650 Suffolk St., Suite 200
Lowell, MA 01854

T 978.970.5600
TRCcompanies.com

Net Air Emission Benefits from the Remediation of Abandoned Coal Refuse Piles

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Robert G. Fraser, QEP and Patrick Fennell, PE, TRC Environmental Inc.

Executive Summary

Abandoned coal refuse piles represent a legacy environmental hazard throughout the Appalachian coal producing region of the United States. Due to the sheer magnitude of legacy coal refuse abandoned in Appalachia, existing coal refuse piles represent a well-documented threat to the natural environment[1]. While the adverse impacts of rainwater runoff are well documented, the inventory of abandoned coal refuse also represents a substantial ongoing source of uncontrolled air emissions, including planet warming greenhouse gases and other fugitive air pollutants[2]. As measured in terms of carbon dioxide equivalent (CO_2e), annual greenhouse gas (GHG) emissions due to legacy coal refuse piles can no longer be ignored simply because the companies that deposited this waste as much as a century or more ago are long gone, leaving behind only a lasting legacy of pollution.

This study seeks to characterize the magnitude of GHG and other air pollutants being emitted to the environment every day from abandoned coal refuse piles in Appalachia. It is well documented that abandoned coal refuse piles are subject to a natural oxidation process leading to spontaneous combustion, which releases fine particulate and products of incomplete combustion including carbon dioxide (CO_2) and methane to the atmosphere[3]. Fugitive (area-source) air pollutant emissions from abandoned coal refuse piles affect air quality locally as well as GHG emissions globally. The gradual emission of GHGs (such as methane and CO_2) from the natural process of partial oxidation of existing abandoned coal refuse piles, if unabated, will remain virtually "forever emitters" of GHG and other air pollutants. When characterizing potential adverse air quality emissions from abandoned coal refuse piles, it is particularly useful to compare their potential in situ annual and lifetime air pollution impacts with the highly controlled and well documented air emissions from permanently remediating an equivalent annual amount of coal refuse by the reclamation-to-energy industry.

The Appalachian region has relied for years on the coal refuse reclamation-to-energy industry to permanently remediate abandoned coal mining waste, which represents a cost-effective and permanent solution to this significant environmental problem[4]. In addition to addressing the multitude of soil and water environmental benefits performed by the industry as cited in prior studies, the controlled combustion-remediation of coal refuse eliminates its ability to emit additional air pollutants every year, as it has since being originally piled. Combustion of coal refuse in a highly-controlled manner permanently removes over 5.5 million tons of actively emitting abandoned coal refuse from the global emission inventory every year[5]. There is no question that coal refuse reclamation-to-energy plants, by permanently breaking the fossil GHG emission chain, also emit CO_2. It is therefore the

purpose of this study to numerically compare air quality and GHG emissions from ongoing remediation of coal refuse to the uncontrolled and ongoing air emissions of allowing existing coal refuse piles to remain in situ (including potential re-planting alternatives).

This study estimates that the coal refuse reclamation-to-energy facilities in Pennsylvania (PA) and West Virginia (WV) alone reduce the equivalent *net* GHG emissions that would otherwise be emitted from the same amount of coal refuse by over 20 million tons of CO_2e in a single year. The numerical characterization of this study converted to CO_2e are presented in Table 1 below. Avoided GHG emissions from the permanent remediation of abandoned coal refuse piles in Northern Appalachia are presented in (red)[6,7,8].

Table 1

Estimated Net Lifecyle GHG Emission Reductions from Permanent Remediation of 5,546,818 tons of Coal Refuse Annually					
Pollutant	**Unremediated Coal Refuse Estimated Annual Air Emissions) (5,546,818 (tons)**	**Unremediated Coal Refuse Estimated Lifecycle Emissions (5,546,818 tons X assumed 10-yrs of continuous air emissions)**	**Coal Reclamation to Energy Industry Emissions to Remediate 5,546,818 tons of coal refuse (tons)**	**Net Lifecycle Emissions from Remediation of 5,546,818 tons of coal refuse (tons)**	**Net Lifecycle Emissions from Remediation of each ton of Coal Refuse by the Reclamation to energy Industry[1] (tons emitted per ton remediated)**
CO_2	6,553,760	65,537,596	7,587,349	(57,950,247)	(10.4)
CH_4	906,655	9,066,551	825	(9,065,726)	(1.6)
N_20					
CO_2e	29,220,138	292,201,380	7,607,978	**(284,593,402)**	**(51)**

The coal refuse to reclamation industry permanently remediated 5,546,818 tons of coal refuse in 2020. The values presented in Table 1 show that permanent remediation of this existing abandoned coal refuse in Northern Appalachia by the coal refuse reclamation-to-energy industry is responsible for the net ten-year (lifecycle) reduction of over 284 million tons of CO_2e. Net lifecycle CO_2e emissions will continue to be reduced by a similar amount every year that these facilities continue to operate at comparable levels. Coal refuse reclamation-to-energy plants are very efficient in terms of converting nearly 100% of the hydrocarbon component of abandoned coal refuse to CO_2 while efficiently producing useful power. When they do so, they destroy the ability of that amount of coal refuse to emit that same carbon, including as methane rather than CO_2, over many more years (a ten-year emission lifecycle has been conservatively estimated in this analysis).

The net climate change benefit of the coal refuse reclamation-to-energy industry is that converting hydrocarbons directly and efficiently to CO_2 avoids the emissions of methane which would otherwise be continuously emitted from coal refuse piles over many more years. Methane is considered to be about 81 times more potent in terms of warming the climate in the near-term (over the first 20 years after its release)[9], and when normalized over 100 years for direct comparison to CO_2 is considered by the U.S. Environmental Protection Agency (USEPA) to be about 25-28 times more potent of a greenhouse gas long-term[10]. The reduction of naturally occurring methane emissions from existing coal refuse piles has a much greater benefit to reversing global climate change than one-time (forever) conversion of coal refuse to CO_2 and useful energy. As such, it is important to compare the bottom row in Table 1, which sums the net lifecycle GHG emissions in units of CO_2e for the same amount of coal refuse either allowed to remain in situ passively emitting uncontrolled air pollutants or remediated forever for responsible energy recovery by the coal refuse reclamation-to-energy industry.

The coal refuse reclamation-to-energy industry was found to eliminate 51 net tons of CO_2e emissions for every ton of Appalachian coal refuse that it permanently eliminates from the environment and converts to useful energy. These emissions would otherwise continue to be released into the environment over the entire coal refuse emission lifecycle (in this case estimated to be at least ten continuous years of CO_2e emissions). In 2020, the coal refuse reclamation industry combusted 5,546,818 tons of coal refuse, resulting in over a quarter billion ton net 10-year reduction of CO_2e that would have otherwise been emitted uncontrolled from coal refuse piles throughout the Appalachian region (5,546,818 tons coal refuse x 51 tons CO_2e = 282,887,718 net tons CO_2e reduced). Continuing operations will yield similar levels of net environmental benefits every year that this industry continues its important mine land reclamation mission.

As demonstrated in this study, combusting the same quantity of coal refuse permanently remediated by the coal refuse reclamation-to-energy industry in 2020 (5,546,818 tons) results in a net CO_2e reduction benefit of over a quarter billion net tons of lifecycle CO_2e emissions. Very simply, while the combustion of coal refuse does emit the greenhouse gas CO_2, doing so avoids the ongoing emissions of the potent greenhouse gas methane that would otherwise have been emitted during its extended lifecycle from that same amount of abandoned coal refuse in piles. It is very challenging to think of another economically viable and environmentally beneficial technology of any kind that could come close to providing a net CO_2e benefit of this magnitude, while eliminating the environmental problems created by coal refuse piles, as part of a national strategy to achieve “net zero” GHG emissions by 2040-2050.

Introduction

It has long been recognized that the enormous inventory of coal refuse piles abandoned by the legacy coal mining industry in Appalachia represents an ongoing ecological threat to the environment. Adverse environmental impacts to soil, stormwater runoff, surface water, and groundwater by these un-remediated, abandoned environmental hazards are well documented[11]. Comparatively fewer examinations of the adverse air quality and CO_2e greenhouse gas emission impacts of un-remediated and abandoned refuse piles have been identified in the literature.

During the 1970s and 1980s, environmental advocates and government agencies promoted and enabled investment in coal refuse reclamation-to-energy facilities capable of remediating abandoned coal refuse by recovering the useful thermal energy of this abandoned waste material to produce needed electricity. Over thirty years later, these plants are still extracting more than 5.5 million tons of polluting legacy coal refuse every year in PA and WV. Unfortunately, lack of understanding that these coal refuse reclamation-to-energy facilities operate to address legacy environmental damage in Appalachia has become confused with the environmental movement to shutter utility-scale coal-fired generating plants that extract new coal from mining for the purpose of generating electricity, all the while generating even more coal refuse from screening.

Today, we broadly recognize the goal of achieving "net zero" GHG emissions by 2040-2050[12]. In recent years, there has been a groundswell of public sentiment that coal combustion should be phased out of existence in favor of renewables that do not emit the greenhouse gas CO_2. Lost in the translation is the unique environmental role, including important net reductions in air pollutants and GHG emissions, provided by the coal refuse reclamation-to-energy industry. While the industry continues to help reverse coal refuse pile runoff pollution to water and soil, it is now incumbent to re-evaluate this industry in the context of its net GHG emissions.

This study seeks to document the coal refuse reclamation-to-energy industry's significant contribution to the net reduction of global CO_2e concentrations by permanently remediating abandoned coal refuse piles in Appalachia. Coal refuse reclamation-to-energy facilities have found a way to finance the cleanup of abandoned coal refuse piles, reducing presently occurring emissions of anthropogenic methane (potent GHGs), while also displacing other CO_2 emitted from that portion of other fossil generation sources still being phased out. Absent the coal refuse reclamation-to-energy industry, legacy coal refuse piles would remain essentially abandoned to the environment and will frustrate regional air quality and climate change goals for multiple additional generations as the abandoned piles themselves continue to emit products of incomplete combustion, CO_2, and the potent greenhouse gas methane[13]. Based on published emission estimates from the literature, the authors have compared CO_2e emissions from the remediation of 5.5 million tons of waste coal annually by the coal refuse reclamation-to-energy industry vs. the CO_2e emissions being naturally emitted to the environment by not remediating that same amount of coal refuse. The emissions of methane from abandoned coal refuse piles in Appalachia, based on measurements by USEPA[14], are many times more potent GHG emissions than the CO_2 emitted from controlled combustion of coal refuse for remediation. This study indicates that, based on published literature, the coal refuse reclamation-to-energy industry plays a very important role in reducing global and regional emissions of CO_2e.

Background

The Eastern Coal Mines of Appalachia fueled America's Industrial Revolution of the 1800s. The form of coal called Pennsylvania Anthracite (in its day referred to as "smokeless" coal) was used to stoke industrial boilers, heat homes, power steamships and railroad locomotives and for many other uses. Evidence of former coal bins can still be found in the basements of homes constructed well into the early 1900s. Eastern Bituminous coal from PA, WV, VA and KY was heavily mined as a lower cost fuel to produce steam power and later electricity for the factories that built the American economy.

The early technology of burning coal on stoker grates created demand for "stoker coal", meaning lump coal with minimal fines content. To produce stoker coal, run-of-mine coal was first processed and sized, including removal and discard of inert material (such as pyrites) and coal fines prior to shipment. In every case, coal mined in Appalachia needed to be transported to its point of use via some combination of barges, railroads and trucks. Depending on logistics, transportation often cost as much as the coal itself. These economics drove the practice of "coal washing" prior to transportation as a cost reduction measure. When mining coal, the useful fuel was often contaminated with naturally occurring inert materials such as soil, rocks and stone. There was no value to the end user in paying to ship inert, non-combustible impurities that were mined together with the coal. For these reasons, it became economically advantageous to "wash" out as much of these inert contaminants as practical prior to shipment.

In coal washing, a specific gravity separation was performed to remove the heavier inert materials such as rock and pyrites as unmarketable waste. After removal of these incombustible inert materials, the coal to be shipped became more valuable in that it contained more British thermal units (Btu) per ton shipped, less ash and less sulfur (much of the native sulfur in Eastern Coal is contained in inert material, such as pyrites). The result was that the waste materials from overburden, size separation and washing prior to shipment had no residual commercial value and were simply discarded as waste over approximately 100 years of mining operations, creating enormous legacy coal refuse piles throughout Appalachia.

Coal mining refuse (a.k.a. culm, gob, tailings, boney, silt, among other names) tends to be wetter, as fines retain more moisture, and higher in ash and sulfur content than the native coal originally mined. The typical remaining heating value of coal refuse, especially after years of weathering, is less than half the specification for steam coal (only about 5,500 Btu/lb. (USEPA AP-42) vs. about 12,000 Btu/lb. for commercial Eastern Bituminous coal). Up until the late 1970s, there was no industrial coal combustion technology capable of utilizing low heating value coal refuse. It was, therefore, a true waste byproduct with no economic value to anyone. As a result, coal refuse was simply piled up and abandoned to the elements.

Under the Surface Mining Control and Reclamation Act of 1977, landowners and companies responsible for abandoning legacy coal refuse piles are no longer liable for remediating these abandoned piles that now litter the historic coal fields throughout Appalachia. This left the cost of remediating this environmental problem, currently estimated at more than $5 billion in PA alone[15], to the state and federal government with limited resources to resolve this massive environmental problem. Even with 25 states expected to receive more than $11 billion in additional federal funding to reclaim abandoned mine land (AML) sites over the next 15 years under the bipartisan Infrastructure Investment and Jobs Act of 2021, this amount will be insufficient to even nearly fund the currently identified AML problems in Appalachia.[16]

In the late 1970s, partially in response to the Arab Oil Embargo, a new technology called circulating fluidized bed (CFB) combustion emerged with the promise of being able to cleanly burn a wide range of difficult-to-burn fuels, including low Btu, high sulfur coal refuse. For the very first time, this technology enabled responsible re-mining and energy recycling of abandoned coal refuse piles while producing electricity for sale to pay for the permanent remediation of these legacy environmental scars. Since that time, the industry has remediated more than 250 million tons of polluting coal refuse across Appalachia. The continued operation of these coal refuse reclamation-to-energy facilities can provide ongoing environmental reclamation benefits to land, water, air quality and greenhouse gas emissions to the environment while offsetting the funding shortfall for cleaning up polluting legacy coal refuse piles.

Permanent Coal Refuse Remediation

Absent permanent remediation, the thousands of legacy abandoned coal refuse piles littering Appalachia represent virtually "forever emitters" of greenhouse gases, windblown fugitive particulate fines (referred to as the inhalable pollutant, PM_{10}), hazardous air pollutants and Clean Air Act (CAA) regulated air pollutants, as they have been for over 100 years since being originally discarded. This is an important concept. When a ton of coal refuse is forever neutralized via useful energy recovery, it can never again emit air pollutants or greenhouse gases, let alone contribute to acidification of soil and water resources.

When considering the air emissions profile of these unmitigated coal refuse piles, it is meaningful to contrast them with the coal refuse reclamation-to-energy industry. We must consider the air quality benefits of permanent remediation of coal refuse under highly controlled CFB combustion conditions, employing USEPA Best Available [emissions] Control Technology (BACT) against the uncontrolled combustion pyrolysis continuously emitting air and climate pollutants within the legacy abandoned coal refuse piles dotting Appalachia.

Emissions from the coal refuse reclamation-to-energy industry are often inappropriately compared to traditional coal-fired electric utility generating units (EGUs); however, the coal refuse reclamation-to-energy industry produces fundamentally different benefits than coal-fired EGUs because they primarily provide mine land reclamation services while co-producing useful energy. These facilities do not directly compete in this regard with coal-fired power plants, which are presently being phased out of operation due to their GHG contributions to global climate change. Those pulverized coal-fired generating units are not capable of remediating abandoned coal refuse to clean up the environment in the same manner as CFB boiler technology. Coal that is mined to produce power in these facilities has been effectively sequestering carbon beneath the earth for millions of years. Mining, processing, and combustion of that sequestered carbon of newly mined coal indeed re-emits this long dormant CO_2. Abandoned refuse piles in Appalachia, however, have already been mined and are now an abandoned environmental legacy pollutant, free to continue emitting greenhouse gases and other harmful air emissions without any further human intervention over hundreds of years.

While some air pollutants and GHGs are emitted at once during controlled combustion in a CFB boiler, those boilers incorporate BACT, are designed to achieve complete combustion of hydrocarbons, and are highly regulated by both state and federal air emissions requirements. Air emissions from abandoned coal refuse piles are not. Societal goals such as net zero GHG emissions by 2050 will be frustrated by this manmade source of nearly continuous “forever” emissions of methane unless abandoned coal refuse are also permanently remediated by then.

As examined quantitatively in this study, USEPA has measured and characterized air emissions from smoldering and spontaneously combusting rogue coal refuse piles[17]. Coal refuse energy recovery and permanent remediation facilities operate very responsibly, are aggressively regulated, and operate in continuous compliance with all applicable state and federal air quality regulations and standards. State and Federal Environmental Regulatory Authorities monitor these facilities to ensure that they do not cause or contribute to a “condition of air pollution”, while air emissions from abandoned coal refuse piles are unregulated and accepted as if “naturally occurring” sources of air emissions. Their polluting emissions over enormous surface areas constitute a source of ground-level anthropogenic air emissions that should be evaluated through the lens of impacts to Environmental Justice Communities in the abandoned coal fields of Appalachia.

For any hydrocarbon fuel to be theoretically completely combusted to CO_2 and water vapor (H_2O) requires the ability to control the ideal, or stoichiometric, air-to-fuel ratio and high combustion temperatures to be continuously maintained. Insufficient, off-stochiometric air-to-fuel ratios and/or smoldering at low temperatures cause incomplete combustion of fuel. This means when there is insufficient oxygen, any fossil fuel will be only partially combusted, emitting intermediate products of incomplete combustion such as the potent greenhouse gas methane, poisonous hydrogen sulfide (H_2S) and likely the potent greenhouse gas nitrous oxide (N_2O) instead of nitrogen dioxide (NO_2).

The combustion of coal refuse lacking the stoichiometric amount of air to complete combustion, therefore, releases different, more polluting, and more dangerous emissions and GHG intermediates such as methane and nitrous oxide, uncontrolled mercury (which is highly controlled in CFB boilers[18]), odorous and poisonous hydrogen sulfide (H_2S), carbon monoxide (CO), and others directly to the local environment as ground-level area sources of air pollutants. This distinction is important because coal refuse reclamation-to-energy facilities control all regulated air pollutant emissions to maintain continuous compliance, and only emit highly controlled flue gases at high temperature and velocity from tall stacks, which are maintained according to USEPA Good Engineering Practice (GEP), to protect healthy National Ambient Air Quality Standards (NAAQS) as set forth by USEPA[19].

Coal refuse pile emissions on the other hand are unpermitted and naturally emit toxic and criteria air pollutants without dilution at ground level, where the residents of affected communities live and breathe. Being emitted at surface level, and particularly for air pollutants that are heavier than air, they can form choking clouds of pollutants that can be detected as visible haze and the odor of sulfur downwind.

These forms of incomplete combustion, which are emitted in Appalachia every hour of every day, are far more dangerous than the highly-controlled combustion environment and resultant controlled emissions of a CAA-permitted coal refuse reclamation-to-energy CFB combustion unit.

Based on these factors, the authors sought to characterize a true net comparison of the GHG and other air pollutant quantities of "forever" air emissions being emitted from legacy abandoned coal refuse piles with the documented net air emissions produced by coal refuse reclamation-to-energy facilities as they permanently remediate (destroy) abandoned coal refuse while recovering it's useful thermal energy[20]. Our comparison shows that the coal refuse reclamation-to-energy industry prevents millions of the tons of CO_2e and other partial combustion products being otherwise emitted by abandoned coal refuse piles at ground level every single year. This very real CO_2e net reduction offset will, in the future, become a necessary component of plans to actually achieve net zero GHG emissions in these States by 2050. Indeed, the authors suggest that the coal refuse reclamation-to-energy industry should be recognized in any program for limiting, banking, or trading GHG emissions for its factual ability to generate net CO_2e offsets.

Coal Refuse Pile Air Emissions

Many of the environmental problems associated with coal refuse occur as a result of pyrite oxidation and the production of acidity. Historic refuse piles are the legacy of extraction and crushing and screening of coal formerly existing as undisturbed solid coal seams. Coal refuse, then, is high in coal fragments and discarded as loose, unconsolidated waste piles that allow oxygen to interact easily with the high internal surface area of the refuse pile. One of the most well-known and noticeable environmental impacts of coal refuse piles is that they create acidic runoff, meaning that precipitation picks up pollutants that leach into surface and ground waters – a process known as Acid Mine Drainage (AMD)[21]. AMD entering a stream from a nearby coal refuse pile causes the stream to turn orange in color due to the iron precipitating out of solution as the solid, iron hydroxide ($Fe(OH)_2$). Much of the total sulfur in coal refuse is present as pyrite such as iron disulfide (FeS_2) and other sulfides that oxidize to sulfuric acid in the presence of water and oxygen.

Often overlooked is that this pyrite oxidation is an exothermic, or heat-producing, reaction. Coal refuse fires typically start as a smoldering, oxygen starved fire producing the necessary oxygen from the generation of steam from the moisture in the coal refuse[22]. The occurrence of this internal combustion within coal refuse piles is often not outwardly visible, but as this slow combustion of the burnable material occurs within the pile it may produce a reddish-brown slate called "red dog". The presence of red dog, a nonvolatile combustion product of the oxidation of coal refuse provides visual evidence of a history of uncontrolled burning of coal refuse in many older coal refuse piles. Slowly, as the fire continues to develop, avenues for oxygen migration through the refuse expand as telltale smoke coupled with the odor of sulfur transitions to open flame. The visible flames from a burning coal refuse pile are primarily fueled by the release of coal gas to the surface upon ignition.

The primary source of polluting air emissions from coal refuse piles is a result of weathering and spontaneous combustion eventually resulting in pyrolysis and surface emissions of products of incomplete combustion[23]. It is well documented that all coal, including coal refuse, decays in carbon content when left for long periods exposed to the weather (sunlight, wind, oxygen and acid precipitation) and that a continuing process of slow oxidation occurs within abandoned refuse piles that inevitably leads to spontaneous combustion[6]. During low temperature gradual oxidation, the carbon atoms that give coal refuse its heating value as a hydrocarbon fuel gradually oxidize to the greenhouse gases methane and carbon dioxide, which will continue to be emitted along with other fuel-bound air pollutants and fine particulates until there is no carbon left to be oxidized – perhaps over hundreds of years given the massive total inventory of coal refuse abandoned in Appalachia. While slow oxidation may not be noticeable to the naked eye, when thousands of acres of coal refuse are exposed to the open air, weathering of coal becomes a significant source of air and methane pollution in addition to open smoldering. These "pop-up" air emission sources continue every year for as long as abandoned coal refuse piles are allowed to persist.

Worse than this, the slow oxidation known as weathering generates heat within the pile, eventually leading to the runaway chemical reaction of increasing temperature, unlimited hydrocarbon fuel and partial oxygen, causing the phenomenon known as spontaneous combustion. Spontaneous combustion occurs first within the interior of coal refuse piles themselves because formerly crushed coal refuse contains voids, known as interstices, between the discreet broken coal fragments whose surfaces are exposed to oxygen between particles[24]. Temperature rise is most pronounced in the interior of the piles since the inner layers are not subjected to radiational or rainwater cooling as at the surface. Thus, heat from the gradual oxidation process results in increasing internal temperatures, culminating in partial, incomplete combustion as evidenced by smoke being emitted from a pile. Inside the pile, there is never sufficient oxygen to fully burn out all of the coal – rather, once coal refuse begins to smolder within an existing coal refuse pile, it can continue to smolder in the absence of an ideal stoichiometric fuel to air ratio for months or years. Unlike the carefully controlled excess air fuel combustion of a CFB boiler where the hydrocarbon content of coal refuse is efficiently burned out to water and CO_2, smoldering coal refuse is only partially converted to CO_2 and the far more potent greenhouse gas methane (CH_4).

Finally, runaway temperatures within a smoldering pile will ultimately erupt into open flame where combustion still occurs at far from the ideal stoichiometric air to fuel ratio. It is the gases generated due to pyrolysis (starved air combustion) that burn as open flame from the combustion of volatile hydrocarbons at the pile surface. From the heat so-generated, the char residue itself begins to burn to the extent sufficient oxygen is available. These types of higher temperature, but still oxygen-starved combustion not only release the greenhouse gases CO_2 and methane, but other uncontrolled air pollutant emissions such as mercury, fine particulate (smoke), oxides of nitrogen, carbon monoxide, sulfur compounds, and likely the extremely potent greenhouse gas nitrous oxide, at a higher rate than would otherwise be minimized in the well-controlled combustion conditions found at coal refuse reclamation-to-energy facilities. It is clear that the ubiquitous abandoned coal refuse piles dotting Appalachia are a significant existing source of CO_2e, hazardous air pollutants, and CAA regulated criteria air pollutants simply due to their continued existence.

Extent and Distribution of Abandoned Coal Refuse Piles in Northern Appalachia

The enormity of existing abandoned coal refuse piles in Northern Appalachia is alarming. According to publicly available inventory data from the Commonwealth of Pennsylvania and State of West Virginia, 17,190 total acres of abandoned coal refuse surface area are continuously exposed to the elements (Table 2) [25,26]. At a typical bulk density of coal refuse of 60 lb./ft^3, the published PA and WV inventories account for at least 303 million tons of coal refuse abandoned by the mining industry in Appalachia.

Similarly, based on estimated pile depths, the total estimated volume of existing coal refuse piles in PA and WV alone is estimated to equate to over 374 million cubic yards of material (for perspective, a typical dump truck holds only about 10 to 14 cubic yards). Considering that these legacy piles are known to cause significant adverse environmental and ecological impacts to soil, water, air quality, climate change, land use, habitat degradation, and aesthetics, these numbers are staggering. No other fossil fuel land disposal activity would be allowed to remain deposited and abandoned in the U.S. without requiring environmental remediation.

The PA and WV inventories alone account for at least 303,207,319 tons of coal refuse continually subjected to gradual internal thermal rise, products of incomplete combustion and potential runaway thermal oxidation. The first several feet of depth of this entire surface area is continuously undergoing the weathering process, emitting fugitive fine particulate matter (smoke and windblown dust), otherwise regulated air pollutants, and greenhouse gases over a tremendous area of Appalachia at a slow, but relentless rate.

Table 2

Northern Appalachia Estimated Extent of Existing Coal Refuse Piles			
Abandoned Coal Refuse Piles	**Acres**	**Cubic Yards**	**Estimated Tons @ 60 lb/ft^3**
PA State Coal Refuse Inventory	12,809	272,982,161	221,115,550
WV State Estimated Coal Refuse Inventory	4,373	101,148,751	81,930,488
Total Estimated Coal Refuse Abandoned in Northern Appalachia	17,181	374,130,912	303,046,039

Projected Life Cycle Air Emissions Due to Surface Weathering

As stated previously, all coal refuse placed in piles gradually weathers (oxidizes)[30]. This process is very slow and not dis-similar to the inevitable rusting of abandoned farm implements, for example. While weathering is a very slow process, due to the extraordinary acreage and volume of abandoned coal refuse discarded, coal refuse piles represent virtually a “forever source” of weathering emissions unless either sealed (capped like a landfill) or permanently remediated. Table 2 summarizes PA and WV estimates of abandoned coal refuse in Northern Appalachia at over 17,180 acres (749 million ft^2 of surface area). If we assume that only the first two feet of depth from the surface of every pile is exposed to continuous weathering (oxygen, sun damage, freeze/thaw cycles, acid rain, etc.) every hour of their "forever" life, the amount of coal refuse in the slow process of weathering amounts to an estimated 1.5 billion cubic feet. At a typical bulk density of about 60 $lb./ft^3$, the amount of un-remediated coal refuse material continuously weathering within the top two feet of the piles in just PA and WV is therefore estimated to be on the order of 45 million tons. This likely represents a very conservative estimate because coal refuse drains readily, and it is likely that oxygen and acid rain reach much more deeply into the piles.

Figures 1 and 2 below show the locations and extent of coal refuse piles in just the State Inventories of Pennsylvania and West Virginia.

Figure 1 - Extent of Abandoned Coal Refuse Piles in PA

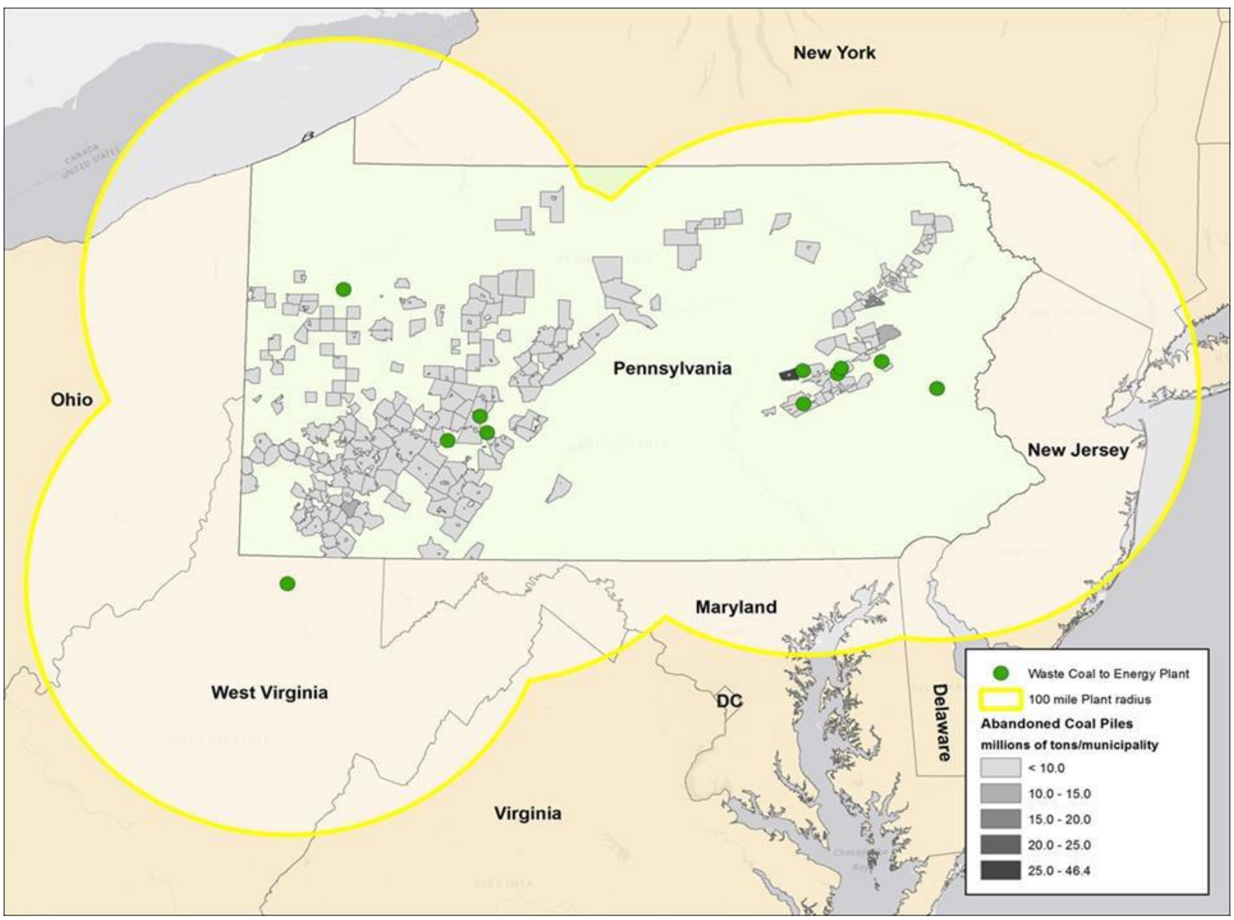
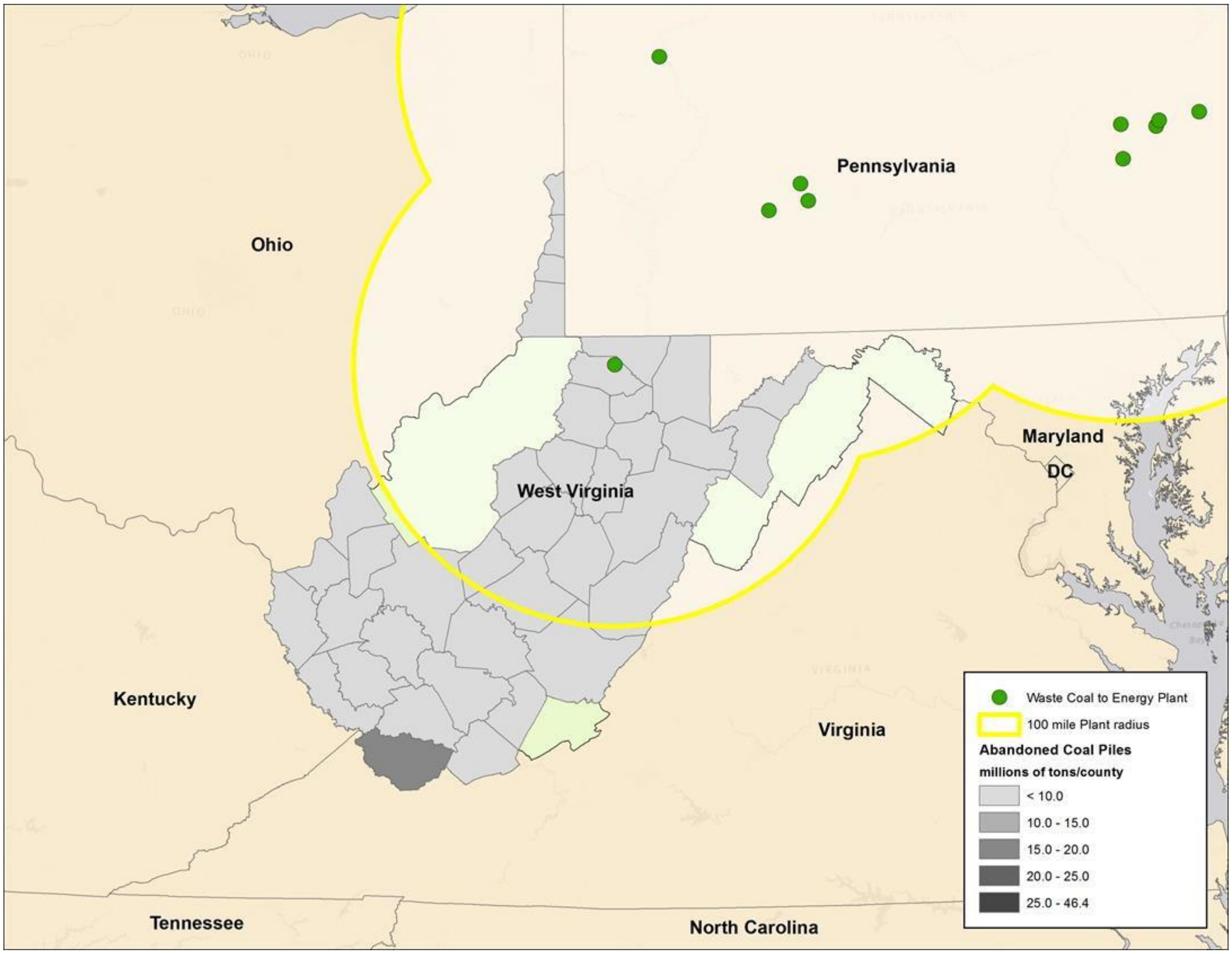


Figure 2 - Extent of Abandoned Coal Refuse Piles in WV



The International Journal of Coal Geology (2017)[23] states that in situ weathering of coal causes a measurable decrease in its carbon content over time, resulting in a proportional percentage decrease in its Gross Calorific (heating) Value (GCV). Jha (2016)[27] states that in situ weathering of coal showed a loss of 5% in calorific value over a period of 25 years. Since the GCV of any hydrocarbon fuel is proportional to its hydrogen/carbon molecular content, a 5% decrease in calorific value can be roughly estimated to also indicate a similar loss in carbon and hydrogen content, which will have slowly oxidized to the GHGs methane and CO_2. According to the North American Combustion Handbook[28], both anthracite and bituminous coals average about 80% carbon and from 2-5% hydrogen. Thus, a 5% decrease in calorific value via the weathering oxidation process may oxidize (reduce) the 80% carbon content of the coal portion of coal refuse by about 5% every 25 years, or an annual decay rate of about 0.2% of the exposed coal refuse each year that it weathers.

USEPA published emission factors[3,8] from the in situ combustion of coal refuse (averaging 6,175 Btu/lb.) has been measured to emit CO_2 at an emission factor of 2,360 lb. CO_2/ton of coal refuse and to emit methane at 1,450 lb. CH_4/ton of coal refuse consumed. Those values have been adapted to the much slower process of weathering. Jha (2016)[27] states that weathering oxidizes standing coal at a rate of about 5% every 25 years. While weathering due to the entire coal refuse inventory alone is responsible for significant life cycle emissions of CO_2e, this factor is still deemed less significant than the process of spontaneous combustion documented by USEPA emission factor measurements from smoldering coal refuse.

Also noteworthy is that as coal refuse weathers and the surface layers oxidize, they also become more friable and continue to generate windblown fugitive dust (PM_{10}). This dust will continue to be emitted from the entire surface of every pile whenever there is a sufficient wind speed to scavenge newly created coal dust to become airborne and therefore transported into offsite ambient air within local communities. This fine particulate matter, together with visible smoke (which is also fine particulate) is emitted at surface level where it can be transported on the prevailing wind to homes, schools and sensitive receptors still residing in the former mining towns of Appalachia.

Projected Annual Air Emissions Due to Spontaneous Combustion

According to Chalekode and Blackwood[3], coal refuse piles undergo a virtually continuous process of spontaneous combustion and maturity to open flame, depending on natural or anthropogenic extinguishment as they have over a century of their existence and still observed today. The Authors defined a representative coal refuse pile as one with a volume of 60 million ft^3 (1.7 million m^3) and a typical burning pile being one with 21% of it burning (or 12.6 million cubic feet/pile smoldering, smoking or openly burning). At an in situ bulk density of about 60 lb./ft^3, a representative estimate of the amount of coal burning at any time from spontaneous combustion = 12.6 million ft^3 x 60 lb./ft^3 x 1 ton/2000 lbs. = 378,000 tons of coal per pile actively burning in situ. That same report identified that in 1972 there were 116 coal refuse piles actively burning in PA and WV alone, or about 40% of all identified coal refuse piles extant in those states. Following the methodology of that study, 378,000 tons of coal burning per pile multiplied by 116 piles would equate to 43.8 million tons of coal refuse actively burning at any one time in PA and WV alone. Alternatively, if we rely on the state inventories of PA and WV and assume the same ratios of 40% of piles and 21% of coal in each burning pile is actively burning, we get 303,207,319 tons of coal refuse X .4 X .21 = 2.5 million tons actively burning. Even just for PA and WV, these are both enormous numbers. For purposes of this study, we have elected to use the lower value for conservatism, noting that the values presented herein could therefore be significantly underestimated.

Emission factors of openly smoldering or burning coal in stationary piles have been assessed in the paper "Quantifying Emissions from Spontaneous Combustion"; Lesley Sloss, 2013[29].

A summary of the application of published emission factors to GHG pollutants as well as criteria and hazardous air pollutants being generated by the conservative value of 2.5 million tons of coal refuse actively burning in PA and WV are provided in Table 3.

Table 3

Estimated Air Emissions from Coal Refuse Piles in PA and WV due to Spontaneous Combustion		
Pollutant	**Emission Factor lb/ton**	**Emissions, tpy**
NO_x	0.06(1)	86
CO	194(1)	278,662
PM_{10}	0.9(1)	1,293
SO_2	66.2(1)	95,084
H_2S	1.22(1)	1,752
Hg	0.0008(1)	1
CO_2	2,361(2)	3,391,053
CH_4	327(2)	469,530
N_2O		
CO_2e	10,533(2)	15,129,314

At the time of this Study, no data for emissions of N_2O from spontaneous combustion of coal refuse had been identified from our review of the literature. The Authors believe this to be a potential area for additional study.

Projected Annual Air Emissions from Un-remediated Coal Refuse Piles in PA and WV

Based upon the source material relied upon and State Agency inventories of the quantity of abandoned coal refuse extant in PA and WV, summing the estimated annual air emissions from doing nothing about these piles suggests that they represent an impediment to achieving net zero GHG emissions in the region, states, U.S. and globally. The environmental community has focused on phasing out extraction of fossil fuel from its sequestered state within the earth, however abandoned coal refuse has already been extracted and then discarded – it can never be returned to a naturally occurring underground coal seam.

In Table 4, we sum the estimated annual air emissions of weathering and spontaneous combustion of these legacy coal refuse piles to identify the sheer magnitude of their continuous contribution of air pollutants to the environment, frustrating the progress being made elsewhere in improvements to air quality and climate change.

Table 4

Estimated Air Emissions from Existing Coal Refuse Piles in Northern Appalachia due to Weathering plus Spontaneous Combustion			
Pollutant	Annual Emissions (tons)		
	Coal Refuse Weathering In-situ; tpy	Coal Refuse Smoldering or Burning In-situ; tpy	Total Estimated Air Emissions, Weathering plus Smoldering or burning in-situ; tpy
NO_x		86	86
CO		278,662	278,662
PM_{10}		1,293	1,293
SO_2		95,084	95,084
CO_2	204,168	3,391,053	3,595,221
CH_4	45,504	469,530	515,034
N_20			
H_2S		1,752	1,752
Hg		1.1	1.1
CO_2e	1,341,768	15,129,314	16,471,082

Beyond the magnitude of the sheer tons of pollutants being emitted every year from coal refuse piles, the local community impacts compared to well-controlled combustion are much greater since products of incomplete combustion, such as poisonous hydrogen sulfide (H_2S) gas and the much more potent greenhouse gases methane and nitrous oxide, are effectively oxidized to more benign pollutants when combusted fully and treated in a CFB boiler. Controlled oxidation CFB emissions such as the sulfur dioxide (SO_2) product of oxidizing hydrogen sulfide, or oxides of nitrogen (NOx) from oxidizing the potent greenhouse gas nitrous oxide, together with fine particulate (PM_{10}) which is also emitted uncontrolled from coal refuse piles as fugitive dust, are then captured and removed at high efficiency using USEPA mandated BACT emission controls. Finally, CFB boilers disperse those small fractions of residual air pollutant concentrations through engineered stacks and are shown via USEPA air dispersion models to document that the resulting emissions meet all U.S. health-based National Ambient Air Quality Standards (NAAQS).

Conversely, uncontrolled air emissions from the surface of un-remediated abandoned coal refuse piles are emitted without the benefit of controlled oxidation, any emission control, any regulated health-based air concentration standards, or any USEPA or state oversight and regulation. Low level emissions from these piles can be observed from the smoke wafting from the piles and the odor of sulfur compounds impacting nearby populations. Abandoned coal refuse piles throughout Appalachia present a clear and present danger to ambient air quality.

Projected Net Air Emissions

Based on the sheer magnitude of both CO_2e and criteria air pollutants estimated to be emitted uncontrolled, unregulated and at ground level every year from un-remediated coal refuse piles in Northern Appalachia, it is then useful to compare those ongoing air impacts on an equivalent tons remediated per year basis with the air emissions reported to USEPA from the coal refuse reclamation-to-energy facilities actively remediating them. At present, coal refuse facilities in PA and WV alone permanently remediate (destroy) at least 5.5 million tons of abandoned coal refuse every year, and this rate is expected to increase in future years. Obviously, once the organic content of each ton of coal refuse is permanently removed from the legacy coal refuse pile inventory, that same amount can never again emit products of incomplete combustion. Absent permanent remediation, coal refuse will continue to generate air emissions well beyond 2050, as some of the oldest piles already have for over one hundred years.

Initially, we compared the actual annual emissions in calendar year 2020 from the facilities remediating the coal refuse piles in Northern Appalachia with the annual emissions that would have been released from the same amount of un-remediated coal refuse if allowed to simply remain in situ. That comparison provides a summary of the GHG and criteria pollutant impacts of permanent remediation through controlled energy recovery in any single year (Table 5). While emissions of NOx are reduced by at least 90% in CFB boilers equipped with selective non-catalytic reduction technology (SNCR), Table 5 shows that Northern Appalachian coal refuse facilities emit somewhat more NOx in a single year than the same amount of coal refuse emitting nitrogen products in situ because NOx formation is extremely combustion temperature dependent. It is important here to consider that both NOx and volatile organic compounds (VOC) contribute to downwind ozone formation and that the same factors that cause higher methane emissions from piles similarly cause higher uncontrolled emissions of VOC. Complete data was not available for abandoned coal pile emissions of CO, VOC, PM_{10} and N_2O, which represent opportunity to further quantify additional air emission benefits.

Net GHG emissions as measured in units of CO_2e from remediating an annual quantity of coal refuse compared to allowing that same amount of material to continue to emit air pollutants passively was the most compelling question for this study. As shown in the bottom row of Table 5, permanent remediation of existing abandoned coal refuse piles in Northern Appalachia by the coal refuse reclamation-to-energy industry is responsible for the net reduction of over 284 million tons of CO_2e (or more) every year that they continue to operate.

Coal refuse reclamation-to-energy plants are very efficient in terms of converting nearly 100% of the hydrocarbon component of abandoned coal refuse to CO_2. When they do so, they remove the ability of that amount of abandoned coal refuse to emit any carbon, ever again. The tremendous net benefit of the coal refuse reclamation-to-energy industry is that purposefully converting hydrocarbons efficiently to CO_2 to produce needed energy nearly eliminates all of the emissions of methane that would otherwise be emitted over many more years.

Since according to USEPA's CO_2e equivalency standard[10] methane is 25-28 times more potent of a greenhouse gas than CO_2, it is much more impactful in frustrating net zero CO_2e reduction goals to help mitigate climate change. Elimination of methane in favor of CO_2 has a much more important benefit in terms of reversing climate change now, as it is estimated to persist in the atmosphere for only about 20 years compared with the 100-year life of CO_2. According to the literature, in the near term (i.e. by 2050), preventing ongoing emissions of methane instead of CO_2 will have about 81 times the global GHG benefit of reducing any ton[2] anywhere in the U.S. of CO_2 [9]. For conservatism in this analysis, these near-term "super benefits" have been ignored in favor of the 100-year lifetime factor of 25-28 times the GHG potency of CO_2 as commonly compared in most GHG sustainability comparisons.

It is important to compare the bottom row of Table 5 (presented in the Executive Summary, Table 1), which compares the net benefit to lifecycle GHG emissions measured in CO_2e from the same amount of coal refuse either allowed to remain in situ passively emitting pollutants or remediated forever for responsible energy recovery. At the current rate of coal refuse reclamation, the global GHG inventory will have been reduced by a quarter billion tons or more of CO_2e over the next ten years for each year the existing Northern Appalachian coal refuse reclamation-to-energy plants alone continue operating. Increased operation in this industry across Appalachia would yield even greater and more immediate climate and environmental benefit.

Table 5

Estimated Net Lifecyle Air Emission Reductions from Permanent Remediation of 5,546,818 tons of Coal Refuse Annually

Pollutant	Unremediated Coal Refuse Estimated Annual Air Emissions (5,546,818 (tons/yr)	Unremediated Coal Refuse Estimated Lifecycle Emissions (5,546,818 tons X assumed 10-yrs of continuous air emissions) (tons)	Coal Refuse Reclamation Industry Emissions to Remediate 5,546,818 tons of coal refuse (tons)	Net Lifecycle Emissions from Remediation of 5,546,818 tons of coal refuse (tons)	Net Lifecycle Emissions from Remediation of each ton of Coal Refuse by the Reclamation to Energy Industry[1] (tons emitted per ton remediated)
NO_x	166	1,664	4,140	2,476	0.0004
CO	538,041	5,380,413			
PM_{10}	2,496	24,961			
SO_2	183,589	1,835,886	10,011	(1,825,875)	(0.3)
CO_2	6,553,760	65,537,596	7,587,349	(57,950,247)	(10.4)
CH_4	906,655	9,066,551	825	(9,065,726)	(1.6)
N_20					
H_2S	3,384	33,836	0	(33,836)	(0.01)
Hg	2	22	0.1	(22)	(0.000004)
CO_2e	29,220,138	292,201,380	7,607,978	**(284,593,402)**	**(51)**

[1] Data Fields Highlighted in Yellow were not available or located as of the date of this study.

Alternatives to Permanent Coal Refuse Pile Remediation

Governments and environmental advocates have been seeking practical alternatives for the remediation of abandoned coal refuse piles for generations – yet, smoking piles persist.

Sporadically extinguishing individual coal refuse pile fires and/or re-vegetation to improve their aesthetics does not eliminate their air and water quality impacts to the environment. It has been postulated that increased taxpayer funding could be used to plant abandoned coal refuse piles with “green” shallow root system plants, such as beach grass. It is important to note that naturally occurring and undisturbed seams of bituminous or anthracite coal prior to mining are essentially uniform prehistoric deposits of CO_2 and other pollutants already sequestered within the earth and have existed there in the lack of oxygen for millions of years. Coal refuse piles, on the other hand, contain mechanically shattered remnants, fragments, and fines of coal brought to the surface that exhibit tiny voids in the interstices between the crushed and broken chips. These voids are open to oxidation surrounding every coal particle surface. They are, on a gaseous level, porous.

These facts draw upon our collective experience and regulations regarding municipal waste landfills. Municipal solid waste is largely organic (hydrocarbon) based material that has been placed and compacted on top of an impervious liner, typically in multiple ten-foot “lifts”. U S EPA regulations require such landfills to be encapsulated (“capped”) with impermeable liners, to prevent gaseous release of continuously generated methane to the air. In fact, methane emissions are required to be collected and burned to CO_2 in reciprocating engines or turbines to produce “renewable” electricity. Lessons learned from this industry indicate that unless abandoned coal refuse piles could also be somehow permanently capped with a “forever” impervious barrier, they would still generate methane gas over many years requiring an engineered methane collection system and then a mandate to combust that methane to the less potent GHG CO_2. It is not an accepted or allowed practice to simply plant over municipal waste landfills with beach grass or other vegetation, as those plantings could not prevent the generation and emission of evolving methane gas. The authors believe that USEPA municipal waste landfill closure requirements hold parallels to the much larger problem of abandoned coal refuse piles throughout Appalachia. There are two main differences, however – most active municipal landfills are still managed by an existing ownership, and secondly are much smaller in extent than abandoned coal refuse piles shown in Figures 1 and 2. Simply, maintaining an oxygen free deep pile via capping and collection of methane does not represent an economically or logistically sustainable possibility simply due to the sheer magnitude of legacy coal refuse piles in Appalachia. Even just planting and/or maintaining shallow root system plantings over thousands of acres of abandoned coal refuse is not self-funding nor economically sustainable. While planting abandoned coal refuse piles may reduce impacts from wind-blown dust and rainwater runoff entering downstream soil and surface water, planting or reforestation would not eliminate the presence of oxygen, remove the hazard of spontaneous combustion beneath the shallow roots, or permanently prevent future emissions of the potent greenhouse gas methane.

One-time and permanent removal of the root cause of CO_2e emissions from abandoned coal refuse by the coal refuse reclamation-to-energy industry is therefore the only known forever remediation process that is both permanent, proven over many years of operation, already in place and economically sustainable. While some alternatives may have aesthetic and acid run-off merits, they cannot avoid the passive GHG emission legacy of the potent GHG methane.

USEPA studies of potential alternatives to prevent spontaneous combustion of coal refuse piles[3,8] suggest that every pile would need to be permanently and anaerobically sealed from the air and that methane collection systems or padding with an inert gas such as nitrogen would need to be continuously maintained to preclude the possibility of future spontaneous combustion and surface emissions. A simple field of beach grass growing on top of a coal refuse pile could not materially eliminate the ability of the pile to spontaneously combust or vent products of incomplete combustion to the surface from deep within.

In the authors' opinion, only permanent removal of the coal refuse itself or impermeable capping with methane collection systems is capable of eliminating forever air emissions of gaseous methane resulting from oxidation and incomplete combustion of coal refuse piles. As with municipal waste landfills, once collected the most environmentally responsible solution is to then reduce its global warming potential by 25-28 times by simply combusting it to CO_2 in a highly controlled manner. Of course, this is exactly what the coal refuse reclamation-to-energy industry has already been doing, at a significant savings to taxpayers, for over thirty years.

Conclusions

This study seeks to provide a characterization of the role of abandoned coal refuse piles located in Appalachia in frustrating local, national and to a lesser extent global efforts to achieve ambitious net zero greenhouse gas emissions goals, as well as understanding how these existing abandoned sources of pollution are disproportionately impacting residents of once thriving coal mining areas of Appalachia. It is well documented that abandoned coal refuse piles gradually emit uncontrolled and unregulated air pollutant emissions as long as such existing piles remain abandoned and, in many cases, "under the radar".

The region relies on the coal refuse reclamation-to-energy industry, which is presently the only practical permanent solution to remediate this legacy environmental hazard. Having characterized the potential adverse air quality emissions from abandoned coal refuse piles if allowed to continue releasing greenhouse gases and other air pollutants unabated, it is particularly useful to compare their adverse lifetime air pollution impacts with the highly controlled emissions from permanently remediating them by the coal refuse reclamation-to-energy industry. A comparison of the air emissions from not remediating existing legacy coal refuse piles shows that this industry is providing very significant net air quality and CO_2e benefits to the environment and should be further encouraged to do so. The data evaluated indicates that the coal refuse reclamation-to-energy industry eliminates 180 net tons of CO_2e (Scope 1) for every ton of Appalachian coal refuse that it permanently eliminates from the environment by converting its residual energy to useful power. That same amount of "net carbon reduced" energy will offset the equivalent grid produced CO_2e for that same amount of electricity it would not have to produce for an additional CO_2e reduction in Scope 2. This added benefit to global GHG emissions will vary over time and has not been quantified in this study.

It is the opinion of the authors that the negative impact to our environment of doing nothing is much greater than actively remediating this self-polluting coal refuse material by harnessing its useful thermal energy with CFB technology, thereby dramatically reducing (especially in the near- term) the global budget of CO_2e, eliminating future pollution and improving local air quality. By conducting a side-by-side comparison of uncontrolled coal refuse emissions versus controlled emissions in the coal refuse-to-energy facilities, we arrive at a compelling conclusion. The impactful net benefit to the environment resulting in substantial reductions in CO_2e more than justifies maintaining this important, environmentally-friendly industry.

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