Climate Royalty Surcharges

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Abstract

Concerns about climate change have led to calls for reforming or eliminating the extensive US federal fossil fuel leasing program. One proposed reform is adding a climate surcharge to the existing royalty rate. We consider determining this surcharge by maximizing social welfare, including the climate damages from combusting federal fossil fuels and the value of raising revenue when the marginal value of public funds exceeds one. We estimate that the resulting climate royalty surcharge would lead to meaningful declines in global emissions, would significantly increase royalty receipts, and would result in royalty rates substantially greater than those currently in place. We also evaluate the change in onshore royalty rates made by the Inflation Reduction Act of 2022, finding the law's modest rate increases leaves substantial welfare gains, emissions reductions, and royalty revenues on the table.

Key words: extraction royalties, social cost of carbon, Federal minerals program
JEL codes: Q54, Q58, Q35, Q38, H23

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Starting in the 19th century for coal, and in the 20th century for oil and gas, the US government promoted fossil fuel extraction from federal lands. Federal fossil fuel leasing helped drive settlement of the American West, provided a secure domestic supply of energy to a growing nation, and created jobs and wealth. In 2019, production on federal lands comprised 40% of domestic coal production, 22% of domestic oil production, and 12% of domestic natural gas. Now, however, we understand that CO_2 emitted by burning fossil fuels is the primary driver of climate change. As a result, there have been calls to rethink the federal government's role in fossil fuel leasing, including potentially reforming or ending the fossil fuel leasing program.

One proposed reform is to adjust the royalty rate assessed on federal fossil fuels to account for the climate impacts of using those fuels, that is, to adopt what we will call a climate royalty surcharge.[1] Royalties are the primary source of revenue in the federal fossil fuel leasing program. Accounting for the social opportunity costs of fossil fuel extraction and use stemming from climate change creates a new economic rationale for using royalties on fossil fuel extraction to internalize those costs, absent an economy-wide carbon tax.[2] There are, however, basic questions of what economic principles could be used to determine a climate royalty surcharge, what the resulting rates would be quantitatively, and what would be the effects of adopting those rates on CO_2 emissions and royalty revenues.

In this paper, we tackle these questions regarding the economics of a climate royalty surcharge in the federal fossil fuel royalty rate for new leases.[3] Because there is essentially no demand for new coal leases, we focus on federal oil and gas leasing. Also, because a decrease in federal production will in general be partially offset by an increase in nonfederal production, we focus on the net emissions reductions that account for this leakage.

The climate consequences of combusting a fossil fuel stems from the resulting release of carbon dioxide to the atmosphere. Carbon damages are therefore monetized as dollars per ton of CO_2 emitted, which can be converted to units of fuel quantity (e.g., dollars per barrel of oil) using a fuels emissions intensity. By this logic, climate damages would be assessed on a quantity bases (dollars per tons CO_2 or fuel quantity units). We will refer to an assessment in quantity units, specifically dollars per ton CO_2, as a carbon fee. Royalties, however, are assessed *ad valorem*. At a constant price for a given fuel, a carbon fee can be converted to a royalty surcharge. When

[1] For example, in January 2021, President Biden issued Executive Order 14008, which, among other things, instructed the Secretary of the Interior to consider "whether to adjust royalties associated with coal, oil, and gas resources extracted from public lands and offshore waters, or take other appropriate action, to account for corresponding climate costs" (White House 2021).

[2] As a matter of economic theory, royalties distort decisions away from a private optimum, see Garnaut and Clunies-Ross (1983) for an example. However, royalties provide a tool for sharing risk under price or resource quantity uncertainty (e.g., Leland 1978); for an overview of the theoretical literature on resources taxation, see Boadway and Keen (2010). Royalties also can be adjusted to incorporate the social opportunity cost of resource extraction such as residual reserve value (Conrad et al. 2018).

[3] Royalty rates are established contractually when the lease is issued, so a change in the royalty rate would apply only to new leases.

prices change or when there are multiple fuels, this equivalence breaks down. Because the prices and emissions intensities of oil and gas differ, a given carbon fee implies different climate royalty surcharges (measured in percentage points) for oil and for gas. We therefore consider three options for incorporating climate costs: applying the same climate royalty surcharge to both oil and gas (which implies different fees), applying the same fee (which implies different royalty surcharges), and determining the carbon fee (or royalty surcharge) separately for oil and gas.

To provide a conceptual framework for determining a climate royalty surcharge or carbon fee on federal fossil fuel production, we consider the social planner's problem, which includes the climate damages resulting from all emissions (not just emissions from combusting federal fossil fuels). Because royalty revenues can be used to offset taxes or to provide public services – in practice, half of royalties on onshore federal fossil fuel leases are returned to the states, where they typically fund schools and other locally-provided services – the social planner includes the royalty revenue weighted by the marginal value of public funds. The planner then maximizes welfare using a price instrument (royalty surcharge or carbon fee) that applies only to federal leases, given existing royalties on nonfederal land and global demand for oil and gas. This formulation nests two important limiting cases. First, if the marginal value of public funds is one (the value for a nondistortionary transfer), this formulation simplifies to a standard welfare maximization problem that includes only the climate damages (e.g., in the context of Pigovian taxation, Sandmo (1975), Nordhaus (1982), and, in the paper most closely related to this one, Holland (2012)). Second, as the marginal value of public funds becomes large, the planner's welfare maximization problem reduces to maximizing the revenue from oil and gas leases, which aligns with the long-standing principle of obtaining value for the taxpayer from selling federally owned resources.[4]

Using this framework, we show that the optimal royalty rate is the sum of three components: an allocative efficiency component, which takes into account existing royalty rates on nonfederal lands; a climate royalty surcharge that incorporates marginal climate damages as measured by the Social Cost of Carbon (SCC); and a revenue-raising component that increases in importance as the marginal value of public funds increases. The climate royalty surcharge is proportional to the SCC, where the factor of proportionality depends on the fuel-specific leakage rate which in turn depends on demand and co-production. In the special case of a single fuel, the climate royalty surcharge simplifies to the royalty equivalent of a carbon fee set equal to the SCC scaled down by the leakage rate, found by Holland (2012) to be the optimal fee when the fee covers some but not all of production.

An alternative perspective is to approach the federal fossil fuel leasing program from the perspective of a global carbon budget, designed to achieve a given target of global temperature

[4] CEA (2016) provides additional discussion of setting royalty rates to maximize revenue and estimates the revenue-maximizing royalty rate for new federal coal leases.

rise (e.g., Calverley and Anderson 2022; Mulvaney et al 2016; McGlade and Ekins 2015; Welsby 2021).[5] Because the royalty rate is a price tool, in practice this implies choosing the royalty rate to achieve a quantity target, for example as implied by a carbon budget for the federal fossil fuel leasing program. We incorporate this approach – choosing the royalty rate to achieve a carbon budget, expressed as an annual emissions target – into the social planner's problem, although we show that if the benefits of overachieving, and the costs of underachieving, are linear, then this approach is equivalent to the standard method of including marginal environmental damages in the welfare function.

We use these theoretical results on optimal royalties and fees and the econometric model of oil and gas production in Prest (2022a) to address two questions. First, we estimate the optimal (welfare-maximizing) royalty rate for federal onshore oil and gas leasing, which (consistent with practice and law) is constrained to be the same for oil and gas. Because this optimal rate is actually a schedule depending on the cost of public funds, we report the two extreme points, one in which the marginal value of public funds is one (the value for a nondistortionary transfer, for which the revenue-raising motive disappears, e.g. see Finkelstein and Hendren 2020 and Hendren and Sprung-Keyser 2020) and another where the social planner only cares about maximizing revenue. These calculations allow us to compare the optimal rates to the rate of 16.67% set for onshore leases in the Inflation Reduction Act (IRA) of 2022, which for the first time changed this rate from its value of 12.5% established in the Mineral Leasing Act of 1920. Using a SCC value of $50/ton (rising at 2% annually), we find that the optimal rates, regardless of the marginal value of public funds, are substantially larger than the IRA's 16.67% rate. For example, putting aside the revenue-raising motive, in our base case we estimate that the climate royalty surcharge alone contributes 21 percentage points. We can, however, rationalize the IRA increase as embodying the optimal climate surcharge if legislators did not include the revenue-raising motive and used a SCC value of $7 per ton of CO_2e emitted.

Second, because the IRA rate of 16.67% leaves revenue and (if the SCC exceeds $7/ton) welfare gains on the table, the question arises as to whether a carbon fee might additionally be applied to federal fossil fuel leases, given the royalty adjustments in the IRA. Burger (2016), for example, argues that a carbon fee could be assessed under existing legal authority that permits the U.S. Department of the Interior to assess additional fees on its leases to address environmental damage (referred to as "compensatory mitigation"); alternatively, such a fee could be established through legislation. We find that a common fee could be used to achieve very similar outcomes, as measured by emissions reductions and revenue raised, as would have been achieved had the IRA raised the common royalty rate to the level our calculations suggest would have been optimal. Interestingly, allowing for different fees across the different fuels turns out not to matter

[5] For example, Welsby (2021) estimates that 31% of US oil reserves, 52% of US gas reserves, and 97% of US coal reserves are unextractable under a 1.5°C scenario. All of those values exceed the corresponding share of US fossil fuel production from federal lands.

substantially for outcomes, compared to a common fee. That conclusion could differ in other contexts where there is more heterogeneity in production's price responsiveness, such as when making policy affecting offshore production, which is less price elastic (Prest 2022a).

1. The Federal Fossil Fuel Leasing Program

Federal fossil fuel leasing is governed by the Mineral Leasing Act of 1920 (MLA) and the Federal Land Policy Management Act of 1976 (FLPMA). The fossil fuel leasing program is administered by the Department of the Interior, with the Bureau of Land Management (BLM) managing onshore leasing and the Bureau of Ocean Energy Management (BOEM) managing offshore leasing.

The MLA established a minimum royalty rate of 12.5% for federal oil and gas leases. Although this legal rate is a floor, in practice the 12.5% rate was used for onshore leases until the passage of the IRA, which increased the rate to 16.67% for ten years after which 16.67% would become the new floor. In 2008, deepwater offshore rates for new drilling leases were increased from 12.5% to 16.67%, then raised further in 2009 to 18.75%,[6] where they currently stand for drilling in depths exceeding 200 meters. Royalty rates are one of the terms of a lease. Federal oil and gas leases have a primary lease period of 10 years, with 2-year extensions. Once producing, a lease is extended indefinitely so long as wells on it produce oil or gas.

Royalties are the primary, but not sole, source of US government revenues from federal fossil fuel leasing. For onshore leases, tracts for potential mineral leasing are either identified by the BLM or nominated by private parties. Mineral rights to those tracts are first auctioned competitively to the highest bidder. If BLM receives at least one bid above the statutory minimum, set in nominal terms to $2 per acre in the MLA and increased to $10 per acre by the IRA, then BLM awards the bid to the highest bidder. The upfront payments are referred to as bonus bids. In addition, the BLM receives small amounts of rental fees.[7]

Royalty payments account for the vast majority of receipts under the federal fossil fuel leasing program. Of the three primary components of revenue – royalties, bonus bids, and rents – royalties comprised between 83% and 93% annually. In fiscal year 2019, the oil and gas program received $7.745 billion in royalties, of which 85% was from oil, $496 million in bonus bids, and $130 million in rents.

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[6] Congressional Research Service (2015).

[7] The IRA also requires that royalties be paid on gas produced, not gas sold, in an effort to reduce flaring. The IRA also requires a minimum amount of annual lease sales as a prerequisite for issuing solar or wind leases or rights of way, however the acreage requirement is less than historical leasing and the language requires only an auction, not an actual lease sale; for these reasons we ignore these provisions in our analysis. See GAO (2020) for pre-IRA details, see Congressional Research Service (2022) for a summary of IRA leasing provisions, and see Prest (2022b) for a discussion of the implications of the minimum auction requirements introduced in the IRA.

In 2016, the Department of the Interior issued a moratorium on new leases while it conducted a programmatic environmental review of the coal leasing program (DOI 2017). The DOI suggested a royalty surcharge, or adder, as one way to account for climate damages from burning the fossil fuels. Legal analyses concluded that the Department of the Interior had the legal authority to adjust royalties to account for climate damages, both for coal (Krupnick et al. 2016) and for oil and gas (Hein 2018). Because existing leases, once granted, confer legally binding property rights and royalty rates, all policies we consider apply only to new leases.

2. The Economics of Fossil Fuel Leasing Reform[8]

The traditional economic theory of royalty determination focusses on aligning incentives and enhancing taxpayer return.[9] Under a balanced budget steady state, the resulting royalty receipts can be used to reduce taxes or to increase expenditures elsewhere in the federal budget. When the marginal value of public funds exceeds one, the welfare cost of the royalty can be more than offset by benefits derived from the use of royalty receipts. This motivation for setting royalties is general and applies to non-fossil fuel resources as well as fossil fuel leasing.

Climate externalities provide a second motivation for adjusting royalties or for levying a per-ton carbon fee on federal fossil fuels. If a fee (or tax) could be applied to all fossil fuels, federal and nonfederal, then the optimal policy in a standard model of welfare maximization, absent the revenue-raising motive, is to set the carbon fee equal to the marginal value of the avoided climate damage (e.g., Nordhaus 1982). The marginal damage is the net present value of current and future monetized climate damages in units of dollars per ton CO_2, that is, the Social Cost of Carbon (SCC).

A climate royalty surcharge and/or fee increases the price of the extracted fossil fuel to the end user, partially or completely internalizing the carbon externality. A climate royalty surcharge or fee would make some proposed drilling projects unprofitable, thereby reducing federal

[8] The economics literature on incorporating climate considerations into fossil fuel leasing reform consists of Gerarden, Reeder, and Stock (2020), Erickson and Lazarus (2018), and Prest (2022a). Gerarden, Reeder, and Stock (2020) consider climate royalty surcharges in the federal coal program and their interaction with demand-side CO_2 regulation. Erikson and Lazarus (2018) estimate potential reductions from the cessation of coal and oil (but not gas) leasing by 2030, using a static constant-elasticity model that drew from estimates from the literature. Prest (2022a) developed an eight-component combined model oil and gas leasing, where each component is separately econometrically parameterized, to estimate the effect of percentage-based and SCC-based royalty surcharges on emissions, production, and royalties annually through 2050. This research fits into a growing body of research on supply-side climate policies, see Lazarus and van Asselt (2018) for a survey.

[9] Royalty rate determination for enhancing taxpayer return is part of the theory of contracting and regulation with asymmetric information. A textbook treatment is Laffont and Tirole (1993), which connects auctions and regulation under asymmetric information and moral hazard. For a review of the theoretical literature on royalty auctions, see Skrzypacz (2013). Haile, Hendricks, and Porter (2010) summarize the relation between auction structure and government revenues. For additional references to auction theory in the context of US oil and gas leasing (a bonus bid auction not a royalty auction), see Compiani, Haile, and Sant'Anna (2020).

production, tightening total supply, increasing the market prices of oil and gas, and in turn spurring an increase nonfederal production. From the perspective of reducing CO_2 emissions, this partial shift of production from federal to nonfederal production results in "leakage." The leakage rate λ is the fraction of direct emissions reductions from federally produced oil and gas that is offset by increased production elsewhere: $\lambda = -\frac{\partial E^{tot,u}}{\partial \tau} / \frac{\partial E^{tot,c}}{\partial \tau}$, where $E^{tot,c}$ and $E^{tot,u}$ are total emissions from covered (federal) and uncovered (nonfederal) production, and τ is the carbon fee (in \$/ton CO_2e) (note that $\frac{\partial E^{tot,c}}{\partial \tau}$ is negative). Holland (2012) considered a single fuel with leakage showed that when there is no preexisting royalty rate the welfare-maximizing carbon fee equals the marginal *net* damages avoided after accounting for offsetting leakage, that is, $\tau = (1 - \lambda)\theta$, where θ is the SCC.

This section lays out a static model of royalty and/or carbon fee determination, based on maximizing social welfare, that encompasses both the revenue enhancement and climate externality motivations. The model allows for two different approaches to the climate externality. The first introduces the externality through its marginal social cost per ton of CO_2e emitted, that is, by accounting for the climate damages using the SCC. The second supposes that a separate calculation has delivered an aggregate carbon budget for oil and gas combined, which has been translated into an annual cap on total emissions. In this latter case, the royalty surcharge or fee is a price mechanism used to hit a quantity target.

2.1. Theoretical Model

The model, which extends Hoel (1996), Holland (2012), and Fæhn et al. (2017), allows allow for multiple fuels (oil and gas), co-production (some wells produce both oil and gas), and some production covered by the royalty (superscript c) with the rest uncovered (superscript u). The social planner maximizes welfare, which incorporates the climate motive through damages from emissions, the revenue enhancement motive through a positive marginal value of public funds, and the carbon budget constraint through an emissions target.[10] The regulator's tools are a common (scalar) *ad-valorem* royalty rate r^c on covered fuels[11] and a vector of carbon fees τ^c on covered fuels, which can vary across fuel.

The n-vector of production of covered fuels is $Q^c = (q_1^c, \ldots, q_n^c)'$ and uncovered fuels is $Q^u = (q_1^u, \ldots, q_n^u)'$; the vector of total production is $Q = Q^c + Q^u$. The representative consumer derives utility $U(Q)$ from consumption of the fuels, where consumption equals production. The cost functions for producing fuels are $C^c(Q^c)$ and $C^u(Q^u)$ for covered and uncovered fuels

[10] We thank an anonymous reviewer for extensive comments that encouraged us to adopt the unifying framework presented in this section.
[11] Restriction to a scalar common royalty rate accords with historical practice in the federal fossil fuel leasing program.

respectively. Each fuel q_i produces emissions at rate, e_i, so emissions from fuel i are $e_i q_i$. Vectors of emissions intensities, covered, uncovered, and total emissions are e, E^c, E^u, and $E = E^c + E^u$. Covered emissions are $E^{tot,c} = e'Q^c$, uncovered emissions are $E^{tot,u} = e'Q^u$, and total emissions are $E^{tot} = e'Q$. External damages from emissions are linearized as $D(E^{tot}) = \theta E^{tot}$.[12] We assume that uncovered production is not subject to a carbon fee ($\tau^u = 0$), although it is subject to a common exogenous royalty r^u.

Consumer and firm behavior. The models of consumer and firm behavior are standard. Price-taking consumers choose the vector of quantities of the n fuels, represented by the vector Q, to maximize utility net of purchase cost at the vector of prices $P = (p_1, \ldots, p_n)'$:

$$\max_Q U(Q) - P'Q.$$

The resulting first-order conditions equate marginal utility of each fuel to its price:

$$\frac{\partial U}{\partial Q'} = P'. \tag{1}$$

Covered and uncovered firms, $j \in \{c, u\}$, maximize profits, net of the royalties, production costs, and carbon fees,

$$\max_{Q^j} P'Q^j(1 - r^j) - C^j(Q^j) - \tau^{j\prime}E^j$$

The first-order conditions for the firms yields the n equations equating each fuel's marginal cost to its price net of royalties and carbon fees.

$$p_i(1 - r_i^j) - \tau_i^j e_i = \frac{\partial C^c}{\partial q_i^j} \quad \forall i, j$$

This can be written in the form of a $1 \times n$ vector:

$$P'(1 - r^j) - \tau^{j\prime} \frac{\partial E^j}{\partial Q^{j\prime}} = \frac{\partial C^j}{\partial Q^{j\prime}} \quad \forall j. \tag{2}$$

[12] This linearization assumes that the SCC, which represents the marginal damages per ton of carbon emissions, is unaffected by the policy. This is a reasonable assumption for two reasons. First, marginal damage curves for stock pollutants like carbon dioxide tend to be relatively flat with respect to emissions, implying a relatively constant SCC (see, e.g., Nordhaus 1994, Kolstad 1996, and Pizer 2002). Second, when the covered sector represents a small share of global emissions as it does in our application, changes in global equilibrium emissions and hence marginal damages are small.

where $\frac{\partial E^j}{\partial Q^{j'}} = diag(e_1, \ldots, e_n)$ is a diagonal matrix with the emissions intensity vector e on the main diagonal, and zero otherwise.

The social planner's problem and first order conditions. The social planner chooses the royalty rate r^c and the vector of carbon fees τ^c for the covered sector to maximize social welfare, which includes damages from emissions, the marginal value of public funds, and the possibility of an emissions target for total fossil fuel emissions arising from a carbon budget:

$$max_{\tau^c, r^c}\, W(Q) = [U(Q) - C^c(Q^c) - C^u(Q^u)] - \theta E^{tot} + \alpha\left(r^c P' Q^c + \tau^{c\prime} E^c\right) + \mu(\overline{E^{tot}} - E^{tot}). \quad (3)$$

The first term (inside the brackets) is private benefits and costs, the next term reflects the climate damages valued at the SCC θ, the next term reflects the social value of revenues where α is the marginal value of public funds minus 1, so $\alpha = 0$ corresponds to a nondistortionary transfer and hence no revenue-raising motive (royalty revenues on covered sales are $r^c P' Q^c$ and receipts from the carbon fee are $\tau^{c\prime} E^c$), and the final term is the cost of exceeding the total emissions target $\overline{E^{tot}}$, with shadow value $\mu \geq 0$ measured in dollars per ton.

The first-order condition from (3) for the carbon fee vector τ^c is,

$$\frac{\partial U}{\partial Q'}\left(\frac{\partial Q^c}{\partial \tau^{c\prime}} + \frac{\partial Q^u}{\partial \tau^{c\prime}}\right) - \frac{\partial C^c}{\partial Q^{c\prime}}\frac{\partial Q^c}{\partial \tau^{c\prime}} - \frac{\partial C^u}{\partial Q^{u\prime}}\frac{\partial Q^u}{\partial \tau^{c\prime}} - \theta\frac{\partial E^{tot}}{\partial \tau^{c\prime}} + \alpha\left(r^c P'\frac{\partial Q^c}{\partial \tau^{c\prime}} + E^{c\prime} + \tau^{c\prime}\frac{\partial E^c}{\partial \tau^{c\prime}}\right) - \mu\frac{\partial E^{tot}}{\partial \tau^{c\prime}} = 0. \quad (4)$$

Combining equations (1) and (2) yields $\frac{\partial U}{\partial Q'}(1 - r^j) - \tau^{j\prime}\frac{\partial E^j}{\partial Q^{j\prime}} = \frac{\partial C^j}{\partial Q^{j\prime}}$. Inserting this expression for $j \in \{c, u\}$ into the second and third terms in (4) leads the first term to disappear. Further noting that $\tau^u = 0$, $P' = \frac{\partial U}{\partial Q'}$, and $\frac{\partial E^c}{\partial \tau^{c\prime}} = \frac{\partial E^c}{\partial Q^{c\prime}}\frac{\partial Q^c}{\partial \tau^{c\prime}}$, we have,

$$r^c P'\frac{\partial Q^c}{\partial \tau^{c\prime}} + \tau^{c\prime}\frac{\partial E^c}{\partial \tau^{c\prime}} + r^u P'\frac{\partial Q^u}{\partial \tau^{c\prime}} - \theta\frac{\partial E^{tot}}{\partial \tau^{c\prime}} + \alpha\left(r^c P'\frac{\partial Q^c}{\partial \tau^{c\prime}} + E^{c\prime} + \tau^{c\prime}\frac{\partial E^c}{\partial \tau^{c\prime}}\right) - \mu\frac{\partial E^{tot}}{\partial \tau^{c\prime}} = 0.$$

The welfare-maximizing vector of carbon fees therefore satisfies,

$$\tau^c = \left(\frac{\partial E^{c\prime}}{\partial \tau^c}\right)^{-1}\frac{1}{1+\alpha}\left[\left(\frac{\partial E^{tot}}{\partial \tau^c}\theta - r^c\frac{\partial Q^{c\prime}}{\partial \tau^c}P - r^u\frac{\partial Q^{u\prime}}{\partial \tau^c}P\right) - \alpha\left(r^c P'\frac{\partial Q^{c\prime}}{\partial \tau^c} + E^c\right) + \mu\frac{\partial E^{tot}}{\partial \tau^c}\right]. \quad (5)$$

For the optimal common revenue r^c, the first-order condition from (3) is,

$$\frac{\partial U}{\partial Q'}\left(\frac{\partial Q^c}{\partial r^c} + \frac{\partial Q^u}{\partial r^c}\right) - \frac{\partial C^c}{\partial Q^{c\prime}}\frac{\partial Q^c}{\partial r^c} - \frac{\partial C^u}{\partial Q^{u\prime}}\frac{\partial Q^u}{\partial r^c} - \theta\frac{\partial E^{tot}}{\partial r^c} + \alpha\left(P' Q^c + r^c P'\frac{\partial Q^c}{\partial r^c} + \tau^{c\prime}\frac{\partial E^c}{\partial r^c}\right) - \mu\frac{\partial E^{tot}}{\partial r^c} = 0,$$

which, upon using (1) and (2), combining, and canceling, yields,

$$r^{c\prime}P'\frac{\partial Q^c}{\partial r^c}+\tau^{c\prime}\frac{\partial E^c}{\partial r^c}+r^uP'\frac{\partial Q^u}{\partial r^c}-\theta\frac{\partial E^{tot}}{\partial r^c}+\alpha\left(P'Q^c+r^cP'\frac{\partial Q^c}{\partial r^c}+\tau^{c\prime}\frac{\partial E^c}{\partial r^c}\right)-\mu\frac{\partial E^{tot}}{\partial r^c}=0.$$

The optimal royalty rate therefore satisfies

$$r^c=\left(P'\frac{\partial Q^c}{\partial r^c}\right)^{-1}\frac{1}{1+\alpha}\left[\left(\frac{\partial E^{tot}}{\partial r^c}\theta-\tau^{c\prime}\frac{\partial E^c}{\partial r^c}-r^uP'\frac{\partial Q^u}{\partial r^c}\right)-\alpha\left(P'Q^c+\tau^{c\prime}\frac{\partial E^c}{\partial r^c}\right)+\mu\frac{\partial E^{tot}}{\partial r^c}\right]. \qquad (6)$$

2.2. Discussion

Inspection of (5) and (6) reveals that the contribution of the marginal climate damages and the contribution of the shadow value of the carbon budget both enter as penalties on a marginal increase in total emissions. This is a consequence of the carbon budget constraint entering linearly in the social welfare function. If the social cost of carbon approach is dropped, then the shadow price μ mathematically plays the same role as the SCC, and vice versa. As a result, nothing is gained by including both terms, and we henceforth set μ to 0 and interpret θ as the SCC.[13]

Decomposition of the optimal fee in the absence of a carbon budget. Both the optimal carbon fee in (5) and the optimal royalty surcharge in (6) are the result of three distinct factors. To see this, rewrite (5) as,

$$\tau^c=\frac{1}{1+\alpha}\left(\tau^{c,allocative}+\tau^{c,climate}\right)+\frac{\alpha}{1+\alpha}\tau^{c,revenue}\ , \qquad (7)$$

where

$$\begin{aligned}\tau^{c,allocative}&=-\left(\frac{\partial E^{c\prime}}{\partial\tau^c}\right)^{-1}\left(r^c\frac{\partial Q^{c\prime}}{\partial\tau^c}P+r^u\frac{\partial Q^{u\prime}}{\partial\tau^c}P\right),\\ \tau^{c,climate}&=\left(\frac{\partial E^{c\prime}}{\partial\tau^c}\right)^{-1}\frac{\partial E^{tot}}{\partial\tau^c}\theta\text{ , and}\\ \tau^{c,revenue}&=-\left(\frac{\partial E^{c\prime}}{\partial\tau^c}\right)^{-1}\left(r^c\frac{\partial Q^{c\prime}}{\partial\tau^c}P+E^c\right).\end{aligned}$$

[13] The carbon target and SCC equivalence would not arise if a different functional form were used for the carbon target penalty, for example a squared deviation penalty for departures from the target. Such an approach might be appropriate if, in a dynamic setting, the target was determined as a sequence of emissions to "spend" a carbon budget, so the squared terms would proxy for costs from overachieving emissions reductions. Absent such a calculation, however, we choose to model overachieving emissions reductions as beneficial, with those benefits increasing linearly in the emissions reductions.

Note that $\frac{\partial E^{c'}}{\partial \tau^c}$ is negative in the scalar case.

The component $\tau^{c,allocative}$ is the vector of fees that corrects for allocative inefficiencies arising from disparities in the royalty rates between covered and uncovered sources. For example, if covered royalties are positive but (exogenous) uncovered royalties are zero, then $\tau^{c,allocative}$ is negative to correct for the distortion induced by this asymmetry in royalties. In general, this term can be positive or negative.

The component $\tau^{c,climate}$ is the vector of fees that compensate for the externality from burning fossil fuels. In the scalar case, this reduces to Holland's (2012) formula cited above, that is, $\tau^{c,climate} = (1-\lambda)\theta$. If there is no co-production and no substitution in demand across fuels, then $\frac{\partial E^{c'}}{\partial \tau^c}$ is diagonal and Holland's formula applies to each fuel separately, however if the fuels have different leakage rates then the optimal fee will differ. In general, the optimal fee depends on cross-effects resulting from coproduction and substitution in demand.

The component $\tau^{c,revenue}$ is the vector of fees that maximizes revenues. This can be seen by considering the case where welfare is dominated by the marginal value of public funds term, that is, as $\alpha \to \infty$. If the covered royalty rate is zero and there is a single fuel, then the revenue maximizing fee satisfies the familiar requirement that the fee should be raised to the point that the elasticity of emissions with respect to the fee is –1. When there are multiple fuels then the regulator can assess different fees based on their elasticities as in Ramsey (1927) pricing. A preexisting royalty on covered production reduces the optimal fee.

Equation (7) shows that the optimal fee is the weighted average of these three components, with weights that reflect the marginal value of public funds. With $\alpha = 0$, only the allocative efficiency and climate terms enter; the more that the marginal value of public funds exceeds one (i.e., $\alpha > 0$) , the more weight is put on the revenue-enhancing feature of the carbon fee.

Decomposition of the optimal royalty in the absence of a carbon budget. The optimal common royalty in (6) can be decomposed into allocational, climate, and revenue terms, analogously to (7):

$$r^c = \frac{1}{1+\alpha}\left(r^{c,allocative} + r^{c,climate}\right) + \frac{\alpha}{1+\alpha} r^{c,revenue} \quad , \tag{8}$$

where

$$r^{c,allocative} = -\left(P' \frac{\partial Q^c}{\partial r^c}\right)^{-1} \left(\tau^{c'} \frac{\partial E^c}{\partial r^c} + r^u P' \frac{\partial Q^u}{\partial r^c}\right),$$

$$r^{c,climate} = \left(P' \frac{\partial Q^c}{\partial r^c}\right)^{-1} \frac{\partial E^{tot}}{\partial r^c} \theta, \text{ and}$$

$$r^{c,revenue} = -\left(P'\frac{\partial Q^c}{\partial r^c}\right)^{-1}\left(P'Q^c + \tau^{c\prime}\frac{\partial E^c}{\partial r^c}\right).$$

The interpretation of each of these terms is analogous to the terms in (7), noting that here the royalty rate and its components are scalars so the expressions involve either totals (as in emissions) or price-weighted averages. Note that, if $\tau^c = 0$, then $r^{c,allocative} = \lambda^{pw} r^u$, where $\lambda^{pw} = -\left(P'\frac{\partial Q^c}{\partial r^c}\right)^{-1}\left(P'\frac{\partial Q^u}{\partial r^c}\right)$ is the price-weighted average leakage rate of production across fuels for an increase in the common royalty rate.

The climate contribution to the royalty, $r^{c,climate}/(1+\alpha)$, is the climate royalty surcharge.

Relation between royalty rate and carbon fee. In this static model, a carbon fee on fuel *i* can be converted to a royalty rate by multiplying by e_i/P_i, so that the carbon fee receipt in native units is expressed as a fraction of the price. Thus the optimal carbon fee (absent a royalty) and the optimal royalty (absent a carbon fee) yield the same equilibrium outcomes and indeed are the same up to these conversion factors, as can be derived using (7) and (8). With multiple fuels, however, a common royalty rate implies different fees on the fuels and vice versa. In a dynamic setting – and in reality – prices change, so the equivalence between the fee and the royalty breaks down, even for a single fuel, because that equivalence would require the royalty to be expressed as a schedule depending on the price if it were to replicate a fee. This is not, however, an extant institutional structure. An interesting extension, which is beyond the scope of this paper, is to investigate the question of the optimal royalty in a dynamic setting with price uncertainty.

3. Quantitative Results

We now use the expressions for optimal royalty rates and fees in Section 2.2 to evaluate the two policy counterfactuals laid out in the introduction. First, in the IRA, Congress increased onshore royalties from 12.5% to 16.67%. Congress could have chosen a different rate, so how does the choice of 16.67% compare to an estimate of the optimal onshore common royalty rate? How do emissions reductions and revenues under the 16.67% rate compare to those under the optimal royalty rate?

Second, we find that the common royalty rate of 16.67% is substantially less than the optimal rate for any value of α, leaving revenues, emissions reductions, and welfare benefits on the table. Because the IRA did not consider carbon fees, what would be optimal carbon fees assessed on federal fossil fuel production, either a common fee or differentiated by fuel, given the royalty rates in the IRA, and what would be their effect on revenues and emissions?

We address these questions quantitatively using the model in Prest (2022a), which we briefly describe, along with parameter assumptions, before turning to the results.

3.1 Quantitative model and assumptions

We use Prest's (2022a) model of oil and gas production on federal lands. That model combines a detailed, econometrically calibrated simulation model of US supply with a rest of world (ROW) module with responsive supply based on the IEA 2019 World Energy Outlook. The model of US supply has three stages of production (drilling, well completion, and production) for wells differentiated by federal/nonfederal, oil-directed/gas-directed, and onshore/offshore, for a total of eight well types. The model accounts for cross-price effects on US supply (co-production) and dynamics (lags in the various stages of production). By modeling federal and nonfederal production as well as demand, the model estimates leakage from federal policies. For details, see Prest (2022a).[14]

Parameter values. The optimal rates depend on quantity and emissions partial derivatives and on the parameters θ, r^u, and α. The partial derivatives are either taken directly from Prest (2022a) or are estimated numerically using the Prest (2022a) model. For the SCC θ, we use the Biden Administration interim estimates of $50/ton in 2020 dollars, rising at 2% per year.[15] We set the uncovered royalty rate to r^u = 18.75%, which is in the center of the range charged for oil and gas leases on state and private land, as well as the value charged on federal offshore leases.[16] Because the IRA only meaningfully addressed onshore royalty rates, we treat federal offshore leases as in the uncovered sector.

Concerning the marginal value of public funds, equations (7) and (8) show that the optimal common royalty and fees are linear combinations of the cases $\alpha = 0$ and $\alpha \rightarrow \infty$. We therefore report these two extremes, which with some expositional liberty we refer to as the welfare-

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[14] We briefly summarize the structure of the model here. The response of drilling activity to changes in prices (net of royalties) is estimated using econometric distributed lag models of drilling activity, allowing us to simulate how a change in prices and/or royalties would affect drilling activity over time. Drilled wells are assumed to begin production over time with a lag corresponding to historically estimated distributions of drilling-to-production time, and thereafter operating wells produce oil and gas according to production profiles estimated using historical averages. Each such component is estimated separately by type of well to account for heterogeneity by well type. Oil and gas production are simulated forward 30 years using a "business as usual" price trajectory to form a baseline. Then, for each carbon fee or royalty modeled, we find new market-clearing oil and gas prices, equilibrium production from each source, and equilibrium demand using a constant-elasticity demand curve for each fuel. Leakage arises because reduced covered production makes uncovered production more profitable.

[15] https://www.whitehouse.gov/wp-content/uploads/2021/02/TechnicalSupportDocument_SocialCostofCarbonMethaneNitrousOxide.pdf

[16] See Covert and Kellogg (2021) and https://revenuedata.doi.gov/how-revenue-works/revenues/.

maximizing and revenue-maximizing case, where "welfare" is used in the sense of Nordhaus (1982) excluding the marginal value of public funds. The optimal rates or fees for $0 < \alpha < \infty$ can be computed from these two end points using the weights in (7) and (8).[17]

Finally, as previously discussed, the optimal fees and royalties depend strongly on the leakage rate, which in turn depends on the elasticity of demand for oil and gas: the more elastic is demand, the more a negative supply shock is absorbed by lower overall demand than by increased supply elsewhere. Historically, the demand for oil has been inelastic because there are few alternatives to gasoline, diesel, or jet fuel. Looking ahead, as alternatives like electric vehicles become more common, both short- and long-run oil demand elasticities could increase. Similarly, technological change could result in more substitutes for gas in energy consumption, for example a substitution margin between storage and gas generation in the power sector and between gas and heat pumps for residential heating. For these reasons, we use low demand elasticities as our base case, but also consider a scenario with more elastic demand as in Prest (2022a). For the base case, we use demand elasticities of -0.2 for both oil and gas, based on several empirical estimates and surveys of the literature (Erickson and Lazarus 2018, Hamilton 2009, Bordoff and Houser 2015, Arora 2014, and Auffhammer and Rubin 2018). For the high elasticity case, we use estimates from the higher end of the literature: -0.51 for oil (Balke and Brown 2018, Metcalf 2018, Allaire and Brown 2012) and -0.42 for gas (Hausman and Kellogg 2015, Metcalf 2018).

The prices of natural gas and oil influence emissions and revenues, and the conversion of royalty rates to carbon fees and vice versa can be sensitive to oil and gas prices. We use the same oil and gas price trajectories as Prest (2022a), which are based on futures curves and are shown in appendix figure A.7 of that paper.[18]

An important parameter is the average price-weighted leakage rate, λ^{pw}. For the base case elasticities, we estimate this to be 74% for an increase in the common royalty rate and 73% for an increase in a common carbon fee. For the high elasticity case, this estimate is 53% for an increase in the common royalty rate and 56% for an increase in the common fee. These estimates are consequences of supply and demand elasticities and are largely insensitive to the covered royalty and/or carbon fee.

[17] We do not present a case for an intermediate value of the marginal value of public funds because of the wide range of estimates for it (see Hendren and Sprung-Keyser 2020). However, in our setting we find that the welfare-maximizing and revenue-maximizing royalties and fees are often similar in magnitude, suggesting their weighted-average will be relatively insensitive to the value of α.

[18] That paper also ran a "high price" sensitivity analysis, finding that the emissions impacts of all policies increased by approximately 50% due to more covered production in the baseline that would be affected by the policy. The leakage rates were largely unaffected, as leakage is primarily driven by relative supply and demand elasticities, suggesting alternative price scenarios would have little impact on welfare-maximizing royalties or fees.

3.2 Results #1: IRA and counterfactuals

We consider five IRA scenarios: a pre-IRA status quo, which serves as the baseline; the common royalty in the IRA ("IRA"); a counterfactual in which there is a ban on new federal fossil fuel program ("leasing ban"); a common royalty, first revenue-maximizing ($\alpha \to \infty$) then welfare-maximizing ($a = 0$).

Base case results. The results for the base case elasticities are summarized in part (a) of Table 2. Under the pre-IRA baseline, we project annual average royalty revenues of \$9.2 billion (2020 dollars). The IRA onshore royalty increase from 12.5% to 16.67% is estimated to raise an additional \$0.6B annually, and to reduce emissions by 3 million metric tons (mmt) per year, or 6% of the emissions reductions resulting from an onshore leasing ban. Note that average revenues over the 2020-2050 period under a leasing ban fall only to \$7.0B because the ban only applies to new leases so existing leases continue to produce (at grandfathered royalty rates) and because revenues are generated by offshore leasing, which is not subject to the hypothetical ban.

The welfare-maximizing common royalty rate is estimated to be 35%. Of this, the term $r^{c,allocative}$ contributes approximately 14 percentage points (using the formula $r^{c,allocative} = \lambda^{pw} r^{u}$ following (8), $\lambda^{pw} = 0.74$ so $r^{c,allocative} = 0.74 \times 18.75 \approx 14\%$), and the climate royalty surcharge contributes 21 percentage points.

The revenue-maximizing common royalty rate is estimated to be 45%. *A-priori*, this rate could be larger or smaller than the welfare-maximizing rate, depending on the supply and demand elasticities and the social cost of carbon. Here, it exceeds the welfare-maximizing rate because, with low demand elasticities, the high leakage rate of 74% leads to a lower royalty for climate purposes.

Both the revenue- and welfare-maximizing royalty rates are far higher than the 16.67% rate in the IRA. Compared to the IRA, the revenue-maximizing rate increases annual revenues by \$1.8B/year and decreases annual emissions by 17 mmt, and the welfare-maximizing rate would increase revenues by \$1.6B and decrease emissions by 12 mmt. Note that the emissions reductions are larger under revenue-maximization than under welfare-maximization simply because the revenue-maximizing royalty rate is higher given our \$50 SCC; however, this could change if covered supply were more elastic (implying a lower revenue-maximizing rate) or if the SCC were higher (implying a higher welfare-maximizing rate).

The effective carbon fee implied by these common royalty rates differs substantially across the two fuels, with the per-ton fee on oil being approximately three times the per-ton fee on gas. This is a mechanical consequence of oil being significantly more valuable, on an energy value basis than gas, combined with oil having a greater carbon intensity than gas. The effective carbon fee for oil implied by the welfare-maximizing common royalty is in the vicinity of the SCC. This might seem surprising initially because the optimal royalty incorporates leakage, however the common royalty also incorporates the allocative efficiency term which drives up the total royalty and thus the effective carbon fee, which places the total royalty closer to the SCC on a per-ton basis.

Figure 1 shows annual average revenues and emissions reductions under a continuum of common royalty rates (the solid line denotes the base elasticity case). Revenues are shown as gross annual values, and emissions reductions are expressed as a fraction of the reductions that would be achieved under an onshore leasing ban. Revenues follow an inverted U-shaped curve, with the initial increase in revenues eventually offset by production declines as the royalty rate increases. The relationship between the royalty and emissions reductions is approximately linear.

Results for high-elasticity case. The results for the high-elasticity sensitivity analysis are summarized in part (a) of Table 3 and are shown in the dashed lines in Figure 1. The lower leakage rate in the high-elasticity case (53%, compared to 74%) leads to a higher welfare-maximizing common royalty rate (the climate royalty surcharge contribution increases from 21 to 37 pp, while the allocative efficiency contribution falls from 14 to 10 pp), which is now approximately the same as the revenue-maximizing common royalty rate. Although royalty revenues are insensitive to the demand elasticities, the total emissions reductions under the high-elasticity case are uniformly much greater than for the base elasticity case, with the leasing ban emissions reduction increasing from 48 to 82 mmt/year.

IRA-implied SCC. Given that the optimal common onshore royalty rates far exceed the 16.67% value in the IRA using the \$50 SCC, one question is what value of the SCC would rationalize the IRA increase. For this calculation we put aside revenue-raising considerations by setting $\alpha = 0$. For the base case elasticities, the allocative efficiency term contributes about 14 pp, so the climate term would contribute slightly less than 3 pp (totaling 16.67%). For that climate royalty surcharge to be appropriate, the SCC would need to be \$7 per ton of CO_2, which coincidentally is the same value used by the Trump administration, which excludes international climate damages.

3.3 Post-IRA carbon fees

We now turn to the second question, what would be the effect of carbon fees on top of the onshore royalty rate of 16.67% in the IRA, and what are the optimal such fees.

The results are summarized in part (b) of Table 2 for base elasticities and in Table 3 for the high elasticity case, first for a common carbon fee, then for separate carbon fees. In both cases, for purposes of comparison to the results for a common royalty rate, we convert the fee to an implied royalty increment then add it to the 16.67% rate in the IRA, yielding the implied royalty rates in the second column of results in Table 2. Note that, because of differences in value per unit of energy and emissions intensity, the gas royalty surcharge exceeds that for oil under a given common fee.

Base case results. The optimal common carbon fee under the base case elasticities is $18/ton CO_2, both for revenue and welfare maximization. The total implied royalties of 30% for oil and 63% for gas bracket the welfare- and revenue-maximizing common royalty rates.

Five features of the results are noteworthy. First, despite the increase in royalties under the IRA, the optimal common and fuel-specific fees substantially increase revenues and reduce emissions, relative to the IRA.

Second, revenues and emissions reductions under the optimal common fee are quite close to those under the revenue-maximizing common royalty, because the reduced revenues (and emissions) from gas under the common fee, relative to the common royalty, are offset by increased revenues (and emissions) from oil.

Third, the optimal fees that differ by fuel are not particularly different from the common optimal fee.

Fourth, in the high-elasticity case the revenue-maximizing fees are similar to those in the base case, however the welfare-maximizing fees are greater because of the reduced leakage. At those high fees, the implied royalty on gas is very large and revenues fall by more than $1B/year, relative to the revenue-maximizing value, although they remain above projected revenues under the IRA alone.

Fifth, returning to the base case estimates and looking across all the results in Table 2, from the perspective of emissions and revenues, the results are relatively insensitive to the price instrument used, whether a common royalty, a common fee, or fuel-differentiated fees. In all cases, revenues increase by $1.6-1.9B and emissions decrease by 12-18 mmt, both relative to the IRA case.

Figure 2 shows revenues and fractional emissions reductions as a function of a common carbon fee on top of the 16.67% onshore royalty. Unlike Figure 1, both the revenue and emissions curves exhibit a kink around a common fee of $35/ton. This arises because, for a given common fee, the percentage impact on gas is substantially greater than on oil: a $18 carbon fee is 46% of the benchmark price of gas shown in Table 1, but only 14% of the price of oil. Accordingly, by

$35/ton little new gas is being produced on federal lands except as residual co-production, and the tail of the curves above $35/ton reflect the response of new oil production.

Finally, Table 4 and Table 5 show the effects of distinct oil and gas carbon fees on the change in revenues relative to pre-IRA baseline (top panels) and on emissions (bottom panels). Table 4 provides values for the base case elasticities, and Table 5 shows them for the high elasticity scenario. Because of coproduction and the different types of wells, the interaction between the two carbon fees is complex. For a given value of the oil fee, as the gas fee increases, total royalties initially increase, then decline as gas-directed drilling diminishes. The revenue-maximizing and welfare-maximizing cells (or the closest approximation thereof on this relatively coarse grid) are bolded and bordered in green and blue respectively. In the base case in Table 4, these two are similar, around $20 per ton, whereas they are quite different under the high elasticity case in Table 5. The bottom panels show emissions reductions, demonstrating that in the high elasticity case in Table 5, the welfare-maximizing pair of fees forgoes substantial revenue gains in favor of larger emissions reductions.

3.4 Revenue paths for all policies

The revenue figures so far are annual averages over the 2020-2050 period. Figure 3 shows projected revenue paths over this period for different policies. Because all policies only affect new leases, for the first few years the policy change has negligible effect on revenues, which are generated by existing wells with grandfathered leasing provisions. The revenue path under the IRA increases modestly over the pre-IRA revenue path. In contrast, all the optimal paths under various policy counterfactuals substantially increase the level of the revenue path, with meaningful revenue increases, relative to the IRA, occurring in the late 2020s and increasing thereafter. There is little difference among the revenue paths under the common royalty rate, common fee, or differentiated fee counterfactuals.

4. Discussion

These results come with caveats. First, a change in the royalty rate or fee could interact with the federal competitive auction process, plausibly leading to lower bonus bids at auction. In practice, however, these interactions are likely to have a limited effect on projected total revenues. From 2013 to 2019, oil and gas royalty revenues averaged 7.5 times bonus bids; in FY 2019, oil and gas royalty receipts were $7.745 billion, whereas bonus bids were only $496 million. Thus, the scope for a decline in bonus bids offsetting an increase in royalties is limited.

Second, we hold nonfederal royalties constant, however states and private landowners might raise their royalty rates in response to an increase in federal royalties, thereby leading to more state revenues and lower production on nonfederal lands. While there is no clear data with which to estimate this effect, such a response would, in effect, reduce the leakage from an autonomous increase in federal royalties or fees, leading to greater emissions reductions but slightly lower federal revenues.

Third, the reduced gas supply could lead to further coal-gas switching in the US power sector, partly offsetting the emissions reductions we estimate. Prest (2022a) addressed this channel in a sensitivity analysis, finding it to have only modest effects on the estimated emissions reductions because most of the emissions impacts of a royalty increase are estimated to come disproportionately from oil, not gas. In addition, the prospects for gas-to-coal substitution are less than they once were due to the widespread closure of US coal-fired power plants.

Looking across the multiple cases – the alternative instruments of royalties or fees, the low and high demand elasticities, revenue maximization and welfare maximization absent the revenue motive, and whether there is a common carbon fee or a different carbon fee for oil and gas – suggests three main conclusions.

First, all cases imply a substantially higher royalty rate for onshore oil and gas production than the 16.67% rate set in the IRA. According to our estimates, the rate established by the IRA leaves substantial welfare gains, emissions reductions, and royalty revenues on the table. While in principle raising royalties could reduce taxpayer receipts because of decreased production, we estimate that not to be the case. Thus, all the royalty increases considered have both a traditional taxpayer return justification and a climate externality justification.

Second, for royalties based on revenue or welfare maximization, both the revenue gains and emissions reductions are substantial compared to the either a pre-IRA or post-IRA baseline. For example, for a common royalty in our base elasticity case, the revenue-maximizing royalty of 45% reduces emissions by 43% of what would be achieved by an end to onshore leasing, while increasing annual average revenues by $1.8B, compared to post-IRA BAU.

Third, although the revenue-maximizing royalties and projected revenues do not depend significantly on the elasticity of demand, projected emissions reductions do. For the revenue-maximizing common royalty of 45%, we estimate emissions reductions ranging from 20 to 35 $MMTCO_2e$/year. As a point of comparison, these round to nearly one percent of US CO_2 emissions in 2019.

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Table 1. Bulk fuel prices and carbon fees in fuel price units

	Oil ($/barrel)	Natural gas ($/thousand cubic feet)	Coal ($/short ton)
2019 wholesale price	$57	$2.56	$12.5
12.5% royalty rate	$7.13	$0.32	$1.56
18.75% royalty rate	$10.69	$0.48	$2.34
$25 carbon fee	$10.75	$1.65	$42.41
$50 carbon fee	$21.50	$3.30	$84.42
$75 carbon fee	$32.25	$4.95	$127.23

Notes: Oil price is West Texas Intermediate spot price; natural gas is Henry Hub spot price; and coal is 8800 Btu/lb Powder River Basin subbituminous spot price. Prices are 2019 averages from the Energy Information Administration. Royalty rates are 12.5% for surface-mined coal and for onshore oil and gas (until IRA) and are 18.75% for deepwater offshore oil and gas. These rates are converted to native price units using the 2019 price in the first line and the carbon intensities for the relevant fossil fuel.

Table 2. Estimated effects of IRA and optimal royalty surcharges and carbon fees: Base elasticities case

	Effective Carbon Fee ($/ton CO_2)		Effective Royalty Rate (%)		CO_2e Reduced (relative to 12.5% Pre-IRA Baseline)		Revenues ($B/year)
	Oil	Gas	Oil	Gas	million tons/year	% of ban	
(a) IRA and IRA common royalty counterfactuals							
Pre-IRA Baseline	na		12.5% onshore 18.75% offshore		0	0%	$9.2
IRA - 16.67% Onshore Royalty Rate	na		16.67% onshore 18.75% offshore		3	6%	$9.8
Leasing Ban (Onshore Only)	na		na		48	100%	$7.0
Optimal common royalty:							
Revenue-maximizing	$60	$17	45%		20	43%	$11.6
Welfare-maximizing	$46	$14	35%		14	30%	$11.4
(b) Optimal carbon fees given the IRA							
(i) Common carbon fee							
Revenue-maximizing	$18		30%	63%	20	41%	$11.6
Welfare-maximizing	$18		30%	63%	20	41%	$11.6
(ii) Fuel-specific carbon fees							
Revenue-maximizing	$25	$15	36%	55%	21	44%	$11.7
Welfare-maximizing	$18.5	$17.5	31%	62%	20	41%	$11.6

Notes: Entries are computed using the oil and gas model in Prest (2022a). Revenues in the final column combine receipts from royalties and fees. The revenue-maximizing common royalty is given by $r^{c,revenue}$ in (8), the welfare-maximizing common royalty is given by $r^{c,allocative} + r^{c,climate}$ in (8), the revenue-maximizing carbon fee is given by $\tau^{c,climate}$ in (7), the welfare-maximizing common fee is given by $\tau^{c,allocative} + \tau^{c,climate}$ in (7). The effective royalty rates in panel (b) are the sum of the fee's royalty equivalent and the IRA's established 16.67% royalty rate. Emissions reductions and royalties are annual averages over 2020-2050.

Table 3. Estimated effects of IRA and optimal royalty surcharges and carbon fees: High elasticities case

	Effective Carbon Fee ($/ton CO_2)		Effective Royalty Rate (%)		CO_2e Reduced (relative to 12.5% Pre-IRA Baseline)		Revenues ($B/year)
	Oil	Gas	Oil	Gas	million tons/year	% of ban	
(a) IRA and IRA common royalty counterfactuals							
Pre-IRA Baseline	na		12.5% onshore 18.75% offshore		0	0%	$9.2
IRA - 16.67% Onshore Royalty Rate	na		16.67% onshore 18.75% offshore		5	6%	$9.8
Leasing Ban (Onshore Only)	na		na		82	100%	$7.0
Optimal common royalty:							
Revenue-maximizing	$60	$17	45%		35	43%	$11.6
Welfare-maximizing	$62	$18	47%		37	45%	$11.6
(b) Optimal carbon fees given the IRA							
(i) Common carbon fee							
Revenue-maximizing	$18		30%	63%	34	41%	$11.6
Welfare-maximizing	$32		41%	99%	63	77%	$9.7
(ii) Fuel-specific carbon fees							
Revenue-maximizing	$25	$15	36%	55%	36	44%	$11.7
Welfare-maximizing	$30.5	$29.0	40%	91%	57	70%	$10.4

Notes: See the notes to Table 2.

Table 4. Effect of distinct oil and gas carbon fees on total revenues (in \$b/year top panel) and emissions (in MMTCO2e/year, bottom panel), relative to Pre-IRA BAU, 2020-2050 annual average, under base case elasticities

a) Change in Revenues (\$b/year)

Oil carbon fee (\$/ton)	Gas carbon fee (\$/ton): \$0	\$5	\$10	\$15	\$18	\$20	\$25	\$30	\$35	\$40
\$0	\$0.6	\$1.1	\$1.4	\$1.6	\$1.7	\$1.7	\$1.5	\$0.8	\$0.1	\$0.1
\$5	\$1.0	\$1.5	\$1.8	\$2.0	\$2.0	\$2.0	\$1.7	\$0.9	\$0.2	\$0.3
\$10	\$1.4	\$1.8	\$2.1	\$2.2	**\$2.2**	\$2.2	\$1.9	\$1.1	\$0.3	\$0.3
\$15	\$1.7	\$2.0	\$2.3	\$2.4	\$2.4	\$2.3	\$2.0	\$1.1	\$0.3	\$0.4
\$18	\$1.8	\$2.1	\$2.4	\$2.5	**\$2.4**	\$2.4	\$2.0	\$1.2	\$0.3	\$0.4
\$20	\$1.9	\$2.2	\$2.4	\$2.5	\$2.5	\$2.4	\$2.1	\$1.2	\$0.3	\$0.3
\$25	\$2.0	\$2.3	\$2.5	**\$2.5**	\$2.5	\$2.4	\$2.1	\$1.1	\$0.3	\$0.3
\$30	\$2.0	\$2.3	\$2.5	\$2.5	\$2.4	\$2.4	\$2.0	\$1.1	\$0.2	\$0.2
\$35	\$2.0	\$2.3	\$2.4	\$2.4	\$2.3	\$2.3	\$1.9	\$1.0	\$0.1	\$0.1
\$40	\$2.0	\$2.2	\$2.3	\$2.3	\$2.2	\$2.1	\$1.7	\$0.8	\$0.0	\$0.0
\$45	\$1.8	\$2.0	\$2.1	\$2.0	\$2.0	\$1.9	\$1.5	\$0.6	-\$0.2	-\$0.2
\$50	\$1.6	\$1.7	\$1.8	\$1.8	\$1.7	\$1.6	\$1.2	\$0.4	-\$0.4	-\$0.4

b) Change in Emissions (MMTCO2e/year)

Oil carbon fee (\$/ton)	Gas carbon fee (\$/ton): \$0	\$5	\$10	\$15	\$18	\$20	\$25	\$30	\$35	\$40
\$0	-3	-5	-8	-10	-12	-14	-18	-26	-31	-32
\$5	-5	-7	-10	-13	-14	-16	-20	-27	-33	-33
\$10	-7	-10	-12	-15	-16	-18	-22	-29	-34	-34
\$15	-10	-12	-14	-17	-18	-20	-24	-30	-35	-35
\$18	-11	-13	-15	-18	**-20**	-21	-25	-31	-35	-36
\$20	-12	-14	-16	-19	-20	-22	-26	-31	-36	-36
\$25	-14	-16	-18	**-21**	-22	-24	-27	-33	-37	-37
\$30	-17	-19	-21	-23	-24	-25	-29	-34	-38	-38
\$35	-19	-21	-23	-25	-26	-27	-31	-36	-39	-39
\$40	-21	-23	-25	-27	-28	-29	-32	-37	-40	-40
\$45	-24	-25	-27	-29	-30	-31	-34	-38	-41	-41
\$50	-26	-27	-29	-31	-32	-33	-35	-39	-42	-42

Note: Bolded and outlined cells are the closest approximation in the table to the revenue-maximizing (green outline) and welfare-maximizing (blue outline) carbon fees.

Table 5. Effect of distinct oil and gas carbon fees on total revenues (in $b/year top panel) and emissions (in MMTCO2e/year, bottom panel), relative to Pre-IRA BAU, 2020-2050 annual average, under high elasticities

a) Change in Revenues ($b/year)

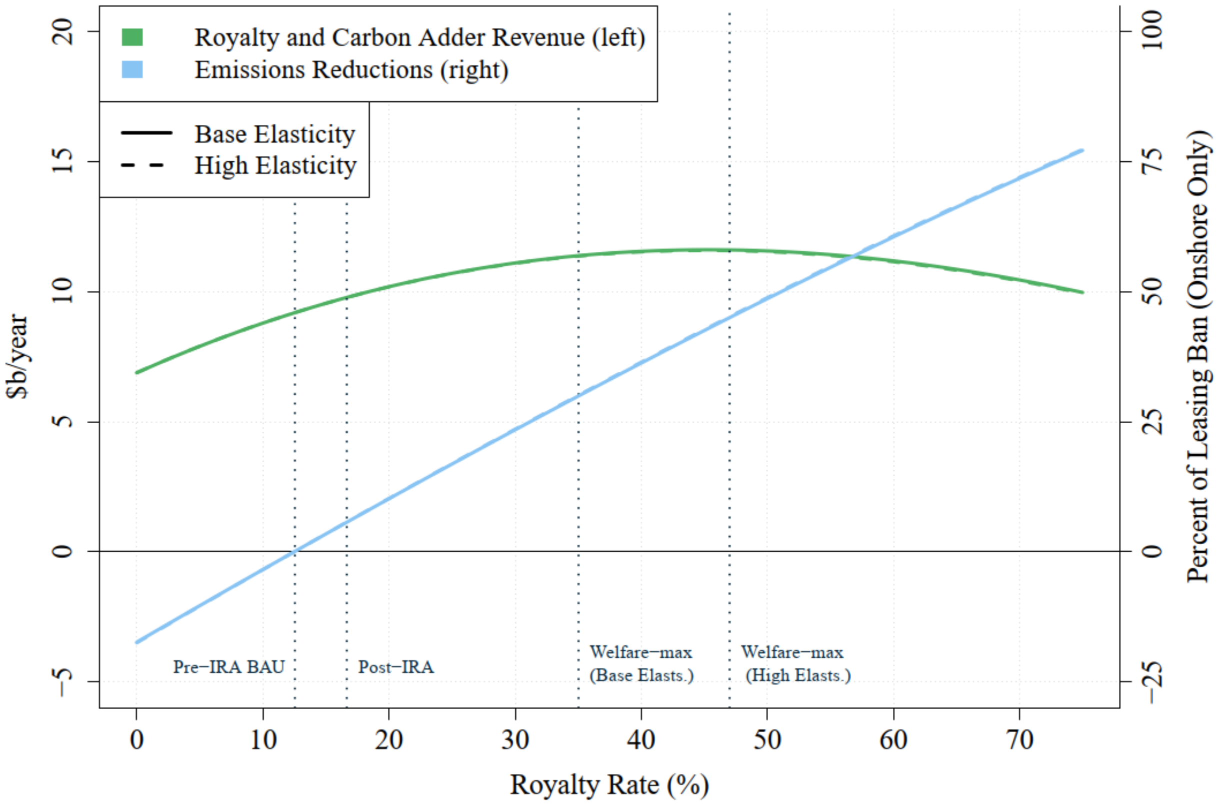
Oil carbon fee ($/ton)	Gas carbon fee ($/ton)									
	$0	$5	$10	$15	$18	$20	$25	$30	$35	$40
$0	$0.6	$1.1	$1.4	$1.6	$1.7	$1.7	$1.5	$0.7	$0.0	$0.1
$5	$1.0	$1.4	$1.8	$1.9	$2.0	$2.0	$1.7	$0.9	$0.1	$0.2
$10	$1.4	$1.8	$2.0	$2.2	$2.2	$2.2	$1.9	$1.0	$0.2	$0.3
$15	$1.7	$2.0	$2.2	$2.4	$2.4	$2.3	$2.0	$1.1	$0.3	$0.3
$18	$1.8	$2.1	$2.3	$2.4	$2.4	$2.4	$2.0	$1.1	$0.3	$0.3
$20	$1.8	$2.2	$2.4	$2.5	$2.4	$2.4	$2.0	$1.1	$0.3	$0.3
$25	$2.0	$2.3	$2.4	**$2.5**	$2.5	$2.4	$2.0	$1.1	$0.2	$0.3
$30	$2.0	$2.3	$2.4	$2.5	$2.4	$2.3	$1.9	**$1.0**	$0.2	$0.2
$35	$2.0	$2.2	$2.4	$2.4	$2.3	$2.2	$1.8	$0.9	$0.1	$0.1
$40	$1.9	$2.1	$2.2	$2.2	$2.1	$2.1	$1.7	$0.7	-$0.1	$0.0
$45	$1.8	$1.9	$2.0	$2.0	$1.9	$1.8	$1.4	$0.6	-$0.2	-$0.2
$50	$1.6	$1.7	$1.8	$1.7	$1.7	$1.6	$1.2	$0.3	-$0.4	-$0.4

b) Change in Emissions (MMTCO2e/year)

Oil carbon fee ($/ton)	Gas carbon fee ($/ton)									
	$0	$5	$10	$15	$18	$20	$25	$30	$35	$40
$0	-5	-9	-13	-18	-21	-23	-31	-44	-53	-54
$5	-9	-13	-17	-21	-25	-27	-34	-46	-55	-56
$10	-13	-17	-20	-25	-28	-30	-38	-49	-57	-58
$15	-17	-20	-24	-29	-32	-34	-41	-51	-59	-60
$18	-19	-23	-27	-31	-34	-36	-42	-53	-60	-61
$20	-21	-24	-28	-32	-35	-37	-44	-54	-61	-62
$25	-25	-28	-32	**-36**	-38	-40	-47	-56	-63	-63
$30	-29	-32	-35	-39	-42	-44	-49	**-58**	-65	-65
$35	-33	-36	-39	-43	-45	-47	-52	-61	-67	-67
$40	-37	-40	-43	-46	-48	-50	-55	-63	-68	-69
$45	-41	-43	-46	-49	-52	-53	-58	-65	-70	-70
$50	-45	-47	-50	-53	-55	-56	-61	-67	-72	-72

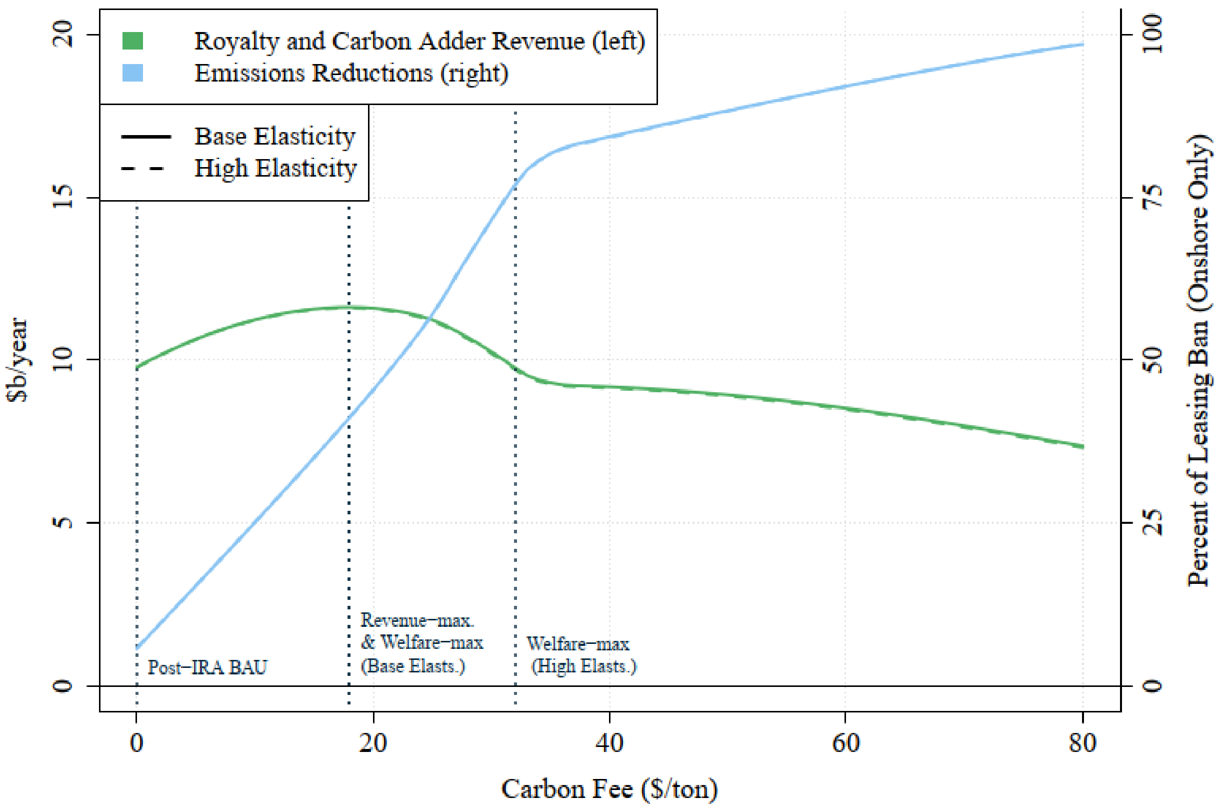
Note: Bolded and outlined cells are the closest approximation in the table to the revenue-maximizing (green outline) and welfare-maximizing (blue outline) carbon fees.

Figure 1. 2020-2050 average royalty and carbon revenues (left axis) and emissions reduction relative to those achieved by an onshore leasing ban (right axis) as a function of a common royalty rate



Notes: All y-axes are measured as changes relative to the pre-IRA 12.5% onshore royalty rate. Annual average emissions reductions under an onshore leasing ban are estimated to be 48 $MMTCO_2e$/year in the low-elasticity base case and 82 $MMTCO_2e$/year in the high-elasticity case.

Figure 2. 2020-2050 average royalty and carbon revenues (left axis) and emissions reduction relative to those achieved by an onshore leasing ban (right axis) as a function of a common carbon fee



Notes: Carbon fees are in addition to the IRA's 16.67% royalty rate. All y-axes are measured as changes relative to the pre-IRA 12.5% onshore royalty rate. See the notes to Figure 1.

Figure 3. Time path of total royalty revenues for alternative carbon fees or royalties (billions of 2020 dollars)