Applied Economics Clinic
Economic and Policy Analysis of Energy, Environment and Equity

Comparative Costs of Alaska Fire Management

Report Prepared for the Union of Concerned Scientists

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I. Introduction

This background report estimates the costs of wildfire damage and wildfire mitigation in Alaska, and places these costs in the context of other mitigation measures. The cost per acre of wildfire damage varies greatly depending on the location of the fire and the types of damages included in the cost estimate. Property damage alone has been estimated at more than $2,500 per acre in Alaska. Regression analysis of recent Alaskan fires showed that a 1.0 percent increase in total spending on fire management is associated with a 0.7 percent reduction in the number of acres burned, while a 1.0 percent increase in fire management spending per acre is associated with a 0.5 percent reduction in the number of acres burned. Based on these same data, the average cost of fire management in Alaska is $1.19 per metric tonne of CO_2 avoided. The costs of other negative emission policies range from $0 to $1,061 per tonne. Policies that focus on renewables and energy efficiency measures have costs ranging from -$195 for adopting behavioral energy efficiency to $2,151 for implementing solar PV subsidies. For transportation policies costs range from -$18 for mixing gasoline with corn starch ethanol, to $1,016 for establishing low carbon fuel standards.

II. The Cost of Wildfire Damage

An extensive review of the recent literature on the cost of damages from wildfires for Alaska and other regions in the United States, including dozens of journal articles, reports, and news articles, shows a wide range of damage costs from fires. Fire damage costs disaggregated into specific categories of damage were available only from a small subset of studies. Some studies provide cost estimates across a number of fires in a single season (labeled "201x State Fires" below). Most of the literature reviewed, however, focused on specific fires allowing the collection of detailed information on different categories of damages: property damage, lost economic activity, lost timber, costs to public utilities, and medical costs. Unfortunately, this fire-specific focus also makes results across studies less comparable.

This review found a large variation in costs per burned acre across regions and fires, suggesting that the costs per acre burned are highly specific to individual fire and forest characteristics, such as the location of the fire, the weather conditions at the time of the fire, the type of trees and vegetation in the area, and whether the fire affects or threatens property and human lives. This report section focuses on damage categories that can be reasonably monetized, omitting estimates for the loss of human lives, psychological damages, and aesthetic losses;[1] costs in these categories either differ substantially across studies or are not reported. A 2004 study from Colorado State University, for example, uses a value of $3 million dollars to value a human life in the case of the 2002 Hayman Fire, where six people lost their lives,[2] while a 2012 study in the *Journal of Forest Economics* uses a range of $1.3 – 13 million to value a life lost due to health effects of the 2003 southern California wildfire.[3] According to the American Psychological Association wildfires can be very stressful and affected people may experience strong emotions, including anxiety and irritability.[4] A 2013 study by the non-profit research group Earth Economics provides estimates of the aesthetic loss in the range of $32 to more than $12,600 per acre for the case of grasslands, riparian, river, and forest coniferous.[5]

Property damages

Property losses include estimates of the value of lost houses, and commercial and industrial buildings. The Miller's Reach fire near Houston, Alaska in 1996 resulted in property losses of $2,527 per acre (see Table 1).[6] For other regions of the country the cost of property losses varies substantially, from $37 per acre in the Florida fires of 1998 to over $6,000 per acre in the case of the 2003 Old, Grand Prix, and Padua Complex fire in California. Differences in the value of property loss per acre depend on characteristics of the properties (homes, commercial buildings, or industrial facilities) and the extent of the damages.

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[1] Since this report focuses on damages, fire suppression costs are also not included. A recent study of Alaska estimates that fire suppression costs may reach $1.1–$2.1 billion from 2006 to the end of the century due to climate change. Melvin et al. (2017). "Estimating wildfire response costs in Alaska's changing climate." *Climatic Change, Volume 141*, p. 783-795. Available at: https://doi.org/10.1007/s10584-017-1923-2

[2] Lynch, D. L. 2004. "What Do Forest Fires Really Cost?" *Journal of Forestry, Volume 102* (6), p. 42–49. Available at: https://academic.oup.com/jof/article/102/6/42/4613189

[3] Kochi, I. et al. (2012). "Valuing mortality impacts of smoke exposure from major southern California wildfires." *Journal of Forest Economics, Volume 18*, p. 61-75. Available at: https://doi.org/10.1016/j.jfe.2011.10.002

[4] American Psychological Association. 2019. Recovering from wildfires. Available at: https://www.apa.org/helpcenter/wildfire

[5] Batker et al. (2013). *The Economic Impact of the 2013 Rim Fire on Natural Lands*. Earth Economics. Available at: https://www.dwt.com/files/energyenvironmental/2014/01/Earth-Economics-Rim-Fire-Report-11.27.20131.pdf

[6] All costs in this memo are expressed in 2015 dollars using the Consumer Price Index.

Table 1. Range of property loss per acre in recent literature (2018$/acre)

Year and location of fire	Cost per acre burned ($2018/acre)
1996 Miller's Reach Fire (Alaska)	$2,527
1998 Florida Fires	$37
2010 Shultz Fire (Arizona)	$238
2002 Hayman Fire (Colorado)	$392
2000 Bobcat Gulch Fire (Colorado)	$700
2016 Loma Fire (California)	$1,684
2003 San Diego County Fires (California)	$4,229
2003 Old, Grand Prix, and Padua Complex (California)	$6,290

Source: Data sources are listed in Appendix A

Lost economic activity

The cost of lost economic activity includes estimates of lost profits and wages due to fire damages. This category shows the largest variation in costs per acre across regions and across fires within regions. Data for Alaska were not available, but studies for other regions show cost estimates from $2 per acre for the 2000 Bobcat Gulch fire in Colorado to over $4,700 per acre in the tourism sector alone for the 2002 season fires in Colorado (see Table 2). This range of values likely reflects differences in the amount and type of business activity in the area affected by the fire. For example, in the Bobcat Gulch fire only one business was affected (the Sylvan Dale Guest Ranch), while in the case of the 2002 season Colorado fires the business losses include all losses to the tourism sector.

Table 2. Range of cost to economic activity per acre in recent literature (2018$/acre)

Year and location of fire	Cost per acre burned ($2018/acre)
2000 Bobcat Gulch Fire (Colorado)	$2
2002 Hayman Fire (Colorado)	$26
2012 Waldo Canyon Fire (Colorado) (Tourism only)	$122
1998 Florida Fires (Tourism only)	$425
2003 San Diego County Fires (California)	$1,327
2002 Colorado Fires (Tourism only)	$4,727

Source: Data sources are listed in Appendix A

Lost timber

The cost of lost commercial timber in the Miller's Reach Fire in Alaska in 1996 was $13 per acre, while the cost for other regions ranges from $37 per acre in Colorado (Hayman fire) to more than $1,800 per acre in Florida (see Table 3). Some studies also present cost estimates that include timber salvage and estimates of the benefits to unaffected tree owners from higher timber prices due to the timber lost.[7]

Table 3. Range of cost of timber lost per acre in recent literature (2018$/acre)

Year and location of fire	Cost per acre burned ($2018/acre)
1996 Miller's Reach Fire (Alaska)	$13
2002 Hayman Fire (Colorado)	$37
2000 Bittreroot National Forest Fire (Montana)	$41
2002 Biscuit Fire (Oregon)	$144
1998 Florida Fires	$1,867

Source: Data sources are listed in Appendix A

Medical costs

Medical costs from forest fires are measured in a variety of different ways in the literature. A 2013 article in *Land Economics*, for example, reports estimates of health costs of the 2009 California's Station Fire in the range of $96 and $105 per wildfire smoke–induced symptom day.[8] Medical costs per acre have been found to be in the range of $1.75 per acre to $5.45 per acre for Nevada and Alberta, Canada. A study of the 2003 San Diego County fires reported medical costs of $40 per acre (see Table 4).

[7] Prestemon, J. P. et al. 2006. "Wildfire, timber salvage, and the economics of expediency." *Forest Policy and Economics, Volume 8* (3), p. 313-322. Available at: https://doi.org/10.1016/j.forpol.2004.07.003 Prestemon, J. P., & Holmes, T. P. 2008. Timber salvage economics. *The Economics of Forest Disturbances: Wildfires, Storms, and Invasive Species.* Holmes, T. P. et al. (eds.). p. 167-190. Springer Science + Business Media B.V. Available at: https://www.srs.fs.usda.gov/pubs/ja/ja_prestemon028.pdf

[8] Richardson, L. et al. (2013). "Valuing Morbidity from Wildfire Smoke Exposure: A Comparison of Revealed and Stated Preference Techniques." *Land Economics, Volume 89* (1), p. 76–100. Available at: https://www.fs.fed.us/rm/pubs_other/rmrs_2013_richardson_l001.pdf

Table 4. Range of medical cost per acre in recent literature (2018$/acre)

Year and location of fire	Cost per acre burned ($2018/acre)
2006 Chisholm (Alberta, Canada)	$1.75-2.33
2005-2008 Reno/Sparks (Nevada)	$1.41-5.45
2003 San Diego County Fires (California)	$40

Source: Data sources are listed in Appendix A

Costs to public utilities

Wildfires can also results in costs to public utilities, which may experience damages to infrastructure, such as electric lines. The literature includes data on the cost of fire damage to public utilities for only a few fires and is limited to electric line damage. For the Miller's Reach fire in Alaska, the estimated cost to public utilities was $50 per acre, while for other regions costs ranged from $2 per acre (2000 Bobcat Gulch fire, Colorado) to $764 per acre (2003 Old, Grand Prix, and Padua Complex, California) (see Table 5).

Table 5. Range of cost to public utilities per acre in recent literature (2018$/acre)

Year and location of fire	Cost per acre burned ($2018/acre)
1996 Miller's Reach Fire (Alaska)	$50
2000 Bobcat Gulch Fire (Colorado)	$2
2002 Hayman Fire (Colorado)	$9
2003 San Diego County Fires (California)	$258
2016 Loma Fire (California)	$412
2003 Old, Grand Prix, and Padua Complex (California)	$764

Source: Data sources are listed in Appendix A

III. The Cost of Alaskan Fire Management

AEC estimated the effect of fire management on the number of acres burned using a data set created for the Fire Research and Management Exchange System (FRAMES) with information for 120 wildfires in Alaska that took place between 2007 and 2015, and for which cost data were recorded.[9] This analysis uses econometric techniques to estimate the causal effect of fire suppression activities on the number of acres burned. The results of this analysis show that a 1.0 percent increase in total spending on fire management is associated with a 0.7 percent reduction in the number of acres burned, while a 1.0 percent increase in fire management spending per acre is associated with a 0.5 percent reduction in the number of acres burned. These results suggest that fire management has a significant impact on the size of wildfires.

Description of data used in estimation

The FRAMES data set is a sample of 134 wild fires that took place in Alaska between 2007 and 2015. These data include information on the number of acres burned, the cost of fire suppression, the location of the fire (latitude and longitude), characteristics of the affected area (elevation and vegetation), and weather variables, such as temperature and windspeed, at the time of the event.

The data also include each fire's Alaska Department of Natural Resources' fire management zone:

- **Critical Protection**: complete protection from fires that threaten human life, inhabited property, designated physical developments and structural resources,
- **Full Protection**: control of fires that threaten uninhabited private property, with high-valued natural resource, and other high-valued areas,
- **Modified Protection**: suppression provided in areas where the value to be protected does not justify full protection, and
- **Limited Protection**: lowest level of suppression action.[10]

Of the fires included in the data set, the 120 fires with information on the cost of fire suppression are used in this econometric analysis.

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[9] Little, J., Jandt, R., Drury, S., Molina, A. & Lane, B. 2018. *Final Report Evaluating the Effectiveness of Fuel Treatments in Alaska*. JFSP Project 14-5-01-27. FRAMES. Available at: https://www.firescience.gov/projects/14-5-01-27/project/14-5-01-27_final_report.pdf

[10] Alaska Department of Natural Resources. Division of Forestry. n.d. "Fire Management Plans." Available at: http://forestry.alaska.gov/fire/fireplans

Econometric approach

To examine the effect of fire management on the number of acres burned, the following equation was estimated:

(1) $$\ln(a_i) = \beta_0 + \beta_1 \ln(c_i) + \theta x_i + \delta_{2008} + \cdots + \delta_{2015} + \varepsilon_i,$$

where $\ln(a_i)$ is the natural log of the number of acres burned in fire i, $\ln(c_i)$ is the natural log of the cost of fire management for fire i, x_i is a vector of control variables that includes fire characteristics such as location (latitude and longitude), weather (the natural log of temperature, windspeed, and relative humidity, snow depth, and a variable measuring vapor pressure deficit), and vegetation (percent of the area that is burnable), $\delta_{2008}, \ldots, \delta_{2015}$ are dummy variables for each year (2008-2015), and ε_i is an error term.

Two different treatments of the cost of fire management are commonly used in the literature: total expenditures and total expenditures per acre (see, for example, Hand et al. 2014).[11] Following this practice, equation (1) is estimated separately using the total value of fire management expenses in crews, aircrafts, engines and supplies, and the ratio of the total value of fire management to the number of acres burned. One advantage of using cost per acre over total cost is that it can potentially avoid the endogeneity problem discussed below.

If fire management is effective in reducing the number of acres burned, then the estimate of the coefficient for the cost of fire management (β_1) should be negative and statistically significant. Since both variables are measured in logs, the coefficient β_1 provides an estimate of the percent change in the number of acres burned expected in response to a 1.0 percent increase in the cost of fire management.

The main econometric issue in this analysis is the possible endogeneity problem due to simultaneity; that is, that the explanatory variables are too closely related to one another. Simultaneity occurs when an explanatory variable and the independent variable are closely correlated (or "jointly determined"). In the context of fire management, the cost of fire management (c_i) is likely to affect the number of acres burned (a_i) but a_i may also affect c_i. If endogeneity exists, estimating equation (1) using ordinary least squares (OLS) may provide biased estimates. To address endogeneity, equation (1) is also estimated using instrumental variables (IV) techniques. IV estimation requires finding a variable z_i that is correlated with c_i but not with a_i other than through its effect on c_i. A plausible instrument is the variable "Fire management zone" that classifies areas of Alaska in four groups according to their priority

[11] Hand, M., Gebert, K., Liang, J., Calkin. D., Thompson, M. & Zhou M. Economics of Wildfire Management: The Development and Application of Suppression Expenditure Models. New York, NY: Springer.

level for fighting fire. This variable is likely to be correlated with the amount of resources spent on fighting fires but not affected by the individual fire sizes.

The IV estimation is done using two-stage least squares as follows. The first stage estimates the following equation:

$$(2) \qquad \ln(c_i) = \alpha + \gamma_1 FMZ_1 + \cdots + \gamma_4 FMZ_4 + \lambda x_i + \delta_{2008} + \cdots + \delta_{2015} + \eta_i,$$

where $FMZ_1, \ldots, FMZ_4$ are dummy variables for each fire management zone and η_i is an error term. The use of IV estimation requires that the excluded instruments ($FMZ_1, \ldots, FMZ_4$) are correlated with the cost variables, but uncorrelated with the error term in equation (1). Based on standard tests for IV post estimation, these two conditions are met.[12]

The estimated coefficients of this regression are then used to calculate the predicted value of c_i, denoted as $\hat{c_i}$. This predicted value is then used in the second stage to estimate equation (1) as:

$$(3) \qquad \ln(a_i) = \beta_0 + \beta_1 \ln(\hat{c_i}) + \theta x_i + \delta_{2008} + \cdots + \delta_{2015} + \varepsilon_i.$$

As seen in equations (2) and (3), variables $FMZ_1, \ldots, FMZ_4$, called "excluded instruments", are included in the first stage only.

Equation (1) is estimated using OLS for both measures of costs, total cost and the cost per acre. Equation (2) provides the IV estimates for both measures of costs, and equation (3) repeats equation (1) using the IV estimates for both measures of costs. Both methods, OLS and IV, use robust standard errors to account for potential heteroscedasticity.

If the IV technique to ameliorate endogeneity is successful, the predicted value of the cost variable ($\hat{c_i}$) in equation (3) will reflect the effect of fire management but not the potential effect of the number of acres burned on the cost of fire management. The estimated β_1 in equation (3), therefore, would provide an unbiased estimate of the causal effect of fire management on the number of acres burned.

Impact of fire management

The results of estimating equation (1) using OLS (without accounting for the endogeneity of the cost of suppression) are presented in columns (1) and (2) in Table 6.

[12] This is done as follows. First, we examine the first-stage estimates to see if the excluded instruments have enough explanatory power. The results show that the four dummy variables for fire management zones are statistically significant and that the F-test of joint significance cannot be rejected at the 5 percent level, which indicates that these instruments are appropriate. Second, we calculate the Sargan test of overidentifying restrictions. For both regressions, we reject the null hypothesis that the instruments are correlated with the error term in equation (1), which indicates that our instruments are valid.

The estimated coefficients for most of the control variables are not statistically significant, likely due to the low number of observations in the data set. The coefficient for cost per acre is statistically significant at the 1 percent level while the estimate for total cost is significant only at the 10 percent level. The coefficient for the cost per acre measure is negative (higher per acre costs are correlated with smaller fires) but the coefficient for the total cost is positive.

Table 6. OLS and IV regression results

	Dependent Variable: Natural Log of Number of Acres Burned							
	(1) OLS		(2) OLS		(3) IV		(4) IV	
	Coef.	SE	Coef.	SE	Coef.	SE	Coef.	SE
ln(Total Cost)	0.16+	(0.09)			-0.69*	(0.35)		
ln(Cost Per Acre)			-0.51**	(0.05)			-0.49**	(0.11)
Latitude	0.09	(0.13)	-0.08	(0.09)	-0.09	(0.17)	-0.07	(0.09)
Longitude	-0.02	(0.06)	0.08+	(0.04)	0.11	(0.09)	0.08+	(0.04)
Snow Depth	28.32	(17.19)	33.15+	(17.36)	55.99*	(26.04)	33.16*	(16.00)
ln(Elevation)	0.42	(0.31)	-0.00	(0.26)	0.11	(0.42)	0.01	(0.25)
ln(Relative Humidity)	-1.20	(3.37)	6.33*	(2.49)	8.81	(5.84)	6.15*	(2.66)
ln(Temperature)	1.69	(2.63)	0.37	(2.09)	1.02	(3.35)	0.41	(2.00)
ln(Windspeed)	-0.56	(0.64)	0.07	(0.41)	-0.06	(0.71)	0.05	(0.40)
Vapor Pressure Deficit	0.00	(0.00)	0.00*	(0.00)	0.01	(0.00)	0.00*	(0.00)
Percent Burnable	-0.06+	(0.03)	-0.05*	(0.03)	-0.09*	(0.04)	-0.05*	(0.02)
No. Observations	120		120		120		120	
R-squared	0.927		0.957					

*Notes: Year dummy variables were included but not reported. Absolute value of robust standard errors (SE) in parentheses. ** significant at 1 percent, * significant at 5 percent, + significant at 10 percent.*

Columns (3) and (4) report the results of the IV estimation controlling for endogeneity in total costs. Again, most of the control variables are not statistically significant but the estimates of both cost variables are. Using the IV technique, total cost now has the expected negative effect on the number of acres burned: a 1.0 percent increase in spending on fire suppression is associated with a reduction in the number of acres burned of 0.7 percent on average (see Figure 1). Fifty-eight percent of the fires cost $50 or less per acre (see Figure 2). Using the cost per acre variable, the IV coefficient is also negative: a 1.0 percent increase in the spending in fire suppression per acre is associated with a reduction in the number of acres burned of 0.5 percent, approximately the same result estimated using the OLS technique.

Figure 1: Predicted effect of a 20 percent increase in fire management

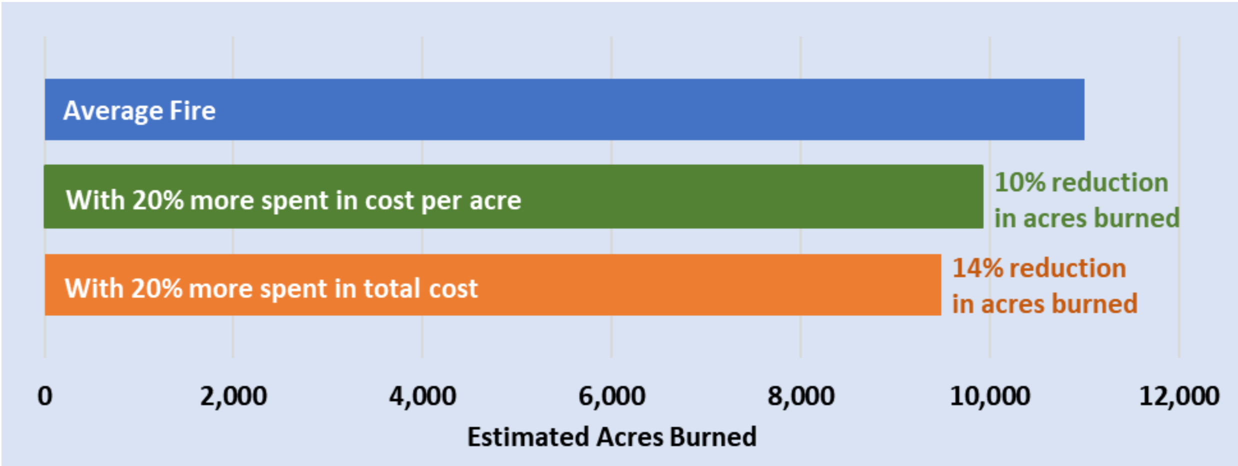
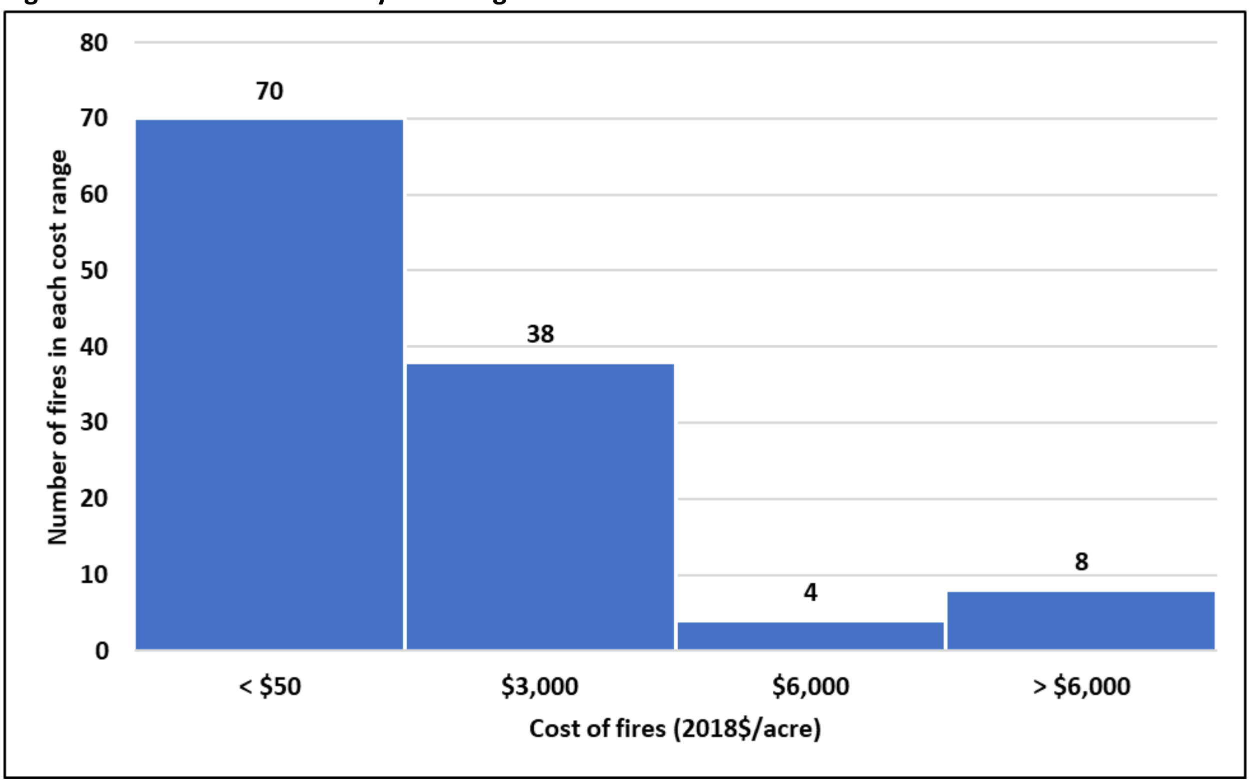


Figure 2: Distribution of fires by cost range



IV. CO_2 Mitigation Cost Comparison

The results of this analysis show that the average cost of fire management in Alaska is $1.19 per metric tonne of CO_2 avoided.[13] A comparison of this cost to those of other policies reveals that the cost of fire management is at the lowest end of the costs reported for other negative emission policies, which range from $0 to $1,061 per tonne of CO_2.

Negative emission policies

Recent research from the Intergovernmental Panel on Climate Change's (IPCC) 2018 *Special Report*[14] and from 2018 collaborative research published in *Environmental Research Letters*[15] estimates the range of costs per tonne of CO_2 of other "negative emission" mitigation measures:

- **Afforestation and reforestation:** Planting new forests and replanting forests in deforested areas.[16]
- **Soil carbon sequestration:** The process by which land management change increases the organic carbon content of soil, which results in a net removal of CO_2 from the atmosphere.[17]
- **Biochar:** Producing biochar by pyrolysis (a process that decomposes biomass by heating it at high temperatures in the absence of oxygen) of biomass can store CO_2.[18]
- **Bioenergy with carbon capture and storage (CCS):** Combining CCS with the use of biomass as an energy source.[19]
- **Ocean Fertilization:** Adding lime to the oceans, which enhances their uptake of CO_2.[20]

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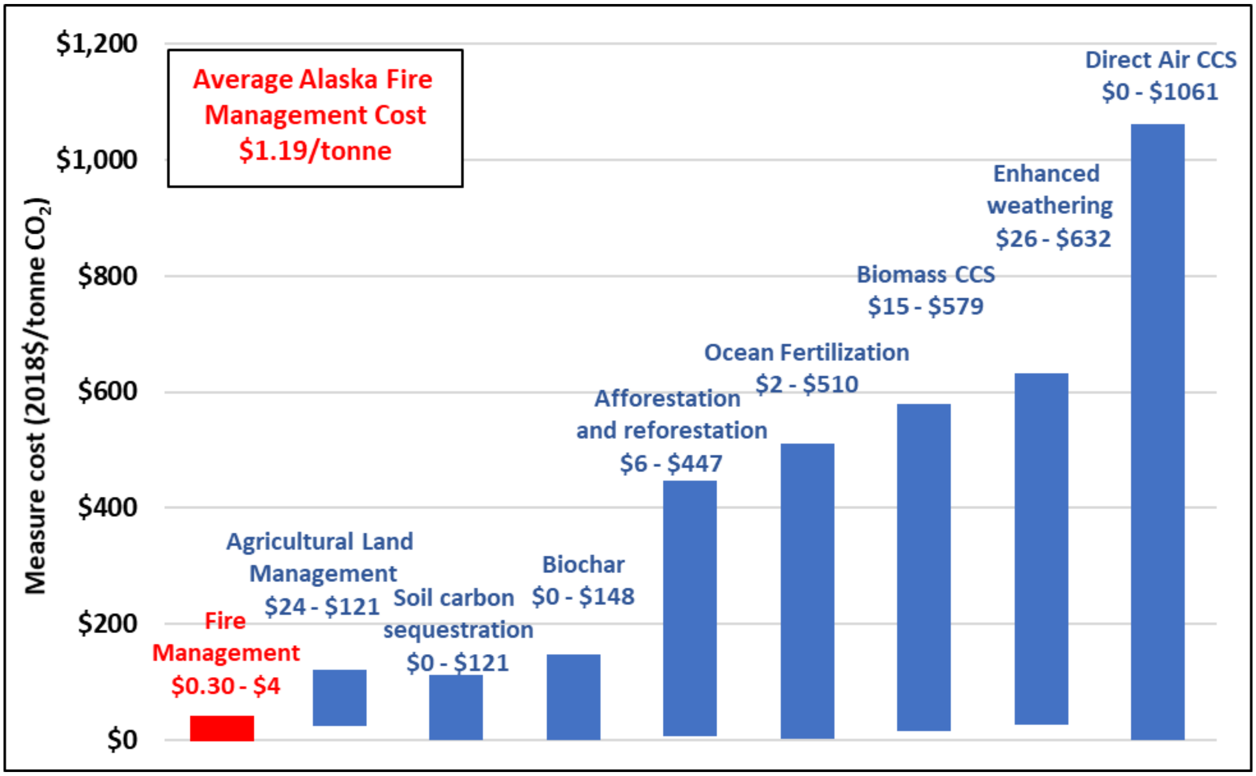
[13] Cost to avoid a tonne of CO_2 based on FRAMES data
[14] Hoegh-Guldberg, O. et al. 2018. "Impacts of 1.5°C Global Warming on Natural and Human Systems." In: *Global Warming of 1.5°C*. Masson-Delmotte, V. et al. (eds.). IPCC special Report. Available at: https://www.ipcc.ch/sr15/
[15] Fuss, S. et al. 2018. "Negative Emissions—Part 2: Costs, Potentials and Side Effects." *Environmental Research Letters, 13*, 1-47. Available at: https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f/pdf
[16] Fuss, S. et al. 2018. "Negative Emissions—Part 2: Costs, Potentials and Side Effects." *Environmental Research Letters, 13*, 1-47. Available at: https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f/pdf
[17] Ibid.
[18] Woolf, D., Amonette, J.E., Street-Perrott, F.A., Lehmann, J. & Joseph, S. 2010. "Sustainable Biochar to Mitigate Global Climate Change," *Nature Communications, 1*, 1-9. DOI: https://doi.org/10.1038/ncomms1053
[19] Fajardy, M. & Mac Dowell, N. 2017. "Can BECCS Deliver Sustainable and Resource Efficient Negative Emissions?" *Energy & Environmental Science, Vol. 10 (6)*, 1389-1426. DOI: https://doi.org/10.1039/C7EE00465F
[20] Caldecott, B., Lomax. G. & Workman, M. 2015. *Stranded Carbon Assets and Negative Emissions Technologies*. Working Paper. Smith School of Enterprise and the Environment. University of Oxford. Available at: http://www.ilcambiamento.it/files/Carbon_oxford.pdf

- **Enhanced weathering:** Applying finely ground minerals over the land surface to increase the biological processes that sequester CO_2 as part of the natural carbon cycle.[21]
- **Direct air CCS:** Chemical processes used to remove CO_2 directly from the atmosphere.[22]

Costs of negative emissions measures range from $0 to $1,061 per tonne across all measures (see Figure 3). The cost of Alaskan fire management ranges from 1 one-thousandth of a cent to $40 per tonne of CO_2 avoided, with an average cost of $1.19 per tonne and first standard deviation of $4.49 per tonne (see Table 7 below).

Figure 3: Cost of negative emission mitigation policies (2018$/metric tonne CO_2)



Source: Appendix B, Cost of Negative Emission Measures

Other mitigation policies

In reviewing additional sources for the impact of other mitigation policies, AEC found that for renewable and energy efficiency-related measures costs range from -$195/tonne for adopting behavioral energy

[21] Pidgeon, N.F. & Spence, E. 2017. Perceptions of enhanced weathering as a biological negative emissions option." Biology Letters, 13, 1-5. DOI: https://doi.org/10.1098/rsbl.2017.0024

[22] Fuss, S. et al. 2018. "Negative Emissions—Part 2: Costs, Potentials and Side Effects." *Environmental Research Letters, 13*, 1-47. Available at: https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f/pdf

efficiency measures to $2,151/tonne for solar photovoltaic subsidies (see Appendix C). For transportation-related measures, costs range from -$18/tonne for mixing gasoline with corn starch ethanol[23], to $1,016/tonne for adopting low carbon fuel standards (see Appendix D). Negative net costs, as with values for behavioral energy efficiency measures, mean that the cost of a mitigation measure are outweighed by its benefits. Of all the other mitigation policies, energy efficiency measures, certain renewable portfolio standards, and the lower range of wind energy subsidies are the most similar to the costs of fire management with values below or close to zero.

Calculating the cost/avoided tonne CO_2

Define:

A = number of acres burned

C = cost of fire management

$\hat{\beta}$ = estimated effect of cost management on number of acres burned in absolute value

e = Alaska-specific emissions rate (tonne CO_2 / acre)

E = emissions avoided from not burning an acre

dx = change in variable x

From the econometric analysis in Memo 1:

$$\frac{\left(\frac{dA}{A}\right)}{\left(\frac{dC}{C}\right)} = \hat{\beta},$$

$$\left(\frac{dA}{dC}\right)\left(\frac{C}{A}\right) = \hat{\beta},$$

$$\frac{dA}{dC} = \left(\frac{A}{C}\right)\hat{\beta},$$

$$\frac{dC}{dA} = \left(\frac{C}{A}\right)\left(\frac{1}{\hat{\beta}}\right).$$

[23] Based on a California Air Resources Board estimate for the cost of new corn ethanol plants. See Appendix D.

Emissions avoided are calculated as $dE = e(dA)$. Therefore $dA = dE/e$. Thus,

$$\frac{dC}{dA} = \frac{dC}{(dE/e)} = \left(\frac{C}{A}\right)\left(\frac{1}{\hat{\beta}}\right),$$

$$\frac{dC}{dE} = \left(\frac{C}{A}\right)\left(\frac{1}{e\hat{\beta}}\right).$$

This last equation gives the cost of avoided tonne of CO_2 for a given level of C and A.

The FRAMES data set includes emissions and the cost of fire management for each fire. Together the 120 wildfires in the data set resulted in the emission of 40.1 million metric tonnes of CO_2 over the 2007-2015 year period. Since the number of acres burned in these fires was 1.3 million, the average emissions rate (e) is 30.4 tonnes of CO_2 per acre. The total cost of fire management for these 120 wildfires, adjusted for inflation to be expressed in 2018 dollars, is $56 million.[24]

To estimate the cost per avoided tonne, costs of fire management are combined with the impact that dollars spent on fire management has on the number of acres burned (total cost has a negative effect on the number of acres burned: a 1.0 percent increase in spending on fire suppression is associated with a reduction in the number of acres burned of 0.7 percent on average).

The average cost per avoided tonne of CO_2 is calculated as the average of all estimated individual fire costs per avoided tonne:[25]

$$Cost\ per\ avoided\ tonne\ of\ CO_2 = \left(\frac{C_i}{A_i}\right)\left(\frac{1}{e\hat{\beta}}\right),$$

where C_i is the cost of fire management for the i^{th} fire, A_i is the number of acres burned in the i^{th} fire, e is the Alaska-specific emissions rate as defined above, and $\hat{\beta}$ is the estimated effect (in absolute value) of cost management on the number of acres burned from the regression analysis in Memo 1.

Individual costs per avoided tonne of CO_2 range from 1 one-thousandth of a cent to $40 per tonne. The average value across all fires in the FRAMES database is $1.19 per tonne of CO_2 avoided.

This methodology provides an average cost to avoid a tonne of CO_2 through fire management in FRAMES data. The small size of this data set and perennial difficulty of estimating the effect of a thing

[24] Nominal values were converted to 2018 dollars using the average Consumer Price Index (CPI) for each year.
[25] See Appendix A for details on how this formula is derived.

that did not happen (here, acres not burnt) suggests that some care should be taken in applying this result to fires, whether historical or future, not included in this dataset. This analysis provides a preliminary estimate of the potential value of Alaskan fire suppression measures on limiting CO_2 emissions. More analysis, using larger data sets, is needed to lend further confidence to these results.

Using the same methodology (and assuming the average emissions rate across all four zones), AEC calculated the cost of fire management per tonne of CO_2 avoided for each of the four fire management zones: critical, full, modified, and limited. The average cost to avoid a tonne of CO_2 through fire management varies only by a factor of 2, ranging from $0.90 per tonne of CO_2 for the Modified zone to $1.91 per tonne of CO_2 for the Full zone (see Figure 4). Results by zone are made on the basis of even smaller datasets and require the same caveats provided above for average value across zones.

It should be noted that costs to avoid a tonne of CO_2 through fire management in the FRAMES dataset vary widely, both within and among Fire Management Zones (see Figure 4 and Table 7). Costs in the Critical zone, which accounts for 6 percent of the fires in the dataset, range from less than one cent to about $10 per tonne. The greatest variation in cost is found in the Full zone, which accounts for 59 percent of the fires in the data set, where costs range from less than one cent to $40 per tonne of CO_2.

Figure 4: Cost of fire management across Fire Management Zones (2018$/metric tonne CO_2)

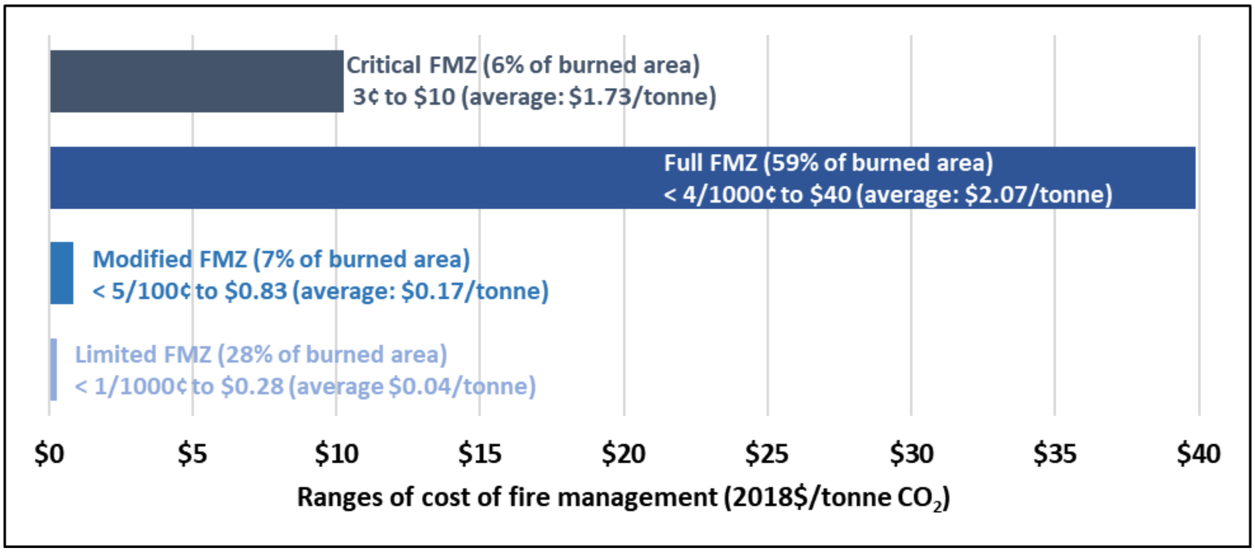


Table 7. Distribution of cost per tonne results

FMZ	Mean	Median	Maximum	Minimum	First Standard Deviation
All	$1.19	$0.05	$39.90	<$0.01	$4.49
Critical	$1.73	$0.21	$10.27	$0.03	$3.79
Full	$2.07	$0.20	$39.90	<$0.01	$6.06
Modified	$0.17	$0.06	$0.83	<$0.01	$0.24
Limited	$0.04	$0.01	$0.28	<$0.01	$0.07

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Appendix A: Literature Review Data Sources

Fire	Source	Link
1996 Miller's Reach Fire (Alaska)	Berman, M., Juday, G. P., & Burnside, R. 1998. "Climate Change and Alaska's Forests: People, Problems, and Policies." Assessing the Consequences of Climate Change for Alaska and the Bering Sea Region. Proceedings of a Workshop at the University of Alaska Fairbanks.	http://www.besis.uaf.edu/besis-oct98-report/Forestry.pdf
2003 San Diego County Fires (California)	Rahn, M. 2009. *Wildfire Impact Analysis*. San Diego State University.	http://universe.sdsu.edu/sdsu_newscenter/images/rahn2009fireanalysis.pdf
1998 Florida Fires	Butry, D. T. et al. 2000. The Economic Effects of the 1998 Florida Wildfires. In: *Economic Effects of Catastrophic Wildfires: Assessing the Effectiveness of Fuel Reduction Programs for Reducing the Economic Impacts of Catastrophic Forest Fire Events*. Chapter 2. D. E. Mercer et al.	https://www.srs.fs.usda.gov/econ/pubs/misc/fl-fire-report2000-lores.pdf
2012 Waldo Canyon Fire (Colorado)	Cleetus, R., & Mulik, K. 2014. *Playing with Fire: How Climate Change and Development Patterns Are Contributing to the Soaring Costs of Western Wildfires*. Union of Concerned Scientists.	https://www.ucsusa.org/sites/default/files/legacy/assets/documents/global_warming/playing-with-fire-report.pdf
2002 Biscuit Fire (Oregon)	Prestemon, J. P., & Holmes, T. P. 2008. Timber salvage economics. *The Economics of Forest Disturbances: Wildfires, Storms, and Invasive Species.* Holmes, T. P. et al. (eds.). p. 167-190. Springer Science + Business Media B.V.	https://www.srs.fs.usda.gov/pubs/ja/ja_prestemon028.pdf
2002 Hayman Fire (Colorado), 2000 Bobcat Gulch Fire (Colorado), 2002 Colorado Fires	Lynch, D. L. 2004. "What Do Forest Fires Really Cost?" *Journal of Forestry, Volume 102* (6), p. 42–49.	https://academic.oup.com/jof/article/102/6/42/4613189
2000 Bittreroot National Forest Fire (Montana)	Prestemon, J. P. et al. 2006. "Wildfire, timber salvage, and the economics of expediency." *Forest Policy and Economics, Volume 8* (3), p. 313-322.	https://www.sciencedirect.com/science/article/pii/S138993410400142X?via%3Dihub

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Appendix B: Cost of Negative Emission Measures

Estimate/measure	$/tonne ($2018)	Source
Afforestation and reforestation	$17-447	Fuss, S., et al. 2018. "Negative emissions—Part 2: Costs, potentials and side effects." Environmental Research Letters, 13 063002. Available at: https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f/pdf
Afforestation and reforestation	$23-117	Caldecott, B., Lomax, G., and Workman, M. 2015. Stranded Carbon Assets and Negative Emissions Technologies. Stranded Assets Programme at the University of Oxford's Smith School of Enterprise and the Environment. Available at: https://ora.ox.ac.uk/objects/uuid:258c4d8e-3ea7-4b72-a24e-44acd01405d1/download_file?file_format=pdf&safe_filename=2015.02.03_NETs.pdf&type_of_work=Report
Afforestation and reforestation	$6-56	IPCC. 2019. Strengthening and Implementing the Global Response. SR 1.5 Ch 3, Ch4. Available at: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/02/SR15_Chapter4_Low_Res.pdf
Agricultural Land Management	$24-121	Caldecott, B., Lomax, G., and Workman, M. 2015. Stranded Carbon Assets and Negative Emissions Technologies. Stranded Assets Programme at the University of Oxford's Smith School of Enterprise and the Environment. Available at: https://ora.ox.ac.uk/objects/uuid:258c4d8e-3ea7-4b72-a24e-44acd01405d1/download_file?file_format=pdf&safe_filename=2015.02.03_NETs.pdf&type_of_work=Report
Biochar	$0-148	Caldecott, B., Lomax, G., and Workman, M. 2015. Stranded Carbon Assets and Negative Emissions Technologies. Stranded Assets Programme at the University of Oxford's Smith School of Enterprise and the Environment. Available at: https://ora.ox.ac.uk/objects/uuid:258c4d8e-3ea7-4b72-a24e-44acd01405d1/download_file?file_format=pdf&safe_filename=2015.02.03_NETs.pdf&type_of_work=Report
Biochar	$67-134	Fuss, S., et al. 2018. "Negative emissions—Part 2: Costs, potentials and side effects." Environmental Research Letters, 13 063002. Available at: https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f/pdf
Biochar	$33-134	IPCC. 2019. Strengthening and Implementing the Global Response. SR 1.5 Ch 3, Ch4. Available at: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/02/SR15_Chapter4_Low_Res.pdf
Biomass CCS	$33-447	Fuss, S., et al. 2018. "Negative emissions—Part 2: Costs, potentials and side effects." Environmental Research Letters, 13 063002. Available at: https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f/pdf
Biomass CCS	$93-305	Fuss, S., et al. 2018. "Negative emissions—Part 2: Costs, potentials and side effects." Environmental Research Letters, 13 063002. Available at: https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f/pdf
Biomass CCS	$21-74	Fuss, S., et al. 2018. "Negative emissions—Part 2: Costs, potentials and side effects." Environmental Research Letters, 13 063002. Available at: https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f/pdf
Biomass CCS	$49-273	Caldecott, B., Lomax, G., and Workman, M. 2015. Stranded Carbon Assets and Negative Emissions Technologies. Stranded Assets Programme at the University of Oxford's Smith School of Enterprise and the Environment. Available at: https://ora.ox.ac.uk/objects/uuid:258c4d8e-3ea7-4b72-a24e-44acd01405d1/download_file?file_format=pdf&safe_filename=2015.02.03_NETs.pdf&type_of_work=Report
Biomass CCS	$112-223	IPCC. 2019. Strengthening and Implementing the Global Response. SR 1.5 Ch 3, Ch4. Available at: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/02/SR15_Chapter4_Low_Res.pdf
Biomass CCS	$22-195	Fuss, S., et al. 2018. "Negative emissions—Part 2: Costs, potentials and side effects." Environmental Research Letters, 13 063002. Available at: https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f/pdf
Biomass CCS	$15-82	Fuss, S., et al. 2018. "Negative emissions—Part 2: Costs, potentials and side effects." Environmental Research Letters, 13 063002. Available at: https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f/pdf
Direct Air CCS	$33-1061	Fuss, S., et al. 2018. "Negative emissions—Part 2: Costs, potentials and side effects." Environmental Research Letters, 13 063002. Available at: https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f/pdf
Direct Air CCS	$112-335	IPCC. 2019. Strengthening and Implementing the Global Response. SR 1.5 Ch 3, Ch4. Available at: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/02/SR15_Chapter4_Low_Res.pdf
Enhanced Weathering	$26-632	Renforth, P. 2012. "The potential of enhanced weathering in the UK." International Journal of Greenhouse Gas Control 10, p.229-243. Available at: https://www.sciencedirect.com/science/article/pii/S1750583612001466
Enhanced Weathering	$56-223	IPCC. 2019. Strengthening and Implementing the Global Response. SR 1.5 Ch 3, Ch4. Available at: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/02/SR15_Chapter4_Low_Res.pdf
Ocean Fertilization	$2-510	Fuss, S., et al. 2018. "Negative emissions—Part 2: Costs, potentials and side effects." Environmental Research Letters, 13 063002. Available at: https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f/pdf
Ocean Fertilization	$78-171	Carbon Brief Staff. November 4, 2016. "Explainer: 10 ways 'negative emissions' could slow climate change" [Blog Post]. Carbon Brief. Available at: https://www.carbonbrief.org/explainer-10-ways-negative-emissions-could-slow-climate-change
Soil Carbon Sequestration	$21-112	Fuss, S., et al. 2018. "Negative emissions—Part 2: Costs, potentials and side effects." Environmental Research Letters, 13 063002. Available at: https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f/pdf
Soil Carbon Sequestration	$0-112	IPCC. 2019. Strengthening and Implementing the Global Response. SR 1.5 Ch 3, Ch4. Available at: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/02/SR15_Chapter4_Low_Res.pdf

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Appendix C: Cost of Other Emission Measures: Renewable and Energy Efficiency

Estimate/measure	$2018/metric ton	Source
Advanced Nuclear (compared to existing coal generation)	$60	Gillingham, K. and Stock, J. 2018. The Cost of Reducing Greenhouse Gas Emissions. Available at: https://scholar.harvard.edu/files/stock/files/gillingham_stock_cost_080218_posted.pdf
Behavioral Energy Efficiency	-$195	Gillingham, K. and Stock, J. 2018. The Cost of Reducing Greenhouse Gas Emissions. Available at: https://scholar.harvard.edu/files/stock/files/gillingham_stock_cost_080218_posted.pdf
Behavioral Energy Efficiency	-$190	Allcott, H. and Mullainathan, S. 2010. "Behavior and Energy Policy". Science Magazine, Volume 327, 1204-1205. Available at: https://scholar.harvard.edu/files/sendhil/files/behavior_and_energy_policy.pdf
Clean Power Plan	$11	Gillingham, K. and Stock, J. 2018. The Cost of Reducing Greenhouse Gas Emissions. Available at: https://scholar.harvard.edu/files/stock/files/gillingham_stock_cost_080218_posted.pdf
Direct Subsidies for Renewable Fuels	$92	Holland, S. P., et.al. 2011. "Some Inconvenient Truths about Climate Change Policy: The Distributional Impacts of Transportation Policies." National Bureau of Economic Research. Working Paper Series. https://www.nber.org/papers/w17386
Energy Efficiency	$41	American Council for an Energy Efficient Economy. 2014. How Much Does Energy Efficiency Cost? Available at: https://aceee.org/sites/default/files/cost-of-ee.pdf, Calculated using EIA 923: Generation and EIA 861: Sales Data.
National Clean Energy Standard	$52-113	Gillingham, K. and Stock, J. 2018. The Cost of Reducing Greenhouse Gas Emissions. Available at: https://scholar.harvard.edu/files/stock/files/gillingham_stock_cost_080218_posted.pdf
Offshore Wind (compared to existing coal generation)	$108	Gillingham, K. and Stock, J. 2018. The Cost of Reducing Greenhouse Gas Emissions. Available at: https://scholar.harvard.edu/files/stock/files/gillingham_stock_cost_080218_posted.pdf
Onshore Wind (compared to existing coal generation)	$26	Gillingham, K. and Stock, J. 2018. The Cost of Reducing Greenhouse Gas Emissions. Available at: https://scholar.harvard.edu/files/stock/files/gillingham_stock_cost_080218_posted.pdf
Renewable Portfolio Standards	$0-195	Gillingham, K. and Stock, J. 2018. The Cost of Reducing Greenhouse Gas Emissions. Available at: https://scholar.harvard.edu/files/stock/files/gillingham_stock_cost_080218_posted.pdf
Solar PV Subsidies	$143-2151	Gillingham, K. and Stock, J. 2018. The Cost of Reducing Greenhouse Gas Emissions. Available at: https://scholar.harvard.edu/files/stock/files/gillingham_stock_cost_080218_posted.pdf
Solar Thermal (compared to existing coal generation)	$136	Gillingham, K. and Stock, J. 2018. The Cost of Reducing Greenhouse Gas Emissions. Available at: https://scholar.harvard.edu/files/stock/files/gillingham_stock_cost_080218_posted.pdf
Utility-scale Solar Photovoltaic (compared to existing coal generation)	$30	Gillingham, K. and Stock, J. 2018. The Cost of Reducing Greenhouse Gas Emissions. Available at: https://scholar.harvard.edu/files/stock/files/gillingham_stock_cost_080218_posted.pdf
Wind	$23	Allcott, H. and Mullainathan, S. 2010. "Behavior and Energy Policy". Science Magazine, Volume 327, 1204-1205. Available at: https://scholar.harvard.edu/files/sendhil/files/behavior_and_energy_policy.pdf
Wind Energy Subsidies	$2-299	Gillingham, K. and Stock, J. 2018. The Cost of Reducing Greenhouse Gas Emissions. Available at: https://scholar.harvard.edu/files/stock/files/gillingham_stock_cost_080218_posted.pdf

Appendix D: Cost of Other Emission Measures: Transportation

Estimate/measure	$2018/metric ton	Source
Biodiesel	$154-430	Gillingham, K. and Stock, J. 2018. The Cost of Reducing Greenhouse Gas Emissions. Available at: https://scholar.harvard.edu/files/stock/files/gillingham_stock_cost_080218_posted.pdf
CAFE Standards	$49-318	Gillingham, K. and Stock, J. 2018. The Cost of Reducing Greenhouse Gas Emissions. Available at: https://scholar.harvard.edu/files/stock/files/gillingham_stock_cost_080218_posted.pdf
Carbon Trading	$22	Holland, S. P., et.al. 2011. "Some Inconvenient Truths about Climate Change Policy: The Distributional Impacts of Transportation Policies." National Bureau of Economic Research. Working Paper Series. https://www.nber.org/papers/w17386
Cash for Clunkers	$277-430	Gillingham, K. and Stock, J. 2018. The Cost of Reducing Greenhouse Gas Emissions. Available at: https://scholar.harvard.edu/files/stock/files/gillingham_stock_cost_080218_posted.pdf
Corn startch ethanol	$-18-215	Gillingham, K. and Stock, J. 2018. The Cost of Reducing Greenhouse Gas Emissions. Available at: https://scholar.harvard.edu/files/stock/files/gillingham_stock_cost_080218_posted.pdf
Dedicated Battery Electric Vehicle Subsidy	$359-656	Gillingham, K. and Stock, J. 2018. The Cost of Reducing Greenhouse Gas Emissions. Available at: https://scholar.harvard.edu/files/stock/files/gillingham_stock_cost_080218_posted.pdf
Gasoline Tax	$18-48	Gillingham, K. and Stock, J. 2018. *The Cost of Reducing Greenhouse Gas Emissions.* Available at: https://scholar.harvard.edu/files/stock/files/gillingham_stock_cost_080218_posted.pdf
GHG Reduction Benefit between Petroleum and EVs	$43-65	Marc, M., Bush, B., et al. 2016. "National Economic Value Assessment of Plug-in Electric Vehicles". *National Renewable Energy Laboratory.* Available at: https://www.nrel.gov/docs/fy17osti/66980.pdf
Low Carbon Fuel Standards	$70-1016	Hughes, J. et.al. 2009. "Greenhouse Gas Reductions under Low Carbon Fuel Standards?" NBER Working Paper No. 13266https://www.nber.org/papers/w13266.pdf
Low Carbon Fuel Standards	$54	Holland, S. P., et.al. 2011. "Some Inconvenient Truths about Climate Change Policy: The Distributional Impacts of Transportation Policies." National Bureau of Economic Research. Working Paper Series. https://www.nber.org/papers/w17386
Renewable Fuel Standard	$65	Holland, S. P., et.al. 2011. "Some Inconvenient Truths about Climate Change Policy: The Distributional Impacts of Transportation Policies." National Bureau of Economic Research. Working Paper Series. https://www.nber.org/papers/w17386
Renewable Fuel Subsidies	$92	Holland, S. P., et.al. 2011. "Some Inconvenient Truths about Climate Change Policy: The Distributional Impacts of Transportation Policies." National Bureau of Economic Research. Working Paper Series. https://www.nber.org/papers/w17386
Renewable Fuel Subsidies	$102	Gillingham, K. and Stock, J. 2018. The Cost of Reducing Greenhouse Gas Emissions. Available at: https://scholar.harvard.edu/files/stock/files/gillingham_stock_cost_080218_posted.pdf