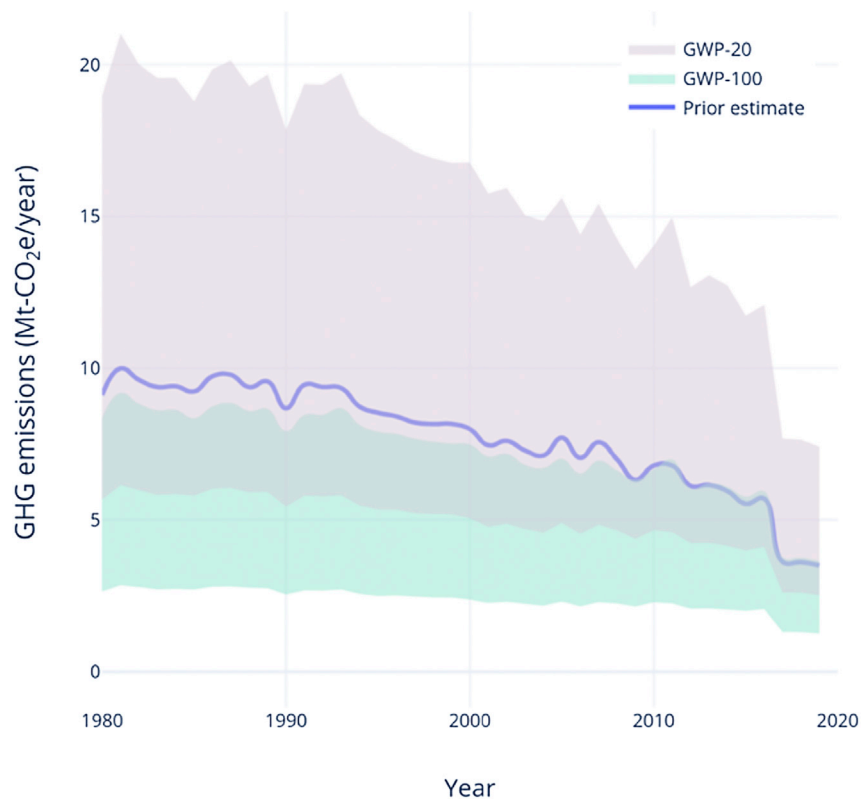


Figure 4. GHG emissions from Indian underground coal mining activities

The results of our analysis are reported on the basis of the 100-year and the 20-year GWPs, and compared to the 100-year GWP analysis from the prior analysis (Singh and Kumar, 2016).

Table 2 shows the projected results for emissions from 2030 to 2050. Several important trends are visible here. As stated before, if coal decline occurs (e.g., in the 1.5°C scenario), we may assume that methane emissions will also decrease significantly. Thus, in the 1.5°C scenarios would result in reduction of median GHG emissions below a 100 Mt-CO₂. It may be noted here that this trajectory is not inclusive of residual CH₄ emissions, which Kholod et al. (2020) have considered. This is because of data limitations that are discussed in the discussion section.

In scenarios where coal use increases, we have assumed that 40% of the incremental coal production will be from underground mining. This is in line with the Government of India's policy statements to increase underground coal production by 100 Mt over the next five years. Thus, under a 2°C constraint, median GHG emissions from underground coal mines would increase beyond 10 Mt-CO₂e in 2030, before declining to about 1 Mt-CO₂e in 2050. An increase in underground coal production would be accompanied with an increase in mitigation opportunities from Degree-II and Degree-III mines. Our assumption of 60% methane recovery potential from these mines indicates more than 50 kt-CH₄ that could be extracted via coal mine methane. This is about a quarter of India's current coalbed methane production from virgin reservoirs where coal mining has not occurred (Singh and Singh, 2018; Dhir, 2019).

DISCUSSION

The results of our analysis are useful in informing several key practices in GHG inventory preparation in the coal mining sector. First, emission inventories in the underground coal mining sectors have focused on CH₄ emissions over the last three decades and not necessarily on CO₂ emissions. This was, in part, because of safety and regulatory concerns to ensure reduced risks of accidents in underground mines (Banerjee and Dhar, 1996; Banerjee et al., 1994). This made reporting of CH₄ emissions relatively intuitive within the UNFCCC reporting standards. Our analysis shows that in several mines of low gassiness, CO₂ emissions may be very significant as well. While this CO₂ does not pose any safety risk, it is imperative to include it

Table 2. Projected (2030 and 2050) coal production and GHG emissions from Indian underground coal mines

	2030			2050		
	1.5°C	2°C	2.5°C	1.5°C	2°C	2.5°C
Coal use relative to 2015 (%)	55 (34–71)	148 (100–153)	151 (111–159)	2 (0–17)	31 (22–107)	76 (45–145)
Production from underground mining (Mt)	36 (22–46)	194 (65–209)	203 (95–225)	2 (0–11)	20 (14–84)	50 (29–185)
Total GHG emissions (Kt-CO ₂ e/year), GWP-100	1831 (1121–2368)	10,003 (3339–10775)	10,463 (4874–11593)	79 (5–565)	1030 (725–4329)	2551 (1514–9555)
Mitigation Potential; upper-bound (kt-CH ₄ /year)	9 (6–12)	51 (17–55)	54 (25–60)	0 (0–3)	5 (4–22)	13 (8–49)

Medians are shown as nominal values while parentheses indicate interquartile range.

within inventory reporting, as recommended by the 2019 IPCC Refinements. Some past analyses did report these numbers but such measurements were carried out on fewer mines. For instance, the Government of Australia's 2015 inventory report provided CO₂ emission factors from 45 underground mines (Commonwealth of Australia, 2015). In the peer-reviewed literature, Bonetti et al. (2019) carried out CO₂ measurements over two mines in Brazil while Singh (2019) made these estimates for three mines. Across these studies, CO₂ emissions have been shown to be significant in underground mines of moderate gassiness.

Second, the study also brings into focus the role of incorporating regional heterogeneity into GHG inventory. Past work in China has shown the significance of regional variability in such analyses (Wang et al., 2019). As Figure 3 shows, there is a significant variance of CH₄ and CO₂ emissions in various coalfields. Use of a default, deterministic emission factor can ignore these variabilities. For instance, the upper bound of the CO₂ emission factors in the 2019 IPCC Refinements is 12.3 m³/tonne (IPCC, 2019). However, Table 1 shows that this is close to the median value for Indian underground mines and the upper-bound of the interquartile range is substantially higher. These deviations arise because of differences in geological conditions as well as operational conditions of mine ventilation. Accounting for such regional differences is essential to obtaining robust GHG inventories.

Finally, inventory practice in the coal mining sector has evolved over the years. Underground coal mining emission factors have been reported by several countries on a Tier-3 basis, which follows a mine-by-mine estimation. Surface mining emission factors for India have also been calculated on a Tier-3 basis. Some studies have also attempted to estimate CO₂ emissions from surface mining due to low-temperature oxidation (Day et al., 2010). Other countries such as the United States, where the share of surface mining is less, report these emissions on a Tier-1/2 basis. However, it is necessary to calculate other emission factors to account for the whole coal supply chain. For instance, several countries report the fugitive CH₄ emissions from abandoned coal mines. These calculations often have a different set of variables, which include the condition of the mine, i.e., whether it is flooded, sealed or venting. Although the Government of India has published an indicative list of 228 abandoned mines (Ministry of Coal, 2015), the condition of mines is unclear. As such, we recommend this as the next step in GHG inventories. Similarly, the 2019 Refinements also include a new category of fugitive methane emissions during coal exploration. This would depend on the amount of coal resource explored each year and the emission factor, that would need to be regionally determined. To our knowledge, there is no exhaustive study in this domain because the default emission factor is a thousand times less than the coal mining emission factor. Nevertheless, because of large coal exploration by several countries, it is imperative to improve the reporting of these emissions. Over 1980–2019, the emissions from underground coal mining in India have largely decreased as coal production from such mines has decreased (Figure 1). However, as further underground mining increases – as per the Coal India Limited's projections – it would likely result in higher emissions.

Limitations of the study

The study used spot measurements instead of daily measurements, which would lead to ±20% error as emissions vary across time scales (both during different times of days, as well as seasonally during different months of the year) (UNECE, 2021). The mitigation potential estimated in this study is assuming a generic 60% recovery based on the literature. Future work can carry out detailed gas potential studies at specific mines and also incorporate continuous measurements at selected mines to reduce uncertainty here.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

- **KEY RESOURCES TABLE**
- **RESOURCE AVAILABILITY**
 - Lead contact
 - Materials availability
 - Data and code availability
- **METHOD DETAILS**
 - Determination of rate of emission
 - Frequency of measurement and uncertainty
 - Calculation of emission factors and overall GHG inventory
 - Projecting future emissions

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at <https://doi.org/10.1016/j.isci.2022.104946>.

ACKNOWLEDGMENTS

AKS thanks the Ministry of Environment, Forest and Climate Change (MoEFCC), Government of India for financial research support. Authors are also grateful to Dr. J.R. Bhatt, Advisor, MoEFCC, and Professor Amit Garg, NIIF Chair Professor, IIM Ahmedabad, for their insights into GHG emission inventories.

AUTHOR CONTRIBUTIONS

Conceptualization: A.K.S. and U.S.; Methodology: A.K.S., U.S., and D.C.P.; Investigation: A.K.S. and D.C.P., Visualization: U.S. and J.S.; Writing - Original draft: A.K.S. and U.S.; Writing - Review and editing: D.C.P. and J.S.

DECLARATION OF INTERESTS

The authors declare no competing interests.

INCLUSION AND DIVERSITY

One or more of the authors of this paper received support from a program designed to increase minority representation in science. While citing references scientifically relevant for this work, we also actively worked to promote gender balance in our reference list. The author list of this article includes contributors from the location where the research was conducted who participated in the data collection, design, analysis, and/or interpretation of the work.

Received: May 30, 2022

Revised: July 10, 2022

Accepted: August 11, 2022

Published: September 16, 2022

REFERENCES

- Andrew, R.M. (2020). Timely estimates of India's annual and monthly fossil CO₂ emissions. *Earth Syst. Sci. Data* 12, 2411–2421.
- Banerjee, B.D., and Dhar, B.B. (1996). Issues and options for reducing methane emission to the atmosphere from Indian coal mining. *Energy Convers. Manag.* 37, 1175–1179.
- Banerjee, B.D., Singh, A.K., Kispotta, J., and Dhar, B.B. (1994). Trend of methane emission to the atmosphere from Indian coal mining. *Atmos. Environ.* 28, 1351–1352.
- Bonetti, B., Abruzzi, R.C., Peglow, C.P., Pires, M.J.R., and Gomes, C.J.B. (2019). CH₄ and CO₂ monitoring in the air of underground coal mines in southern Brazil and GHG emission estimation. *REM Int. Eng. J.* 72, 635–642.
- Byers, E., Krey, V., Kriegler, K., Riahi, K., Schaeffer, R., Kikstra, J., Lamboll, R., Nicholls, Z., Sanstad, M., Smith, C., et al. (2022). AR6 Scenarios Database Hosted by IIASA (International Institute for Applied Systems Analysis).
- Clarke, L., Wei, Y.M., de la Vega Navarro, A., Garg, A., Hahmann, A.N., Khennas, S., Lima De Azevedo, I.M., Löschel, A., Singh, A.K., Steg, L., et al. (2022). Energy systems. In *Climate Change 2022: Mitigation of Climate Change. Working Group III Contribution to the IPCC Sixth Assessment Report* (Cambridge University Press).
- Commonwealth of Australia (2015). In *National Inventory Report 2015*, 1. <https://www.industry.gov.au/sites/default/files/2020-07/national-inventory-report-2015-volume-1.pdf>.
- Day, S.J., Carras, J.N., Fry, R., and Williams, D.J. (2010). Greenhouse gas emissions from Australian open-cut coal mines: contribution from spontaneous combustion and low-temperature oxidation. *Environ. Monit. Assess.* 166, 529–541.
- Dhir, S. (2019). *Essar oil*. In *Cases in Strategic Management* (Springer), pp. 73–89.

- Garg, A., Singh, A.K., Singh, U., and Vishwanathan, S. (2021). Future of Coal in India: what do the stakeholders think? *MGMI News J.* 47, 14–21.
- GMI (2022). Global Methane Emissions and Projections. <https://www.globalmethane.org/methane-emissions-data.aspx>.
- Harmsen, J.H.M., van Vuuren, D.P., Nayak, D.R., Hof, A.F., Höglund-Isaksson, L., Lucas, P.L., Nielsen, J.B., Smith, P., and Stehfest, E. (2019). Long-term marginal abatement cost curves of non-CO₂ greenhouse gases. *Environ. Sci. Pol.* 99, 136–149.
- Hummel, J.A., Ruiz, F.A., and Kelafant, J.R. (2018). Quantifying the benefits of coal mine methane recovery and use projects: case study on the application of in-mine horizontal pre-drainage boreholes at gassy coal mines in India and the optimization of drainage system design using reservoir simulation. *Environ. Technol. Innovat.* 10, 223–234.
- IPCC (2006). 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Hayama, Kanagawa, Japan: Institute for Global Environmental Strategies).
- IPCC (2019). 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Hayama, Kanagawa, Japan: Institute for Global Environmental Strategies).
- Karacan, C.Ö., Ruiz, F.A., Coté, M., and Phipps, S. (2011). Coal mine methane: a review of capture and utilization practices with benefits to mining safety and to greenhouse gas reduction. *Int. J. Coal Geol.* 86, 121–156.
- Kholod, N., Evans, M., Pilcher, R.C., Roshchanka, V., Ruiz, F., Coté, M., and Collings, R. (2020). Global methane emissions from coal mining to continue growing even with declining coal production. *J. Clean. Prod.* 256, 120489.
- Ministry of Coal (2015). Information on Abandoned Coal Mines in India. <http://164.100.94.214/sites/default/files/uploads/Abandoned-Coal-Mines-in-India.pdf>.
- Ministry of Coal (2021). Provisional Coal Statistics. <http://coalcontroller.gov.in/writereaddata/files/download/provisionalcoalstat/provisional-coal%20statistics-2020-21.pdf>.
- Mishra, D.P., Panigrahi, D.C., and Kumar, P. (2018). Computational investigation on effects of geo-mining parameters on layering and dispersion of methane in underground coal mines-A case study of Moonidih Colliery. *J. Nat. Gas Sci. Eng.* 53, 110–124.
- Nayak, R.C., and Dalai, S.K. (2010). Evaluation of Bord and Pillar Mining System in MCL Coal Mines, Doctoral Dissertation (National Institute of Technology Rourkela).
- Pachauri, R.K., Allen, M.R., Barros, V.R., Broome, J., Cramer, W., Christ, R., Church, J.A., Clarke, L., Dahe, Q., Dasgupta, P., et al. (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, p. 151.
- Panwar, D.S., Saxena, V.K., Chaurasia, R.C., and Singh, A.K. (2017). Prospective evaluation of coal bed methane in Raniganj coal field, India. *Energy Sources, Part A Recovery, Util. Environ. Eff.* 39, 946–954.
- Roy, B., and Schaffartzik, A. (2021). Talk renewables, walk coal: the paradox of India's energy transition. *Ecol. Econ.* 180, 106871.
- Shukla, P.R., Mittal, S., Liu, J.Y., Fujimori, S., Dai, H., and Zhang, R. (2017). India INDC assessment: emission gap between pledged target and 2 C target. In *Post-2020 climate action* (Singapore: Springer), pp. 113–124.
- Saikia, B.K., Saikia, A., Choudhury, R., Xie, P., Liu, J., Das, T., and Dekaboruah, H.P. (2016). Elemental geochemistry and mineralogy of coals and associated coal mine overburden from Makum coalfield (Northeast India). *Environ. Earth Sci.* 75, 660.
- Singh, A.K. (2019). Better accounting of greenhouse gas emissions from Indian coal mining activities—a field perspective. *Environ. Pract.* 21, 36–40.
- Singh, A.K., and Kumar, J. (2016). Fugitive methane emissions from Indian coal mining and handling activities: estimates, mitigation and opportunities for its utilization to generate clean energy. *Energy Proc.* 90, 336–348.
- Singh, A.K., and Hajra, P.N. (2018). Coalbed Methane in India: Opportunities, Issues and Challenges for Recovery and Utilization (Cham, Switzerland: Springer), p. 98.
- Singh, A.K. (2022). Evolution and future prospects for coalbed methane and coal mine methane in India: approaches for addressing mine safety, climate change, and energy security. In *Innovative Exploration Methods for Minerals, Oil, Gas, and Groundwater for Sustainable Development* (Elsevier), pp. 101–126.
- Singh, U., Singh, A.K., and Singh, D.B. (2018). Coalbed methane-produced water characteristics and insights from the Jharia coalfield in India. *Energy Sources, Part A Recovery, Util. Environ. Eff.* 40, 1897–1909.
- Singh, U., and Singh, A.K. (2018). Improved climate change understanding and projections for coal businesses create urgent need to initiate stronger measures toward coalbed methane in India. *Carbon Manag.* 9, 83–85.
- The Economic Times (2022). Coal India to Offer its 20 Closed Underground Mines to Private Players. <https://economictimes.indiatimes.com/industry/indl-goods/svs/metals-mining/coal-india-to-offer-its-20-closed-underground-mines-to-private-players/articleshow/91380824.cms>.
- Tongia, R. (2016). Brookings India Roundtable on “Future of Coal – 2020”. <https://www.brookings.edu/research/report-brookings-india-roundtable-on-future-of-coal-2020/>.
- Tripathy, D.P., and Ala, C.K. (2018). Identification of safety hazards in Indian underground coal mines. *J. Sustain. Mining* 17, 175–183.
- US EPA (2019). India Coal Mine Methane Market Study. <https://nepis.epa.gov/Exe/ZyNET.exe/P100WVZE.TXT?ZyActionD=ZyDocument&Client=EPA&Index=2016+Thru+2020&Docs=&Query=&Time=&EndTime=&SearchMethod=1&TocRestrict=n&Toc=&TocEntry=&QField=&QFieldYear=&QFieldMonth=&QFieldDay=&IntQFieldOp=0&ExtQFieldOp=0&XmlQuery=&File=D%3A%5Czifiles%5CIndex%20Data%5C16thru20%5CTxt%5C00000013%5CP100WVZE.txt&User=ANONYMOUS&Password=anonymous&SortMethod=h%7C-&MaximumDocuments=1&FuzzyDegree=0&ImageQuality=r75g8/r75g8/x150y150g16/i425&Display=hpfr&DefSeekPage=x&SearchBack=ZyActionL&Back=ZyActionS&BackDesc=Results%20page&MaximumPages=1&ZyEntry=1&SeekPage=x&ZyPURL>.
- UNECE (2021). Best Practice Guidance for Effective Management of Coal Mine Methane at National Level: Monitoring, Reporting, Verification and Mitigation. https://unece.org/sites/default/files/2022-07/2119167_E_ECE_ENERGY_139_WEB.pdf.
- Vishal, V., Singh, L., Pradhan, S.P., Singh, T.N., and Ranjith, P.G. (2013). Numerical modeling of Gondwana coal seams in India as coalbed methane reservoirs substituted for carbon dioxide sequestration. *Energy* 49, 384–394.
- Vishwanathan, S.S., and Garg, A. (2020). Energy system transformation to meet NDC, 2 C, and well below 2 C targets for India. *Climatic Change* 162, 1877–1891.
- Wang, K., Zhang, J., Cai, B., and Yu, S. (2019). Emission factors of fugitive methane from underground coal mines in China: estimation and uncertainty. *Appl. Energy* 250, 273–282.
- Zhang, M., Jordaan, S.M., Peng, W., Zhang, Q., and Miller, S.M. (2020). Potential uses of coal methane in China and associated benefits for air quality, health, and climate. *Environ. Sci. Technol.* 54, 12447–12455.
- Zhou, F., Xia, T., Wang, X., Zhang, Y., Sun, Y., and Liu, J. (2016). Recent developments in coal mine methane extraction and utilization in China: a review. *J. Nat. Gas Sci. Eng.* 31, 437–458.

STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
Data for individual coal mines has been presented in the supplemental information Section.	N/A	Data S1
Data for future coal use projection has been obtained from the IPCC AR6 Scenario Explorer and Database	https://data.ecce.iiasa.ac.at/ar6	N/A
Software and algorithms		
Microsoft Excel, used for data analysis and preparing graphs	Commercially Available Software	N/A

RESOURCE AVAILABILITY

Lead contact

Further information and requests can be directed to Dr. Udayan Singh (udayan.singh@northwestern.edu).

Materials availability

This study did not generate new physical materials.

Data and code availability

- All data used in this study is reported in the [supplemental information](#) section or obtained from the sources cited in the study.
- The article does not report any new code.
- Any additional information required to reanalyze the data reported in this article is available from the [lead contact](#) on request.

METHOD DETAILS

Determination of rate of emission

Field data was collected from 108 coal mines from India. These belonged to Gondwana coalfields in eastern and central India, as well the Tertiary coalfields in north-eastern India. For details of the coal mines surveyed in this exercise, coalfields and coal production, the reader may refer to Table 1 in the [supplemental information](#) section. A field measurement methodology provided by the Intergovernmental Panel on Climate Change (IPCC, 2006; IPCC, 2019) was used to estimate emission of a gas from coal mining. Total emissions of a gas from all its source categories are obtained by summing up the emissions from all source categories.

The IPCC formula for estimating emissions of a gas from underground coal mining and post-mining emissions for Tier 1 and Tier 2 approaches is written as

$$\text{Greenhouse gas emissions} = \text{Raw coal production} \times \text{Emission Factor} \times \text{Units conversion factor}$$

The activity data on raw coal production is expressed in tonnes. Emission factors for fugitive CH₄ and CO₂ emissions are the amount of CH₄ and CO₂ released per tonne of coal production and have units of cubic meter per tonne (m³/tonne). The conversion factor represents the density of the gas which converts volume of the gas to its mass. The density of CH₄ at 20°C and 1 atmospheric pressure is taken as 0.67 × 10⁻⁶Ggm⁻³ and that of CO₂ at 20°C and 1 atmosphere pressure is considered as 1.84 × 10⁻⁶Ggm⁻³.

The formulae used for calculating fugitive CH₄ and CO₂ emissions from underground coal mining are as follows:

$$\begin{aligned} \text{CH}_4 \text{ emissions} &= \text{CH}_4 \text{ Emission Factor} \times \text{Underground Coal Production} \times \text{Conversion Factor} \\ \text{CO}_2 \text{ emissions} &= \text{CO}_2 \text{ Emission Factor} \times \text{Underground Coal Production} \times \text{Conversion Factor} \end{aligned}$$

The total annual emission of CH₄ and CO₂ is obtained by summation of equivalent GHG emissions of CH₄ and CO₂ generation from all underground mining activities for a particular year under consideration.

The underground mines are generally ventilated by a high-capacity fan. To calculate emission factor of a gas from underground coal mines, we conducted measurements in 108 mines. The quantity of air passing through the intake and return airways in each of the underground mines was measured. To quantify air quantity, air velocity in m/min was measured in the intake and return airways with the help of an anemometer (Make: Shot and Mason). This was multiplied by cross sectional areas (in m²) of the airways to obtain quantity of air in m³/min. The staff members involved in operating this equipment were provided hands-on laboratory training (for equipment and safety).

Mine air samples were collected in the intake and return airways over the entire cross-sectional area by moving the sampling tubes across the airways. CH₄ and CO₂ concentrations in air samples were determined by gas chromatography. Air samples were collected by displacement of water and analyzed within 24 h using a gas chromatograph of Thermo Fisher make (Model Trace 1110) equipped with 2 TCD and 1 FID detectors.

The make of gas in cubic meters per minute (say G) was then calculated as given below:

$$G = \frac{\left(\text{Air Quantity in Return Airway} \left(\text{in } \frac{\text{m}^3}{\text{minute}} \right) \times \text{Percentage of Gas in Return Airway} \right)}{100} - \frac{\left(\text{Air Quantity in Intake} \left(\text{in } \frac{\text{m}^3}{\text{minute}} \right) \times \text{Percentage of Gas in Intake} \right)}{100}$$

The rate of emission of gas (say R) in cubic meters per tonne of coal produced was then calculated by the following formula:

$$R = \frac{G \times 60 \times 24}{\text{Coal production in tonnes during the day}}$$

The rate of emission of gas (say R) computed for each underground mine is used to arrive at the emission factor.

The measurements – in units of m³/min were multiplied by total coal production per day (times 24 h per day × 60 min per hour). The daily coal production per mine has been noted in the [supplemental information](#) section. This provided us the rate of emission in m³/tonne.

Frequency of measurement and uncertainty

The frequency and periodicity of measurements determine the overall uncertainty associated with measured emission factors. It is preferable to have continuous or daily measurements which entail the uncertainty of only ±2%. However, because of several reasons (including weather conditions), this was not possible. As such, we used spot measurements – which are reported in [Table 1](#) of the SI. Based on the 2006 IPCC Guidelines, these might lead to uncertainty of ±20–30% (IPCC, 2006).

Calculation of emission factors and overall GHG inventory

Because the activity data is presented by categorizing into the degree of mines, we also calculated the emission factors for individual degree of mines. Particularly, the rates of emission from individual mines ([Data S1](#)) were weighted on the basis of production, and the weighted average was used as the emission factor of the particular degree of mines. Because this study also characterizes the uncertainty, we also calculated the 50% (interquartile range) and 90% confidence interval associated with the emission factors. The activity data was then multiplied by the emission factors to obtain the historical trend in GHG emissions. These emissions are reported in both the 100-year and 20-year global warming potential values

presented by the IPCC Fifth Assessment Report, which assume the CO₂ equivalence potential of fossil methane to be 28 and 84 respectively (Pachauri et al., 2014).

Projecting future emissions

The obtained emission factors may be applied to project future GHG emissions from Indian underground coal mining activities. However, the activity data is speculative as coal production is subject to several competing factors. As described above, the government's plans indicate an increase in future coal mining based on privatization of coal mines. At the same time, modeling projections indicate rapid phase-down of coal over the next two decades if global temperatures are to be restricted to 1.5°C (Clarke et al., 2022).

We used the data from the IPCC's Sixth Assessment Report Database to adapt the future trends in coal production in India (Byers et al., 2022). We considered three sets of scenarios where there is a 50% likelihood end-of-century temperature rise staying below 1.5°C (without overshoot), 2°C and 2.5°C respectively. These trajectories of coal production are compared to their relative levels in 2015. The IPCC Database does not differentiate between underground and surface coal production. Thus, we make some additional assumptions. The share of the three degrees of gassiness is assumed to be the same as 2015 levels, where the share of degree-I mines is 84%, degree-II mines is 15% and degree-III mines is 1%. Historic data is used for the analysis because there is no data source projecting future coal production based on different degrees of gassiness. In contrast, scenarios with increased coal production are assumed to have 40% incremental coal production from underground mines. This is because of the government's stated target to achieve 100 Mt coal production from underground mines out of a total 250 Mt increase in the next five years.

Methane emissions from Degree-II and Degree-III mines can be mitigated by recovery and utilization of coal mine methane, based on expert elicitation (Garg et al., 2021). In past studies, gas content has been used as a proxy to the amount of methane that be mitigated from such mines (Kholod et al., 2020). Although our analysis did not particularly evaluate the gas content of the 108 mines, previous analyses have shown that the gas content may be ~60% in an average gassy coal mine (Singh and Hajra, 2018; Panwar et al., 2017). As such, we have assumed that 60% of methane emissions may be mitigated from Degree-II and Degree-III mines in the form of CMM. The 60% estimate is noted in past works as the ratio of the gas content to specific emissions, i.e., the amount of emissions that can be mitigated through coal mine methane. Thus, we have assigned 60% to all scenarios not as a policy assumption, but instead as a technical parameter based on observed values in pilot and commercial-scale coal mine methane studies (Kholod et al., 2020; Singh and Hajra, 2018).