ETH zürich

Master Thesis
Building a Global Bottom-Up Coal Mine Methane Inventory at Facility-Scale

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Abstract

Coal mines are responsible for 12% of the anthropogenic methane emissions and are a good target for emissions reduction. Inverse modeling techniques are used to interpret atmospheric methane observation and improve the understanding of coal mine methane (CMM) emissions. But to perform inversions, prior information on bottom-up estimated emissions and location of the emission sources are needed. Uncertainties in spatial resolution of emissions can infer biases in the results of the inverse models and in our understanding of methane emissions.

To answer this need, we present a bottom-up high-resolution CMM emissions inventory in two products: a gridded (0.1° × 0.1° resolution) inventory, and a mine-level emissions inventory. Our inventory uses very recent information on 2690 operating coal mines from the Global Coal Mine Tracker of the Global Energy Monitor (GEM) to compute mine-specific methane emissions. It also includes more precise mine-level methane measurements for the major coal-producing countries. We obtain higher total emissions than the Emissions Database for Global Atmospheric Research (EDGAR) and the Global Fuel Exploitation Inventory (GFEI) v2, and a more heterogeneous emissions distribution since we take into account coal rank and mine depth.

There was no global mine-level CMM inventory available prior to this work to our knowledge. The added spatial resolution as well as the precision in the methane emission computation for individual mines, will be useful to guide the future mitigation of coal-related methane emissions. This comprehensive dataset will be included in the next version of the GFEI and the gridded product will thus be used for inverse modeling to improve emissions estimations based on atmospheric measurements.

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1 Introduction

Methane is a potent greenhouse gas, with anthropogenic methane emissions contributing to about 0.5°C of observed warming between the 1850-1900 and 2010-2019 periods [1]. According to scenarios analyzed by the Intergovernmental Panel on Climate Change (IPCC), global methane emissions must be reduced by 40 to 45% by 2030 to achieve the least cost-pathways that limit global warming to 1.5°C, alongside substantial simultaneous reductions of all climate forcers.

Coal mining is responsible for 12% of the anthropogenic emissions of methane. Achieving substantial reductions in methane emissions from coal mining is not only technically viable, but also economically interesting as methane can be used as an energy source as natural gas. A comprehensive understanding of emission sources is essential for targeted mitigation efforts.

The rapid developments in satellite remote sensing of methane is very promising for a better mapping and quantification of the emissions and their sources. Atmospheric inverse modeling is a method to determine the origins of greenhouse gas emissions by analyzing their atmospheric concentrations, given by flight campaigns or satellite observations, and tracing them back to their most likely sources. Inverse modeling requires prior information on emission sources and quantification of methane emissions, because it narrows down the search for emission sources and makes the estimation more precise and reliable. This prior knowledge helps in efficiently allocating emissions to specific locations or sectors, enhancing the accuracy of the analysis.

Unfortunately, the majority of the bottom-up inventories lack spatial granularity and only provide national or regional totals. National emission inventories submitted to the United Nations Framework Convention on Climate Change (UNFCCC) only give sectoral and subsectoral total emissions without high resolution spatial information. Independent studies have produced national estimates of emissions, but very few worldwide and high spatial resolution emission inventories exist. The most widely used in inverse modelling are the Emissions Database for Global Atmospheric Research (EDGAR), which provides global gridded emissions for all industries, and the Global Fuel Exploitation Inventory (GFEI) for oil, gas and coal. The GFEI distributes the total emissions reported by each country to the UNFCCC on the spatial proxy given by EDGAR emissions distribution. It is thus very relevant to energy policy to relate the country reported emissions to actual emission sources. However for coal mine methane, EDGAR methodology for computing emissions is not transparent and its spatial distribution is outdated.

The objective of the master thesis was to build a 0.1° × 0.1° resolution gridded global inventory of coal mine methane emissions. This inventory will constitute the coal part of the third version of the GFEI, to be published soon. A second product was also produced with even better resolution, since we produced a mine-scale inventory.

In this thesis, first the context is given on methane, Coal Mine Methane (CMM) emissions and its sources.

The methodology for building such an inventory is then explained: methane emission factors are applied to a comprehensive global coal mine database, to calculate CMM emissions at mine level. A model was developed to compute methane emissions based on mine production, mine depth and coal type. Then, higher precision mine-specific or coal basin-specific methane measurements were included.

Finally, this inventory is compared to the previous version of the GFEI and to UNFCCC-reported country emissions, to understand its qualities and limitations. Discussions and possible improvements are also included.

2 Coal Mine Methane

2.1 Methane as a potent greenhouse gas

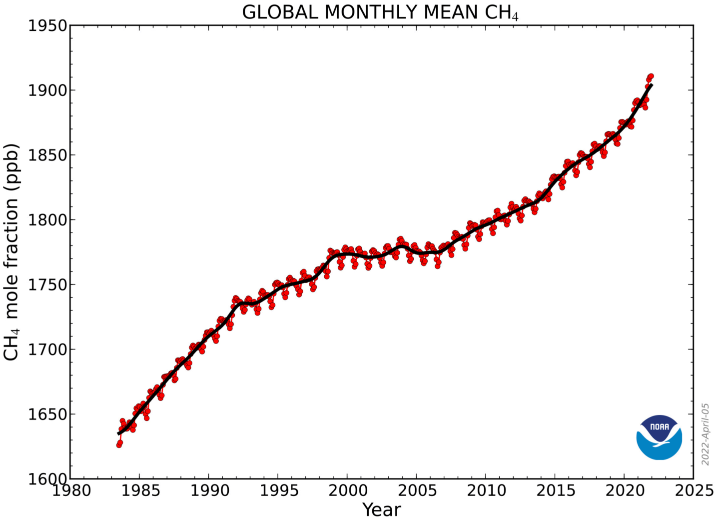


Figure 1: Atmospheric methane concentration increase over time (NOAA, 2022)

Greenhouse gases can have a direct and indirect greenhouse effect. Direct greenhouse gases directly absorb energy emitted by the surface (in the infrared spectrum) while being transparent to incoming solar energy. In this way, the atmosphere is directly heated. Some gases also have an indirect greenhouse effect by being "precursors" of other greenhouse gases. Methane has a predominant direct effect: CH_4 strongly absorbs infrared radiation in two fundamental bands at wavelengths of 3.3μm and 7.7μm, which are related to the stretching and bending modes of the CH bond [2]. But methane is also a very powerful indirect greenhouse gas because an important portion of its effective radiative forcing (ERF) comes from the gases it produces, mainly H_2O and O_3 (ozone) but also CO_2. The total methane-induced forcing is approximately 1.65 times that of methane alone [3].

Methane has a higher radiative efficiency than CO_2 but has a much lower concentration in the atmosphere, which results in a lower radiative forcing and a lower impact on the climate than CO_2: the radiative efficiency (the capacity of a gas to trap and re-radiate heat downwards) of CO_2 is $1.33 \cdot 10^{-5}$ W m^{-2} ppb^{-1}, and that of CH_4 is $3.88 \cdot 10^{-4}$ W m^{-2} ppb^{-1}. In 2019, the annual average atmospheric concentrations were 410 parts per million for CO_2 [1] and in comparison, methane concentrations are presented in Fig. 1 (in parts per billion). Multiplying the radiative efficiency with the concentration gives the radiative forcing, which is lower for methane by a factor of 10.

Moreover, methane is a short-lived climate pollutant (SLCP) with a lifetime of 11.8 years, and then transforms into other molecules also affecting climate as explained before. In contrast, a large fraction of anthropogenic CO_2 emissions will persist in the atmosphere for millennia without active, large-scale efforts to remove them. While reducing carbon dioxide emissions remains a long-term priority, taking action to curb methane emissions offers an effective means to slow the rate of global temperature rise and meet near-term climate goals.

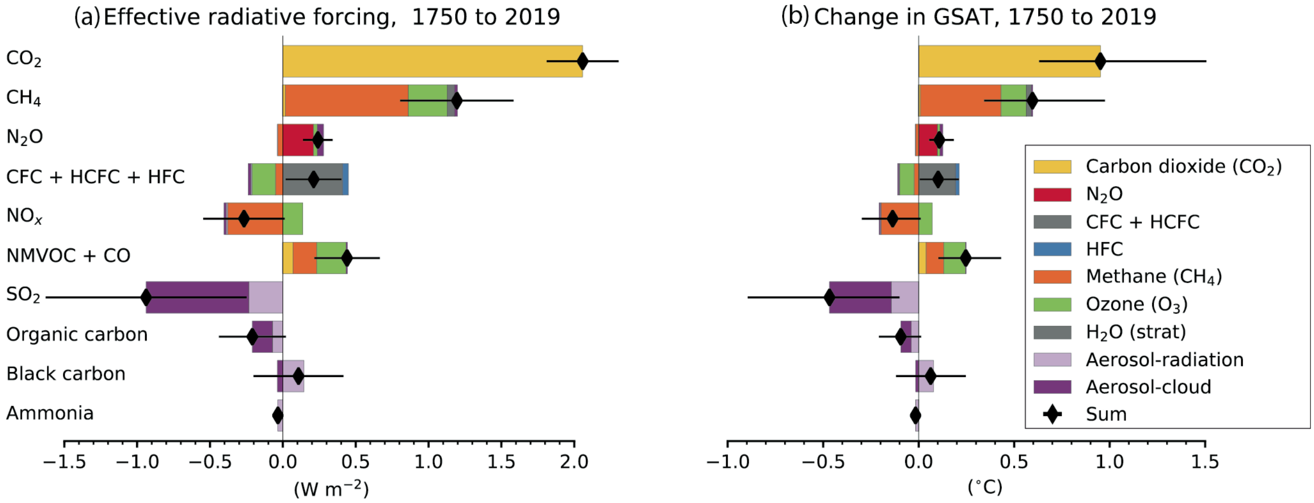


Figure 2: Effective radiative forcing and their impact on the Global mean Surface Air Temperature of different climate forcers [1]

2.2 Sources and sinks of methane

Most of the Earth's methane has a biological origin and is produced by methanogenesis, which is a form of anaerobic respiration conducted by some single-celled organisms (Archaea). These organisms are found in landfills (sites of waste disposal), soils, ruminants, or termites. Methanogenesis mostly occurs in anaerobic (air-free) environments, and can be:

- acetoclastic: the micro-organisms produce methane by fermenting acetate and H_2-CO_2 into methane and carbon dioxide [4]: $H_3C\text{-}COOH \longrightarrow CH_4 + CO_2$
- hydrogenotrophic: the micro-organism oxidizes hydrogen with carbon dioxide to yield methane and water: $CO_2 + 4H_2 \longrightarrow CH_4 + 2H_2O$.

Methane emissions today have both natural and anthropogenic sources as represented in the summary figure of the Global Methane Budget 2000-2017 in Fig. 4.

The largest natural methane emission sources are wetlands, freshwater and geological processes. A wetland is an ecosystem that is flooded by water, either permanently or seasonally, with a variety of plant and animal species that have evolved and adapted to the constant presence of water. Flooding results in creating an anoxic (oxygen-free) environment in which methanogenesis is favored. Methanogenesis also occurs in the sedimentary strata under fresh water (glaciers, lakes, reservoirs, ponds, rivers, streams, and even groundwater) and seafloors through the breakup of organic matter. However, in the seafloor sediments, other organisms use methane for energy (methanotrophs) which is why most of the methane produced at depth does not reach the atmosphere and freshwater systems are greater sources of methane emissions. Geological inorganic mechanisms such as magmatic processes or water-rock reactions at low temperatures and pressures also contribute to methane production.

The largest anthropogenic emissions are from agriculture (enteric fermentation, manure treatment, and rice cultivation), landfills, waste treatment plants, and fossil fuel exploitation.

Enteric fermentation is the digestive process by which carbohydrates are broken down by microorganisms into simple molecules for absorption into the bloodstream of an animal, producing methane, carbon dioxide, and hydrogen, subsequently expelled by the animal. Manure needs to be stored to be used as a land fertilizer: when stored in a liquid state, manure is a very conducive environment for the production of methane from organic matter [5]. The ongoing intensification of livestock production leads to increasing volumes of manure to be managed and increasing enteric fermentation during livestock digestion. Rice cultivation requires the flooding of large surfaces of land which, as explained previously, favors the production of methane.

In landfills and waste treatment plants, methanogenesis occurs as organic matter decomposes.

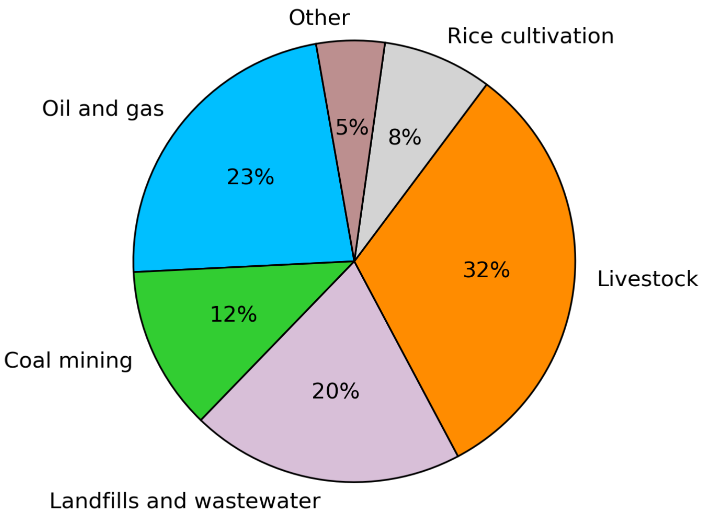


Figure 3: Distribution of the anthropogenic methane emissions. [6]

Finally, in heating, transportation and in industry, methane is used as a fuel, burnt in gas turbines or steam generators for electricity production, but also largely used for cooking and heating in homes. Methane is the principal component of natural gas, which is used to produce hydrogen gas needed in petroleum refineries, in chemicals production and in food processing. In the oil, gas and coal industries, methane is released into the atmosphere at several points in the production chain: when methane is vented during the extraction of coal and crude oil as a safety procedure, but also in leaks from valves and other equipment used in drilling and distribution. Vast methane reserves lie beneath the Earth's surface, and during energy extraction processes, a portion of this potent greenhouse gas escapes into the atmosphere.

Other indirect methane emissions occur from melting permafrost in Arctic regions, due to global warming, which is caused by human activities. Permafrost soils contain previously frozen organic matter that decays due to thawing and releases the trapped CH_4 among others. The Northern pole's permafrost soils could generate one gigaton of methane by 2100 [7].

The primary sink of methane, accounting for about 90% of the loss of atmospheric methane in the troposphere [1], is the reaction with tropospheric hydroxyl radicals ($\cdot$ OH): CH_4 + OH –> CH_3OO + H_2O

$$\mathrm{CH_4} + \cdot\mathrm{OH} \rightarrow \mathrm{CH_3OO}\cdot + \mathrm{H_2O} \tag{1}$$

Methane is also removed by soil uptake (methanotrophic bacteria) and reactions with atomic chlorine and stratospheric oxidants, but these losses are small [8].

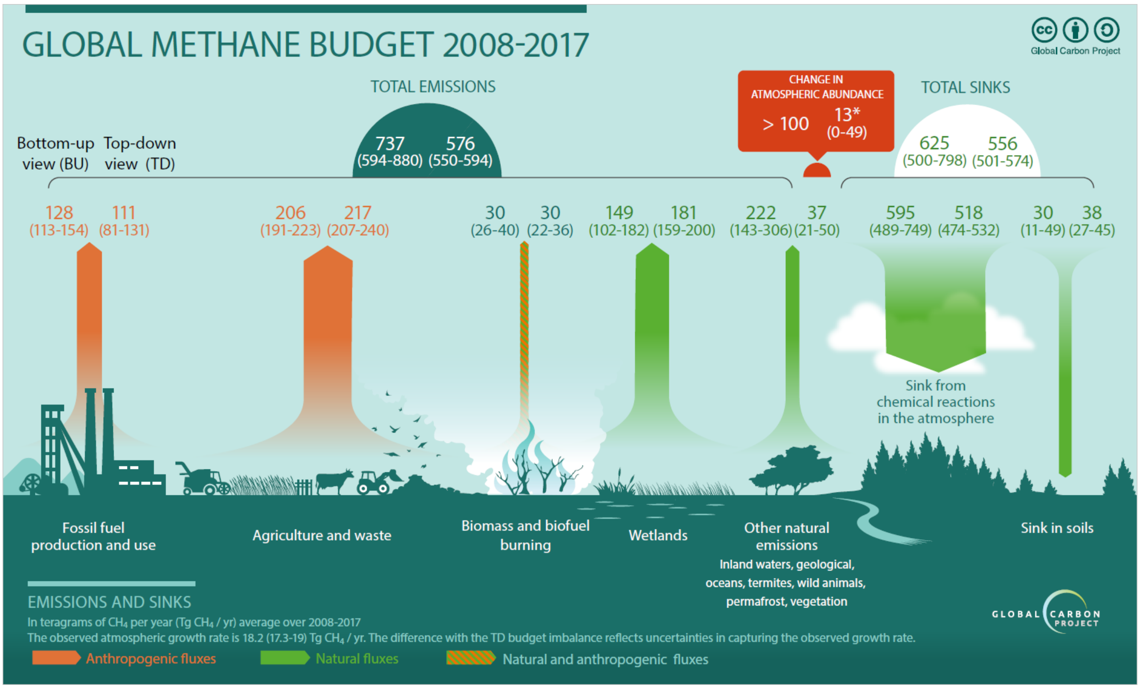
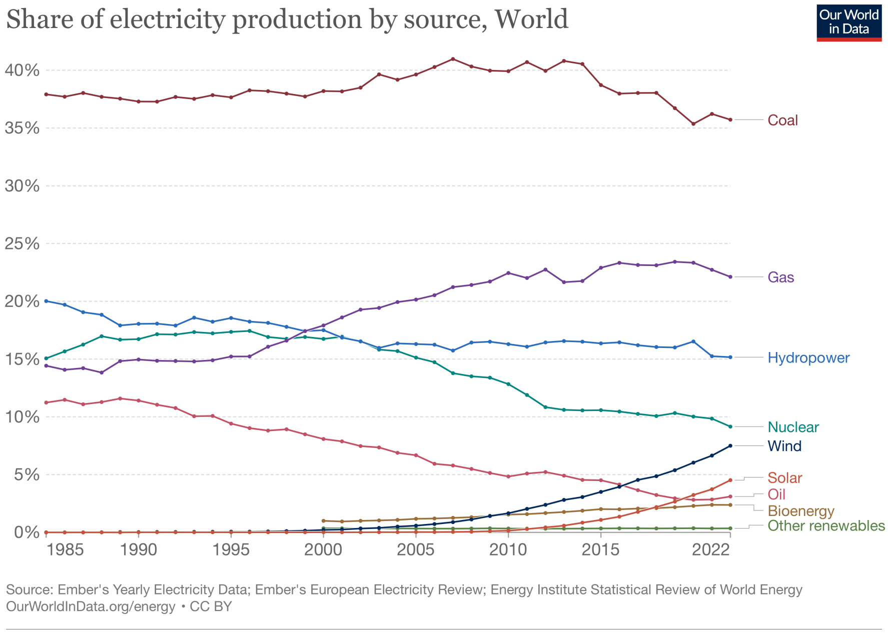


Figure 4: Global methane budget for the 2008–2017 decade. Both bottom-up (left) and top-down (right) estimates (Tg CH4 yr^1) are provided for each emission and sink category, as well as for total emissions and total sinks. [9]

2.3 Coal mining and its effect on the climate

An abundant and versatile energy source



Source: Ember's Yearly Electricity Data; Ember's European Electricity Review; Energy Institute Statistical Review of World Energy
OurWorldInData.org/energy • CC BY

Figure 5: Share of electricity production by source over time (Ember; Energy Institute Statistical Review of World Energy (2023))

Coalification is a geological process that transforms vegetation that died in wetland environments such as swamps, into coal, over millions of years. It involves a series of complex physical and chemical changes under conditions of heat and pressure. Coal is an abundant fossil fuel that can be extracted from underground, and used in a variety of ways. Coal has powered the industrial revolution: it was used to power steam engines, heat homes, and was a fuel source for early industrial processes. It is still central in our society, as it represents 36% of the electricity and 27% of the global energy production.

Fig. 5 shows how dominant coal has been and still is in electricity production, but also shows its use is starting to decrease, as some countries are transitioning to cleaner and more sustainable energy sources. Coal end uses include:

- Coal combustion, which provides high temperatures required for various industrial processes such as steel production, cement manufacturing, and chemical industries.

- Coal gasification, used to produce synthesis gas (syngas), which can be further processed into various chemicals and fuels.

- Metallurgical or coking coal, a crucial component in steel production. It is heated in the absence of air to produce coke, a porous carbon-rich material used in blast furnaces to reduce iron ore to molten iron.

- Activated carbon production from coal, which finds applications in water purification, air filtration, and gas adsorption.

- Research has been done in recent years into using coal as a precursor for carbon fiber production, which has applications in aerospace, automotive, and sporting goods industries.

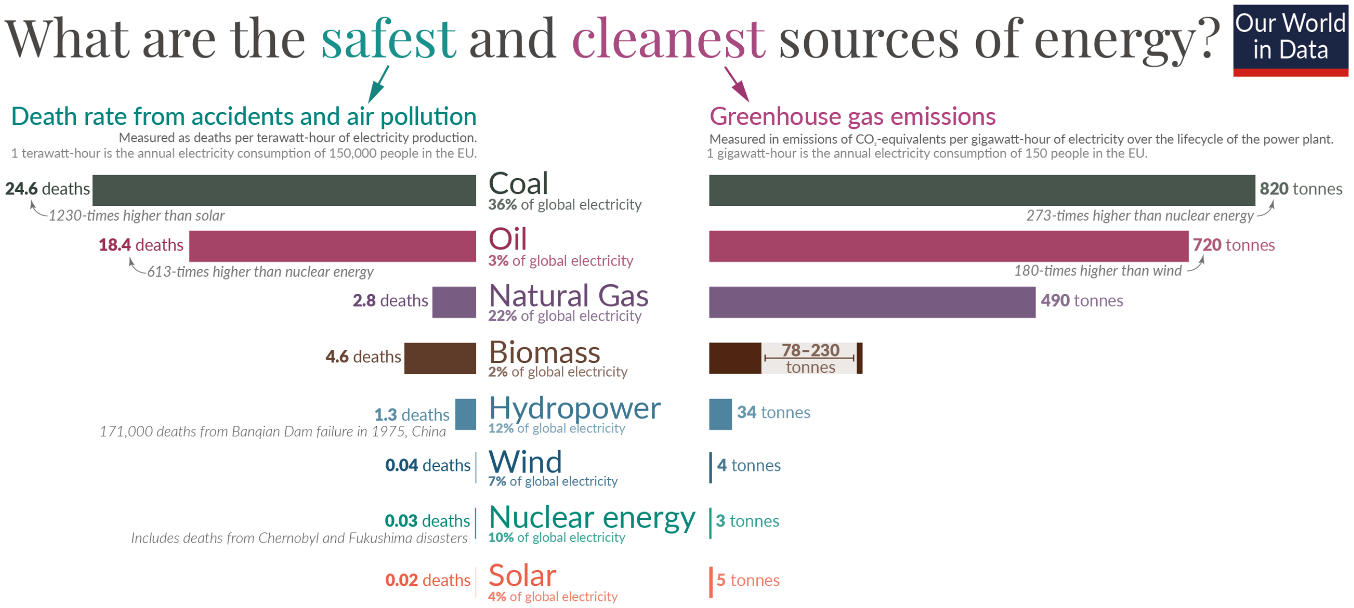
Unfortunately, this crucial energy source with so many end uses comes with many downside. Fig. 6 shows that in terms of safety, public health, and greenhouse gas emissions, coal is actually the worst energy source.

Coal mining operations often involve the removal of extensive areas of forests and ecosystems, resulting in habitat destruction and soil erosion. Working in a coal mine remains one of the most hazardous occupations in the world. Underground mining, in particular, poses challenges related to mine collapses, tunnel collapses, and the release of harmful gases. Explosions due to methane concentration in the mine, fires, and accidents involving heavy machinery are still very common. Miners are also at risk of developing black lung disease (pneumoconiosis) and other respiratory diseases, which results from prolonged exposure to coal dust.

The coal ash also contaminates the nearby water bodies with heavy metals and various chemicals, which harms ecosystems and can pose risks to drinking water supplies.

Coal emits greenhouse gases all along its lifecycle: mostly methane during mining, carbon dioxide and methane during transportation, and carbon dioxide during combustion.

The burning of coal releases other pollutants such as sulfur dioxide (SO2), nitrogen oxides (NOx), and particulate matter into the atmosphere. These pollutants contribute to smog formation, acid rain, lung cancers, development defects, and more.



Death rates from fossil fuels and biomass are based on state-of-the art plants with pollution controls in Europe, and are based on older models of the impacts of air pollution on health. This means these death rates are likely to be very conservative. For further discussion, see our article: OurWorldinData.org/safest-sources-of-energy. Electricity shares are given for 2021.
Data sources: Markandya & Wilkinson (2007); UNSCEAR (2008; 2018); Sovacool et al. (2016); IPCC AR5 (2014); Pehl et al. (2017); Ember Energy (2021).
OurWorldinData.org – Research and data to make progress against the world's largest problems. Licensed under CC-BY by the authors Hannah Ritchie and Max Roser.

Figure 6: Coal, the worst energy source in terms of safety and greenhouse gas emissions (OWID)

Methane in coal

Methane is generated at the same time coal is formed, and becomes trapped and stored in the coal itself through the process of sorption. Methane can also accumulate in adjacent porous rock layers or naturally occurring fractures [10].

Different types of coals exist, depending on the conditions during coalification. The greater the temperature, pressure, and duration of coal burial, the more methane is formed and the higher the coal rank is. As a result, deeper coal seams usually hold more methane. Geological movements such as tectonic activities, faulting, it can create pathways for methane to escape into surrounding rock formations or even reach the surface. The theory behind sorption and methane content increasing with depth (called methane sorption isotherms) is thus only a theoretical maximum of the methane content. In reality, methane content varies significantly across different coal basins worldwide.

The different steps of coalification, forming coal of higher and higher rank, are:

1. Peat: the accumulated plant material is compacted, the water content is reduced and a brown, spongy substance known as peat is formed. Peat has a high moisture content and low carbon content, and is not considered coal yet.

2. Lignite: as more layers of peat accumulate, the weight and pressure increase and the peat becomes lignite (or brown coal). Lignite is soft, brownish-black, and has a low energy content and a low methane content (25-35% carbon).

3. Subbituminous: with continued heat and pressure, lignite becomes subbituminous coal, with higher energy and methane contents (35-45% carbon).

4. Bituminous: the most common type of coal, bituminous coal is a hard coal with

high energy and methane content (45-86% carbon).

5. Anthracite: the last stage of the coalification produces anthracite coal, a hard, glossy, and black coal. Anthracite coal is of high quality and burns cleanly and efficiently, and has a high methane content (86-97% carbon).

The distinction between those four types of coal will be important to compute methane emissions from coal mines. But the methane emissions are influenced not only by the in-situ methane content of coal, but also by the mine design, the coal seam permeability, the thickness of the coal seams, the strength of the coal-bearing strata, and the overlying and underlying, formations, the rate of coal production There is thus a factor (between 1 and 2 [11]) between in-situ gas content and what we call the methane emission factor: the amount of methane released per ton of coal produced.

CMM emissions come from different sources, each explained below, and their relative importance in total CMM emissions is presented in Fig. 7.

- In **surface mines** (open cast mines), the overburden is removed, and coal extraction takes place in the open air. Methane is liberated when coal and associated strata (overburden and underburden) are blasted, disturbed and exposed as part of the mining process. Methane emissions from surface mines are diffuse over the whole area of the mine, and are usually lower because the depth and coal rank mined are lower.
- In **underground mines**, where the mine is connected to the atmosphere by ventilation and equipment shafts, the hydrostatic pressure on the coal seam is lowered, which causes methane to desorb and migrate into the coal cleats and natural fractures, and eventually into the mine workings. Since methane is explosive in underground mines at concentrations of 5 to 17% volume in air, the mine air is continuously ventilated to ensure concentrations lower than 2%. The Ventilation Air Methane (VAM) is then transported to the surface. In especially gassy mines, methane is drained before and/or during mining to supplement mine ventilation, using a system of boreholes and gas pipelines to remove and transport gas to the surface. Methane emissions from underground mines are point sources emissions at the surface ventilation shafts.
- Not all the coal is desorbed from the coal grains during mining, and **post-mining** emissions occur during the storage, processing, and transport of coal.
- **Abandoned** or closed coal mines that were significant methane emitters during active mining continue to emit methane, although at a reduced rate [12]. If a closed mine floods, the increased hydrostatic pressure and filling of the residual voids, pores, fissures with water reduces the emissions to almost zero.

There are several methods and mine designs in underground mining, that can influence the methane release as well. Room-and-pillar mines extract coal from relatively shallow coal deposits and the coal pillars left in the ground help support the shallow overburden, aiming at preventing surface subsidence. These mines emit relatively low CMM unless the coal pillars are extracted, and the roof is allowed to cave. Longwall mining is the mining method most commonly used in exploiting deeper coal deposits, particularly in countries such as China, Russia, US and Australia that are big producers and CMM emitters. In longwall mining, the coal is excavated in slices along a straight front, and the roof is allowed to cave as the production face advances to consolidate the mine structure. Open-pit mining, strip mining and mountaintop mining are several surface mining methods.

Finally, coal mine methane can be recovered, in operating or abandoned underground mines mostly, to be flared to reduce emissions or to be used for electricity production or heating, as natural gas.

In this project, factors that are taken into account to compute methane emissions are coal production, mine depth, mine type (underground or surface), and coal rank -the most important for operating mines-, completed by actual methane emissions measurements when available. Unfortunately, we do not have enough global information on mining method, its quantified influence on emissions, abandoned mines and their flooding status, or other factors to take them into account.

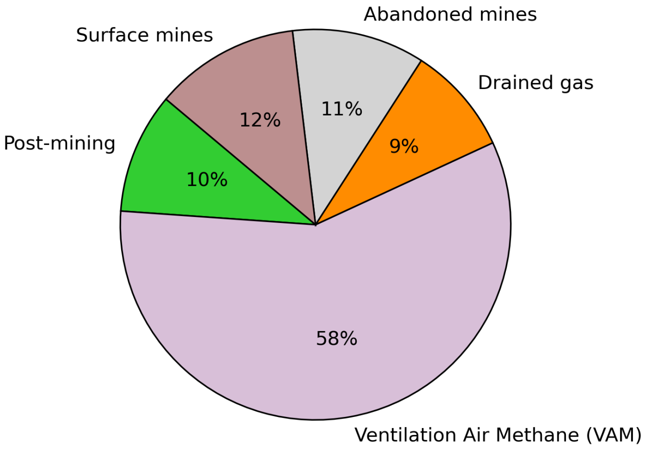


Figure 7: Repartition of net CMM emissions (emitted - used) between sources (IEA course on Coal Methane Basics)

3 Methodology and results

3.1 Global Coal Mine Tracker

The non-profit organisation Global Energy Monitor produces complete trackers for various energy subsectors: wind, solar, hydraulic, nuclear, oil and gas extraction, coal terminals... Their Global Coal Mine Tracker (GCMT) has been chosen for this project as it is to our knowledge the most exhaustive worldwide coal mine database. What is especially interesting for our project is that they provide for each mine details on ownership structure, development stage and status, coal type, production, workforce size, reserves and resources, geolocation, and over 30 other categories. The database structure is visible in Fig. 8. The most recent version was released in April 2023 so the activity data used in our inventory is very up to date.

Mine Name	Mine Name AKAs	Mine Name (Non-ENG)	GEM Wiki Page (ENG)	GEM Wiki Page (Non-ENG)	Status	Status Detail	Project Type	Project Phase	Operators	Owners	Parent Company	Company HQs	Production or Capacity Data (Mtpa)	Coal Output (Annual, Mt)	Coal Output (Annual, Mst)	Mine Type	Mining Method	Mine Size (Km2)	Mine Depth (m)	Depth Accuracy	Workforce Size	W Ac
Dahna Toor Coal Mine	Dhena Toor, Dahan-e-Tor		https://www.gem.wiki/Dahna_Toc		Operating				North Coal Ente	North Coal Ente	North Coal Ente	Afghanistan	Production	0,85		Underground	Shovel & Spade	-	494	Estimate	779	Es
Garmak Project Coal Mine	Western Garmak		https://www.gem.wiki/Garmak_Pr		Operating				Khoshak Brothe	Khoshak Brothe	Khoshak Brothe	Afghanistan	Production	0,04		Underground	Shovel & Spade	6,5	494	Estimate	783	Es
Shadashak Coal Mine			https://www.gem.wiki/Shadashak		Operating				North Coal Ente	North Coal Ente	North Coal Ente	Afghanistan	Production	1,1		Underground	Shovel & Spade	-	494	Estimate	673	Es
Tala Wa Barfak Coal Mine			https://www.gem.wiki/Tala_Wa_E		Operating				North Coal Ente	North Coal Ente	North Coal Ente	Afghanistan	Production	0,1		Underground	Shovel & Spade	-	494	Estimate	960	Es
Valius Coal Mine			https://www.gem.wiki/Valius_Coa		Operating				-	-	-	-	Production	0,13		Underground		-	494	Estimate	888	Es
Río Turbio Coal Mine																						
Airly Coal Mine																						
Appin Coal Mine	West C																					
Aquila Coal Mine																						
Ashton Coal Mine	Watag																					
Baralaba Coal Mine	Barala																					
Bengalla Coal Mine																						
Blackwater Coal Mine	Stewa																					
Blackwood Coal Mine	Blackw																					

	Workforce Accuracy	Coal Type	Coal Grade	Total Reserves (Proven and Probable)	Resource (Inferred, Indicated, Measured)	Reserve to Production Ratio (R/P)	Opening Year	Reported Life of Mine		Location	Prefecture, District	State, Province	Country	Subregion	Region	Latitude	Longitude	Location Accuracy	Primary Consumer, Destination	Coal Plant, Steel Plant, Terminal	Coal Plant, Steel Plant, Terminal GEM Wiki	Methane Emissions Estimate (MCM/yr)
79	Estimate	Subbituminous	Thermal	-	-	-		-			Dara-e-Suf	Samangan	Afghanistan	Southern Asia	Asia	35,70499225	67,31219552	Approximate				6,1
33	Estimate	Subbituminous	Thermal	-	-	-		-			Balkhab	Samangan	Afghanistan	Southern Asia	Asia	35,733	67,308	Approximate				0,3
73	Estimate	Bituminous	Met	-	-	-	1967	-		Shabashak	Dar-I-Suf	Samangan	Afghanistan	Southern Asia	Asia	35,863255	67,596674	Approximate				24,1
30	Estimate	Subbituminous	Thermal	-	-	-		-			Kahmard	Baghlan	Afghanistan	Southern Asia	Asia	35,33194	68,12	Approximate				0,7
38	Estimate	Lignite	Thermal	-	-	-		-	Tirana Coal Basin		Kamez	Tirana	Albania	Southern Europ	Europe	41,39151824	19,73642639	Exact				0,9
)0	Exact	Subbituminous	Thermal	450	-	6250	1943	-	Río Turbio	Argentina	Río Turbio	Santa Cruz	Argentina	Latin America a	Americas	-51,538363	-72,324353	Exact				0,5
55	Exact	Bituminous	Thermal	32	85	27	1998	25	Western	Capertee		New South Wal	Australia	Australia and N	Oceania	-33,1130709	150,0149367	Exact	Coal Plant	Mount Piper Po	https://www.gen	25,8
75	Exact	Bituminous	Met	113	774	24	1962	19	Southern	Appin		New South Wal	Australia	Australia and N	Oceania	-34,211194	150,792736	Exact	Terminal (Expor	Port Kembla Co	https://www.gen	107,5

Figure 8: Visual of the Global Coal Mine Tracker database, with in depth information on each of the 4299 mines

Preliminary lists of coal mines in each country are gathered from public and private data sources including Global Energy Observatory, Global Methane Initiative, European Association for Coal and Lignite (EURACOAL), Instrat, Mining Data Online, Oxpeckers

#MineAlert, as well as various company and government sources. The data is then vetted against additional sources of information:

- government data on individual coal mines
- reports by state-owned and private mining companies
- local non-governmental organizations tracking mining permits and mine operations
- on the ground contacts who can provide first-hand information about a project or mine

Table 1 give statistics on the GCMT mines and their status. Shelved, cancelled (never opened), proposed (not yet open), and closed mines are not considered in this version of the inventory: only operating mines are included.

Mines that use a combination of surface and underground techniques to extract coal are considered in our database as underground mines, since the underground part of the mine emits more methane as explained before, and is therefore the important information for our work.

In the GCMT, 13 surface mines have a depth of over 300 meters, and after communication with the GEM coal team, it was decided to consider them as underground mines before they are able to review their status. Indeed, the practical limit for open-pit mining is about 300 metres, due to the angle of repose of the overburden. Some deep mines that are called "surface mines" are actually underground mines with a very large open pit.

Status	Mine type	# of mines	Totals
Operating	Underground	1655	3232
	Surface	1499	
	Underground + surface	77	
Shelved / proposed / cancelled	Underground	346	727
	Surface	336	
	Underground + surface	45	
Closed	Underground	117	341
	Surface	203	
	Underground + surface	16	
TOTAL			**4299**

Table 1: Global Coal Mine Tracker mines statistics (GEM, 2023)

The final facility-scale product of this work has the same Excel structure as the GCMT and all the information are kept (even those that are not used to compute methane emissions), in order to provide as much information as possible to the users.

3.2 IPCC reporting guidelines

The Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories provide a standardized methodology for estimating and reporting emissions of greenhouse gases [13]. They serve as guidelines for countries on how to account for their emissions and report them to the United Nations Framework Convention on Climate Change (UNFCCC). For each activity sector or subsector, there are three levels of precision in the reporting, with Tier 1 being the less precise and Tier 3 the most precise.

For coal mining methane, the Tier 1 and Tier 2 methodologies are based on coal production and an emission factor. The emission factor gives the amount of methane released for each ton of coal produced. The difference between methane content and emission factor is that the methane content is the methane naturally present within the coal deposit and desorbed when the coal is exposed to open air and ambient pressure. The emission factor is the actual volume of methane being released when producing a ton of coal: mining coal can open cracks and fissures in coal strata, and pockets of methane can be released into the atmosphere. The emission factor thus takes into account not only the methane content of the coal but also the specific conditions and practices involved in mining. The emission factor ranges from 1 to 2 times the methane content but varies greatly with the mining method and other factors [11]. The difference between Tier 1 and Tier 2 emissions factors for coal mining is that Tier 2 requires measurement data from underground mines within the country itself, whereas Tier 1 just uses generic emission factors based on depth and type of mine.

The Tier 3 method, uses mine-specific measurement data from ventilation and degasification systems to develop national estimates for underground mines. The Tier 3 method is much more reliable because it takes into account variability in geologic formations and mining practices.

The general equation to compute methane emissions from coal mining and take every source into account is:

$$\text{total CH}_4 \text{ emissions} = \text{mining CH}_4 + \text{post-mining CH}_4 - \text{recovered CH}_4$$

The emissions from mining or post-mining activities are computed as:

$$\begin{aligned} \text{CH}_4 \text{ emissions} &= \text{CH}_4 \text{ emission factor} * \text{coal production} * \text{conversion factor} && (2) \\ [\text{Gg/year}] &= \quad [\text{m}^3/\text{ton}] \quad * \quad [\text{ton/year}] \quad * \quad [\text{Gg/m}^3] && (3) \end{aligned}$$

The conversion factor is the density of methane and converts volume of CH_4 to mass of CH_4. It is given by the IPCC guidelines as $0.67 \cdot 10^{-6}$ Gg m^{-3}.

The Tier 1 emission factors for fugitive emissions from mining are given in Table 2. Tier 2 method will be using emission factors based on country or basin averages or more specific mine information.

Mine type	**Depth of mine**	**Emission factor (m^3/ton)**
Surface	d < 25 m	0.3
	25 m < d < 50 m	1.2
	50 m < d	2
Underground	d < 200 m	10
	200 m < d < 400 m	18
	400 m < d	25

Table 2: IPCC emission factors, as a function of mine type and depth.

The uncertainties on the Tier 1 emission factors, as given by the IPCC, are a factor of 3 for surface mining and post-mining EFs, and a factor of 2 for underground EFs. They are thus very uncertain.

For our inventory, the goal is to get specific mine-measurements in priority (Tier 3) in the most important countries (biggest coal producers). If there are none available for a certain mine, we will search for basin-specific averages of emission factors. If there are none, we use a model we developed, based on the IPCC reporting guidelines, taking into account the coal rank and the gradual depth change, explained in Section 3.3.

For post-mining emissions, the guidelines are that the average emission factor should be used unless there is country-specific evidence to support use of the low or high emission factor. This is thus what we will do, for any country for which we do not have a specific post-mining EF. We apply to all mines the average IPCC EF, for surface mines and underground mines separately.

$$\mathrm{EF}_{\mathrm{surface}} = 0.1\ \mathrm{m}^3/\mathrm{ton} \quad \mathrm{EF}_{\mathrm{underground}} = 2.5\ \mathrm{m}^3/\mathrm{ton} \tag{4}$$

For abandoned mines, the IPCC gives a Tier 1 and a Tier 2 method to estimate the emissions. For Tier 2 emission estimates which are country or basin specific, the approach considers the number of abandoned coal mines remaining unflooded and the fraction of those that are gassy, as well as an average emissions rate, an emission factor that considers a decline curve over time (country or basin specific) and accounts for the coal rank as well. It is the only part of the guidelines in which the coal rank is taken into account. Unfortunately in our database, we do not have enough information on the abandoned mines, and many are missing, so the inventory does not include the abandoned mines (except for the U.S., explained in section 3.5.4).

3.3 Baseline emission factors

We know the in-situ content and the methane emissions of coal mining depend on several factors, including and most importantly coal rank and depth of the mine. The emissions calculation model developped here is based on the IPCC guidelines and improved, taking depth and coal rank into consideration.

Looking at the depths of our database's coal mines worldwide, shown on Fig. 9, there are several interesting aspects to analyze, which can help decide how to build a proper model to compute emission factors.

Especially for surface mines, numerous mines have the same depth. This is the case when the exact depth is not known, and it is then set to the estimated average depth for the country. For China for instance, the average mining depth for underground mines is 456 meters and is used for a few hundred mines.

For **surface mining**, the depth accuracy is low, with only 6 % of mines having a registered "exact" depth. Since surface mining involves removing the overburden and extracting the coal in the open, knowing the exact width of the overburden removed can be difficult and and it seems natural that the estimation is less precise. We can also see that almost all the surface mines are 50 meters deep or more, which means that in terms of IPCC emission factors, the high-methane content EF should be used. Also, as shown in Fig. 10, 83% of the opencast coal mines are mining subbituminous and lignite coals, which have a lower methane content and release less methane. Given the lack of depth accuracy, the guidelines received for the GFEI inventory, and the fact that surface mining only contributes around 12% of coal mine methane emissions, it was decided to simply use the

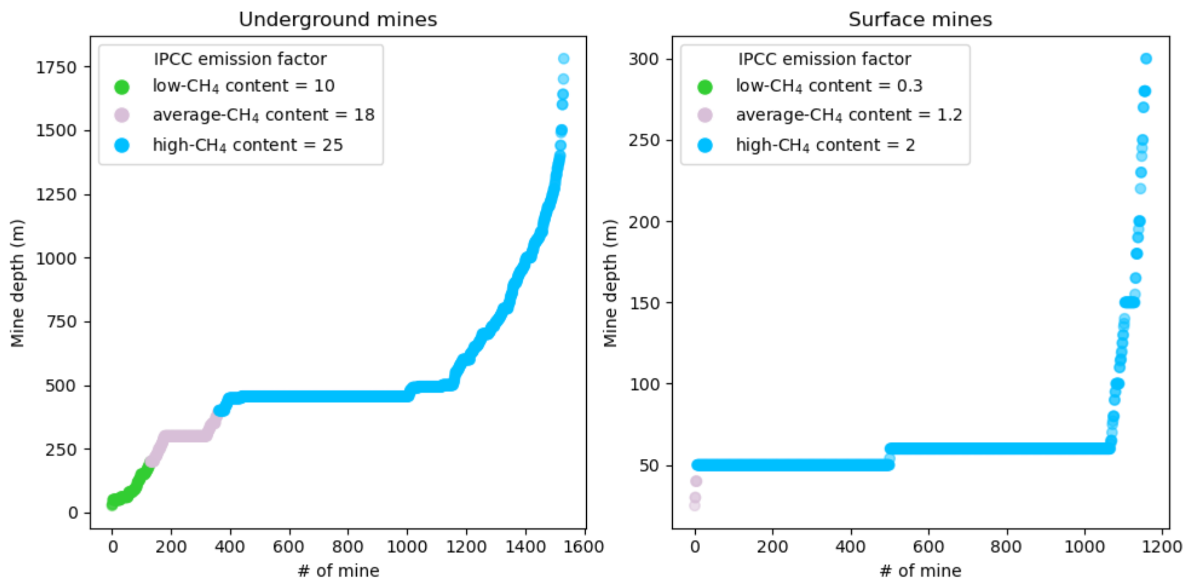


Figure 9: Depths of coal mines around the world, in ascending order, for underground and surface mines, and the associated IPCC advised emission factor

IPCC guidelines as the basis for calculating emissions from surface mines. Most surface mines in the inventory thus have an EF of 2 m^3 of methane released per ton of coal produced.

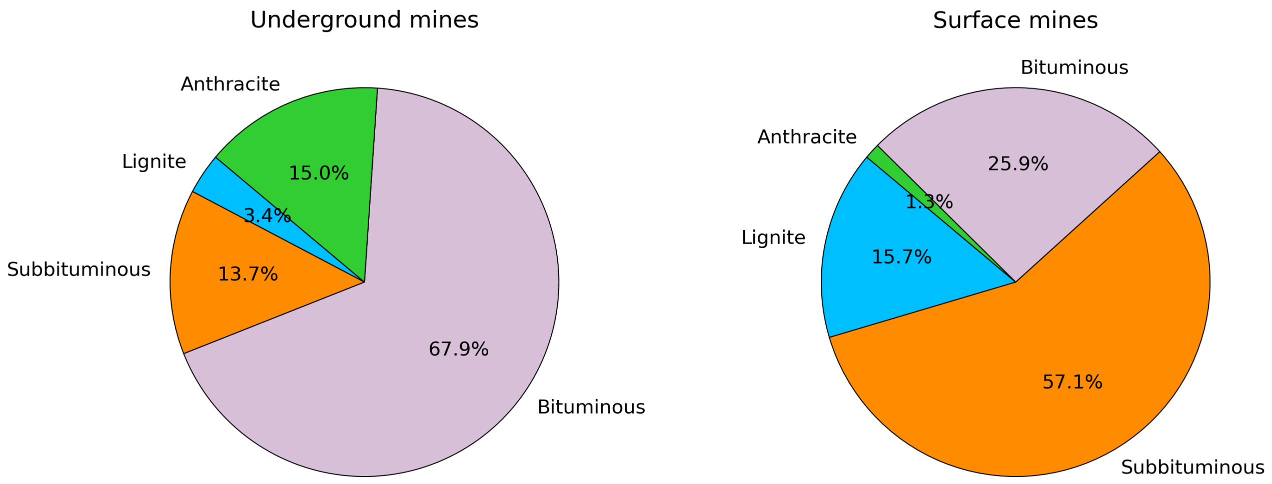


Figure 10: Coal rank shares for underground and surface mines, in % of the number of mines

For **underground mines**, Fig. 10 shows that the coal mined is of higher rank, with 83% of bituminous and anthracite mines. Given what we know about coalification, it is logical that the higher-rank coals are deeper, accessible by digging underground mines, and are linked to more emissions since they have a higher in-situ methane content. Depth accuracy is better with 36% of "Exact" depth. The depths, presented in Fig. 9 show that many underground coal mines, when following IPCC reporting guidelines, should use an emission factor of 25 m^3 of methane released per ton of coal produced, since they are deeper than 400 meters. Indeed, 8% of the underground mines are below 200 meters and should use the low methane content EF, 15% are between 200 and 400 meters and should use the average EF, and 76% are above 400 meters. Applying the IPCC guidelines would mean that a very large number of mines would account for their emissions using the same emission factor, whether they were 500 or 1600 meters deep. For this inventory, it was decided to develop a model that takes into account the depth and the coal rank dependence in the methane emission factors of coal mining.

Below is an explanation of the methodology and the reasoning behind the model we constructed to calculate emission factors for underground mines, factoring in both coal rank and mine depth.

We start by logarithmically interpolating the emission factors given by the IPCC, to obtain EFs that gradually increase with depth. Indeed, theory and many measurements verify that the in-situ gas content of coal increases logarithmically with pressure and depth. The adsorption isotherm of coal methane refers to the relationship between the amount of methane gas that can be adsorbed (or trapped) onto the surface of coal, and the pressure of the methane gas in the surrounding environment, while maintaining a constant temperature. The isotherm is a theoretical cap on the gas content of coal at any given pressure or depth, but it is rare for saturated coal to be mined. Indeed, uplifting and rifting of the strata in geological periods following the coalification process provided opportunities for methane to escape through fracture systems, resulting in the upper coal layers becoming under-saturated with methane. Our emission factor equation should thus be inferior -but very similar in shape- to the coal methane adsorption isotherm.

The adsorption isotherm of coal has a logarithmic shape [11], and theory is validated by measurement data. Gas content from 19 different boreholes in the Sydney basin give a curve that is approximately constant above 100 meters of depth, and then has an inflection point: the in-situ gas content describes a log curve, flattening at 400 meters at an EF of about 8 m^3/ton [14]. Other measurements of the methane content-depth relationship in Russia show a similar curve but this time flattening at 15 to 30 m^3/ton [15]. Some basins may behave a little differently, and the standard deviation often increases with depth, but the generality can still be made for a global emission factor calculation, bearing in mind that for the most emitting countries, specific emission factors will be used.

The EF of 2 m^3/ton, corresponding to the high-methane EF of surface mines, is set to the shallowest underground mine which is 27 meters. Three different depth ranges are identified: 27 to 200 meters, 200 to 400 meters, and 400 to 1780 meters (deepest mine), corresponding to different emission factors in the IPCC guidelines. For each range, the corresponding IPCC EF is allocated to the median mine depth. When interpolating these points with a logarithmic curve, the relation between depth of mine (d) in meters and emission factor becomes:

$$\mathrm{EF}(d) = 7.6227 \times \ln(d) - 23.419 \tag{5}$$

Then the distinction between different types of coal must be included. Comparing the emission factor values given by the IPCC, the in-situ gas content adsorption isotherm, and experimental measurements, we see that the IPCC EFs are based on the measured EF values for bituminous coal. The reason is that bituminous is the major coal type mined in underground mines, accounting for 80% of the production. Equation 5 is thus the equation giving the EF as a function of depth for bituminous coal. To determine the ratios between the emission factors of the different coal ranks, we average the data from Kholod et al [11]. Without using their emission factors, as their method is based on the theoretical cap of the Langmuir isotherm, we can nevertheless deduce the ratio between the gas content of anthracite coal, bituminous coal and sub-bituminous coal using their data. For the ratio between bituminous and lignite methane content which is not determined in the study, we use the same as Sadavarte et al. in their India and Australia bottom-up CMM inventory [16]. At all depths, the ratios are:

$$\frac{EF_{\text{anthracite}}}{EF_{\text{bituminous}}} = 1.84 \quad \frac{EF_{\text{bituminous}}}{EF_{\text{subbituminous}}} = 3.3 \quad \frac{EF_{\text{bituminous}}}{EF_{\text{lignite}}} = 4 \tag{6}$$

By combining equation 5 and the ratios between the different coal ranks, we finally have 4 relationships between methane emission factor in units of m^3 of methane released per ton of coal produced, and mine depth. We call these relations the log-rank model and it will serve as baseline emission factor calculation for underground mining for the rest of the work. The curves are shown in Fig. 11, together with the emission factors proposed by the IPCC for each depth range.

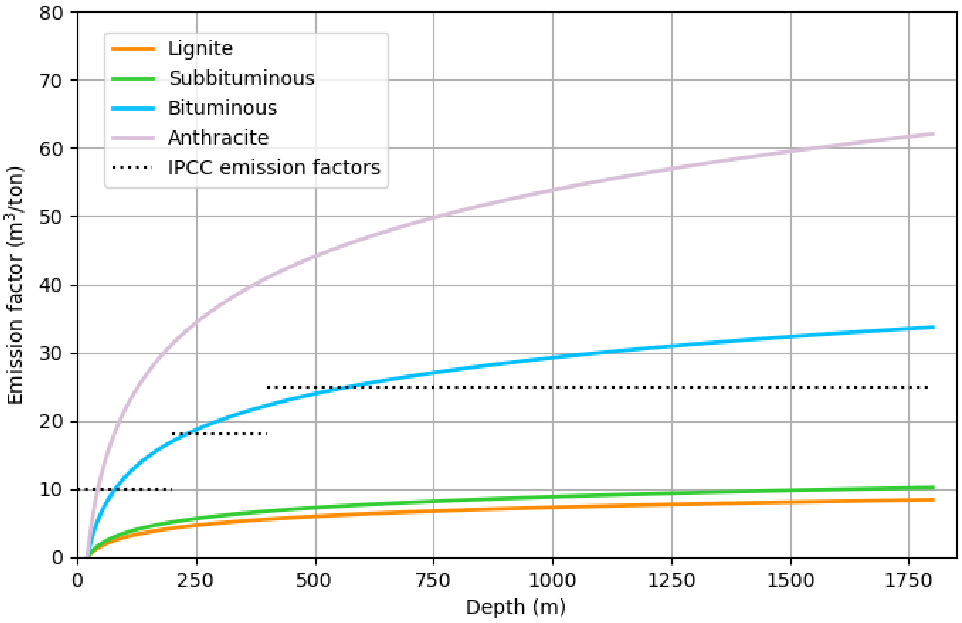


Figure 11: Log-rank methane emission factors increase with mine depth (underground), differently according to coal rank

3.4 Log-rank model results

We apply the log-rank model to all mines in our database. Each mine now has a log-rank emission factor in function of its depth, and what type of coal being mined. The total CMM emissions are:

- 63423 Gg / year when using the IPCC advised emission factor in function of type of mine and depth.
- 63979 Gg / year when using our log-rank model, very close but emphasizes on the difference in emissions for different types of coal, as well as a gradual increase of the EF with depth.

- 91589 Gg / year when using the Langmuir isotherm emission factors (computation by GEM directly), highlighting that the isotherm is a theoretical maximum which is far from what the IPCC recommends in the guidelines.

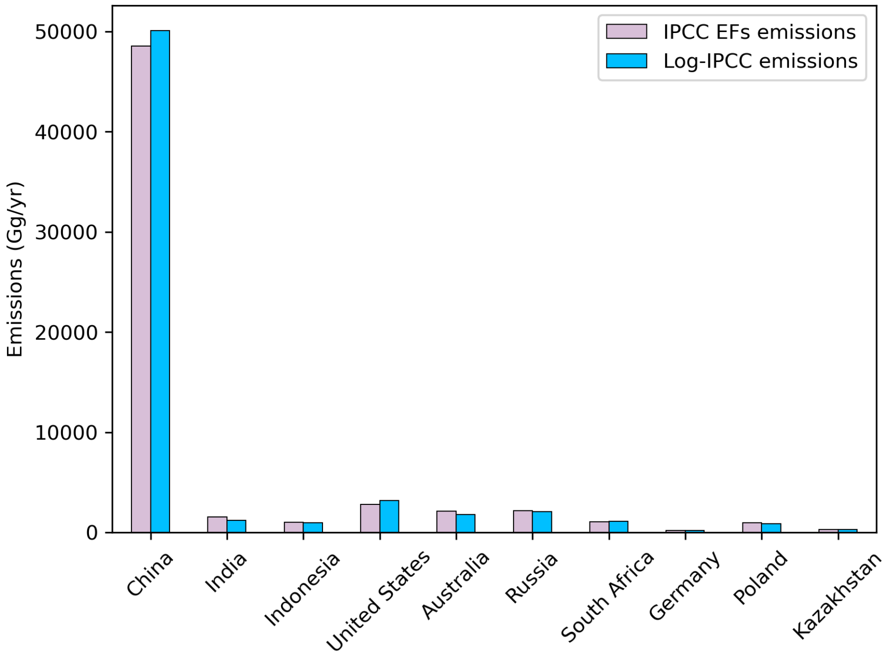


Figure 12: Country totals using both methods

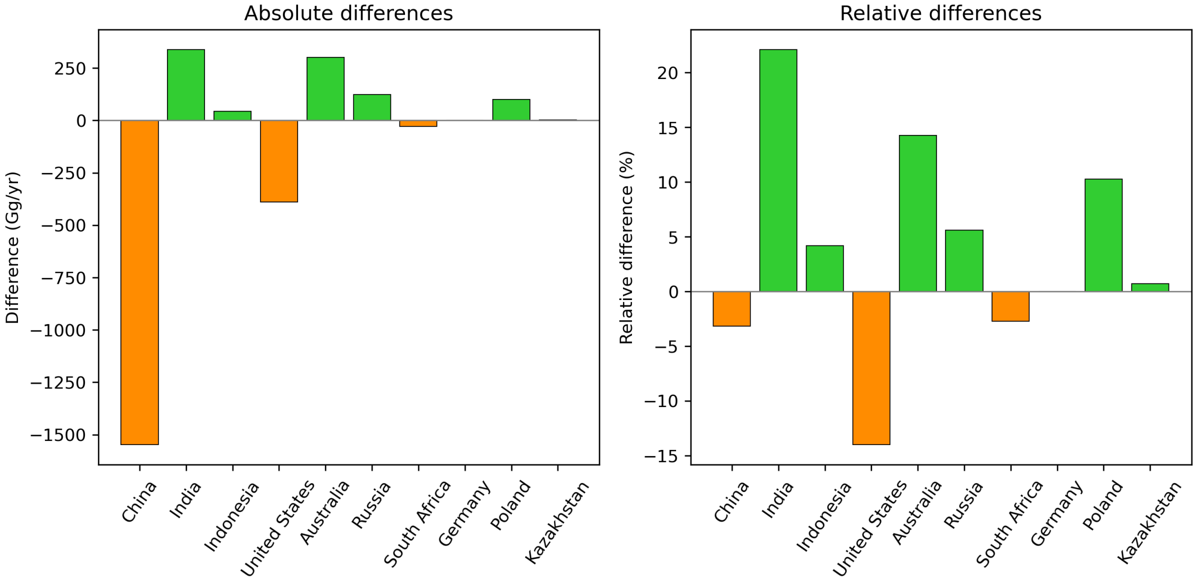


Figure 13: Left: Difference between IPCC-based CMM emissions computation and our model's emissions (= IPCC - log-rank). Right: relative difference.

Fig. 12 shows the country totals for the biggest coal producing countries, both with using only the basic IPCC advised emission factors, and with our improved approach taking into account coal type and gradual depth change (log-rank). China is by far the country that emits the most coal mine methane, with 10 times more emissions than the U.S. appearing in second position. We can also see little difference between the 2 methods, not always in the same way. Fig. 13 zooms in on the difference between using the IPCC emission factor and our improved approach, in both absolute and relative differences. A country's total is lower using the log-rank model if it has lower rank coal statistically, and then the difference plotted (IPCC minus log-rank) will be positive. There is no difference for Germany because it has only surface mines, and for Kazakhstan, the difference is small because the underground mines are all bituminous. Since IPCC emission factors are based on bituminous, our log-rank bituminous EFs are close to the IPCC advised.

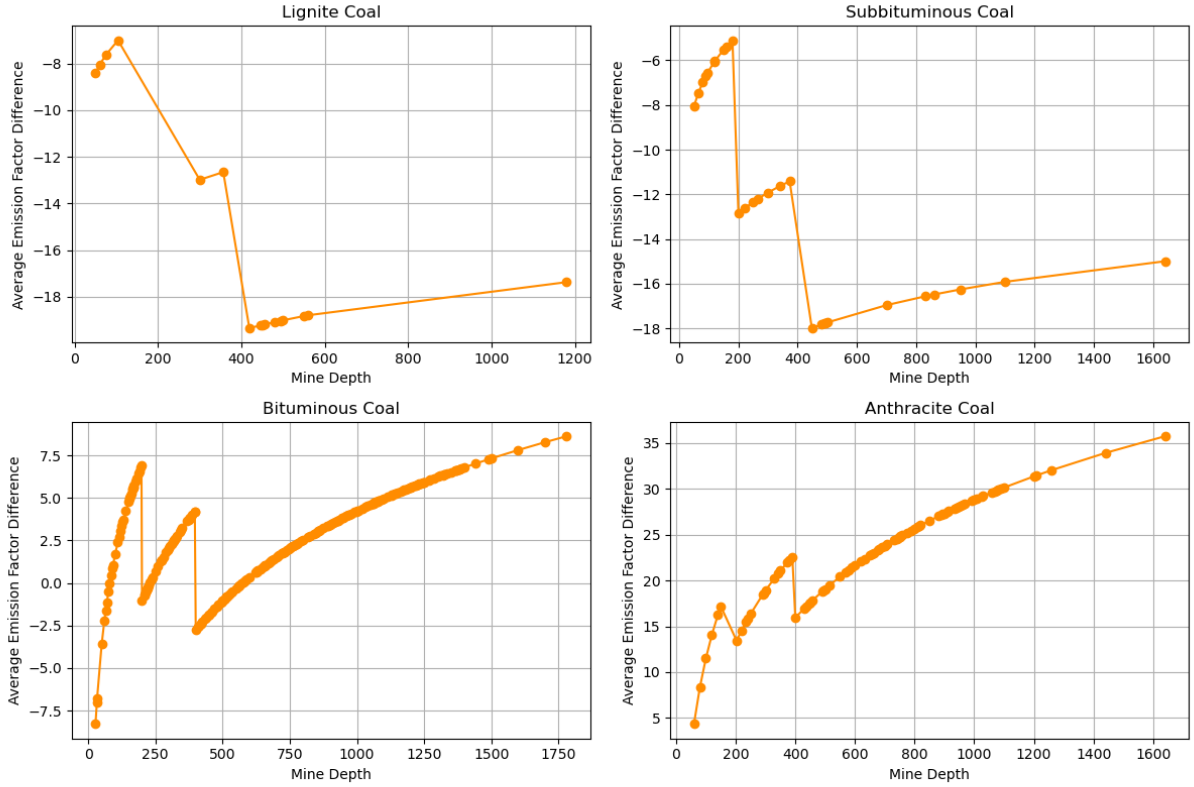


Figure 14: For each coal type, the difference between the emission factor given by the IPCC and ours is plotted as a function of depth. The boundaries of 200 and 400 meters, where the IPCC EF changes, are clearly visible.

Fig. 14 illustrates the discrepancy between the emission factors of the two methods over depth. Each dot represents a mine, each plot represents a different coal rank and the difference in EF associated. At each IPCC boundary depth (200 and 400 meters) there is a gap, since the IPCC advises a sudden change in EF, and our model increases continuously. The difference for bituminous coal revolves around 0, but gradually increases from 500 onwards. Emission factors in our model are lower for subbituminous and lignite, as we knew, and are much higher for anthracite, which is the coal rank for which it differs the most from the IPCC, especially at greater depths. What is interesting in this graph is to see the depth repartition for each coal rank. There are very few underground low-rank mines, and even less as the depth increases. We see clearly what we expect from the theory behind coalification and coal ranks that lignite and subbituminous coals are found at shallower depth (much more in surface mines), especially lignite. There are more deep anthracite coal mines than shallow ones. Bituminous coal is on the other hand found at all depth.

3.5 Improvement of the inventory per country

The log-rank model is the basis for our emission factor calculations, with IPCC emission factors for surface mines, but the best way to account for CMM emissions is to have mine-specific emission factors and methane emissions measurements. An in-depth literature review (limited by the time at our disposal) was carried out to identify the best available data on methane content and CMM emissions for inclusion in our database. Research into specific emission factors has been carried out for the 11 countries that produce the most coal in the world, and the methodology and sources for each is detailed in this section.

3.5.1 China

China is by far the biggest coal producing country in the world, with about 3800 Mt of coal mined per year (GEM, 2023), i.e. almost 5 times India's production in second position. China relies on coal power for approximately 70-80% of its energy, with 45% used for the industrial sector and the remainder used to generate electricity [17].

The coal mining industry in China is divided among state-owned mines, and thousands of small town and village mines. In February 2006, the NDRC began restructuring the coal sector towards the goal of shutting down all small coal mines by 2015, and establishing five or six large state-owned conglomerates. About a fifth of the 28000 coal mines operating in 2005 were illegal mines, responsible for a large number of accidents [17].

To improve coal mine safety and cutting overcapacity, China closed more than 20000 mines since 2005. Now there are about 4500 coal mines, and 85% of China's production comes from about 1200 of them [18].

The GEM Global Coal Mine Tracker includes 1226 coal mines for China, of which 1080 are underground mines. We have the exact depths of 43% of the underground mines, and the rest of the mines are set to an average national depth of 456 meters deep [11]. The geolocalisation data is very good, with 97% of the mine locations being stated as "Exact" in the database. In China, a large majority of the mines are producing hard coal (77% bituminous, 17% anthracite), and only 6% of the mines produce brown coal (4% lignite, 2% subbituminous).

For 98% of Chinese mines, our database only has "capacity" data and not the yearly coal production. This is not a problem because China scaled up production so much these past 2 years that many mines are now operating at capacity or near to [18]. We will thus use the capacity data as our activity data for Chinese mines.

Since China is such a major player in global coal production, and in coal mine methane emissions, numerous studies have been carried out on its CMM emissions, unlike in other countries. Gao et al. in 2020 published a review of 29 bottom-up inventories of chinese coal mine methane emissions, done between 1993 to 2019 [19]. The most recent inventories and their methods have been reviewed to select the best method and emission factors to apply to our mine database.

In China, the average mining depth of state-owned coal mines increases at the rate of 10 to 25 meters per year [20]. With depth, methane content changes a lot, which highlights the importance of not using old data that could have high errors. Indeed, a study published in 2017 estimates emissions from coal mining between 2005 and 2010, and calculates predicted emission factors up to 2020 in the Heilongjiang region of China [21]. They show that emission factors could rise from 13 or 14 in 2010, to over 25 in 2020. Below are studies that provide important insights into emissions in China (and beyond), and why we chose or rejected them.

Wang et al. developed in 2014 a statistical model to compute emission coefficients for each 25 regions of China [22]. Since we do not have the expertise to review the statistical model, and that the coefficients given are at the scale of immense regions, we haven't chosen to apply this study.

Ju et al. published in 2016 a new method to estimate CMM emissions based on analyzing the features of gas-geology distribution, coal properties, mining operations, and CMM emission processes in China [23]. Their method was verified on two different coal fields, and proved to have small errors compared to other models. They also calculated the mining coefficient, which coupled with the in-situ gas content gives the mines' CMM emissions. For these two coal fields, the mining coefficient is between 1.3 and 2. Kholod et al. used these for their average emission factor in the MC2M method [11]. We used the data from this paper for the 9 mines that matched our database (Tier 3), giving emission factors between 8.4 and 28.77 m^3/ton.

Zhu et al. in 2017 published emission factors at the region scale for underground mining [21]. Their calculations are based on 2009 data of 787 underground mines in 25 different provinces. While the data is considered representative of China's underground coal mining, the methodology has been questioned in scientific literature [14], and the study we chose to apply in the end was more recent and at a better resolution, including surface mines as well.

A very recent study (in preprint) by Qin et al. in 2023 built an inventory of CMM emissions in the Shanxi province (12% of global coal output) at the mine-level. Indeed they first build a bottom-up inventory for 636 individual coal mines based on data from the National Coal Mine Safety Administration and the National Energy Administration in China. Then they set up an eddy-covariance tower[1] near the output flow of a well characterized high rank coal mine in Changzhi, over two two-month long periods. They use their measurements to produce a set of scaling factors and update the preliminary bottom-up emissions. Their results are compared with the EDGAR and GFEI v2 inventories. They find that the overall emissions are overestimated in the region, and that there are significant spatial disparities: both EDGAR and GFEI include a very large amount of emissions occurring where there are no coal mines. The results are not available yet, but should definitely be looked at closely for future versions of this work.

We chose to apply to our mine database the emission factors developped by Sheng et al. in 2019 [24]. The base of their research is a database of the National Coal Mine Methane Level Identification for 2011, compiled by the SACMS (State Administration of Coal Mine Safety). In this database are compiled the emissions of 10093 mines, that were continuously monitoring their ventilation and degasification systems during their 2 to 3 months annual safety evaluation. This study develops a gridded inventory of coal mine methane in China, which has since been used and cited by many other studies, but we adapt it: we take their emission factors per province, and apply the EFs to our GEM

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[1] Eddy covariance: key atmospheric measurement technique to measure and calculate exchange rates of trace gases over natural ecosystems and agricultural fields, and to quantify gas emissions rates from other land and water areas. It is frequently used to estimate momentum, heat, water vapour, carbon dioxide and methane fluxes. (Wikipedia: Eddy covariance)

coal mine database which should be more up to date considering the rate of closure of Chinese mines. The emission factors (and their uncertainties) are presented in the table in Fig. 15. The emissions data is based on 2011 and thus we do not take it into account. To differentiate low-CH_4 and high-CH_4 mines, we look at the classification method for coal mine gas grades in China from the National Coal Mine Safety Administration and the National Energy Administration. The criteria for the relative gas emission is ≤ 10 m^3/ton for low gas mines, and > 10 m^3/ton for high gas mines (REF Wang 2019). We thus have to classify our mines dataset to apply the corresponding emissions factor.

- All underground anthracite mines in China are deeper than 100 meters, they are thus considered high-gas mines. Indeed in our baseline log-rank model, they correspond to EFs ≥ 21 m^3/ton.
- Underground bituminous mines that are deeper than 150 meters are treated as high-gas mines. Indeed regarding our log-rank model, the emission factor for bituminous coal goes above 10 for mines that are deeper than 80 meters. Taking into account model uncertainties, and in order not to overestimate emissions, we consider mines more than 150 meters deep as high-gas, corresponding to emission factors of above 14 m^3/ton for our log-rank model.
- All underground lignite and subbituminous coal mines, as well as bituminous mines under 150 meters deep, are considered low-gas mines.
- All surface mines are low-gas mines.

Province	Emissions (Tg CH_4 a^{-1})	EF (m ton^{-1}) (low CH_4-content)	Uncertainty (%) (EF_{low})	EF (m ton^{-1}) (high CH_4-content)	Uncertainty (%) (EF_{high})
Anhui	0.77	3.87	43%	10.62	73%
Beijing	0.002	1.43	48%	-	-
Chongqing	0.65	6.65	26%	28.80	56%
Fujian	0.05	4.02	42%	-	-
Gansu	0.02	2.39	52%	12.25	8%
Guangxi	0.03	5.52	45%	22.12	8%
Guizhou	2.27	7.66	24%	31.30	56%
Hebei	0.24	2.88	74%	16.60	100%
Heilongjiang	0.61	3.51	66%	20.53	64%
Henan	0.91	3.41	61%	12.63	61%
Hubei	0.20	5.04	41%	18.05	52%
Hunan	0.64	6.42	31%	27.57	49%
Jiangsu	0.03	2.70	73%	7.34	47%
Jiangxi	0.18	6.14	30%	16.42	48%
Jilin	0.20	5.48	46%	11.80	38%
Liaoning	1.04	0.46	100%	12.01	100%
Inner Mongolia	0.28	1.45	100%	18.56	59%
Ningxia	0.15	1.71	100%	31.16	69%
Shaanxi	0.49	2.46	84%	22.06	78%
Shandong	0.13	1.93	71%	9.73	42%
Shanxi	5.75	3.34	69%	22.05	65%
Sichuan	1.26	6.50	34%	32.29	51%
Xinjiang	0.12	2.92	54%	13.73	47%
Yunnan	0.70	6.09	30%	30.09	63%

Figure 15: China CMM emissions (2011), emission factors (EFs) for low and high-CH4 content mines, and EF uncertainties (relative error standard deviations) [24]

After including all the specific emission factors in our data, 2 mines remain in the Qunghai province. They are both very close to the Gansu border (about 20 km) so we decide to apply the Gansu emission factors for these as well. In the end, 100% of the mines in China have a specific, measurement-based emission factor to compute methane emissions.

China has strong measures in place to mitigate its methane emissions, and ambitious goals. The country is thus a leader in the recovery and use of their CMM emissions. In 2010 already, 9.4% of their CMM emissions was recovered and utilized [21, 14]. The Global Methane Initiative case study on CMM Development and Utilization showed that while the drainage volume increased a lot in a decade, from 2.2 billion in 2005 to 13.5 billion m^3 in 2017, the utilization rate has been pretty stable, oscillating between 30 and 35%. Unlike other countries, the number of mines practicing methane drainage and recovery is very big. Indeed in 2007, more than 300 coal mines were equipped [26], and in 2011, about 1050. In 2019 the utilization rate of underground CMM extraction was 40%, lower than the 5 year plan which was 50% but still consequent.

With these numbers in mind, we choose to consider a 13.5 billion m^3 of CMM drainage per year, with a 35% utilization rate. The data is several years old and we can only imagine we are underestimating the utilization of CMM in China, but we have not seen more recent numbers. Since the cost of deploying recovery is high, bigger coal mines are more likely to have drainage equipment in place. Yearly coal output in our database's Chinese underground mines range from 0.7 to 26 Mt per year. We thus distribute the 4.725 billion m^3 of used CMM, proportionally to their yearly methane emissions, to all underground mines that produce more than 1 Mt per year of coal (84% of underground mines). The CMM use represents 9.13% of the methane emissions of those mines, and 8.26% of China's emissions from all mines.

Abandoned mine methane (AMM) are not taken into account in our inventory, because The China Coal Information Institute established the Abandoned Mine Methane Project Advice Centre in 2010 to advise and promote the countrys abandoned mine methane use, since they represent such a huge amount of emissions. Indeed, tens of thousands of coal mines have been closed since the 1990s (100000 mines estimated in 1990, GMI 2020). As of 2019 however, no abandoned mine methane recovery projects have been initiated in China (GMI, 2019).

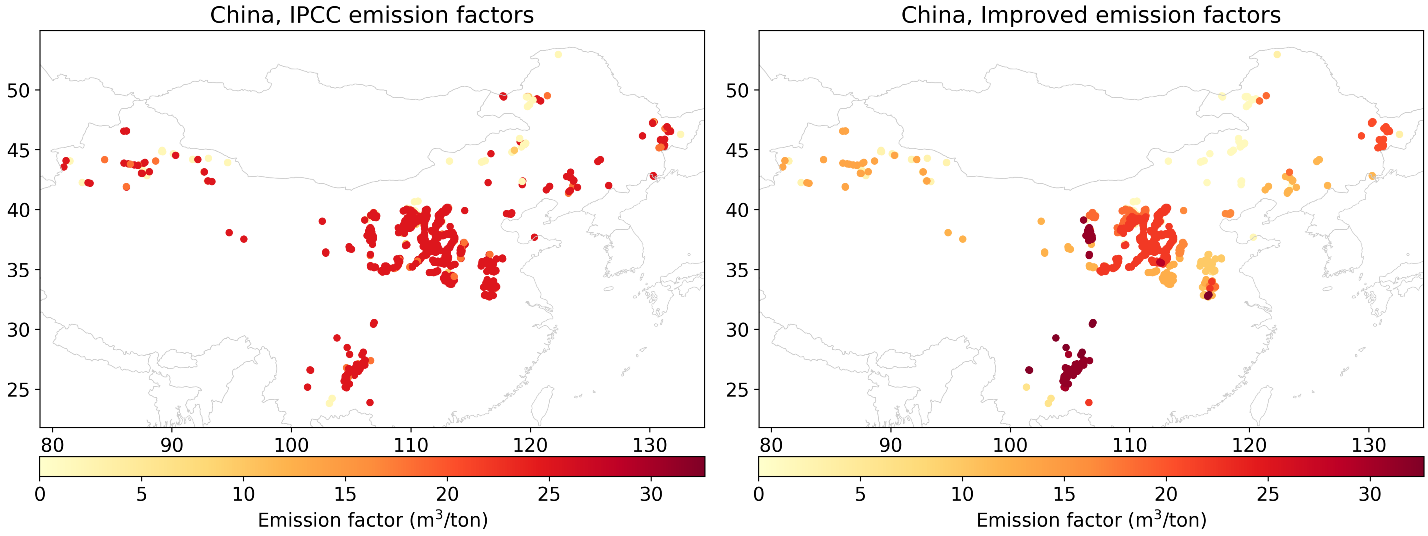


Figure 16: Emission factors for all mines in China. Left: emission factors advised by the IPCC guidelines. Right: improved emission factors for 100% of the mines, obtained with the methodology described above.

Fig. 16 presents the results of this method to find specific emission factors for mines in China, and apply them to our database. It shows the EFs of each mine if the IPCC advised emission factors were used, and the improved EFs based on measures and regional averages from the studies cited above. The repartition of the methane content or emission factor is much more heterogeneous than what would be obtained with the IPCC basic EFs. Two regions can be identified as methane rich, in the center of the country. When looking at Fig. 17 which shows for each mine its type (surface, underground) and the coal rank being mined, we see the regions with high EFs are associated with a high number of anthracite underground mines. The 77% of bituminous mines stated above is visible on this figure as well. Now looking at the actual emissions for each mine, presented in Fig. 18, it can be noted that these high methane regions are not the ones with highest emissions. The production of coal is lower in the South. Globally in the central-north regions of Shanxi, Shaanxi, and Inner Mongolia, there is a very high concentration of mines, of high rank and deep mines, with a high yearly production.

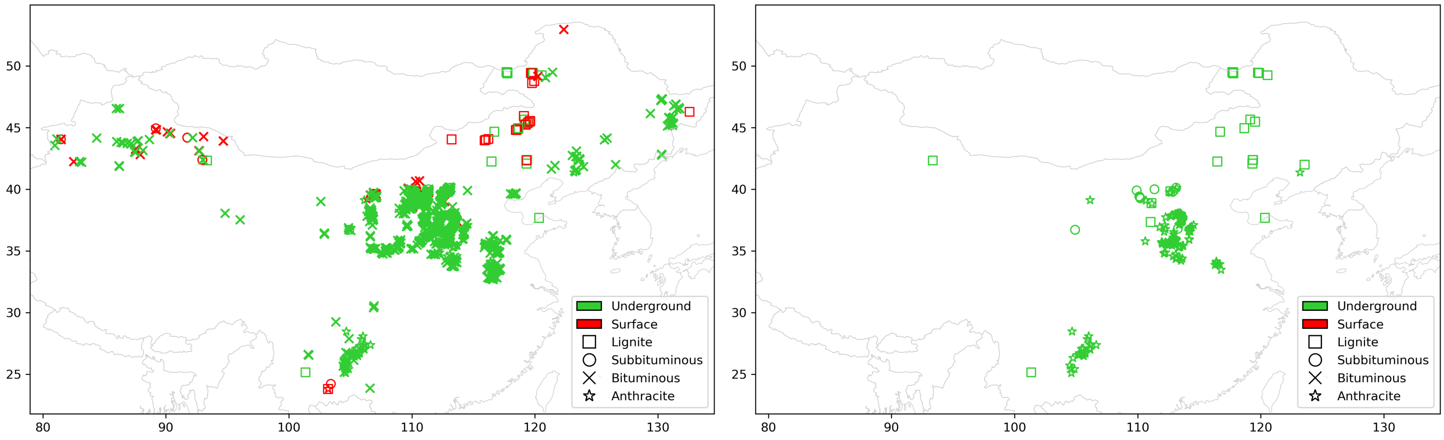


Figure 17: Mine types in China. Left: all mines. Right: all anthracite, subbituminous and lignite mines: bituminous mines removed for visibility.

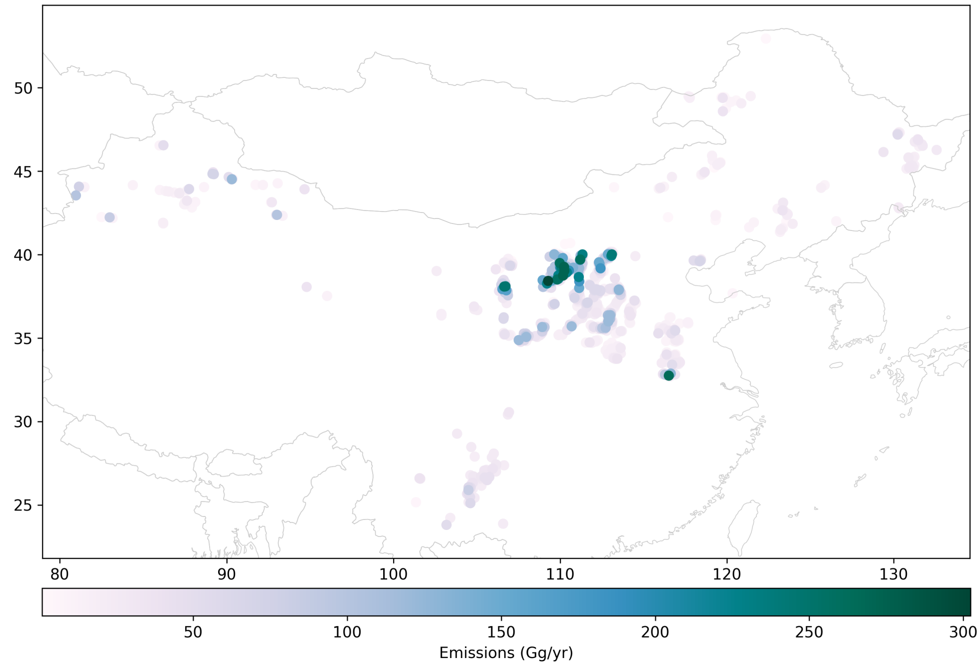


Figure 18: Methane emissions from all Chinese mines, in Gg per year.

Fig. 19 shows yearly methane emissions from coal mines in Chinese provinces, highly concentrated in the three provinces mentioned before. Indeed, as we will see in the general results, the country that emits the most CMM after China is Russia, with 2'708 Gg per year per our inventory. Looking at the plot for the provinces emissions, it means that 3 regions of China each have higher emissions than Russia. The Shanxi province emits more CMM than what is emitted by every country (except China) in the world combined. In our inventory, China accounts for 40'341 Gg per year of CMM emissions, or 74.7% of the worldwide CMM emissions.

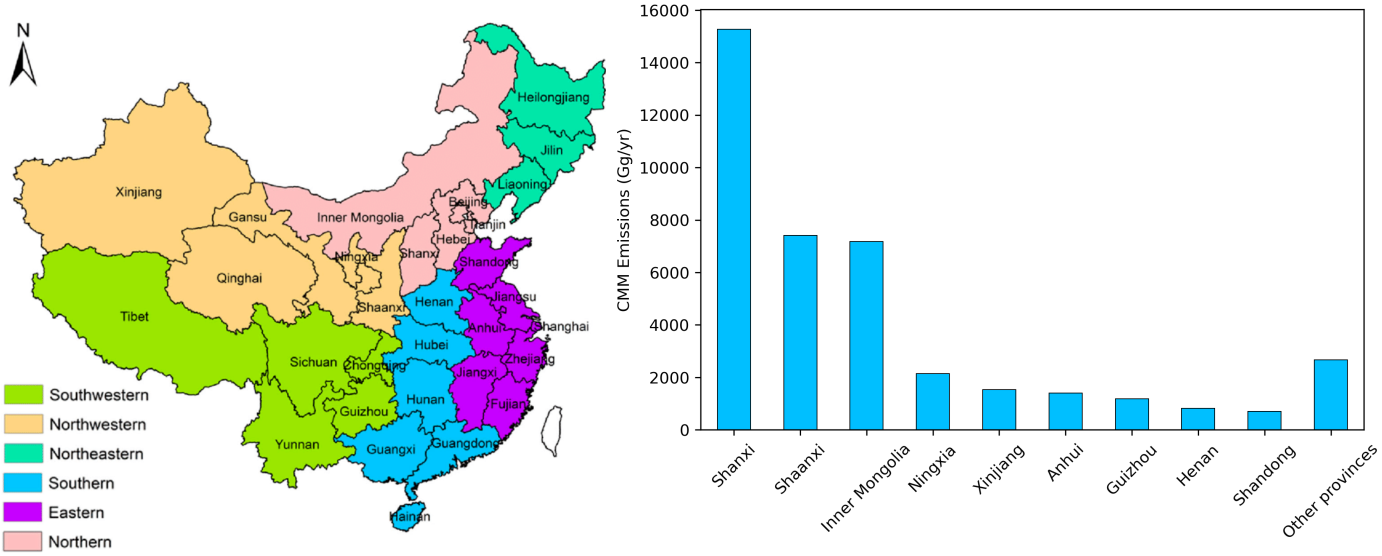


Figure 19: Left: map of the Chinese provinces [27]. Right: Yearly methane emissions from the 9 highest emitting provinces in China, and sum of the emissions of all the other provinces.

3.5.2 India

India is the 2^{nd} largest coal producer in the world, with 783 Mt per year (GEM, 2023) and holds over 319 billion tonnes of coal reserves. Over 56% of Indias primary power production is supplied by coal and this number is expected to grow with the population and energy needs increase (GMI, 2020). The major coal fields are located in the central and eastern parts of the country.

The GEM Coal Mine Tracker lists 392 coal mines in India, 42% are underground. Most of the coal is of low rank: 13% of lignite, 78% of subbituminous, and only 9% of bituminous coal. The exact depth is known for only 8% for the mines, but the location accuracy is really good at 87%. Inspired by Sadavarte et al. study on Australia and India CMM emissions, we adapt the emission factors and data they are using to our mine database [16].

India has a classification system for mine gassiness that is dependent on the amount of methane emissions (specific emissions) per tonne of coal mined (Ministry of Labour and Employment, 2017).

- Degree I: between 0.01 and 1 m^3/ton of coal produced
- Degree II: between 1 and 10 m^3/ton of coal produced
- Degree III: more than 10 m^3/ton of coal produced

Most of the mines in India are degree I and II mines, but statistics per region are available.

The country surface emission factor of 1.18 m^3/ton comes from a study and measurement campaign by the CIMFR (Central Institute of Mining and Fuel Research), which results are presented in Table 3[28]. Since almost all surface mines are reported in the GEM database to be deeper than 50 meters, their initial IPCC emission factor was 2 m^3/ton. The study also gives underground emission factors for each gassiness category based on 16 surface and 83 underground mines measurements, which have been widely used in studies and national reports (Ministry of Environment, Forest and Climate Change [MoEFCC], 2015, 2018, 2021; Singh and Mallick, 2015).

But more recently in 2022, Singh et al. published an updated CH_4 and CO_2 inventory of underground coal mining in India. Based on measurements of CH_4 concentrations in the shafts of 108 underground mines, and production data for each mine from the Directorate General of Mines Safety (DGMS, Government of India), they provide emission factors for 108 underground mines. These mines have been chosen to represent 31, 20, and 100% of all the active coal mines in the respective degree-I, degree-II and degree-III gassiness categories. We could also extract from the study the depth of the deepest coal mine, the Moonidih (600 m).

When two measurements were available for the same mine, we choose the best measurement on a case-by-case basis: the most recent, the one that gives total concentration at the main shaft, or the one from the deepest seam. The measured mine-specific emission factors are much smaller than the IPCC EFs, since apart from the deepest and high rank mine (600m, bituminous) that has a 24 m^3/ton emission factor, all the EFs are below 10 m^3/ton.

After applying the emission factors to all the mines matching our database, we apply the emission factors from the CIMFR to the remaining 135 underground mines [28]. We use the gassiness distribution for each region in India given by the government to compute emission factor for each mine [29]. In the Chhattisgarh state for example, all the mines are classified as degree-I by the governmental statistics, so we apply the emission factor of 2.91 m^3/ton [30]. The 29 mines of this district appear to be mining subbituminous coal (GEM) so it matches our expectation of a lower gas content.

Type of mine	**Degree of gassiness**	**Emission factor (m^3/ton)**
Underground (mining)	I	2.91
	II	13.08
	III	23.64
Underground (post-mining)	I	0.98
	II	2.15
	III	3.12
Surface (mining)	I	1.18
Surface (post-mining)	I	0.15

Table 3: Coal mining and post-mining emission factors, measured and computed by the Central Institute of Mining and Fuel Research in India [28]

In the Jharkand state, we have 33 underground mines, 13 of which have mine-specific EFs from the Singh 2022 inventory. We can thus see if there is a pattern in this area between type of coal, estimated depth (very few exact depths), and gassiness. Unfortunately, both deep bituminous mines and shallow subbituminous mines are categorized as degree-I mines, so we cannot attribute mines in categories depending on our knowledge on methane content. We thus decide to compute new ratios for each district (best spatial resolution possible). In the Dhanbad district, we know there are 56 degree I, 7 degree II and 3 degree III coal mines. After subtracting the mines that we already accounted for with the direct measurements (10 deg-I and 2 deg III mines), we can compute the weighted emission factor:

$$EF_{Danbad} = \frac{1}{54} \cdot (46 \cdot EF_{deg-I} + 7 \cdot EF_{deg-II} + 1 \cdot EF_{deg-III}) = 4.61 \tag{7}$$

Doing the same method for all states and district, we compute all emission factors, presented in Table 4.

The weighted post-mining emission factors are computed with the same method as the mining EFs. The CIMFR EF for post-mining was applied when the gassiness of the mine was known.

As a result, 100% of the mines in our database have an improved specific emission factor.

At the Jharia mine, one of the gassiest underground coal mines in India, an exploratory CMM recovery and use project is underway, assessing the quantity and quality of CMM in sealed off areas of the mine (GMI, 2020. A pre-drainage project at Moonidih is also under development, but no operational recovery is taking place as of now in India.

State	**District or mine**	**Mines gassiness categories**	**Weighted mining emission factor (m^3/ton)**	**Weighted post-mining emission factor (m^3/ton)**
Chhattisgarh	All	I	2.91	0.98
Jharkhand	Dhanbad	I, II, III	4.61	1.17
	Ramgarh	II	13.08	2.15
	Ranchi	I	2.91	0.98
	Damagoria, Jharia, Sarubera (mines)	I, II, III	5.84	1.31
Madhya Pradesh	Betul	I, II	10.17	1.82
	Chhindwara	I, II	5.45	1.27
	Annupur, Shahdol, Umaria	I	2.91	0.98
Maharashtra, Telangana	All	I	2.91	0.98
Odisha	Angul	I	2.91	0.98
West Bengal	Burdwan	I, II, III	8.67	1.64
	Rest of mines	I, II, III	8.77	1.63

Table 4: Weighted emission factors used for Indian mines, based on the CIMFR measured emission factors, and the mine gassiness statistics per state and district in the country [28, 29]

The results of the application of specific emission factors for all mines are presented in Fig. 20. As expected we see a big decrease in emissions factors all over the country, as emission factors in Table 4 are lower than IPCC ones. Yearly emissions per mine, presented in Fig. 21 are low compared to other high emitting countries with the maximum emissions just between 25 and 30 Gg/yr. There are many mines in the country and it is the second biggest producer, but it comes 8^{th} in terms of methane emissions.

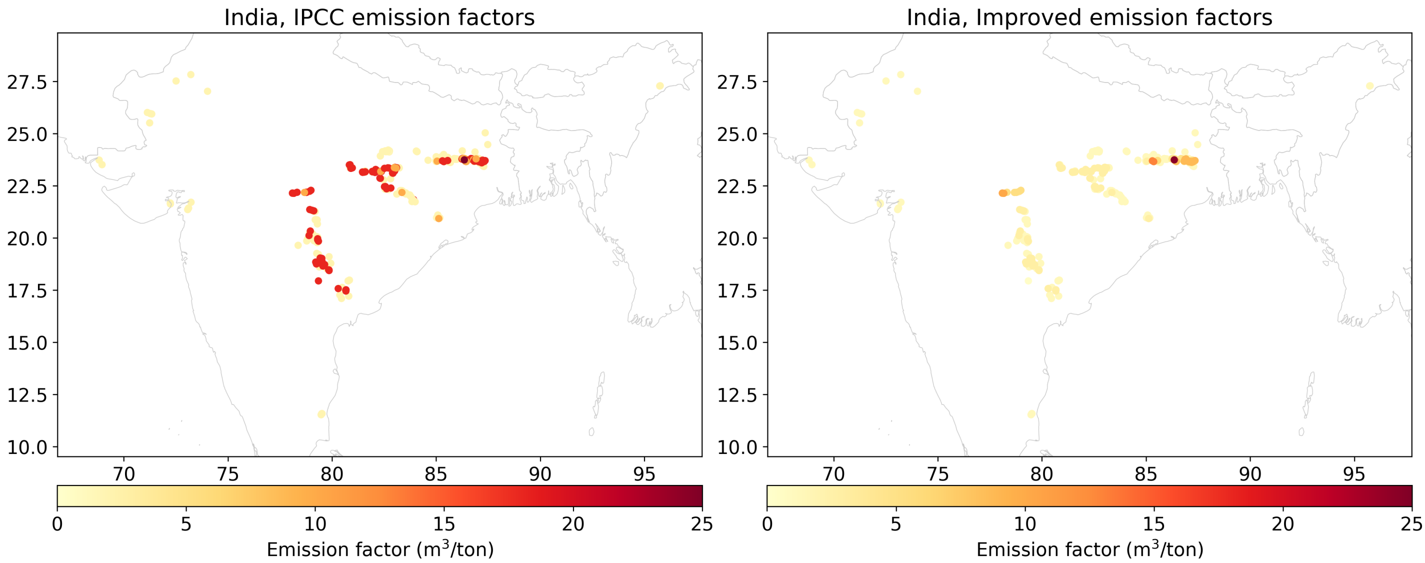


Figure 20: Emission factors for all mines in India. Left: emission factors advised by the IPCC guidelines. Right: improved emission factors obtained with the methodology described above.

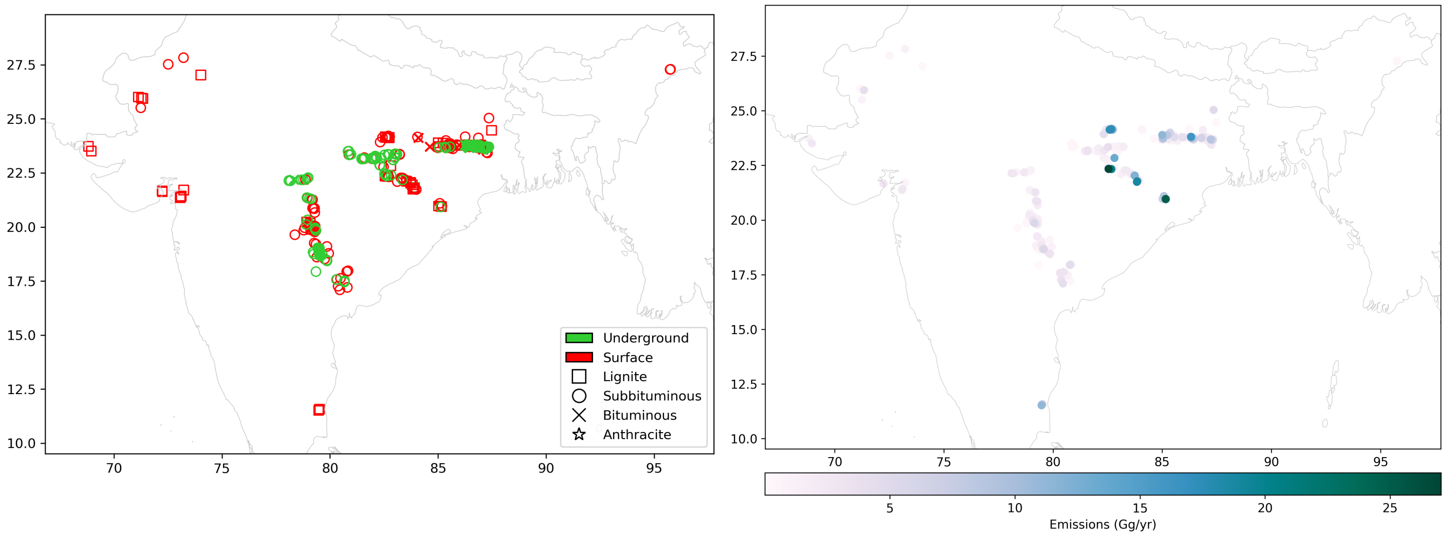


Figure 21: Left: Mine types in India. Right: Mine-level yearly CMM emissions in India.

3.5.3 Indonesia

Indonesia is the 3rd coal producing country in the world with 642 Mt per year mined (GEM, 2023). Indonesia is also home to the single most producing mine on the planet: the KPC Operation complex producing 56,1 Mt per year. Four mines are in the following 15 most producing mines. The main particularity of Indonesia is that its coal production comes almost only from surface mines: 95% of the annual coal output, for 99% of the mines. The report submitted by Indonesia to the IPCC in 2021 even reports no emissions in the *Underground mining* category.

Unfortunately, we have very little data for Indonesia, despite the fact that it is a country that mines a great deal of coal, with 419 operating mines in the GEM database. Geolocalisation, production, mine depth and type of coal mined would need much improvement.

In terms of production and type of coal mined, GEM has very good data. We have this data for each mine, showing that the vast majority of the mines are producing subbituminous coal. Only 6 are mining lignite, 20 are mining bituminous, and there is no anthracite mining. The location data is also pretty good: we have exact coordinates for 79% of the mines. Sumatra and Kalimantan holds approximately 49.9% and 49.6%, respectively of Indonesias total coal resources [31].

However, the exact depths are known for only 3 mines, 2 surface mines and 1 underground. But in reality, excluding Indonesia, only 6.82% and 10% of surface mines in GEM have exact depths, and often an estimate based on national or regional averages is made. The fact that we don't have precise depths makes no difference to our calculation, since all surface mines are over 50m deep. The depth of Tutupan, for example, has been changed to 250 meters rather than 50 [32], but the emission factor remains at 2m^3/ton since it's a surface mine.

Even the number and location of mines is highly uncertain because there is a lot of illegal mines. In South Sumatra in 2021, it was estimated that more than 700,000 hectares of land were occupied by illegal mining operations run by local residents [33].

As almost all mining takes place close to the surface, and coal rank is low throughout the country (sub-bituminous), very few methane recovery projects have taken place and therefore very few gas content measurements have been carried out. In fact, almost all methane recovery in coal mines worldwide is carried out in underground mines. However, a study conducted by PT Caltex Pacific Indonesia and Advanced Resources International, Inc. assessed Indonesia's coalbed methane potential [34], and several exploration projects have since been launched.

In 2019, the total CBM reserves were estimated to be 12,8 billion m^3 (Ministry of Energy and Mineral Resources). CBM projects explore reservoirs between 300 and 1500 meters, where the coal rank and therefore the gas contents are much higher than in surface mines [35]. Gas contents measurements are highly variable given the wide range of basins and depths explored: between 0.8 and 13 m^3/ton gas content [36, 37, 38]. Indonesian mines mostly have depths of 50-60 meters, and thus shallower than the high-methane gas reservoirs, with 3 exceptions. The Pasir mine and the Parambahan mines mine at 100 and 150 meters respectively, which are shallower than the exploration projects, and the KRU underground mine mines at an estimated depth of 494 meters but is not in an area of an exploration study from which we could apply the results. We thus cannot conclude on any specific emission factor to apply to Indonesian mines.

CBM production is very low in Indonesia, and no project of recovery and use have been put in place in coal mines to mitigating methane emissions [39, 40].

Fig. 22 shows the very high concentration of mines in Indonesia, almost entirely surface mines. If we relate this to Fig. 23 showing yearly emissions by mine, we can see that one mine in particular emits much more than the others: the underground mine on Sumatra. In this inventory, Indonesia is the 6^{th} largest emitter of CMM. This is justified by a high annual production and the large number of mines (3^{rd} country overall in terms of number of mines), counter balancing the fact almost all the mines are open pit and therefore not gassy.

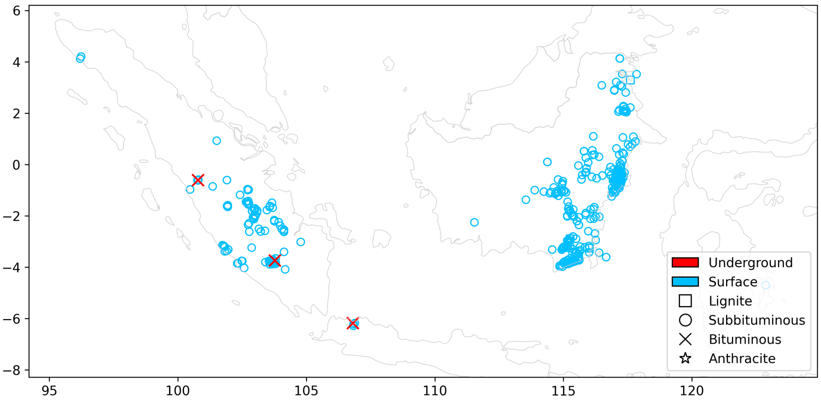


Figure 22: Mine types in Indonesia.

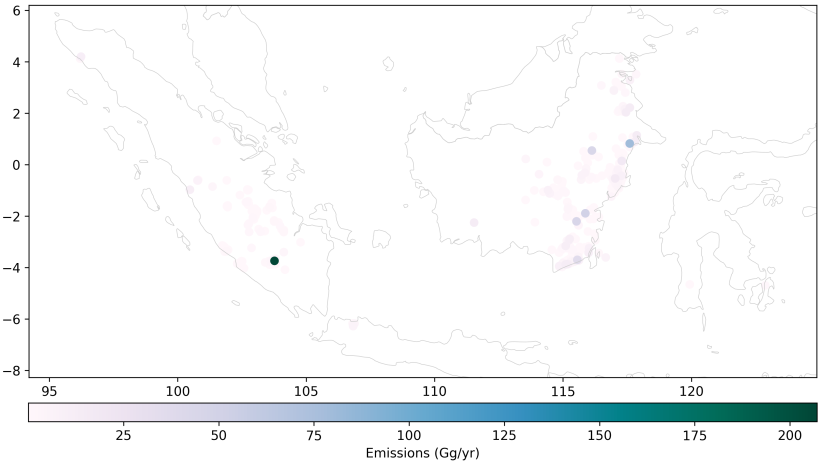


Figure 23: Mine-level yearly CMM emissions in Indonesia.

3.5.4 United States

The United States is the 4^{th} largest producer of coal worldwide with 550 Mt per year, and ranks first in terms of resources (how much coal is actually in the ground) and reserves (how much coal could be expected to be mineable under the current economic and technological conditions).

For the United States, we use the latest EPA inventory, in preprint for now [41]. It spatially allocates on a 0.1° × 0.1° grid the methane emissions by sub-sector for the years 2012 to 2018. We include in our inventory the 2018 emissions, showed in Fig. 25. The EPA comprehensively accounts for fugitive methane emissions from: operating underground mines (mining and post-mining), operating surface mines (mining and post-mining), abandoned mines, and subtract the CMM recovered and used for operating underground mines and abandoned mines. All mine locations are from the Mine Safety and Health Administration (MSHA). The methodology of the EPA inventory is outlined here.

Operating underground coal mines: the annual net state-level emissions (mining, post-mining, and recovered and used) are taken from the Inventory of U.S. Greenhouse Gas Emissions and Sinks (GHGI). They are then gridded and weighted based on

- annual mine-specific relative emissions from the Greenhouse Gas Reporting Program

(GHGRP) - not all facilities report to the GHGRP.

- annual mine-specific coal production from the U.S. Energy Information Administration (EIA).
- basin-level in situ methane coal content in states with multiple basins.

Operating surface coal mines: active surface mines do not report to the GHGRP and therefore annual net GHGI state-level emissions (mining and post-mining) are gridded using mine-specific coal production from the EIA, also weighted by methane content for states with multiple coal basins.

Abandoned coal mines: To estimate mine-specific emissions (net emissions minus CMM recovered and used), they use emission decay curves (GHGI), which are based on the time since mine closure, mine status (venting, sealed, flooded), basin, and the emissions rate when the mine was last active. If the status of a mine is unknown, they compute emissions weighted based on the relative percentages of sealed, flooded, and vented mines within the same basin. For abandoned mines without precise MSHA locations (∼20% or 100 mines), emissions are spread uniformly across the reported county, which explains the wide spreads on Fig. 25. What could be interesting as a future improvement would be to compare the abandoned mines without precise MSHA locations with the GEM database, since 92% of GEM's abandoned mines have an exact locations and GEM validated by hand the locations when they can.

The EPA inventory gives the average flux (in units of molecules of $CH_4/cm^2/s$) for each grid cell, for underground, surface and abandoned mines separately. The flux can be converted by multiplying by the area of each grid cell depending on longitude and latitude, and summing over the year (exact conversion factor given by the EPA). Although we don't have granular information on mine type, coal mined, depth, or emissions per mine, we can still analyze the results for each of the three sub-sectors.

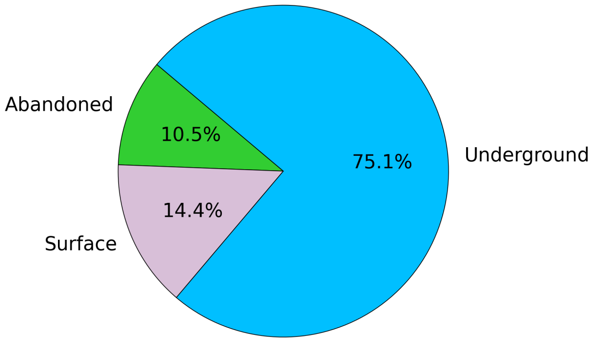


Figure 24: U.S. Coal Mine Methane emissions, by category

The EPA inventory shows that surface and underground coal mine emissions are largely centralized in southwest Appalachia, with some additional emissions from mines in the Midwest and Alabama, as well as abandoned coal mine emissions in parts of Colorado and Utah. Between 2012 and 2018, the bottom-up EPA inventory reports a decrease of 19% of fugitive methane emissions from this sector, explained by decreased coal production and increased methane recovery, most importantly over Appalachia [41].

Using the EPA inventory adds precision to what we could have done to the spatial distribution and the amount of emissions. However, it still removes a certain amount of information from our database: in our inventory for the other countries, we have mine-level information on depth, coal type, mining method, exact geolocalisation... since we are incorporating the gridded inventory. In the general results section, to analyze the distribution of coal types, the number of mines, etc., we use the initial GEM database with operating mines for the U.S. But in the final emissions product, only gridded emissions are included.

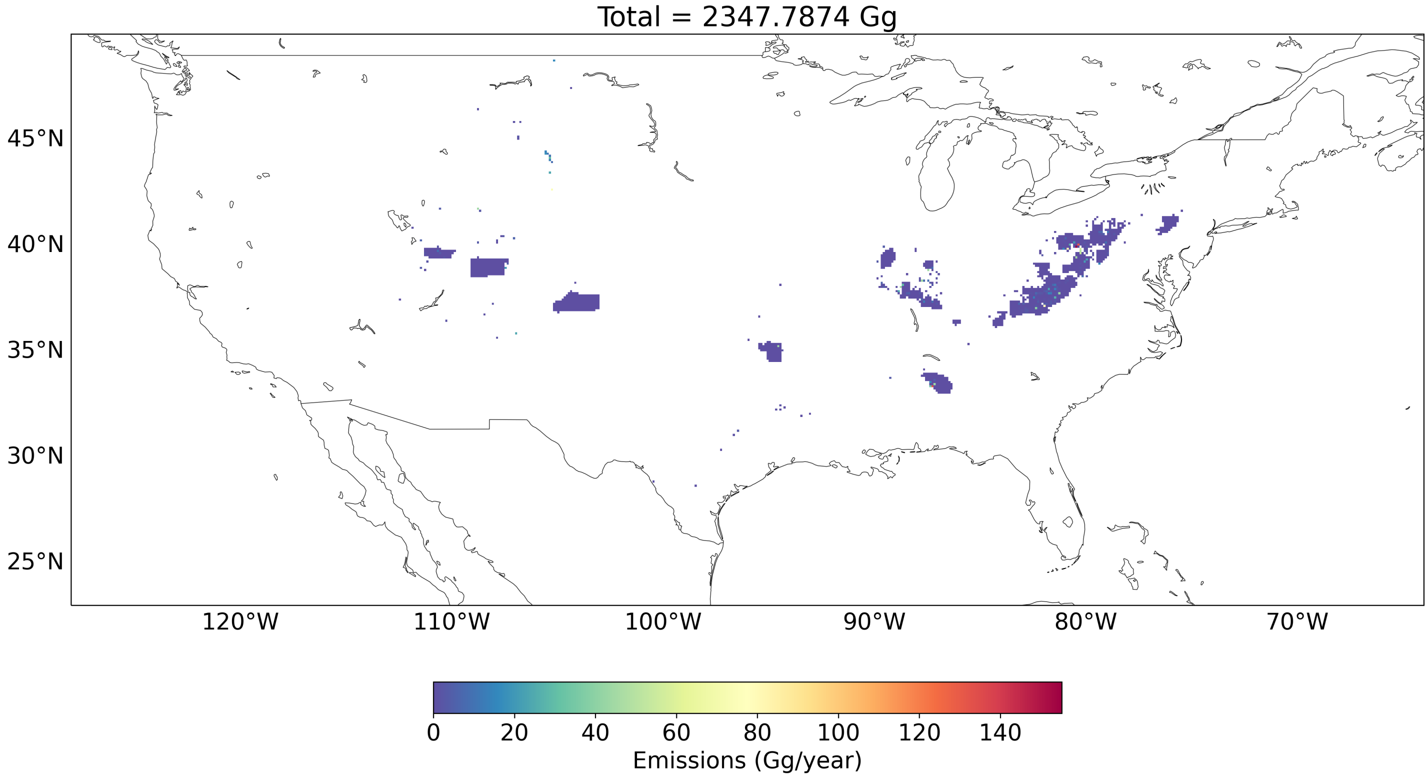


Figure 25: Gridded U.S. Coal Mine Methane emissions inventory, including underground mining, surface mining, abandoned mines, and post-mining emissions.

3.5.5 Australia

Australia is the 5th largest coal producing country, with 524 Mt of raw coal mined per year (GEM, 2023). Most of the coal mines are located in Queensland (North-East) and New South Wales (South-East), with only a few mines in Tasmania, Western Australia and Victoria. Australia has large deposits of both brown and black coals on the east part of the country. The main coal fields are the Northern and Central Bowen basins, and the Southern basin (GMI, 2016).

The GEM Coal Mine Tracker lists 99 coal mines, 35% of which are underground. We have the exact depth for 27 mines total, and 51% of the underground mines. Australia has 78 bituminous coal mines, 20 subbituminous, and only 1 mining lignite. The location is known for 96 mines so we should have a very good spatial distribution of the emissions.

Australia has very precise reporting of its methane emissions, by mine and by company, and has developed the National Greenhouse and Energy Reporting guidelines (NGER) under which mining companies are obliged to report. The inventory of fugitive emissions from coal mining is very accurate compared to other countries, especially for underground mines where uncertainty is estimated at 10.2%, since they measure emissions directly at the mines (Tier 3). Unfortunately, these data are not available at mine level [42], and only emission factors by region are given in the National Inventory Report (NIR) of 2023 (2021 data) [43]. We develop a method based on the information extracted in the NIR.

For surface mines, a distinction is made between brown and black coal mines.

- Brown coal mines (lignite and subbituminous): default emission factor of 0.0162

m^2/ton of coal. The emission factor is based on a gas measurement program conducted in 2013, which consisted of 96 samples taken from six boreholes across three brown coal mining deposits (HRL 2013).

- Black coal mines (bituminous): region-specific emission factors are given for 3 major coal regions, based on a study of methane flux measurements in New South Wales and a database of in-situ measurements from Queensland gas seams:
  - New South Wales EF = 3.2 m^2/ton
  - Bowen EF = 1.65 m^2/ton
  - Tasmania EF = 1.0 m^2/ton

After applying these EFs, 8 bituminous coal mines are not in either of these basins, and we apply the implied EF reported by Australia in the NIR for its surface mines: 0.66 kg/ton = 0.98 m^3/ton, using the methane volume to mass conversion factor of 0.67 kg/m^3. Australia considers there is no post-mining emissions associated with surface mining.

For the underground mines, the gas content profile of six different coal fields are given in the NIR 2023, averages of precise measurements at the facilities. Since they are given in tons of CO_2-eq per ton of coal mined, we need to convert these using the GWP_{100} of methane which is 28, and the methane volume to mass conversion factor of 0.6767 kg/m^3, both of them used in the NIR. The resulting emission factors are presented in Table 5.

Based on the calculated emission factors per region, the gassiest coal field is the Bowen Northern, while the least gassy field is the Western New South Wales (coal seam gas mainly composed of CO_2). The only underground mine that is not in one of these basin is the Blackwood coal mine, in Tasmania. We apply the NIR implied emission factor for underground mining, 8.2 m^3/ton. 100% of the mines (underground and surface) thus have specific emission factors.

Coal field	Gas content (m^3/ton)
Newcastle	8.46
Western	0.79
Southern	12.42
Hunter	7.93
Bowen Central	8.72
Bowen Northern	13.48

Table 5: Emission factors of Australian coal fields

Australia considers the only post-mining emissions occurring are from black coal gassy mines. By looking at the implied national emission factor for post-mining reported in the NIR 2023, and the associated emissions, we can compute how much of the total has post-mining emissions. With a post-mining EF of 0.38 kg/ton and post-mining emissions of 36.54 kt, we conclude that 96.16 Mt of mined coal are considered to generate post-mining emissions. By analyzing which underground, bituminous coal mines are the most gassy, we apply the post-mining emission factor of 0.56 m^3/ton to the mines in the Bowen Northern and in the Southern New South Wales basins. All the other Australian mines are considered not to generate any post-mining emissions.

The Australian NIR 2023 estimates emissions for 128 decommissioned mines, accounting for only 2.14% of total coal mining methane emissions. The implied emission factor is 0.43 m^3/ton of coal mined as a national average. Since we do not have the mine-specific information on flooding status, production at closure, etc... we cannot attribute mine-specific emissions to the (only) 10 closed mines registered in the GEM database. We thus do not account for abandoned coal mines for Australia.

The NIR 2023 reports 372.14 Gg of methane being recovered or flared in 2021, which corresponds to 38.5% of their reported underground emissions [43]. Unfortunately the data at our disposal is not good enough to distribute the recovery of CMM to the right mines. Indeed, the EPA lists 16 CMM recovery and use projects in Australia, including one at an abandoned mine. A few projects are flaring methane at the mines, others are generating power, and only one is treating the recovered CMM and injecting the gas in pipelines. The annual methane emissions reduction is available for only 6 of them, but we cannot apply those as the emissions reduction are reported higher than the emissions themselves and seems to be outdated. There is a big margin for improvement in accounting for the CMM recovery and use in Australia.

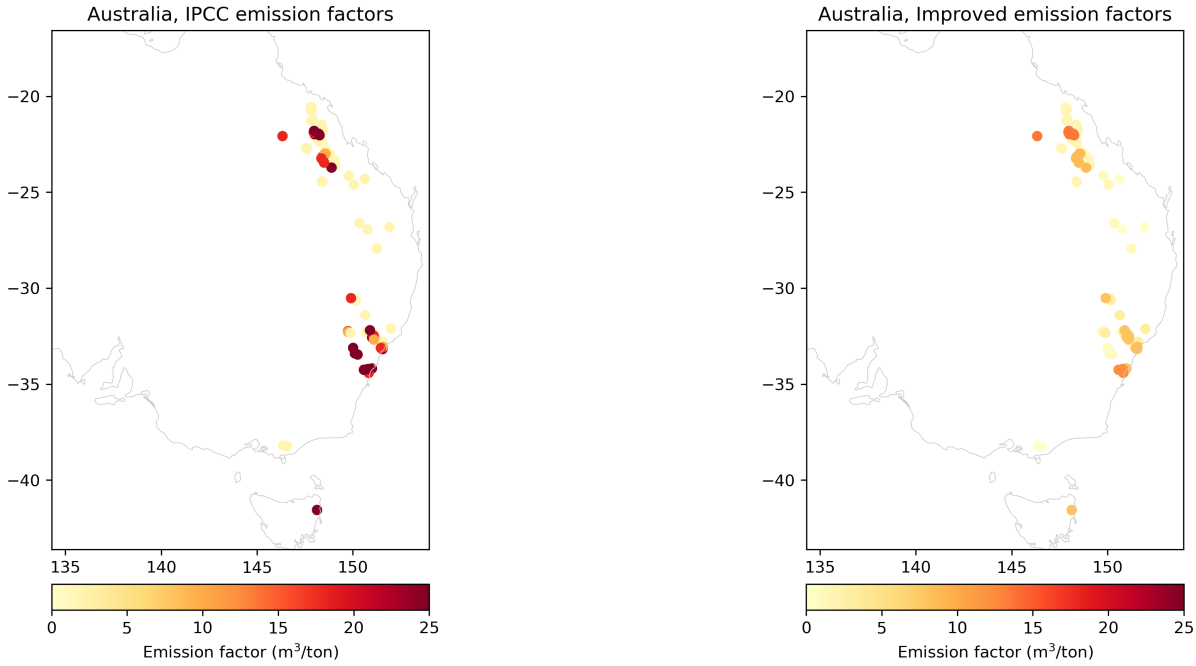


Figure 26: Emission factors for all mines in Australia. Left: emission factors advised by the IPCC guidelines. Right: improved emission factors obtained with the methodology described above.

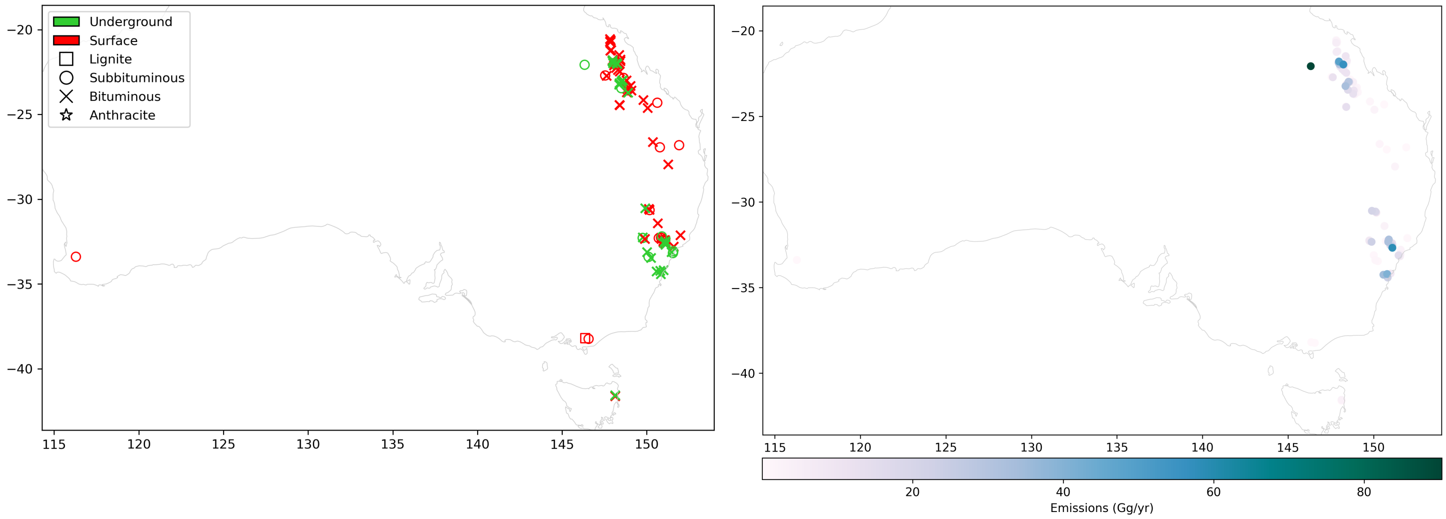


Figure 27: Left: Mine types in Australia. Right: Mine-level yearly CMM emissions in Australia.

Fig. 26 shows the change in emission factors when applying the methodology above. Underground mines are definitely less gassy than the IPCC would suggest. Fig. 27 shows that mines (and emissions) are concentrated on the west coast of the country, with one specific underground mine in the north emitting much more than the others and could be targeted for methane recovery.

3.5.6 Russia

Russia is the 6th largest coal producing country, with 432 Mt produced per year, and ranks second in terms of proved reserves (GEM, 2023). Russia is estimated to have significant coal-bed methane (CBM) resources: more than 13 trillion m^3 of CBM could be accessible at 1800–2000 meters deep in the Kuzbass basin (Gazprom, 2014). In addition to the Kuzbass basin, which hosts some extremely gassy mines, other significant coal production hubs include the Donbass basin, the Pechora basin, and the southern areas of Siberia.

The GEM database lists 149 operating mines, of which 31% are underground. Unfortunately, the database has 96% of approximate depths, based on national averages. On the other hand, spatial accuracy is very good, since we know the exact location of 93% of the mines. Coal mined in Russia is 16% lignite, 20% subbituminous, 58% bituminous and 6% anthracite.

Unfortunately, much of the data on methane content or methane emissions from coal mines in Russia dates back a very long time, giving data on mines that are no longer operational, or averages over entire basins that are almost equal to our baseline results.

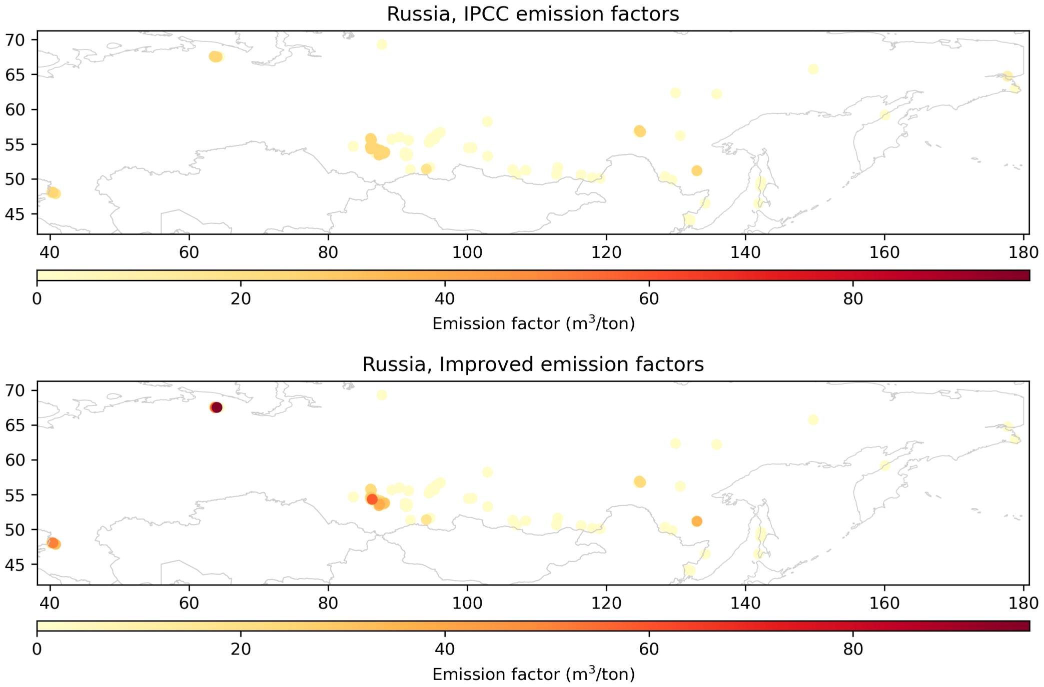
A study from 1996 gives precise averages for 2 basins in Russia (Donbass and Kuzbass) [44]: reserves, methane content, number of mines, volume drained... The average specific emissions given are 22,5 for Donbass mines and 21,0 for Kuzbass mines. Since methane content varies greatly from one mine to another, and our average emission factors using log-rank model is very close to those values, we want to find better results rather than applying an average which, although derived from precise measurements, masks the disparity in methane content. An EPA study, also from 1996, gives also precise information on many mines reported by coal associations [45]. But the majority of them do not exist anymore, and the ones who do have more recent (and sometimes very different) results in the IEA study we decided to apply in the end. Much more recently, in 2021, the Institute of Comprehensive Exploitation of Mineral Resources presented an update on coal mine methane in Russia [46]. For around twenty mines, methane extraction coefficients and total methane resources are given, but are not applicable to our data as they cannot be linked to production to extract emission factors. The most recent National Inventory Report (NIR) from Russia from 2021 only states the country's total fugitive methane emissions so it cannot be used either [47].

A study from the IEA in 2009 [48], based on 2003 data, directly gives the volume of CH_4 emitted per tonne of coal mined, in the Kuzbass and Pechora basins. The data is 20 years old, but mining depths and methods did not change too much over the years in Russia: according to a Government report from 2014, and a study by Minenergo in 2015 [11], the average mining depth of underground mines increases of only 25 meters in 5 years. We can therefore apply with greater confidence the emission factors given by this IEA study. It enables to include the clear distinction between mines with very low methane content, such as the Gramoteinskaya mine (specific emission factor of 3.1 m^3/ton), and mines classified as "Hazardous with risk of sudden outbursts", such as the Chertinskaya mine (specific emission factor of 58.6 m^3/ton), both located in the Kuzbass basin.

Out of the 46 russian underground mines, 18 now have improved emission factors after applying the IEA paper. This could definitely be improved with more measurements and data, but it is a good start.

Methane drainage started as soon as 1951 in the Kuzbass basin, but it was mainly for safety reasons and the vast majority was not used. In 2000 in the Kuzbass basin, not a single project reused drained CMM [49]. In 2006, 252 Mm^3 per year of methane were drained in Russian mines in the Kuznetskiy and Pechorskiy basins, and nearly all of this methane was vented into the atmosphere except 40 Mm^3 used locally in boilers at Vorkuta mines in the Pechorskiy basin [48]. Since 2004, 10 projects have been implemented, 5 of which are no longer operational. The 5 recovery and use projects prevent the emission of 51455 Mt of methane per year, and are included in our database [40].

With Russia having such big CMM emissions, a necessary improvement of the inventory would be to improve mine depths data, and mine-specific methane content measurements, which are pretty poor for now.


Russia, IPCC emission factors

Russia, Improved emission factors

Figure 28: Emission factors for all mines in Russia. Left: emission factors advised by the IPCC guidelines. Right: improved emission factors obtained with the methodology described above.

Only 39% of the mines have a specific emission factors, but looking at Fig. 28 showing how the EFs change when applying them, we can see that mines in Russia are generally more gassy. One specific mine in the north has an emission factor much higher than what both the IPCC and our log-rank model would suggest. Indeed the Vorkutinskaya coal mine is an underground bituminous mine and would thus have an EF of 23 or 25 m^3/ton, but according to measurements its EF is 97.3 m^3/ton. The anthracite mines at the far west of the country have a lower EF, which would be different if using our log-rank model as well. It shows that while the model tries to generalize the methane emissions release of coal mining, in some basins the emissions do not follow at all the theory on methane content, and for more precision, only precise measurements are valuable. As presented in Fig. 29, the majority of the Russian mines are surface mines. Fig. 30 shows the high mine-level emissions entirely come from underground gassy mines.

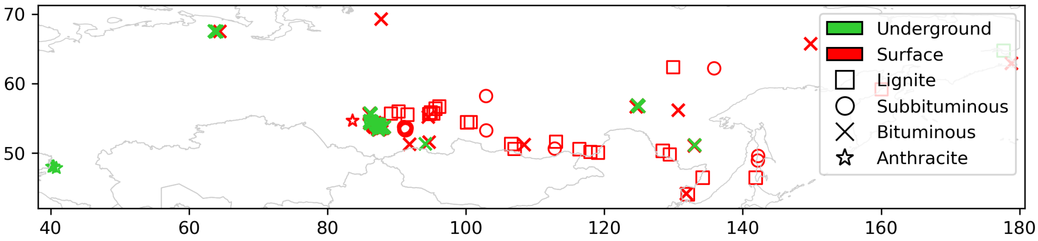


Figure 29: Mine types in Russia.

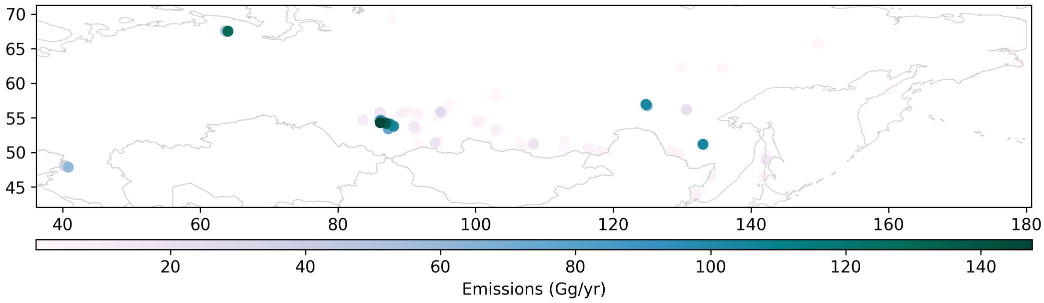


Figure 30: Mine-level yearly CMM emissions in Russia.

3.5.7 South Africa

South Africa is the 7^{th} largest producer of coal with 271 Mt produced per year (GEM, 2023), and a major exporter. 70% of South Africa's recoverable coal reserves lie in the Highveld, Waterberg, and Witbank fields, in the Mpumalanga region, in the north east part of the country.

South Africa has not submitted a national inventory submission to the UNFCCC recently. A list of operational mines and their annual production is available on the Department of Minerals and Energy website, but no recent information on mine-specific methane content has been found. There is a lack of research into the methane content of coal in South Africa, and few CMM recovery and use feasibility studies have been carried out. However, we know that the percentage of operating mines considered gassy is very low. It is estimated that in the shallower fields, methane loss could have approached 80% of initial gas content in the coalification process (UNFCCC, 2000) [50].

The IPCC emission factor database shows an emission factor of 0.77 m^3/ton for bituminous and anthracite coal from operating underground mines of depths between 60 and 140 meters [51]. These numbers are based on 243 high-precision measurements of the methane content of the return air from 27 different production shafts, in 2002-2003. These emission factors are well below IPCC standard Tier 1 emission factor, which is 10 m^3/ton for underground mining shallower than 200 meters deep. A study from 2005, on which the IPCC emission factor is partly based, showed that the average methane release of coal from 6 different underground mines in these depths (3 were abandoned since) was 20% (±15%) of the expected release, indicating severe under-pressurization of the coal [52].

Since the IPCC data to compute the emission factor was based on less than 1% tonnage of anthracite coal, we will apply this EF only to bituminous underground coal mines, that are between 60 and 140 meters deep. When looking at the GEM database, 20 mines correspond, with an average baseline emission factor of 7,26 m^3/ton using the log-rank model, which thus makes a huge difference in the resulting emissions applying the new EF.

South Africa has no active CMM recovery and use projects, but some South African mines have been known to drain methane prior to mining through surface holes (UNFCCC, 2000).

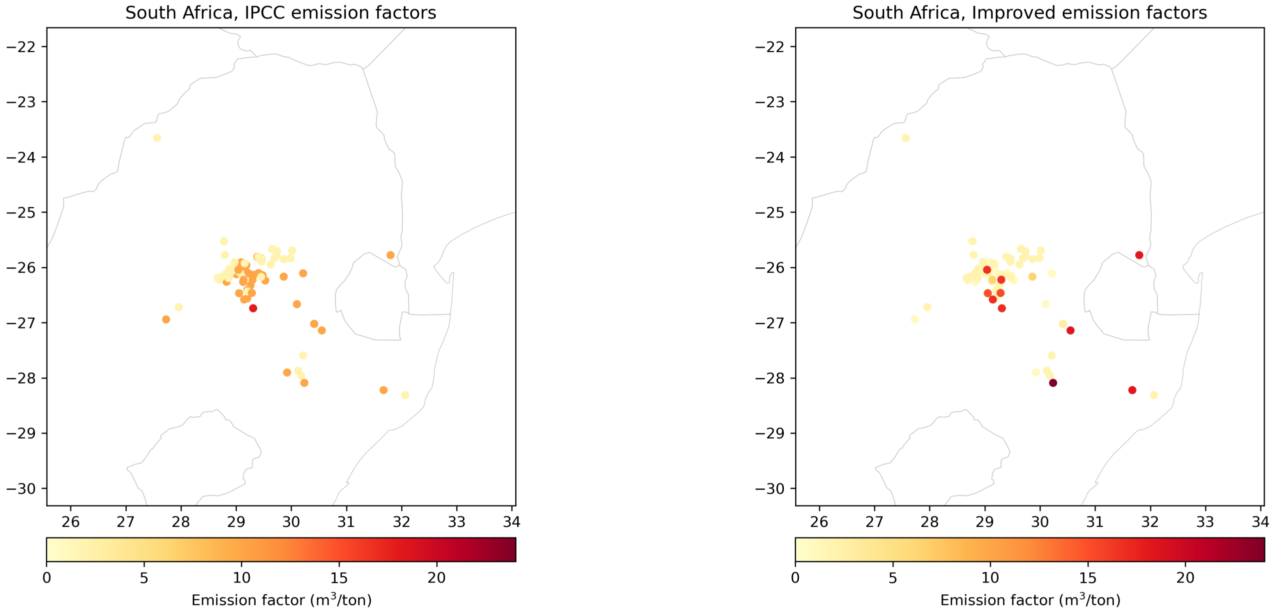


Figure 31: Emission factors for all mines in South Africa. Left: emission factors advised by the IPCC guidelines. Right: improved emission factors obtained with the methodology described above.

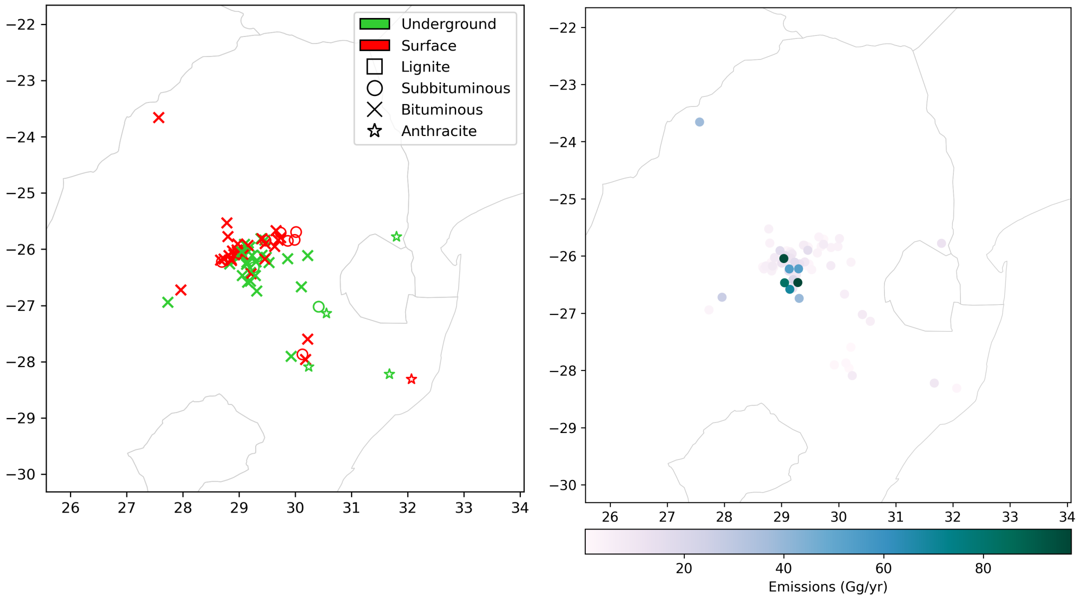


Figure 32: Left: Mine types in South Africa. Right: Mine-level yearly CMM emissions in South Africa.

Fig 31 shows how emission factors per mine change when applying the above methodology. 39% of the mines have a lower emission factor, and for the rest, the log-rank model is applied. Relating this to Fig. 32, we see that for the few anthracite underground mines, the emission factor is thus much higher than what the IPCC suggests. Since South African mines are shallow with a maximum depth of 200 meters according to the GEM database, the emission factors are capped at about 25 m^3/ton. Fig. 32 shows the mine-level emissions and we can see the anthracite gassy mines are not the ones producing and emitting the most, but they are the bituminous mines in the center of the mine agglomeration in the Mpumalanga state.

3.5.8 Germany

Germany is the 8^{th} largest producer of coal with 161 Mt per year (GEM, 2023). Coal is very important in the history of Germany's developement: in 1900, Germany was a chief producer of coal, after the US and the UK. Germany also accounts for about 5% of the global proved coal reserves (EIA, 2014), despite its small relative area.

For many different reasons, Germany gradually closed almost all its mines: coal had to be mined very deep, which was less and less profitable, and later on to meet Paris agreement targets. Only 10 surface lignite mines remain according to the GEM database. However, German mines have an enormous production output: two of the nation's mines, the Garzweiler and Bergheim coal mines, rank as the third and fourth largest globally in terms of output, with 38 and 40 million tons per year respectively. With only 0.37% of mines, Germany produces 2.2% of the world's coal. But Germany's operating mines emit only 0.35% of the world's coal mine methane, since surface mines emit less methane and lignite coal is the coal with the lowest carbon content.

As few measurements are taken in surface mines, since recovery and use projects focus on underground mines, no more precise emission factor per mine could be found for Germany. What would be interesting would be to quantify emissions from abandoned mines, since more than 100 mines closed in the last 50 years, many of which were very deep black coal mines. About 50 projects of CMM recovery and use are operating in Germany, all of them on abandoned mines [40] and are thus not taken into account in this version of the inventory.

Fig. 33 shows mines in Germany are now only surface underground mines, and Fig 34 shows that emissions are overall low except for the two high-producing mines in the west.

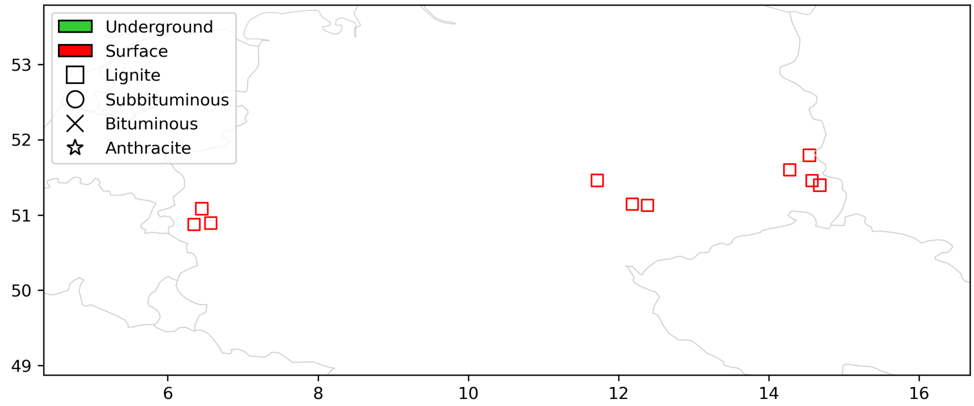


Figure 33: Mine types in Germany.

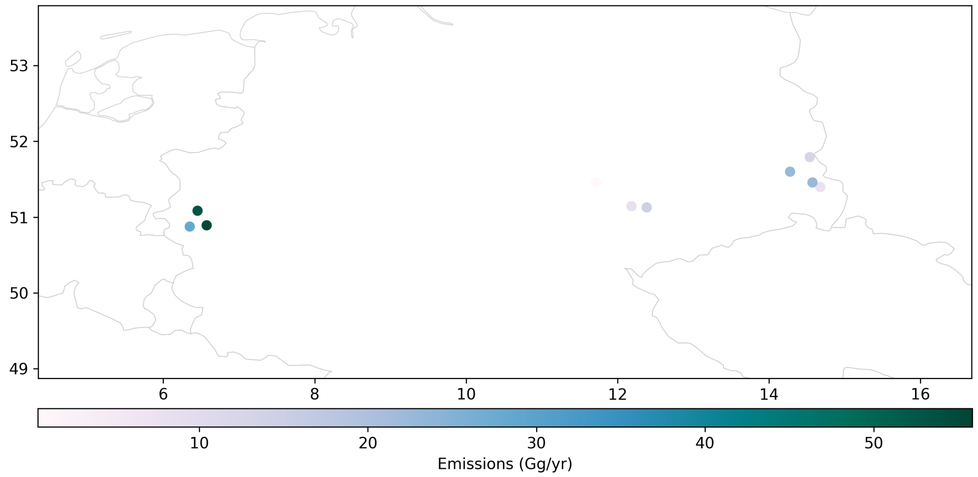


Figure 34: Mine-level yearly CMM emissions in Germany.

3.5.9 Poland

Poland is the 9th largest coal producer, with 109 Mt produced per year (GEM, 2023). Poland's hard coal reserves are located in the Upper Silesian, Lower Silesian basins, and the Lublin basin. The Lower Silesian is not exploited anymore and the Lublin basin only counts one coal mine. Lignite basins are located in the central and western parts of the country. GEM lists 26 coal mines, 6 surface mines and 14 underground mines, with exact location for 24 of them. Production is composed of 53% lignite, 42% bituminous, and 13% sub-bituminous coal.

Poland has many well developed CMM Utilization and Recovery projects, with different end uses: thermal, electricity, and industrial [40]. Methane was already drained and used or sold in some Polish mines in 1997 [53]. The GIG (Gówny Instytut Górnictwa, Central Mining Institute) gives data on coal production, methane emissions, drainage and utilization for 12 hard coal underground mines in the Upper Silesian basin in 2020 [14]. We can also extract the exact depth of the deepest Polish mine (Budryk mine) as of 2017: 1290 meters, which was in GEM previously estimated at 705 meters. Each mine's emission factor before CMM recovery, and its percentage of recovery can then be computed. The results are presented in Table 6, showing precise emission factors for 12 out of the 20 underground polish mines. The percentage of recovery is applied to our activity data.

Based on UNFCCC data from 2013, post-mining emissions for underground mining seemed to increase slightly between 2000 and 2010, from 7% to 7.8% of underground CMM emissions [53]. We choose to apply a post-mining EF of 8.5% of the emissions, knowing post-mining emissions can increase with depth over time with the coal rank. The post-mining EFs vary between 0.5 and 4.6 m^3/ton, instead of the average IPCC of 2.5 m^3/ton. The difference in applying these specific post-mining EFs is –16 Gg of post-mining emissions per year for Poland underground mines, i.e. 17% decrease.

Fig. 35 shows mines are gassier than suggested by the IPCC in Poland, with EFs going up to 55 m^3/ton. Fig. 36 shows the distribution of mine type and the concentration of mines in the Silesian region of Poland, as well as the mine-level emissions of CMM.

Coal Mine	Production (tons)	CH_4 emissions before recovery (Gg)	CH_4 utilized (Gg)	Mine emission factor (m^3/ton)	CH_4 recovered (%)
Ruda	3 721 310	21.72	1.59	8.71	7.32
Row	6 217 280	63.19	9.37	15.17	14.83
Sosnica	1 746 720	34.43	1.95	29.42	5.66
Myslowice-Wesola	2 049 200	60.19	9.36	43.84	15.55
Murcki-Staszic	1 965 270	25.88	7.1	19.65	27.43
Borynia-Zofiówka	3 824 714	36.54	10	14.26	27.37
Bzie-Debina	663 774	7.24	-	16.28	-
Pniówek	3 378 924	66.87	21.9	29.54	32.75
Budryk	2 302 300	47.99	16.36	31.11	34.09
Knurów-Szczyglowice	4 215 252	83.54	9.39	29.58	11.24
Brzeszcze	1 463 451	53.91	26.75	54.98	49.62
Silesia	1 786 521	19.82	2.46	16.56	12.41
Other	9 516 709	24.38	7.76	3.82	31.83

Table 6: Methane emissions, recovery efficiency, emission factors from Polish coal mines in 2020 (computed from GIG data) [14]

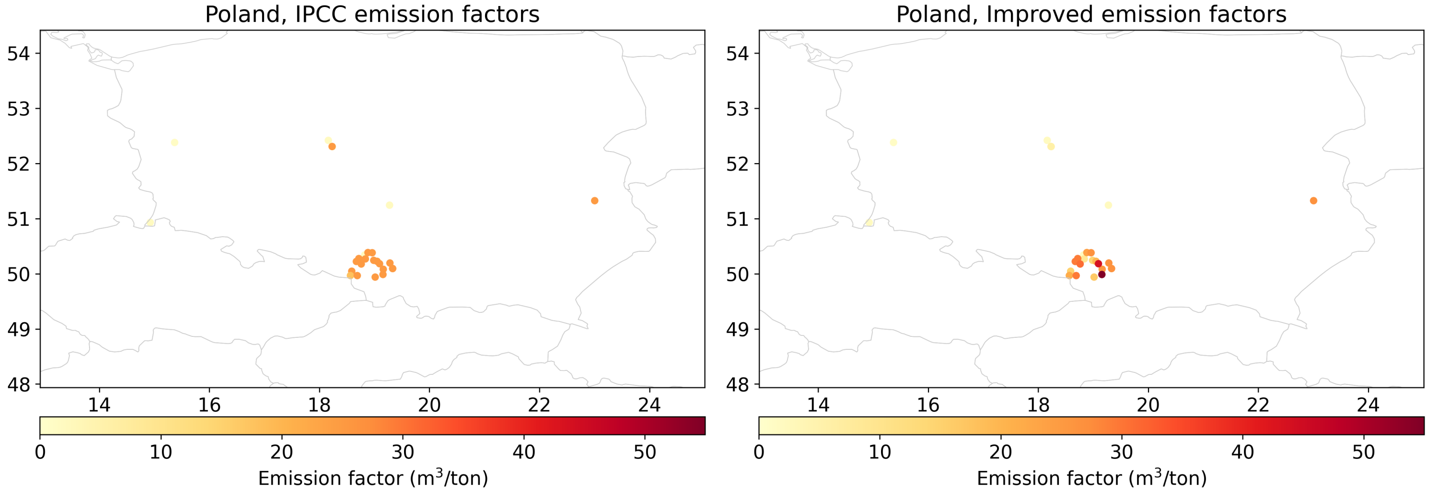


Figure 35: Emission factors for all mines in Poland. Left: emission factors advised by the IPCC guidelines. Right: improved emission factors obtained with the methodology described above.

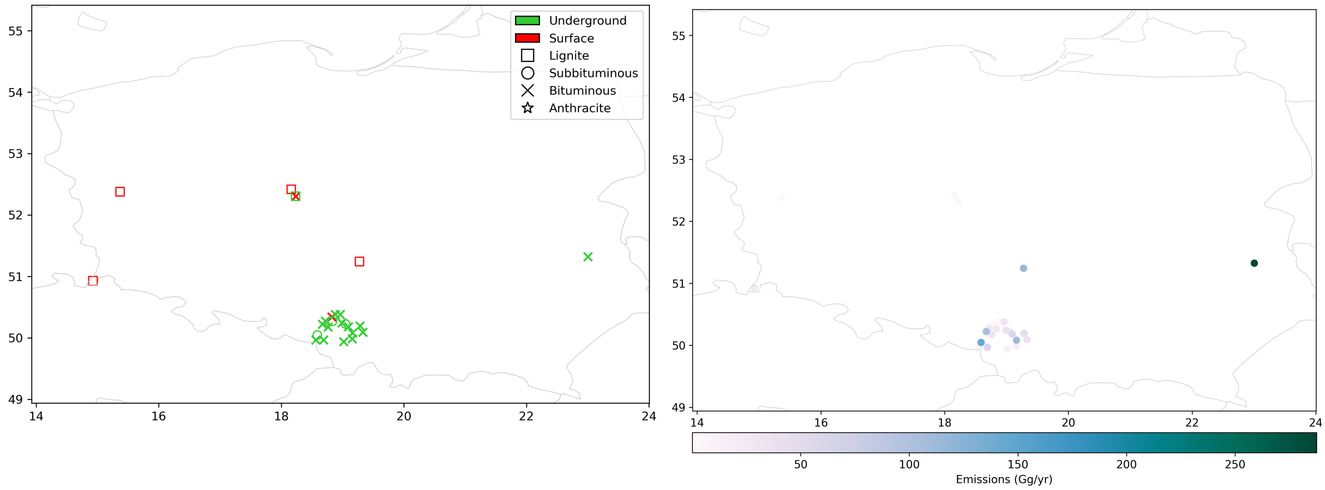


Figure 36: Left: Mine types in Poland. Right: Mine-level yearly CMM emissions in Poland

3.5.10 Kazakhstan

Kazakhstan is the 10^{th} largest coal producer in the world, with about 107 Mt per year (GEM, 2023), and is the 9th country with the most proven coal reserves with 2.5% of world reserves (BP, 2018). Kazakhstan's coal reserves are 64% bituminous coal, and 36% lignite, and are mainly located in the Ekibastuz, the Karaganda, the Shubarkol, and the Turgai coal basins (World Energy Council, 2011). The Ekibastuz basin produces 90% of the country's coal from opencast mines, while the Karaganda basin mostly has underground mines that are among the gassiest in the world [54].

The GEM database contains 20 coal mines: 12 are mining bituminous, subbituminous and lignite coal in surface, and the other 8 are underground, mining bituminous coal. The exact location is known for 18 of the Kazakh mines. A feasibility study for CMM recovery funded by the U.S. EPA measured the exact depths of 6 underground mines.

Kazakhstan's coal sector emits more methane per ton of produced coal than any other large-scale coal-producing country, which has the sole advantage that there have been flow rate and concentration measurements in several gassy mines. A document prepared by the Kazakh Research Institute of Ecology and Climate (KazNIIEK), responsible for preparing the annual GHG emissions inventory, reports the methodological guidelines on calculation of GHG emissions for coal mining in the country. Mine-specific emission factors are given for all underground mines, and 4 of the surface mines [55, 56]. The Kostenko coal mine EF was found on Mining Wiki [57]. The EFs for surface mining range from 7.8 m^3 to 10.5 m^3 of methane per ton extracted, much higher than the IPCC standards (maximum 2 m^3/ton). The underground mines are extremely gassy with EFs up to 54 m^3 of CH_4 per ton mined.

Entering the mines-specific emission factors increases Kazakhstan's methane emissions of 212% compared to the log-rank model, totaling 630 Gg per year.

Kazakhstan only has one operational CMM recovery and utilization project, on the Lenina underground mine [40], which captures only 2% of the country's underground mining methane emissions [54].

Figures 37 and 38 present the results of applying the specific emission factors or the log-rank model, to 60% of the Kazakh mines. The 40% are the surface mines for which we keep the IPCC-advised EF. The maps show the upper right quadrant of the country. Measured emission factors or methane content are quite high in Kazakhstan, similar to the trend we observe in Russia or even Poland. The most emitting mine is a surface bituminous mine, and thus not the one which has the highest EF. It has a high EF for a surface mine (10.5 m^3/ton, compared to maximum 2 for the IPCC), and produces 33 Mt per year. It is the 12^{th} most producing mine in the world according to the GEM database, and the 13^{th} most methane emitting mine when coupled to the methane content measurements, even though it is a surface mine.

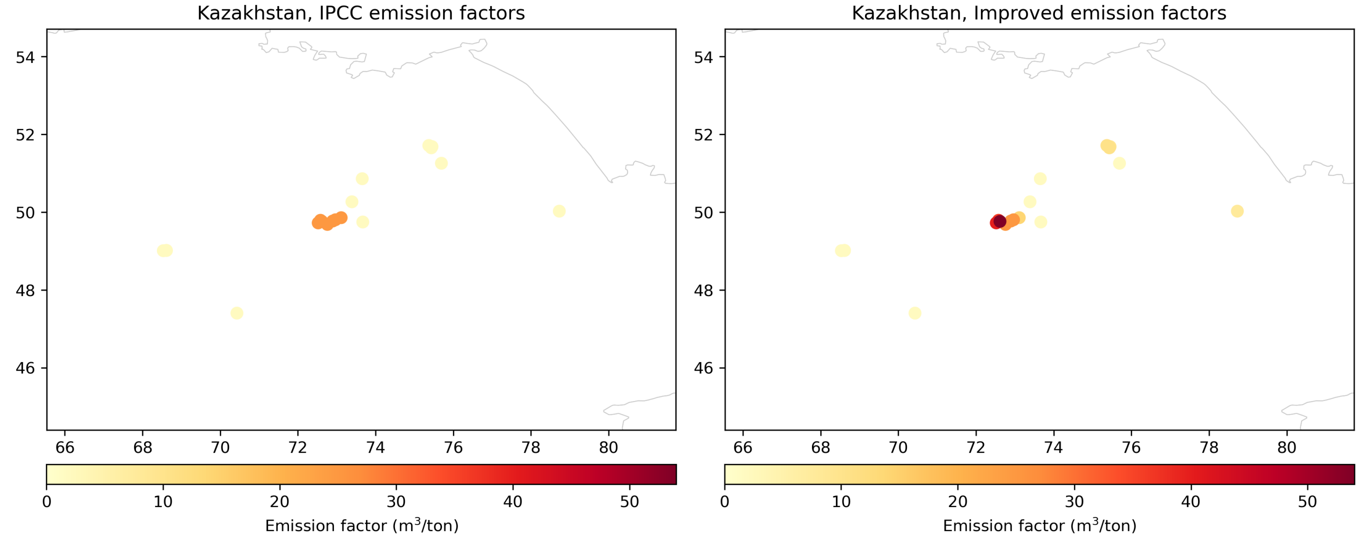


Figure 37: Emission factors for all mines in Kazakhstan. Left: emission factors advised by the IPCC guidelines. Right: improved emission factors obtained with the methodology described above.

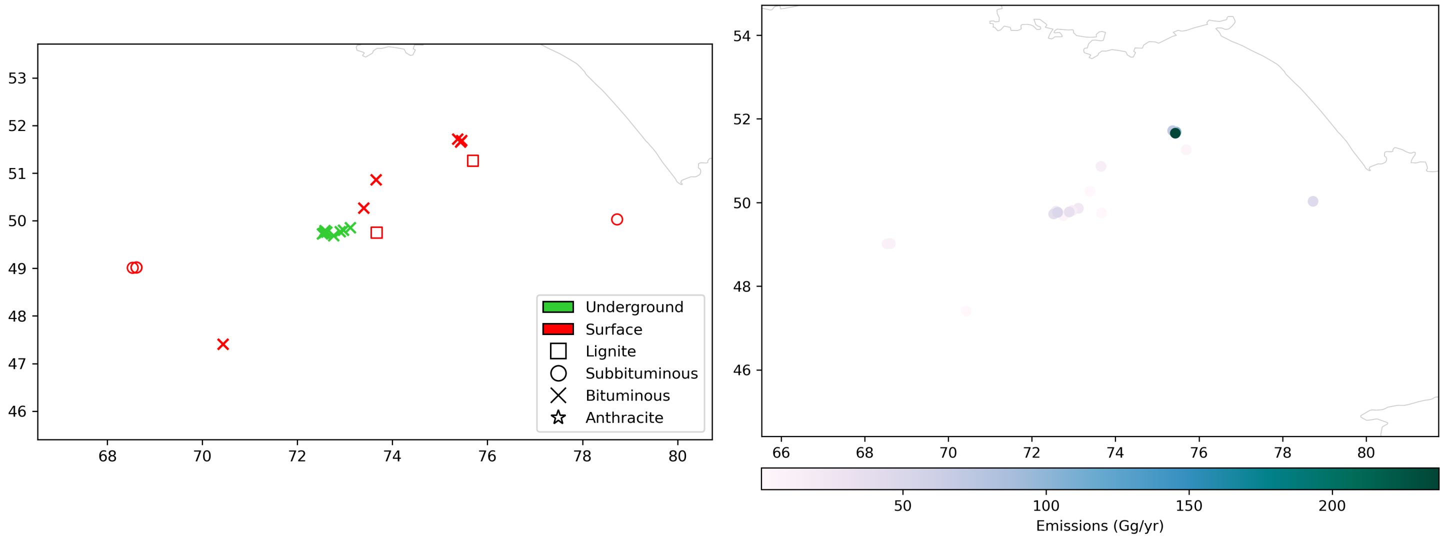


Figure 38: Left: Mine types in Kazakhstan. Right: Mine-level yearly CMM emissions in Kazakhstan

3.5.11 Turkey

Turkey is the 11th country in terms of coal production and reserves. Both are mostly lignite coal (93% of the reserves), the rest being bituminous. Out of the 35 mines, specific emission factors were found only for the Kozlu and Kiaradon coal mines, resulting from a U.S. EPA CMM Utilization feasibility study. EFs are slightly below the log-rank model ones, but do not change significantly the country's coal related emissions. Turkey does not have any active CMM recovery and utilization project [40].

We can see on Fig. 39 that when applying the specific emission factors for those two mines and most importantly when applying our log IPCC model giving emission factors as a function of coal type and depth of mines, the emission factors in Turkey drop. The

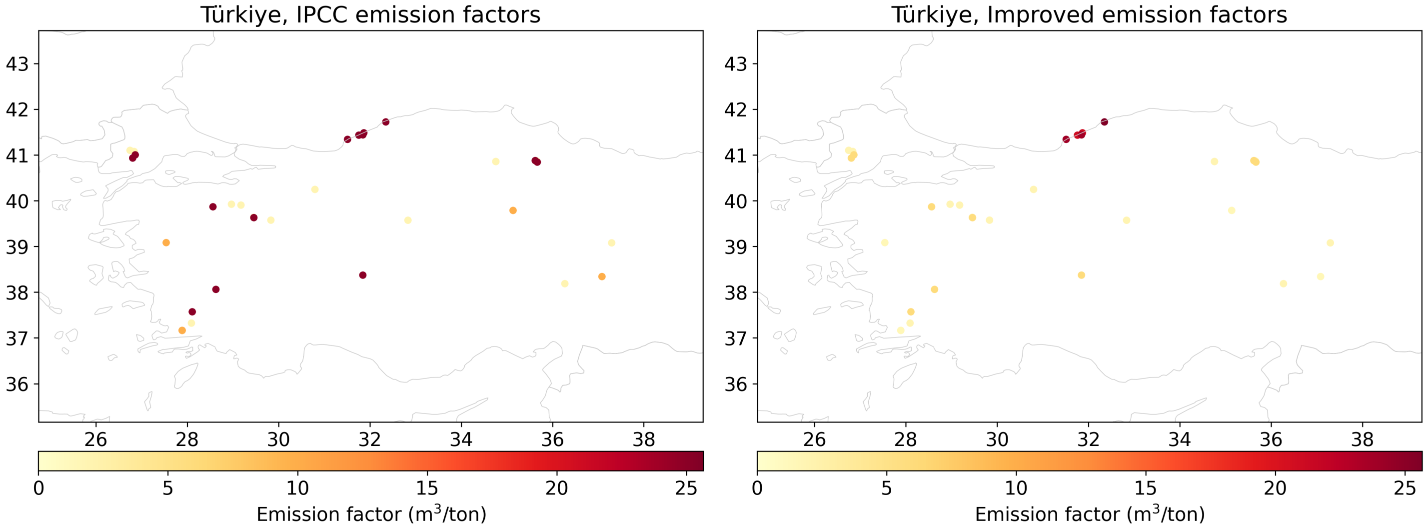


Figure 39: Emission factors for all mines in Turkey. Left: emission factors advised by the IPCC guidelines. Right: improved emission factors obtained with the methodology described above.

reason is, as we can see on Fig. 40, mines in Turkey are mostly lignite, with a low methane content. The mine-level emissions are low compared to other countries and Turkey, while being the 11th biggest coal producer, is only 14th in terms of CMM emissions, surpassed by Vietnam and North Korea in our inventory.

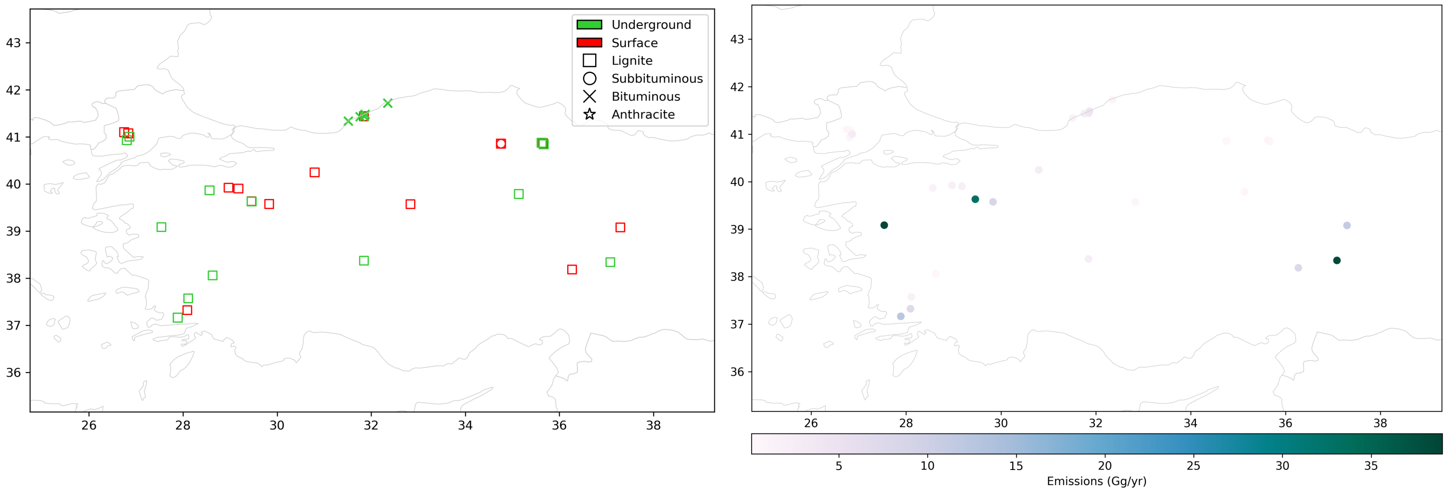


Figure 40: Left: Mine types in Turkey. Right: Mine-level yearly CMM emissions in Turkey.

3.5.12 Ukraine

Ukraine is far on the list, being the 21st most producing country, with 20 Mt per year (GEM, 2023). But since Ukraine has very gassy mines and was once a big producer, with 164.9 Mt in 1990, it is interesting to dig a little and try to improve the total emissions estimation.

Many mines in Ukraine, mostly in the Donbass region, were seized by pro-Russian rebels in 2014 and have endured electricity shortages and flooding ever since (Institute for War and Peace Reporting). Since the current output of these mines is no longer transparent and are likely not operational, they have been removed from the inventory. About 20 other mines have been mothballed since the beginning of the war in Ukraine. We now have 13 registered mines in the GEM database for Ukraine. All underground mines, and mining either bituminous or anthracite coal. The location is known for each mine but the depth is an estimate for 10 of them.

The emission factors in our log-rank emissions model range from 18 to 49 m^3/ton. In the Donets basin, the methane content is mostly around 14.7 m^3/ton, but some seams can contain more than 100 m^3/ton of coal [58]. We do not have the mine-specific methane content, but in the National Inventory Report of 2023, Ukraine reports 438.49 Gg of emissions for its underground mines, based on measurements of the actual flow rate of methane in outgoing air flows of gas mines and the production rate of methane captured by pump on the surface [59]. We choose to scale our emissions to the NIR total, since they use Tier 3 method to measure theirs. We scale our log-rank computed emissions since they take into account coal rank, and compute the implied emission factors. By doing so, the emission factors now range from 24 to 67 m^3/ton.

The NIR also gives abandoned mines emissions (4.21 Gg in 2021), but we cannot include those in our inventories because it seems many closed mines are missing from GEM, and we do not have the status (flooded or not) of the 20 mines we do have.

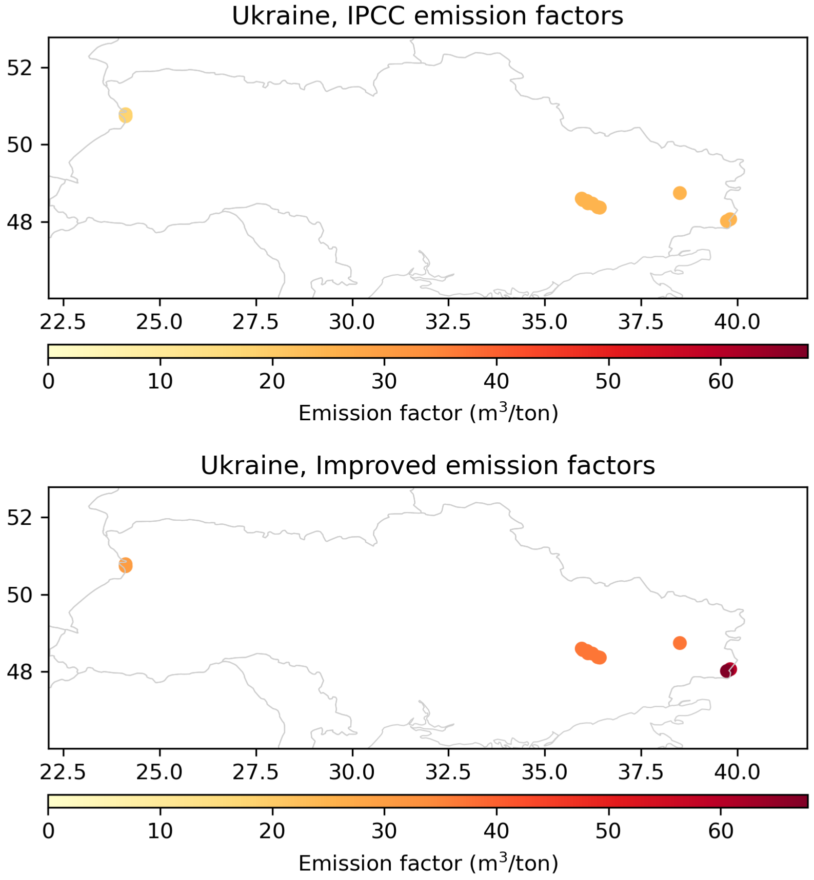


Figure 41: Emission factors for all mines in Ukraine. Left: emission factors advised by the IPCC guidelines. Right: improved emission factors obtained with the methodology described above.

Fig. 41 shows the results of applying our methodology to all Ukrainian mines. Emission factors in Ukraine are much higher than the IPCC suggests, goig as high as 67 m^3/ton. Fig. 42 highlights the facts that there are only high rank coal underground mines in Ukraine, and Fig. 43 shows their emissions, higher for the anthracite mines as expected but all relatively low, explained by their low production compared to other countries. The current context of war in the country calls into question which mines are really emitting, and which have been abandoned and flooded. A reassessment of this work will be necessary once the geopolitical situation returns to normal.

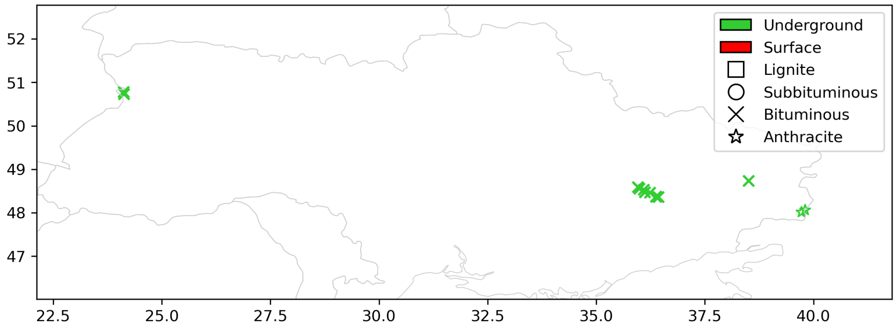


Figure 42: Mine types in Ukraine.

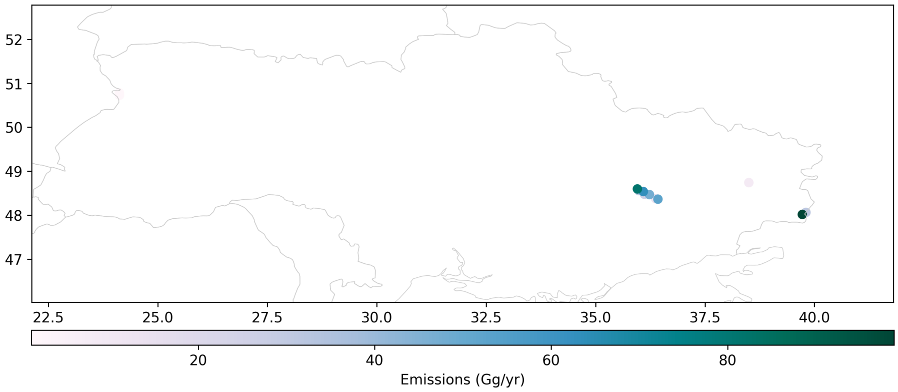


Figure 43: Mine-level yearly CMM emissions in Ukraine

3.5.13 Methodology conclusion

Here is a summary of the steps involved in building this inventory:

- getting a coal mine database and the activity data on coal production
- apply to all mines their emission factors, given by our log-rank model based on absorption theory, the IPCC emission factors, and the mine-specific information on depth and coal rank
- apply more precise emission factors (basin-specific or mine-specific) based on experimental measurements, when available

Table 7 summarizes for each of the countries studied in greater depth the source of specific emission factors (sometimes non-exhaustive but the main ones), the percentage of mines in the country now having a specific emission factor, and the level of reporting equivalent to the IPCC Tiers. Tier 1 is when the standard IPCC emission factors are used for part of the surface mines of the country. Tier 2 is when our log-rank model is used, or if the specific emission factors are averages over regions. Tier 3 is when we have mine-specific measurements of emission factors.

Country	**Source for emission factors**	**Tier level**	**Mines with a specific EF (%)**
China	Ju et al. (2016) Sheng et al. (2019)	Tier 2 / Tier 3	100 %
India	Government measurements Singh et al. (2022)	Tier 2 / Tier 3	100 %
United States	EPA gridded inventory (2023)	Tier 2 / Tier 3	-
Australia	National Report (NIR) to the UNFCCC (2023)	Tier 2	100 %
Russia	IEA (2009)	Tier 1 / Tier 3	39 %
South Africa	IPCC EF database Lloyd et al. (2005)	Tier 1 / Tier 2	39 %
Poland	Polish Central Mining Institute (2020)	Tier 1 / Tier 3	46 %
Kazakhstan	Kazakh Research Institute of Ecology and Climate (2010)	Tier 1 / Tier 3	60 %
Turkey	U.S. EPA feasibility study (2015)	Tier 1 / Tier 3	6 %
Ukraine	National Report (NIR) to the UNFCCC (2023)	Tier 2 / Tier 3	100 %
Indonesia, Germany	Only surface mines, no reliable data	-	0 %

Table 7: Summary of the methodology to find and apply specific emission factors to our mine database, for each of the high-producing countries considered

3.6 General results

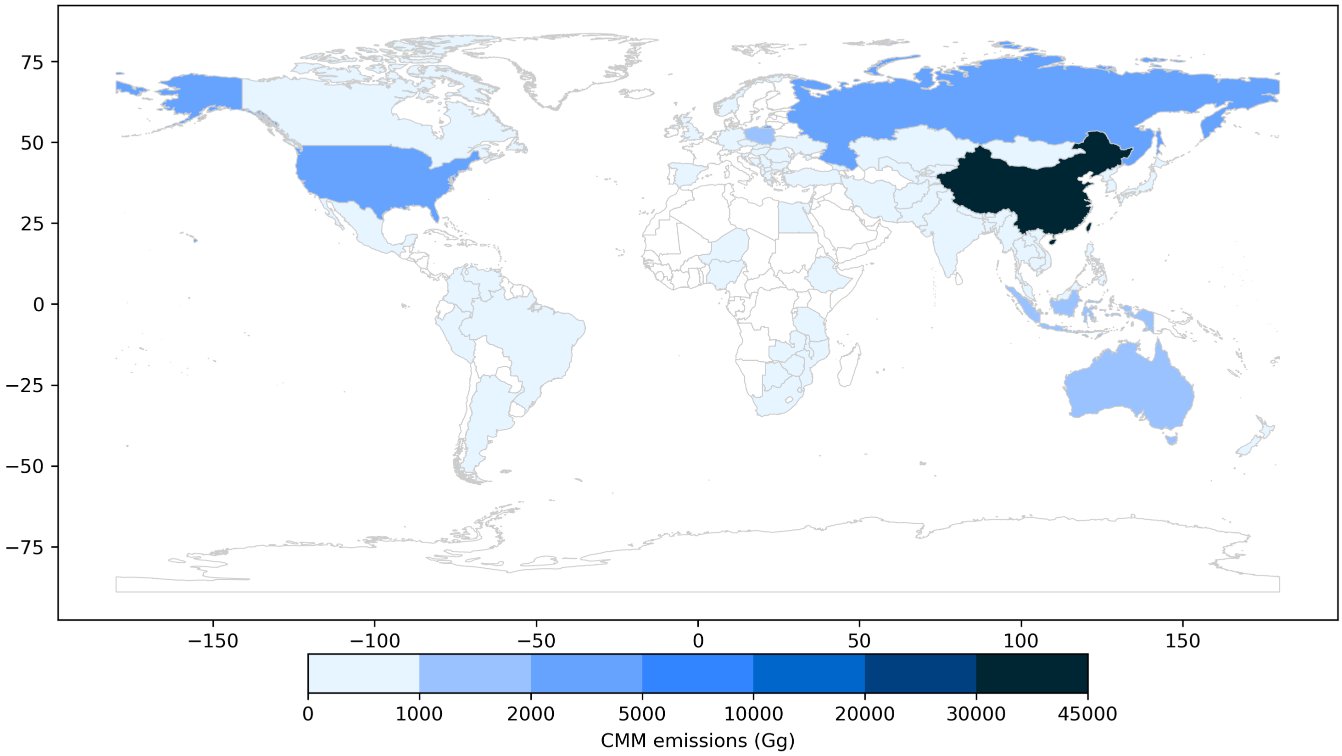


Figure 44: Map of the country CMM emissions, including mining emissions, post-mining emissions, and methane recovery. Non-linear scale.

Fig. 44 shows the country totals per our inventory. The scale is non-linear to be able to see emissions from other countries than China. We find total CMM emissions of 53977 Gg/yr.

Fig. 45 gives the share of CMM emissions coming from underground and surface coal mines. It is consistant with the estimation done by the IEA (Fig. 7): VAM and drained gas are from underground mines, and a major part of the post-mining emissions and abandoned emissions come from underground mines as well. We find in our inventory a number a little inferior to the IEA for surface mines, since we obtain 10.7% (including their post-mining emissions), and the IEA estimates a little over 12%. Indeed since the post-mining emissions from underground mines are 25 times the ones from surface mines according to the IPCC guidelines, a very small part of the 10% post-mining emissions must be attributed to underground mines.

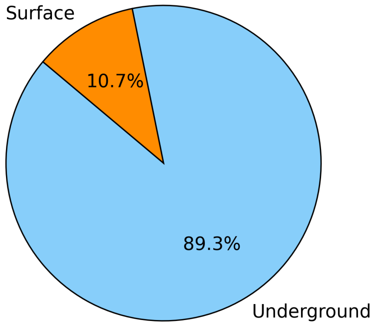


Figure 45: CMM emissions share between underground and surface coal mines

Precise total emissions for the 15 most emitting countries are given in Fig. 46. The 15 biggest coal producers have also been displayed in Fig. 47. Although China dominates in both cases, there is less of a gap with other countries in terms of production than in terms of emissions. The order is also not the same between production and emissions, which shows for each country whether they extract coal with a high methane content and a high emission factor or not. There is an even smaller gap between China and other countries in terms of number of mines per country, displayed in Fig. 48.

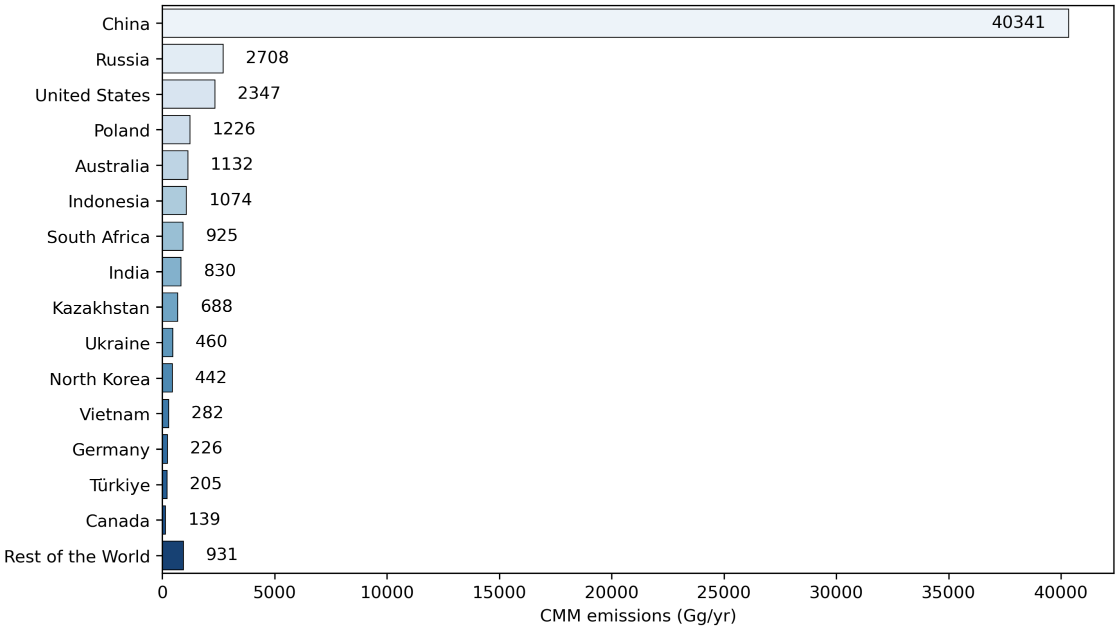


Figure 46: CMM emissions country totals for the 15 biggest CMM emitters.

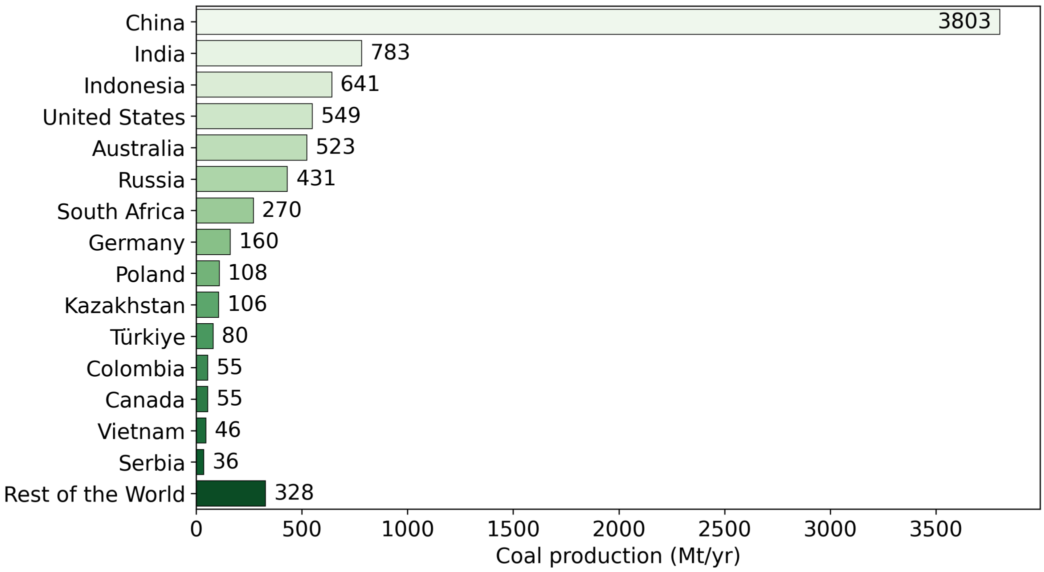


Figure 47: Coal production country totals for the first 15 biggest producers.

There is an even smaller gap between China and other countries in terms of number of mines per country, displayed in Fig. 48.

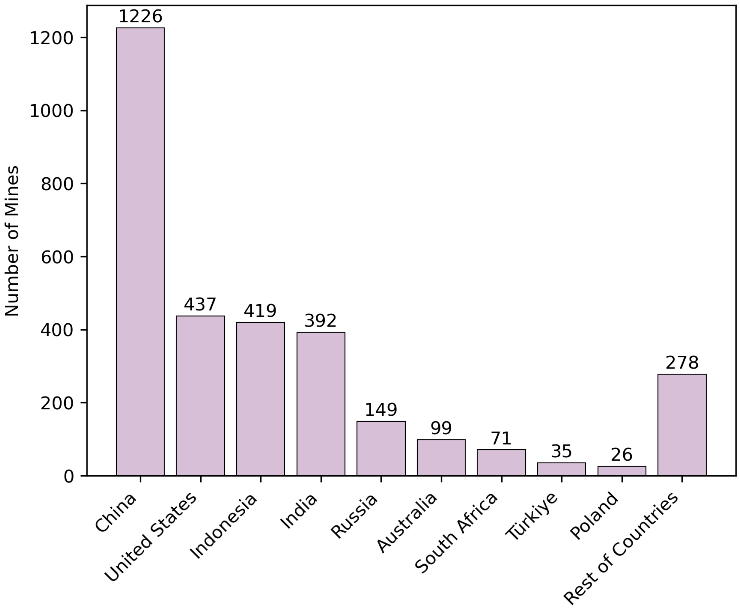


Figure 48: Number of mines per country

Fig. 49 shows, for all countries, the average emission factor of the country's mines. The average is not necessarily a good representation of anything for a country. For example Eswatini has a high average emission factor (the highest), but only has one anthracite mine, with an estimated depth of 494m. North Korea (14 deep mines, mostly anthracite) and South Korea, have respectively 14 (mostly) anthracite and 4 anthracite mines, deep mines, which also justifies their high emission factor. Ukraine has a high emission factor since its mines are the deepest with approximately 600 meters deep on average. It is followed by Poland, and then China with just over 500 meters deep on average. Many countries have average emission factors of 2 as they only have surface mines. Fig. 49 also displays all 67 countries that have operating coal mines.

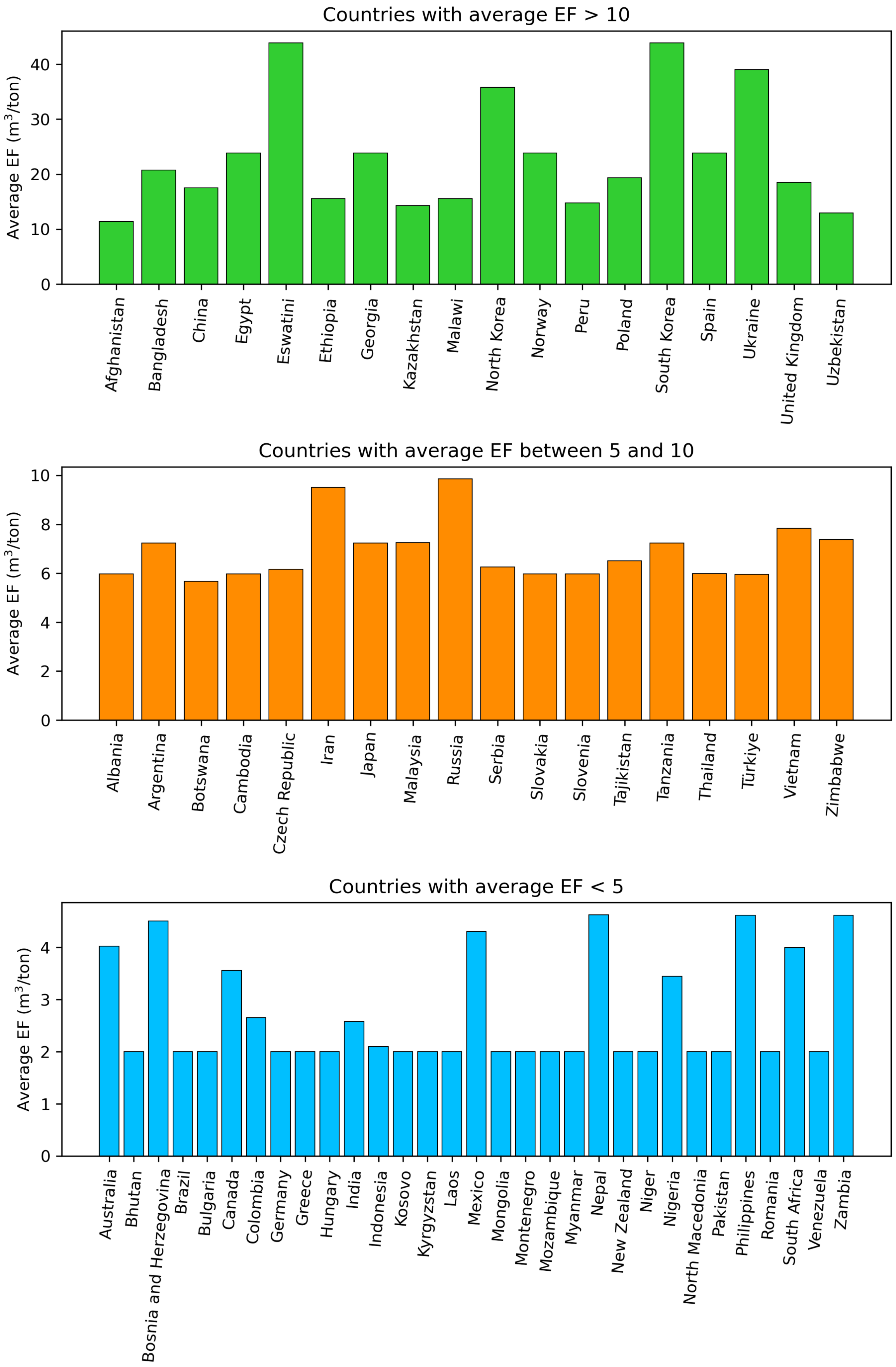


Figure 49: Average emission factor per country, sorted by range of emission factor.

The final facility-scale emission inventory is presented in Fig. 50 and the 0.1° × 0.1° resolution gridded product is presented in Fig. 51.

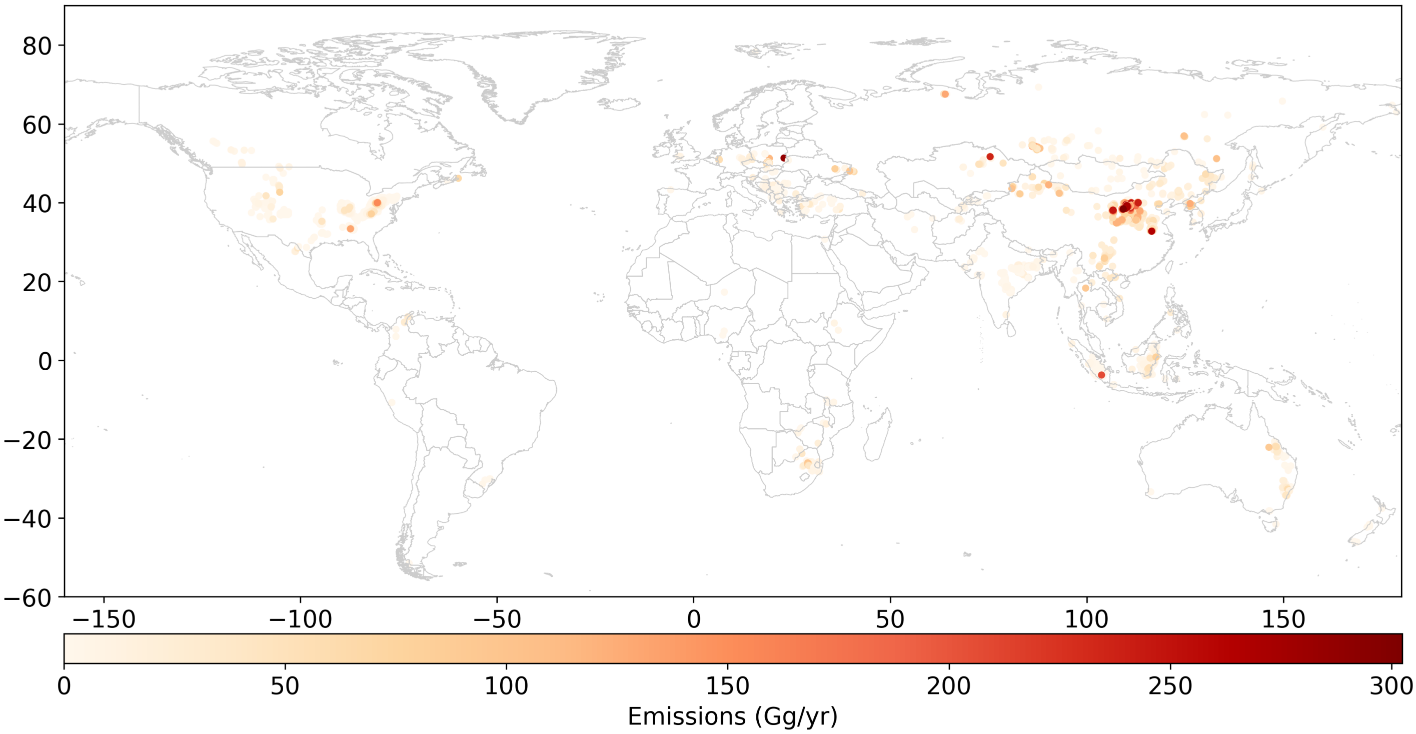


Figure 50: Final mine-level CMM inventory

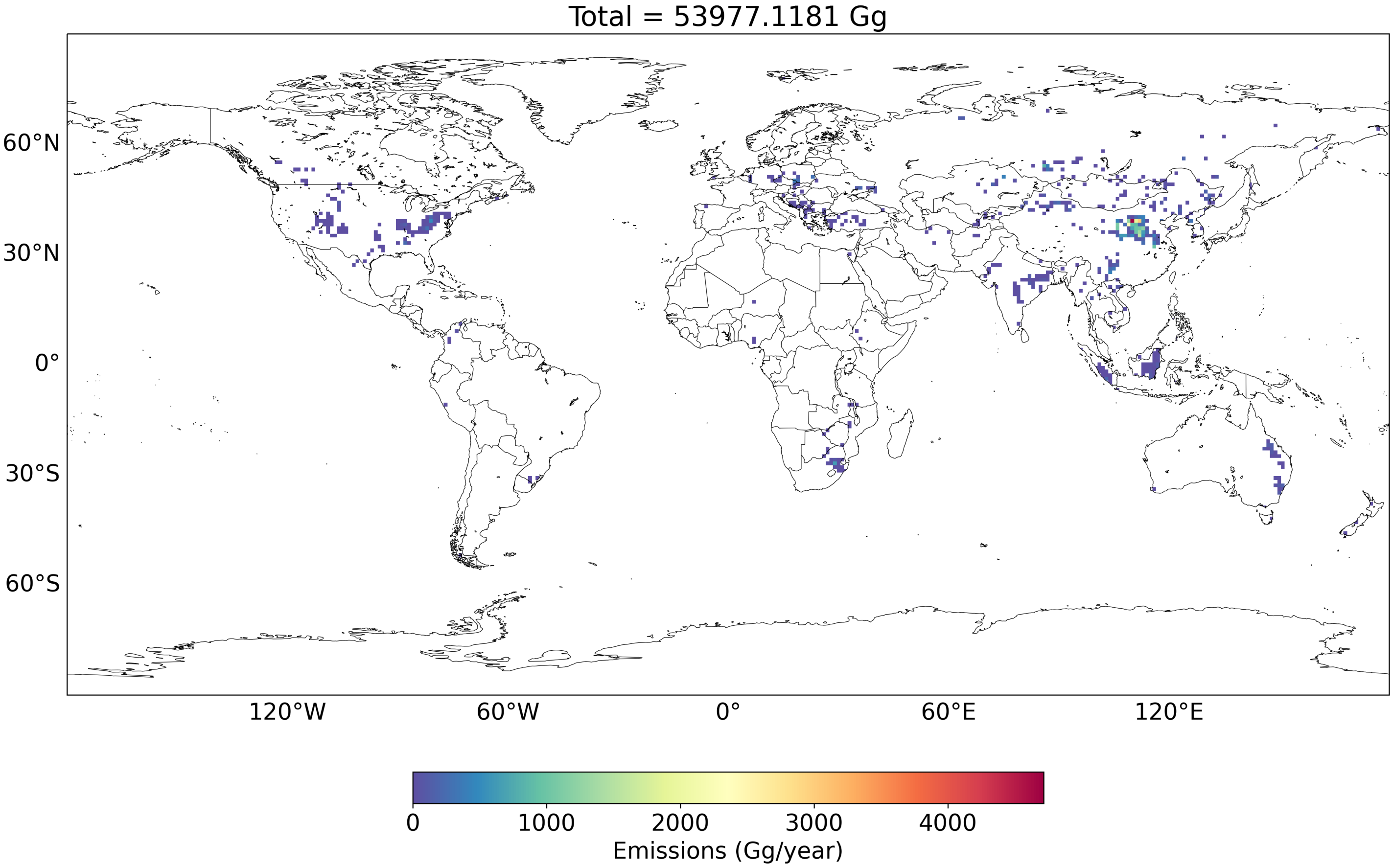


Figure 51: Final gridded product, here at 1° × 1° resolution for lisibility

4 Validation and discussions

The limitations of this inventory are those already mentioned before. The mine depths data could be improved a lot, which could make a big difference especially in the depths up to 500 meters for which the emission factor increases a lot. More direct emission rates and methane concentrations, especially for gassy mines, would also improve the inventory of course.

For the U.S., the EPA inventory is taken as it is in our inventory since they have direct measurements for many of the underground mines. A limitation which would be worth looking into is that they have only 60 underground mines reporting to the GHGRP, when the GEM Global Coal Mine Tracker has 180 operating mines. They get a total CMM emissions from underground mines of 29 Mt of CO2-eq per year, while applying our log-rank model to the GCMT operating mines, we obtain a total of 67 Mt per year (using GWP_{100}=25).

More work would be needed to verify and validate this final inventory, especially to compare our inventory and spatial distribution to satellite observations. It would also be interesting to compare to independant national inventories (Sadavarte for India, Sheng for China for example), but modified and weighted to the specific year the inventories were made for. Indeed, most national inventories are not done with up to date mine information and thus we did not compare them to our inventory in this work. But we can already compare this work with the GFEI inventory, as well as looking at the country-reported UNFCCC emissions.

Comparison to UNFCCC reported country totals

Within the United Nations Framework Convention on Climate Change (UNFCCC), countries are categorized into two groups: Annex I and non-Annex I nations. Annex I countries are mainly industrialized nations, which have greater historical responsibility for greenhouse gas emissions and are thus required to set emission reduction goals and provide detailed emission reports. On the other hand, non-Annex I countries, primarily developing nations, are encouraged to take voluntary climate action and report their emissions and mitigation efforts. This classification recognizes the diverse historical emissions and capabilities of nations in addressing global climate challenges.

Country	Year of last reporting to UNFCCC
China	2014
India	2016
Mexico	2013
Indonesia	2000
South Africa	never
Colombia	2004
North Korea	2002
Vietnam	2013

Table 8: Examples of last reporting years for some of the biggest CMM emitters in the non-Annex I countries.

Non-Annex I countries reportings are often (very) outdated. Table 8 shows the last reporting year for a few of the big CMM emitters in the non-Annex I countries. For Annex-I countries (European Union, Canada, Australia, Japan, Kazakhstan, New Zealand, Russia, U.S.) we have access to their reporting of 2020.

Fig. 52 shows the difference between this inventory and the UNFCCC reported country totals, for a few of the most emitting countries. China is not included for lisibility of the bar plot, but China reported CMM emissions to a total of 21015 Gg in 2014, and our inventory computes a total of 40341 Gg/yr for 2023.

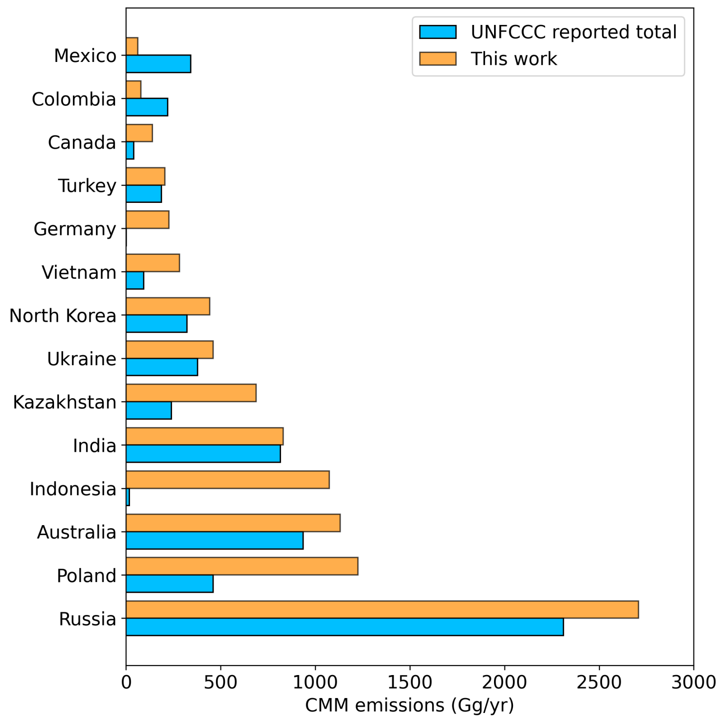


Figure 52: Difference between our country totals and the total CMM emissions they reported to the UNFCCC, for a few high-emitting countries

Showing a map of the difference between the reported emissions and the country totals we get, shows primarily a huge difference for China. Plotting the relative difference also does not add a lot of information, because many countries have a 100% relative difference. Indeed, countries for which we have emissions but do not report any, as well as South Africa who never reported anything, account for a total of 1046 Gg/yr in our inventory (15 different countries).

The difference is especially big for Germany and Indonesia who report almost no emissions, but also Kazakhstan, Poland, the U.S. and Russia.

Comparison to GFEI v2

The GFEI inventory for which this work is being carried out takes the national emissions reported to the UNFCCC and allocates them spatially to a 0.1° × 0.1° grid. The spatial proxy was, in the v2, the gridded emissions inventory EDGAR (Emissions Database for Global Atmospheric Research). For the GFEI v3, the goal was to improve the method to get a better and more precise spatial information as well better information on the methane emissions at the facility-scale. This is why this work was developed, to improve the coal part of the GFEI inventory. This work will then be scaled back to the UNFCCC country totals to be included in GFEI v3: each mine's emissions will be scaled, by multiplying by the ratio between 2021 production of the country, and the production at the reporting year.

When scaling the UNFCCC totals to their 2021 production, we obtain the totals presented in Fig. 53, compared to our totals. Most of the countries appear as under reporting, except for Mexico and Colombia. We find with our model that those two countries have low emission factors on average, which they might have been overestimating.

As a conclusion regarding the reportings to UNFCCC, we find that they are often for non-Annex I countries (including China) out of date, and even for Annex I countries or for non Annex I scaled to 2021 production, there are big differences with our bottom-up inventory. From what we have seen in the litterature review, very few countries have sufficiently precise and satisfactory reporting systems, so it is not very surprising.

Now comparing the spatial distribution of emissions between this inventory for GFEI v3 and GFEI v2, to assess the improvement resulting from our work. We obtain the gridded difference presented in Fig. 55. A zoom is done on China where the biggest differences are on Fig. 54. We can see that for GFEI, emissions were very spread out over the whole country, whereas our inventory has more concentrated emissions. In China, we are only taking into account operating mines and they have tens of thousands of closed mines. So we can understand the difference as outdated operating mines information. Indeed, we do know that abandoned mines emissions are not estimated for the majority of the countries, especially China which as a non-Annex I country just reports a total CMM emissions without a subsectoral division. The small emissions that we do not have in our inventory are thus not overlooked abandoned mines emissions.

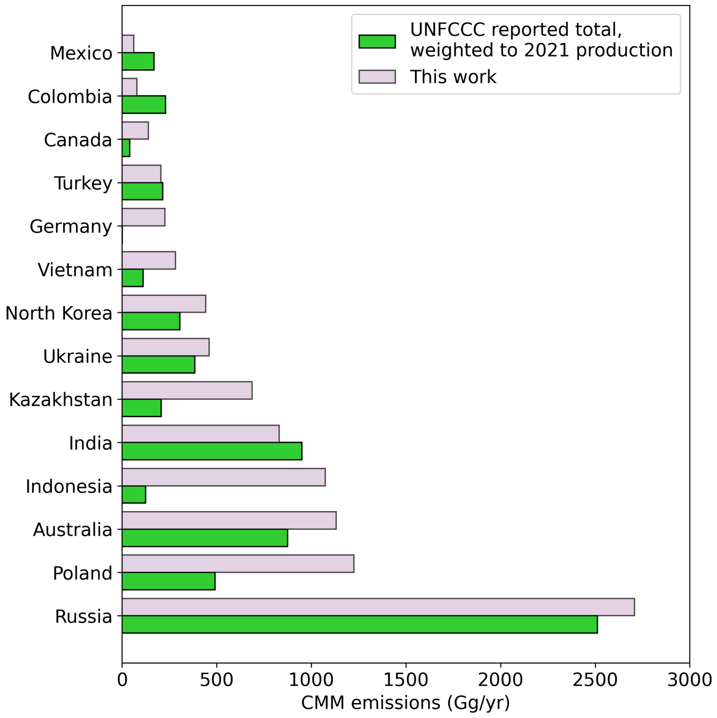


Figure 53: Difference between our country totals and the total CMM emissions they reported to the UNFCCC, weighted to their 2021 production, for a few high-emitting countries

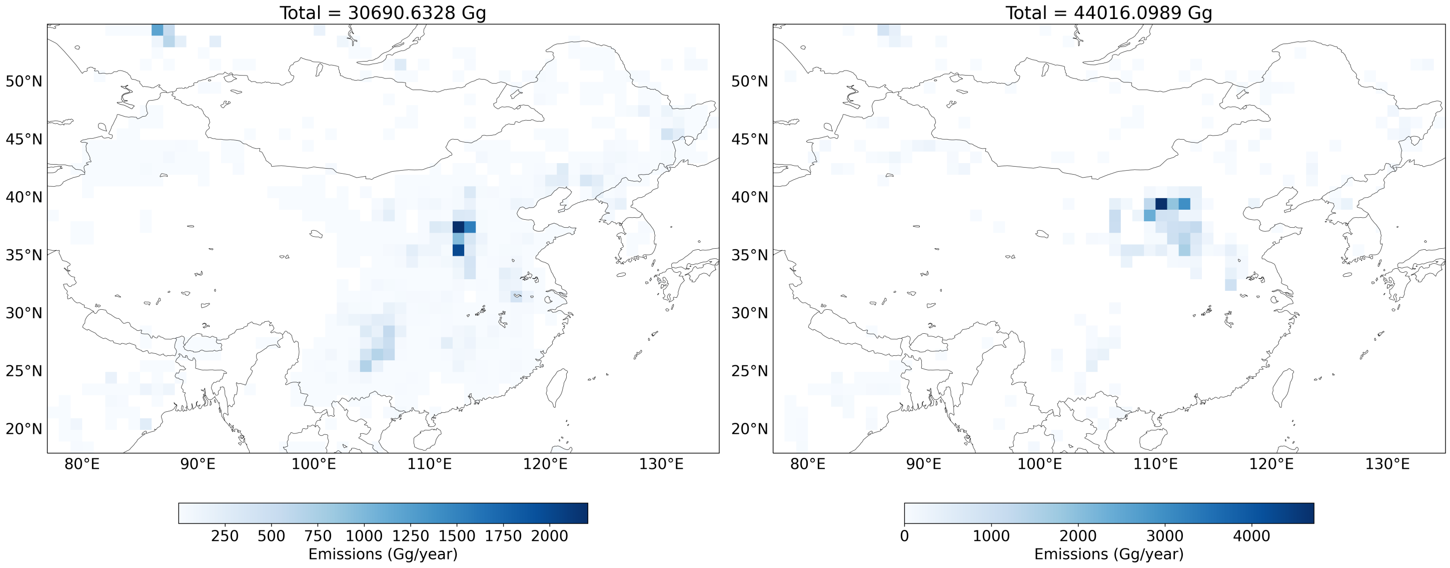


Figure 54: Left: GFEI v2 emissions in China. Right: This work's emissions in China

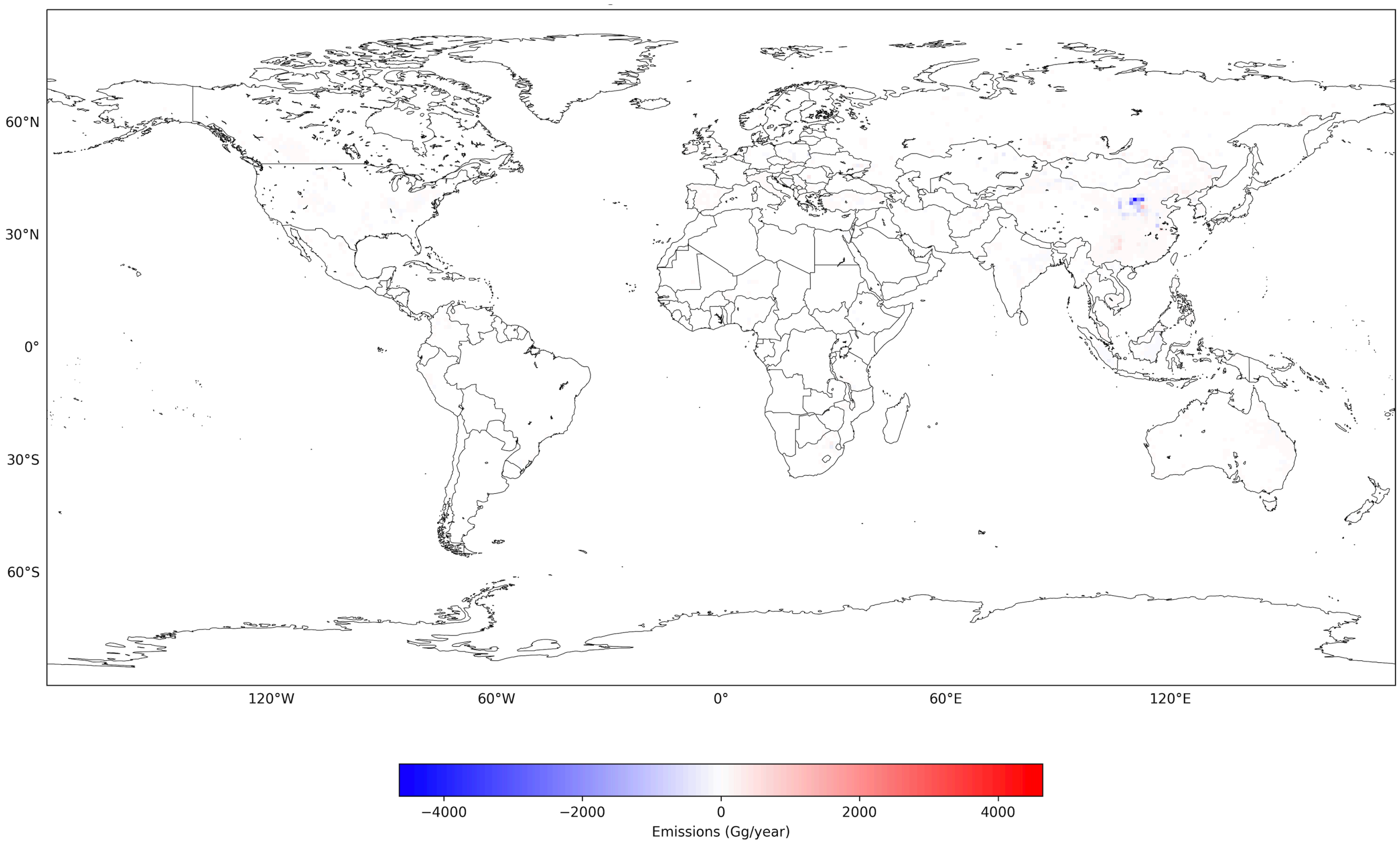


Figure 55: Gridded difference between this inventory and GFEI v2, at 1° resolution for better visibility

Fig. 56 shows all the grid cells for which the GFEI v2 inventory had emissions for, that we do not. The grid cells that have emissions for both, or only for this work, are also presented in Annex but there are much less.

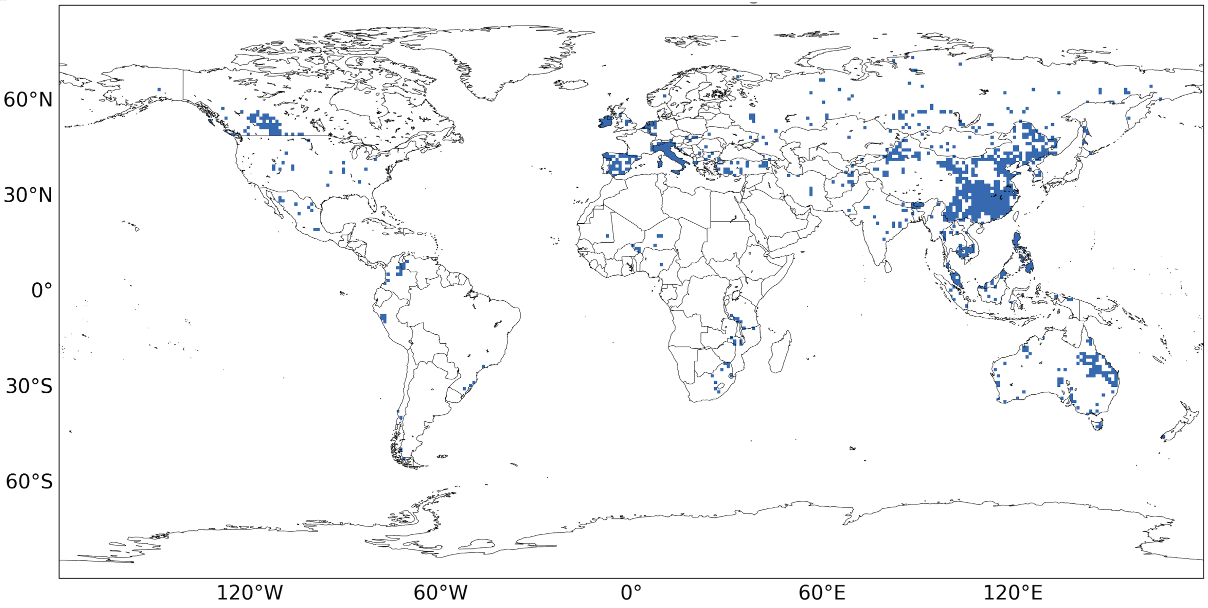


Figure 56: Colored grid cells have non-zero emissions in GFEI v2, but zero emissions in this work

To conclude the comparison with other global inventories, the total CMM emissions in this work, EDGAR and GFEI are presented in Fig. 57. Since the methodology is not transparent for the EDGAR inventory, we cannot analyze why it is that much lower. EDGAR is even lower than what the country reports, which seem to be under reporting, especially for China.

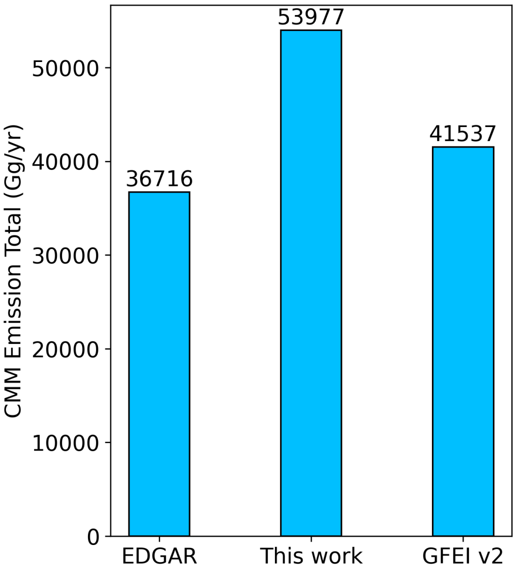


Figure 57: Total CMM emissions for GFEI v2, EDGAR, and this work.

5 Conclusion

We have therefore built a high-resolution inventory of methane emissions from coal mines worldwide. Our work shows that this is an important issue that needs to be understood, as it is a consequent share of methane emissions and there are real opportunities to reduce them. It also shows how complex and uncertain the quantification of emissions still is. The in-depth search for more precise emission factors for the most emitting countries has shown the heterogeneity of methane content from one basin to another, and highlighted the importance of direct measurements. The precise impact on emissions of coal rank and depth of mine, as well as other parameters not considered here such as mine volume, is not fully known or understood, since even the IPCC guidelines have high uncertainties. There is room for improvement in the inventory for future versions of the GFEI, by adding abandoned mines, improving the inclusion of methane captured at mines, and adding more precise measurements for China in particular. The tens of thousands of recently abandoned mines in China would definitely make a big difference in the CMM emissions.

This inventory already presents a good improvement in the estimation of coal mine methane emissions worldwide. Addressing the complex issue of CMM emissions necessitates collaboration among governments, industry stakeholders, and the scientific community, and it is our aspiration that this work will help guide atmospheric studies, fostering deeper insights and effective strategies to mitigate these emissions.

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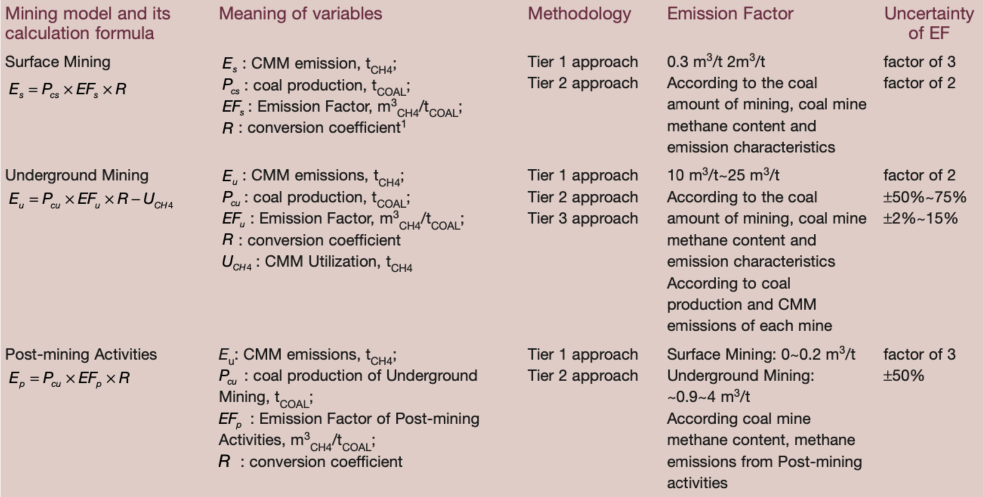
6 Appendix

The Annex presents maps and plots that were not presented in the core of the thesis but are interesting results or visualizations nonetheless.

Fig. 58 shows a summary of the emission factors in the IPCC guidelines, and their uncertainties. The table is from Wang et al (2015) in their study of Coal mine Methane in China.



Mining model and its calculation formula	Meaning of variables	Methodology	Emission Factor	Uncertainty of EF
Surface Mining $E_s = P_{cs} \times EF_s \times R$	E_s : CMM emission, t_{CH4}; P_{cs} : coal production, t_{COAL}; EF_s : Emission Factor, $m^3{}_{CH4}/t_{COAL}$; R : conversion coefficient^1	Tier 1 approach Tier 2 approach	0.3 m^3/t 2m^3/t According to the coal amount of mining, coal mine methane content and emission characteristics	factor of 3 factor of 2
Underground Mining $E_u = P_{cu} \times EF_u \times R - U_{CH4}$	E_u : CMM emissions, t_{CH4}; P_{cu} : coal production, t_{COAL}; EF_u : Emission Factor, $m^3{}_{CH4}/t_{COAL}$; R : conversion coefficient U_{CH4} : CMM Utilization, t_{CH4}	Tier 1 approach Tier 2 approach Tier 3 approach	10 m^3/t~25 m^3/t According to the coal amount of mining, coal mine methane content and emission characteristics According to coal production and CMM emissions of each mine	factor of 2 ±50%~75% ±2%~15%
Post-mining Activities $E_p = P_{cu} \times EF_p \times R$	E_u: CMM emissions, t_{CH4}; P_{cu} : coal production of Underground Mining, t_{COAL}; EF_p : Emission Factor of Post-mining Activities, $m^3{}_{CH4}/t_{COAL}$; R : conversion coefficient	Tier 1 approach Tier 2 approach	Surface Mining: 0~0.2 m^3/t Underground Mining: ~0.9~4 m^3/t According coal mine methane content, methane emissions from Post-mining activities	factor of 3 ±50%

Figure 58: Summary of the IPCC guidelines for reporting CMM emissions, with IPCC estimated uncertainties

Fig. 59 shows measured adsorption isotherm for four coal samples, showing the methane content increasing with pressure. Moisture % decreases as coal rank increases in the process of coalification.

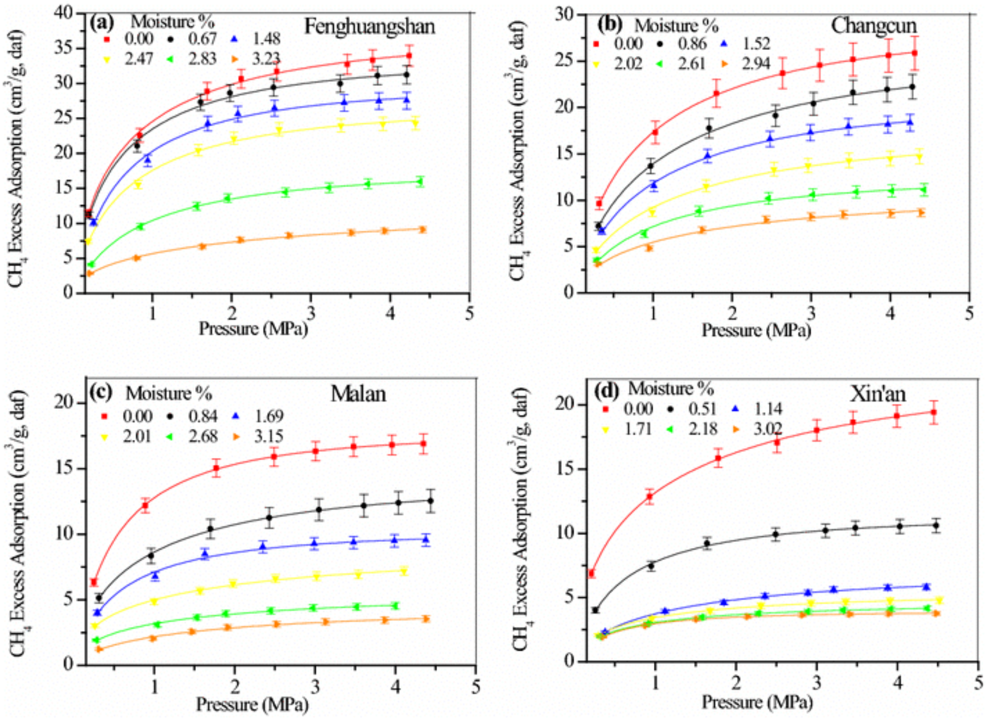


Figure 59: Methane adsorption isotherms measured on four coal samples [60]

Following are series of comparisons per country between our final emissions and the mine-level emissions using the IPCC advised emissions factors. The difference is compute by subtracting the latter to the first, so that we see for China for example that the IPCC advised emission factors are over estimating the emissions compared to this work.

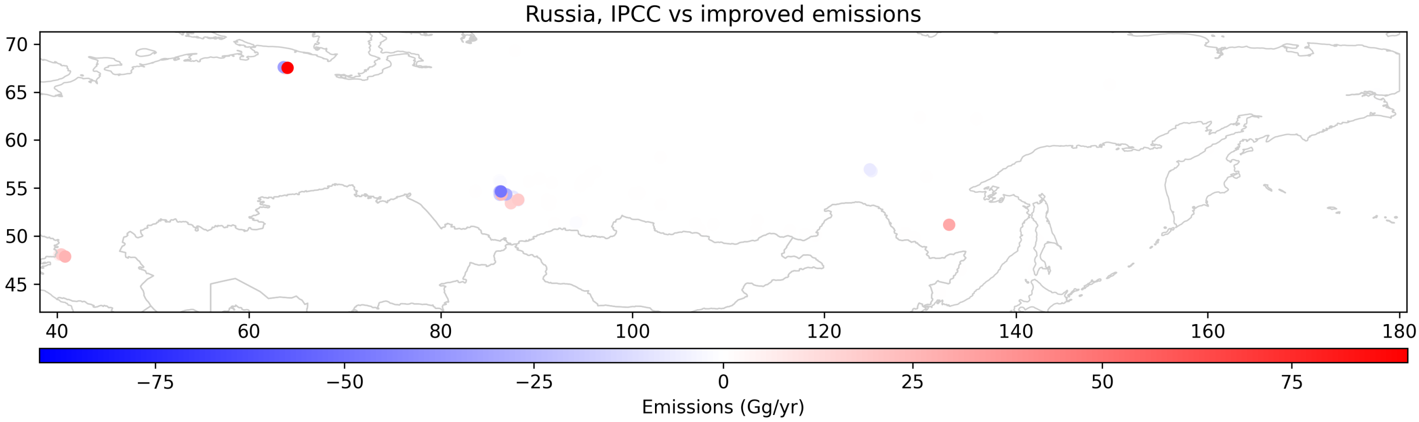


Figure 60: This work's mine-level emissions, minus the IPCC-advised mine-level emissions, for Russia

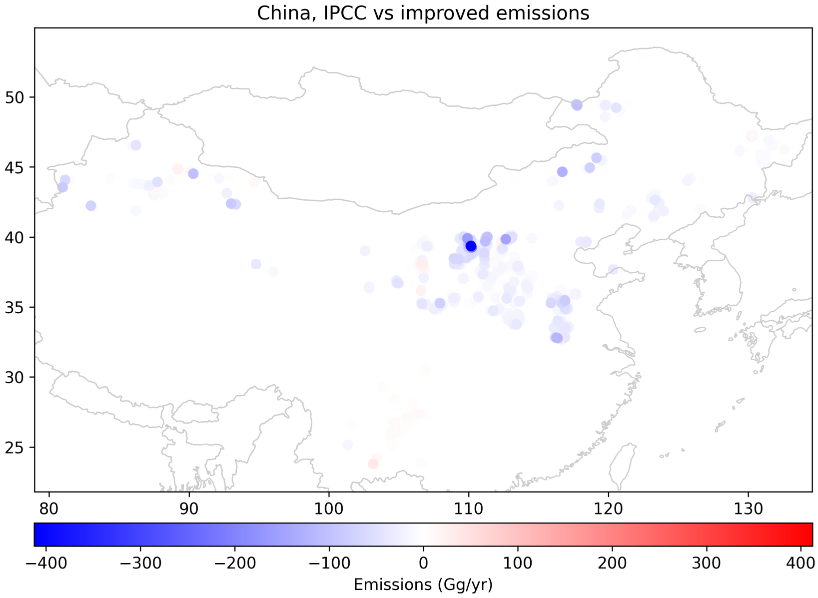


Figure 61: This work's mine-level emissions, minus the IPCC-advised mine-level emissions, for China

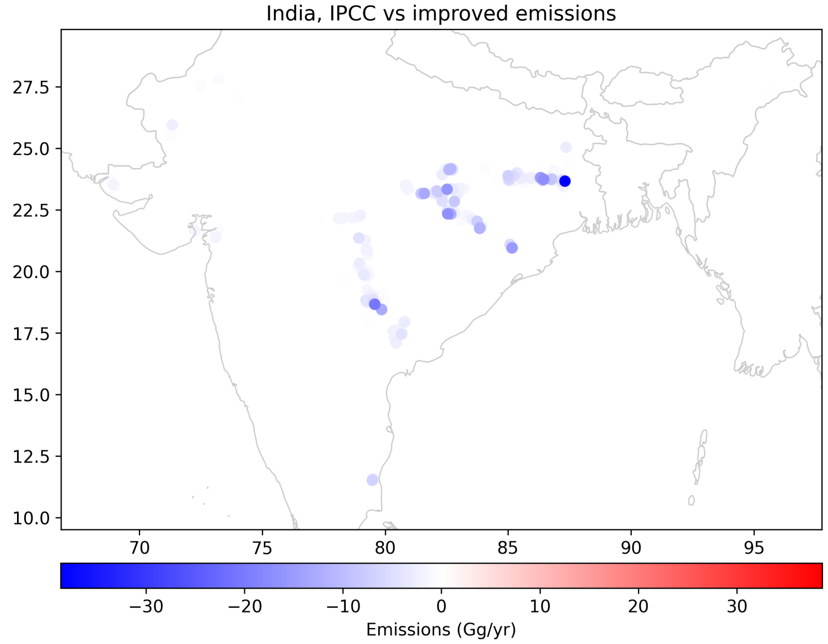


Figure 62: This work's mine-level emissions, minus the IPCC-advised mine-level emissions, for India

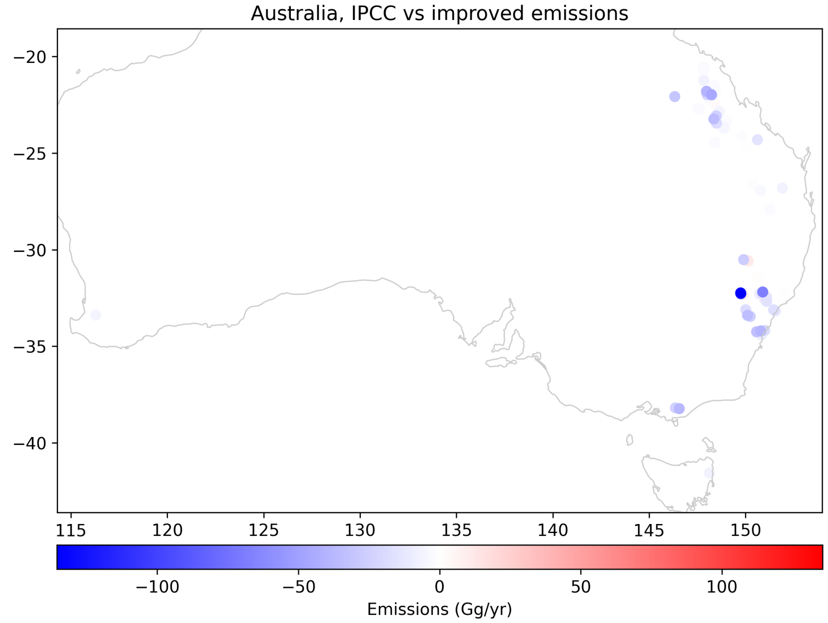


Figure 63: This work's mine-level emissions, minus the IPCC-advised mine-level emissions, for Australia

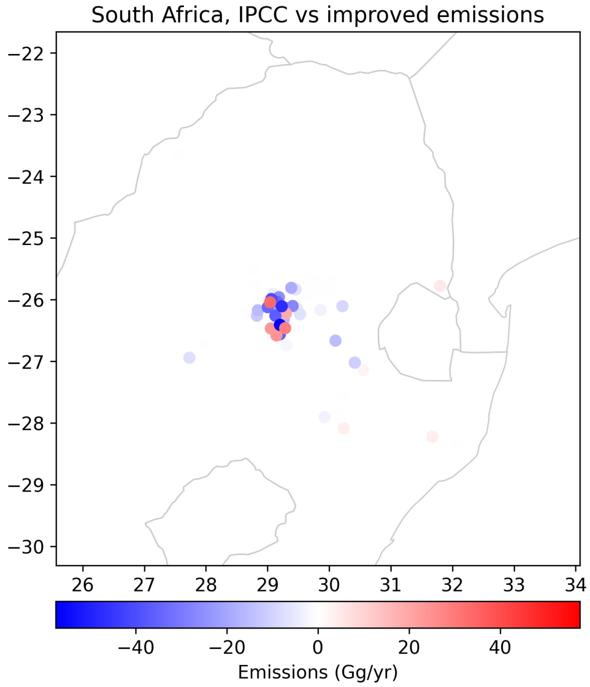


Figure 64: This work's mine-level emissions, minus the IPCC-advised mine-level emissions, for South Africa

Fig. 65 shows the mine depths for the 5 most emitting countries. The shallow underground mines are not in the most emitting countries. Chinese mines are the deepest by far.

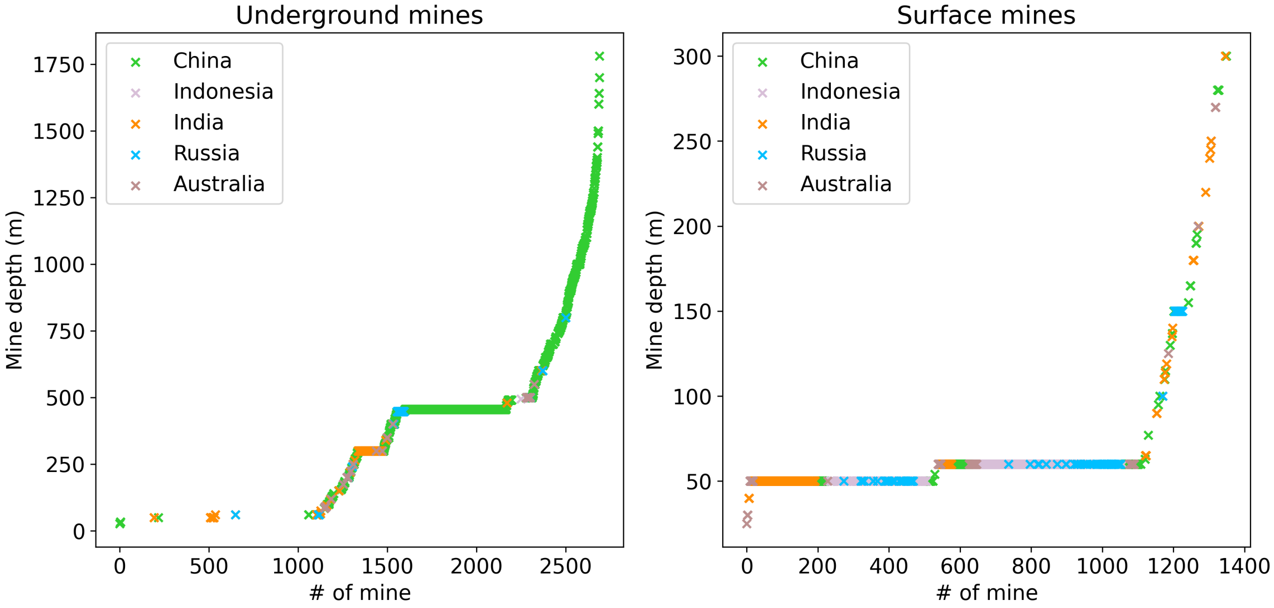


Figure 65: Mine depths for the 5 most CMM emitting countries, for underground mines (left), and surface mines (right)

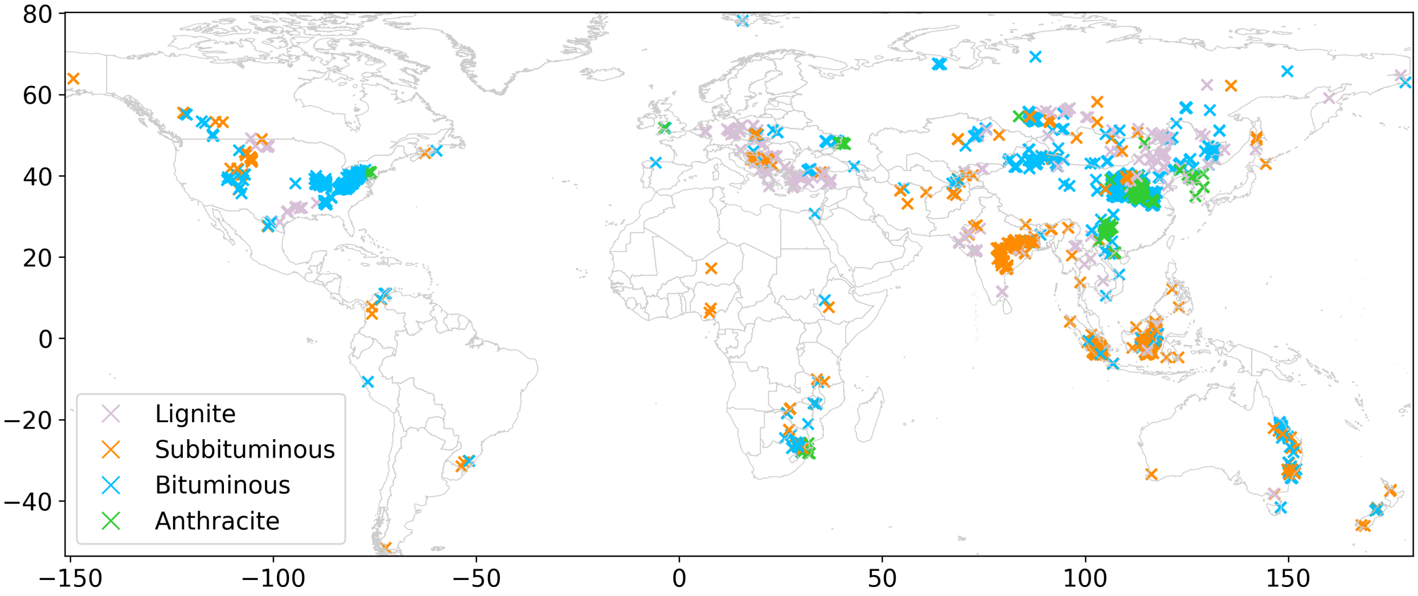


Figure 66: Final inventory, with coal mines color coded by coal type

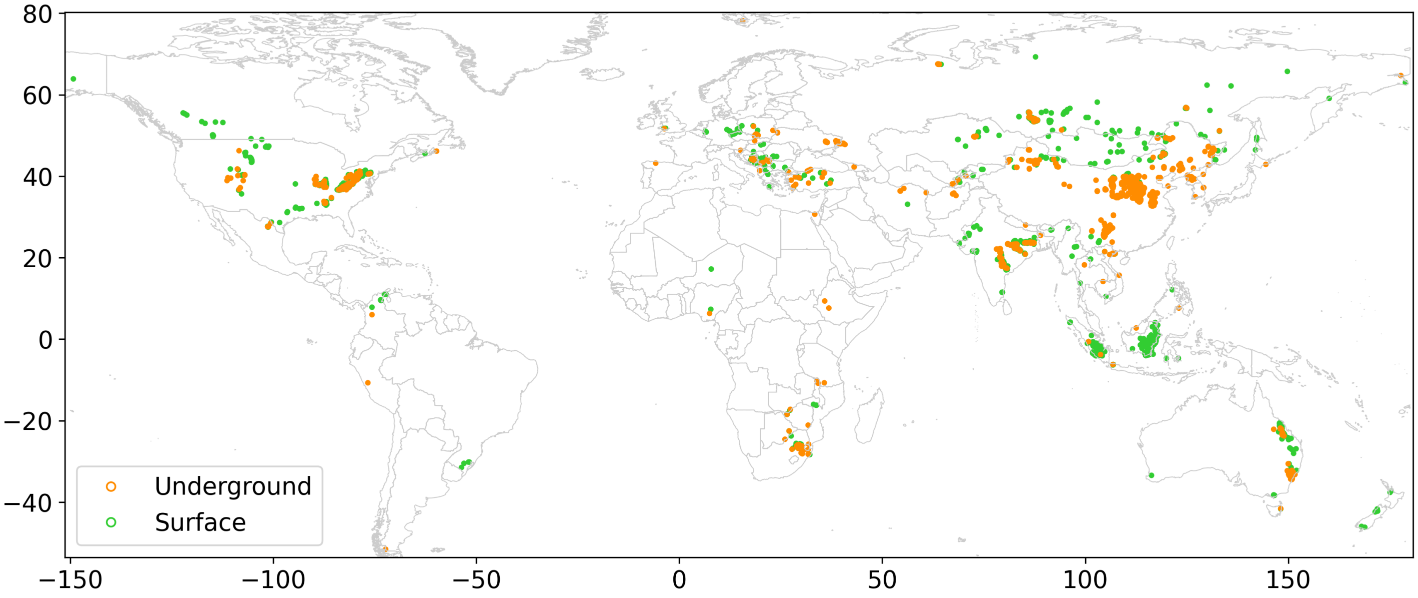


Figure 67: Final inventory, with coal mines color coded by mine type

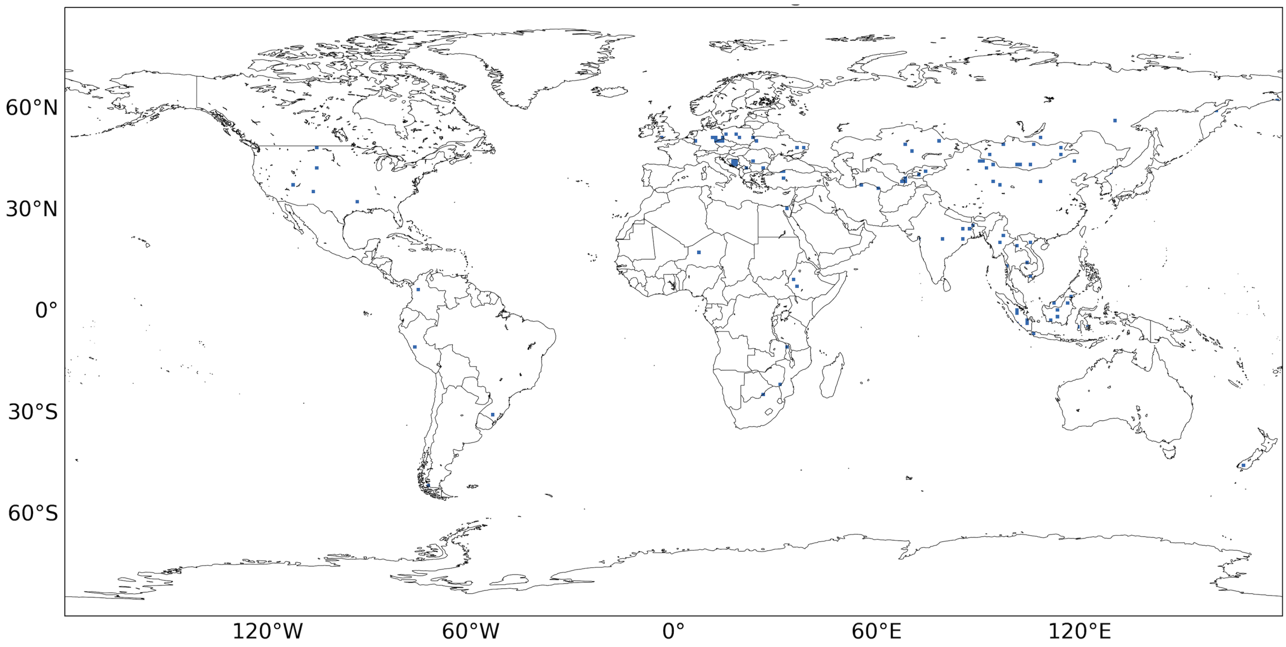


Figure 68: Grid cells colored have non-zero emissions in this global inventory, but zero emissions in GFEI v2

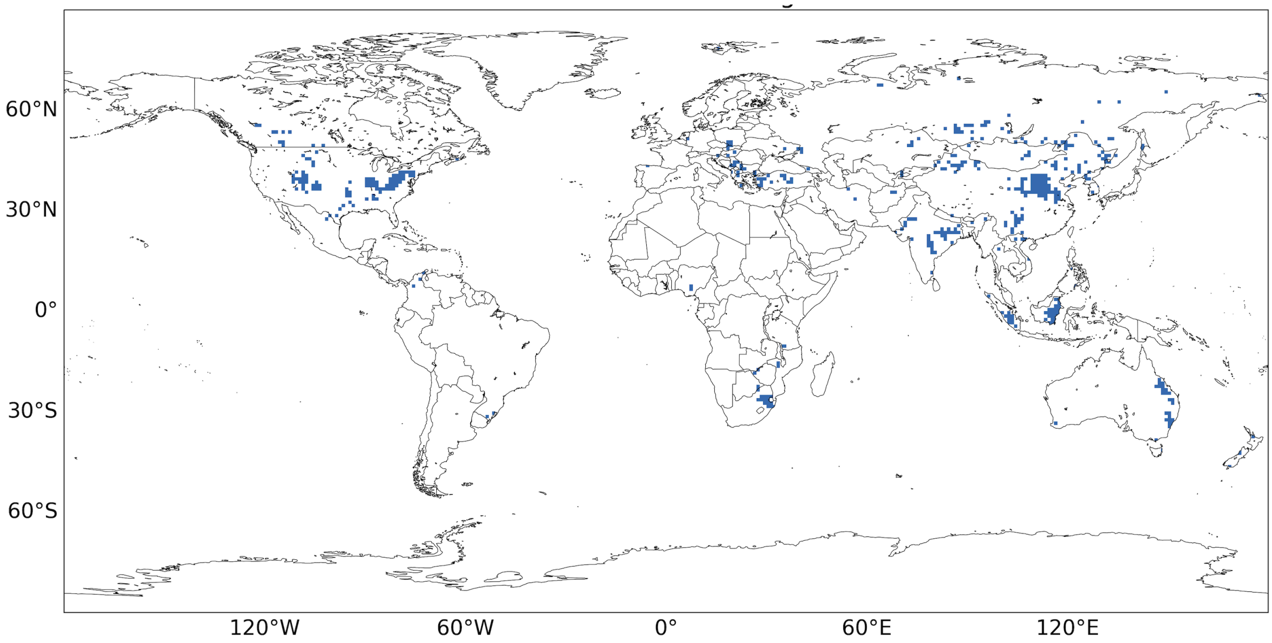


Figure 69: Grid cells colored have emissions in both this inventory and GFEI v2

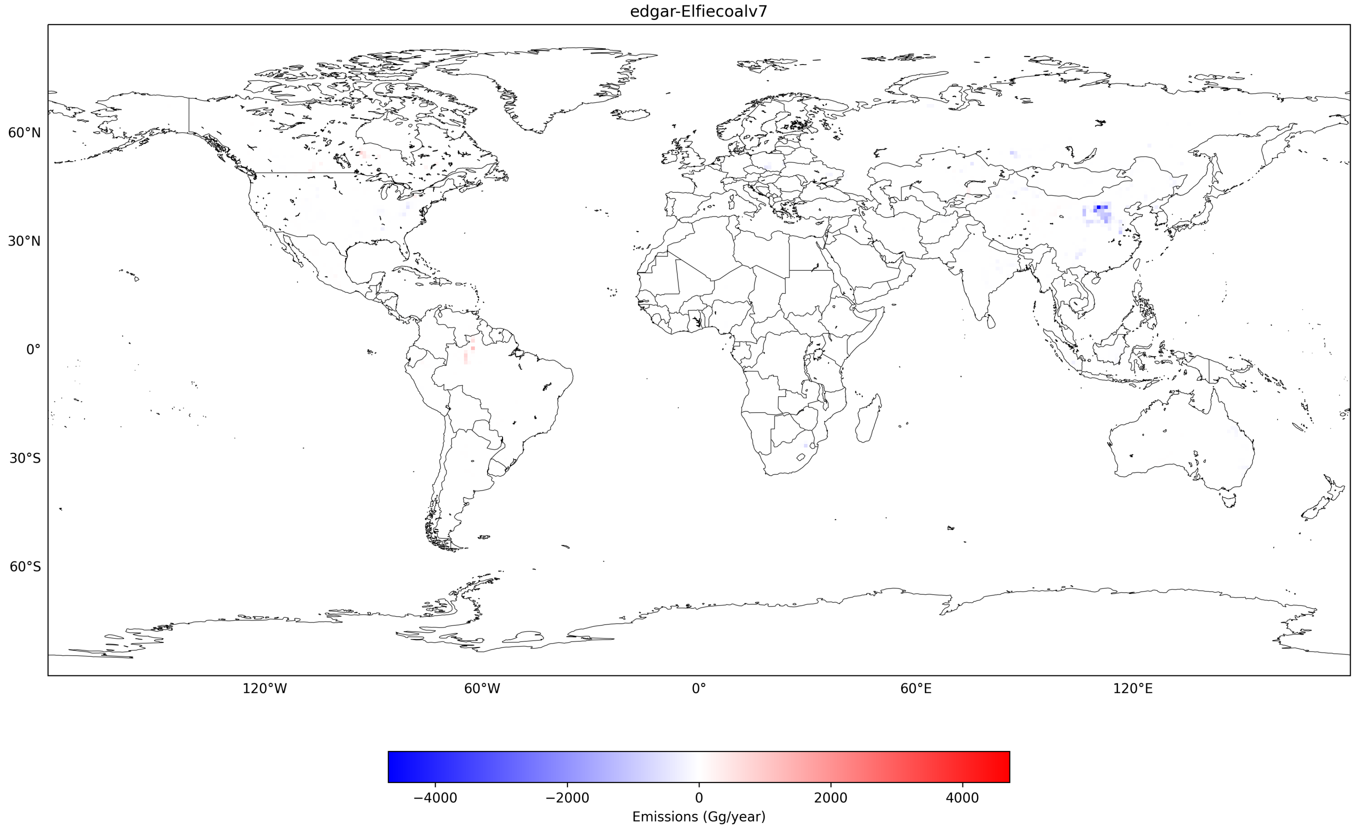


Figure 70: Comparison between EDGAR inventory and this work, with major differences in China