EPA Public Access
Author manuscript
Clean Eng Technol. Author manuscript; available in PMC 2021 December 01.
About author manuscripts | Submit a manuscript

Published in final edited form as:
Clean Eng Technol. 2020 December 1; 1: . doi:10.1016/j.clet.2020.100017.

Incorporating upstream emissions into electric sector nitrogen oxide reduction targets

Samaneh Babaee[a], **Daniel H. Loughlin**[b], **P. Ozge Kaplan**[b,*]

[a]Oak Ridge Institute for Science and Education, U.S. Environmental Protection Agency, 109 TW Alexander Drive, Research Triangle Park, NC, 27711, United States

[b]U.S. Environmental Protection Agency, Office of Research and Development, 109 TW Alexander Drive, Research Triangle Park, NC, 27711, United States

Abstract

Electricity production is a major source of air pollutants in the U.S. Policies to reduce these emissions typically result in the power industry choosing to apply controls or switch to fuels with lower combustion emissions. However, the life-cycle emissions associated with various fuels can differ considerably, potentially impacting the effectiveness of fuel switching. Life-cycle emissions include emissions from extracting, processing, transporting, and distributing fuels, as well as manufacturing and constructing new generating capacity. The field of life-cycle analysis allows quantification of these emissions. While life-cycle emissions are often considered in greenhouse gas mitigation targets, they generally have not been included in air quality policymaking. We demonstrate such an approach, examining a hypothetical electric sector emission reduction target for nitrogen oxides (NO_x) using the Global Change Assessment Model with U.S. state-level resolution. When only power plant emissions are considered in setting a NOx emission reduction target, fuel switching leads to an increase in upstream emissions that offsets 5% of the targeted reductions in 2050. When fuel extraction, processing, and transport emissions are included under the reduction target, accounting for 20% of overall NO_x reduction goal, the resulting control strategy meets the required reductions and does so at 35% lower cost by 2050. However, manufacturing and construction emissions increase and offset up to 7% of NO_x reductions in electric sector, indicating that it may be beneficial to consider these sources as well. Assuming no legal obstacles exist, life-cycle-based approaches could be implemented by allowing industry to earn reduction credits for reducing upstream emissions. We discuss some of the limitations of such an approach, including the difficulty in identifying the location of upstream emissions, which may occur across regulatory authorities or even outside of the U.S.

This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

*Corresponding author. sbabaee@ncsu.edu (S. Babaee), Loughlin.Dan@epa.gov (D.H. Loughlin), Kaplan.Ozge@epa.gov (P.O. Kaplan).

Declaration of competing interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data
Supplementary data to this article can be found online at https://doi.org/10.1016/j.clet.2020.100017.

Disclaimer
The views expressed in this article are those of the authors and do not necessarily represent the views or policies of the U.S Environmental Protection Agency.

EPA Author Manuscript
EPA Author Manuscript
EPA Author Manuscript

EPA Author Manuscript EPA Author Manuscript EPA Author Manuscript

Keywords

Life-cycle analysis (LCA); Global change assessment model (GCAM)-USA; Power generation; Electricity production; Nitrogen oxide (NOx) emissions

1. Introduction

Electricity production is a major source of air pollutants, including nitrogen oxides (NOx), sulfur dioxide (SO_2), and particulate matter (PM) emissions. These emissions can vary considerably based on how the electricity is generated and/or whether pollutant controls are applied. In the U.S., several federal regulations have been instituted to reduce emissions from the electric sector. These regulations reduce emissions at the power plant, typically by specifying emission rate limits or capping electric sector emissions. For example, new electric sector boilers are subject to New Source Performance Standards (NSPS), which are emission rate limits, for NOx, SO_2, and PM emissions (Federal Register 2012a). In contrast, the Cross-State Air Pollution Rule (CSAPR) is a cap-based regulation. CSAPR was instituted to limit the transport of pollutants into states with attainment challenges. Under CSAPR, electric sector emissions in 27 states are capped for NOx, SO_2, or both (Federal Register 2011). Many states have also passed legislation limiting power plant emissions, such as North Carolina and Maryland (CSA 2002; HAA 2009).

One approach for complying with these regulations is to apply emission controls at the power plant that either modify the combustion process or that strip pollutants from the exhaust gas. While uncontrolled coal-fired power plants are among the highest emitters of many air pollutants, devices such as selective catalytic reduction, flue gas desulfurization, and electrostatic precipitators can reduce NOx, SO_2, and PM emissions from coal combustion by 90%, 95–99%, and 99–99.9%, respectively (EPA 2005). Another option is switching to fuels with lower combustion emissions. Natural gas combustion in combined-cycle turbines produces lower emissions than controlled coal, further reducing per-kWh totals of NOx, SO_2, and PM by 82%, 99.8%, and 75% (Massetti et al., 2017). Solar and wind farms have negligible pollutant emissions during operation.

However, electricity production represents only one source of electricity-related emissions. There also are emissions from the extraction, processing, transport, and distribution of fuels, such as natural gas, coal, and biomass. Furthermore, emissions are produced during the manufacturing of electric sector equipment, including turbines and solar panels, as well as in constructing new power plants. From an electric sector emissions accounting perspective, these activities produce “up-stream” emissions. There are also “downstream” emissions associated with decommissioning power plants and managing waste. Together, these various categories represent the life-cycle emissions of a technology.

As summarized above, policies for reducing the emissions associated with electricity production typically have focused only on combustion emissions at the power plant. Omitting life-cycle emissions can lead to instances where a portion of the benefits of a control strategy are offset by an increase in upstream emissions. The field of life-cycle analysis (LCA) provides policymakers with a means to evaluate the broader, system-wide

EPA Author Manuscript

EPA Author Manuscript

EPA Author Manuscript

emission impacts of technologies and policies. LCA is a well-known and widely used method to assess the environmental performances of products and processes over their lifetime (Lacirignola et al., 2017). Ling-Chin et al. (2016) provide a detailed review of LCA methodologies, scope, and boundaries.

Application of LCA to electricity production technologies have been gaining traction in the literature for the past two decades. Following studies present life-cycle emission factors for generating electricity from solar and wind electricity (Nugent and Sovacool 2014), geothermal (Eberle et al., 2017), nuclear energy (Warner and Heath 2012), bioenergy (Brander 2017), natural gas (Heath et al., 2014), coal (Whitaker et al., 2012), and storage (Denholm and Kulcinski 2004). The insurgence of cheap natural gas resources in early 2010s have increased the role of natural gas in electricity production and resulted in many studies highlighting the importance of upstream emissions (Alvarez et al., 2018). A lot of these studies though focused in potential impact on greenhouse gas (GHG). For instance, Heath et al. (2014) synthesize and produce harmonized life-cycle emission factors for shale gas used for electricity production. Of particular interest is the net GHG impact once the methane (CH_4) emissions associated with natural gas extraction, processing, and transport are considered (Balcombe et al., 2017). Bistline (2014) investigated how natural gas prices, upstream emissions, and potential climate policies may impact electricity generation from natural gas in the U.S. Lenox and Kaplan (2016) estimated GHG impacts associated with an array of natural gas price and quantity scenarios, accounting for various levels of upstream CH_4 leakage from oil and gas extraction, processing and transmission processes. The results from Lenox and Kaplan (2016) showed a higher upstream CH_4 leakage rate can shift the system away from the benefit that natural gas brings. Furthermore, Tanaka et al. (2019) assessed the life-cycle climate impacts of coal-to-gas shift in the electric sector depending on CH_4 leakage rates, emission locations, and time scales. One option for addressing upstream emissions is to include upstream emissions within the policy target. Pehl et al. (2017) demonstrated that such an approach can lead to different choices for reducing GHG emissions.

The transition from coal to gas in the electric sector also has upstream GHG and air pollutant emission implications. McLeod et al. (2014) explored both GHG and air pollution emissions from natural gas production in the U.S. and Rocky Mountain region for a variety of scenarios. Pacsi et al. (2013) examined air quality impacts of electricity generation from high natural gas use in Texas considering upstream emissions from coal mining and shale gas production. Mac Kinnon et al. (2018) conducted a comprehensive literature review on life-cycle GHG and air pollutant emissions from natural gas electricity production, proposing potential pathways for supporting renewable power integration while maximizing GHG and air quality co-benefits. Luderer et al. (2019) compared global environmental co-benefits of power sector decarbonization pathways by combining different integrated assessment models and LCA approaches. While natural gas combined-cycle (NGCC) turbines are a key player in transitioning to renewable energy and generate fewer air pollutant emissions than coal-fired boilers, the equipment and operational activities related to supply of natural gas can have a wide range of air pollutant implications (Allen 2016). Specifically, the compressors associated with extraction and transport of natural gas have relatively high NOx emission rates (Skone et al., 2014; Skone and James 2010).

EPA Author Manuscript

EPA Author Manuscript

EPA Author Manuscript

The goal of this paper is to present a framework where full life-cycle emission factors for electricity generation including life-cycle emissions for fuels are added to the Global Change Assessment Model with state-level resolution (GCAM-USA). The resulting framework is then applied to evaluate the life-cycle air emissions of electricity generation in the U.S. through application of a scenario framework. A Reference Case scenario along with two hypothetical policy scenarios are designed. In the first policy scenario, a NO_x emission reduction target is applied to power plant emissions only, and we examine the upstream emission implications. The second policy scenario examines a case in which the emission reduction target can be achieved through a combination of power plant and upstream emission reductions.

In addition to quantifying emission changes for these scenarios, we estimate how providing credit for upstream emission reductions decreases the overall control cost. We also assess the GHG implications of each scenario to examine whether there are GHG mitigation co-benefits.

While there are many recent such applications that seek to quantify upstream air pollutant emissions, to the best of our knowledge, there are no studies where researchers have explicitly incorporated life-cycle emissions into the optimization of holistic control strategies for air pollutants.

2. Methods

2.1. Life-cycle analysis and electricity production

LCA can be used to evaluate the “cradle-to-grave” environmental impacts of electricity production, including extraction, processing, and transport of fuels; the manufacturing of the equipment used at the power plant; power plant construction; fuel combustion; and eventual decommissioning. The life-cycle emissions for power generation are often described in four stages as presented in Table 1.

Our study focuses specifically on NO_x emissions. The life-cycle emission factors (EFs) for NO_x for various types of power plants are drawn from several studies. Table 2 summarizes the sources used to construct NO_x EFs for our analysis and breakdown of EFs by life-cycle stage in units of gram of NO_x per kWh of electricity produced. section 1 of Supplemental Information (SI) provides additional detail on life-cycle NO_x EF calculations.

Fig. 1 illustrates the total NO_x EFs per each power plant technology type. For instance, fuel combustion emissions at the power plant dominates the life-cycle NO_x emissions for coal- and oil-fueled generation. In contrast, for natural gas-fueled generation, power plant NO_x emissions are considerably less than those associated with extracting and transporting natural gas. For coal, oil and gas, technologies, manufacturing and construction emissions are small relative to other life-cycle categories. For wind and solar power, the converse is true: manufacturing and construction are the major sources of NO_x. The life-cycle NO_x from hydro is set to zero since we assume that no new hydro power plants will be built over the time horizon associated with our analysis.

EPA Author Manuscript

EPA Author Manuscript

EPA Author Manuscript

2.2. GCAM-USA model

GCAM is an open-source, dynamic-recursive, partial equilibrium model. The model characterizes the energy, water, agriculture and land use, economy, and climate systems, as well as the interactions among those systems. GCAM operates at a global scale, with 32 energy-economic regions, and over a time horizon from 1990 to 2100 (PNNL 2018a). For each time step, the GCAM solution algorithm solves for a set of equilibrium market prices at which supplies equal demands for all modeled goods and services.

Key input assumptions to GCAM include population growth, economic activity, technology characteristics (e.g., costs, efficiencies, emission factors, and water use), agricultural and land system characteristics, and environmental, climate, and energy policies. Using this information, GCAM produces estimates of fuel use and prices; technology deployment; emissions of air pollutants, GHGs, and short-lived climate pollutants; and values for global climate change metrics (PNNL 2018a). GCAM apportions the market shares of competing technologies as a function of their relative costs (Kim et al., 2006).

Pacific Northwest National Laboratory (PNNL) has developed a derivative of GCAM, GCAM-USA, that also includes state-level resolution for the US energy system (PNNL 2018b). GCAM-USA endogenously produces estimates of emissions by technology and sector, including emissions of NO_x, SO_2, particulate matter with diameters of less than 10 and 2.5 μm (PM_{10} and $PM_{2.5}$, respectively), carbon monoxide, ammonia, volatile organic compounds, carbon dioxide (CO_2), CH_4, nitrous oxide, Hydrofluorocarbons (HFCs), black carbon, and organic carbon. Pollutant emissions are estimated by multiplying an EF by an associated activity level such as level of electricity generation in kWh for the modeled year. State-level emissions are estimated for activities such as fuel extraction, refineries, electricity production, manufacturing, space heating, passenger vehicles, and other transportation technologies.

U.S. EPA has modified GCAM-USA version 4.3 to enhance its usability in air quality management applications (Shi et al., 2017), including assessing the air pollutant emission implications of energy scenarios (Ou et al., 2018). For example, EFs have been updated to align the totals with the U.S. EPA's National Emissions Inventories (NEI) and regulatory emission projections (EPA and NEI, 2014). Key regulations and policies that affect emissions have also been added, including the CSAPR (Federal Register 2011), NSPS on boilers and engines in the electric and industrial sectors (Shi et al., 2017), Tier 3 emissions limits on mobile sources and fuels (Federal Register 2014), and Corporate Average Fleet Efficiency targets for light duty vehicles (Federal Register 2012b). A representation of the Regional Greenhouse Gas Initiative (RGGI 2005), which limits electric sector CO_2 emissions in the Northeast U.S., is also included, as are state-level zero-emission vehicle targets for California, Oregon, Colorado, and eight Northeast states (EIA 2017). Representations of common emission controls have been added in the electric and industrial sectors. The Clean Power Plan (CPP) (Federal Register 2015a) and NSPS under Clean Air Act section 111(b) for GHG emissions from new coal power plants (Federal Register 2015b) are not included in this analysis.

EPA Author Manuscript

EPA Author Manuscript

EPA Author Manuscript

2.3. Updates to GCAM-USA: integration of life-cycle emission factors from power generation

While GCAM-USA estimates emissions across the energy and agricultural systems, linking changes in upstream emissions to changes in electricity production is problematic in non-trivial scenarios because of the complex dynamics represented within the model. To overcome this hurdle, in our study, we directly link the life-cycle EFs to power plant activity within the model. Thus, for any given scenario, the power plant would "produce" emissions categorized as being LCA-S1, LCA-S2, LCA-S3, and LCA-S4, even though in reality only LCA-S3 emissions are being emitted at the power plant. In our analysis, instead of using LCA-S3 emission factors reported in the literature, we used the emission accounting resulting from GCAM-USA scenario analysis. This choice is made because GCAM-USA model accounts for NSPSs and the state-level control requirements associated with CSAPR and RGGI, which are not captured in the national average LCA-S3 EFs shown in Fig. 1. Hence, the LCA-S1, LCA-S2, and LCA-S4 factors that we compiled and summarized in Table 2, are added along with GCAM-USA's power plant combustion emissions. This approach is applied to NO_x (Table 2) and GHG (Table S4 in the SI) emission factors.

Fig. 1 and Table 2 show the LCA-S1 NO_x EFs for natural gas and oil extraction in 2010. Compression engines have high NO_x EFs when uncontrolled. An NSPS for these engines was promulgated in 2013, greatly reducing the emissions from subsequent capacity additions (Federal Register 2013). We analyzed recent EPA emission data to assess the extent to which controls have been applied, then estimate turnover and capacity additions to project these LCA-S1 EFs into the future. Details regarding the development of LCA-S1 EFs for oil and natural gas over time are described in the SI.

2.4. Scenarios

GCAM-USA is used to evaluate the energy and emission implications of three scenarios. The first is a Reference Scenario which assumes current legislation is in place through 2050, but no new legislation affecting emissions or energy is introduced, aside from the final emission caps specified by CSAPR and RGGI being carried through 2050.

The Reference Case is compared with two policy cases. In Policy Case 1, a constraint is added that requires an 80% reduction in electric sector NOx emissions by 2050, implemented linearly from 2020 through 2050. In Policy Case 2, a constraint is added that provides the same tons of NO_x reductions as in Policy Case 1, but those reductions can occur either at the power plant or through reductions in upstream emissions from fuel extraction, processing, and transport (e.g., LCA-S1 and LCA-S2). Emissions associated with manufacturing and construction (LCA-S4) are tracked, but are not counted toward the reduction target. The decision not to include LCA-S4 under the target was made because the location of manufacturing emissions is not known, and some portion likely occurs outside of the U.S. If our policy had targeted GHG reductions instead of NOx, such a distinction may not matter with respect to the policy goals.

Fig. 2 illustrates resultant NOx emissions from scenarios. The Reference Case reflects an expected decrease in U.S. electric sector NOx over time, as estimated by GCAM-USA.

EPA Author Manuscript

EPA Author Manuscript

EPA Author Manuscript

Tanaka et al. (2019), the decrease is driven by the emission reductions required by the CSAPR, as well as cost-motivated fuel-switching from coal to natural gas. After 2035, expansion of solar and wind power capacity drives additional decreases in NO_x. The line labeled "Reference plus LCA-S1 and LCA-S2" represents the sum of fuel extraction, processing, transport, and combustion. Policy Case 1 reflects the 80% NO_x reduction target in the electric sector. The difference between Reference and Policy Case 1 is used to construct Policy Case 2, which is shown as a dashed gray line.

3. Results and discussion

3.1. Reference Case

Fig. 3 shows GCAM-USA outputs for the Reference Case. Electricity production increases gradually over the modeling period, with an annual average increase of approximately 0.7% (Fig. 3a). Coal-fired generation decreases slightly. While gas-fired capacity increased substantially between 2010 and 2015, growth after 2015 is modest. From 2020, electricity demand growth is increasingly met by solar and wind power.

The electric sector contribution of NO_x to the national total in 2015 is approximately 13% (Fig. 3b). While electric sector NO_x decreases over time, transportation sector NO_x experiences a larger decrease, driven by the Tier 3 standards and vehicle electrification. The sum of LCA-S1 and LCA-S2 NO_x slightly decreases over time. It accounts for 5 and 9% of total NOx in 2015 and 2050, respectively.

3.2. Policy cases

Policy Case 1 leads to fuel switching in the electric sector (Fig. 4a), including decreases in generation from coal and oil, which are replaced by natural gas, wind and solar. Policy Case 2, which allows changes in LCA-S1 and LCA-S2 of NOx emissions to count toward the reduction target, yields a different response (Fig. 4b). While there is still fuel-switching away from coal, this shift is smaller relative to natural gas. We observe less electricity production from natural gas (around 10% lower), as fuel switching to gas is no longer beneficial under the reduction target. Instead, generation from solar and wind increases.

In Policy Case 1, electric sector NO_x emissions are reduced increasingly, with the reductions reaching 252 kT by 2050 (Fig. 5a). However, the sum of LCA-S1 and LCA-S2 increases by 12 kT, driven by increased natural gas use.

In Policy Case 2, GCAM-USA opts to reduce NO_x by also targeting some upstream emissions (Fig. 5b). By 2050, electric sector reductions are 207 kT, while LCA-S1 and LCA-S2 are reduced by 22 and 26 kT, respectively. There are small amounts of market-driven increases in NO_x in the industrial and residential sectors.

While our policy cases target NOx emissions, there are also GHG emission co-benefits. Applying Policy Case 1 reduced GHG emissions by 199 MT CO_2e (Fig. 6a). GHG emissions associated with fuel extraction resulted in a decrease of 12 MT CO_2e. Policy Case 2 results in 21 MT less GHG reductions in electric sector but 4 MT greater GHG reductions

EPA Author Manuscript

EPA Author Manuscript

EPA Author Manuscript

in extraction, processing, and transportation emissions (Fig. 6b). The net GHG reduction co-benefits decrease by 25 MT CO_2e in Policy Case 2 relative to Policy Case 1.

When upstream emission reductions are allowed to count toward the emission reduction target, the system is given more flexibility. This flexibility, in turn, reduces compliance costs. We can compare the marginal compliance costs for Policy 1 and Policy 2, showing a 35% decline in marginal cost by 2050 (Fig. 7).

4. Discussion

The sum of upstream NOx emissions from LCA-S1 and LCA-S2 is 431 kT in 2050 in the Reference Case. The NO_x cap on electric sector in Policy Case 1 leads to fuel switching from coal and oil to natural gas, solar, and wind. The high NO_x emission rate associated with natural gas extraction, processing, and transportation increases the upstream NO_x to 441 kT, which offsets 5% of the policy goal. The fuel switching to natural gas and renewables are logical as unit NOx emission rate at power plant for coal and oil is more than ten times higher than natural gas. In Policy Case 2, electric sector NO_x and LCA-S1 and LCA-S2 NO_x are included under the cap. As a result, GCAM-USA shifted a portion of NO_x reductions to these upstream categories, which account for 20% of overall emission reduction goal. This flexibility results in cost savings as well. Policy Case 2 reduces the marginal cost of NO_x abatement by 35% in 2050 relative to Policy Case 1. This saving could be greater if GCAM-USA included NO_x control options for the existing compression engines used in fuel extraction, processing, and transportation. Future work could focus on exploring the effects of additional upstream controls.

Policy Case 2 also yielded several unexpected impacts. By making natural gas less attractive from a life-cycle standpoint, less natural gas capacity was added to the electric sector. This resulted in a delay of coal power plant retirement, resulting in lower system-wide GHG co-benefits. GCAM-USA also predicted that market forces would lead to fuel-switching in other sectors, increasing residential, commercial, and industrial NO_x emissions. Increased NO_x from these sectors offsets 5% of the reduction target. This result suggests that the impact of increasing electricity prices on fuel choices in other energy sectors should be considered.

While this study has focused on LCA-S1, LCA-S2, and combustion emissions, both Policy Case 1 and Policy Case 2 also had implications on manufacturing and construction (LCA-S4) NO_x emissions. Fig. 8 shows sectoral and life-cycle NO_x emission differences for Policy Case 1 and Policy Case 2 relative to Reference Case in 2050. While LCA-S1 and LCA-S2 NO_x emissions are spread out over the life of a power plant, LCA-S4 NO_x occurs only when a new power plant is built or a plant is decommissioned. The LCA-S4 NO_x in Fig. 8 is estimated by multiplying new electricity generation (kWh) in 2050 by LCA-S4 NO_x EFs (g/kWh). The resultant NO_x emissions are then multiplied by the power plant lifetime of 30 years and divided by the average construction duration of 2–10 years, depending on technology, to estimate the LCA-S4 NO_x contribution in 2050. LCA-S4 NO_x increases by 9 kT in Policy Case 1 and 14.5 kT in Policy Case 2, driven by manufacturing and construction

EPA Author Manuscript

EPA Author Manuscript

EPA Author Manuscript

of solar and wind power plants. These LCA-S4 NO_x increases offset 3.6% and 7% of NO_x reductions in electric sector in Policy Case 1 and Policy Case 2, respectively.

An important consideration in quantifying the life-cycle emissions associated with power generation is location. While NO_x emissions from fossil fuel extraction, processing, and transportation likely occur in the U.S., they are in a different location than the power plant and may even be in a different state or states. Therefore, the exposure and the resulting health implications would differ in magnitude and location from the power plant emissions. Still, the emission locations of LCA-S1 and LCA-S2 are easier to consider than those of LCA-S4, the combined manufacturing and construction EFs. While the construction emissions occur at the power plant site, a portion of LCA-S4 manufacturing emissions can take place overseas (e.g., wind turbines and solar panels). This shows the importance of developing separate construction and manufacturing EFs to more accurately estimate the localized LCA-S4 emissions and to allow alternative assumptions regarding the location of manufacturing.

Nonetheless, there are several limitations to the modeling approach presented here that could be addressed with additional refinement. First, NO_x controls for existing compression engines used in natural gas extraction, processing, and transport are not considered in the study. Including these controls can shift more NO_x reductions to upstream sources, which may result in a significant reduction of compliance costs or an increase in NG use and some of the GHG reduction co-benefits. Second, the EFs associated with power plant construction and manufacturing of materials should be separated, allowing construction emissions to be accounted for the power plant location. The methodology could also be modified to account for alternative assumptions regarding the fraction of manufacturing emissions that are domestic. Third, future work could examine the upstream and power plants water consumption and emissions trade-offs for other air pollutants, including SO_2, PM_{10}, and $PM_{2.5}$ and at a finer scale such as state and regional levels.

5. Conclusions

We incorporated life-cycle EFs for fuel used in electric generation directly into the GCAM-USA human-earth systems model. The modified model thus allows us to directly quantify the upstream NO_x and GHG emissions related to electricity production for various scenarios. Furthermore, we demonstrate how these life-cycle emissions can be included under emissions constraints in the model. GCAM-USA then determines the most cost-effective strategy for meeting these emission constraints, including the options of applying pollutant controls and fuel-switching.

While regulations on electric sector emissions have traditionally focused on the power plant, we demonstrate that the inclusion of life-cycle emissions within the emission reduction target can result in different choices in a control strategy. For example, the relatively high NOx emissions rates associated with natural gas extraction and compression result in fuel switching and therefore, natural gas would play a lesser role in the NO_x reduction strategy. Instead, the control strategy incorporates additional controls on power plants and integrates additional renewable generation. Furthermore, our modeling results illustrate that

EPA Author Manuscript

EPA Author Manuscript

EPA Author Manuscript

incorporating life-cycle emissions under the NO_x reduction target can result in lower compliance costs and higher renewable electricity generation, representing an economic pathway towards sustainable energy system development in the long-term.

We also find that this strategy may have some downsides. Providing more flexibility by allowing emission reductions from upstream sources resulted in delayed coal retirement, decreasing GHG reduction co-benefits. Furthermore, the locations of upstream emission reductions are not known, and thus the overall air quality benefits of NO_x reductions would likely not be equivalent in location or magnitude. In the U.S., current regulatory efforts are not focused on providing electric utilities with credits for reducing upstream NO_x. However, the high NO_x emission factors associated with natural gas extraction and transportation, combined with potential cost savings, suggest that such control strategy could be viable. Thus, studies such as this are necessary for understanding the potential ramifications on electric sector stock turnover as well as GHG and air pollutant emissions co-reductions. This study demonstrates the value of incorporating life-cycle emissions of electricity generation into a framework such as GCAM-USA, and facilitating an analysis that examines cost-effective electric sector emission reduction targets as a part of holistic air quality management strategies.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgement

This research was supported in part by an appointment of Samaneh Babaee to the Research Participation Program for the U.S. Environmental Protection Agency (EPA), Office of Research and Development, administered by the Oak Ridge Institute for the Science and Education (ORISE). The authors acknowledge Yang Ou (EPA/ORISE), Steve Smith and Gokul Lyre from Pacific Northwest National Laboratory (PNNL) for their technical assistance with GCAM model. We would like to thank Christian Fellner (EPA) and Kristen Brown (EPA) for their valuable input during the administrative technical review of this manuscript.

References

Allen DT, 2016 Emissions from oil and gas operations in the United States and their air quality implications. J. Air Waste Manag. Assoc. 66 (6), 549–575. [PubMed: 27249104]

Alvarez RA, Zavala-Araiza D, Lyon DR, Allen DT, Barkley ZR, Brandt AR, Davis KJ, Herndon SC, Jacob DJ, Karion A, Kort EA, 2018 Assessment of methane emissions from the US oil and gas supply chain. Science 361 (6398), 186–188. [PubMed: 29930092]

Argonne, 2016 The Greenhouse Gases, Regulated Emissions and Energy in Transportation (GREET) Model. Argonne National Laboratory, 2016. https://greet.es.anl.gov/net.

Argonne, 2018 The Greenhouse Gases, Regulated Emissions and Energy in Transportation (GREET) Model. Argonne National Laboratory, 2018. https://greet.es.anl.gov/.

Balcombe P, Anderson K, Speirs J, Brandon N, Hawkes A, 2017 The natural gas supply chain: the importance of methane and carbon dioxide emissions. ACS Sustain. Chem. Eng. 5 (1), 3–20.

Bistline JE, 2014 Natural gas, uncertainty, and climate policy in the US electric power sector. Energy Pol. 74, 433–442.

Brander M, 2017 Comparative analysis of attributional corporate greenhouse gas accounting, consequential life cycle assessment, and project/policy level accounting. Bioenergy Case Stud. J. Clean. Prod. 167, 1401–1414.

EPA Author Manuscript EPA Author Manuscript EPA Author Manuscript

Carreras-Sospedra M, MacKinnon M, Dabdub D, Williams R, 2015 Assessment of the Emissions and Energy Impacts of Biomass and Biogas Use in California, vol. 11 California Air Resources Board, p. 307. Contract.

Clean Smokestacks Act (CSA), 2002 North Carolina environmental quality. https://deq.nc.gov/about/divisions/air-quality/air-quality-outreach/news/clean-air-legislation/clean-smokestacks-act (Accessed 29 September 2019).

Denholm P, Kulcinski GL, 2004 Life cycle energy requirements and greenhouse gas emissions from large scale energy storage systems. Energy Convers. Manag. 45 (13), 2153–2172.

Draucker L, Bhander R, Bennet B, Davis T, Eckard R, Ellis JW, et al., 2012 Life Cycle Analysis: Integrated Gasification Combined Cycle (IGCC) Power Plant. NETL-403/110209.

Eberle A, Heath G, Nicholson S, Carpenter A, 2017 Systematic Review of Life Cycle Greenhouse Gas Emissions from Geothermal Electricity (No. NREL/TP-6A20–68474). National Renewable Energy Lab (NREL), Golden, CO, US.

Energy Information Administration (EIA), 2016 Electricity emissions data by state. https://www.eia.gov/electricity/data/state/emission_annual.xls (Accessed 29 August 2019).

Energy Information Administration (EIA), 2017 Analysis of the effect of zero emission vehicle policies: state level incentives and the California zero-emission vehicle regulations. https://www.eia.gov/analysis/studies/transportation/zeroemissions/pdf/zero_emissions.pdf (Accessed 23 April 2019).

U.S. Environmental Protection Agency (EPA), 2005 Multipollutant emission control technology options for coal-fired power plants. https://nepis.epa.gov/Exe/ZyPDF.cgi/90150M00.PDF?Dockey=90150M00.PDF Accessed 29 Sep. 2019.

U.S. Environmental Protection Agency (EPA), National Emissions Inventory (NEI), 2014 available at. https://www.epa.gov/air-emissions-inventories/2014-national-emissions-inventory-nei-data Accessed 29 Sep. 2019.

Federal Register, 2011 Federal implementation plans: interstate transport of fine particulate matter and ozone and correction of SIP approvals. Final Rule 76 (152). htt ps://www.gpo.gov/fdsys/pkg/FR-2011-08-08/pdf/2011-17600.pdf Accessed 15 June 2018.

Federal Register, 2012a National emission standards for hazardous air pollutants from coal- and oil-fired electric utility steam generating units and standards of performance for fossil-fuel-fired electric utility, industrial-commercial-institutional, and small industrial-commercial-institutional steam generating units. Final Rule 77 (32). https://www.govinfo.gov/content/pkg/FR-2012-02-16/pdf/2012-806.pdf Accessed 26 Sep. 2019.

Federal Register, 2012b 2017 and later model year light-duty vehicle greenhouse gas emissions and corporate average fuel economy standards. Final Rule 77 (199). https://www.govinfo.gov/content/pkg/FR-2012-10-15/pdf/2012-21972.pdf Accessed 26 Sep. 2019.

Federal Register, 2013 National emission standards for hazardous air pollutants for reciprocating internal combustion engines; new source performance standards for stationary internal combustion engines. Final Rule 78 (20). https://www.govinfo.gov/content/pkg/FR-2013-01-30/pdf/2013-01288.pdf Accessed 31 Oct 2019.

Federal Register, 2014 Control of air pollution from motor vehicles: tier 3 motor vehicle emission and fuel standards. Final Rule 40. CFR Parts 79, 80, 85, et al. Part II Environmental Protection Agency, Vol. 79, No. 81 https://www.gpo.gov/fdsys/pkg/FR-2014-04-28/pdf/2014-06954.pdf Accessed 15 June 2018.

Federal Register, 2015a Carbon pollution emission guidelines for existing stationary sources: electric utility generating units. Final Rule 80 (205). https://www.gpo.gov/fdsys/pkg/FR-2015-10-23/pdf/2015-22842.pdf Accessed 15 June 2018.

Federal Register, 2015b Standards of performance for greenhouse gas emissions from new, modified, and reconstructed stationary sources: electric utility generating units. Final Rule 80 (205). https://www.gpo.gov/fdsys/pkg/FR-2015-10-23/pdf/2015-22837.pdf Accessed 15 June 2018.

Healthy Air Act (HAA), 2009 Maryland department of environment. https://mde.state.md.us/programs/Air/Pages/MD_HAA.aspx (Accessed 26 September 2019).

EPA Author Manuscript EPA Author Manuscript EPA Author Manuscript

Heath GA, O'Donoughue P, Arent DJ, Bazilian M, 2014 Harmonization of initial estimates of shale gas life cycle greenhouse gas emissions for electric power generation. Proc. Natl. Acad. Sci. Unit. States Am. 111 (31), E3167–E3176.

Kim SH, Edmonds J, Lurz J, Smith SJ, Wise M, 2006 The ObjECTS framework for integrated assessment: hybrid modeling of transportation. The Energy Journal 63–92. 10.5547/ISSN0195-6574-EJ-VolSI2006-NoSI2-4 (Special Issue# 2).

Lacirignola M, Blanc P, Girard R, Perez-Lopez P, Blanc I, 2017 LCA of emerging technologies: addressing high uncertainty on inputs' variability when performing global sensitivity analysis. Sci. Total Environ. 578, 268–280. [PubMed: 27836349]

Lenox C, Kaplan PO, 2016 Role of natural gas in meeting an electric sector emissions reduction strategy and effects on greenhouse gas emissions. Energy Econ. 60, 460–468. [PubMed: 32632338]

Ling-Chin J, Heidrich O, Roskilly AP, 2016 Life cycle assessment (LCA) – from analysing methodology development to introducing an LCA framework for marine photovoltaic (PV) systems. Renew. Sustain. Energy Rev. 59, 352–378.

Littlefield J, Bhander R, Bennett B, Davis T, Draucker L, Eckard R, Ellis W, et al., 2010 Life Cycle Analysis: Existing Pulverized Coal (EXPC) Power Plant. DOE/NETL-403–110809.

Luderer G, Pehl M, Arvesen A, et al., 2019 Environmental co-benefits and adverse side-effects of alternative power sector decarbonization strategies. Nat. Commun. 10 (1), 1–13. [PubMed: 30602773]

Mac Kinnon MA, Brouwer J, Samuelsen S, 2018 The role of natural gas and its infrastructure in mitigating greenhouse gas emissions, improving regional air quality, and renewable resource integration. Prog. Energy Combust. Sci. 64, 62–92.

Massetti E, Brown MA, Lapsa M, Sharma I, Bradbury J, Cunliff C, Li Y, 2017 Environmental Quality and the Us Power Sector: Air Quality, Water Quality, Land Use and Environmental Justice. Oak Ridge National Lab ORNL/SPR-2016/772.

McLeod JD, Brinkman GL, Milford JB, 2014 Emissions implications of future natural gas production and use in the US and in the Rocky Mountain region. Environ. Sci. Technol. 48 (22), 13036–13044. [PubMed: 25329514]

Nugent D, Sovacool BK, 2014 Assessing the Lifecycle Greenhouse Gas Emissions from Solar PV and Wind Energy: A Critical Meta-Survey Energy Policy, vol. 65, pp. 229–244.

Ou Y, Shi W, Smith SJ, Ledna CM, West JJ, Nolte CG, Loughlin DH, 2018. Estimating environmental co-benefits of U.S. GHG reduction pathways using the GCAM-USA Integrated Assessment Model. Appl. Energy 216C, 482–493, 2018.

Pacsi AP, Alhajeri NS, Zavala-Araiza D, Webster MD, Allen DT, 2013 Regional air quality impacts of increased natural gas production and use in Texas. Environ. Sci. Technol. 47 (7), 3521–3527. [PubMed: 23441728]

Pehl M, Arvesen A, Humpenöder F, Popp A, Hertwich EG, Luderer G, 2017 Understanding future emissions from low-carbon power systems by integration of life-cycle assessment and integrated energy modelling. Nat. Energy 2 (12), 939–945.

PNNL, 2018a GCAM v4.4 Documentation: Global Change Assessment Model (GCAM). In: Joint Global Change Res. Inst. Univ. of Maryland and Pacific Northwest National Laboratory. Available at. http://jgcri.github.io/gcam-doc/index.html (Accessed April 2018).

PNNL, 2018b GCAM v4.4 Documentation: GCAM-USA, Joint Global Change Research Institute. Univ. of Maryland and Pacific Northwest National Laboratory. Available at. http://jgcri.github.io/gcam-doc/gcam-usa.html (Accessed April 2018).

RGGI, 2005 The regional greenhouse gas initiative (RGGI), an initiative of Northeast and mid-atlantic states of the US. https://www.rggi.org/program-overview-and-design/elements Accessed 15 June 2018.

Sheehan J, Camobreco V, Duffield J, Graboski M, Shapouri H, 1998 Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus. National Renewable Energy Lab, Golden, CO (US) Final report (No. NREL/SR-580–24089).

EPA Author Manuscript

EPA Author Manuscript

EPA Author Manuscript

Shi W, Ou Y, Smith SJ, Ledna C, Nolte CG, Loughlin DH, 2017. Projecting state-level air pollutant emissions using an integrated assessment model: GCAM-USA. Appl. Energy 208, 511–521, 2017. [PubMed: 30046218]

Skone T, James R, 2010 Life Cycle Analysis: Natural Gas Combined Cycle (NGCC) Power Plant. National Energy Technology Laboratory, Pittsburgh, PA.

Skone TJ, Littefield J, Cooney G, Marriott J, 2013 Power Generation Technology Comparison from a Life Cycle Perspective. National Energy Technology Laboratory, DOE/NETL-2012/1567. Pittsburgh, PA, USA https://www.netl.doe.gov/projects/files/FY13_PowerGenerationTechnologyComparisonfromaLifeCyclePerspectiveReport_060113.pdf (Accessed 1 December 2020).

Skone TJ, Littlefield J, Marriott J, Cooney G, Jamieson M, Hakian J, Schivley G, 2014 Life Cycle Analysis of Natural Gas Extraction and Power Generation. DOE/ NETL-2014/1646 Office of Fossil Energy, National Energy Technology Laboratory, US Department of Energy.

Tanaka K, Cavalett O, Collins WJ, Cherubini F, 2019 Asserting the climate benefits of the coal-to-gas shift across temporal and spatial scales. Nat. Clim. Change 9 (5), 389–396.

Warner ES, Heath GA, 2012 Life cycle greenhouse gas emissions of nuclear electricity generation. J. Ind. Ecol. 16, S73–S92.

Whitaker M, Heath GA, O'Donoughue P, Vorum M, 2012 Life cycle greenhouse gas emissions of coal-fired electricity generation: systematic review and harmonization. J. Ind. Ecol. 16, S53–S72.

EPA Author Manuscript

EPA Author Manuscript

EPA Author Manuscript

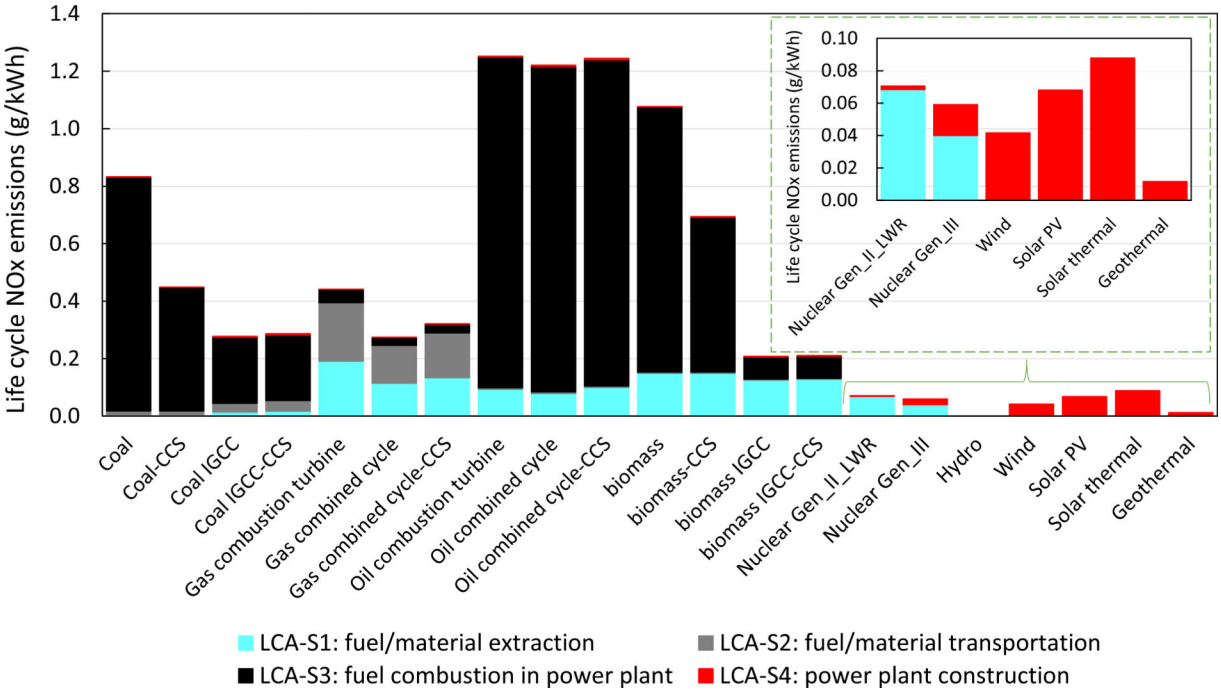

Fig. 1.

NOx emission factors for four life-cycle stages by power plant type.

EPA Author Manuscript

EPA Author Manuscript

EPA Author Manuscript

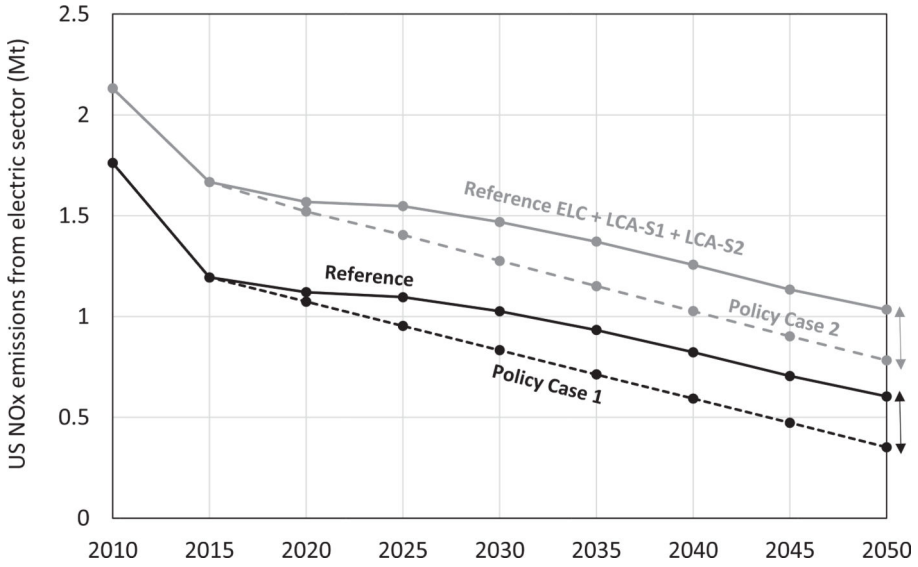

Fig. 2.

U.S. NOx emission projections from electric sector for GCAM Reference in a solid black line, 80% cap on electric sector by 2050 relative to 2010 (Policy Case 1) in a dashed black line, and NOx cap on electric sector and upstream emissions of power generation (Policy Case 2) in a dashed gray line.

EPA Author Manuscript

EPA Author Manuscript

EPA Author Manuscript

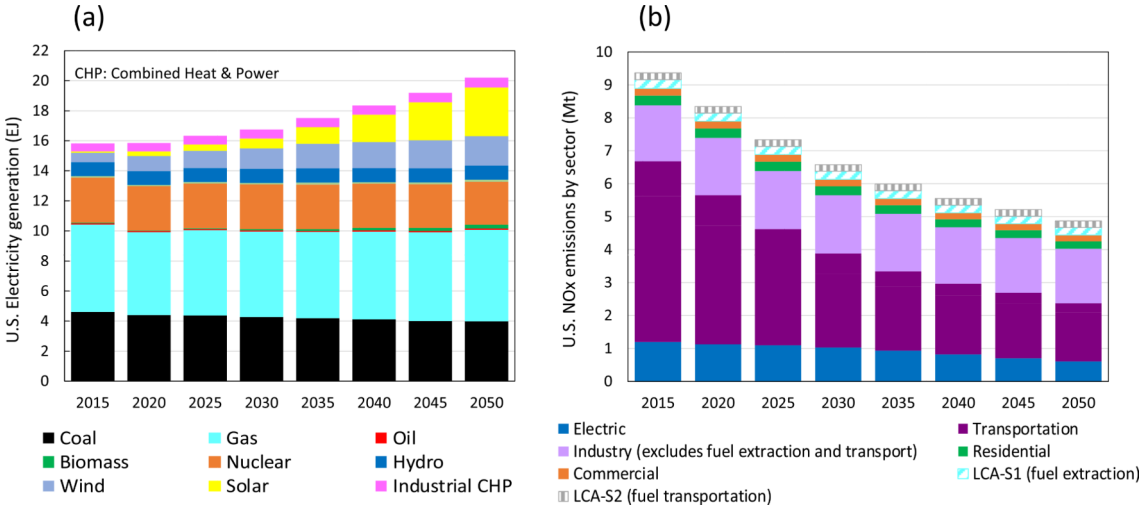

Fig. 3.

Reference Case results, showing (a) electricity production by fuel category, and (b) sectoral NOx emissions, with electricity production-related life-cycle emissions from fuel extraction, processing, and transportation shown separately from the remaining industrial emissions.

EPA Author Manuscript

EPA Author Manuscript

EPA Author Manuscript

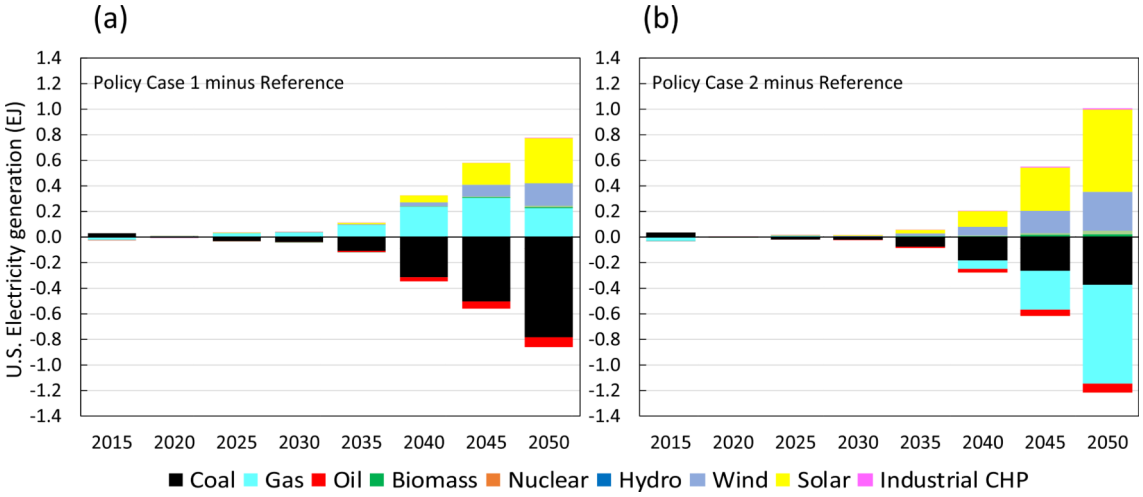

Fig. 4.

Changes in electricity production relative to the Reference Case for Policy Case 1 (a) and Policy Case 2 (b).

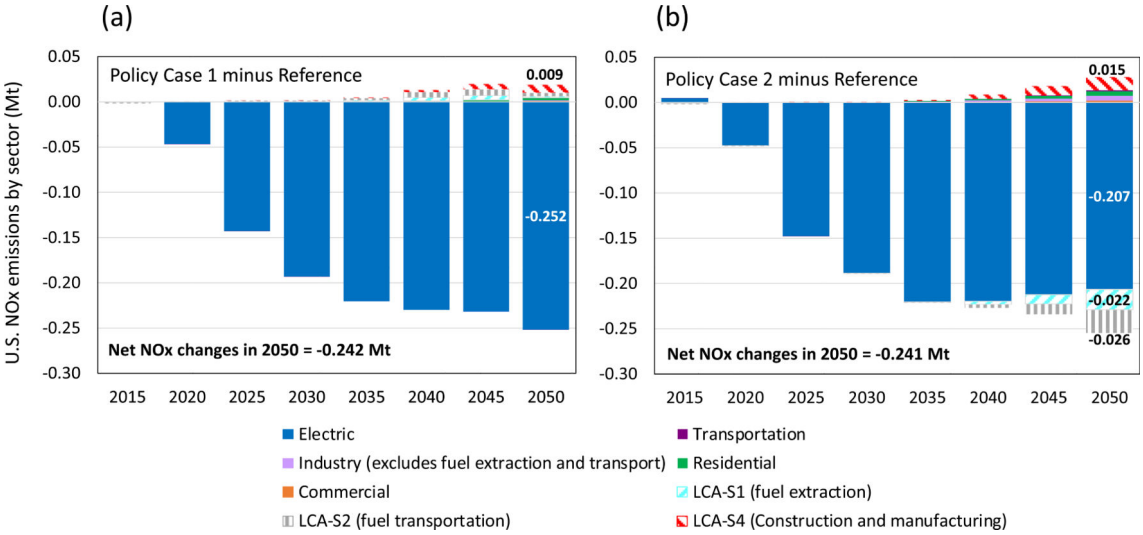

Fig. 5.

Changes in sectoral NOx emissions relative to the Reference Case for Policy Case 1 (a) and Policy Case 2 (b).

EPA Author Manuscript
EPA Author Manuscript
EPA Author Manuscript

EPA Author Manuscript

EPA Author Manuscript

EPA Author Manuscript

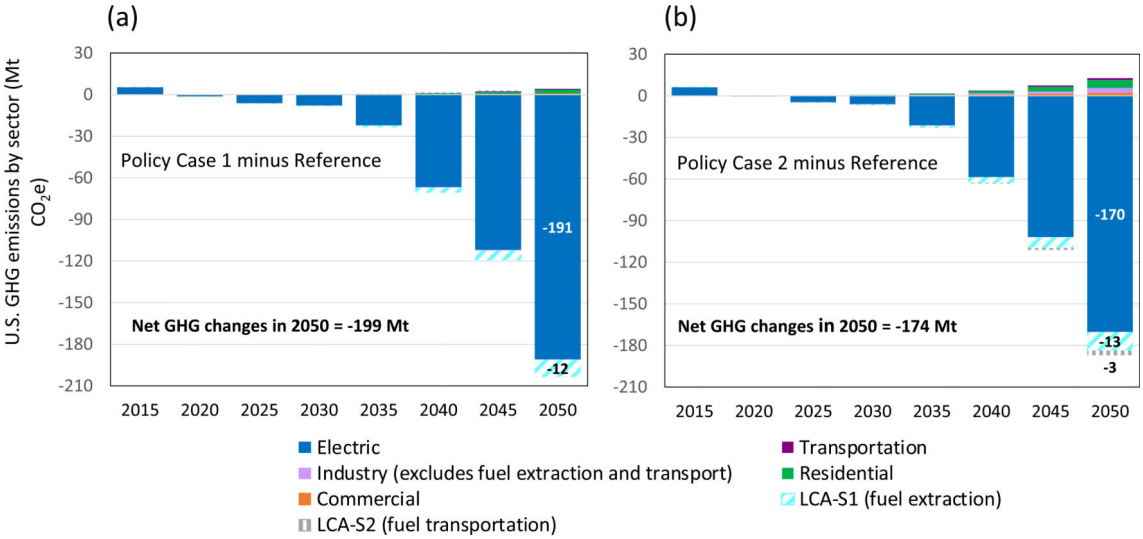

Fig. 6.

Changes in sectoral GHG emissions relative to the Reference Case for Policy Case 1 (a) and Policy Case 2 (b).

EPA Author Manuscript

EPA Author Manuscript

EPA Author Manuscript

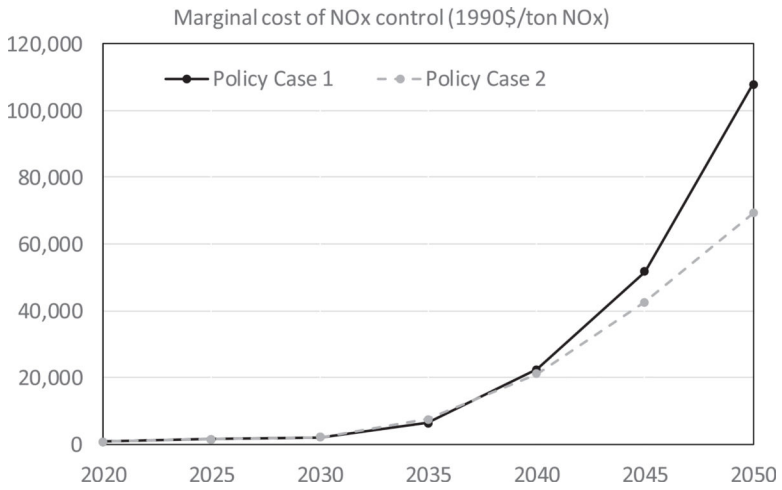

Fig. 7.

Marginal reduction costs for Policy Case 1 and Policy Case 2. These results show the marginal cost reductions associated with the increased flexibility provided under Policy Case 2.

EPA Author Manuscript

EPA Author Manuscript

EPA Author Manuscript

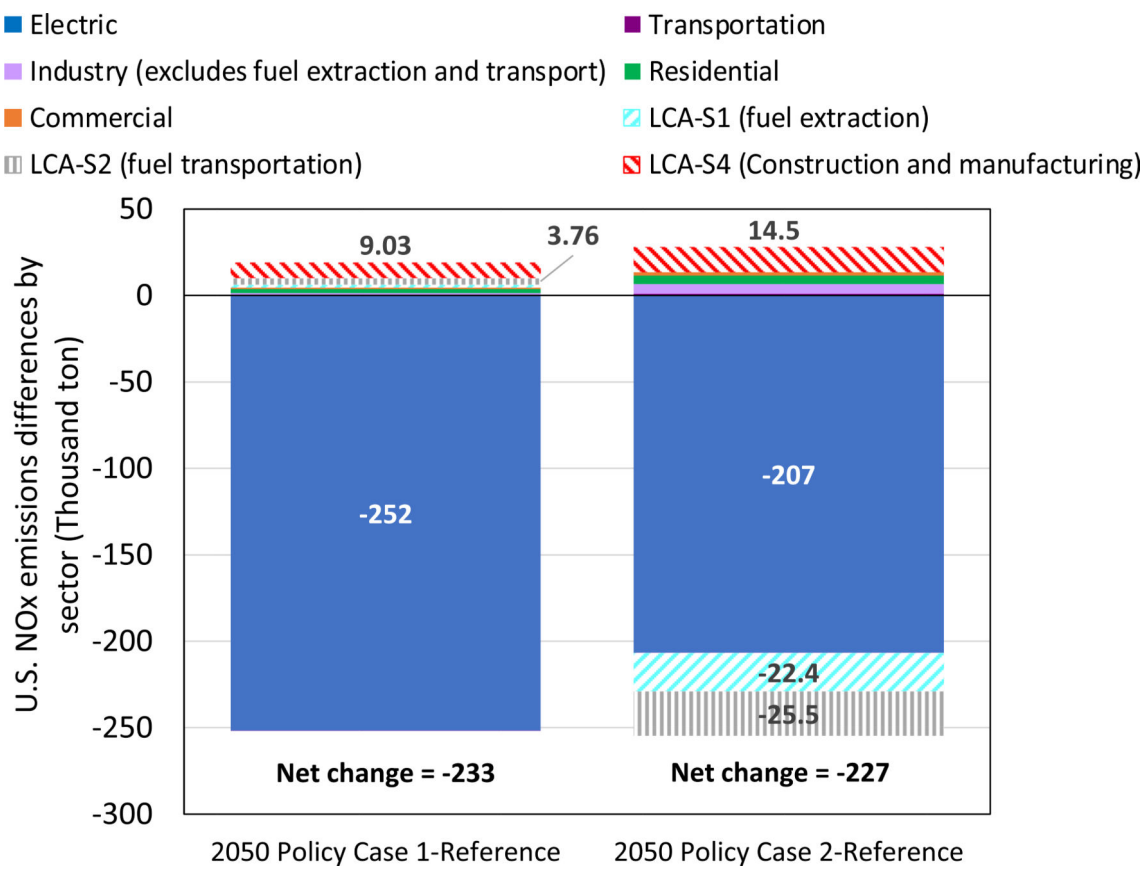

Fig. 8.

Changes in sectoral NOx emissions including construction and manufacturing for Policy Case 1 and Policy Case 2 relative to the Reference Case in 2050.

EPA Author Manuscript

EPA Author Manuscript

EPA Author Manuscript

Table 1

The description of four life-cycle stages.

Life Cycle Stages	Description
LCA Stage 1 (LCA-S1): Fuel extraction and procesing[a]	Extraction of the primary fuel from the ground, field, or forest and then processing the fuel.
	Primary fuels include coal, natural gas, uranium, and forest residue. For example, LCA-S1 of natural gas (NG) includes construction and development of wells, steady-state operations, intermittent maintenance activities, NG processing (acid gas removal, dehydration, hydrocarbon liquids removal) and NG compression.
LCA Stage 2 (LCA-S2): Fuel transport[a]	Transport of the primary energy source from the point of extraction to the energy conversion facility. It includes emissions associated with construction and operation activities for fuel transport (such as pipelines for natural gas).
LCA Stage 3 (LCA-S3): Power plant operation	Conversion of primary energy source to electricity. It includes the emissions from fuel combustion in the power plant.
LCA Stage 4 (LCA-S4): Power plant construction	includes the fuels used in the preparation and the decommissioning of the power plant site, materials for the buildings, power plant equipment (including material and fuels for solar panels and wind turbines manufacturing), switchyards and transmission trunk line, and in the case of carbon capture and sequestration; equipment and infrastructure to capture, compress, transport, inject, and monitor carbon dioxide.

[a]Wind, water, solar, and geothermal energy do not require extraction, processing, or transport, so they are not included in LCA-S1 and LCA-S2 stages.

EPA Author Manuscript

EPA Author Manuscript

EPA Author Manuscript

Table 2

NO_x emission factors for four life-cycle stages by power plant type.

	NO_x (g/kWh) from 2010 to 2050			
	LCA-S1: fuel/material extraction	**LCA-S2: fuel/material transportation**	**LCA-S3: fuel combustion in power plant**	**LCA-S4: power plant construction**
Coal	0.0053 [a]	0.0130 [a]	0.8140 [b]	0.0003 [a]
Coal-CCS	0.0064 [m]	0.0158 [m]	0.4300 [a]	0.0007 [a]
Coal IGCC	0.0140 [c]	0.0307 [c]	0.2300 [c]	0.0025 [c]
Coal IGCC-CCS	0.0167 [c]	0.0372 [c]	0.2290 [c]	0.0035 [c]
Gas combustion turbine	0.1911 [n]	0.2037 [e]	0.0458 [e]	0.0005 [e]
Gas combined cycle	0.1142 [n]	0.1321 [e]	0.0275 [f]	0.0009 [f]
Gas combined cycle-CCS	0.1340 [n]	0.1553 [e]	0.0302 [f]	0.0016 [f]
Oil combustion turbine	0.0930 [n]	0.0060 [h]	1.1510 [o]	0.0014 [g]
Oil combined cycle	0.0783 [n]	0.0060 [h]	1.1327 [j]	0.0036 [j]
Oil combined cycle-CCS	0.0992 [n]	0.0060 [h]	1.1354 [k]	0.0043 [k]
biomass	0.1490 [i]	0.0042 [i]	0.9230 [g]	0.0014 [g]
biomass-CCS	0.1490 [l]	0.0042 [i]	0.5390 [l]	0.0018 [l]
biomass IGCC	0.1250 [i]	0.0035 [i]	0.0780 [g]	0.0014 [g]
biomass IGCC-CCS	0.1278 [m]	0.0035 [i]	0.0770 [m]	0.0024 [m]
Nuclear, second generation, LWR	0.0684 [d]	0 [d]	0 [d]	0.0022 [d]
Nuclear, third generation	0.0400 [d]	0 [d]	0 [d]	0.0191 [d]
Hydro	0 [d]	0 [d]	0 [d]	0.0000 [d]
Wind	0 [d]	0 [d]	0 [d]	0.0416 [d]
Solar PV	0 [d]	0 [d]	0 [d]	0.0680 [g]
Solar thermal	0 [d]	0 [d]	0 [d]	0.0878 [d]
Geothermal	0 [d]	0 [d]	0 [d]	0.0116 [d]

[a] Littlefield et al., (2010).

[b] Argonne (2018).

[c] Draucker et al. (2012).

[d] Skone et al. (2013).

[e] Skone et al. (2014).

[f] Skone and James (2010).

EPA Author Manuscript

EPA Author Manuscript

EPA Author Manuscript

[g]Argonne (2016).

[h]Sheehan et al. (1998).

[i]Carreras-Sospedra et al. (2015).

[j]Calculated based on emissions difference between NG combustion turbine and NGCC, which is added to oil combustion turbine emissions.

[k]Calculated based on emissions difference between NGCC and NGCC-CCS, added to oil combined cycle emissions.

[l]Calculated based on emissions difference between coal steam and coal-CCS, added to biomass emissions.

[m]Calculated based on emissions difference between coal IGCC and coal IGCC-CCS, added to biomass IGCC and coal emissions.

[n]EPA and NEI, 2014.

[o]EIA 2016.