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COMPARISON OF THE IMPACT ON GREENHOUSE GAS EMISSIONS BETWEEN UNABATED COAL REFUSE PILES AND RECLAMATION-TO-ENERGY POWER PLANTS

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EXECUTIVE SUMMARY

Coal refuse is a legacy of earlier mining in the U.S. Coal refuse is a mixture of low-quality coal and rock that was discarded during the extraction of higher quality coal. A significant amount of this refuse has been deposited in piles that spread across the Appalachian region and are a hazard to the environment. The piles leach acid mine water into Pennsylvania and West Virginia waterways and can also spontaneously combust releasing greenhouse gas (GHG) emissions into the air without proper emission controls. A 2020 inventory of refuse piles kept by the Pennsylvania Department of Environmental Protection (DEP) identified 840 piles throughout Pennsylvania, which are estimated to consist of nearly 443.9 million metric tons of coal refuse, covering approximately 18,170 acres. It has been estimated by the Pennsylvania DEP's Bureau of Abandoned Mine Reclamation (BAMR) that the total cost of coal refuse reclamation would be about $16.1 billion in Pennsylvania alone. One option for abatement of coal refuse piles is "reclamation-to-energy" (RTE) of the waste material in circulating fluidized bed power plants. This option, aligned after the Public Utility Regulatory Policies Act (PURPA) of 1978, has been capable of disposing a total of over 230 million tons of coal refuse and reclaiming more than 7,000 acres of abandoned mine land (AML) in Pennsylvania alone since the startup of these plants. These plants serve the double purpose of processing historic mining waste and cleaning up AML, while producing power.

The combustion process that takes place in these RTE units is of concern in regard to the GHG emissions associated with these plants. However, there are a number of reports that have documented the GHG emissions footprint of coal refuse pile spontaneous combustion, diffused over a large "ill-defined" area and from different vents and fissures in the pile. There are documented specific mass emissions and emission factors for GHG from burning coal refuse piles, impoundments, abandoned mines and outcrops. Calculations were carried out to obtain a comparative assessment on the impact on GHG emissions from unabated coal refuse pile fires vs. the RTE option in the Appalachian region. GHG emissions estimations were carried out for equivalent coal volumes processed by the RTE industry in Pennsylvania and West Virginia in 2019, which if not burned will remain scattered in piles around former coal mine sites, representing a risk to vegetative life and negatively impact human health. Four emissions factors were used in combination with the particular reference case, which is the amount of coal refuse processed by the RTE plants in 2019. Depending on the emission factors selected, the expected GHG emissions equivalent ($CO_{2,eq}$) from unremedied waste piles range from 13,662,919 to 36,239,374 tons for 2019 (see table below). This compares to the corresponding $CO_{2,eq}$ emissions reported by the RTE stations in the region in 2019 at 7,128,113 tons, at a rate of GHG reduction per ton of coal refuse reclaimed by RTE of 1.27 tons $CO_{2,eq}$/ton coal refuse. Thus, each ton of coal refuse is expected to produce GHG emissions between 2.43 and 6.44 tons $CO_{2,eq}$ with a net reduction of between 1.16 and 5.17 tons CO2,eq per ton of coal refuse reclaimed by the coal refuse RTE industry. The calculations suggest that coal refuse pile GHG emissions exceed by a factor that can be between 1.9 to 5.1 larger than the corresponding emissions if burned under controlled conditions in the RTE units. Based upon the four emissions factors used in this study, when the full emissions profile of the coal refuse RTE industry is considered, including the reduction of emissions from reclamation of coal refuse piles, the coal refuse RTE industry produces a net reduction in GHG emissions. For a 20-year global warming potential (GWP) cycle, the total offset amount of carbon dioxide equivalent ($CO_{2,eq}$) is of the order of 0.13 to 0.58 billion tons.

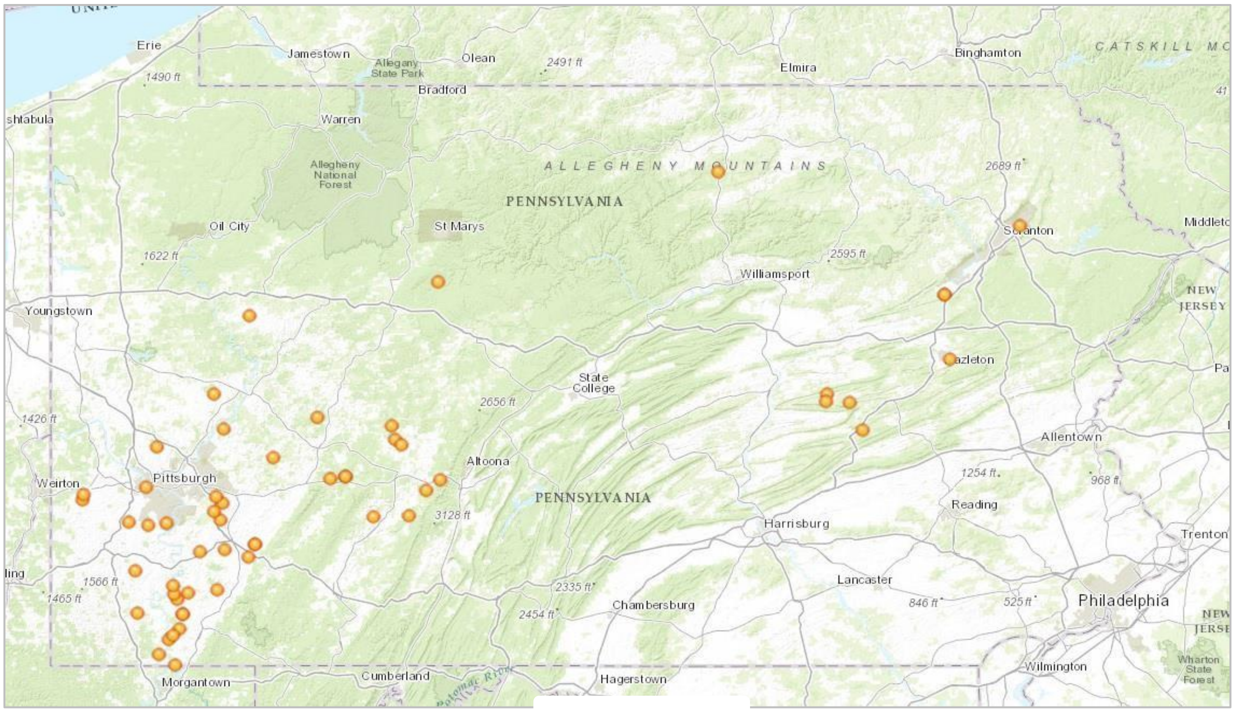
Comparative Estimate of GHG Emissions from Coal Pile Refuse and RTE Reclamation

	CO2 Emissions Factor [kg/t coal]	CH4 Emissions Factor [kg/t coal]	Coal Processed by RTE 2019 [t]	CO2 Emissions [t]	CH4 Emissions [t]	CO2,eq Emissions [t]
Reference 20	1,300	180	5,627,232	7,315,402	1,012,902	35,676,651
Reference 21	1,952	17	5,627,232	10,984,357	95,663	13,662,919
Reference 25	2,520	101	5,627,232	14,180,625	566,475	30,041,916
Reference 28	3,500	105	5,627,232	19,695,312	590,859	36,239,374

BACKGROUND

One important issue related to coal production is coal waste and its remediation. Pennsylvania and West Virginia have been the largest coal-producing states in the nation, after only Wyoming, with still substantial reserves of bituminous coal. Additionally, northeastern Pennsylvania has almost all the nation's anthracite coal reserves and production. In regard to active coal production, the number of coal mines and amount of coal production in Pennsylvania has declined over the years due to the impact of coal conversion on air emissions and climate, and associated coal-fired power plant closures and reduced international coal demand. In 2021, the state's coal production increased by 17%, as demand from the electric power sector increased as a result of higher natural gas prices [1,2]. However, one issue related to coal production is coal waste or refuse, the material left over from mining, which typically represents 40% of the total mined material. Legacy coal refuse consists of low-quality coal mixed with rock, shale, slate, and clay. The refuse materials vary from coarse fragments removed by physical screening to very fine materials removed by flotation and density separation processes.

This coal refuse has been sitting in piles for decades, spread across the Appalachian region on thousands of acres of both permitted and abandoned mine lands (AML), with the associated environmental risk that toxic metals in it can leach out of the piles and drain into surface water streams and contaminate ground water resources. Bituminous piles in particular can leach highly concentrated acid mine drainage (AMD) with acidity values in the thousands of milligrams/liter (mg/L). Refuse piles can also be barren, erosive, produce particulate matter (PM) emissions due to downwind effect, and lead to catastrophic failures impacting nearby communities due to structural instabilities. However, one additional and very important detrimental impact of coal refuse piles is oxidation and spontaneous combustion, which can lead to many of the same types of gaseous emissions that arise from coal combustion in power plants but, since there are no control technologies in place in comparison to highly pollution-controlled power plants, the emission factors are generally higher for spontaneous combustion. The emissions of most concern nowadays are the greenhouse gases (GHG’s), carbon dioxide (CO_2) and methane (CH_4). Carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and mercury and other toxic substances are also of concern. This is not a problem unique to Pennsylvania, neighboring West Virginia, and much of the eastern United States. Spontaneous coal and coal refuse combustion is a significant global problem. It is estimated that the global mass of coal burnt in coal seam and coal waste stockpile fires could vary considerably from 0.5% to 10% of annual global coal production [3]. In Pennsylvania, the Department of Environmental Protection (DEP) reported a total of 52 coal refuse pile fires in 2016 [4]. Figure 1 illustrates the locations of coal refuse pile fires in the state in 2005, connected with the coal geological locations.



Source BAMR (2005)

Figure 1: Sites of Burning Coal Refuse Piles in Pennsylvania [4]

While present-day mine sites in Pennsylvania are occasionally abandoned, the Pennsylvania DEP has well-established programs in place to reclaim those sites. However, much of the vast AML problem from pre-1977 mining (in 1977 the federal government enacted the federal Surface Mining Control and Reclamation Act (SMCRA)) still remains. The main reason is the process of reclaiming these piles using conventional environmentally-sound techniques is cost-prohibitive. It requires site stabilization and refuse treatment, land planting and maintenance of a viable plant coverage, and addressing water pollution. Establishment and maintenance of permanent vegetation on refuse is complicated by physical, mineralogical, and chemical factors. As an example, the Simpson Northeast coal refuse bank fire and reclamation project in 2014 cost $2,180,130 for a project area of 17.6 acres, as reported by the Pennsylvania DEP's Bureau of Abandoned Mine Reclamation (BAMR) [5]. It has been estimated by the BAMR that the total cost of coal refuse reclamation would be about $16.1 billion in Pennsylvania alone [4]. There are more than 5,000 abandoned, unreclaimed mine problem areas encompassing more than 185,000 acres in Pennsylvania alone, according to the BAMR. A 2020 inventory of refuse piles kept by the Commonwealth's DEP (which is acknowledged to be noncomprehensive) identified 840 piles throughout Pennsylvania (excluding completed reclamation), which are estimated to consist of nearly 443.9 million tons (*metric ton - equal to 1000 kg - is used in this report, represented by tons or "t"*) of coal refuse and to cover 18,170 acres, equivalent to about 403.6 million cubic yards (308.5 million m^3) [4,6,7,8].

Different programs have been funded to address the Appalachian region's AML problem. In Pennsylvania, this includes the Operation Scarlift Program that included mine fire suppression and surface subsidence, and the Growing Greener Program which funds projects that use passive treatment technologies to clean up abandoned mine discharges. However, one option that has provided consistent results to solve the coal refuse accumulation problem is based on the fuel value of the material. Despite its low quality as a fuel, coal refuse has an associated calorific value (since its heating value is about 60% that of coal) that would make it still suited for a disposal solution that involves combustion of the waste material. About 75% of the finer material in refuse coal can be used in fluidized and circulating fluidized bed combustion (FBC and CFB) boilers for power generation. These FBC and CFB boilers are capable of serving a critical environmental mission in the sense that become reclamation power plants, processing historic mining waste to produce power and clean up AML sites. FBC units are environmentally compliant due to its particular design and air pollution control (APC) technology incorporated with the boilers. This includes limestone and amine-based reagent injection for SO_2 and NO_x emissions control, respectively, as well as cyclones and fabric filters for PM control. Additionally, FBC units use Maximum Achievable Control Technology (MACT) to mitigate the impact of coal refuse burning on air toxics, such as mercury, and acid gases, such as hydrogen chloride (HCl). Aligned after the Public Utility Regulatory Policies Act (PURPA) of 1978, there have been 15 plants in Pennsylvania, two in West Virginia and one in Virginia over the last three decades capable of coal waste firing, solely or in combination with high-quality coal or other feedstock, like biomass, representing about 2,400 megawatts of electric power capacity (MW_e) (see Figure 2 corresponding to the plants in Pennsylvania alone). These plants have been capable of disposing a total of over 230 million tons of coal refuse and reclaiming more than 7,000 acres of AML in Pennsylvania alone since the startup of these plants and represent a "reclamation-to-energy" (RTE) option for abatement of coal refuse piles [8].

In Pennsylvania, 10% of the energy is required to come from the Tier II sources under the Alternative Energy Portfolio Standards Act of 2004, which supports operation of these coal refuse burning plants to promote remediation of coal waste piles. Pennsylvania's Alternative Energy Portfolio Standards (AEPS) program includes waste coal in its "Tier II" category under which facilities collectively received over $2.5 million in subsidies in 2018. Pennsylvania's Coal

Refuse Energy and Reclamation Tax Credit also provides up to $20 million in annual subsidies until 2036 [9].

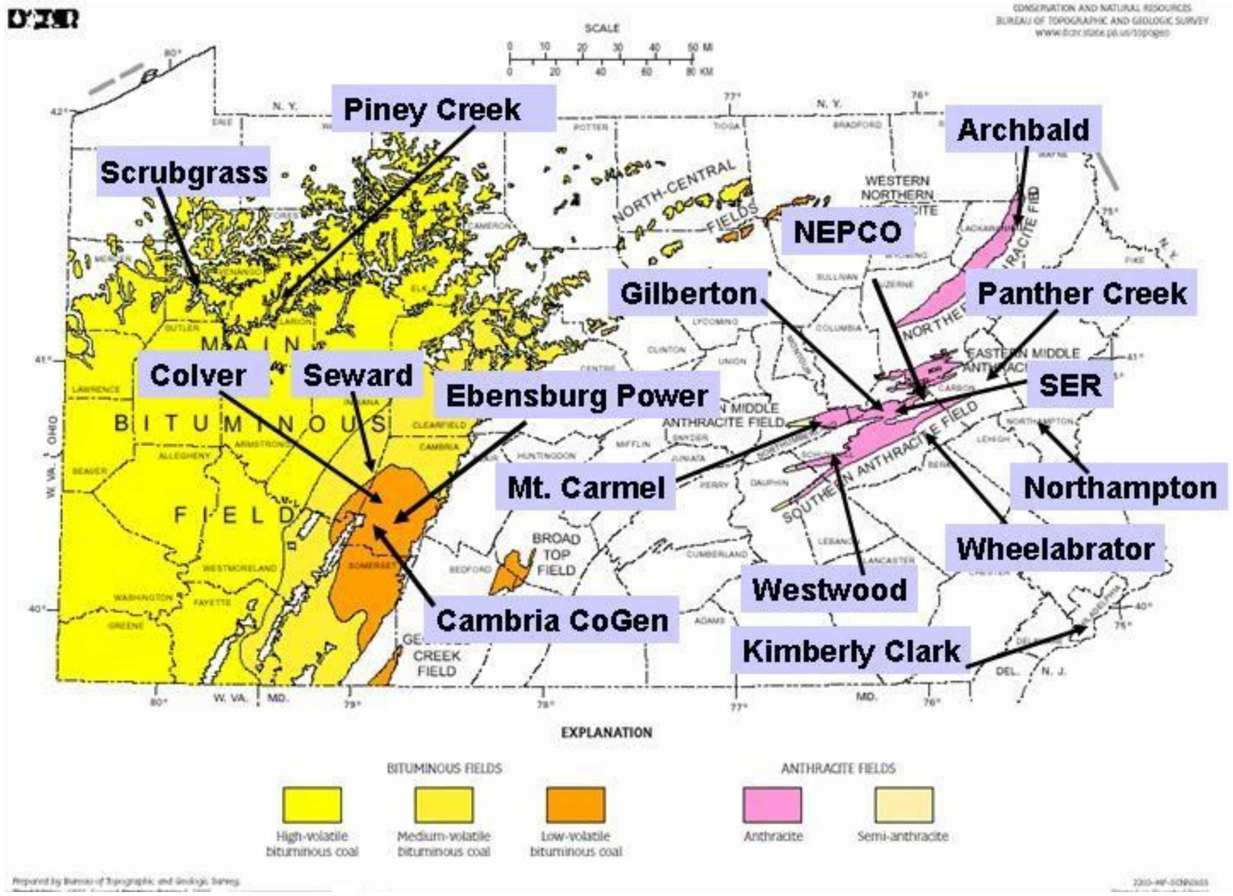


Figure 2: Distribution of FBC Power Plants in Pennsylvania [5]

A 2019 inventory of 14 FBC plants in the U.S. indicates that the range in capacity is between 33 and 525 MW_e. Currently, there only 11 coal waste reclamation plants in the Appalachian region, 10 in Pennsylvania and one in West Virginia. There is also one hybrid remediation facility in Virginia, the Virginia City Hybrid Energy Center. Based on an inventory of data provided by the Appalachian Region Independent Power Producers Association (ARIPPA) from plants in this region, these coal waste reclamation plants are estimated to consume a total between 5.5 and 9.1 million tons (5,610 short tons) of coal refuse annually (the 9.1 million figure corresponds to the 2010-2014 high electrical power generation period). These plants were reported to operate in 2019 at an average capacity factor of 42% (total 5.85 GWh produced) and average heat rates of about 14,946 kJ/kWh (14,166 Btu/kWh). These plants produced in 2019 approximately 4.55 million tons of ash [8,9]. An additional benefit of current coal refuse processing by FBC plants is the production of highly alkaline ash, which meets state defined beneficial use criteria and has been demonstrated to provide a successful reclamation media for restoration of polluted AML sites.

This report provides a discussion and comparative estimate of the impact on climate change from unabated coal refuse piles vs. disposal of the waste coal in RTE power plants. Appalachian region reclamation plants were targeted. The discussion is based on CO_2 and CH_4 only, since according to the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories, only CO_2/CH_4 emissions from 'uncontrolled combustion' in coal should be reported in the sub-category 1.B.1.b. – 'Uncontrolled Combustion, and Burning Coal Dumps' (http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html).

COAL REFUSE GREENHOUSE GAS EMISSIONS ESTIMATION

Although there is a wealth of data on stack emissions from power plants, less consideration has been given to gaseous emissions from coal refuse stockpiles. A good deal of knowledge of gaseous emissions from coal refuse piles has been learned from coal piles. Piled coal refuse undergoes low temperature atmospheric oxidation (known as weathering) during storage in open air. If heat dissipation is insufficient, subsequent autogenous heating of the stored coal will occur. As the temperature in the coal refuse pile increases due to oxidation, gas desorption happens. It is well known that CO_2 and CH_4, with traces of CO and sulfuric gases, are the main degassed compounds [10]. Together with gas desorption, increased rates of oxidation (the rate of oxidation roughly doubles with an increase of 10°C in ambient temperature) will yield additional and uncontrolled gas emissions and potentially spontaneous combustion [10]. The initial weathering stages involve physical adsorption and chemical absorption of atmospheric oxygen. The next stage is the formation of surface oxide which then decomposes to produce low molecular gases. A parallel reaction occurs during coal refuse oxidation at low temperatures – direct burn-off. The burn-off reaction sequence is suggested to be similar to the direct combustion reactions of solid fuel resulting in the direct formation of additional gaseous products, including CO, CO_2 and water [11]. Oxidation of pyritic impurities in coal refuse piles is another supplementary factor that enhances coal combustion. Oxidation of pyrite is a highly exothermic reaction that increases the temperature of the coal and thus enhances its rate of oxidation. This process requires the presence of moisture to proceed. High concentrations of CO and CO_2 (~6%) have been reported from coal pile oxidation at a depth of 1.5 m within a stockpile and a dangerous level of CO (400–600 ppm_v) above the stockpile (1 m) [12]. Emissions of CH_4 have been reported from coal stockpiles weathering, exceeding 75,000 parts per million (ppm) at depths as deep as 4 m [13]. Despite the importance of coal weathering in coal pile combustion, data have suggested that only around 14% of the total GHG emissions (expressed as equivalent CO_2, $CO_{2,eq}$) from coal and coal refuse pile fires arise from waste coal oxidation, which was assumed to include some combustion [14]. Due to this low contribution from coal weathering, this contribution was not considered in the estimates of GHG emissions from coal refuse pile fires.

Materials such as coal refuse, which are prone to spontaneous combustion, have a critical temperature of self-heating (SHT). If the temperature of the waste coal in a pile reaches the SHT before any equilibrium is attained (through dissipation of heat) then the oxidation accelerates until combustion occurs. It is not just exposure to air that can cause spontaneous combustion, as water can also have a drastic effect on coal refuse pile combustion. Water will, at first, cause the waste coal to swell as it is absorbed and then shrink as the water evaporates. This exposes more waste coal surface area as the waste coal structure changes and can lead to higher rates of oxidation, self-heating and combustion. Combustion will occur anywhere between 110 and 170°C, and flames will appear around 200°C, with CH_4 released at about 240°C [15]. It is generally accepted that lower rank coals and their refuse are more prone to spontaneous combustion than higher rank coals.

Quantifying spontaneous combustion emissions of coal refuse piles is difficult due to the mechanisms that participate in the process, including convective transport through vents and other surface openings and diffusion through the pile material and overburden (see Figure 3) [16]. Figure 3 illustrates the spontaneous combustion emissions resulting from a coal seam; however, the process is similar for coal and coal refuse piles. A study verified that the ratio of the surface to the volume of a coal pile, including coal refuse piles, is one of the main key factors for spontaneous combustion [17]. Unlike stack emissions, emissions from coal refuse pile spontaneous combustion are often diffused over a large “ill-defined” area and from different sources (vents and fissures) in the pile. This makes measurement of all coal refuse pile combustion emissions difficult to measure, requiring selection of sampling points and areas to provide an overall representative indication of the emissions across the burning site.

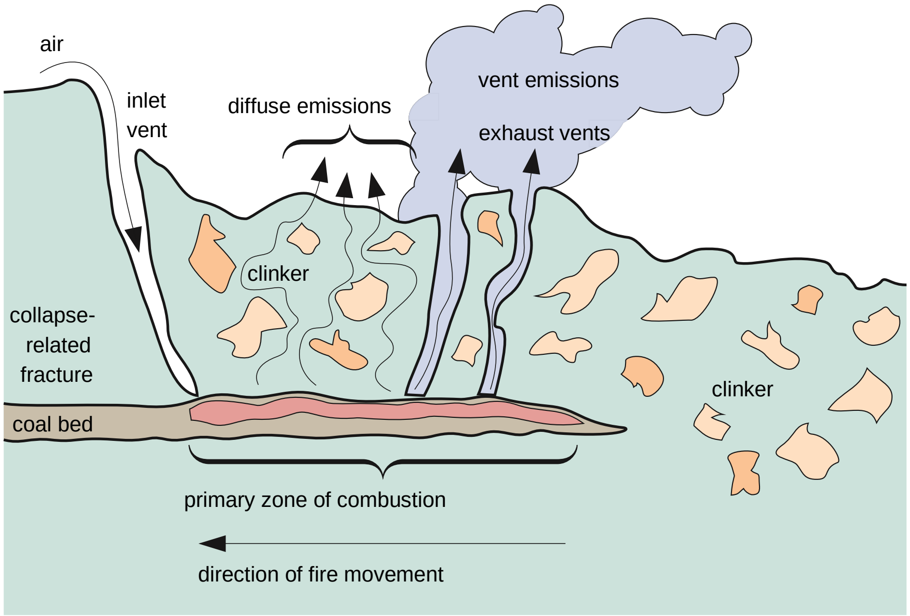


Figure 3: Conceptual Model of Spontaneous Combustion from Coal Piles [16]

For sources such as coal-fired power plants, the methods used for reporting emissions to inventories are specified in standards. However, there are no known national or international methods prescribed for quantifying emissions from spontaneous combustion. This is complicated by the fact that coal pile fires are sporadic, not evenly distributed and often underground. Two options are available to quantify GHG emissions from coal pile fires; viz, measurements from site mapping or remote sensing in order to obtain a representative distribution of sampling sites across the entire affected area; or simpler empirical approaches for obtaining pollutant emission rates from spontaneous combustion, where the chemical characteristics of the coal, such as the carbon content, are used to estimate the formation of GHG's.

There are a number of reports that provide site-specific measurement data on a range of waste coal pile scenarios. These data can be used to create emissions factors for coal pile emissions. For example, measurements from different bituminous waste coal pile scenarios in South Africa - rehabilitated pile not on fire, burnt pile and smoking pile-, under different wind conditions, showed CO_2 fluxes in the range from 0.2 to 321, to 7,393 kg/m^2/y, respectively; which, when accounted for the specific pile area resulted in CO_2 emissions from 7 up to 633,915 t/y. The apparent standard deviation of the data was put at ±20% [18]. Another study of CO_2 fluxes from the Mulga gob (bituminous coal refuse piles are named gob, while anthracite coal refuse piles are referred as culm) fired in northern Alabama resulted in CO_2 fluxes between 876 and 1,606 kg/m^2/y, and total CO_2 emissions for the 21.5 acres studied at 76,650-137,970 t/y [19].

Temperature measurements showed localized hot spots in the Mulga coal fire, some of which exceed 300°C. When an average emission rate per unit area (approximately 3,800 $kg/m^2/y$) is put in context with respect to the potential acreage that can be subject to spontaneous combustion (18,170 acres of coal refuse in Pennsylvania alone), this gives approximately 280 million t/y of CO_2 emissions solely. For comparison, a 500 MW coal-fired power plant can emit around 10,000 t/d (1.8 t/y at a capacity factor of 0.5) of CO_2. Power plants would have a capacity factor, while the coal pile fire could burn the entire year. Some of the variability in emissions reported is due to 'breathing cycles' which vary from seconds to minutes, and also coal fire dynamics which vary with the coal and rock within the pile combustion zone. This would include the suppression of fire by waste rock. There is also variability of measurements over time between vents. For example, at one site in the U.S. the CO_2 flux varied from 50,458 to over 2,775,168 $kg/m^2/y$, meaning the variability between vents in this one location was over two orders of magnitude [16].

There are also a number of references that report simplistic ways of estimating potential GHG emissions from coal refuse pile spontaneous combustion. For example, they assume that all the carbon in the coal is combusted and multiply this by an assumed amount of coal consumed. However, the kinetics of coal combustion dictate the rate of reactions in the pile, and the degree of full combustion of all carbon (C) in the pile may not be complete, with subsequent partial GHG emissions. One of these simplified approaches exemplifies that incomplete combustion of 1,000 kg of coal with 750 kg of C leads to 1.3 tons (1,300 kg/t) of CO_2, and 0.18 tons (180 kg/t) of CH_4. It further utilizes a 21:1 CH_4/CO_2 greenhouse impact in the atmosphere to provide an emissions factor of 5,100 kg CO_2 equivalent ($CO_{2,eq}$) per ton of coal for pile spontaneous combustion [20]. Another similar approach that utilizes a 225:2 molar ratio of GHG (CO_2:CH_4) and an average carbon content of 54% resulted in 1,952 kg/t for CO_2 and 6.2 kg/t for CH_4, with a 2,085 kg $CO_{2,eq}$ per ton of coal [21].

Other sources have published results of methods used to establish emissions factors for several broad categories of coal fire sites. As early as 1978, the U.S. Environmental Protection Agency (EPA) published mass emissions and emission factors for a range of pollutants, including CH_4 for burning coal refuse piles, impoundments, abandoned mines and outcrops (see Table 1) [22]. The Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia provided emissions factors for sites with obvious combustion and gas venting, sites with combustion but no venting and sites where there is no visible combustion. The GHG emissions factors given for those scenarios are: 29,518, 552 and 107 $kg/m^2/y$ for CO_2, respectively; and 492, 95 and 0 $kg/m^2/y$ for CH_4. The coal for these factors was reported to have a total carbon content of 80% [23]. Additionally, a 2015 publication reports emissions characteristics and emission factors for estimation of GHG emissions (in g/t/s, where t is the GHG emission time (in seconds)) from spontaneous coal combustion in China for two types of patterns, spontaneous coal combustion involving mining activities (air leakage patterns called “Pattern A”) and coal-gangue-dump spontaneous combustion, coal-piles spontaneous combustion and unexploited-crop spontaneous combustion, which are simply caused by surface wind leakage (air leakage patterns are called “Pattern B”) [24]. Values are given for three temperature ranges representative of different stages in the combustion process. Table 2 includes lower, upper, mean and standard deviation of these emissions factors for different combustion stages (corresponding to combustion below 200°C, 200 to 450°C, above 450°C, and above 700°C.) The Norwegian Government follows a simple emissions factor, equivalent to 2,520 kg CO_2/t coal combusted [25].

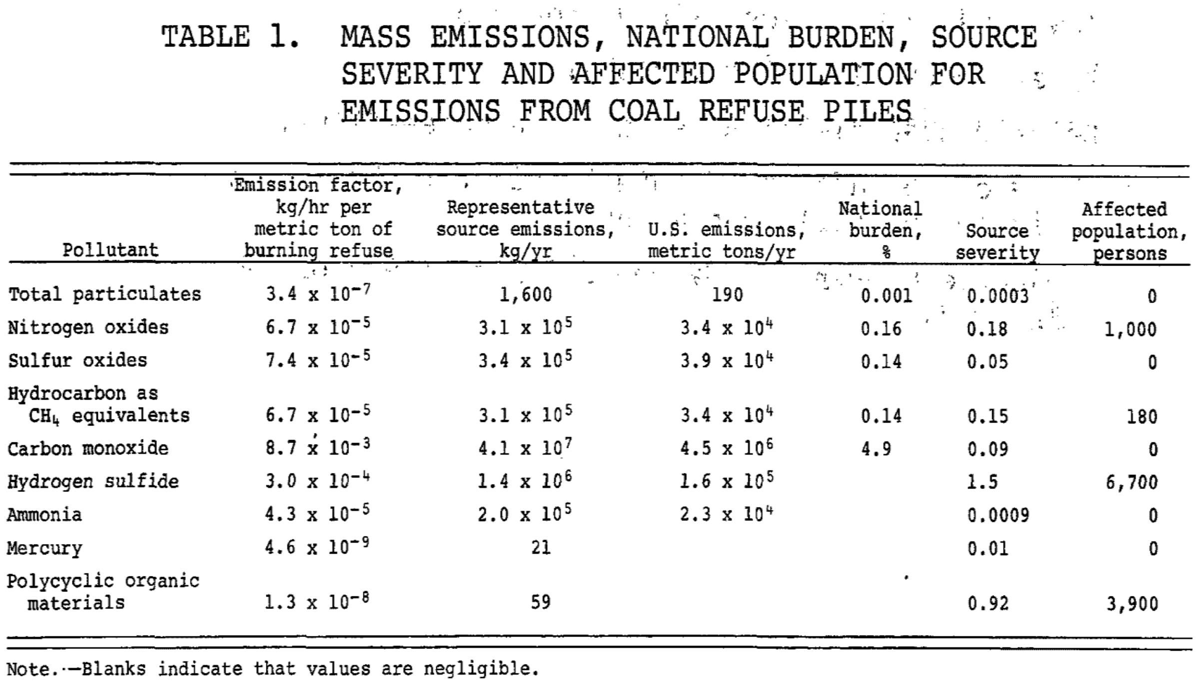
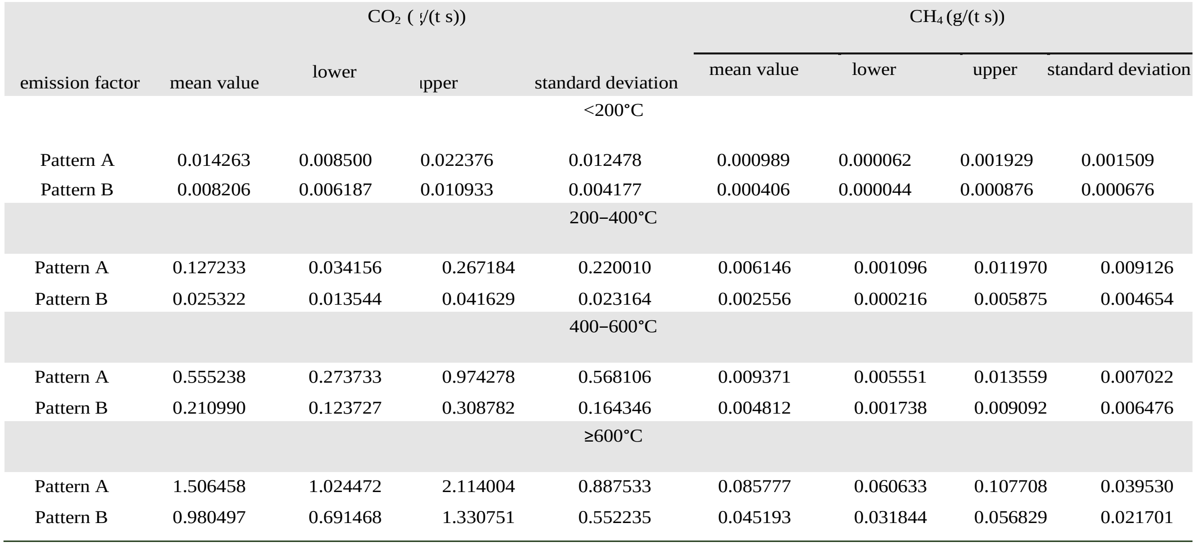


TABLE 1. MASS EMISSIONS, NATIONAL BURDEN, SOURCE SEVERITY AND AFFECTED POPULATION FOR EMISSIONS FROM COAL REFUSE PILES

Pollutant	Emission factor, kg/hr per metric ton of burning refuse	Representative source emissions, kg/yr	U.S. emissions, metric tons/yr	National burden, %	Source severity	Affected population, persons
Total particulates	3.4×10^{-7}	1,600	190	0.001	0.0003	0
Nitrogen oxides	6.7×10^{-5}	3.1×10^{5}	3.4×10^{4}	0.16	0.18	1,000
Sulfur oxides	7.4×10^{-5}	3.4×10^{5}	3.9×10^{4}	0.14	0.05	0
Hydrocarbon as CH_4 equivalents	6.7×10^{-5}	3.1×10^{5}	3.4×10^{4}	0.14	0.15	180
Carbon monoxide	8.7×10^{-3}	4.1×10^{7}	4.5×10^{6}	4.9	0.09	0
Hydrogen sulfide	3.0×10^{-4}	1.4×10^{6}	1.6×10^{5}		1.5	6,700
Ammonia	4.3×10^{-5}	2.0×10^{5}	2.3×10^{4}		0.0009	0
Mercury	4.6×10^{-9}	21			0.01	0
Polycyclic organic materials	1.3×10^{-8}	59			0.92	3,900

Note.—Blanks indicate that values are negligible.

Table 2: GHG Emission Factors Caused by Spontaneous Coal Combustion during Different Combustion Stages



	CO_2 (g/(t s))				CH_4 (g/(t s))			
emission factor	mean value	lower	upper	standard deviation	mean value	lower	upper	standard deviation
				<200°C				
Pattern A	0.014263	0.008500	0.022376	0.012478	0.000989	0.000062	0.001929	0.001509
Pattern B	0.008206	0.006187	0.010933	0.004177	0.000406	0.000044	0.000876	0.000676
				200−400°C				
Pattern A	0.127233	0.034156	0.267184	0.220010	0.006146	0.001096	0.011970	0.009126
Pattern B	0.025322	0.013544	0.041629	0.023164	0.002556	0.000216	0.005875	0.004654
				400−600°C				
Pattern A	0.555238	0.273733	0.974278	0.568106	0.009371	0.005551	0.013559	0.007022
Pattern B	0.210990	0.123727	0.308782	0.164346	0.004812	0.001738	0.009092	0.006476
				≥600°C				
Pattern A	1.506458	1.024472	2.114004	0.887533	0.085777	0.060633	0.107708	0.039530
Pattern B	0.980497	0.691468	1.330751	0.552235	0.045193	0.031844	0.056829	0.021701

RESULTS AND DISCUSSION

Calculations were carried out to obtain a comparative assessment on the impact on GHG emissions from unabated coal refuse pile fires vs. the RTE option in the Appalachian region. RTE plants are under constant scrutiny and pressure due to their tax status and subsidies, power sale competition and environmental performance. Environmental regulations factor in the negative environmental externalities of coal refuse plants; however, they do not consider the AML remediation aspect of these plants, subjecting the industry to an unbalanced regulatory environment. At the core of the regulatory challenges for coal refuse plants is the EPA policy that emissions standards consider only the impact of plant emissions on the environment and health, while disregarding the primary function of these plants, which is beneficiation of coal refuse piles and the associated environmental benefit of pile combustion reductions. Historically, the EPA has acknowledged the environmental benefits of coal refuse-fired plants. In 2011, the EPA reported that “units that burn coal refuse provide multimedia environmental benefits by combining the production of energy with the removal of coal refuse piles and by reclaiming land for productive use.” It also acknowledged that coal refuse burning facilities equipped with circulating fluidized beds (CFBs) meet comparable air emissions targets than most existing pulverized boilers and argued that “because of the unique environmental benefits that coal refuse-fired electric generating units (EGU’s) provide these units warrant special consideration.” However, a subcategory for coal refuse plants does not exist, and they are treated within the same category and standards as conventional coal-fired units [26].

Tables 3 and 4 include data from ARIPPA (transcribed from EPA's Compliance Assurance Monitoring (CAM) inventory) for coal refuse consumption and CO_2 emissions in tons for selected available years from 2010 to 2020 [8]. Eleven stations are reported, corresponding to Colver Green Energy, Ebensburg Power Company, Gilberton Power Company, Mt. Carmel Cogen, Northampton Generating Company, Panther Creek Power Operating, Westwood Generation, Schuylkill Energy Resources, Scrubgrass Generating Company and Seward Generation in Pennsylvania, plus Grant Town in West Virginia. The average annual processed refuse coal by all these stations is 7,009,970 tons (ranges from about 5.5 to 9.1 million tons of coal refuse). The average CO_2 emissions tonnage is 8,949,666 (ranges from about 6.8 to 11.6 million tons). This represents an average emissions factor of 1,277 kg CO_2 per ton of coal refuse burned by the RTE power plants in the Appalachian region.

Table 3: Coal Refuse Consumption by RTE Plants in Pennsylvania and West Virginia for Selected Years

Plant	2010	2012	2014	2015	2016	2017	2018	2019	2020
Colver Green Energy	748,094	610,361	629,004	617,146	536,867	573,999	596,392	592,514	388,966
Ebensburg Power Company	494,707	502,197	427,654	238,675	250,711	281,681	384,315	290,967	327,397
Gilberton Power Company	556,832	410,026	609,378	613,437	601,949	586,437	656,697	648,655	676,295
Mt. Carmel Cogen	413,754	523,781	541,066	559,590	546,535	565,804	524,318	177,876	88,998
Northampton Generating Company	511,697	602,157	480,069	315,950	197,215	176,476	175,253	113,409	7,068
Panther Creek Power Operating	626,410	622,799	577,953	478,182	130,290	90,195	145,145	101,419	58,358
Westwood Generation	317,499	327,945	358,362	343,479	95,576	36,409	335,289	226,938	329,154
Schuylkill Energy Resources	1,144,273	1,361,596	1,328,023	1,258,446	1,340,829	1,269,238	1,387,820	1,185,422	1,231,504
Scrubgrass Generating Company	606,349	606,486	415,387	267,940	399,632	446,918	469,098	349,290	13,619
Seward Generation	3,209,684	1,567,190	2,443,146	1,495,538	2,203,292	1,999,982	1,908,056	1,450,490	1,910,629
Grant Town Power Plant, VW	416,728	551,160	434,084	434,050	419,030	521,950	523,592	490,253	455,235
Industry Total	9,046,027	7,685,696	8,244,126	6,622,431	6,721,926	6,549,089	7,105,976	5,627,232	5,487,224

Table 4: CO_2 Emissions from RTE Plants in Pennsylvania and West Virginia for Selected Years

Plant	2010	2012	2014	2015	2016	2017	2018	2019	2020
Colver Green Energy	942,962	967,531	1,041,234	1,038,955	907,763	975,334	993,160	920,699	602,775
Ebensburg Power Company	611,693	592,246	565,559	310,163	329,222	419,572	548,322	391,372	469,822
Gilberton Power Company	795,228	570,622	835,445	887,097	962,144	913,441	874,019	882,688	897,178
Mt. Carmel Cogen	505,555	470,804	488,427	489,637	517,125	517,821	478,559	156,486	82,699
Northampton Generating Company	936,642	946,095	832,462	574,102	343,885	287,081	270,247	202,048	12,599
Panther Creek Power Operating	931,469	901,835	879,383	711,547	185,668	112,383	201,920	127,885	64,506
Westwood Generation	320,236	334,816	381,582	360,042	100,370	41,749	386,864	225,344	316,480
Schuylkill Energy Resources	1,088,633	1,231,338	1,166,993	1,149,145	1,158,965	1,081,351	1,195,451	1,126,431	1,140,077
Scrubgrass Generating Company	1,012,118	944,754	683,518	385,776	709,989	661,183	610,827	367,813	11,497
Seward Generation	3,748,835	1,935,319	2,647,888	1,761,841	2,840,036	2,532,856	2,609,007	1,900,603	2,459,035
Grant Town Power Plant, VW	721,797	907,737	831,796	744,538	917,535	874,633	859,231	829,928	755,922
Industry Total	11,615,168	9,803,098	10,354,286	8,412,842	8,972,701	8,417,405	9,027,608	7,131,296	6,812,590

For the particular estimations used for comparison of the GHG footprint of both RTE and uncontrolled, unregulated coal refuse pile fires, the 2019 EGrid ARIPPA database was utilized [8]. This year contains GHG data fully documented for 13 FBC plants, including Grant Town

Power Plant in West Virginia. However, only the 11 plants for which coal refuse data is available, as included in Table 3, was used. Detailed performance and emissions data for these plants is included in Table 5. As the data in Table 5 indicate, the reported GHG tonnage for 2019 for all these plants is 7,759,289 for CO_2, 836 for CH_4 and 126 for nitrous oxide (N_2O). In order to estimate the level of $CO_{2,eq}$ for the GHG's, a factor of 28 was used for CH_4. Methane is a powerful greenhouse gas with a 100-year global warming potential 28-34 times that of CO_2. Measured over a 20-year period, that ratio grows to 84-86 times. The lowest intensity factor was used since it is more aligned with estimations in the environmental community. Releasing 1 kg of N_2O into the atmosphere is about equivalent to releasing roughly 298 kg of CO_2. Nitrous oxide persists in the atmosphere for more than a century. Its 20-year and 100-year GWP are basically the same. The $CO_{2,eq}$ for the combined CO_2 plus CH_4 effect is 7,782,687 tons. When the impact from N_2O is included, the $CO_{2,eq}$ reaches a level of 7,820,176 tons. However, the impact of N_2O was not included in the comparison due to lack of N_2O emission factors for coal refuse pile spontaneous combustion.

Table 5: 2019 Performance and Emissions Data for RTE Plants in Pennsylvania

Plant name	Data Year	State	Plant primary fuel	Plant capacity factor	Plant nameplate capacity (MW)	Plant annual heat input from combustion (MMBtu)	Plant total annual heat input (MMBtu)	Plant annual net generation (MWh)	Plant nominal heat rate (Btu/kWh)	Estimated CO2 (tons)	Estimated CH4 (tons)	Estimated N2O (tons)
Cambria Cogen	2019	PA	WC	0.1283	98.0	1,176,099	1,176,099	110,109	10,681	118,214	11.7	1.6
Colver Green Energy	2019	PA	WC	0.7417	118.0	9,721,258	9,721,258	766,678	12,680	928,541	97.0	13.2
Ebensburg Power Company	2019	PA	WC	0.4673	57.6	3,250,711	3,250,711	235,779	13,787	321,367	35.4	5.9
Gilberton Power Company	2019	PA	WC	0.8062	88.4	8,081,620	8,081,620	624,307	12,945	868,287	91.6	14.7
Mt. Carmel Cogeneration	2019	PA	WC	0.1960	47.3	1,263,937	1,263,937	81,195	15,567	134,962	13.2	1.7
Northampton Generating Plant	2019	PA	WC	0.1314	134.1	1,875,877	1,875,877	154,377	12,151	201,808	26.4	3.4
Panther Creek Energy Facility	2019	PA	WC	0.1280	94.0	1,205,647	1,205,647	105,383	11,441	115,159	15.9	2.2
Scrubgrass Generating Plant	2019	PA	WC	0.2906	94.7	3,993,649	3,993,649	241,077	16,566	367,812	39.9	5.4
Seward	2019	PA	WC	0.2653	803.2	20,218,472	20,218,472	1,866,633	10,832	1,900,596	229.3	36.7
St. Nicholas Cogeneration Project	2019	PA	WC	0.6910	99.2	10,009,713	10,009,713	600,494	16,669	1,074,791	95.3	13.6
Wheelabrator Frackville Energy	2019	PA	WC	0.8046	48.0	5,246,368	5,246,368	338,306	15,508	534,433	57.1	9.5
WPS Westwood Generation, LLC	2019	PA	WC	0.4039	36.0	2,602,120	2,602,120	127,388	20,427	278,480	24.8	3.5
Grant Town Power Plant	2019	WV	WC	0.8533	80.0	8,916,529	8,916,529	598,016	14,910	914,839	98.1	14.3
									TOTAL	7,759,289	836	126

GHG emissions estimations were then carried out for equivalent coal volumes processed by the RTE industry in Pennsylvania in 2019, which if not burned will remain scattered in piles around former coal mine sites, representing a risk to vegetative life and negatively impact human health. The Pennsylvania DEP has estimated that 6.6 million tons of coal refuse burn each year (2016) in unintended, uncontrolled fires – releasing 9 million tons of CO_2 and other regulated air pollutants [4]. The environmental footprint of these fires is hard to quantify precisely since the following factors affect emissions from coal refuse piles: oxygen concentration in the pile, particle size distribution, wind speed, type of coal, moisture content of coal and relative humidity, temperature [22]. From a study of the distribution of coal piles, a representative coal pile has been defined by the EPA as containing 100,000 tons of coal, with an average pile height of 5.8 m, located with an annual wind speed of 10 mph [26]. The EPA has also indicated that a representative burning coal pile/impoundment is defined as one with a volume of 1.7 x 10^6 m^3 and an average in situ dry density of 1.5 t/m^3, with about 21% of it burning [27]. If the EPA estimates are used, in combination with Pennsylvania's DEP inventory of refuse piles, there will be 100,000 t/pile x 840 piles x 0.21 burn proportion = 17.6 million tons of coal refuse burned in 2020. This estimate mismatches with the 2016 Pennsylvania estimate of 6.6 million tons of coal refuse burnt in a year. The difference is most likely due to the estimated size of the coal pile by EPA (which was developed in 1978) of 2.55 million ton/pile vs. 0.53 million ton/pile reported by the Pennsylvania DEP's inventory (443.9 million tons/840 piles). These calculations illustrate the difficulty in using emissions factors that include pile dimensions.

In order to compute GHG emission estimates for coal refuse piles, emissions factors were used. As it was previously mentioned, emission factors are typically provided in terms of kg (or mg) or ppm per volume of emitted gas (m^3), or per area of land (m^2), and may have a time factor associated with them (kg/m^2/day or year (assuming a full year of burning)). However, information on pile area is very scarce. For example, it has been suggested to use 3,000 t/CO_2 per year for each km of affected land [23]. Other emission factors may be provided in units of kg per hour or year, per ton of burning refuse. These factors require an estimate of coal burn rate and are more appropriate for underground mines. Thus, for estimating emissions from large coal piles this would involve multiplying the emission factor prepared for the coal piles by the size of the stockpile and/or the total activity data or coal burnt. For spontaneous combustion, obtaining the activity data is challenging. Estimating the quantities of coal involved in fires it is not simple. One possible option is to use specific visual assessments, or optical, radar or thermal data of the pile(s) fire/changes.

For this particular study, emissions factors (in kg CO_2 or CH_4/t coal burnt) were used in combination with the particular reference case, which is the amount of coal refuse processed by the RTE plants in 2019 (5,627,232 tons). Four emissions factors were used from the references identified in this review. A fifth reference (Reference 24) provides a very low emission factor that was considered an outlier. Table 6 includes a summary of the calculations to quantify CO_2, CH_4 and $CO_{2,eq}$ emissions for the four different emission factors. Depending on the emission factors selected, the expected GHG emissions equivalent from unremedied waste piles in the Appalachian region, for a volume of coal refuse adjusted for 2019 for the 11 RTE units reported in Table 5 would range from 13,662,919 to 36,239,374 tons. This compares to the corresponding

$CO_{2,eq}$ emissions reported by the RTE stations in the region in 2019 at 7,128,113 tons, at a rate of GHG reduction per ton of coal refuse reclaimed by RTE of 1.27 tons $CO_{2,eq}$/ton coal refuse. Thus, each ton of coal refuse is expected to produce GHG emissions between 2.43 and 6.44 tons $CO_{2,eq}$ with a net reduction of between 1.16 and 5.17 tons $CO_{2,eq}$ per ton of coal refuse reclaimed by the coal refuse RTE industry. The calculations suggest that coal refuse pile GHG emissions exceed by a factor that can be between 1.9 to 5.1 larger than the corresponding emissions if burned under controlled conditions in the RTE units. Based upon the four emissions factors used in this study, when the full emissions profile of the coal refuse RTE industry is considered, including the reduction of emissions from reclamation of coal refuse piles, the coal refuse RTE industry produces a net reduction in GHG emissions. For a 20-year GWP cycle, the total offset amount of $CO_{2,eq}$ is of the order of 0.13 to 0.58 billion tons.

Table 6: Comparative Estimate of GHG Emissions from Coal Pile Refuse and RTE Reclamation

	CO2 Emissions Factor [kg/t coal]	CH4 Emissions Factor [kg/t coal]	Coal Processed by RTE 2019 [t]	CO2 Emissions [t]	CH4 Emissions [t]	CO2,eq Emissions [t]
Reference 20	1,300	180	5,627,232	7,315,402	1,012,902	35,676,651
Reference 21	1,952	17	5,627,232	10,984,357	95,663	13,662,919
Reference 25	2,520	101	5,627,232	14,180,625	566,475	30,041,916
Reference 28	3,500	105	5,627,232	19,695,312	590,859	36,239,374

REFERENCES

1. U.S. EIA, Weekly U.S. Coal Production, Year-to-date and 52 weeks ended, October 20, 2022.
2. U.S. EIA, Coal Data Browser, Aggregate coal mine production for all coal (short tons), 2001-20.
3. O'Keefe, J. et al., CO_2, CO and Hg emissions from the Truman Shepherd and Ruth Mullins Coal Fires, Eastern Kentucky, USA. Science of the Total Environment; 408: 1628-1633 (2010).
4. Econsult Solutions, Economic and Environmental Analysis of Pennsylvania's Coal Refuse Industry. Report September 2016.
5. PA DEP, Office of Active and Abandoned Mine Operations. Simpson Northeast Coal Refuse Bank Fire – Fact Sheet, May 2014.
6. Patel, S., The Coal Refuse Dilemma: Burning Coal for Environmental Benefits. Power, July 2016.
7. Dalberto, A., et al., Chapter 1. Overview: Coal Ash Beneficial Use and Mine Land Reclamation, https://files.dep.state.pa.us/Mining/DistrictMining/, 2022.
8. ARIPPA Database, October 2022.
9. Pennsylvania Public Utility Commission, Alternative Energy Portfolio Standards Act (AEPS) Fact Sheet," www.puc.state.pa.us.
10. Zhang, X., Gaseous Emissions from Stockpiles. CCC/213, London, UK, IEA CCC, January 2013.
11. Wang, H., et al., Coal Oxidation at Low Temperatures: Oxygen Consumption, Oxidation Products, Reaction Mechanism and Kinetic Modelling. Progress in Energy Combustion Science; 29(6); 487-513 (2003).
12. Grossman, S., Davidi S. and Cohen, H., Emission of Toxic and Fire Hazardous Gases from Open Air Coal Stockpiles. Fuel; 73(7); 1184-1188 (1994).
13. Davidi, S., Grossman, S. and, Cohen, H., Organic Volatiles Emissions Accompanying the Low Temperature Atmospheric Storage of Bituminous Coals. Fuel; 74(9); 1357-1362 (1995).
14. Day, S. and Riley, K., Waste Streams in Black Coal Mining and Coal-Fired Power Generation. Research Report 42. Pullenvale, Qld, Australia, CCSD (Cooperative Research Centre for Coal in Sustainable Development), CQAT Technology Transfer Centre http://www.ccsd.biz/publications/files/, 32 pp, January 2004.
15. Stracher, G. and Taylor, T., Coal Fires Burning Out of control Around the World: Thermodynamic Recipe for Environmental Disaster. International Journal of Coal Geology: 59: 7-17 (2004).
16. Sloss, L., Quantifying Emissions from Spontaneous Combustion. CCC/224, London, UK, IEA CCC, September 2013.
17. Krietsch, A., et al., Laboratory Investigations on the Ignition and Burning Process of Coal: Fire Characteristics and Gas Emissions. In Drebenstedt C (editor): Latest Developments in Coal Fire Research- Bridging the Science, Economics, and Politics of a Global disaster; Proceedings of "ICCFR2; Second International Conference on Coal Fire Research, p. 147-152, Freiberg, (2010).
18. Cook, A. and Lloyd, P., The Estimation of Greenhouse Gas Emissions from South African Surface and Abandoned Coal Mines. Journal of the Southern African Institute of Mining and Metallurgy; 112: 1087-1090 (2012).

19. Engle, M., et al., Methods to Quantify Diffuse CO_2 Emissions from Coal Fires using Unevenly Distributed Flux Data. Coal and Peat Fires: A Global Perspective. vol 2. Stracher GB, Prakash A, and Sokol EV(eds) Multimedia, Elsevier (2010).
20. Gielish, H. and Kripp, C., Coal Fires a Major Source of Greenhouse Gases – A Forgotten Problems. Environmental Risk Assessment Remediation 2017 Vol. 2 Issue 1. http://www.alliedacademies.org/environmental-risk-assessment-and-remediation/. ISSN: 2529-8046.
21. Engle, M., et al., Quantifying Greenhouse Gas Emissions from Coal Fires using Airborne and Ground-Based Methods. International Journal of Coal Geology: 88: 147-151 (2011).
22. EPA Source Assessment: Coal Refuse Piles, Abandoned Mines and Outcrops, State of the Art. EPA 600 2-78 004v, July 1978.
23. Carras, J., et al., Greenhouse Gas Emissions from Low Temperature Oxidation and Spontaneous Combustion at Open-Cut Mines in Australia. International Journal of Coal Geology; 78; 161-168 (2009).
24. Wang, H. and Chen, C., Experimental Study on Greenhouse Gas Emissions Caused by Spontaneous Coal Combustion. DOI: 10.1021/acs.energyfuels.5b00327, Energy Fuels 29, 5213−5221 (2015).
25. Sandmo, T., The Norwegian Emission Inventory 2012: Documentation of Methodologies for Estimating Emissions of Greenhouse Gases and Long-Range Transboundary Air pollutants. Norway, Statistics Norway. http://www.ssb.no/a/english/publikasjoner/pdf/doc201243_en/doc_201243_en.pdfv, 2012.
26. Environmental Protection Agency, Solid Waste Rule-Identification of Non-Hazardous Secondary Materials That Are Solid Waste, Federal Register 76: 54, March 2011.
27. EPA Source Assessment: Coal Storage Piles. EPA 600 2-78 004k, May 1978.
28. Van Dijk P, Zhang J, Jun W, Kuenzer C, Wolf K-H (2011) Assessment of the Contribution of Insite Combustion of Coal to Greenhouse Gas Emission: Based on a Comparison on Chinese Mining Information to Previous Remote Sensing Estimates. International Journal of Coal Geology: 86:108-119 (2011).