Submission ID: 32433

Dear Mr Underwood,
I write to comment further on the brief mention of impact on local residents any CCS plant could have in Save Crossness Nature Reserve's written representation and on the comprehensive written representation on marginalised communities (focusing on the impact on local Romani graziers) by Ridgeway Users Group both of which were submitted under Deadline 1.
Organised local opposition from residents in close proximity to the proposed plant (as opposed to users of the reserve etc) has been notable by its absence in written representations and at the recent compulsory purchase hearings. This is not surprising. Both Cory's incinerators and its proposed plant sit in areas if high diversity and deprivation (as studies show is by far the preferred location for builders of waste incinerators). A very high proportion of residents in this area will not be owner-occupiers but tenants who stay no longer than a couple of years in the area and therefore have less interest in local matters. Moreover, compared to the level of local opposition in more affluent areas or for more emotive issues – the current high-profile campaign against Portland waste incinerator being an excellent example of both - it is clear that in an area such as Lower Belvedere there will be much less organised resident opposition (indeed I do not believe that the "Riverside 2" incinerator was subject to large-scale, concerted local residents opposition).
I have lived in the [redacted], [redacted] of the incinerators, since 2015. The applicant is proposing to build another significant source of emissions - and potential major industrial accidents - in addition to a second incinerator which will see its combined emissions outstrip those of the UK's current largest (the "Runcorn EfW" incinerator in Cheshire the catastrophic impacts on neighbouring residential areas - and its operators solution of paying each household around £4,500 with accompanying NDAs - of which have been prominently reported recently in the national press).
The applicant's stock answer to any enquiry regarding their intensely polluting effects or ability to hit self-proclaimed targets as seen at the planning hearings – ie that they will "adhere to environmental permits" - is not adequate. They are proposing this third source of serious pollution 500 metres from a densely populated mixed residential/commercial development and within approximately 600-700 metres of the densely populated residential area of North Thamesmead and environs.
As mentioned in my relevant representation, both areas are within the Bexley Riverside Opportunity which itself is within the broader London Riverside Opportunity area which has been targeted for creation of 44,000 new homes and 29000 new jobs 2041 by the London Mayor's Office (6000 and 19000 of which have been designated for Bexley alone). Allowing a company that is building an incinerator which will see it become the greatest source of incinerator-generated pollutants in the UK to further build another source of CO2, SO2 and ammonia (among others) emissions in an area designated for housebuilding clearly does not conform with the London-specific goals described, national public health goals, or protection of human rights.
Areas such as Lower Belvedere and North Thamesmead have poor levels of health due to social deprivation anyway. A third source of pollution from [redacted] will clearly exacerbate the problem. Similarly to the powerful written representation on Romani rights, which makes clear [redacted] has made no attempt to liaise with them regarding their centuries old use of these lands to graze horses, this becomes a human rights issue too.
Given the UK's current (and welcome) dearth of operational carbon capture plants, three of my four supporting attachments concern countries which do currently employ significant operational levels (ie the USA and Canada). Firstly, I attach an article from The Guardian dated 19th April 2024 describing a leak of 2,548 barrels of CO2 from an Exxon carbon capture pipeline which occurred in the amply named city of Sulphur, Louisiana on 3rd April 2024. The article makes it starkly apparent that leakages can occur both on site and anywhere along the carbon dioxide transport infrastructure (be that pipelines or, as in the applicant's proposal, transport by ship).
I also attach a letter signed by 400 concerned academics and addressed to [redacted], the current Deputy Prime Minister of Canada, regarding carbon capture tax credits which touches on the adverse health effects for marginalised Canadian communities.
Thirdly, I attach a study from the Department of Engineering and Public Policy at Carnegie Mellon University which "found that ammonia emissions from amine-based carbon capture systems at a rate typical of current pilot plants would create a significant increase in PM2.5 concentrations, resulting in worrisome public health impacts."
Finally, as this representation concerns the devastating cumulative polluting impact of the proposed plant in addition to the applicant's two incinerators, I also attach a 2020 review of their health impacts from the Australian and New Zealand Journal of Public Health. While the role of incinerator emissions in increasing birth defects and cancers is well known, this systemic review of previous research identifies "61 (66%) papers that demonstrated a significant adverse outcome in relation to waste incineration" with "nine (10%) (identifying) an increased risk of developing some neoplasia" and "nine (10%) finding a link to other diseases such as hypertension or reduced lung function". Among the dozens of other health effects identified in the paper are: Non-Hodgkin lymphoma; soft tissue sarcoma; bowel cancer; developmental delays in children; skin lesions; and low sperm count.
Permission should be denied on the basis of the applicant's appalling cumulative impact on public health in areas of high diversity and deprivation (I include the catastrophic effect its proposed plant being built on their desired location will have on enjoyment of Crossness Nature Reserve for mental well being) and on human rights bases.
Your sincerely,
Daniel Bell

Louisiana

This article is more than **7 months old**

‘Wake-up call’: pipeline leak exposes carbon capture safety gaps, advocates say

Estimated 2,548 barrels of carbon dioxide leaked from Exxon pipeline in Louisiana on 3 April, triggering alarm among residents

An Exxon gas station in 2020. Photograph: [redacted]/Bloomberg via Getty Images

[redacted] *in Sulphur, Louisiana*

Fri 19 Apr 2024 11.00 BST

A major leak of CO_2 from an ExxonMobil pipeline in Louisiana exposes dangerous safety gaps that should halt the planned multibillion-dollar carbon capture industry, environmental advocates say.

An estimated 2,548 barrels of carbon dioxide (CO_2) leaked from the Exxon pipeline in Sulphur in Calcasieu parish on 3 April, triggering an emergency response and alarm among residents who live in close

proximity to scores of polluting pipelines, petrochemical and fossil fuel facilities.

It took more than two hours to fix the leak, which is “unacceptable”, according to [redacted] from the Pipeline Safety Trust non-profit.

“Any release of this size of carbon dioxide should be taken seriously, especially given the proximity to homes in Sulphur … The operator should have promptly known about the leak from the pressure loss and quickly closed the valves and, as reported, they failed to do that,” said [redacted].

“There are dangerous gaps in the federal regulations that we hope will be addressed.”

CO_2 - a greenhouse gas released by burning fossil fuels - is an asphyxiant and intoxicant, which in large quantities can cause injury or death by replacing oxygen in the air. Potent clouds of CO_2 can hang in the air for hours, depending on the weather conditions.

About 5,000 miles of CO_2 pipelines are currently operating in the US, which are predominantly for transporting the gas to oilfields where it is used to extract hard-to-reach oil - a process known as enhanced oil recovery. The pipeline running through Sulphur is part of a network stretching more than 900 miles through Louisiana, Texas and Mississippi, which ExxonMobile acquired from Denbury last year.

A pump station in Louisiana where a leak occurred. Photograph: [redacted]

Interviews by the Guardian suggest that no pipeline operator was on site at the pump station where the leak occurred - and the camera monitoring the facility was not working. Exxon staff located 50 miles away in Beaumont, Texas, learned about the leak after it was reported to emergency services, the Guardian understands. It took more than two hours for an operator to arrive at the facility and fix the leak, according to the local fire department.

Earlier this week, the Guardian observed contractors carrying out anti-corrosion maintenance work at the pump station, where a significant leak was previously reported in 2011.

[redacted], whose family lives opposite the pump station, said she reported the leak to the sheriff's office around 6pm on 3 April - after calls to the company went unanswered. Photographs and video seen by the Guardian show a dense white gas gushing out vertically and horizontally from the pipeline. According to [redacted], the leak sounded like a pressure cooker, and smelt like chemicals.

"This wasn't like the usual gas release that we see from time to time, this went on for a long time. I knew we should leave," said [redacted], who evacuated to her grandparents home two streets away where they could still hear the CO_2 leaking. "If it had not been so windy, it could have been worse. We know what happened in Mississippi ... I am more vigilant now."

In 2020, almost 50 residents required hospital treatment after the Denbury (now Exxon) pipeline ruptured in Satartia, Mississippi, releasing 31,000 barrels of CO_2. The incident exposed major flaws in the existing health and safety regulations for CO_2 pipelines, which as a result are currently being updated by the Pipeline and Hazardous Materials Safety Administration (PHMSA). The update is already facing delays, and could take years.

Yet the CO_2 pipeline network is forecast to grow as much as tenfold thanks in part to billions of dollars of tax incentives in the 2022 Inflation Reduction Act - as well as hundreds of millions of dollars in direct investment for CO_2 transport and storage infrastructure. The Biden administration is counting on CCS to meet its climate goals - despite compelling evidence that the technology is inefficient and will probably prolong the use of fossil fuels.

The Sulphur incident should raise "alarm bells" in Louisiana, where the

oil and gas industry is backing political efforts to fast-track the construction of CO_2 pipelines and carbon capture and storage, according to [redacted], director of law and public policy at the Deep South Center for Environmental Justice.

“Exxon and all the other folks marching forward blindly without adequate regulations and protections are putting all of us at risk. We can expect more CO_2 disasters in communities with plans for more gas plants, CO_2 pipelines and underground injection of CO_2 waste,” said [redacted].

An ExxonMobile spokesperson said: “We’ve completed repairs to the pump station and continue with our investigation of the incident.”

Exxon is requited to submit an incident report to PHMSA, a federal agency within the US Department of Transportation, within 30 days. PMHSA is responsible for investigations into the root cause and any compliance issues, but is not obliged to publish its findings.

Thanks to the windy dry conditions, the leaked CO_2 in Sulphur appears to have dispersed without causing any harm to humans or animals. But residents, who are frequently subjected to leaks and other major incidents at the polluting industrial plants, fear that this was down to luck.

A shelter-in-place order - not an evacuation order - was issued for residents within a 0.25-mile radius of the leak and the road closed off for several hours, news of which circulated on social media and a local news channel.

“I only found out about the leak after the shelter-in-place order was lifted. There should have been an emergency alert for the whole parish, we should have been evacuated, but we don’t have good regulations. I went to bed and had nightmares,” said [redacted], a community organiser in Sulphur.

“We are already living with PTSD from all the industrial plants. Now they want to add CCS, which makes absolutely no sense for the climate or public health,” [redacted] added.

“This should be a wake-up call, carbon dioxide is corrosive and an asphyxiant, it’s a huge risk and we’re not prepared fro CCS,” said [redacted], a local environmental justice campaigner and former oil refinery technician.

“The CO_2 and oxygen levels were continuously monitored and did not pose a risk to the residents close to the plant. If life was endangered, we would have evacuated,” a firefighter who attended the incident said.

The Calcasieu parish office of homeland security and emergency preparedness, which is responsible for local disaster planning and response, did not respond to the Guardian.

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Letter from Academics re CCUS tax investment credit January 2022

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January 19, 2022

To: [redacted], Deputy Prime Minister & Minister of Finance

CC: [redacted], Minister of Natural Resources
[redacted], Minister of Environment and Climate Change

Letter from scientists, academics, and energy system modellers: Prevent proposed CCUS investment tax credit from becoming a fossil fuel subsidy

Dear Deputy Prime Minister,

As scientists, academics, and energy system modellers we are deeply concerned with the government's proposal to introduce a new investment tax credit for carbon capture, utilization and storage (CCUS).

We urge you to not introduce the proposed investment tax credit for CCUS because it will constitute a substantial new fossil fuel subsidy. As well as undermining government efforts to reach net-zero by 2050, the introduction of this tax credit would contradict the promise made by your government to Canadians during the election period to eliminate fossil fuel subsidies by 2023 as well as our international commitments under the Paris Agreement. And once new subsidies are put in place, they are very hard to repeal.

Effective solutions to achieve deep emission reductions in the next decade along a pathway to zero emissions are already at hand, including renewable energy, electrification and energy efficiency. Funding CCUS diverts resources from these proven, more cost effective solutions that are available on the timeframes required to mitigate climate change.

Despite decades of research, CCUS is neither economically sound nor proven at scale, with a terrible track record and limited potential to deliver significant, cost-effective emissions reductions.[1] For example, one of Canada's flagship CCUS projects, Boundary Dam 3, initially promised a capture rate of 90%. It never reached that rate, so SaskPower eventually lowered its expectations to 65%—a target the facility still regularly fails to meet.[2] Current global carbon capture capacity is 39 MT; 0.1% of annual emissions from fossil fuels.[3] Yet for CCUS to play a significant role in achieving the Paris Agreement goal, gigatonnes (Gt) of CO2 would need to be captured and permanently stored. Moreover, CCUS remains prohibitively expensive, while the

[1] Anderson, K. & Peters, G. (2016) The trouble with negative emissions. Science, 354(6309). Available: [redacted]

[2] Schlissel, D. (2021) Boundary Dam 3 Coal Plant Achieves Goal of Capturing 4 Million Metric Tons of CO2 but Reaches the Goal Two Years Late. IEEFA. Available: [redacted]

[3] Garcia Freites, S. & Jones, C. (2020) A Review of the Role of Fossil Fuel Based Carbon Capture and Storage in the Energy System. Friends of the Earth Scotland. Online: [redacted]

costs of renewables have plummeted to the point that they are cheaper than fossil fuels.[4] So unsurprisingly, over 80% of CCUS projects in the United States have failed.[5]

Carbon capture for the oil and gas sector is not a climate solution. At best, it prevents some carbon dioxide from polluting facilities from reaching the atmosphere, but it is not a negative emissions technology. Despite the billions of taxpayer dollars spent by governments globally on CCUS, the technology has not made a dent in CO2 emissions. Nor is it anticipated to expand to the scale needed: for this reason, the Intergovernmental Panel on Climate Change (IPCC) points to uncertainty in the future deployment of CCUS and cautions against reliance on the technology.[6]

Carbon capture methods are being used to boost oil production, and have therefore resulted in increased emissions.[7] The only existing commercially available market for captured carbon is enhanced oil recovery, whereby CO2 is injected into depleted underground oil reservoirs to boost oil production—extraction that otherwise wouldn't have been possible. Globally 80% of captured carbon is being used for enhanced oil recovery.[8] In addition, CCUS does not address downstream emissions, which constitutes 80% of oil and gas emissions.

Furthermore, CCUS does not address environmental, social and health impacts associated with the mining, extraction, and transport of fossil fuels, faced primarily by Indigenous and front-line communities.[9] The buildout of CCUS infrastructure would require an enormous system of pipelines to transport the carbon. This presents serious health, safety, and environmental risks, particularly for marginalized frontline communities, which are already overburdened by industrial hazards. For example, when a CO2 pipeline ruptured in Mississippi in 2020, 300 people were evacuated and 45 people had to be hospitalized.[10]

Finally, CCUS is financially risky. Safe, permanent, and verifiable storage of CO2 is difficult to guarantee. The financial and liability risks related to carbon storage are highly likely to be transferred from the private sector to the public.

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[4] Luderer, G. et al. (2021) Impact of declining renewable energy costs on electrification in low-emission scenarios. Nature Energy. Available: [redacted]

[5] Abdulla et al. (2021) Explaining successful and failed investments in U.S. carbon capture and storage using empirical and expert assessments. Environmental Research Letters. Available: [redacted]

[6] IPCC, Summary for Policymakers in IPCC, Global Warming of 1.5°C: An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (2018) Ch. 5, Section 5.4.1.2.

[7] Sekera, J. & Lichtenberger, A. (2020) Assessing Carbon Capture: Public Policy, Science, and Societal Need: A Review of the Literature on Industrial Carbon Removal. Biophysical Economics and Sustainability. Available: [redacted]

[8] Garcia Freites, S. & Jones, C. (2021) A Review of the Role of Fossil Fuel-Based Carbon Capture and Storage in the Energy System, Tyndall Centre. Online: [redacted]

[9] Donaghy, T. & Jiang, C. (2021) Fossil Fuel Racism: How phasing out oil, gas and coal can protect communities. Greenpeace. Available: [redacted]

[10] Zegart, D. (2021) Gassing Satartia: Carbon Dioxide Pipeline Linked to Mass Poisoning. The Huffington Post. Available: [redacted]

Put simply, rather than replacing fossil fuels, carbon capture prolongs our dependence on them at a time when preventing catastrophic climate change requires *winding down* fossil fuel use. Relying on CCUS preserves status quo fossil fuel development, which must be curtailed to meet global climate commitments.[11] Introducing a tax credit for CCUS for the energy sector will lock-in continued dependence on Canada's largest and most rapidly growing source of greenhouse gas emissions. Indeed, numerous modelling studies show that Canada is not on track to meet its climate change targets and this is in part due to Canada's current approach of leaning too much on short-term solutions that promote more efficient use of fossil fuels.[12]

The creation of a CCUS investment tax credit will not be an effective way to reduce emissions. **We strongly urge you not to introduce the tax credit.** If the Government of Canada proceeds with the tax credit, it must meet the following conditions:

- Enhanced oil recovery projects should not be eligible for the tax credit. Only 'permanent' storage projects should be considered.
- The tax credit should only be made available for sectors for which there are no decarbonization options. Oil and gas projects, including fossil or blue hydrogen, as well as plastics and petrochemical production, should not be eligible for the credit.
- The implementation of a tax credit must be contingent on the development of independent monitoring, reporting, verification, and enforcement requirements.
- The development of a governance structure to maintain and ensure the long-term environmental and fiscal integrity of CO2 storage sites should be in place prior to the implementation of a CCUS tax credit.
- Companies receiving tax credits must be held accountable to mitigate harmful impacts on Indigenous and frontline communities, and provide compensation where mitigation is not possible. These communities must be involved in the design and implementation of the tax credit.

Canada can learn from the mistakes of how a similar tax credit—Section 45Q—was implemented in the US. The biggest beneficiaries of the American tax credit are oil companies.[13] Analysis done on the 45Q tax credit found it could result in at least an additional 400,000 barrels per day of CO2-enhanced oil production in the United States by 2035, which would directly lead to as much as 50.7 million metric tons of net CO2 emissions annually—and possibly far more.[14] The issue of companies claiming credits for unverified tons of captured carbon is rampant in the United States under Section 45Q. In fact, an investigation by the US Internal Revenue Service

[11] Welsby, D., Price, J., Pye, S., & Ekins, P. (2021). Unextractable fossil fuels in a 1.5 °C world. Nature, 597(7875), 230–234. [redacted]

[12] Langlois-Bertrand, S. *et al.* (2021). Canadian Energy Outlook 2021 — Horizon 2060. Institut de l'énergie Trottier and e3c Hub. Available: [redacted]

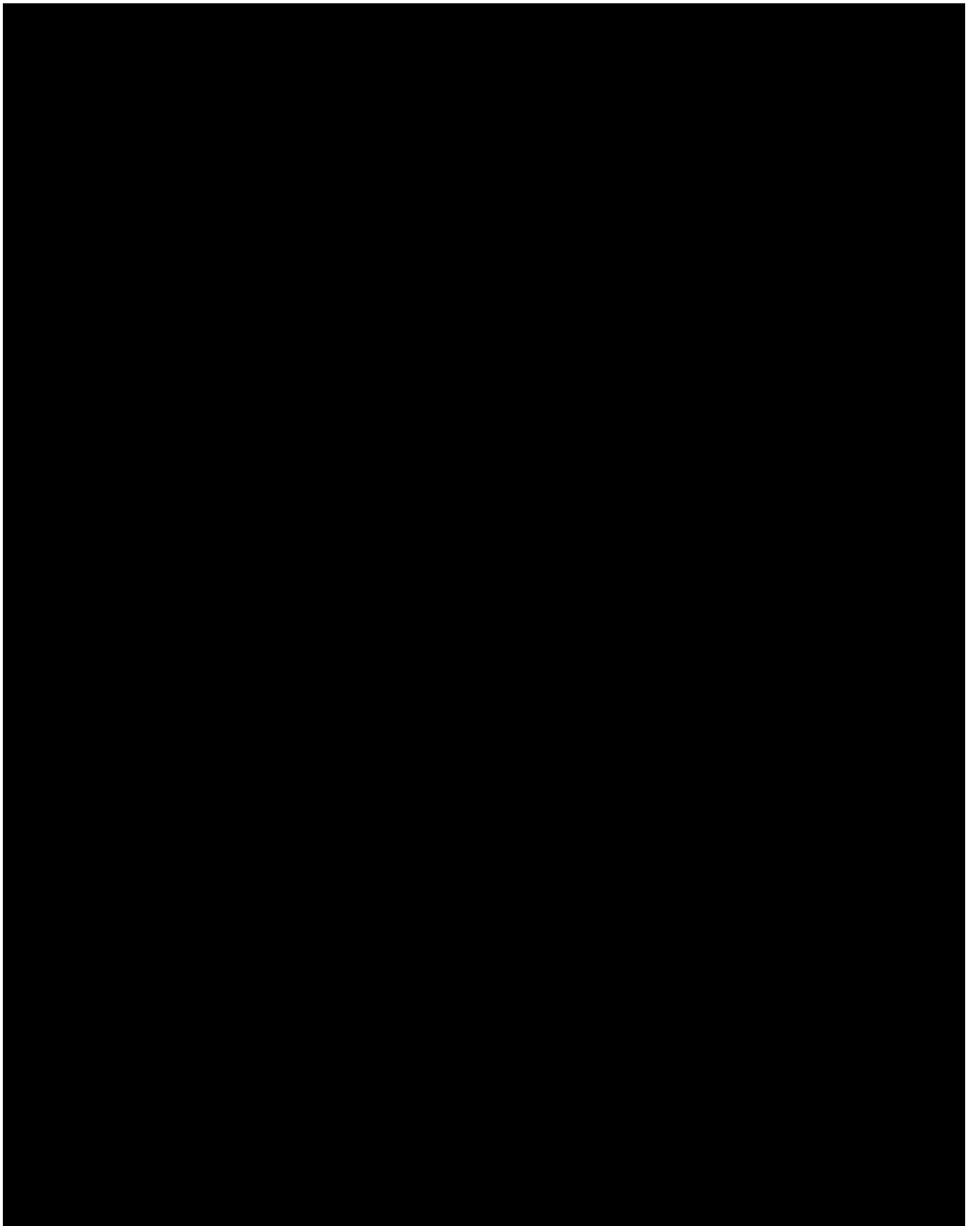
[13] CIEL (2021) Confronting the Myth of Carbon-Free Fossil Fuels: Why Carbon Capture Is Not a Climate Solution. Available: [redacted]

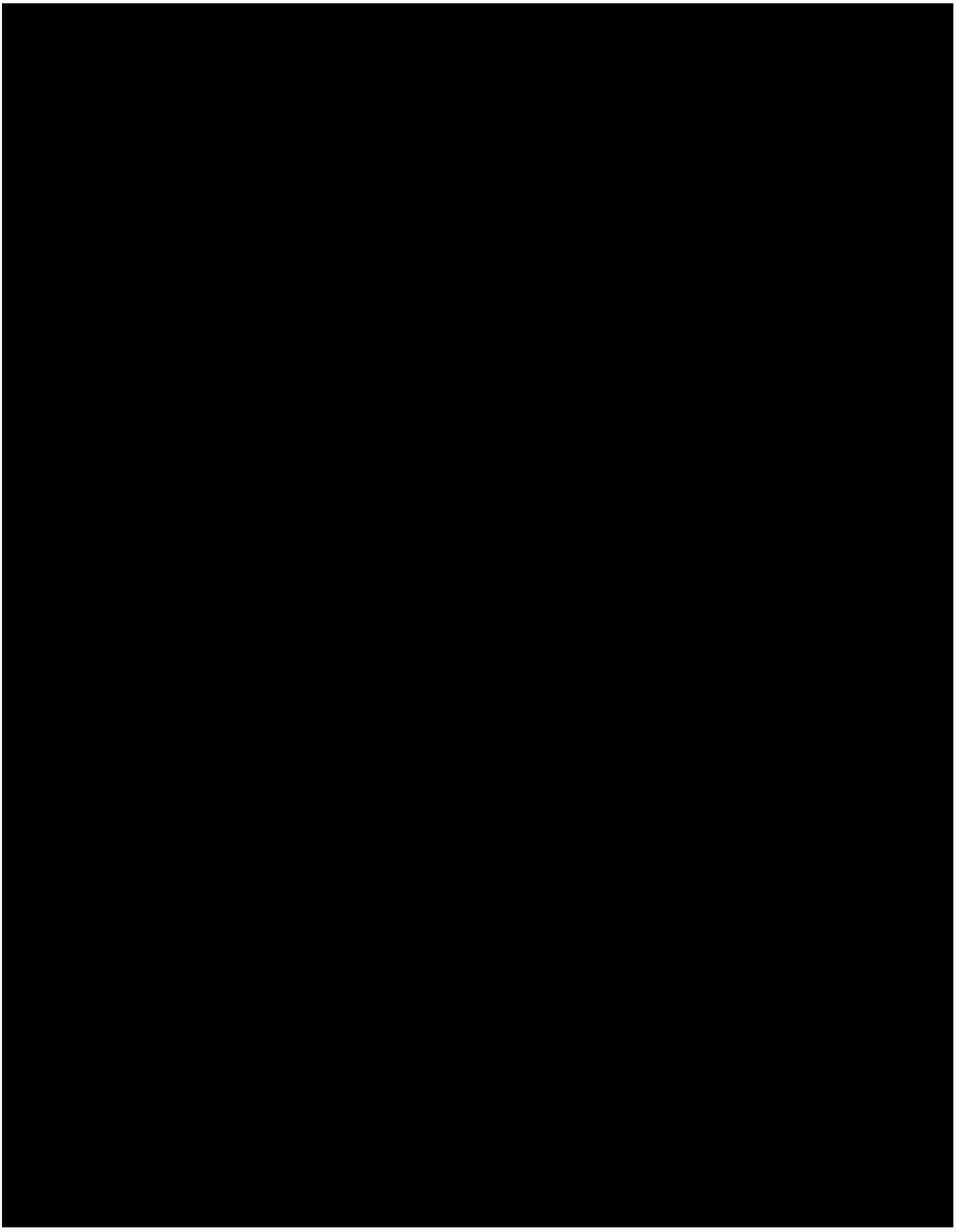
[14] Oil Change International (2017) Expanding Subsidies for CO2-Enhanced Oil Recovery: A Net Loss for Communities, Taxpayers, and the Climate. Online: [redacted]

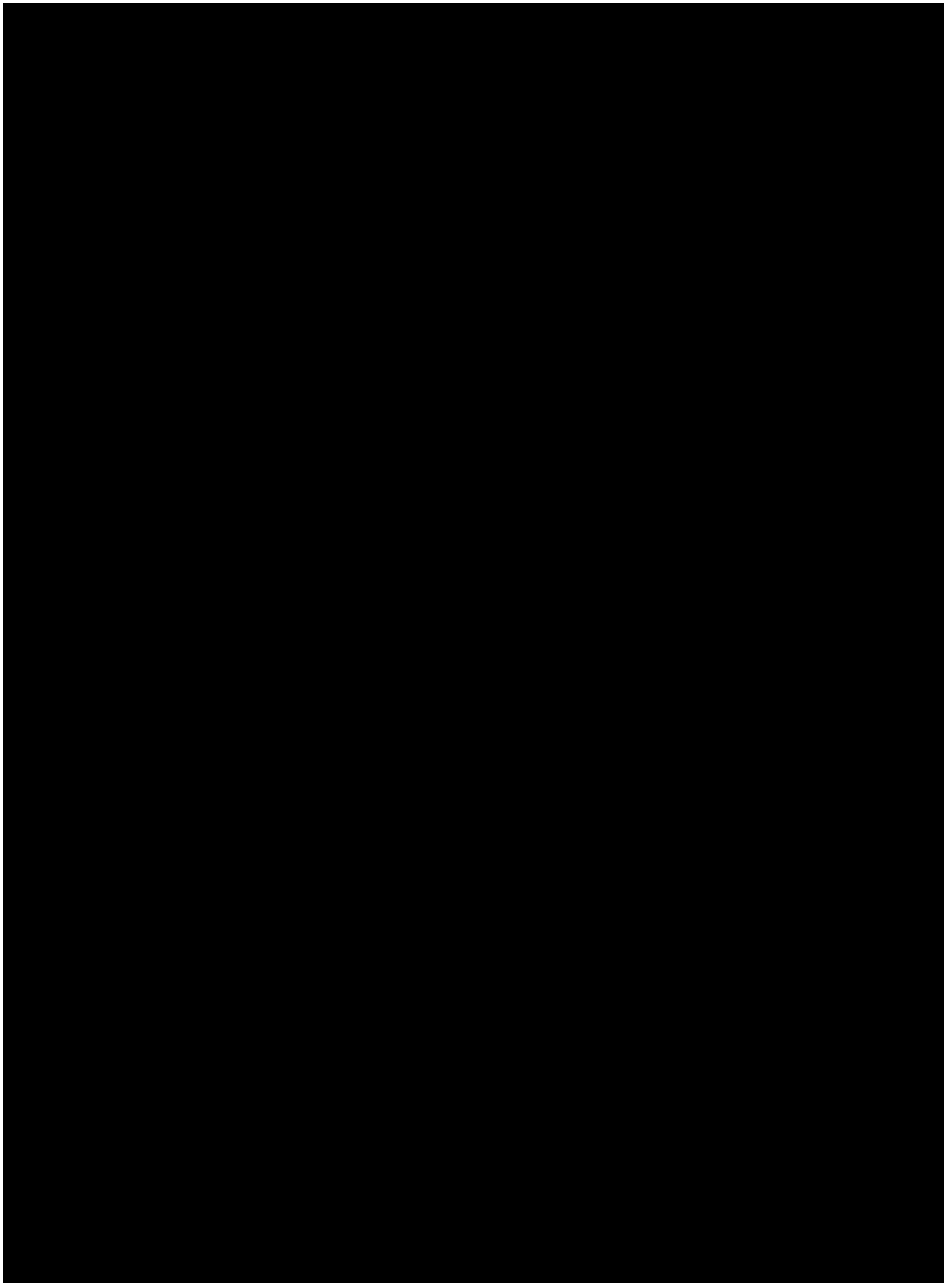
found that 87% of the total credits claimed, amounting to nearly US $1 billion, were not in compliance with the Environmental Protection Agency.[15]

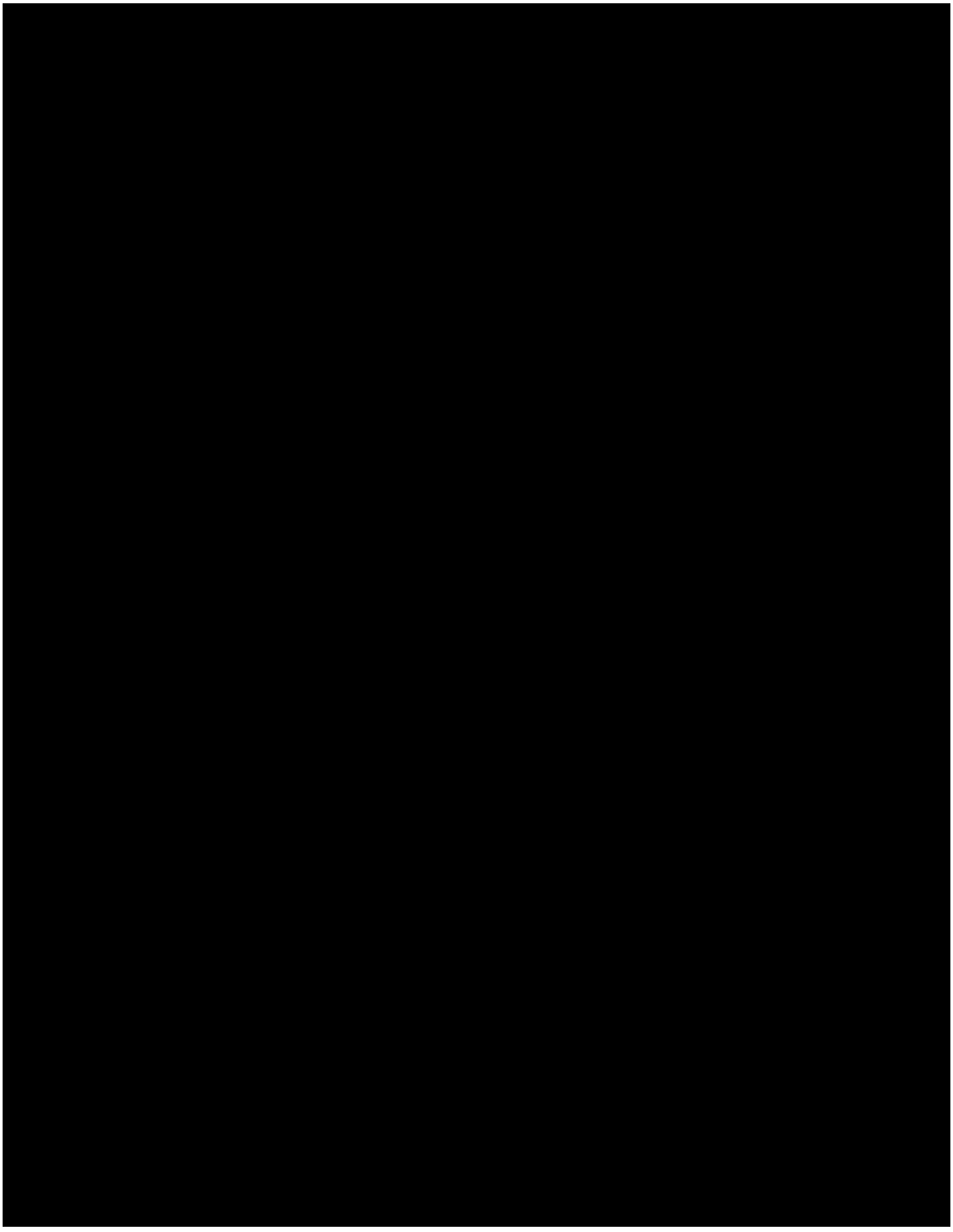
Deploying CCUS at any climate-relevant scale, carried out within the short timeframe we have to avert climate catastrophe without posing substantial risks to communities on the frontlines of the buildout, is a pipe dream. We must instead move forward with proven climate solutions that will contribute the most to emissions reductions: increased electrification, wide-scale use of renewable energy, and intensifying energy efficiency.

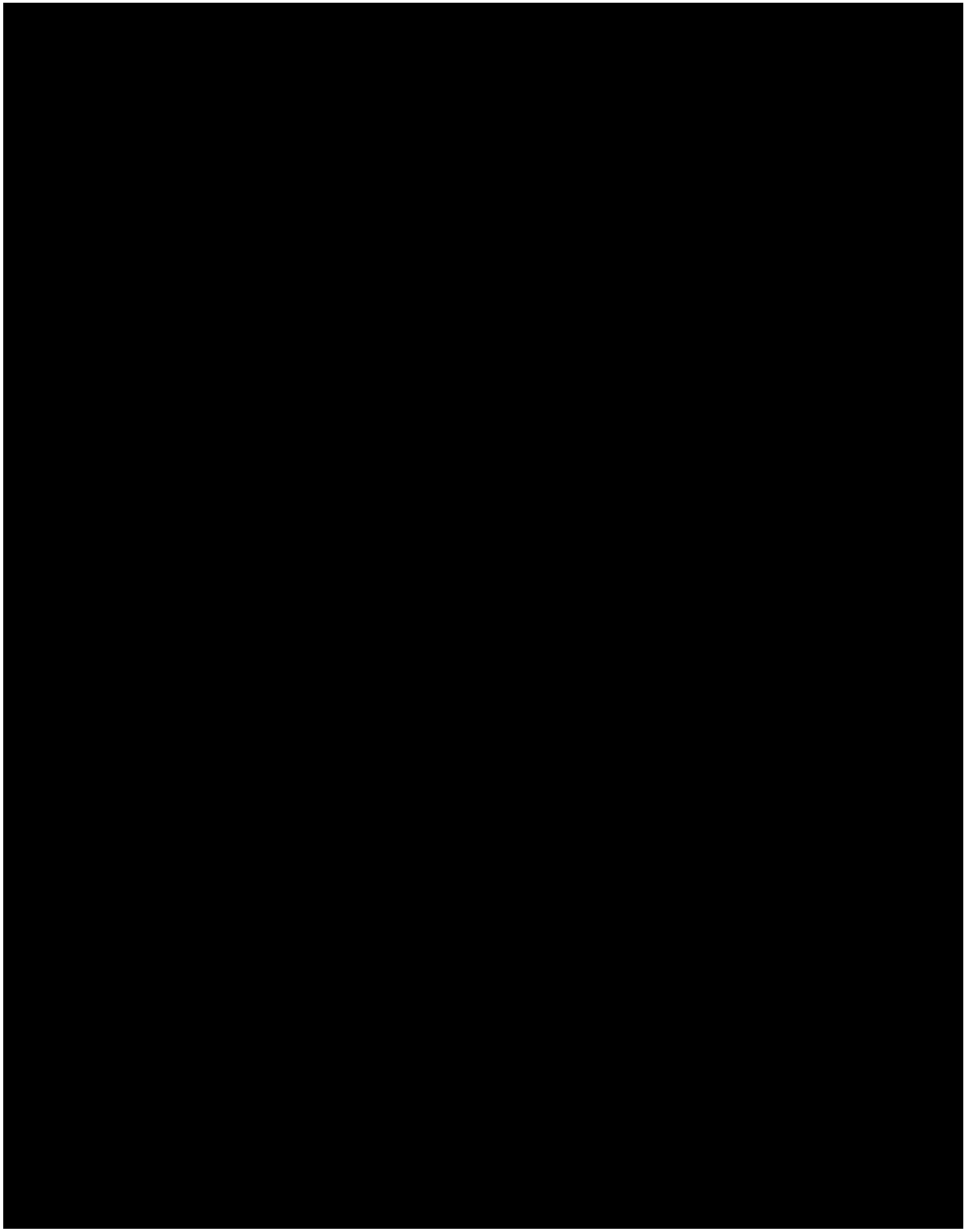
Sincerely,

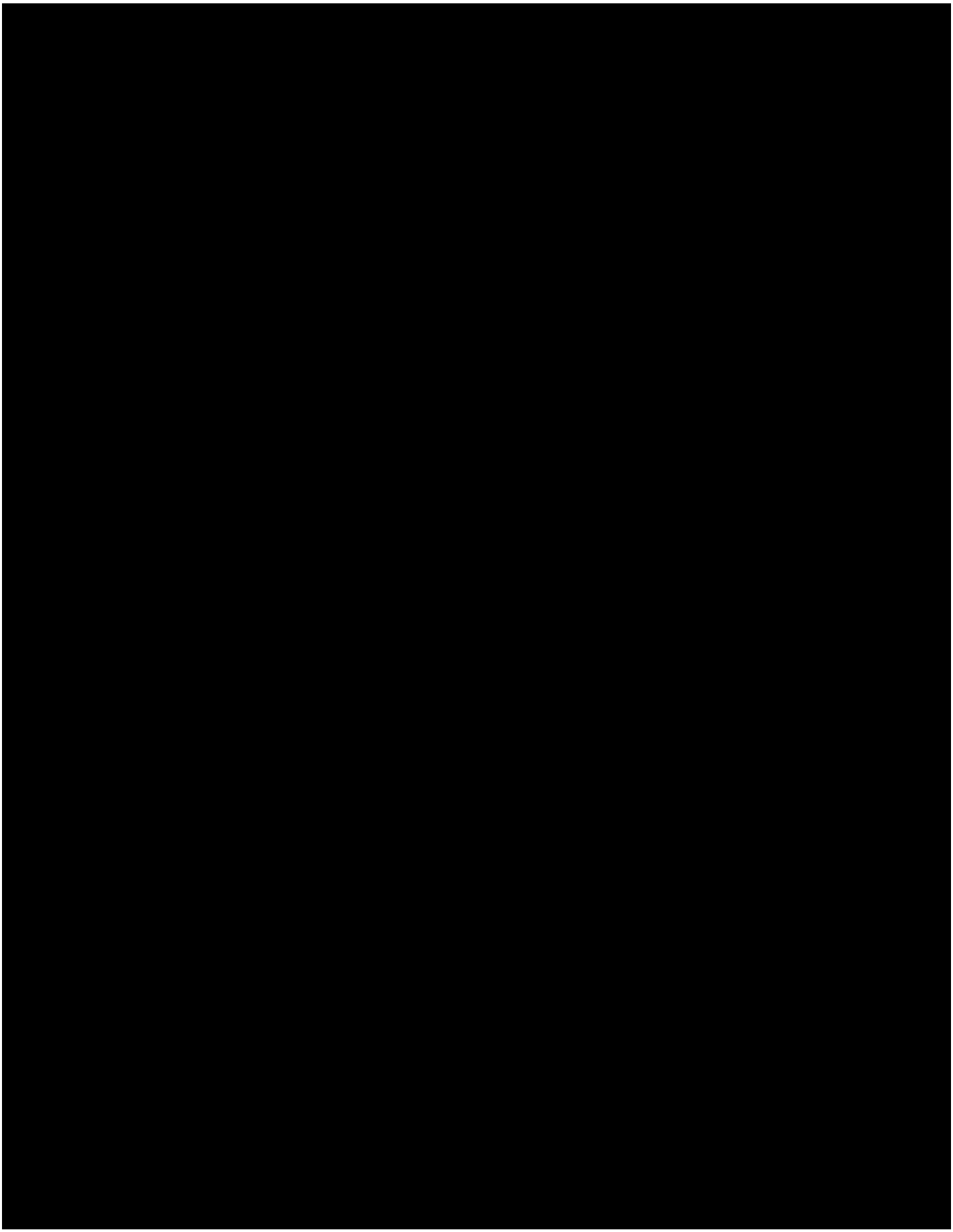


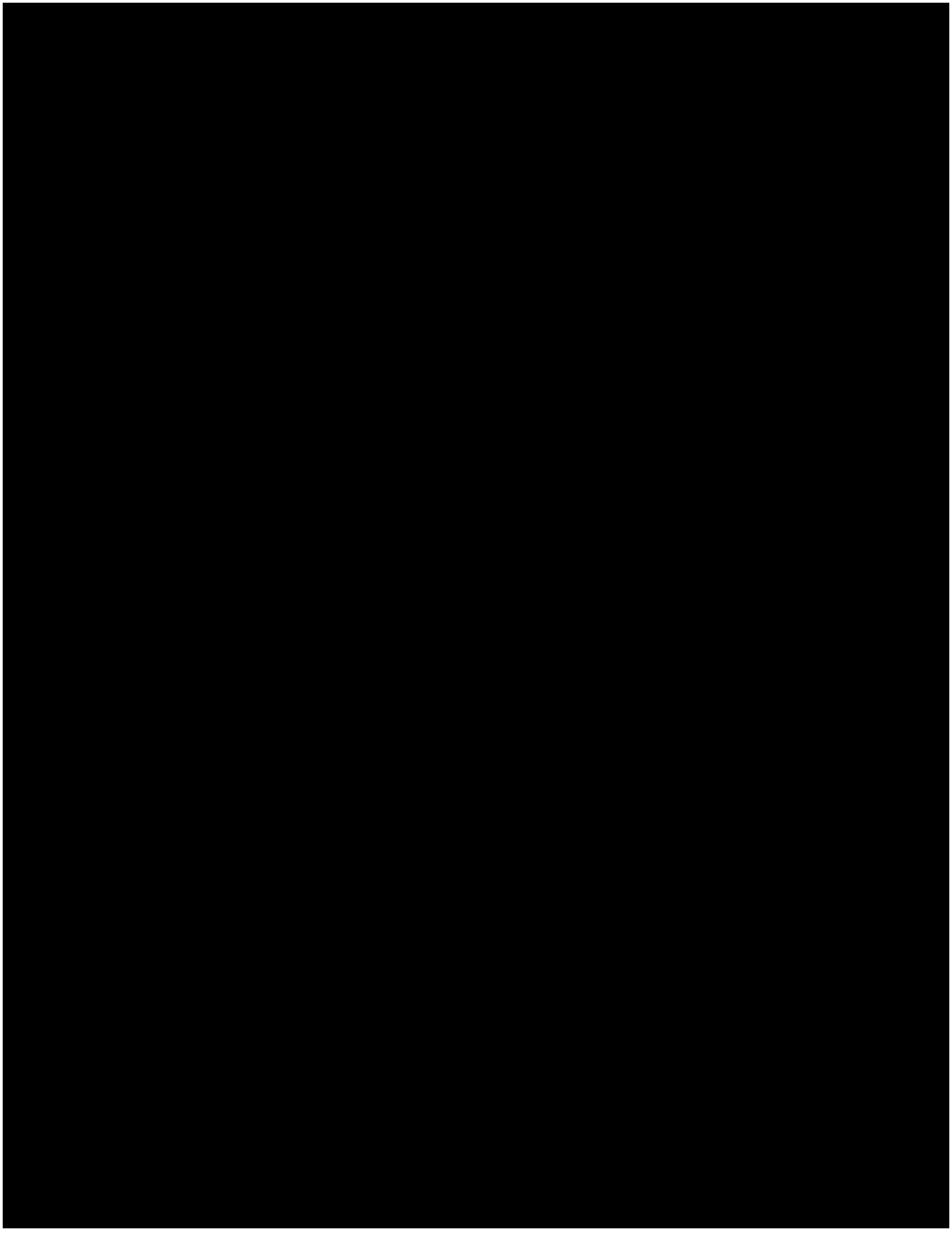


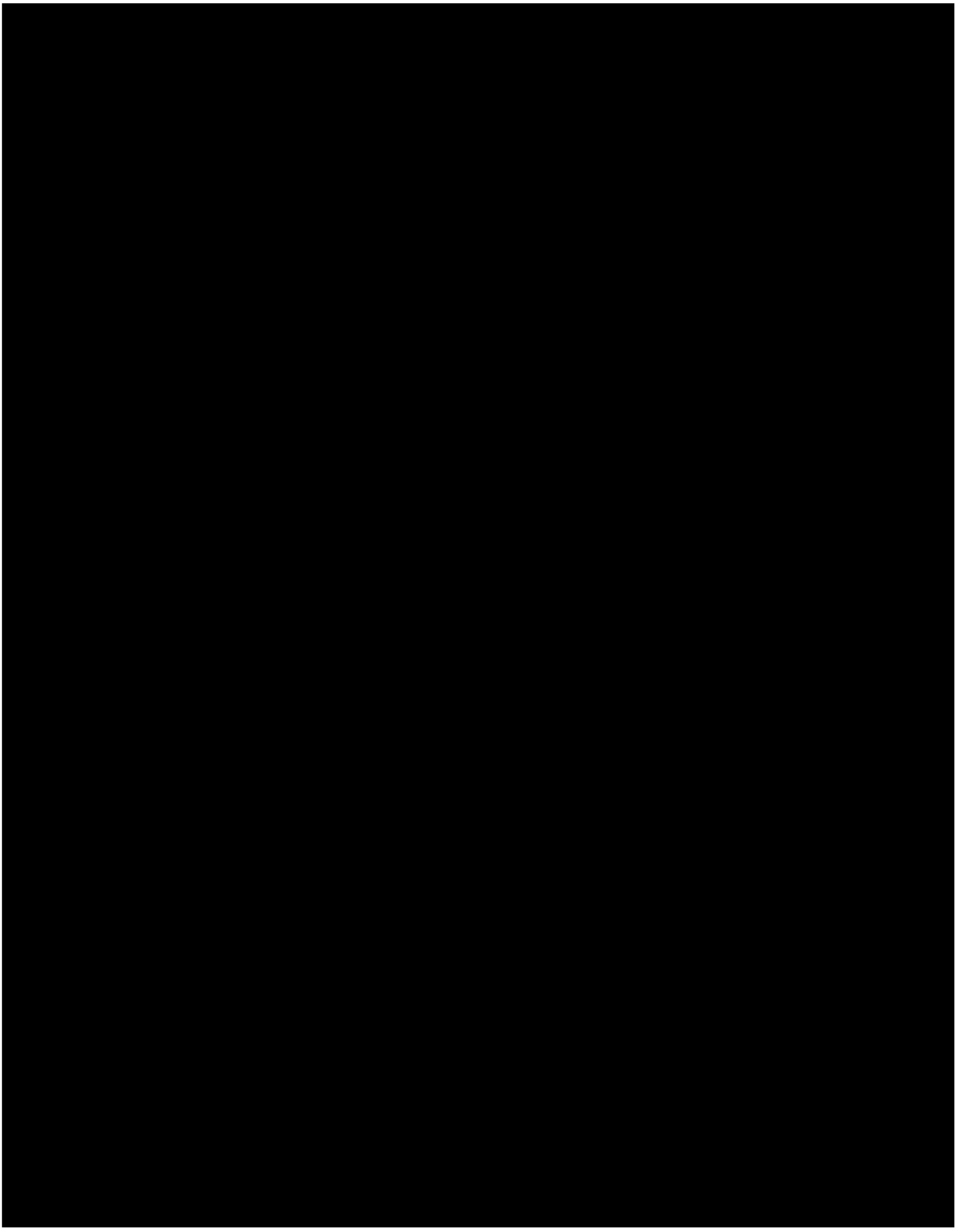


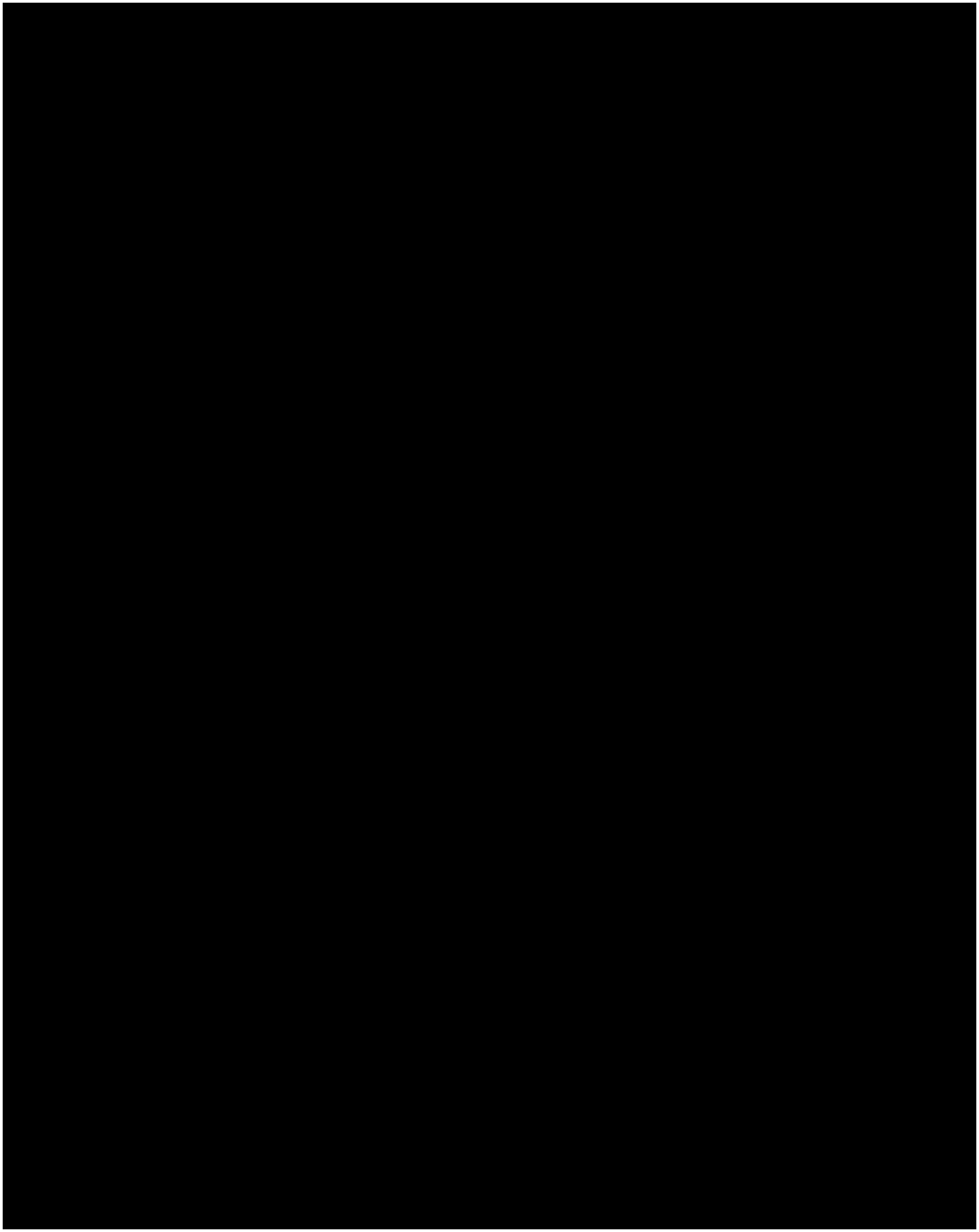


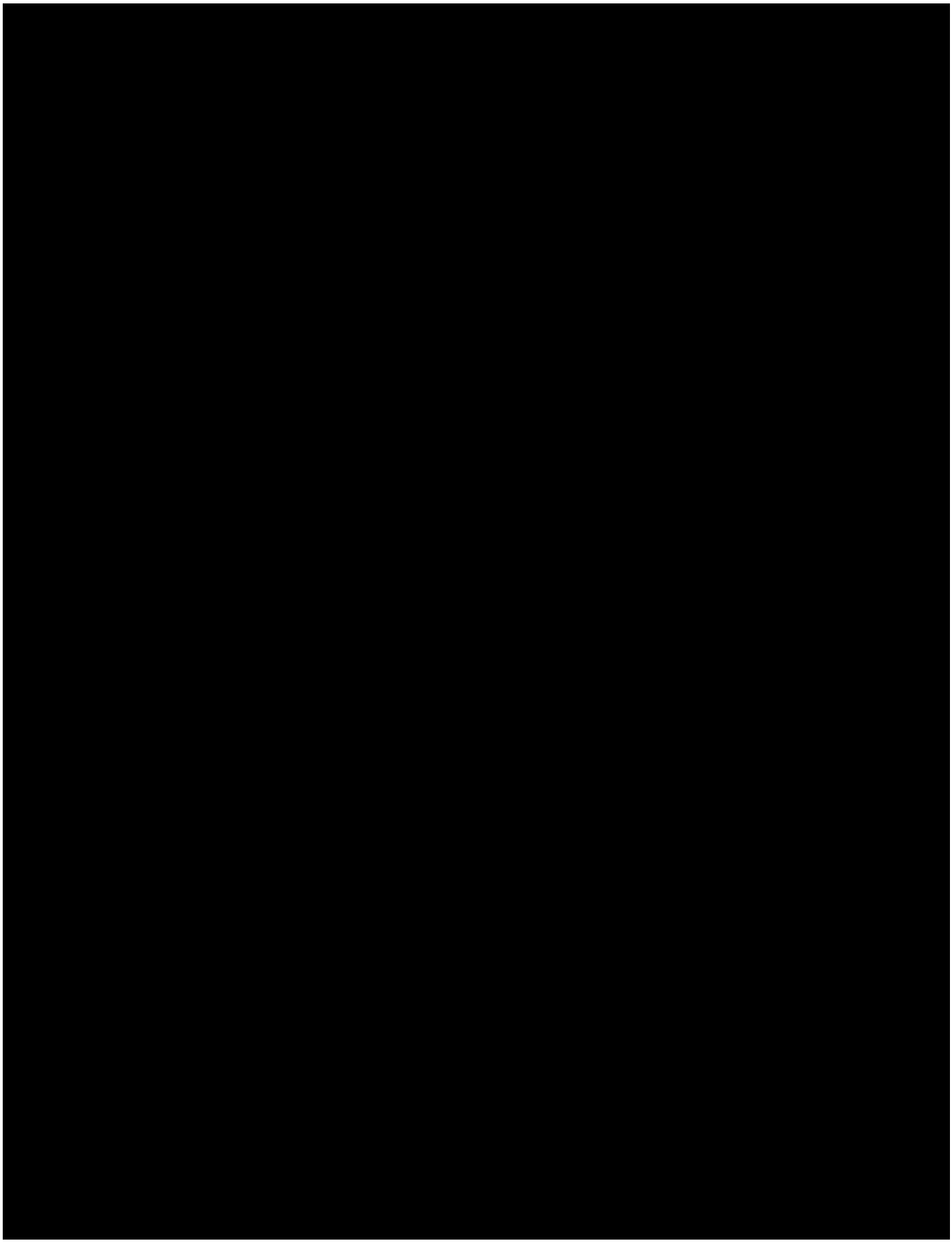












Environmental Science & Technology

Article

Implications of Ammonia Emissions from Post-Combustion Carbon Capture for Airborne Particulate Matter

Jinhyok Heo,*[,†] Sean T. McCoy,[†] and Peter J. Adams[†,‡]

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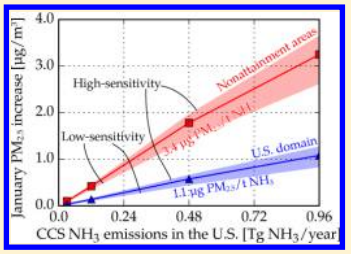
Supporting Information

ABSTRACT: Amine scrubbing, a mature post-combustion carbon capture and storage (CCS) technology, could increase ambient concentrations of fine particulate matter ($PM_{2.5}$) due to its ammonia emissions. To capture 2.0 Gt CO_2/year, for example, it could emit 32 Gg NH_3/year in the United States given current design targets or 15 times higher (480 Gg NH_3/year) at rates typical of current pilot plants. Employing a chemical transport model, we found that the latter emission rate would cause an increase of 2.0 μg $PM_{2.5}/m^3$ in nonattainment areas during wintertime, which would be troublesome for $PM_{2.5}$-burdened areas, and much lower increases during other seasons. Wintertime $PM_{2.5}$ increases in nonattainment areas were fairly linear at a rate of 3.4 μg $PM_{2.5}/m^3$ per 1 Tg NH_3, allowing these results to be applied to other CCS emissions scenarios. The $PM_{2.5}$ impacts are modestly uncertain (±20%) depending on future emissions of SO_2, NO_x, and NH_3. The public health costs of CCS NH_3 emissions were valued at $31−68 per tonne CO_2 captured, comparable to the social cost of carbon itself. Because the costs of solvent loss to CCS operators are lower than the social costs of CCS ammonia, there is a regulatory interest to limit ammonia emissions from CCS.



INTRODUCTION

Carbon capture and storage (CCS) technology is considered an important potential climate change mitigation option.[1−3] Amine scrubbing is currently the most mature post-combustion capture technology.[4] Ammonia-based CO_2 capture, which uses aqueous ammonia as a solvent for CO_2 instead of amines, is another promising post-combustion option because it may have energy and cost advantages over the amine-based system.[5]

There have been various environmental concerns associated with using amines for CCS.[6] One that is the focus of this study is that amine scrubbing could create an air quality problem associated with its ammonia emissions. Ammonia is a significant precursor of $PM_{2.5}$,[7,8] which refers to particulate matter having a diameter of 2.5 μm and smaller. Exposures to $PM_{2.5}$ pollution are strongly associated with increases in mortality and morbidity.[9]

Another concern is that amine systems produce a hazardous waste. Amines react with acid gas impurities such as SO_2, SO_3, NO_x, and HCl to form corrosive heat-stable salts (HSS).[6,10] While some amines can be released from HSS for reuse by adding a strong alkali, the remaining HSS must be treated as a hazardous waste. In addition, amines emitted to the atmosphere may react with NO_x to form nitrosamines, which are known carcinogens. However, nitrosamines are broken down rapidly by photolysis under sunlight,[11] and nitrosamines were not detected in an experimental study on amines emitted by amine-based CO_2 capture technology.[12,13] Lastly, ammonia emissions may also increase nitrogen deposition. Ecosystems with excess nitrogen could suffer from eutrophication and soil acidification.[14,15]

The role of ammonia in $PM_{2.5}$ formation is largely determined by nonlinear interactions between SO_2, NO_x, NH_3, and their products.[7,8,16] A unit ammonia emission from CCS may result in highly variable impacts on $PM_{2.5}$ concentrations depending on the ambient concentrations of these species as shown in Figure S1 of the Supporting Information. Once emitted to the air, ammonia may remain in the gas phase if sulfuric acid and nitric acid are not available, which therefore causes no change in $PM_{2.5}$ concentrations. If unneutralized sulfuric acid exists, ammonia first reacts with it to form PM sulfate ($(NH_4)_2SO_4$). Because unneutralized sulfuric acid already exists overwhelmingly in the particle phase, this reaction increases $PM_{2.5}$ concentrations only marginally by replacing hydrogen with ammonium. If sulfate is neutralized, however, any remaining ammonia may form PM nitrate (NH_4NO_3) by reacting with nitric acid. The formation of ammonium nitrate may be limited either by ammonia or by nitric acid. When ammonia is the limiting reagent, a unit of ammonia emitted creates much more $PM_{2.5}$ mass by PM nitrate formation than by neutralizing sulfate. Because PM nitrate formation is favored at cold temperatures, ammonia emissions may create a significant amount of $PM_{2.5}$ especially in winter or at night. Therefore, changes in ammonia emissions will tend to have stronger impacts on $PM_{2.5}$ in regions where ammonia is limiting PM nitrate formation, which corresponds to cold temperatures, lower SO_2 emissions, higher NO_x emissions, and

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Published: March 26, 2015

intermediate ammonia levels (sufficient to neutralize sulfate but limiting for ammonium nitrate formation). Such conditions occur regularly in the eastern United States in winter.[7,8,16]

Because the role of ammonia in $PM_{2.5}$ formation in the atmosphere is sensitive to ambient copollutants and atmospheric conditions, it is necessary to employ a chemical transport model to understand the impacts of CCS ammonia on ambient $PM_{2.5}$ concentrations. Although there have been studies looking into the environmental impacts of amine capture systems,[17−26] no study has been done yet to explore the actual physical and chemical interactions of the emitted ammonia in the atmosphere, which determine their consequences to society.

This study focuses on an amine system using monoethanolamine (MEA, C_2H_7NO), the most common solvent found in the literature, but the results are readily applicable to other post-combustion capture systems such as an ammonia-based process. We focus on the $PM_{2.5}$ impacts of the ammonia emissions themselves even though CCS may also reduce SO_2 emissions and, therefore, $PM_{2.5}$. We feel that this framing is cleaner and more decision-relevant for two reasons. First, independent of any decision to deploy CCS, the normal processes of air quality regulation[27−29] will continue to reduce SO_2 emissions. Therefore, attribution of these SO_2 reductions in the future involves considerable guesswork about the course of air quality regulation in future decades. Furthermore, once the decision to deploy CCS is made, the SO_2 reductions come either from CCS or air quality regulations, whereas regulators and operators are left with a separate decision about how much to control the associated ammonia emissions, which we seek to inform in our analysis. This study does not consider the potential contribution of amines themselves to $PM_{2.5}$ creation[12,30] due to the lack of data on emissions and atmospheric chemistry of amines. It has also been suggested that ammonia and/or amines contribute to the number concentration of ultrafine particles by enhancing the rates and frequencies of new particle formation events,[11,31−33] but this chemistry is still highly uncertain and is not considered here. Our calculations neglect potential effects of pH changes on organic $PM_{2.5}$ via acid-catalyzed oligomerization. However, the importance of this process is debated and uncertain[34] and has not been generally adopted in chemical transport models.

This study aims to evaluate the potential changes in $PM_{2.5}$ concentrations and resulting health impacts from amine scrubbing CCS in the United States. We estimated the ammonia emissions under an aggressive amine scrubbing deployment scenario in 2050. To demonstrate the potential for $PM_{2.5}$ impacts, we chose a CCS ammonia emission rate typical of current pilot plants, although these are substantially higher than design targets. Then, we simulated $PM_{2.5}$ concentrations with and without CCS ammonia for 2050. Several additional simulation analyses were carried out to test the sensitivity of our results to major uncertainties and to make our results applicable to a wide range of CCS ammonia emissions. Finally, the health impacts and associated social costs of the $PM_{2.5}$ changes were evaluated.

All monetary values in this study were converted to year 2010 U.S. dollars unless otherwise noted. GraphSketcher[35] was used to create Figures 1 and 2, and Matplotlib[36] was used to create all other figures.

AMMONIA EMISSIONS FROM AMINE SCRUBBING

Ammonia is created from the oxidative degradation of amines in the scrubbing process.[6,37] It has been reported that 30−50% of the amine lost in the process oxidizes to ammonia.[6,38] Differences in ammonia emissions between coal and natural gas plants have not been found in the literature. Because ammonia emissions are controllable by after-treatment, ammonia emissions probably will not depend on fuel type.

Figure 1. Amine loss rates reported or estimated in the literature. An ammonia emissions of 0.24 kg NH_3/t CO_2 was chosen for this study, which was reported in Rubin et al.[45] based on a coal power plant model assuming an amine loss rate of 1.5 kg MEA/t CO_2.[6] Note that the chosen rate is 15 times higher than the current U.S. NETL design target.

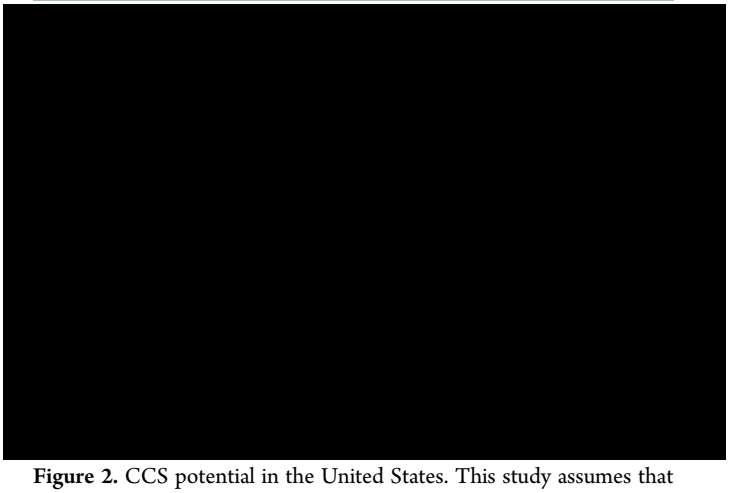

Figure 2. CCS potential in the United States. This study assumes that amine scrubbing CCS will capture 2.0 Gt CO_2/year in 2050.

Figure 1 summarizes the amine loss rates reported in the literature. Current pilot-scale applications show amine loss rates of 0.5−2 kg MEA/t CO_2. Pilot-scale natural gas power plants equipped with the Fluor Daniel Econamine system reported 1.5,[6,39] 1.6,[40] and 0.5−2 kg MEA/t CO_2.[41] A pilot-scale coal-fired power plant with an amine system reported losses of 1.4 kg MEA/t CO_2.[38]

However, other studies suggest that the amine loss could be smaller in the future. An expert elicitation study[42] reported that experts on amine-based CCS expected losses to be 0.05−2 kg MEA/t CO_2 by 2015 assuming modest R&D. A commercial power plant was able to reduce the solvent loss to 0.35 kg/t CO_2 using the amine solvent, KS-1, and further down to 0.1−0.2 kg/t CO_2 by modifying operational conditions.[43] On the basis of engineering modeling, U.S. NETL[44] projected a loss rate of 0.1 kg MEA/t CO_2.

This study selected an ammonia emission rate of 0.24 kg NH_3/t CO_2 from an amine loss rate of 1.5 kg MEA/t CO_2,

which is based on a supercritical pulverized coal power plant model with amine scrubbing and including a typical water wash.[45] The performance of the plant model was reported in the IPCC Special Report on Carbon Capture and Storage.[2] However, it should be noted that our chosen value is substantially higher than the current U.S. NETL design target listed above. We have deliberately selected this value because it is supported by current operations, and we wish to evaluate whether CCS has the potential to create air quality problems. Because amines and ammonia are highly soluble in water, their emissions are technically controllable, and control strategies can be designed depending on the economics of and/or regulations on amine scrubbing.

The other important variable is the level of CCS deployment in 2050, which is difficult to estimate because amine scrubbing systems are only now being demonstrated at the commercial scale and carbon mitigation plans are not yet clear in the United States nor in most other nations. Figure 2 shows the context for the CCS deployment assumed in this study. On the basis of the IPCC SRES A2 scenario,[46] Toth and Rogner[47] estimated that the technical potential of CCS in the United States would be 3.6 Gt CO_2/year in the power sector in 2050 under the A2-IMAGE scenario and 1.8 Gt CO_2 under the A2-AIM scenario. Riahi et al.[48] reported that OECD90, defined as all members of OECD in 1990, would capture 3.5−5.9 Gt CO_2 in 2050. About 50% of this potential, or 1.7−2.9 Gt CO_2, would come from the United States, reflecting coal primary energy consumption in 2000.[49] The Energy Modeling Forum 22 study[50] reported that coal electricity production with CCS ranges from 2.8 to 6.7 EJ/year among six models for United States transition scenarios targeting 80% emissions reductions below 1990 levels. This would be equivalent to 0.7−1.8 Gt CO_2/year if they are captured from a coal plant similar to the plant model cited above. All these deployment levels are not limited to post-combustion technology or amine scrubbing systems.

To estimate the potential air quality problem from CCS ammonia, we assumed that amine scrubbing in the United States would capture 2.0 Gt CO_2/year from coal-fired power plants and large industrial facilities in 2050. This assumption represents a future with aggressive amine scrubbing deployment because the amount is similar to the CCS deployment levels comprised of all CCS technologies in the scenario studies mentioned above but is realized with only amine scrubbing. The amount of captured CO_2 we assumed is similar to the amount of CO_2 emitted by coal power plants alone annually from 2005 to 2008.[51] The CO_2 emissions from natural gas power plants were 320−360 Mt CO_2/year during the same period. Recent shale gas development and new air quality regulations may force old power plants to retire and result in more intensive use of natural gas in electricity generation. Although a natural gas combined cycle (NGCC) emits about half the carbon dioxide to generate a unit of electricity compared to conventional coal plants,[44,52] it would be necessary to equip a portion of the NGCC fleet with CCS to achieve large (~80%) GHG reductions.[50]

From the two factors assumed above, the NH_3 emissions per CO_2 captured of 0.24 kg NH_3/t CO_2 and the amount of CO_2 captured with amine scrubbing of 2.0 Gt CO_2/year, the amount of ammonia emitted from amine scrubbing CCS was estimated to be 480 Gg NH_3/year. This amount of CCS ammonia is ~10% of the current anthropogenic ammonia emissions in the United States, which are 3.5−4.0 Tg NH_3/year.[53]

Non-CCS NH_3 emissions are larger in spring and summer than in other seasons because animal husbandry and synthetic fertilizer application are dominant sources of NH_3.[53] Thus, the CCS NH_3 emissions would result in a relatively larger increase of NH_3 in winter than in summer, precisely when $PM_{2.5}$ concentrations are most sensitive to ammonia emissions.

EMISSIONS SCENARIOS AND SENSITIVITY SIMULATIONS

Main Scenarios. We have designed three main scenarios to explore the role of CCS ammonia based on reasonable current and future levels of ambient SO_2, NO_x, and non-CCS NH_3 as shown in Figure S2 of the Supporting Information. We focused on these three species because the effect of CCS ammonia on ambient $PM_{2.5}$ depends on their relative availability as discussed above.

The first one is *Current*, which corresponds to the current air quality resulting from the emissions database of year 2005,[54] which was built for a U.S. EPA regulatory impact assessment.[27] The database includes emissions from Canada and Mexico and from marine vessels over the oceans. However, in the following scenarios, we did not change these emissions but only those emitted on land over the contiguous U.S. domain.

Next, *No-CCS-NH_3 2050* represents a future with significant CCS deployment but without any CCS NH_3 emissions. Because the future emissions of SO_2, NO_x, and NH_3 would be reduced by CCS or normal air quality regulation,[27−29] we assumed that the net impact of these factors is a reduction of 85% of SO_2 point emissions relative to 2005, 50% of SO_2 area emissions, 50% of NO_x emissions, and 30% of NH_3 emissions. Amine-based CCS removes almost all SO_2 because SO_2 reacts with amines to form heat stable salts. Therefore, a future with high CCS adoption would easily achieve an 85% reduction of SO_2 point emissions by 2050. Although more difficult than SO_2 point sources, SO_2 area emissions and NO_x emissions may also be substantially reduced. Although NH_3 emissions are not currently regulated, a 30% reduction in NH_3 emissions is assumed because NH_3 reduction is a cost-effective $PM_{2.5}$ control measure and regulatory interest in it has increased.[7,55,56]

Lastly, *CCS-NH_3 2050* is the same as the *No-CCS-NH_3 2050* scenario just described but with the additional 480 Gg NH_3/year of CCS ammonia as estimated above. Assuming large SO_2 sources represent the likely locations of future CCS plants, either coal plants or other large industrial sources, we added CCS NH_3 to the largest SO_2 point sources, which in total emit the same amount of SO_2 emissions by electricity generation in our 2005 emissions inventory.[54] We distributed CCS ammonia to the SO_2 point sources proportionally to their SO_2 emissions on an hourly basis throughout the year.

Sensitivity to Future Emissions, to CCS Ammonia Emissions and Locations, and to Climate Change. We did sensitivity analyses to address four major uncertainties associated with our main scenarios developed above. One is the future emissions of SO_2, NO_x, and non-CCS NH_3. In order to explore this uncertainty, two more sets of scenarios are developed—High-sensitivity and Low-sensitivity—as shown in Table S1 of the Supportiung Information. Because it is computationally too expensive to run the Comprehensive Air Quality Model with Extensions (CAMx) with many possible emissions combinations, the two scenarios are developed based on the understanding of inorganic $PM_{2.5}$ thermodynamics discussed above. High-sensitivity represents a future combination of SO_2, NO_x, and non-CCS NH_3 emissions that would

Figure 3. Monthly changes in $PM_{2.5}$ concentrations. United States domain is the contiguous United States in the simulation grid. Estimated $PM_{2.5}$ increases from CCS ammonia (red) represent a future scenario that captures 2.0 Gt CO_2/year at 0.24 kg NH_3/t CO_2, an ammonia emission rate typical of current pilot plants.

result in more $PM_{2.5}$ formation per unit CCS ammonia emissions, and Low-sensitivity represents one that would result in less $PM_{2.5}$ formation. SO_2 is assumed to decrease by 95% for High-sensitivity, considering a thorough reduction of SO_2 by amine scrubbing and other measures, and by 70% for Low-sensitivity, considering a future that would capture a substantial amount of CO_2 from natural-gas burning facilities while keeping a part of coal generation without CCS. NO_x is assumed to decrease by 70% for Low-sensitivity considering aggressive reduction efforts and by 20% for High-sensitivity considering modest control efforts. Lastly, non-CCS NH_3 is assumed to be reduced by 50% for High-sensitivity considering the cost effectiveness of NH_3 control[7,55,56] and by 0% for Low-sensitivity considering no action for NH_3 control.

The other major uncertainty is the amount of ammonia emitted from CCS. Despite nonlinearities in the thermodynamics of inorganic $PM_{2.5}$, we assume that the impacts will be approximately proportional to emissions. To test the linearity of impacts over the range of possible CCS ammonia emissions, CAMx was run for CCS-NH_3 2050, Low-sensitivity, and High-sensitivity scenarios that have 6.25%, 25%, 100%, and 200% of the CCS ammonia emissions assumed in CCS-NH_3 2050 scenario.

Also, in order to test the sensitivity of our results to the spatial distribution of CCS NH_3, we performed an additional sensitivity simulation in which we added the CCS ammonia to large NO_x point sources. This also allows us to look at the case of deploying CCS to natural gas power plants and other large natural gas burning facilities as well as coal plants.

Lastly, future temperature increase may affect our results. Under a strong warming climate scenario (Representative Concentration Pathways 8.5), climate models estimate the mean United States temperature may increase by 2 °C by 2050 on average.[57] We analyzed a case in which we imposed a 2 °C increase uniformly in space and time on the 2050 meteorology as a sensitivity scenario for this potential effect.

METHODS

Air Quality Simulations. We used the Comprehensive Air Quality Model with Extensions (CAMx) version 5.41[58] to simulate the air quality of the scenarios. CAMx is a state-of-the-art CTM that simulates horizontal and vertical advection, dispersion, wet and dry deposition, gas and liquid phase chemistry, and aerosol formation and growth. We used the CAMx air quality modeling platform, which was evaluated as a part of a U.S. EPA regulatory impact analysis.[27] The platform covers the continental United States with 36 km × 36 km horizontal grid resolution and 14 vertical layers reaching up to 16 km, which is fine enough for $PM_{2.5}$ human health impact analysis.[59] The initial and boundary conditions were provided by a global chemical transport model.[60] For inorganic $PM_{2.5}$ species, the modeling system showed a good performance (a 10−30% bias compared to observations).[60] Additional evaluations are summarized in the Supporting Information. Figure S3 of the Supporting Information presents CAMx results, showing simulated $PM_{2.5}$ concentrations with our 2005 database.

We ran CAMx for an entire year for each of the three main scenarios. However, due to high computational costs, we limited our sensitivity cases to four months (January, April, July, and October). We ran 7 days before each simulation period as ramp-up to minimize the effect from initial conditions. Special attention is paid to the $PM_{2.5}$ nonattainment areas designated for 1997 and 2006 standards[61] (Figure S4, Supporting Information), which are referred to here as $PM_{2.5}$-burdened areas.

Public Health Impacts. The health impacts from CCS-related $PM_{2.5}$ increases were quantified using standard methods adopted by the U.S. EPA.[62,63] First, for each model grid cell, we estimated the changes in mortality rate given the changes in annual-average $PM_{2.5}$ concentrations associated with air quality improvements in 2050 (Current to No-CCS-NH_3 2050) and with CCS ammonia impacts (No-CCS-NH_3 2050 to CCS-NH_3 2050). We used the concentration−response relations from two landmark cohort-based PM mortality studies; for each $PM_{2.5}$ concentration increase of 10 μg $PM_{2.5}/m^3$. Lepeule et al.[64] reported that all-cause mortality increases by 14% (95% confidence interval: 7−22%), and Krewski et al.[65] reported 6% (95% confidence interval: 4−8%). We quantified only the $PM_{2.5}$ impact on mortality as this accounts for more than 90% of monetized costs.[62,63,66] We also assumed that all $PM_{2.5}$ species have the same health effect on a mass basis because there is not sufficient epidemiological evidence that supports a metric better than $PM_{2.5}$ mass.[62,67] Second, for each grid cell, we estimated the number of premature deaths by multiplying population by the changed mortality rates. We used the year 2040 population forecast provided in the environmental Benefits Mapping and Analysis Program (BenMAP)[68] based on Woods & Poole Economics, Inc.,[69] which is 37% larger than the population in 2010. Although our scenarios were developed for 2050, we used the BenMAP population forecast for 2040, as no later forecast is available. Finally, we multiplied the number of premature deaths by the value of a statistical life (VSL), which is people's willingness-to-pay to avoid the risk of

Figure 4. Estimated increase in $PM_{2.5}$ concentrations due to CCS ammonia in 2050. $PM_{2.5}$ increase is most sensitive to ammonia emissions during wintertime and relatively insensitive during summertime.

premature death. We used a Weibull distribution having a mean VSL of $8 million, which is recommended by the U.S. EPA.[70] This value is derived primarily based on "revealed preference" studies that use marketplace behaviors to infer the willingness-to-pay of individuals to avoid mortality risks and "stated preference" studies that surveys people how they would choose in various hypothetical situations of different mortality risks. We carried out Monte Carlo simulations, each with 5000 iterations, to quantify uncertainties surrounding the concentration−response relation and VSL.

RESULTS

$PM_{2.5}$ Impacts. The monthly changes in $PM_{2.5}$ concentrations are presented in Figure 3. Nonattainment regions show larger changes than the entire United States domain because changes in emissions occur relatively nearby to nonattainment regions. The assumed air quality controls between now and 2050 result in a significant reduction of 3.4 $\mu g/m^3$ in $PM_{2.5}$ (Current to No-CCS-NH_3 2050) for the annual average over nonattainment areas and 1.7 $\mu g/m^3$ over the contiguous United States domain. The annual $PM_{2.5}$ concentration increases due to CCS (between No-CCS-NH_3 2050 and CCS-NH_3 2050) are smaller but significant: 0.72 $\mu g/m^3$ over nonattainment areas and 0.20 $\mu g/m^3$ over the United States domain. To better visualize the CTM results, difference maps of $PM_{2.5}$ concentrations are presented in Figure 4 and Figure S5 of the Supporting Information. A summary of the PM concentrations of all scenarios is presented in Table S2 of the Supporting Information.

Whereas the projected $PM_{2.5}$ reduction is the least in January and the largest in July (Figure S5, Supporting Information), the $PM_{2.5}$ increase from CCS ammonia is the largest in January and the lowest in July (Figure 4). This result agrees with the known $PM_{2.5}$ thermodynamics discussed above. Wintertime $PM_{2.5}$ is sensitive to additional ammonia emissions, and summertime $PM_{2.5}$ is generally sensitive to reductions in SO_2 emissions.[7,8,16] In winter, the impacts of CCS ammonia offset 86% of the projected future air quality improvements for the nonattainment areas and 38% for the United States domain. In summer, by contrast, CCS ammonia impacts on $PM_{2.5}$ concentrations are negligible. The $PM_{2.5}$ increases in nonattainment areas in spring and fall by CCS ammonia are about 20% of the increase in winter.

$PM_{2.5}$ concentrations increase linearly over a wide range of CCS ammonia for all four months as shown in Figure 5 and

Figure 5. Sensitivity analysis of January $PM_{2.5}$ to future emissions of copollutants (SO_2, NO_x, and non-CCS NH_3) and the amount of ammonia emitted by amine scrubbing.

Figure S6 of the Supporting Information. The slope in January is 3.4 μg $PM_{2.5}/m^3$ per Tg NH_3/year for nonattainment areas and 1.1 μg $PM_{2.5}/m^3$ per Tg NH_3/year for the United States domain. The sensitivity of the $PM_{2.5}$ increase to CCS ammonia is also linear in other months, although the slopes are shallower. Figure S6a of the Supporting Information shows that the impact of CCS ammonia on $PM_{2.5}$ has a modest sensitivity to the mix of other pollutants: SO_2, NO_x, and non-CCS NH_3. In addition, our results are not sensitive to the location of CCS ammonia and the temperature increase as shown in Figures S7 and S8 of the Supporting Information.

Estimation and Valuation of Premature Deaths. The projected changes in annual premature deaths and their valuations are presented in Figure S9 of the Supporting Information. Two mean estimates calculated based on the two epidemiological studies are presented as an estimated range here. Comparing improved air quality in 2050 without CCS ammonia to the present, the number of annual premature deaths is expected to decrease by 51,000−120,000, which is evaluated at $410 billion to $930 billion. Under the increased $PM_{2.5}$ from CCS ammonia, the number of annual premature deaths attributed to CCS ammonia is estimated to be 7600−17,000, a social cost of $61 billion to $140 billion. Given the seasonality of the $PM_{2.5}$ response discussed previously, 68% of the annual-average $PM_{2.5}$ increase resulted from wintertime $PM_{2.5}$ changes with a negligible contribution from summertime changes.

On the basis of these results, the per unit social health costs of CCS ammonia is calculated to be $130,000−280,000/t NH_3. Wintertime CCS NH_3 costs are higher at $340,000−770,000/t NH_3. On the basis of CO_2 captured, the costs of CCS ammonia are calculated to be $31−68/t CO_2 per year and $82−186/t CO_2 during the winter.

DISCUSSION

This paper has explored the air quality and human health impacts that could be imposed by ammonia emissions from amine-based post-combustion CO_2 capture processes. First, we estimated potential ammonia emissions based on current emission factors and analyzed the possible changes in concentrations of fine particulate matter ($PM_{2.5}$), of which ammonia is a major precursor, with a state-of-science chemical transport model, CAMx. Then, we estimated the premature mortality associated with the $PM_{2.5}$ formation and monetized the impacts. We also explored major uncertainties surrounding our results.

We found that ammonia emissions from amine-based carbon capture systems at a rate typical of current pilot plants would create a significant increase in $PM_{2.5}$ concentrations, resulting in worrisome public health impacts, although these could be lessened greatly if the current U.S. NETL design target[44] is achieved. With an emission factor of 0.24 kg NH_3/t CO_2, a substantial deployment of amine scrubbing to capture 2Gt CO_2/year would emit 480 Gg NH_3/year in the United States. This amounts to 14% of annual ammonia emissions or 34% of winter emissions of the United States in 2005. This scenario is intentionally chosen to demonstrate the potential for significant $PM_{2.5}$ impacts, but sensitivity to differing emissions rates was analyzed. Such emissions would increase the winter $PM_{2.5}$ concentrations in nonattainment areas by 2.0 $\mu g/m^3$ on average and up to 4.3 $\mu g/m^3$ in some locations.

This work has examined the key uncertainties governing the impacts of CCS NH_3, which are summarized in Table S3 of the Supporting Information. Because CCS ammonia emissions are uncertain and because ammonia impacts depend on the levels of copollutants available from other sources, we performed a sensitivity analysis over a wide range of CCS ammonia emissions and potential emissions of copollutants (SO_2, NO_x, and non-CCS NH_3) as shown in Figure S6 of the Supporting Information. We showed that $PM_{2.5}$ impacts are fairly linear with CCS ammonia emissions, and concentrations increase with CCS ammonia at a rate of 3.4 $\mu g/m^3$ per Tg NH_3 in nonattainment areas in January. The $PM_{2.5}$ increase in nonattainment areas in January could vary by about 20% depending upon the future emissions of the copollutants. The approximately linear response is useful. Because ammonia emissions from future systems may be lower than current pilot plants, the $PM_{2.5}$ impacts considered here may be scaled accordingly, noting that Figure S6 of the Supporting Information shows somewhat higher unit impacts for smaller CCS emissions. In addition, our results are not sensitive to the details of how CCS ammonia emissions are distributed around the nation nor to potentially warmer future temperatures (Figures S7 and S8, Supporting Information). As is always the case with $PM_{2.5}$ health valuations, uncertainties in concentration−response relations and VSL are significant (−90% to +160%).

If ammonia emissions were allowed at a level typical of current CCS pilot plants, the $PM_{2.5}$ increase would significantly compromise air quality. Especially, the wintertime $PM_{2.5}$ increase can offset in nonattainment areas 86% of all future air quality improvements including the contribution of CCS to large SO_2 reductions. An increased $PM_{2.5}$ concentration of 2.0 $\mu g/m^3$ is significant when one considers that current nonattainment areas often seek to cut 1−2 $\mu g/m^3$ to meet the $PM_{2.5}$ National Ambient Air Quality Standards (NAAQS). It may also cause other areas to slip into nonattainment, especially if more stringent NAAQS standards are adopted in the future. If future amine scrubbing plants are operated with lower ammonia emissions, the impact will be lower accordingly. For example, the current U.S. NETL design target,[44] which emits 15 times less ammonia than current pilot plots, would result in an average increase of 0.1 μg $PM_{2.5}/m^3$ for nonattainment areas in January.

Our per-tonne costs, $130,000−280,000/t NH_3, are somewhat larger than those in the literature. This is likely because $PM_{2.5}$ formation is more sensitive to ammonia emissions in the atmosphere in 2050 than we assumed, and we used the 2040 population forecast, which is 37% larger than the 2010 population. For comparison, we converted the following literature-reported ammonia social costs to 2010 U.S. dollars and metric ton from their reported units. With the Response Surface Model,[71] an air quality model, Fann et al.[72] reported social costs per ton of NH_3 emitted from mobile sources were $120,000/t NH_3 at the national level and $52,000−170,000/t NH_3 over nine urban areas based on a concentration response relation[73] similar to Lepeule et al.[64] For area source NH_3, they estimated a social health cost of $46,000/ton NH_3 at the national level. With a reduced-form air quality model, Muller et al.[74] reported the costs of NH_3 for all US counties using a VSL similar to this study and a concentration−response relation[75] similar to Krewski et al.[65] They vary from $2200/t NH_3 (fifth percentile) to $130,000/t NH_3 (95th percentile) with a mean of $38,000/t NH_3.

In the absence of controls on ammonia emissions, the $PM_{2.5}$ problem resulting from CCS ammonia emissions could be compared to the climate benefits of the avoided CO_2 emissions. Using a standard method of valuing $PM_{2.5}$ mortality, we estimated the social cost of CCS ammonia at $31−68 per tonne CO_2 captured. Estimates of the social cost of carbon, which includes CO_2 damages on human health, property, and ecosystem services, are uncertain and vary widely, but a United States government interagency working group estimated the social cost of carbon in 2050 to be $28−102/t CO_2.[76] When compared to these estimates, the public health impacts from CCS ammonia emissions are significant in comparison to the climate benefits from CO_2 emissions reductions from CCS and

deserve close attention in the future. CCS ammonia impacts could be minimized compared to CO_2 benefits by reducing CCS NH_3 emission factors below those used here.

Operators of CCS facilities have a natural incentive to reduce amine losses. For a solvent loss rate of 1.5 kg MEA/t CO_2 and an assumed amine solvent cost of \$2250/t MEA,[44] the amine consumption costs about \$3.4/t CO_2. However, our analysis shows that the $PM_{2.5}$ social costs are still much higher than the private costs borne by the operators in the form of solvent makeup. Therefore, it makes sense for regulators to impose limits on ammonia and amine emissions from CCS in order to protect the public interest. Because 68% of the burden occurs in winter and virtually none during the summer, it could be considered to enforce more stringent ammonia controls on a seasonal basis.

The concerns noted here suggest a need to proceed cautiously, but the air quality impacts of CCS ammonia are not necessarily prohibitive of the technology. Because ammonia is highly soluble in water, it is not technically difficult to control by installing more or better water wash units. Water wash units are already included in plant design mainly to reduce solvent loss from mechanical entrainment and evaporation.[44] Water wash systems could be better designed to minimize ammonia and amine emissions to the atmosphere in addition to the current purpose of minimizing solvent losses. If CCS ammonia is managed, for example, at the current ammonia control level of the selective catalytic reduction system (2−10 ppm), our estimate for the $PM_{2.5}$ impact from CCS ammonia is reduced by a factor of 10.

We based our analysis on MEA systems because this capture technology is reasonably well understood, but the results are readily applicable to other post-combustion capture systems such as an ammonia-based process. Although little information is currently available about ammonia leakage from such systems, the impacts per unit ammonia emitted could be applied to these systems given such data. Because the material cost of ammonia is much lower than MEA in terms of solvent costs per tonne of CO_2 captured,[77] an ammonia-based CCS power plant may afford to lose more solvent to the atmosphere than an amine-based one. Therefore, there would be an even stronger need for regulatory intervention to protect the public health.

In summary, widespread deployment of CCS technology could result in significant unwanted increases in $PM_{2.5}$ levels and potentially other impacts on air quality as well. There is a need for regulators to be pro-active in considering appropriate emissions-based standards to avoid such an outcome. Currently, there is no federal regulation on ammonia emissions from power plants. Emissions-based standards low enough to prevent significant air quality degradation will incur some cost but should be technically feasible, and the impact assessment performed here provides quantitative guidance for what level of control is appropriate.

■ ASSOCIATED CONTENT

Supporting Information

Supplemental figures and tables and additional evaluation of the CAMx air quality modeling platform. This material is available free of charge via the Internet at [redacted]

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The health impacts of waste incineration: a systematic review

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Abstract

Introduction: Waste incineration is increasingly used to reduce waste volume and produce electricity. Several incinerators have recently been proposed in Australia and community groups are concerned about health impacts. An overview of the evidence on health effects has been needed.

Method: A systematic review of English language literature for waste incinerators and health using PRISMA methodology.

Results: A range of adverse health effects were identified, including significant associations with some neoplasia, congenital anomalies, infant deaths and miscarriage, but not for other diseases. Ingestion was the dominant exposure pathway for the public. Newer incinerator technologies may reduce exposure.

Discussion: Despite these findings, diverse chemicals, poor study methodologies and inconsistent reporting of incinerator technology specifications precludes firmer conclusions about safety.

Conclusion: Older incinerator technology and infrequent maintenance schedules have been strongly linked with adverse health effects. More recent incinerators have fewer reported ill effects, perhaps because of inadequate time for adverse effects to emerge. A precautionary approach is required. Waste minimisation is essential.

Implications for public health: Public health practitioners can offer clearer advice about adverse health effects from incinerators. We suggest improved research design and methods to make future studies more robust and comparable. We offer ideas for better policy and regulation.

Key words: waste, health, cancer, incineration, toxin

Waste management encompasses the avoidance, reduction, collection, transport, storing and disposal of waste products from municipal, health and industrial sources. Current disposal strategies include recycling, landfill and incineration.[1,2]

Waste management is of growing concern for communities globally and in Australia, with alternatives to traditional landfill increasingly being employed. Waste incinerators provide one alternative for reducing pressure on landfill. Modern incinerators are also designed to generate electricity, which increases their appeal to policymakers.[3–5]

Waste incinerator systems have traditionally been associated with emission of toxic pollutants, impacting human and environmental health. The Stockholm Convention provides international guidance on the safe management of persistent organic pollutants (POPs). The objective of the Convention is to minimise or prevent human exposure to POPs. It incorporates a precautionary and manufacturer/user pays approach. The guidelines cover waste incineration because this is a potential source of POPs, including dioxin-like compounds. Waste reduction is a key recomendation.[6]

Newer waste incinerator technologies are claimed to run more cleanly and with less environmental impact. Nevertheless, pollutants are still produced, with upgraded facilities requiring regular service to maintain emission levels.

Despite technological advancements, local and global health impacts from waste incinerators remain a concern for communities where they are being built. Adverse health outcomes in populations near waste incinerators, including cancers and reproductive dysfunction, have been demonstrated in primary studies.[7–12] Unfortunately, precise evaluation of the health impact of waste incinerators can be difficult due to confounding factors, including pollution from industries, automobiles and agriculture chemicals, latency for carcinogenicity, subacute and delayed reproductive/intergenerational effects, mobility of populations and other factors.

This systematic review aims to identify the health effects on human populations living near waste incinerators to inform the public and guide policymakers, and to define appropriate criteria for approving current and future waste incinerator proposals. We reviewed primary studies investigating levels of known pollutants in human and environmental samples as well as the health effects associated with waste incineration pollutants.

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Methods

Study inclusion criteria

This systematic review was conducted based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.[13] We included peer-reviewed primary literature addressing health effects of waste incineration. Studies had to focus on the impacts of waste incineration on health risk and/or health outcomes. Papers had to be in English and accessible online and could not be protocols.

Search criteria

Relevant papers were found through a search of the PubMed database from 1 January 2002 through 31 December 2017, using the MeSH term 'waste management' AND keyword search terms 'incineration' AND 'health'. We did not search 'waste to energy' because incineration more generally was our primary focus. To keep the volume of literature manageable within time limits, and to harvest more recent and therefore up-to-date and relevant studies, we set the 15-year time horizon. A similar search on the Science Direct database did not yield any additional papers. The reference lists of captured systematic reviews were examined for further papers that met the inclusion criteria.

Study eligibility

Paper eligibility was evaluated independently against the criteria by two researchers using the abstracts. Disagreements were resolved by a third assessor. Eligibility was re-assessed when the full manuscript was read. The broader research team decided exclusions by majority decision.

Data extraction

Papers were randomly assigned to six group members to extract the following data from each manuscript: the study design; methods; country of study; incinerator properties; local and global health outcomes; bias; and main results. Study design was categorised as either randomised-controlled trial, cross-sectional, case-control, cohort, case study, case series, simulation or ecological. Local health outcomes were considered as those that affected populations living or working within the vicinity of waste incineration facilities; whereas, global health outcomes (primarily health impacts of global warming due to waste incineration) were considered for more distant populations.

We further classified papers according to impacts on health risks or health outcomes. Health risks were subclassified by assessment method as either external (measurements of air, soil, water, food, etc) or internal (measurements of serum, urine, breast milk, hair, or direct effects on cells and/or DNA). Health outcomes were further subclassified as neoplasia, reproductive health and other. Many papers examined both health risks and outcomes; they were included in multiple groups. Each paper was evaluated for its assessment of bias.

As a quality control measure, a separate reviewer examined 20% of papers to assess concordance between the different data-extraction teams.

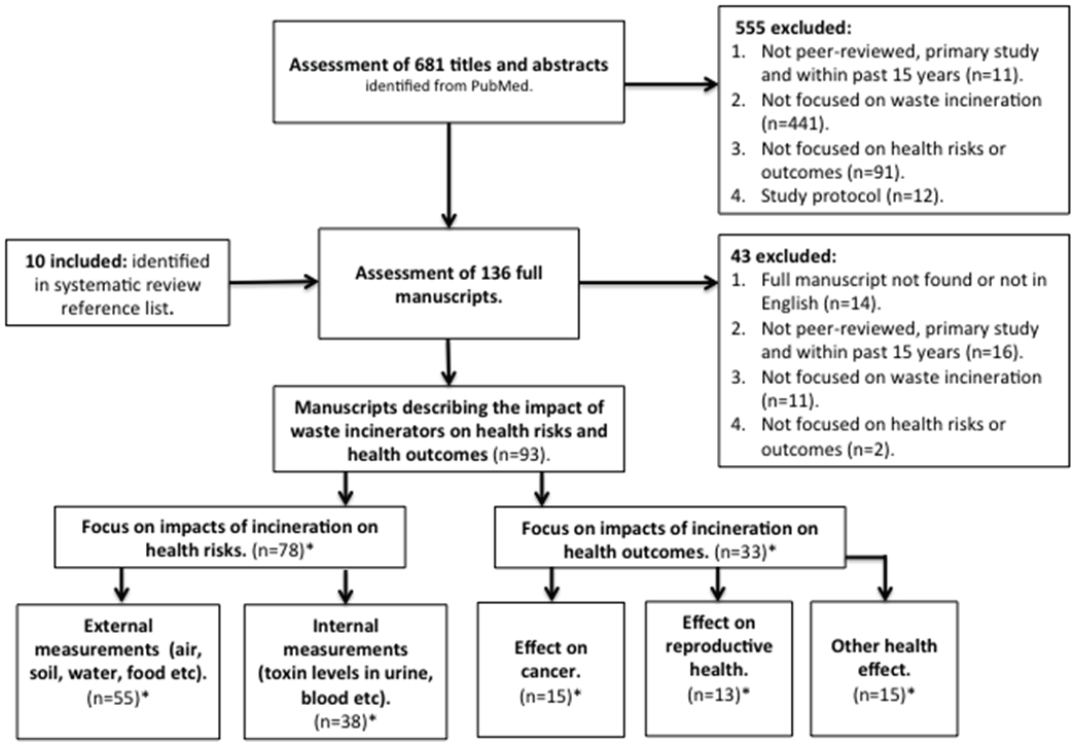
Grade of evidence

Each paper was graded according to the National Health and Medical Research Council (NHMRC) guidelines: A (excellent) to D (poor).[14]

Results and discussion

The identification of 93 manuscripts meeting criteria is detailed in Figure 1. Details are provided in the Supplementary File: Data Table. Most papers were graded low on NHMRC criteria; the highest grade awarded was C (satisfactory), see Supplementary File. The study designs reviewed included 19 cohort (prospective and retrospective) and case-control investigations. Overall methodological quality was satisfactory (five

Figure 1: PRISMA diagram for the identification of peer-reviewed papers included in the review.



Note:

** Some manuscripts fit into multiple subgroup classifications.*

studies) to poor (14 studies), with the absence of randomisation and blinding as the chief impediments to obtaining higher grade. This is not a major limitation given the necessarily observational nature of the studies.

The five studies assessed as satisfactory were based on results gained from a generalisable study population; they reported findings with valuable clinical impact (odds-ratios and risk-ratios) and considered bias.[15-19]

The 74 lower-grade studies comprised cross-sectional (42), case-study (2), longitudinal (4), ecological (2), simulation (19), observational (1) and life-cycle analysis (4) studies. Absence of control groups and no analysis of bias were the chief impediments to obtaining a higher grade.

Concordance between different members of the data-extraction team was satisfactory at greater than 80%.

Overall, we identified 61 (66%) papers that demonstrated a significant adverse outcome in relation to waste incineration. Of these, 34 (37%) showed exposure to elevated levels of known pollutants, nine (10%) identified an increased risk of developing some neoplasia, nine (10%) found a correlation with adverse reproductive outcomes, and nine (10%) found a link to other diseases such as hypertension or reduced lung function. No papers investigated the global health effects of waste incineration.

Note that, while occupational exposure is mentioned in some cases, this is usually as a comparator to local resident exposure. In addition, exposed workers can be sentinels for effects that can be sought in the wider public.

Exposure risk – external measurements

Fifty-five papers analysed external measures of exposure. Most were cross-sectional, ecological or simulation types. A common format for studies involved measuring plant stack emissions (or samples taken at different distances from stacks) and modelling exposure based on a mixture of demographics, food consumption patterns and weather. This was usually based on US EPA modelling guidelines[20] to calculate exposure by inhalation, dermal contact, soil contact and ingestion. Exposure levels were acceptable (within local regulations) in 23 papers, while 25 found that the exposure could lead to adverse outcomes and seven made neither judgement. Eleven of the 55 papers found that newer incinerator technologies led to reduced exposure, either by pre- and post-analysis following incinerator upgrades, or via comparison of multiple incinerators of varying ages.

Dietary ingestion was consistently the largest route for toxic emission exposure. Six papers concluded this explicitly,[21-26] while other studies attributed the majority of exposure burden to food ingestion, based on pre-existing research.

Few studies acknowledged other potential sources of pollutants, despite every incinerator facility operating near other polluters: transport, factories or refineries. Details concerning incinerator design were omitted in 23 studies, precluding comparison of the efficacy of different stack emission cleaning systems and making these results difficult to interpret.

Exposure risk – internal measurements

Thirty-six papers[15,22,27-60] investigated exposure to waste incinerator emissions by measurement of body substances. Upon review, five were found to have been misclassified and were excluded from the analysis. This heterogeneous group of 31 papers measured exposure in a variety of ways, including cell studies and measurements of organic and non-organic substances in body fluids and hair. Substances studied included dioxins, furans, heavy metals and polycyclic aromatic hydrocarbons (PAH). Given the diversity of substances and methods of measurement, the variability in results is unsurprising.

Findings from internal measurements

Increased levels of substances were measured in nearby residents and workers (who may also be nearby residents).

Cell function and damage

Five papers performed cell studies, encompassing studies on cell viability, immune cell activation, markers of mutation and markers of oxidative damage. Of these, three reported significant findings. Cao et al.[56] exposed human A459 cells to particulate matter from incinerator atmospheric samples and found increased production of reactive oxygen species and reduced cell viability. Oh et al.[38] compared blood samples from 31 waste incineration workers and 84 control subjects and found significantly increased T-cell activation in incineration workers. Leem et al.[52] measured urinary markers of oxidative stress in 13 workers and 16 residents near a municipal waste incinerator and compared these to samples from 10 residents near an industrial waste incinerator; residents near the industrial incinerator had significantly higher markers than those near the municipal incinerator. The lack of control group and small sample size limit the utility of this analysis in making conclusions regarding the safety of municipal waste incinerators.

Dioxins and furans (PCDD/Fs)

Nineteen papers assessed effects of exposure to concentrations of polychlorinated dibenzodioxins (PCDDs/dioxins) and polychlorinated dibenzofurans (PCDFs/furans) in the human body. Of these, five reported significant results. Yamamoto et al.[39] measured PCDD/PCDF blood concentrations in 16 incineration workers over an eight-year period after the closure of the incinerator in 1997, finding PCDD levels 4.7 times higher and PCDF levels 21.2 times higher compared to the local farming population. Although this result looks alarming, the age of the incinerator studied may limit its applicability to the modern context. The impact of incinerator age was also demonstrated by Reis et al.,[36] who measured dioxin concentrations in breast milk and found significantly higher concentration in mothers exposed to the older, compared to the modern, incinerator. Leem et al.[52] found significantly higher blood dioxin concentration in 10 residents near an industrial incinerator compared to 29 workers and residents near a municipal incinerator but did not compare these results to controls without exposure to incinerators.

Chen, Su and Lee[22] investigated the relationship between food consumption and blood dioxin concentration in 1,709 residents near 19 incinerators in Spain, finding significantly higher blood dioxins in those consuming locally grown food compared to those who did not ($p<0.0001$). Similar results were found in Ranzi et al.[59] and Cordier et al.[24] Most other studies used residents who lived further away from an incinerator as a control group compared to residents who lived closer as the exposure group; distance was assumed to be a proxy for exposure. The dominance of food ingestion among exposure pathways potentially confounds these results, as the assumed 'controls', who in many cases only lived kilometres away from the 'exposed', may have eaten the same-sourced foods. Further meteorological conditions may carry toxins longer distances.[61] Distance from residence to

incinerator should therefore not be regarded a legitimate proxy for exposure, given the likelihood of confounding factors leading to an underestimation of effect.

Heavy metals

Ten papers assessed concentrations of heavy metals, of which five reported statistically significant results. Deng et al.[34] measured blood mercury concentrations in 35 incinerator workers in China and 269 exposed local residents with 143 control subjects. After controlling for confounders including food consumption habits, they found significantly higher mercury levels in the incinerator workers and exposed group compared to controls (median levels 1.02 mg/L, 0.81 mg/L, 0.70 mg/L, respectively; $p<0.05$). The raised levels in both the workers and exposed residents corroborates the potential problem of using local residents, who might consume the same food sources, as controls. Reis et al.[55] measured lead concentration in hair and blood from 497 children living in Spain, finding that while significantly higher levels of lead were found in the exposed compared to the control group, lead levels were relatively low across the study participants, although the lead action level used was higher than in other countries. This result is consistent with Reis et al.,[35] who also found a significant but mild increase in maternal and newborn blood lead, although the concentrations were all below the established action level. Chao and Hwang[58] found significantly higher concentrations of urinary and blood arsenic in workers compared to age- and sex-matched residents. A modifying factor was workers' use of activated carbon facemasks and gloves during working hours. Ranzi et al.[59] found a dose-response trend for urinary and serum heavy metals and PAH in their study of 65 subjects living near or working in an incinerator and with 103 controls.

Polycyclic aromatic hydrocarbons

Four papers assessed the concentrations of PAH, of which three reported statistically significant results. Oh et al.[38] found urinary PAH metabolites were 15 and 3.5 times higher in incineration workers compared to the controls ($p<0.05$). This result was consistent with a later study performed by Ranzi et al.,[59] which found significantly higher urinary PAH in the exposure group compared to controls. Incinerator technology seems to influence the exposure to PAH, as demonstrated by a study by Ichiba et al.,[32] which found significantly higher urinary PAH in workers at an older incinerator compared to a more modern one.

Waste incinerator exposure and neoplasia risk

Several studies showed that local residents may be exposed to carcinogenic levels of pollutants from waste incinerator emissions. However, the utility of these studies in guiding incinerator design is limited, with many studies omitting crucial information regarding the type of incinerator design, specific criteria to define local residents, and details outlining the analysis of bias and confounders.

Non-Hodgkin lymphoma

Non-Hodgkin lymphoma has been associated with waste incinerator exposure. Floret et al.[15] studied waste incinerator exposure (since 1971 in two locations and 1976 in another) and non-Hodgkin lymphoma cases in local residents compared to a control population. After accounting for confounders, a relationship was established between dioxin exposure and non-Hodgkin lymphoma; exposure levels greater than 0.0004 pg/m^3 resulted in an odds ratio of 2.3 (95%CI 1.4–3.8). Viel et al.[62] identified a low-risk ratio of 1.120 (95%CI 1.002–1.251) for non-Hodgkin lymphoma in local residents, although only in females; the period studied was 1972–85.

Soft tissue sarcoma

Soft tissue sarcomas have also been linked to exposure to waste incinerator emissions. Zambon et al.[63] revealed an increased risk of sarcoma related to exposure to a large variety of incinerators and waste streams. The only exposure associated with a significant odds ratio was for levels greater than 6 fg/m^3 dioxin species (OR 3.27; 95%CI 1.35–7.93). This studied peak exposure over the period 1972–86. Comba et al.[16] studied local residents of an incinerator in Mantua, Italy, and found an alarming odds ratio of 31.4 (95%CI 5.6–176.1) for sarcoma in residents within 2 km of the incinerator. Notably, Mantua was recognised for its unregulated and toxic waste streams through the period 1974–91.

Bowel cancer

Ranzi et al.,[64] using a cohort study, demonstrated bowel cancer risk increased in residents near a waste incinerator. After controlling for confounders, analysis revealed significant bowel cancer risk ratios for mortality in men (RR 2.1; 95%CI 1.1–4.4), and incidence in women (RR 2.0; 95%CI 1.3–3.06). Parodi et al.[65] conducted a cross-sectional study linking lung cancer deaths and heavy metal concentrations in soil utilising a dispersion model. Results included increased risk for women with high (RR 2.14; 95%CI 1.09–4.20) and low (RR 1.54; 95%CI 1.01–2.36) exposure. However, the region studied had multiple pollution sources not factored into the analysis, reducing validity of the results.

Other cancers

Federico et al.[8] performed an ecological study across multiple incinerators and a large population of exposed local residents. The study correlated stomach, gallbladder, lung and pleural cancer mortality with distance to incinerators. All cancer risks were above unity but only slightly, with an overall cancer mortality risk ratio of 1.06 (95%CI 1.04–1.09; $p<0.0001$). Viel et al.[17] found women aged over 60 years in the highest exposure bracket were actually less likely to be diagnosed with invasive breast cancer (OR 0.31; 95%CI 0.08–0.89); however, this study had limited technical incinerator detail.

Several studies showed no association of cancer risk to waste incinerator exposure. In Japan, Fukuda et al.[9] reported that cancers in residents near waste incinerators had no significant relationship to dioxin exposure across a large variety of exposure periods. Additionally, Domingo et al.[66] performed a case study that sampled and then modelled air and soil pollutant levels in the vicinity of waste incinerators. They concluded that carcinogenic risk from waste incinerators was similar to background levels in any industrial or urban area, suggesting that, while waste incineration is at most not worse than traditional industrial and urban pollution sources, this level of exposure would add to the historical baseline level. Finally, Garcia-Perez et al.[18] performed an ecological study of two incinerators and were unable to identify a spatial trend between cancer incidence and proximity to incinerator. These studies suggest that relationships between proximity and effects may be neither direct nor linear.

Overall, results relating to neoplasia were mixed. This is unsurprising given that many use proximity to the incinerator as the independent variable, despite the limitations of this approach described earlier. Further, most papers omitted pertinent details on incinerator design, and several statistically significant results were inconsequential as they approached unity. Nevertheless, the seriousness of neoplasia diagnoses warrants a precautionary approach to incinerator exposure. Further, earlier periods of exposure have a stronger link with cancers such as non-Hodgkin lymphoma and sarcoma.

Reproductive outcomes

Eleven eligible studies[11,12,24,38,49,67-72] examined the effects of waste incinerator exposure on a wide range of reproductive outcomes. Nine of these found significant adverse effects, including preterm delivery, reduced sperm quantity and quality, congenital anomalies, infant deaths, and miscarriage.

Preterm delivery

All three studies examining preterm delivery demonstrated an association between exposure to pollutants from incinerators and preterm and earlier gestational age at birth. Santoro et al.[12] performed a cross-sectional study of 3,153 births from 2001 to 2010 near an incinerator in Italy and found that, after adjusting for confounders, there was an increased risk of preterm birth in primiparous women (OR 2.18; 95%CI 1.05–4.53; p=0.033). This result was consistent with a larger study of 21,157 births conducted by Candela et al.,[67] which found that increased exposure to particulate matter from eight incinerators in Italy was significantly associated with an increase in preterm delivery (OR 1.30; 95%CI 1.08–1.57; p<0.001), as well as for very preterm babies (OR 1.44; 95%CI 1.11–1.85; p<0.001). Lin, Li and Mao[49] found a small reduction in gestational age at birth in exposed groups. Although statistically significant, the effect size was tiny (0.09 weeks). Overall, these results suggest an association between exposure to incinerator pollutants and preterm birth, but further research is required to rule out potential confounders relating to location and time frame used in the first two studies.

Sperm analysis

Oh et al.[38] conducted a cross-sectional comparison of sperm count and motility for six waste incineration workers and eight controls and found that the sperm count was significantly lower in waste incineration workers compared to the control subjects (p=0.05). The authors also found that the incineration workers had more DNA damage in their spermatozoa compared to the controls (mean olive tail moment 1.40 vs. 1.26, p<0.001). The small sample size and lack of adjustment for confounding factors limit the utility and generalisability of this study.

Congenital anomalies

Five studies investigated congenital anomalies, with four finding a significant association between exposure to pollutants from incinerators and increased risk of congenital anomalies. These significant results included lethal heart and neural tube defects, facial clefts and renal tract defects, as well as infant death with congenital anomalies.

A retrospective cohort study by Dummer, Dickinson and Parker[70] used population registries to collect data on 244,758 births in the UK between 1956 and 1993 and found a significantly increased risk of lethal heart defects (OR 1.12; 95%CI 1.03–1.22; p<0.01) and lethal neural tube defects (OR 1.12; 95%CI 1.07–1.28; p<0.01) among births in closer proximity to incinerators. Although the large size of this study increases its value, the study period might limit its applicability to the modern context.

More recent studies have confirmed an association between incinerators and congenital anomalies. A retrospective cohort study by Tango et al.[69] found a dose-response association for infant deaths from congenital malformations for births in Japan between 1997 and 1998 in areas near incinerators with higher compared to lower soil dioxin levels (p=0.047). Cordier et al.[68] conducted a retrospective cohort study in France using data from 1988–97 and found increased frequency of facial clefts (RR 1.30; 95%CI 1.06–1.59) and renal dysplasia (RR 1.55; 95%CI 1.10–1.20) in the incinerator-exposed communities. Additionally, a dose-response association of increased risk of obstructive uropathies was observed between the low, medium and high exposure groups (RR 1, 1.38 and 1.93 respectively). Cordier et al.[24] followed this up with a case-control study in which cases of renal/urinary tract anomalies were matched with controls and assessed for exposure to incinerators. This study controlled extensively for environmental, social and individual confounders and found significantly increased risk of renal/urinary tract birth defects linked to higher exposure from incinerator-produced atmospheric dioxins (OR 2.84, 95%CI 1.32–6.09) and dioxin deposits (OR 2.95; 95%CI 1.47–5.92). The effect size and more rigorous study design provides stronger evidence for an association between exposure to incinerators and renal/urinary tract congenital anomalies.

Miscarriage

Four studies looked at miscarriage and stillbirth; however, only one found a significant association with exposure to incinerator emissions. This cross-sectional study by Candela et al.[11] used population registries and hospital records and found increased risk of hospitalisation for miscarriage among women without previous miscarriages with a higher compared to lower exposure based on incinerator dispersion modelling (OR 1.29; 95%CI 0.97–1.72; p=0.042). They also modelled alternative exposure sources. The use of hospital records did not capture the women who were not surgically managed for their miscarriage and the strength of the association is limited due to the odds ratio crossing unity. Moreover, since the study design was based on EPA dispersion modelling, not real-world emission sampling, the result may underestimate the true effect size.

Dioxins interfere with several biological processes that are key to embryonic and foetal development and are causally linked to poor birth outcomes. The associations found here can be partially explained through a teratogenic pathway. Dioxins, particulate matter and heavy metals, all emitted by incinerators, are known teratogens,[73,74] demonstrating plausibility for a causal link between waste incinerators and congenital anomalies and miscarriage. The association between incinerators and preterm birth, however, demonstrates that dioxin teratogenicity does not account for all adverse reproductive outcomes associated with waste incinerators. Other possible links include effects of dioxins on placental development and function[75] as well as endocrine signalling.[76,77]

Overall, the literature demonstrates increased risk of adverse reproductive outcomes associated with exposure to waste incinerators, in particular preterm birth and congenital anomalies. Conversely, no significant association appeared for sex ratio,[12,67,69] birth weight,[12,49,67,69] small for gestational age[12,67] and neonatal death.[69,70] Nevertheless, the outcomes for which a significant association was found represent severe and potentially tragic health and personal implications, which warrant careful consideration and planning to mitigate risks from proposed waste incinerator facilities in Australia.

Other diseases

Seventeen eligible studies examined waste incinerator impacts on a range of other health outcomes. Adverse health effects, including on overall mortality and burden of disease, cardiovascular, respiratory, metabolic, dermatologic, childhood developmental delay and mental health (see Supplementary File) were absent or insignificant.

Overall mortality and burden of disease

Epidemiological studies in Japan[9] and Italy[64] showed no increased all-cause mortality associated with living in proximity to incinerators and increased exposure to dioxins, oxides of nitrogen or heavy metal emissions from waste incinerator facilities. Galise et al.[78] modelled a 0.12% increase in overall deaths in the studied region attributable to fine particle (PM10, <10μm in diameter) exposure, while Li et al.[79] concluded waste-to-energy incineration had the lowest non-cancer risks under normal operation but carried the highest cancer risk in comparison to other waste management strategies. Kim et al.[80] calculated the burden of disease (measured in years of life lost and disability-adjusted life years) in populations close to waste incinerators in Korea to be small.

Cardiovascular mortality and morbidity

Fukuda et al.[9] demonstrated no evidence of increased ischemic heart disease-related mortality in surrounding populations with adjustment for socioeconomic status, while Ranzi et al.[64] inferred no clear trends for increased cardiovascular or ischemic heart disease mortality in those exposed to heavy metals or living near incinerators regardless of adjustment for co-exposure with oxides of nitrogen.

Galise et al.[78] modelling attributed a 0.19% (95%CI 0.11–0.28) increase in cardiovascular mortality and 0.06% (95%CI 0.00–0.12) of heart disease-related hospital admissions to potential exposure to 40μg/m^3 of PM10 incinerator emissions; these are very low increases in risk ratios. Contrastingly, Chen et al.[81] demonstrated a significant association between serum dioxin levels and the occurrence of hypertension (OR 5.58; 95%CI 1.63–19.62; p=0.007) among populations living close to incinerators.

Respiratory mortality and lung function impairment

Galise et al.[78] demonstrated a 0.27% respiratory mortality and 0.12% hospital admission rate to PM10 incinerator emissions (95%CI 0.11–0.42, 0.04–0.23, respectively), while Ranzi et al.[64] ruled out any increase in mortality or hospital admissions due to lung diseases and COPD among residents in proximity to incinerators compared with a reference population.

Studies by Hours et al.[82] and Charbotel et al.[19] both demonstrated significant impairment of lung function among incinerator workers. However, only Hours et al. were able to demonstrate a correlation between lung function impairment and occupational pollutant exposure. Hazucha et al.[83] were not able to demonstrate a similar link between paired resident and control communities.

Metabolic syndrome and endocrine disorder

Chen et al.[81] investigated serum dioxin levels and biochemical abnormalities in residents living close to incinerators. The study demonstrated elevated blood glucose levels (p=0.003), blood urea/nitrogen (p=0.003) and uric acid (p=0.019) with no significant association to diabetes mellites (p=0.07) and gout. In addition, there was no evidence for any correlation between dioxin exposure and anaemia, gallstones, goitres or hyperthyroidism.

Similarly, Yamamoto et al.[84] found that blood dioxin levels among incinerator workers did not differ from the general Japanese population. Increased $HbA1_C$ levels were shown to correlate with blood dioxin level among incinerator workers; however, the prevalence of diabetes among incinerator workers was similar to that in the general population.

Yoshida et al.[30] found a positive correlation between serum oestradiol (E3) and dioxin levels, but no difference in the oestrone (E1) urinary metabolite after adjustment for age, BMI, smoking and alcohol consumption. The authors of this paper did not comment on the potential health outcomes associated with elevated levels of oestrogen; hence the finding is of uncertain clinical consequence.

Dermatological symptoms

A study by Chen et al.[81] showed that exposure to dioxins was protective against dermal allergies (OR 0.29; 95%CI 0.09–0.91; p=0.034) in populations living near incinerators. Conversely, Oh et al.[82] showed significantly more subjectively and objectively reported skin lesions compared with controls with a dose-dependent relationship (moderate occupational exposure: OR 4.85; 95%CI 2.04–11.51 and high occupational exposure: OR 5.03; 95%CI 2.00–12.67). No relationship between distance of Japanese schools from waste incinerators and incidence of atopic dermatitis or allergic rhinitis was demonstrated in students.[85]

Childhood wellbeing

Lung et al.[86] identified an increased risk of mild-to-moderate developmental delay at ages six months and 36 months in Taiwanese children living near incinerators compared to control populations with adjustment for socioeconomic status. Miyake et al.[85] analysed residential proximity to a waste incinerator and parent-reported illness and symptoms in elementary school children. Living in proximity to a municipal waste incinerator was independently associated with increased prevalence of wheeze (adjusted OR 1.08; 95%CI 1.01–1.15), headache (adjusted OR 1.05; 95%CI 1.00–1.11), stomach ache (adjusted OR 1.06; 95%CI 1.01–1.11) and fatigue (adjusted OR 1.12; 95%CI 1.08–1.17).

Mental health

Only one study investigated stress levels secondary to the fear of occupational exposure to dioxins among municipal solid waste incinerator workers, which was lower than the general stress experienced by office workers.[87]

In vitro and in vivo oxidative stress

Chronic oxidative stress has been implicated in ischemic heart disease, carcinogenesis and respiratory disease. Yoshida et al.[88] investigated the duration of employment of incinerator workers in Japan and levels of serum and urine markers of oxidative stress. The marker of systemic oxidative stress did not correlate with job duration, while the level of urinary 8-hydroxy-2'-deoxyguanosine, a marker of oxidative DNA damage, had a positive correlation with length of employment, after adjustment for alcohol consumption, smoking and age (p<0.05). However, the relation to disease risk is uncertain.

Overall, negative health outcomes were demonstrated by a reduction in measured lung function parameters in incinerator workers. Out of three studies looking at the effects of incineration-associated pollution on cardiovascular morbidity and mortality, only one showed a significant association between serum dioxin levels and hypertension. As such, the contribution of incinerators to cardiovascular disease risk is undetermined. The impact of incinerator pollution on metabolic function was demonstrated by an elevation of blood glucose levels, without an increased risk of diabetes mellitus. Regarding dermatologic symptoms, conflicting results were demonstrated among incinerator workers, paediatric and general populations in both self-reported and objectively measured lesions. Therefore, no firm conclusions can be drawn.

Limitations

Definitive studies on the link between waste incineration and health are difficult to conduct due to the diversity of pollutants emitted, and the complex nature of disease aetiology and pathophysiology. This problem is exacerbated by multiple exposure routes, experimental design limitations, unpredictable and indeterminable weather patterns, confluent and unmeasured alternative sources of pollution, unspecified incinerator design elements and cleaning systems used, unknown maintenance schedules and unrecorded content of waste streams. Proximity of incinerators to the local populace, number of years lived near incinerator, water and food sources and consumption patterns introduce a third set of uncontrolled confounders.

Bias and study design affected robustness of results. Exposure misclassification was a recurring, undefined weakness. Control groups were often poorly matched to experimental groups. Not all studies reported confounders; for example: migration trends, places of occupation and other factors (smoking, alcohol, diet, education, occupation, time spent inside/outside incinerator among workers, age, sex, household condition, urban/rural status, overall health status, breast feeding status and route of toxin contact [dermal, inhalation, ingestion]) were variably reported. Where reported, none of these had significant effect on health outcome. Use of distance as a proxy for exposure, lack of control groups, small sample sizes and an inability to establish a causal relationship weakened ability to draw firm conclusions. Given the diversity of exposure and dispersal routes, it is not clear how important socioeconomic status would be as a confounder.

The diversity found in the literature suggests the true neoplasia risk remains obscure, and evidence implies exposure to incinerators increases risk of cellular damage due to intake of dioxins, furans, metals and polycyclic aromatic hydrocarbons. The variation in results between studies measuring different exposures and different risks suggests that at least some waste incinerators are likely to increase the risk of at least some types of neoplasia.

One limitation of any review like this is the possibility of data dredging. If widespread, it would create the appearance of a causal link between waste incineration and ill health. The risk may be low in this study because there is a presumptive link between waste incineration and ill health. This means that a study not finding a connection would be approximately as notable as one finding a connection.

Despite ingestion being considered the primary exposure route in the literature that specifically examines this variable, most studies only considered inhalation and dermal exposure to pollutants in their study design.

Incinerator design specifics were often omitted from papers and detail about waste streams and stack emission treatments were inconsistent, making comparisons of different design elements and systematic comparison of results difficult.

Waste incinerator designs have changed over the past decades and papers comparing emissions from an incinerator before and after upgrade mostly showed significant reductions in measured pollutant levels. Older incinerator technologies featured in most studies, therefore subsequent improvements in incinerator technologies may mean these results will not accurately represent the health consequences of exposure to current incinerators. However, since many health effects require cumulative exposure and may take many years to manifest, it will be difficult to measure any improved safety from modern incinerator designs for decades.

Finally, compared to other energy sources, the financial costs of waste to energy are high.[89] Further building reliance on maintaining a waste stream for supply of material counteracts the imperative to reduce waste.

Implications for public health

Based on this review, we provide researchers with suggestions for design and methods that will make future studies more robust and their results better comparable. Additionally, public health practitioners can offer the public, policy makers and regulators clearer advice about incinerator safety.

Future studies

This review has revealed substantial gaps and inconsistencies. These preclude clear assessment of which incinerator-related variables are important for health impacts. Future studies should:

- include information on the waste, including content and volume, incinerator technical characteristics such as stack height, type of combustion chamber, stack cleaning mechanisms and maintenance schedules, and the types and quantities of emissions;
- where possible, analyse or control for three exposure pathways: ingestion, inhalation and dermal exposure. The possible lack of correlation between distance from the incinerator and the intensity of all three of the pathways should guide study design and interpretation of results;
- report a range of variables potentially related to health effects;
- control for or account for absence of control for likely confounders; and
- determine whether those living downwind of incinerators are at risk.

Finally, further research is needed to compare different incinerator designs, and incineration with other methods of waste management. This will allow more rigorous and meaningful comparisons between waste disposal options.

Policy and regulation

- Since there has been insufficient time for health effects of newer technology to emerge, a precautionary approach to licensing and monitoring incinerators must continue.
- As a condition of applying for a licence to build waste incinerators, independent third-party conducted baseline population studies and long-term surveillance cohort studies be mandated to measure the longitudinal and emerging effects of the incinerator's presence on the local community and the environment.
- Health and safety standards for workers should be enshrined in law and should include regular health checks and exposure monitoring.
- In countries that have ratified the Stockholm Convention, incinerators should be designed to meet the Convention guidelines.
- Facility upgrades and regular maintenance schedules for incinerators must be adhered to.
- New incinerators should be located away from areas of food production.
- Food grown near an incinerator should be avoided.

Conclusion

This is the first systematic review that links the literature on exposure assessments (internal and external toxin measurements) to health

outcomes. While we recognise that all studies discovered had limitations (only five reached NHMRC criterion C), this review permits assessment of incinerator safety.

This review shows contamination of food and ingestion of pollutants is a significant risk pathway for both nearby and distant residents. While occupationally exposed groups have been shown in primary studies to most likely suffer adverse effects, they are a relatively smaller population than all residents in the vicinity of incinerators. Workers may be considered a sentinel population for adverse effects. Incinerator workers are probably also local residents so also subject to exposures outside the workplace. Both local residents ingesting food grown in close proximity to incinerators, as well as more distant populations consuming food transported from areas near an incinerator, are open to exposure. Because most studies in this review examined only a small subset of potential exposure and disease pathways, together with the low quality, it is likely that our review has 'under-discovered' the full health-effects picture.

This systematic review highlights significant risks associated with waste incineration as a form of waste management. Many older incinerators were linked with neoplasia, reproductive issues and other diseases. While the results were not consistent across the literature, based on a precautionary principle there is insufficient evidence to conclude that any incinerator is safe. There is some suggestion that newer incinerator technologies with robust maintenance schedules may be less harmful, but diseases from exposures tend to manifest only after many years of cumulative exposure, so it is premature to conclude that these newer technologies improve safety.

Incineration for waste management, including waste-to-energy options, is likely to remain an alternative that governments will consider. However, the financial and ecological costs of waste to energy are comparably high. Building reliance on a waste stream for energy counters the need to reduce waste overall. This review suggests that incineration is not without problems and so it is an option that needs to be pursued carefully with close monitoring. Local community groups have a basis for legitimate concern and so siting of incineration facilities needs to take these concerns into account. Early transparent consultation with communities about these facilities is essential.

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Supporting Information

Additional supporting information may be found in the online version of this article:

Supplementary File 1: Data table - Summary of primary peer-reviewed manuscripts looking at the effects of waste incineration on health risks and health outcomes published from 2002 to 2017.