Nonrenewable resources, reserves, and carbon pricing[*]

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Abstract

As society confronts the need to address climate change, calls for actions which would lead fossil fuel producers to "leave it in the ground" – to not develop and produce from new fossil fuel reserves – have increased. It's common in resource economics to treat reserve creation and production as sequential economic decisions, but few papers assessing climate change policies treat reserves as endogenous. Our paper shows that this omits an important channel through which cumulative emissions will be affected by greenhouse gas policies. We analyze the effect of emissions pricing and related policies on nonrenewable resource development and, by allowing reserves to be endogenous, we examine firm decisions on both the intensive and extensive margins. We show that, all else equal, emissions pricing reduces emissions, extraction rates, and reserves, but other policy parameters can distort these effects in important ways. Additions to emissions pricing policies such as output-based allocations of credits or fiscal policies such as resource severance taxes may create distortions which are propagated through changes in reserve development decisions. Further, we show that the nature of abatement technology may alter average carbon costs and thus change reserves and eventual emissions under otherwise identical policies. The upshot of these results is that emissions pricing policies which impose identical marginal costs of emissions may result in very different cumulative emissions and thus different levels of climate change damage.

Keywords: nonrenewable resources, carbon pricing
JEL classification: Q3, Q5

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1 Introduction

As society has increasingly realized the impending need to address climate change, a chorus of voices have argued for aggressive action directed at fossil energy. Perhaps the most dramatic example of this rising chorus is the emerging “leave it in the ground” movement. This movement has argued stridently for rapid action that will leave significant amounts of fossil fuels un-utilized, *i.e.*, left in the ground. This directive might be taken two ways: as a call to abandon fossil fuels in the very near future, essentially abandoning existing proved reserves, or it might be taken as a call to shift investments away from developing new reserves.[1] An important implication of this second argument is that climate policy might well be viewed as influencing the trajectory of proven reserves, in particular by reducing reserve additions relative to “business as usual.” Under this view, an important effect of climate policy will be to delete created reserves from the trajectory one would observe in the absence of that policy, which implies resources left in the ground.

A clear implication of the above arguments is that reserves are endogenous to carbon policy. In much of the extant climate policy literature, however, the reserve base is taken as (exogenously) given. Our paper investigates the effect of carbon pricing on nonrenewable resource development. In particular, we characterize how carbon pricing interacts with other policies and emissions abatement technology to affect resource production and emissions. We find these interactions can undo part or even all of the effect of the pollution price. For example, a cap-and-trade policy that allocates emissions credits to existing firms, perhaps in an attempt to encourage a sector of the economy to buy in to the emerging policy, can have the unintended consequence of discouraging those firms to exit, thereby lengthening the time horizon over which these firms take actions that contribute to emissions.

That free allocations of emissions credits reduces total compliance costs and deters exit is intuitive; this is why several governments combine the allocation of credits with emissions pricing to ensure their jurisdictions remain attractive to industry. Consider, for example, allocations under the EU-ETS (Demailly and Quirion, 2006), under the California’s Cap and Trade Regulation, Alberta’s (2015) Climate Leadership Plan and Canada’s (2018) federal carbon pricing backstop.[2] But this interaction effect also extends to policies unrelated to

[1] On occasion, this latter view is paired with the suggestion that freed-up investment monies be deployed into developing alternative energy.

[2] EU allocation rules are country-specific, but the EU provides a summary document at `https://ec.europa.eu/clima/policies/ets/allowances/industrial_en`. For California allocations, see Sections 95852.2(e), 95870(e), 95890, 95891, and 95894 of the Cap-and-Trade Regulation, Title 17, California Code of Regulations (CCR), sections 95801-96022. Government of Alberta (2017) describes allocation rules

pollution. In particular, we examine the relationship between emissions pricing and royalties that producers pay to the owner of the resource. We consider two broad categories of resource rent extraction: severance taxes, paid on production, and net revenue royalties.[3] Depending on the royalty design, firms may deduct costs from paying for their emissions in their royalty obligations. Deducting emissions taxes implies different after-tax average carbon costs. As with emissions credits, royalties can decrease the average costs from carbon pricing, resulting in greater reserve creation and lifetime emissions.

Taking note of the implied externalities associated with new reserves, Gillingham and Stock (2016) propose "placing a royalty adder on federal coal that is linked to the climate damages from its combustion." Likewise, Erickson and Lazarus (2018) call for implicit policies that will strand reserves of fossil fuels for climate change mitigation reasons. We show that a direct price on the carbon embedded in reserves has a significant impact on reserve creation and thus on lifetime emissions. However, the tax on reserves does not lead to the full exploitation of emissions abatement technology that occurs with a carbon price on extraction.

We adapt a dynamic model of nonrenewable resource extraction with endogenous reserves (Gaudet and Lasserre, 2015) by incorporating greenhouse gas emissions from producing the resource. Firms pay royalties on how much they produce or earn, a common feature of resource development, and a tax on how much they emit. The model allows us to examine firm decisions on the intensive margin – how much to produce and how much to emit – and the extensive margin of reserve creation.

We argue that different policy designs with a common pollution price are not equivalent. This occurs because while emissions pricing affects the firm's marginal cost of emissions, average cost affects reserve creation, and reserve creation is a key determinant of cumulative emissions over time. Policies such as the provision of free emissions credits preserve the marginal cost of emissions from the carbon price but lower average costs because firms do not pay for all of their emissions. As a result, firms create more reserves with credits than without. The ensuing lifetime emissions with credits is greater than without credits, and can be similar to emissions without any pricing, thereby offsetting the greenhouse gas reductions caused by the pollution price.

We also consider the interaction of emissions pricing with the firm's abatement technology, a relationship that, to the best of our knowledge, has not previously been examined in the

under Alberta's Climate Leadership Plan. Government of Canada (2018) describes the Canadian policy.

[3]The latter structure is common in the mining industry. A hybrid of these structures is used to extract rents from production of Albertan oil sands (Heyes et al., 2018).

resource extraction literature. According to a simple model of emissions abatement, firms with different marginal abatement cost curves that coincide at the pollution price will choose the same level of emissions. However, the different shapes of the marginal abatement cost curves yield different total abatement costs. This implies differences in average pollution costs which, like emissions credits and resource royalties, cause different reserves and lifetime emissions.

Our paper contributes to a literature investigating the effect of pollution control policies on nonrenewable resource extraction. Much of this literature analyzes when the production will shift toward less-emissions intensive sources of fuel (Chakravorty et al., 2008; van der Ploeg and Withagen, 2012), the effect of tax instruments on resource extraction and economic growth (Hoel and Kverndokk (1996); Groth and Schou (2007)) and whether there exists a *green paradox*, whereby producers of emissions-intensive resources will speed up resource extraction in advance of emissions policy (van der Ploeg and Withagen, 2015). To the best of our knowledge, we are the first to analyze the effect of environmental policy on nonrenewable resource development while allowing reserves to be endogenously created. In doing so, we highlight how important is the extensive margin in assessing the effects of emissions pricing and how seemingly innocuous policy and technology assumptions can interact with the emissions price to generate significantly different outcomes.

The interaction of environmental and fiscal policies has been extensively studied elsewhere (Goulder, 2013). Much of this literature focuses on the interaction between environmental policies and existing distortions in income taxes and other fiscal regimes. In this work, the key questions are the degree to which new environmental taxes exacerbate distortionary implicit taxes on labour and capital and whether recycling of green tax revenues can mitigate these impacts and, potentially, yield a *double dividend*. Our work is comparable to this, although we concentrate on the degree to which environmental taxes constitute implicit taxes on resource capital and whether revenue recycling in the form of output-based allocations may reduce these distortionary impacts. We also introduce the question of how interaction with a non-policy factor, the shape of the marginal abatement cost curve, determines the size of the average effective tax rate on capital and may impact these results.

Our paper also contributes to the literature on measures designed to mitigate the competitiveness impacts of greenhouse gas policy, such as output-based allocations or lump-sum rebates. In a simple model of abatement, firms react only to the marginal abatement cost and, so long as allocations do not vary with current emissions, the firm's intensive margin abatement decisions should not change. However, the allocations act as a subsidy to output, so they change overall production decisions and, in turn, lead to higher emissions than would otherwise arise. Our analysis extends the findings of Fischer and Fox (2007), Bernard et al. (2007), Fischer and Fox (2012), and Böhringer et al. (2017), among others, to include the extensive margin. By providing a subsidy to output, the output-based allocations also affect the marginal value of reserves, leading to more reserve creation than would otherwise be the case. We find the combination of output subsidy with reserve creation may lead to very limited impacts of emissions reduction policies.

Finally, as we include a discussion of the role of the average cost of emissions reduction, we develop a result which is analogous to the *green paradox* (Sinn, 2008). In our case, we show that a firm with lower costs of abatement at any given level of emissions may see higher emissions under carbon policy than would be the case with more expensive abatement if reserve creation decisions are sufficiently responsive to changes in the average cost of environmental compliance. In our numerical example, we show a case where both total extraction and total emissions are lower with carbon prices than without, they are higher with lower-cost emissions abatement technology and a carbon price than with lower-cost abatement.

2 Model

We use a dynamic, numerical model of nonrenewable resource extraction to study how emissions pricing affects reserve creation and extraction decisions. Our main focus will be on how these outcomes are affected by emissions pricing and by the interaction of emissions pricing with output-based allocations of emissions credits, resource royalties, and abatement technology. We use numerical solutions of our parameterized model but place the emphasis of our discussion on the qualitative implications rather than the specific solution values. As such, the parameter values we use are chosen to be illustrative, not representative.

2.1 Reserve creation

We assume that the resource sector is populated by a large number of identical, price-taking firms and that the resource base is owned by a single owner interested in collecting rents associated with an optimal extraction path. At time t, each resource firm holds a stock of the resource, $X(t)$, where the sum of all $X(t)$ is the total resource reserves. This would be the case in an area such as Alberta's oil sands, where resource rights are held by a wide-range of firms who will each be sufficiently small to be price-takers in the global oil market, yet face decisions on project development scale and technology. Similarly, small to mid-sized firms extracting oil from tight-oil basins such as the Bakken or the Permian Basin are too small to individually impact world oil prices, but regularly must decide how many new wells to drill.

Like Gaudet and Lasserre (2015), we assume endogenous initial reserves, X_0. The cost of creating the initial reserves, through exploration and development, is $E(X_0)$. The function E is increasing in X_0 ($E'(X_0) > 0$) and exhibits strictly decreasing returns to effort ($E''(X_0) > 0$). The return from this effort is deterministic, *i.e.*, there is no uncertainty associated with the exploratory efforts.[4] We assume there are no fixed costs of participation ($E(0) = 0$) and, for computational expediency, the change in marginal costs due to acquiring infinitesimally small reserves is treated as zero ($E'(0) = 0$).[5] The numerical implementation we use for reserve creation, which can be thought of as the construction of fixed extraction assets such as well pads or processing facilities, is shown in Figure 1. In addition to standard extraction costs, reserves may also be subject to a tax on embodied emissions, τ_R, which is charged based on the embodied emissions intensity of the resource, denoted by ξ.

2.2 Resource Extraction

Once reserves X have been created through initial investment, the firm extracts the resource at rate $x(t)$ at a cost $C(x(t), X(t))$, which is increasing in both arguments. Marginal extraction costs, $c(x(t), X(t)) \equiv \frac{\partial C(x,X)}{\partial x}$, are increasing at an increasing rate in extraction in any given time period, $\frac{\partial c(x,X)}{\partial x} > 0$, $\frac{\partial^2 c(x,X)}{\partial x^2} > 0$, and increasing at an increasing rate as reserves are depleted, so $\frac{\partial c(x,X)}{\partial X} < 0$, $\frac{\partial^2 c(x,X)}{\partial X^2} > 0$. We also assume that increases in X raise marginal extraction costs, $\frac{\partial^2 c(x,X)}{\partial X \partial x} > 0$, and that the marginal extraction costs at zero reserves is bounded above, $c(\epsilon, 0) = \overline{C}$ **as** $\epsilon \to 0$.

2.3 Emissions and abatement

Extraction generates emissions $e(t) = e(x(t))$. Emissions are increasing in the rate of extraction and at an increasing rate. While we generally refer here to extraction emissions, the emissions taxes could certainly be vertically targeted as in Mansur (2012) and include eventual emissions from consumption of the resource as well. The firm may reduce emissions from production at costs described by an abatement cost curve $M(e(t), t)$. In a given period

[4]Note that in each of the examples in the preceding paragraph, there is little to no risk associated with the extra drilling: unlike exploratory ventures in the last decade, here firms are virtually assured of obtaining incremental resources from their efforts to expand reserves.

[5]This latter assumption is sufficient to guarantee that positive reserves are profitable.

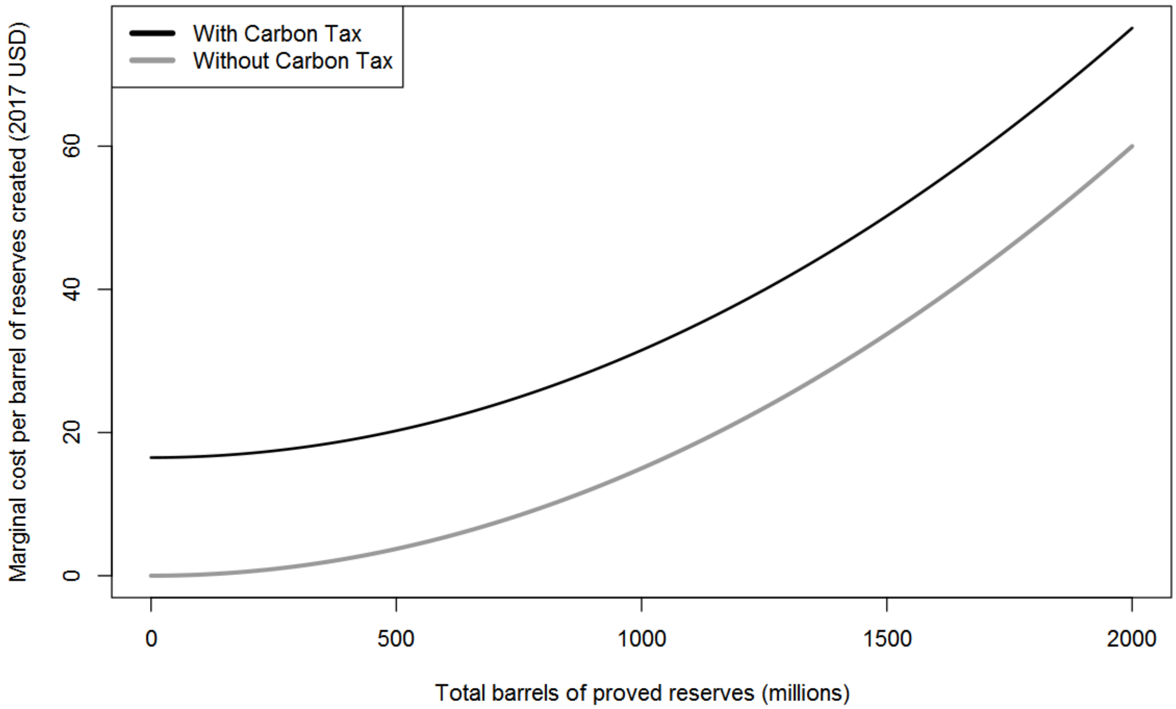

Figure 1: Reserve Creation. Computational equation used: $E'(X) = E_3 E_2 X^{(E_3-1)} + \tau_R \xi$

t, marginal abatement costs are increasing in abatement – or, equivalently, decreasing in emissions – so that $\frac{\partial M}{\partial e} > 0$ and have a finite zero-emissions value, i.e. $\frac{\partial M(0,t)}{\partial e} = \overline{M}$ which is the highest point of the marginal abatement cost curve. This could be thought of as the cost of complete carbon capture or other final abatement technology.

For our base analysis, we use a linear marginal abatement cost curve, which we vary to investigate how changing the shape of this cost curve affects reserve creation and extraction decisions in later sections. The three marginal abatement cost curves used in the analysis are shown in Figure 3.

2.4 Emissions taxation

In each period t, the firm faces an emissions pricing function $F(e(t), t)$ which includes taxes and, in some cases, output-based allocations of emissions credits. The firm's average cost of emissions includes emissions taxes $\tau_x \xi(t) x(t)$, where $\xi(t)$ is the endogenous emissions intensity of production, as well as the value of emissions permit allocations $\tau_x x(t)\beta(t)$. Where the

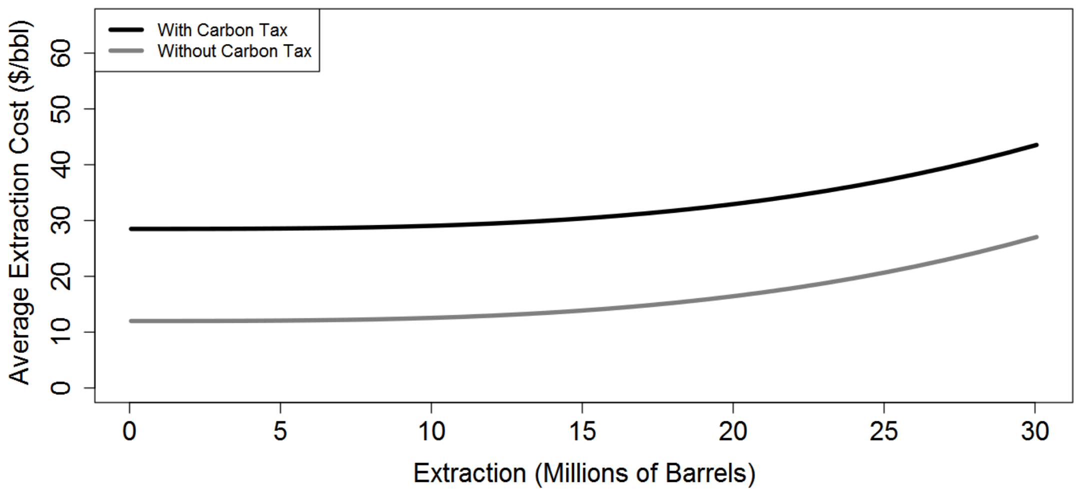

Figure 2: Extraction costs. Function form for numerical analysis is given by $C(x, X) = C_0 + C_3 C_2(x)^{C_3 - 1} C_4(X)^{-1} + \tau_x \xi$

output-based allocations rate, $\beta(t)$, is greater than endogenous emissions intensity, $\xi(t)$, the firm will earn net revenues from allocations and vice versa. The marginal cost of emissions is always equal to the emissions tax rate, τ_x, but the output-based allocation provides a marginal net subsidy to output where it exists. Emissions during extraction that are taxed at rate $\tau_x \xi$ affect the cost of extraction. Figure 2 depicts average extraction costs, with and without an emissions tax.

2.5 Resource taxation

In each period t, the firm faces a resource tax function $G(x(t), t)$. We consider two forms of resource taxation: a severance tax and a profit tax. To avoid confusion with carbon taxes, we use the terminology of a gross and net revenue royalty. With a gross revenue royalty, the firm pays share of production, irrespective of the value of the resource. We denote gross revenue royalties as: $G(x(t), t) = \alpha(t)x(t)$, where $\alpha(t)$ is between zero and one.

Net revenue royalties collect a share of the proceeds from production, and so both the price and the production cost (which may include emissions taxes, $F(e(t), t)$, and abatement costs, $M(e(t), t)$, described above) each affect the amount owed. We denote net revenue

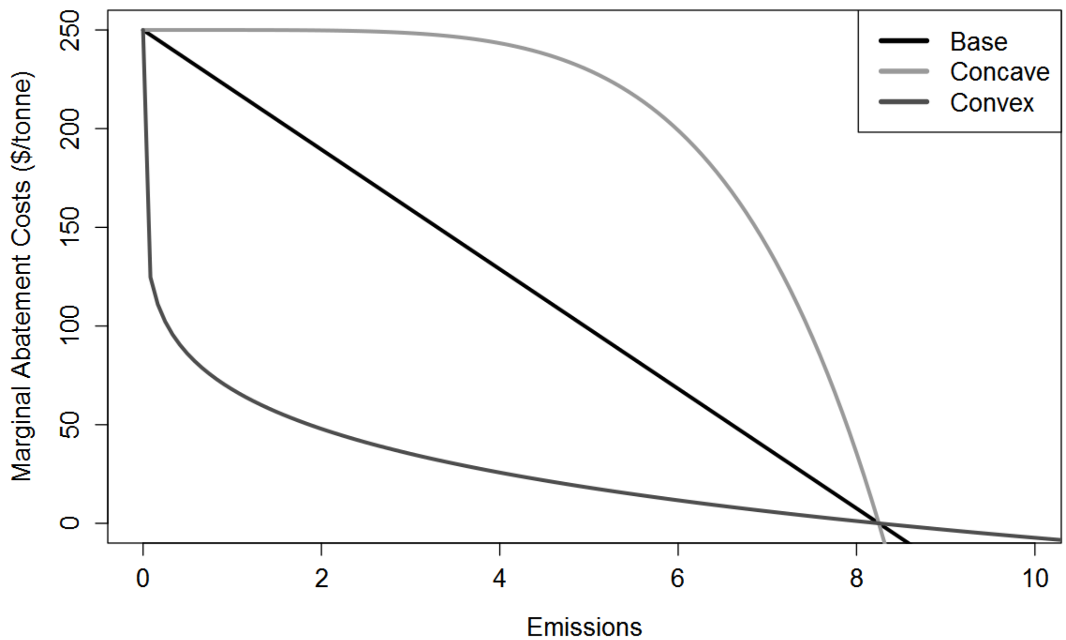

Figure 3: Marginal abatement cost functions used in the paper.

royalties as:

$$G(x(t),t) = \nu(t)\big(Px(t)) - C(x(t)) - M(e(t),t) - F(e(t),t)\big).$$

As mentioned above, each of these are commonly used in resource policy globally. Most agreements between landowners and resource extraction firms would be in the form of severance payments, as are most US state oil takes. US coal taxes are profit taxes and Canadian provinces use both gross revenue and profit taxes or effective approximations of profit taxes for royalties on oil and gas development (see Gillingham and Stock (2016), Plourde (2009)).

2.6 Optimization problem

Market prices are given by $P(t)$, which we choose to be fixed in real terms (growing at the rate of interest, r) for our simulations. Because the firm is small with respect to global markets, it ignores the effect of its actions on prices. In addition to global oil prices, this feature implies the firm neglects the impact of its emissions on emissions taxes; by extension, this implies the firm does not take the level of, nor changes in, the atmospheric carbon stock.

The firm chooses its initial reserves, extraction path, and completion date, T, to maximize its net present value profits:

$$\max_{X_0,x(t),T} \int_0^T e^{-rt}\Big(P(t)x(t) - C(x(t)) - M(e(x(t),t) - F(e(x(t),t) - G(x(t),t)\Big) - E(X_0) \qquad (1)$$

subject to

$$\dot{X}(t) = -x(t) \qquad (2)$$

$$X(0) = X_0, \quad X(T) \geq 0, \quad x(t) \geq 0. \qquad (3)$$

The extraction firm solves a two-stage problem which accounts only for costs internal to its profit maximization problem, so its conditions for a private optimum are:

$$e^{-rt}\Big\{P(t) - C'(x(t)) - \Big(\frac{\partial M(e(x(t)),t)}{\partial e(x(t))} + \frac{\partial F(e(x(t)),t)}{\partial e(x(t))}\Big)\frac{\partial e(x(t))}{\partial x(t)} - \frac{\partial G(x(t),t)}{\partial x(t)}\Big\} = \lambda(t), \qquad (4)$$

$$\dot{\lambda} = 0, \qquad (5)$$

$$\lambda(0) = E'(X_0), \qquad (6)$$

$$\lambda(T)X(T) = 0, \lambda(T) \geq 0, X(T) \geq 0, \text{ and} \qquad (7)$$

$$e^{-rT}\{P(T)x(T) - C(x(T)) - M(e(x(T)),T) - F(e(x(T)),T) - G(x(T),T)\} - \lambda(T)x(T) = 0. \qquad (8)$$

The condition in (4) is altered from the social first-order condition for optimality in that it includes the marginal royalty or severance tax payable on extraction as well as the marginal emissions costs. The first-order condition sets that the marginal future net present values of the marginal revenues (P) equal to the marginal extraction ($C'(x(t))$, marginal abatement costs, marginal royalties and taxes plus the marginal private opportunity cost of extraction of the finite resource, $\lambda(t)$. The remainder of the conditions are standard transversality and terminal conditions.

2.7 Numerical solution

In order to solve and simulate the model, we proceed as follows. First, the model is set up as a dynamic programming problem in discrete time and solved recursively. The value function at each iteration is approximated using a high-order polynomial and, once the iteration has converged, this approximation of the value function (and its derivative with respect to reserves) is used to solve the reserve creation phase of the model, since the solution defines the indirect marginal value of a unit of reserves. This, combined with the exogenous cost of reserve creation, defines the equilibrium of the reserve creation stage. Solutions to the value functions also yield policy functions for the extraction. These, along with endogenous initial reserves from the solution to the reserve creation problem are used to simulate the extraction model over time. We run several scenarios for different combinations of carbon taxes and emissions credit allocations, royalty policies, and oil prices. Each scenario requires a complete solution to the dynamic programming problem.

3 Results

We first provide a description of the numerical results with and without carbon pricing. Then we proceed to report the results from incorporating emissions credits, royalties, and abatement costs, respectively.

3.1 Emissions taxes

In Figures 4 and 5, we introduce our results for a basic solution and simulation of the model with and without a carbon price and, in so doing, introduce the results framework we will use throughout the remainder of the paper.

In the top panel of Figure 4, we depict the optimal extraction decision, left, and the optimal emissions decision, right, as a function of remaining reserves. Recall that reserves are endogenous, but the problem is solved recursively, so these functions are integral to that solution. As expected, the optimal behaviour shows a decreasing level of extraction with fewer remaining reserves and that the carbon price reduces both extraction and emissions rates, all else being equal.

The next stage in the recursive solution uses these optimal policy functions to construct the indirect value of reserves, from which we then calculate the marginal value of reserves. Shown in the bottom panel of Figure 4, the marginal value of reserves slopes downward in reserves, and is higher with no carbon price than with a carbon price for any level of reserves. This follows from the fact that extraction is less profitable when carbon prices are in place since the firm is an oil price taker. The marginal cost of reserves is as introduced above. The intersection of the marginal value of reserves with the marginal cost yields the equilibrium reserves for the firm, and the equilibrium reserves and marginal costs and values are shown in the figure legend. As expected, the carbon price reduces the value of an additional barrel of reserves, which in turn causes equilibrium reserves to be lower under a carbon price than without one.

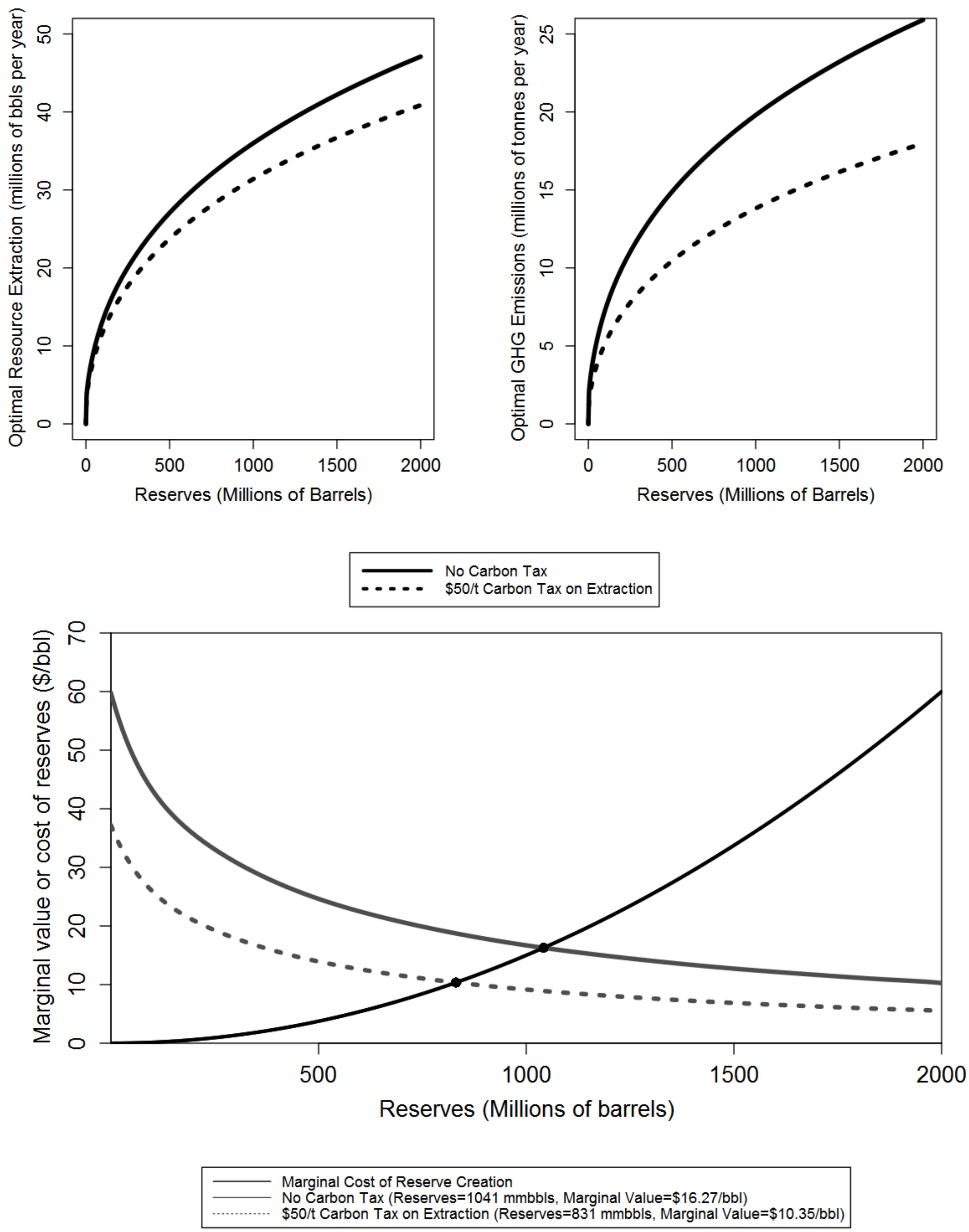

Figure 4: Optimal extraction and emissions decision rules (top) and reserve creation (bottom) with and without a carbon price

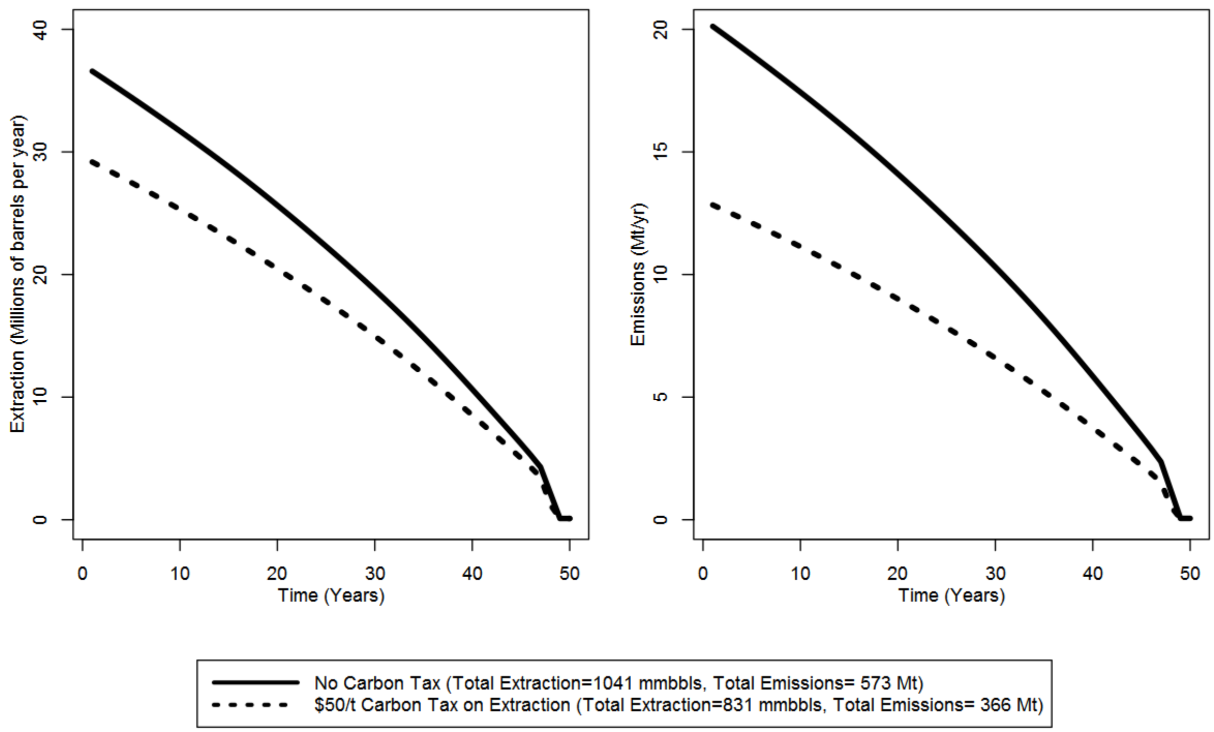

Figure 5: Equilibrium extraction and emissions over time with and without an carbon price.

When reserves are assumed to be exogenous, carbon pricing can affect the total amount that is extracted only through stranding reserves. When reserves are endogenous, two things will be true: first, firms will only establish reserves they plan to extract and, second, more reserves will be created when extraction is more profitable on average. This last point is an important margin on which emissions pricing operates: when firms decide the quantity of resources that are economically recoverable, emissions pricing has an effect on the total amount of resources that will be extracted through its impacts on average extraction costs and thus on the value of the marginal barrel of reserves.

The final element in our results combines the policy functions from the top panel in Figure 4 with the optimal initial reserves solved for in the lower panel of Figure 4 to simulate optimal extraction and emissions paths over time. We plot these values in Figure 5, and include total extraction and emissions values over the transition paths in the legend of the figure. The simulation with the carbon price shows two combined effects of the emissions policy: first, there is lower cumulative extraction (831 million barrels versus 1041 million barrels without the carbon tax), and second, the emissions per barrel produced are lower (0.44t/bbl versus 0.55t/bbl). In other words, the carbon tax has impacts on both the intensive and extensive margins of resource extraction and emissions.

3.2 Reserve taxes

It is certainly more common for taxes to be contemplated on emissions where they occur, although vertical targeting could see emissions taxed at one point in the supply chain rather than at many (Mansur, 2012). One such approach would tax emissions at the point of resource leasing (Gillingham and Stock, 2016). Alternatively, some argue that fossil fuel reserves should be "left in the ground" in order to achieve global climate goals.[6] The shadow value of any particular development constraint, implemented as a carbon tax on reserves, would accomplish the same outcome in terms of discouraging development. The disconnect between current policy and climate goals leads to arguments that a so-called carbon bubble exists (Campanale and Leggett, 2013). A tax on the deemed emissions from reserves is a direct way to penalize the creation of carbon-intensive resource reserves.

We incorporate a tax on the carbon content of reserves under the assumption that emissions from extraction of any created reserves will be unabated. Having deemed potential future emissions in this way, we apply a $50 per tonne tax on potential future emissions from reserves.

The decision rules shown in the top panel of Figure 6 are the same as those in Figure 4, since the extensive margin policies on offer are the same. In the case of a reserve tax, the extraction and emissions decision rules conditional on established reserves are the same as those where no tax exists at all. Because the reserve tax has no effect on the optimal policy rules, it does not effect the indirect marginal value of reserves: the marginal value of reserves with a reserve tax is identical to the marginal value with no carbon tax, as depicted in the bottom panel of Figure 6. However, as the bottom panel depicts, the reserve tax shifts up the marginal cost of reserve creation, thereby changing the equilibrium reserves. In our example, the reserve tax leads to substantially lower reserve creation than would otherwise obtain, with less than one-third as many reserves being established as the case with no carbon tax and less than half (343 versus 831 million barrels) compared to a similarly-valued tax on extraction. These particular values are not important, and the magnitude of the differences in any real-world situation will, of course, depend on the elasticity of the marginal cost of reserves as well as on the emissions abatement costs available in the extraction phase.

The extensive margin time paths shown in Figure 7 provide further insight into the impacts of the two forms of taxation. The reserve tax leads to less extraction over time, a shorter period of extraction, and lower total emissions. As such, it is an effective policy to reduce emissions. However, during production, the emissions intensity is higher with the reserve tax, where it is identical to the case with no tax at all at 0.55 tonnes per barrel. With the emissions tax on extraction, total emissions are higher, but emissions-intensity is lower at 0.44 tonnes per barrel.

[6]For example, the organization `350.org` argues in favor of leaving reserves undeveloped.

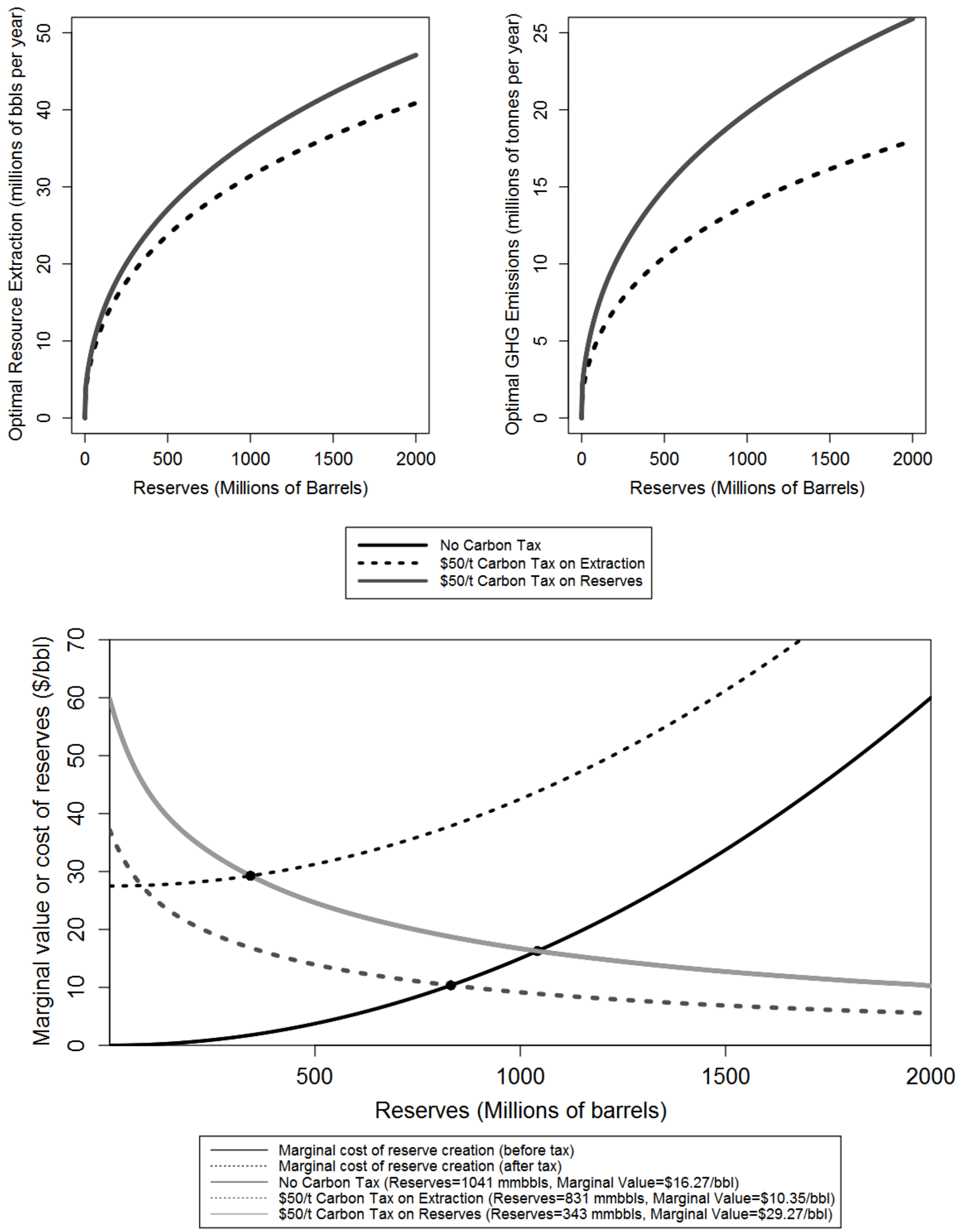

Figure 6: Optimal and equilibrium extraction and emissions decision rules (top), reserve creation (bottom) without any carbon pricing, and with carbon prices applied to extraction emissions or to potential emissions embodied in reserves.

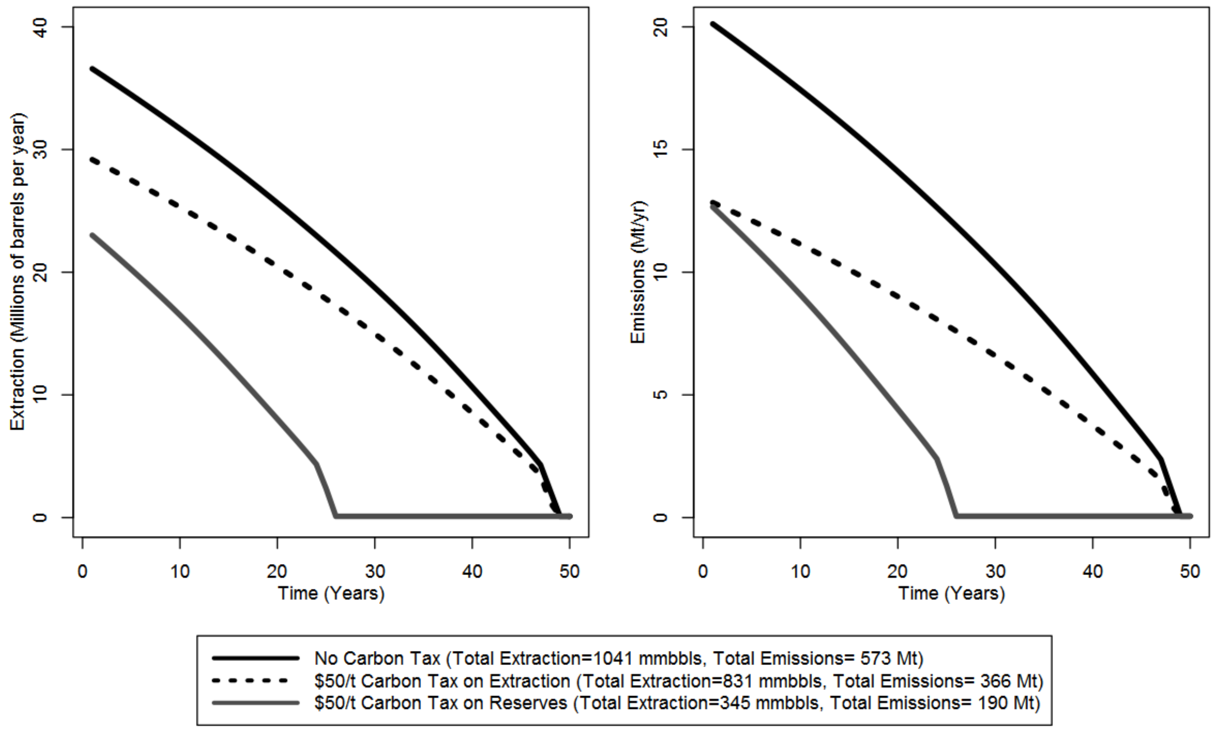

Figure 7: Equilibrium extraction and emissions over time without any carbon pricing, and with carbon prices applied to extraction emissions or to potential emissions embodied in reserves.

Because it imposes no marginal cost on emissions from extraction, the reserve tax leads to under-exploitation of emissions abatement technology compared to an emissions tax. One policy correction would be to then tax extraction as well. However, this would effectively tax the same emissions twice: when the reserve was created and when they were emitted during extraction. This could be avoided, while still allowing outcomes from a reserve tax to be equivalent to a carbon tax applied directly on extraction emissions, by subsidizing any abatement that reduces emissions from extraction below a baseline level. The subsidy would introduce a marginal cost of extraction which would stimulate abatement activity.

3.3 Allocation of emissions credits

Emissions credits are often provided along with an emissions pricing system to not deter industry away from the jurisdiction by keeping total emissions costs low. In this way, emissions crediting systems reduce average costs of the emissions control policy but maintain the marginal cost set by the carbon price. We consider a popular type of emissions crediting system, known as output-based allocations (OBAs), which have been studied in the extant literature (Fischer and Fox, 2007; Bernard et al., 2007; Fischer and Fox, 2012; Böhringer et al., 2017).

OBAs affect outcomes through two channels. First, because they are a subsidy to output, they will alter decision rules on extraction (and thus emissions) at the margin. The increase in emissions due to the output subsidy is offset (although not necessarily fully offset) by increased emissions abatement due to the price on carbon. As the top panel in Figure 8 shows, the extraction rate with an OBA is nearly the same as extraction with no carbon price (and no OBA). Emissions, however, shown on the right, are lower with the price and OBA structure than with no carbon price, but higher than they would otherwise be due to the output distortion from the OBA.

The OBA has a second effect through the endogenous reserves which amplifies the first channel. As shown in the bottom panel of Figure 8, the amount of reserves created under pricing with the OBA is significantly greater than reserves with the pure pricing system and is virtually identical to reserves with no carbon price. For our particular numerical solution, this implies that the OBA completely offsets the incentive to create fewer reserves provided by the carbon price.

As Figure 9 illustrates, combining the two channels yields interesting results. Equilibrium extraction over time, on the left, is effectively identical with and without the carbon price where OBAs are given. In contrast, when no credits are provided, extraction is much lower due to the lower reserve creation caused by the lower marginal profitability of extraction. Conversely, emissions, on the right, are only slightly increased relative to the pure pricing system when credits are supplied through OBAs. This quantitative outcome is a product of our particular parameterization of the emissions abatement cost function and the rate at which OBAs are given. With OBAs, the emissions-intensity of production is lower than without carbon policy. The output subsidy, however, leads to higher production than would otherwise obtain, thereby generating greater total emissions than the pure carbon pricing system. In the case with a completely inelastic marginal abatement cost function, emissions per barrel would be identical, and thus total emissions with the OBA would be higher than those shown here. But emissions would still be lower than the untaxed case unless the OBA rate was higher than the business-as-usual emissions intensity of production.

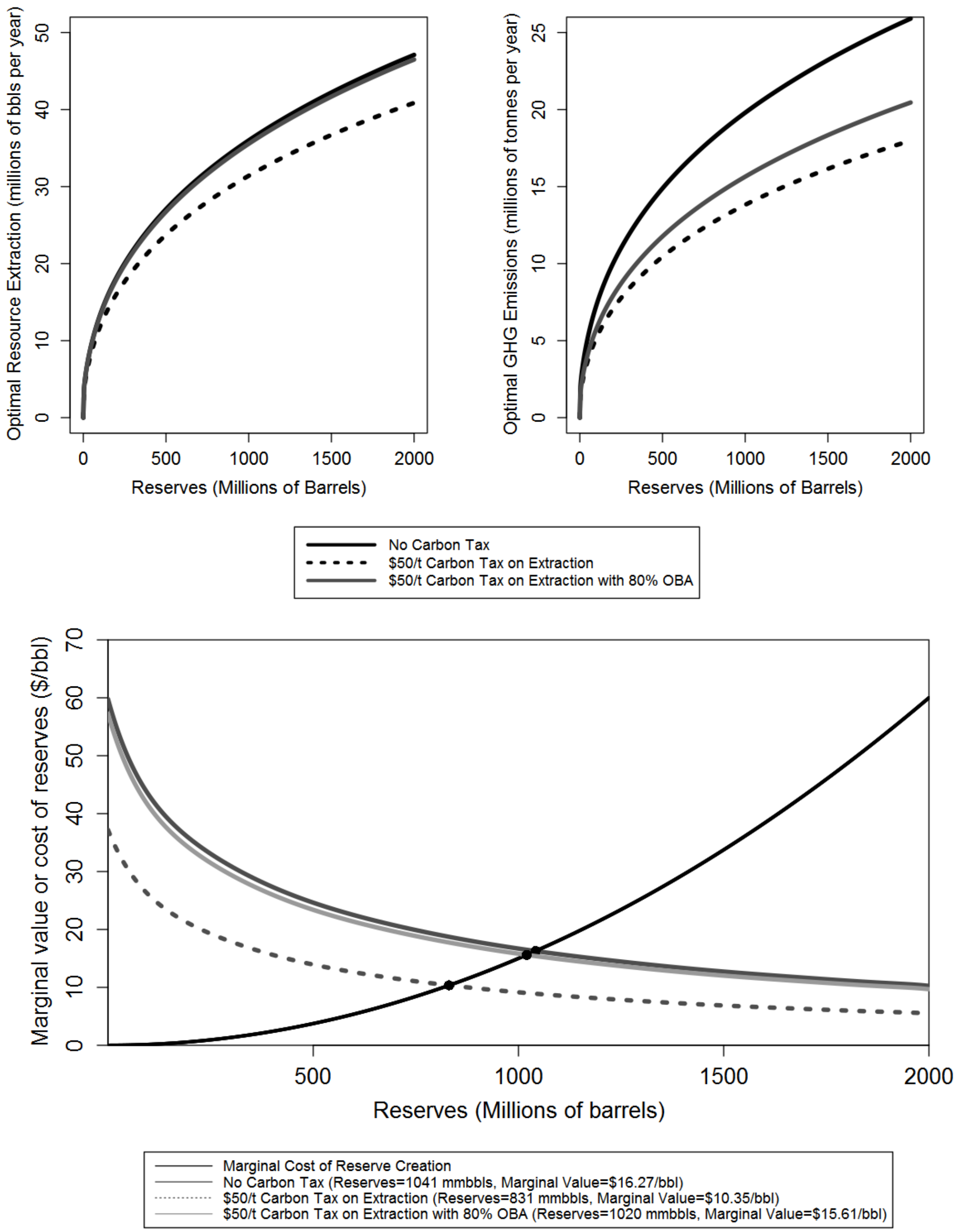

Figure 8: Optimal and equilibrium extraction and emissions decision rules (top) and reserve creation (bottom), with and without a carbon price and once OBAs are provided for 80% of emissions.

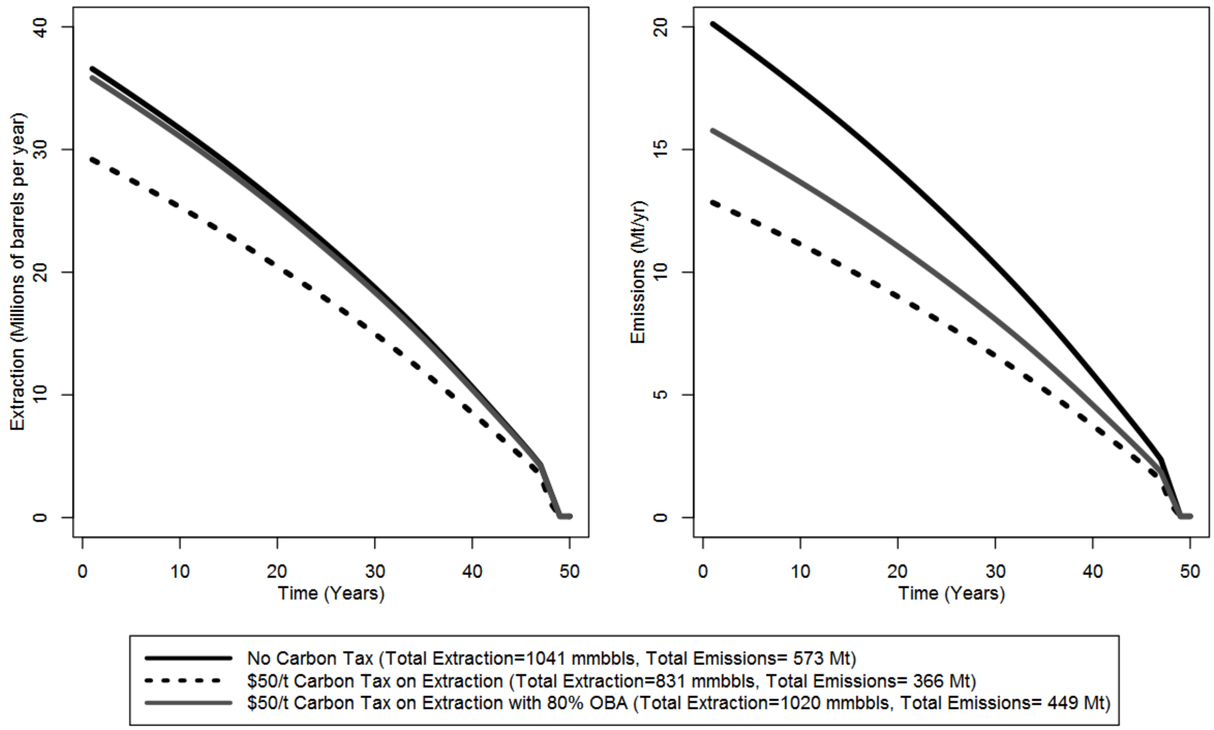

Figure 9: Equilibrium extraction and emissions over time, with and without a carbon price and once OBAs are provided for 80% of emissions.

3.4 Resource royalties

Resource royalties have the potential to interact with emissions pricing in reserve creation, extraction, and emissions abatement decisions. Since resource stocks (reserves) are endogenous and obtained with positive and increasing costs in our characterization, it will always be the case that reserves are entirely extracted as long as no uncertainty exists - it will never be optimal to pay to create reserves that are not used. However, the equilibrium size of initial reserves will vary depending on the taxation policies. Also, since the royalty policies may not be neutral to extraction decisions, the timing of extraction and cumulative extraction amounts may be altered by royalty policies.

Before analyzing the interaction of carbon pricing with resource royalties, we describe how royalties affect resource development in our framework. As discussed in Section 2.5, a severance tax or gross revenue royalty claims a specific output share, α, in each time period. Because the royalty share is not a function of extraction and/or emissions, it acts as an effective lower price in the intensive margin profit maximization problem. As shown in the top panel of Figure 10, the gross revenue royalty reduces optimal extraction and thus optimal emissions at each level of reserves.

Rent taxes are more complex from a regulatory perspective, but less distortionary on the intensive margin since they do not alter the profit-maximization decisions of the firm, conditional on a level of reserves. This is shown in the top panel of Figure 10, where the optimal extraction and emissions decisions under a net revenue royalty are identical to a case with no resource royalties at each level of reserves (in the figure, the two figure appear as only a single line). This lack of distortion is not preserved once we look at the reserve creation stage of the problem, as resource royalties in either form reduce the value of reserves and thus reduce equilibrium reserve creation and cumulative extraction. Since 30% of gross revenues represents a larger loss to the firm than 30% of net revenues, the gross revenue royalty sees fewer reserves created than the net-revenue- or no-royalty case. This particular result is due to the relative profitability of output in our parameterization, and would not be generally the case.

The equilibrium extraction path shown in Figure 11 shows the differences in the effects from the two royalty systems. A net revenue royalty is designed to not distort the intensity of production, even though it may affect the amount of resources that are extracted in total. This prediction is reflected in the nearly constant inward shift of the extraction path from the no-policy case (black line) to the net-revenue royalty case (lighter grey line). In contrast, the gross revenue royalty does distort production, since the revenue, but not the cost, of per-period extraction is lower with such a royalty than without one. To keep rents increasing at the rate of return, the extraction path under the gross revenue royalty is not a downward shift by a constant amount but is instead a pivot inward. Similarly, the effect of a net revenue royalty on the equilibrium emissions path is a near-constant shift inward from the no-policy path, while the gross revenue royalty causes the time path of emissions to pivot inward.

There is an important interaction between resource royalties, in particular those charged on net revenues, and emissions taxes. This interaction occurs because producers can deduct their carbon compliance costs from their royalty obligations. In doing so, their royalty costs decrease, thus affecting profitability and the amount of reserves created.

In Figures 12 and 13, we plot four policy scenarios: (1) no carbon price or royalties, (2) a carbon price but no royalties, (3) a carbon price and net revenue royalties, and (4) a carbon price and gross revenue royalties.

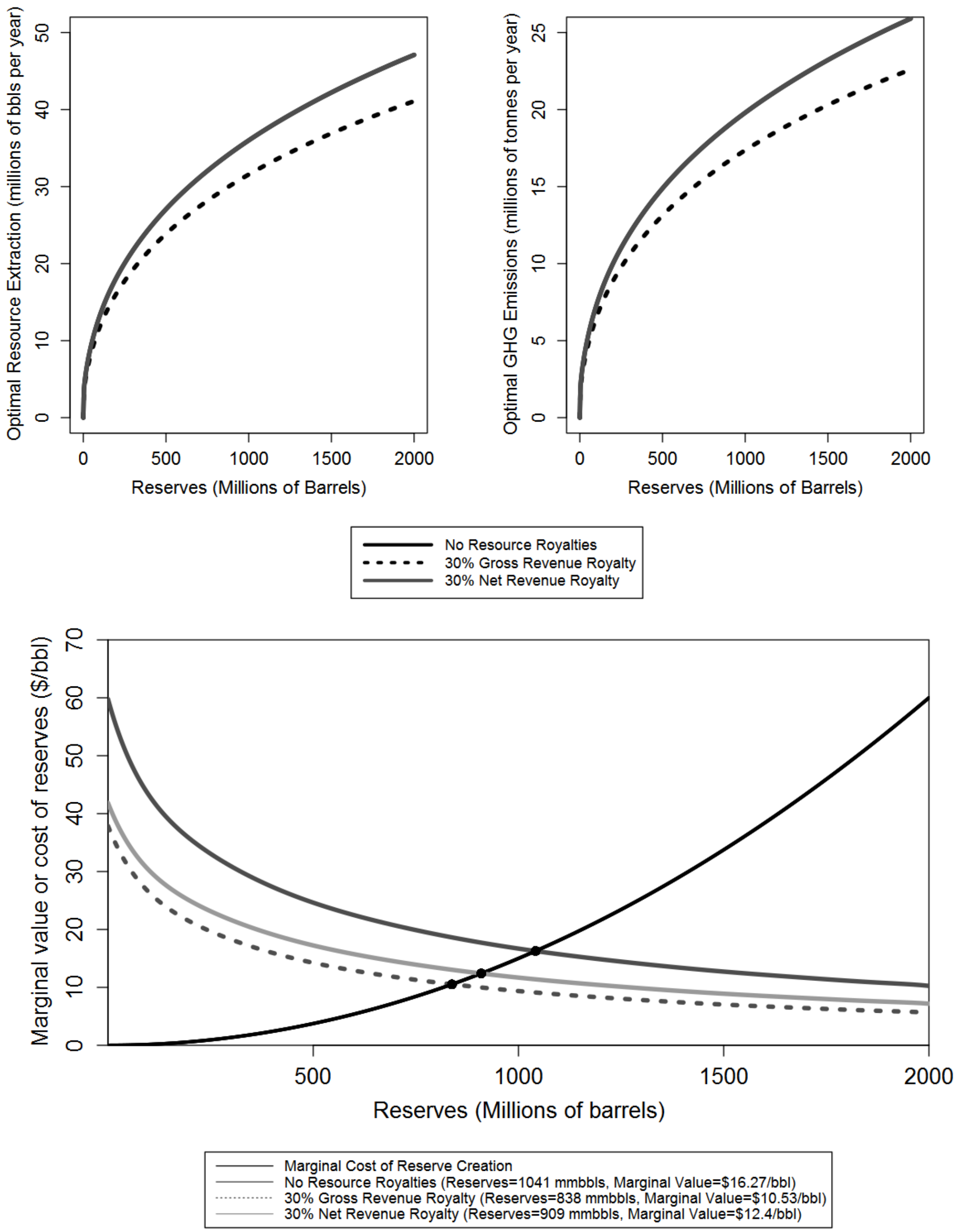

Figure 10: Optimal extraction and emissions decision rules (top)and endogenous reserve creation decision (bottom) with and without net or gross revenue royalties

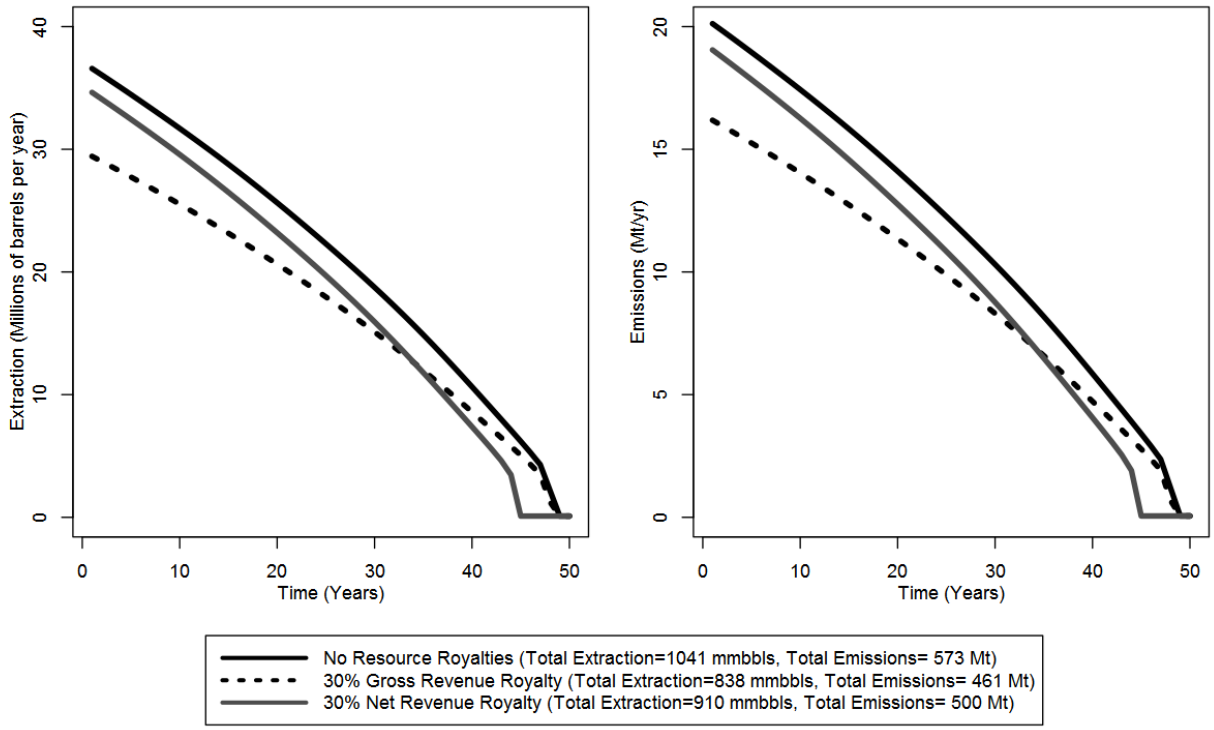

Figure 11: Equilibrium extraction and emissions decision over time with and without net or gross royalties

Consider first the optimal extraction and emissions decisions, conditional on remaining reserves, in the top panel of Figure 12. Compared to the no policy scenario, extraction and emissions are lower with a carbon price with or without royalties in place. The difference in extraction and emissions arises because of the differences in royalty regimes, as it did in Figure 10. Net revenue royalties do not affect the optimal extraction or emissions rate, so extraction and emissions under a carbon price and net revenue royalties are identical to the decision rules under a carbon price with no royalties. In contrast, the combination of a carbon price with a gross revenue royalty decreases both extraction and emissions for a given level of reserves relative to the scenario with only a carbon price, reflecting the same pattern in Figure 10.

The differences in decision rules across royalty regimes has an impact on the marginal value of reserves, which we plot in the bottom panel of Figure 12. There is a clear monotonicity in the policy combination and the amount of reserves that are created. The no-policy case creates the largest amount of reserves, followed by the case with carbon pricing and no royalties. This result will generalize since any positive value for royalties will erode the marginal value of reserves.

The interaction of carbon pricing with royalties can be clearly seen in the creation of reserves, depicted in the bottom panel of Figure 12. The gross revenue royalties have little interaction with the carbon price other than adding another cost to extraction, thereby decreasing reserves significantly from the scenario with a carbon price but no royalties. In contrast, the net revenue royalty – which allows the firm to deduct carbon costs from its royalty obligations – generates reserves that are still lower than the scenario with carbon pricing and no royalties, but greater than the scenario with gross revenue royalties. The difference in reserve creation is due to the interaction between carbon pricing costs and net revenue royalties.

In Figure 13, we plot the equilibrium extraction and emissions paths for the four scenarios. The paths with carbon pricing and the two royalty scenarios are quite different, but again follow the patterns in Figure 11.

3.5 Abatement technology

While much of the literature on carbon taxation and resources focuses on the structure of emissions control policies, the form of emissions-reducing technology can also play an important role in determining the response to emissions policies, especially when reserves are endogenous. This impact occurs because the average cost of emissions policies includes the cost of the carbon price paid but also the total abatement cost and it is this total cost, not the marginal cost of emissions in equilibrium, which drives decisions on the extensive margin with respect to reserve creation. A technology which offers low-cost abatement will see a firm create more reserves because average costs are low, and the firm will see different emissions outcomes over time. In contrast, unless emissions policy strands reserves by making a portion of them uneconomic to extract, a model without endogenous reserves would predict no change in cumulative extraction over time due to the structure of emissions control technology although emissions intensity of production would change with technological assumptions.

Like the output-based allocations, the total cost of abatement - in our case, the areas under the marginal abatement cost curves shown in Figure 3 - affects our results through two channels. First, lower total abatement costs imply higher marginal values of reserves and so more reserves will be created with more cost-effective abatement technology, all else equal. Second because lower abatement costs lead to lower emissions per unit output all else equal, we will see lower emissions intensities with lower costs. Each of our three considered abatement cost functions shown in Figure 3 implies the same no-policy emissions and the same marginal cost of complete abatement, but significantly different total costs to reach lower levels of emissions. Firms with the convex cost curve will, to a much greater degree, be able to avoid policy costs through internal abatement. Firms with concave emissions abatement costs will see almost no gain to internal abatement versus paying carbon taxes.

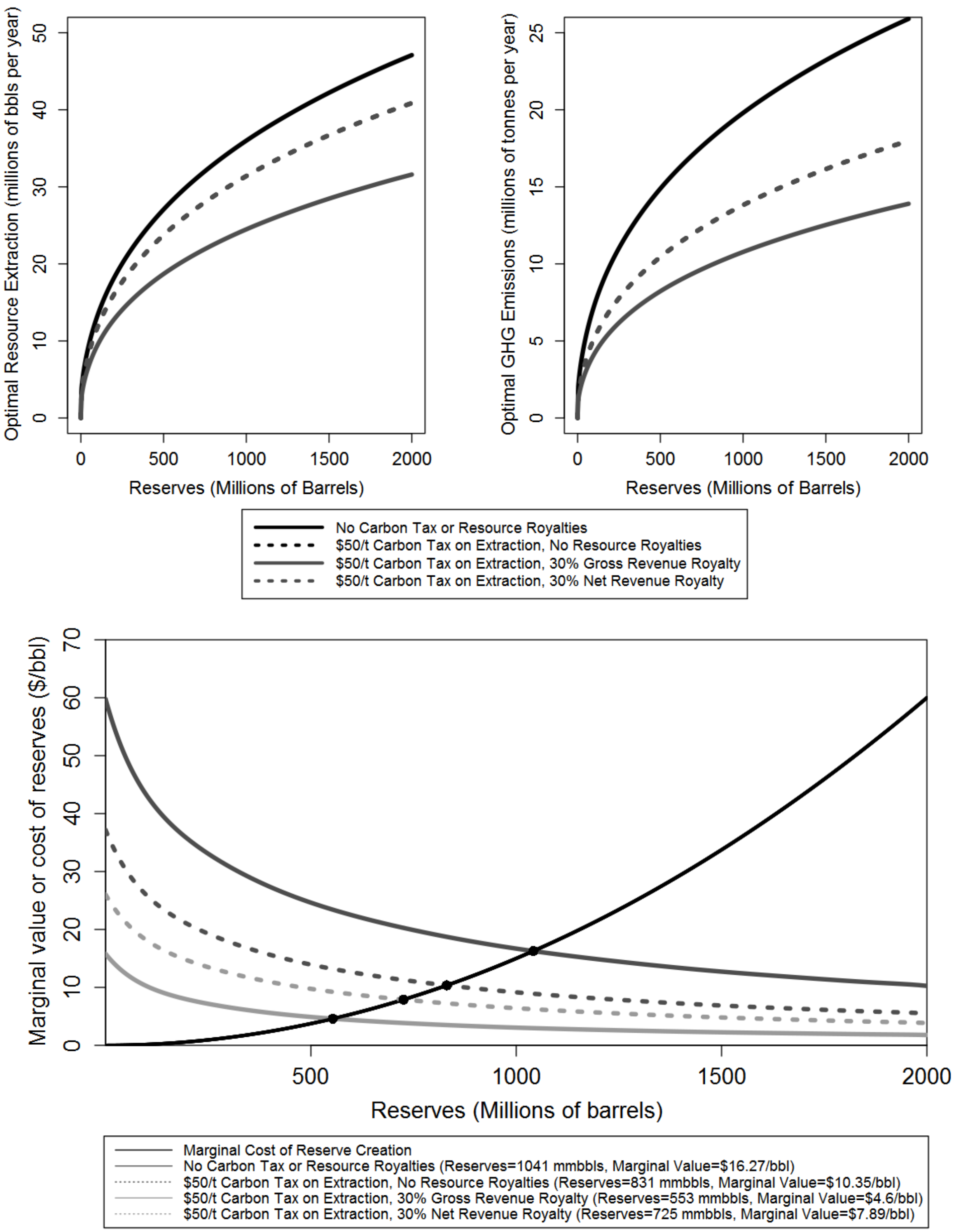

Figure 12: Optimal extraction and emissions decision rules (top) and reserve creation (bottom), for interactions of carbon prices and royalty regimes.

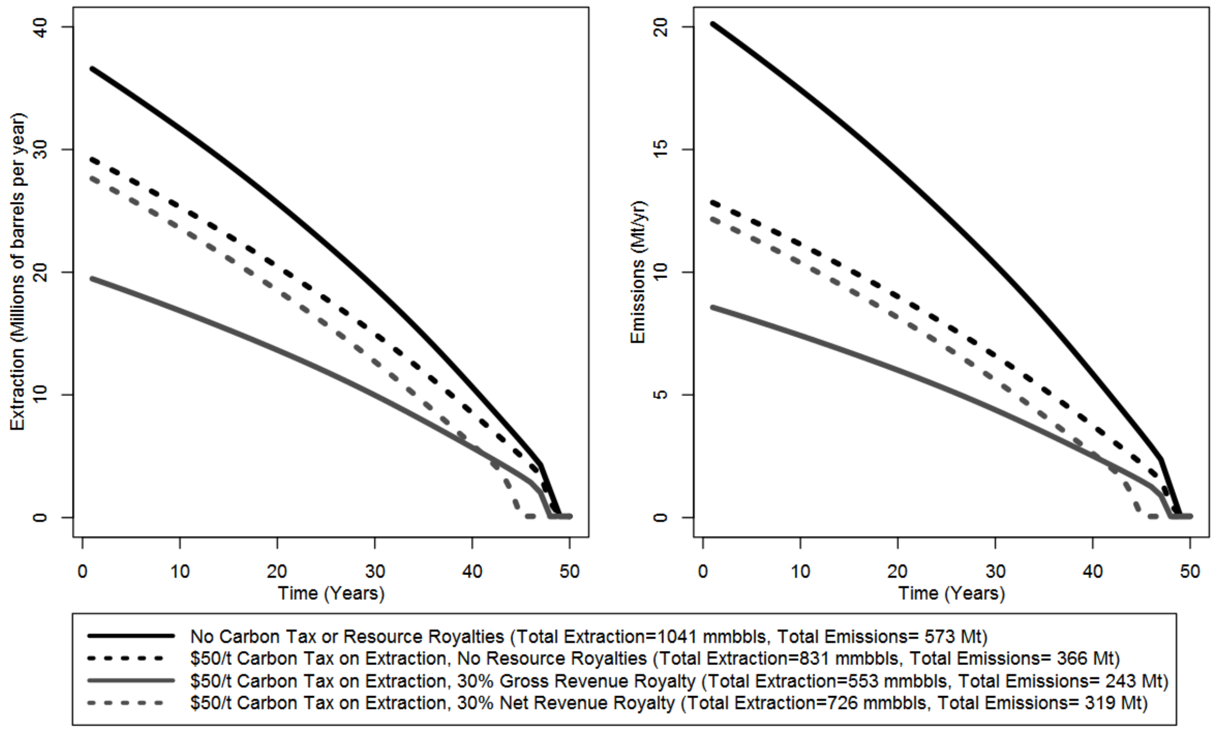

Figure 13: Equilibrium extraction and emissions over time for interactions of carbon prices and royalty regimes

To understand why this would be important beyond our stylized environment, consider an example from global crude oil markets. Masnadi et al. (2018) provides a ranking of global crude oil reserves in terms of their relative emissions intensity. Reserves from Canada's oil sands are consistently ranked among the 20% most emissions-intensive barrels available for production in 2015. Erickson (2018) argues that, among potential 2030 production, oil sands rank among the most emissions-intensive barrels available. This emissions intensity also implies that oil sands resources are less likely than would otherwise be the case to be converted to reserves and eventually produced if there is or is expected to be significant carbon pricing (Boskovic and Leach, 2018). This would, in turn, imply that, in the absence of cost-effective abatement technologies, global oil supplies are more constrained than would otherwise be the case, imposing an implicit downstream carbon price on consumers through higher oil prices. Now consider what would happen if a technology were to become available which allowed oil sands reserves to be produced with relatively low greenhouse gas emissions at a low incremental cost per barrel. This technology would open up significant resources to potential development even under the prospect of carbon pricing on production emissions, and would thus cause a lowering of the global oil supply curve and a reduction in the marginal effective cost of carbon emissions from oil combustion. Where resources are large, relatively homogeneous, and relatively expensive to produce in the global context, a technological change which reduces average costs can have a very large effect. Because this impacts the global oil supply curve at the point were it is most inelastic, the impacts on eventual oil prices and consumption would be large (Bordoff and Houser, 2015; Erickson and Lazarus, 2018).

In terms of motivating the examples we use, it's instructive to think of the concave abatement cost function as a technology akin to carbon capture and storage or fuel switching, where higher operating and/or capital costs are incurred to reduce emissions. Our convex abatement technology would be comparable to a technology which allows nearly identical output, but with only marginally higher operating costs; technologies like the addition of solvents to oil sands production operation or the combined generation of heat and power would be examples of this type of innovation.

As with the other sections, we begin by looking at optimal decision rules conditional on reserves. As shown in the top panel of Figure 14, extraction with a linear MAC is quite different with and without a carbon price. Under a convex MAC, extraction is increased relative to the linear MAC for all reserve levels, but lower than the no-carbon-price case. This occurs because lower abatement costs mean that, conditional on reserves, reducing emissions through reduced extraction is a higher-cost strategy, and so is not used to the same degree as would otherwise be the case if abatement costs were higher. The reverse is true with the concave MAC - abatement is almost all high-cost, and so there is less incentive to extract, all else equal. Emissions are lower than with no carbon tax in all cases, although substantially lower with the lower abatement convex costs than with a linear MAC which is, predictably, lower-emissions than the concave MAC. This is the first sign of a *green paradox*-type result: lower emissions control costs imply that while emissions per barrel are substantially lower with a convex MAC, this is partially offset by producing more barrels despite the imposed carbon price at each level of reserves.

The differences in abatement costs also have the second effect through endogenous reserve creation which amplifies the first channel. As shown in the bottom panel of 14, there are fewer barrels of reserves developed with the linear MAC than with the convex MAC, and fewer still with the concave MAC, although all three cases with carbon prices see development of significantly fewer barrels overall. There is a material increase in reserve creation under the convex MAC: roughly half of the impact of carbon pricing on reserve creation is lost with cheaper abatement technology, relative to the linear or concave MAC assumptions. The quantitative impacts here are particular to our assumptions on the costs of reserve creation and the marginal value of reserves, but the qualitative conclusions are intuitive and robust to changes in parameter values.

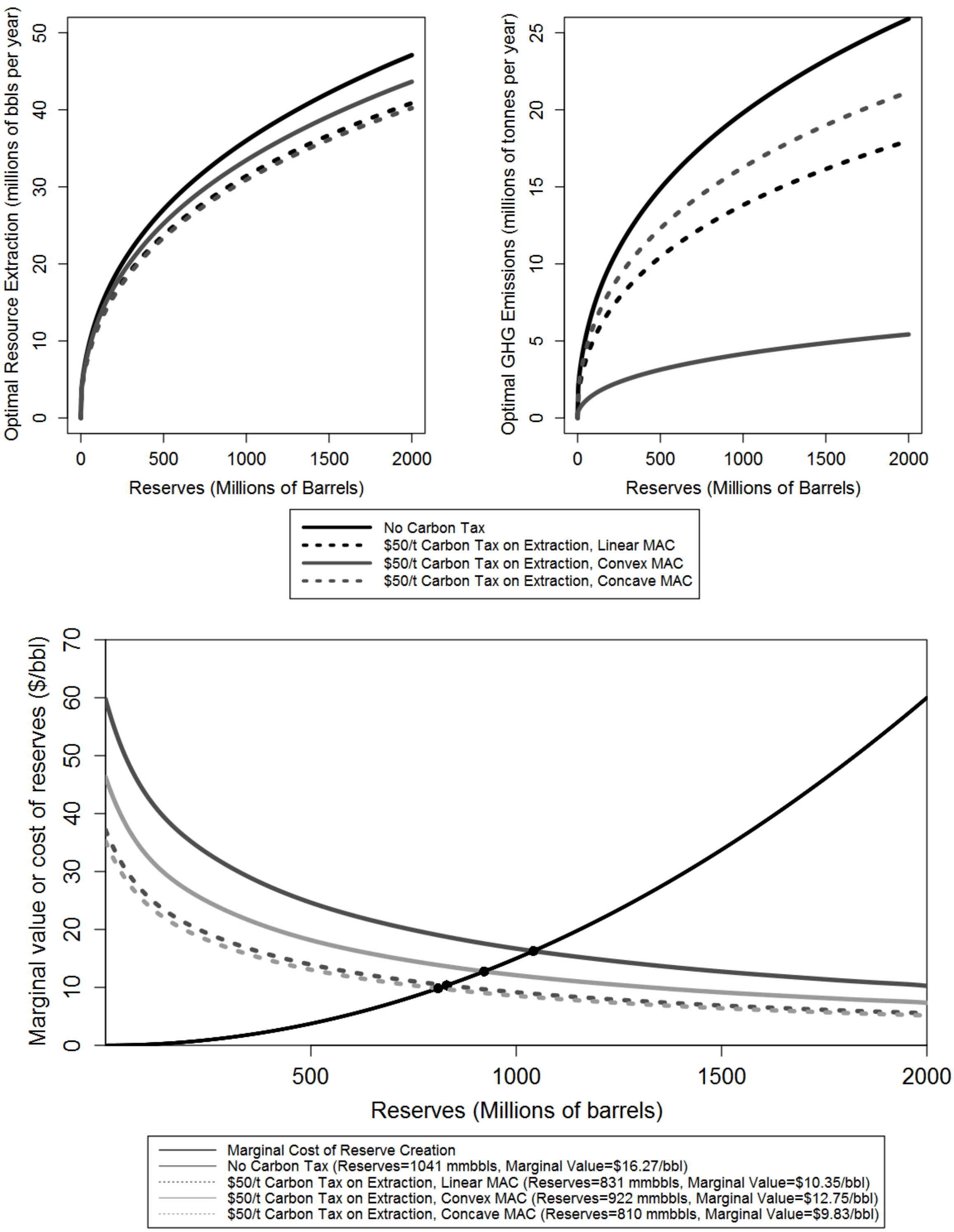

Figure 14: Optimal extraction and emissions decision rules (top) and reserve creation (bottom) with linear and convex marginal abatement cost curves

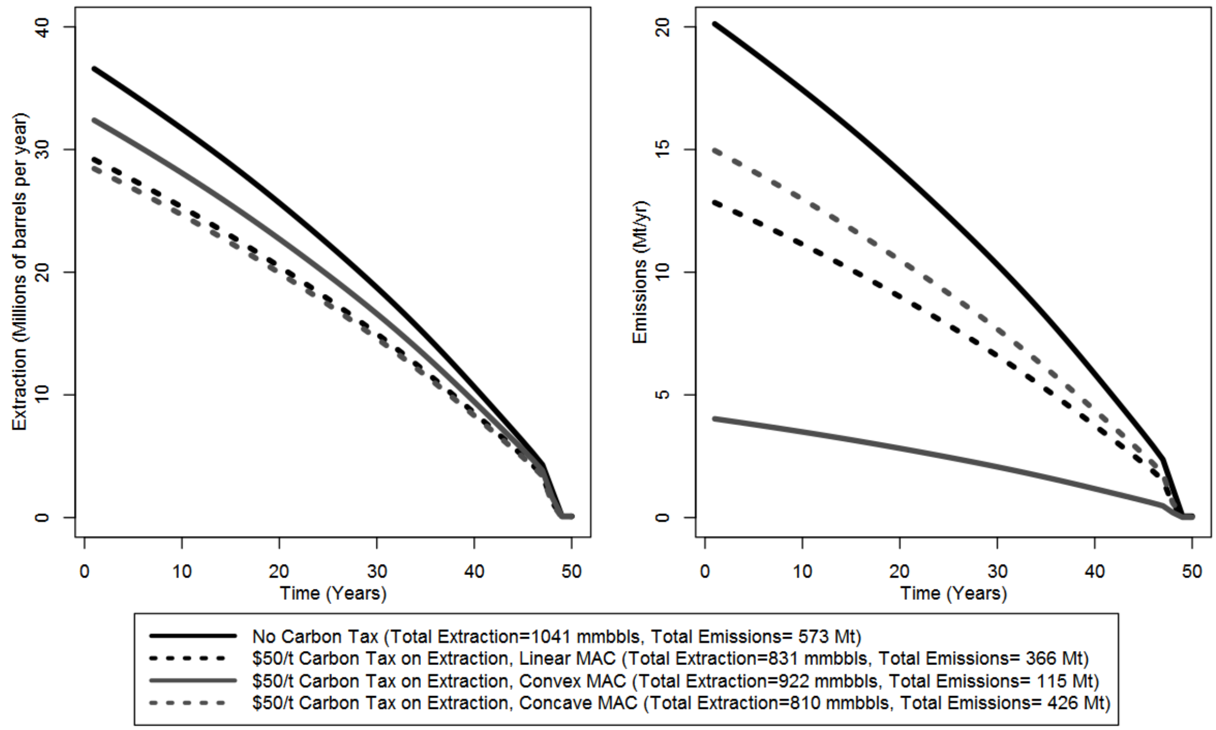

Figure 15: Equilibrium extraction and emissions over time with and without a carbon price, with linear and convex marginal abatement cost curves

When the two channels are combined, we see in Figure 15 that the extraction paths pivot and the *green paradox* result is apparent. With the lower-cost abatement technology – the convex marginal abatement cost curve – more barrels are extracted. However, the technology in this case is sufficient to reduce emissions intensity enough to overcome this effect and emissions are substantially lower even with more extraction when abatement costs are lower.

4 Conclusions

A large literature has analyzed the effects of carbon pricing, including for the context of non-renewable resource development. As a general rule, this literature neglects the potential for climate policy to impact the process of reserve development, *i.e.* the endogeneity of nonrenewable resource reserves. Because extraction follows from proven reserves, the preceding remark implies the extant literature misses an important channel through which carbon pricing can affect the trajectory of emissions stemming from extracted fossil fuels. Our paper fills these gaps in the literature.

In models with exogenous reserves, carbon pricing is restricted to affect only the intensive margins of extraction and emissions. When reserves are endogenous, the effect of carbon pricing is amplified: the carbon costs increase the average cost of production, thereby reducing the value of creating reserves. Thus carbon pricing reduces the amount of reserves created and, as a result, reduces cumulative extraction and emissions.

Because carbon pricing affects not only the marginal but also average cost of production, the endogeneity of reserves complicates the effect of carbon pricing. In particular, other factors that are irrelevant in a setting with exogenous reserves can interact the carbon price by changing its average cost. In this paper, we focus on three factors: (1) emissions credits, provided through output-based allocations, (2) resource royalties, and (3) the shape of the abatement cost curve. These factors interact with the carbon price by changing the average cost of carbon, thus altering the quantity of reserves which are profitably recoverable and, as a result, altering overall extraction and emissions. These interactions typically mitigate the effect of the carbon price – in some cases, offsetting significant portions of the emissions reductions caused by the pollution price.

Our findings have several implications. First, our results indicate that incorporating endogenous reserves is critical to assessing the effects of a carbon price. Even further, incorporating the extensive margin and accounting for interacting factors is likely important for other sectors as well. Second, our results imply that setting optimal carbon policy is not independent from other policies that are perhaps tangential or second-order considerations for climate policy. Our results suggest that in order to achieve a given set of greenhouse gas emissions reductions from nonrenewable resource producers, policymakers need to be aware of the interactive effects of their policies and how it may affect the creation of reserves which, in turn, can largely determine cumulative emissions.

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