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Leakage and Avoided Emissions from Oil and Gas Production:

Private Mineral Rights, Voluntary Carbon Credits & Payments for Conservation

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> *[P]urchasing fossil-fuel deposits, with the intention of preserving them, may be the best possible climate policy.*
>
> *– (Harstad, 2012, pg.79)*

INTRODUCTION

On June 29, 2021, the Canadian Net-Zero Emissions Accountability Act (Canada, 2021a) became law. This Act started Canada on a path toward "net zero" by 2050. Net zero demands that economic activities are either emission-free—power, for example, will be exclusively generated by hydro, nuclear or renewables—or that other steps are taken to offset unavoidable emissions.[1] Building on the Government's initiative, several high profile Canadian firms have also promised net zero operations by 2050 or sooner.

Achieving net zero will require a wide array of policies, program and strategies. "Supply-side" carbon reduction approaches are likely to feature prominently on the road to net zero.[2] Supply-side initiatives include providing incentives to firms such they avoid undertaking high-emitting activities. In particular, supply-side instruments may play a leading role in fairly and equitably decarbonizing Canada's hydrocarbon sector.

Private firms frequently own the rights to energy resource deposits. These rights give companies choices. For instance, one choice involves extracting and marketing oil and gas, earning a margin on exploration and development activities. (Extraction of energy is the primary method of exercising mineral rights.) There is an alternative, however. Rights-holders can opt to not extract the resource. Instead, they can place an easement on the reserves, keeping fossil fuels in the ground and avoiding emissions associated with energy extraction and combustion. Indeed, third parties may be willing to pay rights-holders for this easement. Paying firms to avoid emissions from fossil fuel extraction is an emerging, "supply-side" approach to climate change, one that is garnering greater attention and one that may help support Canada's push towards net zero.[3]

Paying oil and gas companies to avoid production is controversial. Many view these firms as a fundamental cause of climate change and environmentalists often seek to void all claims—without compensation—to emitting resources. This analysis takes as given that mineral rights held by oil producers, that they are transferable and that these rights are treated similarly to other property rights. It asks what occurs if certified payments-for-conservation are consummated, without judging whether the recipient should have this option available.

Critically, pay-for-conservation transactions pose a risk for buyers. When paying existing rights-holders to avoid emissions from oil and gas extraction, buyers need to ensure that they obtain actual reductions in global emissions and that they are paying for environmental improvements. To verify that payments for avoided extraction do lead to lower global emissions, firms on both sides of the transaction frequently ask third parties to certify the level of emissions abatement, often by creating tradeable carbon credits. Carbon credits provide arm's-length authentication that buyers are paying for legitimate emissions reductions. This brief discusses one challenge that arises when issuing credits for carbon emission abatement: the economics of leakage.

Climate change is a missing market problem.[4] Countries, households and companies, without preemptory government policy, are free to emit harmful CO_2 into the atmosphere because there are few mechanisms to prevent it. Establishing private credit markets helps to correct this missing markets problem by making carbon emissions a tradeable commodity. When emissions abatement is costly, companies with high abatement costs, but who are still committed to reducing emissions, will seek to buy reductions in emissions from companies with low abatement costs.[5] These transactions can lead to gains from trade and lower overall emissions.

Yet, while carbon credits facilitate emission mitigation at lower overall cost to society, private offset markets must ensure integrity and be viewed as credible (Rivers et al., 2021). Credible carbon credits must clearly address permanence, additionality and leakage (Murray, 2008).

Permanence involves establishing mechanisms to verify that emissions-reducing activities are "permanent" and not merely shifted to a future date. Payments for avoided extraction in the oil and gas sector, as an example, must be legally-binding, longstanding commitments. Rights-holders cannot unilaterally decide to extract oil and gas at some point in the future, after they have been paid to keep the fuel in the reservoir.

Additionality means that, after issuing a carbon credit, global emissions must be less than in a counterfactual scenario where the credit was not issued. When paying to avoid emissions from foregone hydrocarbon extraction, this means that deposits receiving credits must be "in-the-money".[6] It must be economic to develop the resource and, but for the compensation paid through the carbon credit mechanism, a reasonable expectation is that the energy would be extracted and combusted. Inherently unprofitable deposits are not additional as payments to avoid extraction do not change decisions and issuing a credit yields no change in global emissions.

Leakage is the final criteria in credit design and the focus of this policy paper. Leakage means that emissions cannot be shifted to another location where they remain uncontrolled. Leakage occurs because energy suppliers and consumers interact through markets. It is imperative to understand how carbon credits change incentives in markets to appreciate the prospective scale of leakage. This paper presents a conceptual framework to think about the margins of spatial leakage. It then discusses how to benchmark leakage rates using elasticities of supply and demand. (Leakage can also be intertemporal. The Appendix discusses intertemporal leakage.)

The mechanism driving the leakage dimension of carbon credits is summarized as follows. Private actions that avoid extraction (and emissions) by permanently eliminating reserves from global oil and gas supply induce higher product prices.[7] Higher prices pull new supply in to the market. This new supply, energy that is only economic due to higher prices, neutralizes some of the conserved deposits. The resulting reduction-in-reserves to reduction-in-emissions is, therefore, less than one-to-one. This partial neutralization of supply is what is known as leakage. Leakage is due to economic dynamics arising from interactions in energy markets, and, as Prest and Stock (2021, pg.7) state, its "rate is determined by supply and demand."

Leakage is an empirical problem, requiring a methodology for its measurement (Prest and Stock, 2021). Unlike permanence, which is observable, leakage requires estimating a counterfactual state of the world.[8] Counterfactual analysis compares the observed state of the world with a state that is functionally identical but-for the change induced by the carbon credits. Evaluating leakage depends on comparing the as-is scenario to a but-for world where the difference is the payment for avoided emissions from energy extraction and combustion, all other factors held constant. The counterfactual scenario differs from the as-is world only with respect to the carbon credits, enabling a certifying agency to isolate the effect of the action and exclude changes arising from other causes. Because the counterfactual scenario is never observed, it must be estimated, or benchmarked, using models. Requiring an estimated counterfactual does not undermine the prospect for real and meaningful reductions in emissions from payments for avoided hydrocarbon extraction.[9] But it introduces challenges for determining how many carbon credits should be issued for particular actions, such as avoiding emissions from oil and gas extraction.

QUANTITY OF HYDROCARBONS EXTRACTED, EMISSIONS MITIGATED AND LEAKAGE

Leakage arises because oil and gas are traded in markets. Leakage comes from both within and cross-market sources. A graphical model highlights the sources and causes of leakage. (Mathematical formula and an extended discussion are contained in the Appendix.) A simple two-region model illustrates this where the regions are connected through global trade. To maintain expositional simplicity, the discussion focuses on the market for oil.[10] Refer to the distinct markets as the participating, or "credit", market and the non-participating, or "non-credit", market. A credit market contains credit-seeking firms. This is the region where rights-holders are willing to place an easement on their resources to remove them from the global supply chain in exchange for verified carbon credits. Without these carbon credits, the rights-holders would extract and sell their resource. Non-credit markets cumulate other markets, so encompass all non-participant resources

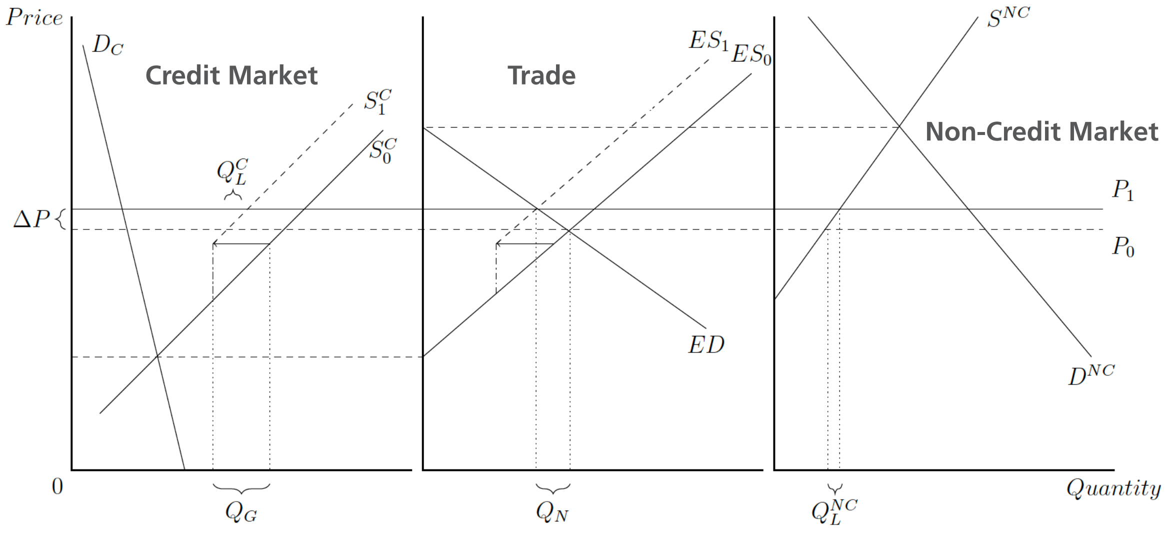
The intuition for why market interactions lead to leakage is illustrated in Figure 1.[11] Figure 1 contains three panels. The left-hand graph represents the credit market. The right-hand panel is the non-credit market. The central panel illustrates that markets are connected via trade and economic interactions.

Both the credit and non-credit markets have supplies of oil reserves, shown, respectively, by the upward sloping S^C and S^{NC} curves. Reserves are characterized by the amount of fuel in the ground and the costs to extract it. Standard, well-behaved supply functions are assumed with resources ordered according to extraction costs. The corresponding demand functions in the credit and non-credit markets are denoted with D^C and D^{NC}.

The central panel in Figure 1 reflects global trade in oil. ED is the excess demand for oil. It is the demand from markets in excess of what can be supplied in an autarkic state at current global prices. ES_0 corresponds to the pre-conservation excess supply. It represents the additional oil that the credit market supplies to the world over and above its local demand (at current global prices). The intersection of ED and ES_0 yields the global equilibrium price of oil. As shown in the figure, (prior to credit-seeking firms exercising their rights to conserve resources) initial prices equal P_0, shown by the horizontal dashed line.

Consider what happens when a credit-seeking rights-holder sets aside a share, Q_G, of its reserves, where the G indicates that it is the "gross" amount of oil conserved. To start, conserved reserves must be additional. They must be in-the-money and economical to extract at forgoing prices. Additionality constrains credit-seeking firms to conserving resources that have extraction costs that are less than P_0, the prevailing pre-credit market price of oil. These are reserves located on the supply function below the current equilibrium price level.

Figure 1: Leakage with Multiple Markets and Trade



Removing Q_G deposits from the credit market causes the credit market's supply curve to become discontinuous, producing a step function. At the point where the deposits are removed, supply jumps up and S_0^C shifts to S_1^C. This shift is shown by the left-pointing arrow at the location (and extraction cost level) where reserves are preserved. The supply function remains unchanged for deposits that have lower extraction costs (i.e., to the left of the jump). Of note, this discontinuity makes the supply function more inelastic and, all else constant, leakage is smaller with inelastic supply functions.

Taking Q_G offline causes a corresponding change to the excess supply function in the global market. The excess supply curve, ES_0, shifts to ES_1, at the point where the shift occurred in the credit market. A corresponding left-pointing arrow replicates the credit market in the global market. Also, as in the credit market, lower cost reserves in the global market remain unaffected.

Conserving Q_G is the first step. Less supply, holding the demand curve constant, yields higher prices. Higher prices, in turn, pull additional oil supply into production from both the non-credit and credit markets. It is because conserving Q_G induces additional supply, there is leakage. Determining the emissions abated, and the number of carbon credits that are warranted, for conserving Q_G, requires calculating how much of this conservation is offset by production induced by higher market prices.

The right-hand panel of Figure 1 represents the non-credit market. There is a cross market effect from higher global oil prices. As prices increase, additional oil supply is added from this market. Production equal to Q_L^{NC} is newly supplied by the non-credit market. The elasticity of the non-credit supply function, S^{NC}, determines the magnitude of Q_L^{NC}. An elastic supply function implies that Q_L^{NC} is larger. If S^{NC} is inelastic, Q_L^{NC} and cross-market leakage are smaller.

Additional oil supply also comes from within the credit market. This is shown by Q_L^C in the left-hand panel. As in the non-credit market, the magnitude of the Q_L^C depends on the credit market's elasticity of supply. Q_L^C and Q_L^{NC} represent marginal quantities that were unprofitable at pre-credit prices (i.e., when Q_G was in market), but are economic once Q_G is removed and the prevailing price has increased to P_1.

To restate, Q_L^C and Q_L^{NC} are leaked barrels that are brought to the market because conserving the Q_G reserves causes prices to rise by ΔP. It is a market interaction (i.e., a price increase) that made previously out-of-market reserves viable. Total barrels of oil conserved are shown by Q_N in the trade panel, where

$$Q_N = Q_G - \underbrace{(Q_L^C + Q_L^{NC})}_{\text{Leakage}} \tag{1}$$

Leakage, therefore, has two components: domestic, or within market, leakage and foreign, or cross market, leakage. The relative sizes of Q_G, Q_N, Q_L^C and Q_L^{NC} depend on the magnitudes of the price response, ΔP, which, in turn, depends on the elasticities, or slopes, of the demand and supply curves.

Q_N reflects the net change in oil production. It is this amount of production, not Q_G, that should receive carbon credits in proportion to emissions. Assuming proportionality between CO_2 emissions and oil production (i.e., no extraction heterogeneity), let e represent emissions per barrel. Emissions mitigated and total carbon credits, Γ, would, therefore, equal $\Gamma = eQ_N$.[12]

Figure 1 shows that reserves just slightly below the P_0 level were removed from supply. These reserves are additional, but, among additional reserves, they are relatively high cost resources. They are marginal and barely in-the-money. These reservoirs earn the smallest scarcity rent and are the most likely to be conserved. Yet, these are precisely the deposits that should be targeted. Indeed, as Hoel (2013, pg.13) states: "Removing the highest-cost [additional] resources has an unambiguously good effect on the climate."[13] Because relatively low cost reserves earn larger inframarginal returns (i.e., scarcity rents), they have a higher opportunity cost of conservation compared with deposits higher on the supply curve.

Related, additionality and leakage are inversely correlated through the price level. At elevated prices, it is more likely that a given reserve will be in-the-money and additional. As prices increase, the elasticity of supply also declines as it is marginally more costly to bring new reservoirs into production. Lower elasticities of supply imply lower leakage rates. Therefore, the positive relationship between price and additionality is complemented by the negative relationship between price and leakage.

BENCHMARKING LEAKAGE

The framework developed in the previous section can be used to benchmark quantitative leakage rates and to determine emissions avoided from foregone extraction of oil and gas. Two illustratitve examples put numbers to the leakage rate, focusing on the roles of supply and demand responsiveness. The central challenge in measuring leakage is the determining the counterfactual state of the world. Oil markets are complex. Many factors, including macroeconomic events, geopolitical developments, expectations and technology influence price paths and production decisions. Disentangling these factors is difficult and models are needed estimate these counterfactual states of the world at particular point in time. The economic model of supply and demand, parameterized using elasticities of supply and demand, facilitates benchmarking these counterfactuals.

Range of Leakage Rates for Different Elasticities

Prior to discussing the examples, it is useful to consider how the leakage varies with the elasticities of supply and demand. The relationship between the responsivenesses of supply and demand and the leakage rate is illustrated in Figure 2. Figure 2 contains two panels, a leakage "surface" and a contour plot. These plots present the same information, but via distinct formats.

Figure 2a is a surface plot with elasticities in the horizontal plane and the leakage rate plotted vertically. The elasticity of demand is a negative number; values from 0 to -1.5 are plotted. Equivalent positive elasticities of supply, ranging from 0 to 1.5, are used. As a touchstone, a reasonable benchmark value for the long-run elasticity of demand is -0.8, with a value of 0.4 for the elasticity of supply.

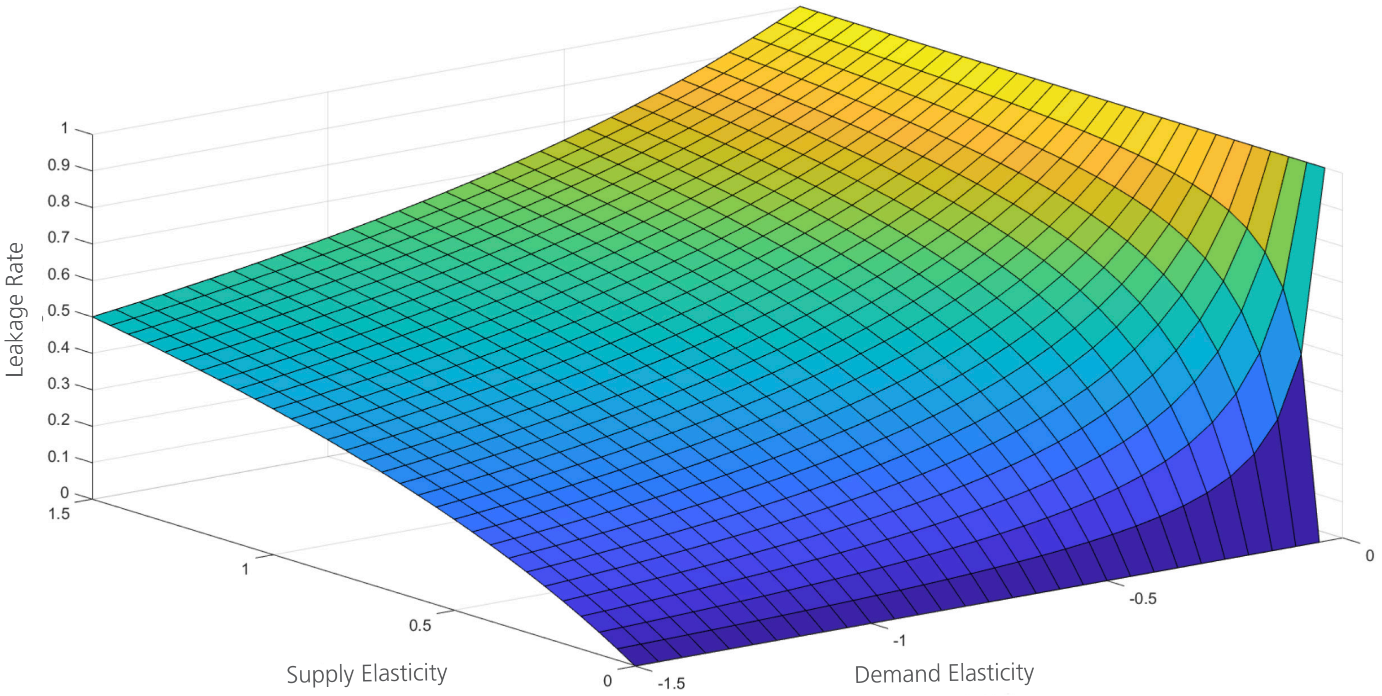
Two important points are evident in Figure 2a. First, when the elasticity of supply equals 0, there is no leakage. An elasticity of supply of 0 means that producers are not able to respond to changes in prices. Therefore, removing existing supply from the value chain cannot induce marginal barrels, or the associated leaked emissions, into the market. More generally, the smaller the elasticity of supply, i.e., the more inelastic is supply, the smaller the leakage rate and the surface slopes down as the elasticity of supply approaches zero.

Second, a perfectly inelastic demand function has an elasticity of 0. Perfectly inelastic demand leads to complete leakage, as buyers are willing to pay any price to induce additional, replacement supply. Yet, generally, a more elastic demand, in contrast to the pattern with supply, yields smaller leakage. This trend can be seen in Figure 2a as the surface slopes downward as the elasticity of demand increases (in absolute value).

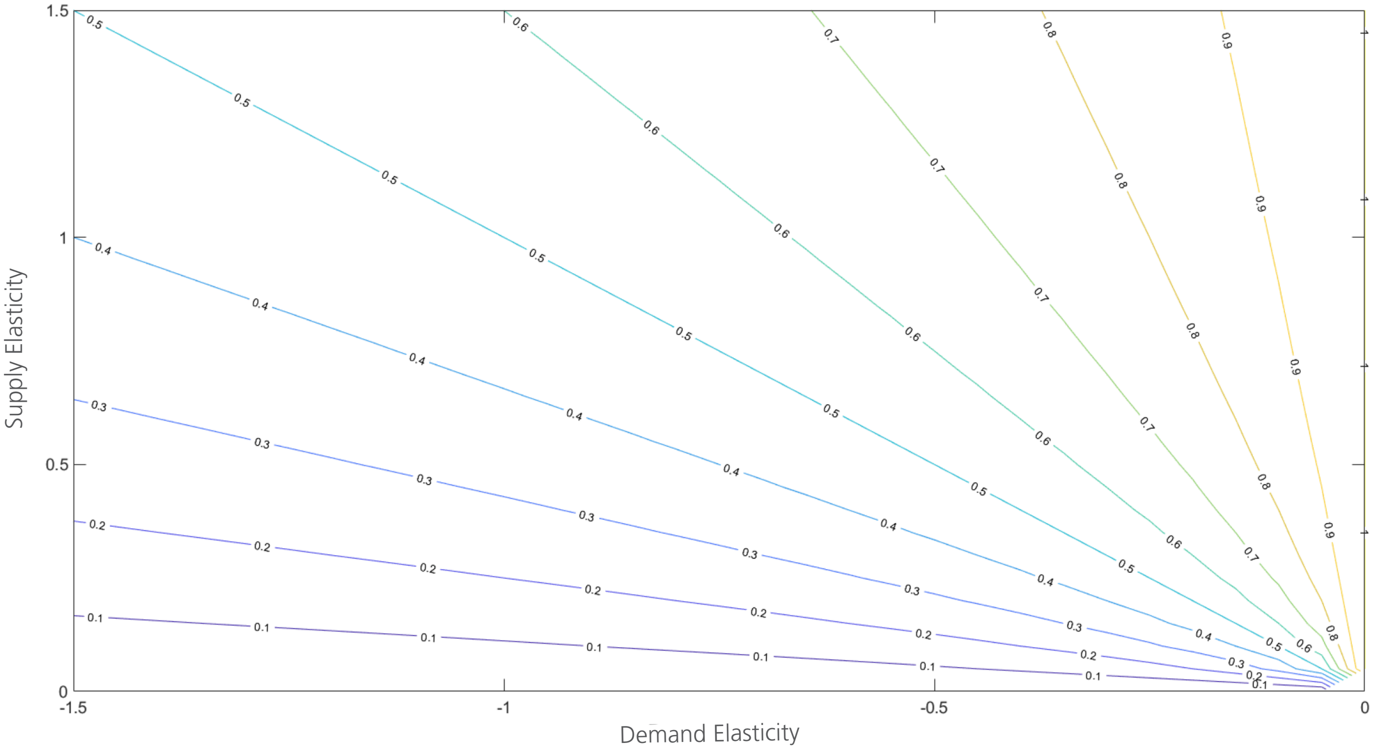
While the surface in Figure 2a shows the full range of leakage rates for combinations of supply and demand elasticities, it can be challenging to read. Figure 2b provides an alternative snapshot of this information. Figure 2b is a contour plot. It is a graph that shows the level sets of leakage rates. Each curve in Figure 2b holds the leakage rate fixed and illustrates which combination of supply and demand elasticities produce that leakage rate. The elasticities of demand are plotted horizontally. If, for example, this demand elasticity equals -1.0 and the corresponding supply elasticity, a value plotted vertically, is 0.1, the level set of the leakage rate is shown as 0.1. This means that 10% of the conserved resource is lost due to leakage. The 45^o line is where the elasticities of supply and demand are equal (in absolute value). As shown in the figure, the leakage rate equals 0.5, or 50%, along this diagonal. Level curves above this diagonal have greater leakage rates, while those below have lower rates.

Figure 2: Sensitivity of Leakage Rate to Changes in Supply and Demand Elasticities

(a) Leakage Rate Surface



(b) Leakage Rate Level Sets in Elasticity Space



Examples of Benchmarking Leakage

Two hypothetical examples demonstrate how to use various estimates to benchmark leakage for prospective projects. The first example is for a small project in the Alberta oilsands. The second represents a Bakken development. Both are purely illustrative and not meant to reflect any specific asset. Simply, they show the steps and inputs needed for benchmarking leakage of prospective credit-seeking deposits. The oilsands example emphasizes the calculation of leakage rates, while the components of emissions mitigated are highlighted in the Bakken scenario.

Alberta Oilsands

Consider a situation where 250,000 barrels per day of oil from the Alberta oilsands region are conserved in a region with 3,000 days of total production. Assume that production is from a mine, rather than in situ. Bošković and Leach (2017) show that the lifecycle emissions per barrel of oilsands mine production is 0.535 tCO_2. For comparison, Carnegie Endowment (2021) estimates that the Cold Lake project had life-cycle emissions 0.667 tCO_2 per barrel, while an Athabasca mine has emissions equal to 0.729/bbl. Conservatively, assume that gross emissions conserved for these rights equal between 400-500 $MtCO_2$. This gross estimate needs to be adjusted for both leakage and to accommodate the differential emissions-intensity of the marginal replacement barrel.

First, the leakage rate can be calculated by using formulas and elasticities presented in the Appendix. Schaufele and Winter (2021) estimate the Alberta-specific elasticity of supply for the Alberta heavy oil and bitumen market. They find a value of 0.11, consistent with the values presented in Table B.1 of the Appendix. Alberta contributes approximately 3% of global oil production. Assume an elasticity of crude oil demand of -0.5. This is more conservative (i.e., more inelastic) than the long-run elasticities of roughly -0.8 suggested in Dahl and Sterner (1991). The leakage rate therefore is:

$$\lambda = \frac{0.03 * 0.11 + (1 - .03) * 0.15}{0.03 * 0.11 + (1 - .03) * 0.15 - (-0.5)} = 22.9\%$$

The net-of-leakage rate is 77.1%. Thus, every barrel of oil conserved should be credited with reducing 77.1% of its emissions (assuming additionality and permanence).

To be clear where the values for this calculation came from, the 0.03 value is because the credit-seeking market, Alberta, represents 3% of production. The elasticity of supply in this region is assumed to be 0.11, alongside an elasticity of demand of -0.5. The non-credit-seeking market is assumed to have an elasticity of supply of 0.15. Using these values along with the formula in the Appendix yields 0.229 and a net-of-leakage rate of $1 - \lambda = 1 - 0.229 = 0.771$ or 77.1%.

A similar situation is taken up by Bošković and Leach (2017). They find a net-of-leakage rate of 35% after market adjustments (i.e., the leakage rate is 65%).[14] So, using a reasonable and conservative interval for the net-of-leakage rate equal to 25% to 65% for this (hypothetical) oilsands rights-holder implies gross of adjustment emissions mitigated will equal 140 $MtCO_2$ to 375 $MtCO_2$.

The purpose of this exercise is to demonstrate the scope of leakage for prospective supply-side initiatives. Yet, so far the calculation overlooks the fact that oilsands production has above average extraction emissions-intensity. Alberta oilsands production is among the most energy intensive in the world. So, there is a high probability that the marginal barrel replacing the preserved oilsands barrel has lower lifetime emissions. Removing an oilsands barrel from the crude oil supply function has a disproportionately larger effect on abated emissions than removing a barrel from a lower emissions-intensity source. Consider, for example, the per barrel emissions estimate of 0.43 tCO_2 associated with the Niobrara play in central Wyoming (Carnegie Endowment, 2021). Use this as a benchmark intensity for leaked barrels. Each barrel of oilsands crude emits 0.535 tCO_2. Adjusting for differential emissions means that there is a 0.105 tCO2 per barrel benefit from preserving the oilsands assets.[15] Adding this additional emissions-intensity adjustment to the previous estimates implies that emissions mitigated from this hypothetical example are between 168 $MtCO_2$ and 385 $MtCO_2$.

Bakken Field, North Dakota

A second example considers a credit-seeking rights-holder operating in the Bakken Field of North Dakota. Assume that this rights-holder wants to (permanently and additionally) conserve 10M barrels of production. The Bakken formation is characterized as a light, sweet crude, often requiring deep wells and hydraulic fracturing. Benchmarking emissions abated and leakage is illustrated in Table 1, where the rows correspond to distinct components of an emissions abatement calculation.

Using estimates from the Carnegie Endowment (2021), it is possible to fill in the Table's rows. Two leakage scenarios are presented. Scenario I has barrels leaked to nearby Wyoming, while scenario II has barrels replaced from drilling in Texas' Eagle Ford play.[16]

Table 1 shows that the per barrel life-cycle emissions of a barrel of Bakken oil equal 0.471 tCO_2 (Carnegie Endowment, 2021). A leaked barrel from Wyoming has life-cycle emissions of 0.467 tCO_2, while one from Eagle Ford has 0.477 tCO_2 (Carnegie Endowment, 2021), giving adjustments of -0.04 tCO_2 and 0.06 tCO_2, respectively. The net-of-leakage rate is calculated using the formula in the Appendix.. The supply elasticity is roughly the midpoint estimate from Smith and Lee (2017), equal to 0.4. A demand elasticity of -0.8 is used, corresponding to the midpoint estimate in Dahl and Sterner (1991) and Brons et al. (2008). This is less conservative (i.e., more elastic) than the one applied in the Alberta oilsands example. The gross volume of oil seeking credits is 10M bbl.

Table 1: Example: Mitigated Emissions from Conserved Bakken Oil Prodction

	I	II
Emissions per barrel	0.471	0.471
Source of leaked barrels		
Wyoming	0.467	
Texas (Eagle Ford)		0.477
Net emissions per barrel	0.475	0.465
Net-of-leakage rate	0.70	0.70
Emissions abated per barrel	0.333	0.326
Number of barrel seeking credits	10M	10M
Total emissions abated	**3.33M**	**3.26M**

Table 1 shows that conserving a gross 10M barrels of production from the Bakken field is the product of three terms: a emissions factor, the net-of-leakage rate, and the number of barrels seeking credits. This formula then gives the net emissions abated, which equals approximately 3.3M tCO_2 after accounting for leakage. Assuming the permanency and additionality criteria are satisfied, 3.3M tCO_2 of carbon dioxide are not emitted compared with a counterfactual scenario where the operator chooses to extract and market the resource.[17]

CONCLUSION

To ensure integrity, carbon credits must be permanent, additional and account for leakage. These three criteria apply to all crediting programs including those designed to compensate mineral rights-holders for avoiding emissions from oil and gas extraction. Leakage, the focus of this brief, occurs because of market interactions. Suppliers and consumers of energy interact almost exclusively in markets. Because of these market processes, fewer emissions will be abated than correspond to the gross volume of an oil and gas resource conserved. It is necessary for credit issuing organizations to adjust the gross deposit size for this leakage.

While the theory of leakage is straightforward, the empirics of leakage requires understanding the properties of different projects and energy markets. Three rules-of-thumb will help guide the development of empirical leakage benchmarks in practice:

- **Estimate project-specific parameters where possible.** Where data are available for specific markets, project proponents should estimate project specific elasticities. Tailoring models to projects reduces the risk that the proponent will miss out on value or that there is greater leakage than expected.

- **When project-specific information is not available, rely on elasticities from survey papers.** If it is not feasible to estimate project-specific elasticities, certifying organizations should rely on the academic literature. The academic literature on energy elasticities is large and can be daunting. Focusing on surveys, reviews and meta-analyses is advised. As a guideline, benchmark leakage rates appear to fall in the 30% to 65% range.

- **Update methodologies and benchmarks regularly.** The Oxford Principles on carbon credits recommend updating methodologies as research improves and with experience (Allen et al., 2020). This applies to benchmarking leakage too. Leakage rates should be updated as conditions in oil and gas markets evolve.[18] New estimates also reflect technological changes, the role of government policies and the evolving incentives of market participants. Leakage rates and benchmarking methodologies should be continuously updated to best practice.

A | MATHEMATICS OF LEAKAGE

Leakage arises through interactions in energy markets. Reducing supply in one region, increases price, providing an incentive for producers to bring previously uneconomic supply to market. This price-induced production comes both from within market and cross market supply. This basic mechanism is described in several articles including Lazarus et al. (2015), Harstad (2012) and Murray (2008). The following derivation is a variant of de Gorter et al. (2011).

Start with the static equilibrium condition in the oil market and then subtract the conserved quantity, $\tilde{q}$:[19]

$$\underbrace{D(p) = S^{NC}(p) + S^{C}(p)}_{\text{Initial Equilibrium}} - \tilde{q} \qquad (2)$$

where $D(p)$ is demand as a function of price. A common "global" demand function is used, with responsiveness of demand to price assumed constant across markets. Supply in non-credit markets is given by $S^{NC}(p)$. Supply in credit (participant) market is $S^{C}(p)$. Extraction costs and elasticities may differ in these two markets so they are treated as distinct. For example, oilsands production has a different technological profile – and, consequently, responsiveness to price – than off-shore rigs in the North Sea. Let $\phi = \frac{S^C}{S^{NC}+S^C}$ be the fraction of total output that is supplied by the participant, credit market.

$\tilde{q}$ is the quantity of prospective oil supply that is preserved and is assumed to be in-the-money. This is equivalent to Q_G in Figure 1. Because of leakage, carbon credits should not be issued for this amount of oil. Leakage requires a discount as, due to the price effect in energy markets, some portion of the saved oil will be offset by reserves pulled into the market from the higher prices.

Totally differentiating (2) gives the price response from the conservation activities:

$$\frac{dp}{d\tilde{q}} = \frac{1}{S_p^{NC} + S_p^{C} - D_p}$$

The price responsiveness depends on the slopes of the supply and demand functions. These slopes are given by the partial derivatives with respect to price: S_p^{NC} for the non-participant market, S_p^{C} for the credit market and D_p for global oil demand.

Leakage in the non-credit market, Q_L^{NC} in Figure 1, is given by the additional supply induced in the non-credit market by the price increase. This equals:

$$\frac{dS^{NC}}{d\tilde{q}} = \frac{dS^{NC}}{dp}\frac{dp}{d\tilde{q}} = \eta_{NC}\frac{S^{NC}}{p}\left(\frac{1}{S_p^{NC} + S_p^{C} - D_p}\right)$$

where η_{NC} is the elasticity of supply in the non-credit market. Higher prices also induce an own-market increase in supply and leakage, Q_L^{C} in Figure 1. This leakage is calculated as:

$$\frac{dS^{C}}{d\tilde{q}} = \frac{dS^{C}}{dp}\frac{dp}{d\tilde{q}} = \eta_{C}\frac{S^{C}}{p}\left(\frac{1}{S_p^{NC} + S_p^{C} - D_p}\right)$$

with η_C being the credit market elasticity of supply. These expressions can be combined to calculate total leakage, written in elasticity form, as:

$$\lambda = \frac{\phi\eta_C + (1-\phi)\eta_{NC}}{\phi\eta_C + (1-\phi)\eta_{NC} - \varepsilon} \qquad (3)$$

where ε is the price elasticity of global oil demand. $(1 - \lambda)$ is the net-of-leakage rate, the rate used to determine the number of carbon credits for a given volume of oil conserved.

(3) is the key formula for calculating the leakage rate. The numerator of (3) is a the weighted average of supply elasticities, with weights determined by each market's contribution to the global oil market. The denominator includes the elasticity of demand, highlighting that the incidence of higher prices is split between demand and supply in accordance with their responsiveness to price. It is possible to simplify (3) slightly. If the elasticities of supply are identical across credit and non-credit markets, $\eta_C = \eta_{NC} = \eta$, or if the contribution of the credit market to global oil production is very small, then this collapses to the familiar market incidence formula:[20]

$$\tilde{\lambda} = \frac{\eta}{\eta - \varepsilon} \tag{4}$$

where $\tilde{\lambda}$ represents the simplified leakage rate. Figure 2 applies (4) to illustrate the sensitivity of leakage to various supply and demand elasticities.

(3) and (4) focus on the effect of price on the quantity of fuel produced. Carbon credits are issued for emissions abated, however. Units of oil (or gas) need to be converted to emissions. Emissions abated from conserving a specific resource, after a unit change, can be approximated as (Fowlie and Reguant, 2018):

$$E_i = \bar{e}_i \tilde{q}_i (1 - \lambda) \tag{5}$$

This equation is comprised of three components. $\bar{e}_i$ is the emissions factor. This is the sum of foregone emissions on the oil subject to the easement in region i, e_i, plus an adjustment factor, Δe_{ij}.

$$\bar{e}_i = e_i + \Delta e_{ij} \tag{6}$$

e_i is the up- and downstream emissions factor for a given fuel type. For instance, the Gordan and Feldman's (2016) estimate of 0.48 tCO_2e per barrel of oil. $\Delta e_{ij} = \bar{e}_i - \bar{e}_j$ represents represents an adjustment factor for the difference in upstream emissions between the barrel covered by the easement and the marginal barrel that replaces it. This replacement barrel could either be comprised of a weighted average of upstream credit and non-credit market emissions or it may represent the upstream emissions of the most likely source of leaked barrels. As an example, assume a low cost, light sweet crude barrel is replaced one-for-λ with heavy oilsands production. Extraction of an oilsands barrel is more emissions-intensive. If $\bar{e}_i$ is the upstream emissions from a barrel of light sweet crude (which is included in the e_i term) and $\bar{e}_j$ is the upstream emissions from the oilsands, then the additional extraction emissions arising from the marginal, "leaked" barrel needs to be subtracted from the emissions receiving credit under a verification scheme.

The second component of (5) is $\tilde{q}_i$, the volume of oil covered by the easement. This is the choice variable of the project proponent. It is the gross volume of energy conserved (e.g., Q_G in Figure 1). Finally, $(1 - \lambda)$ is the net-of-leakage rate.[21]

A.1 Summary of Mathematical Derivation

The critical formula for a certifying agency is expression (5): $E_i = \bar{e}_i \tilde{q}_i (1 - \lambda)$. This formula yields net-of-leakage emissions mitigated from avoided oil and gas extraction. Net-of-leakage avoided emissions, E_i, are the product of three terms:

1. $\tilde{q}_i$, the volume of resource seeking carbon credits
2. $\bar{e}_i$, the emissions factor
3. $1 - \lambda$, the net-of-leakage rate

First, $\tilde{q}$ is the choice variable of the rights-holder. $\tilde{q}$ represents the gross magnitude of the reserve that the credit-seeking energy producer wants to (permanently) conserve, receiving carbon credits as compensation. It is measured in units of energy such as barrels or cubic meters. The magnitude of this volume is determined by geological models of the resource pool, the legal extent of the mineral rights and satisfying the additionality criterion for carbon offsets.

Second, reserves must be converted to emissions. This is done by multiplying $\tilde{q}$ by $\bar{e}$, the emissions factor. The value of $\bar{e}$ is determined by both engineering and economic factors. Engineering models determine the per unit emissions associated with each unit of energy extracted (e.g., the extraction and consumption emissions from a barrel oil). Organizations such as the Carnegie Endowment (2021) provide these estimates. For instance, a barrel of Canadian SAGD dilbit has an emissions factor of 0.60 tCO_2 (Carnegie Endowment, 2021). The emissions factor also needs to be adjusted for leakage. A portion of this barrel will leak due to economic factors, so the economic dimension of the emissions factor adjusts for differentials in extraction emissions. If leakage for the Canadian SAGD barrel accrues to, say, the Bakken shale, a play with an emissions factor of 0.47 tCO_2, there is an additional 0.13 tCO_2 avoided per gross barrel conserved. Bakken production has a lower life-cycle emissions intensity than does Canadian oilsands production, so this swap, even with full leakage, entails lowers emissions compared with the counterfactual outcome. To reiterate, gross emissions factors are determined by the geology and engineering of the conserved resource, but adjustment factors (i.e., emissions differentials) depend on economic processes, indicating to which alternative resources are the source of leaked barrels.

Finally, $1 - \lambda$ is the net-of-leakage rate. This term captures the economic mechanism underlying leakage. As described, credit-seeking firms remove resources from the supply chain. This leads to higher prices which, in turn, pulls new resources into the market. Some portion of the conserved resource is offset by these new resources. The magnitude of this offset is called leakage and is determined by the economic interactions of supply and demand. Only the net volume of energy resources, measured in units of emissions (e.g., tCO_2), should receive carbon credits. The net-of-leakage rate provides information on how the total level of emissions changes as a consequence of the rights-holder's decision. It is calculated using elasticities of supply and demand as shown in (3) and (4).

B | ELASTICITIES OF OIL SUPPLY AND DEMAND

Benchmarking expected leakage rates for projects requires numbers from actual markets. The academic literature offers guidance on these parameters. The initial section briefly discusses the most common methodology for estimating elasticities of supply and demand before presenting several estimates from the academic literature.

B.1 Standard Econometric Methodology to Estimate Energy Supply and Demand Elasticities

The standard approach to obtain elasticities of energy supply and demand involves specifying and estimating an econometric model.[22] Assuming a linear demand-supply specification:

$$\begin{aligned} \text{Demand:} \quad & q_{it}^{d} = \psi_1 p_{it} + x_{it1}' \beta_1 + u_{it1} \\ \text{Supply:} \quad & p_{it} = \psi_2 q_{it}^{s} + x_{it2}' \beta_2 + u_{it2} \\ \text{Equilibrium:} \quad & q_{it}^{d} = q_{it}^{s} \end{aligned}$$

where q_{it} is the quantity of, say, oil in region i and period t, p_{it} is the price of oil in region i and period t, x' are vectors of other variables (shifters) that may include fixed effects, β_js are vectors of coefficients and the us are the error terms. The parameters of interest are the ψ_js. These reflect the responsivenesses of demand and supply to changing market conditions (e.g., prices) and are the coefficients used to calculate elasticities.

Ideally, an analyst would collect data on prices, quantities and other variables and apply standard least squares regression to each equation, obtaining the necessary coefficients. The challenge with equation-by-equation, least squares estimation is that u_{it1} is correlated with u_{it2}. Price is said to be "endogenous" in the demand function and we obtain a "biased" estimate of the elasticities with ordinary least squares regression. Bias means that the recovered parameter, $\hat{\psi}_1$, does not represent the true population parameter, ψ_1 (on average, even as the sample gets large). To avoid bias, analysts apply a method known as instrumental variables. Instrumental variables uses cost shifters x'_{it2} to identify the elasticities of demand and demand shifters x'_{it1} to identify the elasticities of supply. The argument is that x'_{it2} is correlated with p_{it}, but not u_{it1} and x'_{it1} is correlated with q_{it}^{d} but not u_{it2}. Because instrumental variables break the correlation between u_{it1} and u_{it2}, it is possible to recover unbiased estimates of ψ_1 and ψ_2 and, therefore, calculate the elasticities required for (5).

The main challenge in recovering unbiased parameters and eventually calculating leakage involves acquiring appropriate data and identifying valid instruments. For many fuels, data on prices and quantities are opaque or incomplete. For instance, data on gasoline prices and sales is typically readily available, but commensurate data on marine bunker fuel can be more difficult to obtain at appropriate resolutions. Similarly, local institutional knowledge is frequently required to identify valid instrumental variables. Researchers in energy economics often devote substantial energy to overcoming the data and statistical challenges involved in this task. Nonetheless, when possible, it is recommended that proponents attempt to estimate specific elasticities for the their projects.

B.2 Elasticities from the Academic Literature

The academic literature on oil and gas markets is vast.[23] Relying on estimates from this literature can be used to benchmark expected leakage levels without having to collect data and implement an econometric model. Benchmarking involves calibrating (3) or (4) by finding the appropriate elasticities from the academic literature and plugging these into the net-of-leakage rate into (5). Several prominent papers studying supply-side climate policies use calibration to calculate leakage. It is applied in Bordoff and Houser (2015), Erickson and Lazarus (2018) and Bošković and Leach (2017) as examples.[24]

The central question in calibrating leakage is determining which supply and demand elasticities to use. Estimated elasticities can be short- or long-run and may be specific to particular periods or markets. Table B.1 presents a range elasticities, pulled from the academic literature, for oil supply plus oil and gasoline demand.[25] Given the permanence of the carbon credits, long-run elasticities should be used for calculating leakage.[26] Crude oil refining yields a range of products, but gasoline is dominant. Using gasoline elasticities has two advantages. First, there is an extensive and rich academic literature estimating the elasticity of gasoline demand. Second, demand for oil can be viewed, to some degree, as a fixed coefficient derived demand for the demand for gasoline (see footnote 25 for further discussion and derivation). Data on gasoline prices and quantities also tends to be readily available, enabling many estimates over time and across regions. The plethora of studies adds credibility to mid-point values, supported by expansive literature reviews. Indeed, several of the elasticities in Table B.1 are averages from surveys, therefore show greater consistency, but also legitimacy, than the coefficient from any single study.

A more elastic demand function implies smaller leakage. Table B.1 shows five long-run elasticities. Dahl and Sterner (1991), Graham and Glaister (2002) and Brons et al. (2008) are the survey papers that review the large literature on gasoline demand elasticities. Reassuring consisting and stability emerges from these surveys. Collectively they suggest an elasticity of -0.8 to -0.9 for long-run gasoline demand. Notably, these long-run estimates are ten times larger than the short-run estimates (e.g., Hughes et al. (2008); Antweiler and Gulati (2016)). For crude oil, Bornstein et al. (2017) use a larger long-run estimate equal to -1.21 (with a short-run elasticity equal to -0.17).

Finally, Mazraati and Alyousif (2009) estimates short-run fuel price elasticities of aviation fuel equal to -0.08 with income elasticities of 0.55. Mazraati (2011) estimates fuel elasticities of marine bunker fuel, finding an identical short-run value of -0.08. As these estimates reflect short-run responses, their usefulness in calculating leakage is limited. But, as with the gasoline elasticities, long-run values are likely notably greater (in absolute value) than those estimated using short-run variation. Data and price variation on aviation and marine bunker fuels are more challenging to obtain; hence, it is unsurprising that there are fewer available estimates than for gasoline.

Table B.1: Selected Elasticities of Oil Demand and Supply from the Academic Literature

Long-run Elasticities of Demand	
Dahl and Sterner (1991)	-0.86
Graham and Glaister (2002)	-0.77
Brons et al. (2008)	-0.84
Bornstein et al. (2017)	-1.21
Kilian (2020) (short-run)	-0.30
Elasticities of Supply	
Kilian and Murphy (2012)	0.03
Bornstein et al. (2017)	0.16
Caldara et al. (2019)	0.08
Baumeister and Hamilton (2019)	0.15
Estimates using Rystad Model	
Erickson and Lazarus (2018) at $110	0.13
Erickson and Lazarus (2018) at $70	0.46
Erickson and Lazarus (2018) at $60	0.80

Panel B of Table B.1 shows four elasticities of oil supply. The more inelastic the oil supply is, the less leakage. Kilian and Murphy (2012) recommend using a (short-run) value of less than 0.03 for the elasticity of oil supply, with an interval of 0 to 0.045. Caldara et al. (2019) estimate a value of 0.08, while Baumeister and Hamilton (2019) obtain a relatively elastic value of 0.15. Bornstein et al. (2017) estimate short-run elasticities of extraction between 0.08–0.22, with a preferred elasticity equal to 0.16. Supply elasticities are driven by technology and costs. In particular, geological characteristics determine extraction costs – and the ability to vary production in response to economic shocks. Heterogeneity of costs and technologies across regions also makes it more challenging to pin down a consensus elasticity of supply.

The elasticities of supply in Table B.1 are for the global oil market. Smith and Lee (2017) focus on US shale fields, a region with meaningful private ownership of resource deposits. They develop a methodology to obtain a range of elasticities at different price levels for fields including Eagle Ford, Bakkan, Marmaton and Midland Basin Wolfcamp. Their elasticities range from 0.17 at $100/bbl in the Midland Basin Wolfcamp region to 0.54 at $30/bbl in the Eagle Ford region. Overall, they claim that "[t]he overall elastiicty of US shale oil reserves appears to lie between 0.3 and 0.5" (Smith and Lee, 2017, pg.131). Also, Anderson et al. (2018) argue that, due to geological constraints, the relevant (regional, market-specific) elasticity of oil supply is not production's response to price. Rather, they claim that the responsiveness of drilling to variation in price is the appropriate margin. For Texas, Anderson et al. (2018) estimate an elasticity of drilling rig rental with respect to price of 0.77.

Finally, Erickson and Lazarus (2018) base their leakage estimates on elasticities from a Rystad model of global oil supply. Unlike the other values in Table B.1, which were estimated using econometric methods, these are calculated directly, at different price levels, from a proprietary, but widely used, model. At a price of $100 per barrel, oil supply is inelastic (implying low levels of leakage) with an elasticity of 0.13. As prices fall (and demand scenarios change), larger elasticities of 0.46 to 0.80 are calculated. This pattern illustrates the relationship between additionality and leakage. Lower prices imply that fewer resources are additional. Leakage is also greater at lower prices because elasticities of supply are larger.

Table B.1 focuses on the market for crude oil (and gasoline). Global oil markets have dynamics that are largely distinct from natural gas markets. It is less straightforward to discuss general elasticities of natural gas demand or supply. Nonetheless, there are several estimates available for the US. In particular, Daubanes et al. (2021) discuss leakage when there is the possibility of domestic coal to gas substitution alongside international trade in coal but not natural gas. They find that leakage increases in this circumstance and that it is theoretically possible to have a leakage rate that is greater than 100%. Still, for the US, they calculate a leakage rate of 42.5% (pg. 566). Further, Mason and Roberts (2018) demonstrate that well-level natural gas production is driven by geological factors (like Anderson et al. (2018)), but drilling activity is influenced by price. Mason and Roberts (2018) estimate an elasticity of drilling with respect to price of 0.6 to 0.8 in Wyoming. Hausman and Kellogg (2015) estimate an elasticity of drilling activity of 0.81. Newell et al. (2019) obtain an elasticity of drilling activity to price, obtaining an elasticity of production (and reserves) equal to 0.71.

C | INTERTEMPORAL LEAKAGE: EXHAUSTIBLE RESOURCES IN THE LONG-RUN

If the focus on leakage is the long- or very long-run, a pivot in perspective is required. Sinclair (1994) describes that it is not just how much oil is extracted but when that matters. Importantly, under a simple Hotelling model, leakage is a smaller problem and avoiding extraction can imply a permanent elimination of emissions. This appendix sketches the basic Hotelling argument. The seminal reference is Hotelling (1931). See Heal and Schlenker (2019) and Anderson et al. (2018) for recent treatments.

Hotelling provides a model of sectorial equilibrium with endogenous price and quantity, in which producers, at each point in time, determine the amount of oil to be produced. It describes how the owner of an exhaustible resource should manage that resource over time. The essential point is that the owner of a resource will substitute between the present and the future to maximize returns.

A Basic Model

Start with the simplest possible set-up. The following is largely based on Heal and Schlenker (2019). All oil firms want to maximize the present value of profits from a finite resource stock. Assume zero extraction costs. Profits in period t are: $\pi_t = p_t\, q_t$. A firm must decide how much oil to produce each period. Let r be the discount rate.

A model of optimal firm behaviour contains three pieces. First, profit maximizing extraction decisions by firms determine the path of prices over time. Let the initial price be p_0. Hotelling's rule tells us prices evolve according to $p_t = p_0 e^{rt}$ – i.e., they increase at a rate equal to the discount rate.

The logic for this rule follows from a simple inter-temporal arbitrage argument. A two period example makes this evident. Let p_1 be the price in period 1 and p_2 be the price in period 2. A competitive equilibrium must be given by Hotelling's Rule:

$$p_1 = p_2 \frac{1}{1+r} \quad \text{or} \quad (1+r)p_1 = p_2 \quad \text{or} \quad \frac{p_2 - p_1}{p_1} = r$$

What this says is: price in period 2 must be r percent greater than price in period 1.

The arbitrage argument is as follows: a firm has a finite supply of oil (or any resource) that it can sell in either period 1 or period 2. If the price in period 2 was $\tilde{p}_2 > p_2$, then the firm would wait until period 2 to extract its oil. This is because, from the perspective of period 2, oil extracted in period 1 is worth the price obtained in period 1, p_1 plus any return on the profits from their reinvestment, $r * p_1$ per barrel. We know that $(1 + r)\, p_1 = p_2 < \tilde{p}_2$. So it follows that a firm should not sell any oil in period 1 because selling in period 2 is more profitable.

This argument can be pursued further – e.g., waiting to sell oil in period 2 would drive down the price in period 2 and drive up the price in period 1 – but the point is that, in this simplest of models, the price of a finite resource (all else constant) should increase at a rate equal to the discount rate.

The second piece of the model involves defining the stock, $S_0 > 0$, of the resource. This stock is given by nature. Further, the initial price is given by:

$$\int_0^\infty D(p_0 e^{rt})dt = S_0 \tag{7}$$

where $D(\cdot)$ is the demand function. The elasticity of the demand curve only influences the trajectory of the price and extraction paths. It does not influence whether the resource is extracted or left in the ground.

Finally, there is the "choke" or "backstop" price. This choke price is the price at which demand for oil falls to zero because there are cheaper substitutes (e.g., renewables).

Using this simple model to understand very long-run leakage due to an easement

Next, consider what happens when a share, α, is removed from S_0 in perpetuity via a conservation easement. Rewriting (7) gives:

$$\begin{aligned}\int_0^\infty D(p_0 e^{rt})dt &= S_0 - \alpha S_0 \\ &= S_0(1-\alpha)\end{aligned}$$

This new formulation, because there is less of the resource to extract, implies different price and extraction trajectories. But critically, *there is no leakage in the long-run.* This is because the resource is finite or exhaustible and there is no oil with which to replace the αS_0 that was removed. Depending on how the price and extraction paths change, it may appear that there is leakage in the short run. In the very long-run, however, it is not possible to create more oil and emissions will be lower.

Emissions mitigated equal:

$$e = \gamma \alpha S_0$$

where γ is a coefficient representing the conversion of oil to CO_2e (e.g., 0.35tCO_2/bbl). "Leakage" may occur as production today is substituted for production tomorrow, but this is short-run. Over the entire life of the resource, fewer emissions are released. To restate, with a finite resource, there is no leakage in the very long-run; all easement emissions are mitigated. In other words, "[t]he elasticity [of demand] has implications on the timeline of prices and quantity consumed, but not the total amount of oil that will be extracted, which only depends on the extraction cost ... and the costs of the backstop technology" (Heal and Schlenker, 2019, p.19). "[T]he overall emission changes do not depend on the demand elasticity, but the time path does. A larger demand elasticity leads to temporarily larger cumulative emissions reductions as the per-period consumption drops, but these are again offset through a further extension of the time period when the resource is used" (Heal and Schlenker, 2019, p.22).

It is possible to add detail to this simple framework, but most features do not change the qualitative conclusions with respect to leakage. For example, there may be imperfect substitutability between fossil fuels and the backstop technology (e.g., renewables). The simple model implies an immediate and complete switch from fossil fuels to the backstop technology. This is implausible, but it is easy to incorporate imperfect substitutability into a model. Let the demand function be $D(p_t, p^b)$ with $\partial D/\partial p^b > 0$. The price of oil as a function of the backstop technology, $\bar{p}(p^b)$, gives a choke price of $D(\bar{p}(p^b), p^b) = 0$. As $p_t \rightarrow p^b$, we observe a transition from oil to renewables. That is, the demand for oil falls to zero when its price reaches $\bar{p}(p^b)$ (i.e. the choke price is a function of the backstop price), but both technologies exist at the same time. Lowering the choke price, by, say, reducing the cost of alternative energy, makes resource development less attractive.

Similarly, marginal extraction costs vary across grades of oil. This can be added to the model (indeed, this is what Heal and Schlenker (2019) do in their simulation). Let $m_1 < m_2 < \cdots < m_N$ represent marginal extraction costs. Instead of modelling the price path, we trace the path of marginal profit (i.e., the evoluation of $p_t - m_{t,i}$ adheres to Hotelling's Rule rather than $\dot{p}/p = r$). This is a straightforward extension, but doesn't alter the qualitative conclusion as $m_N < p^b$; otherwise, it will never be developed. Marginal extraction costs matter for determining whether a resource is in the money or ever will be. They don't matter for leakage if the resources removed from the supply curve are in the money. (Although technical change might.)

Finally, fixed extraction costs play a role. Assume a fixed cost $F > 0$ must be incurred before a fuel can be extracted at a marginal cost of m. In this case, the fuel will only be produced if the price is high enough to cover both the extraction cost and the fixed cost. The results of Anderson et al. (2018) suggest that fixed costs could be important.

A vital component of the above extensions is that they ignore technical change and resource-specific cost changes. An essential piece of this model is the pace of technical change for (i) the backstop technology and its price and (ii) extraction costs. As renewables become cheaper, the duration until oil is uneconomic shrinks.[27] The key decision threshold for a producers involves a comparison of the expected backstop price, $\mathrm{E}[p^b]$, to the expected returns from producing. With fixed costs, this is boils down to:

$$e^{rT} \geq \frac{rF}{\mathrm{E}[p^b] - \mathrm{E}[m]} + 1$$

Critically, if, for example, extraction costs fall at a faster rate than the backstop technology, then intertemporal (although not necessarily spatial) leakage can be 100%. This is because lower extraction costs relative to the backstop technology imply that oil earns a higher return than alternative sources of energy.

ENDNOTES

[1] The Government's press release suggests "tree planting or employing technologies that can capture carbon before it is released into the air" (Canada, 2021b) as strategies to achieve net zero.

[2] Supply-side instruments are attracting increased attention as effective tools to reduce CO2 emissions from the hydrocarbon sector (e.g., Lazarus et al., 2015). Government sponsored supply-side policies include leasing restrictions on federal lands (Collin, 2021; Gerarden et al., 2020; Erickson and Lazarus, 2018) and levying royalty surcharges (Prest and Stock, 2021), approaches that can be contrasted with demand-side actions such as taxing gasoline or subsidizing investment in energy efficient capital. Demand-side policies target consumption, incentivizing consumers to substitute to less CO2-intensive products or by reducing overall energy demand. Supply-side policies target the production of energy directly. Differences between the effects of demand- and supply-side policies emerge from the rules and institutions involved in implementing them and the types of outcomes that might be expected.

[3] Payments for avoided extraction are analogous to mechanisms used to pay for avoided deforestation within Reducing Emissions from Deforestation and Forest Degradation (REDD) frameworks. Alston and Andersson (2011) claim the main obstacle to REDD's success is poorly defined property rights leading to high transactions costs. As emphasized by Harstad (2012), this problem is less acute for the oil and gas sector as the property rights are more transparent. Indeed, while most attention is on voluntary carbon credit markets, governments have recently pursued pay-for-conservation tactics. As an example, the Government of Quebec passed a law banning future oil and gas development. As part of this bill, they paid producers $100 million to effectively repurchase development rights on existing deposits, in the process paying to avoid future emissions.

[4] Paying for avoided hydrocarbon extraction is an application of the Coase theorem. The Coase theorem states that when property rights are well-defined and there are no transaction costs, bargaining between private agents produces efficient outcomes (Kolstad, 2011). While pollution markets often lack well-defined property rights, Harstad (2012) describes how the complementarity of output and emissions implies that hydrocarbon deposits inherit a pollution property right prior to their combustion or extraction.

[5] Parties may seek carbon credits either to fill compliance obligations or to satisfy over-compliance goals.

[6] On this point, the Oxford Principles for Net Zero Aligned Carbon Offsets state: "Additionality can be difficult to determine and verify, and ultimately involves some degree of subjectivity since the counterfactual world in which the offsetting activity was not performed cannot be observed directly" (Allen et al., 2020).

[7] This is because the supply function becomes less elastic.

[8] This is also true of additionality. Indeed, all carbon mitigation policies, including government regulation, require estimating a counterfactual state of the world. The uniqueness in this setting is that activities are defined, transacted and monitored in a voluntary, private market.

[9] Output and emissions are complements in the production and consumption of hydrocarbons, implying that these rights are non-separable.

[10] Emissions from combustion, while varying by fuel type, are generally proportional to consumed fuel quantities (Phaneuf and Requate, 2016). For example, the EPA (2020) states "The average carbon dioxide coefficient of liquefied petroleum gases is 235.7 kg CO_2 per 42-gallon barrel". Thus, combustion leakage is – to a first approximation – equivalent across markets at 0.24 tCO_2. Gordan and Feldman (2016) find that the average total emissions from an extracted barrel equal 0.48 tCO_2. The Carnegie Endowment (2021), likewise, estimate that total emissions from a Canadian steam-assisted gravity drainage (SAGD) well equals 0.60 tCO_2/bbl. Extraction emissions, in particular, vary according to emissions-intensity of the extraction process and differ by location and resource quality. Heterogeneous extraction emissions is taken up while deriving the mathematical formula for leakage.

[11] Figure 1 represents one depiction of leakage. Others, working through an excess demand rather than an excess supply channel, are also viable.

[12] In reality, extraction emissions differ due to technology and resources quality. As a result, an adjustment is required and emissions are not strictly proportional to energy. In practice, these adjustments tend to be small.

[13] This quote continues: "On the other hand, the effect on the climate of removing lower-cost resources is ambiguous from a theoretical point of view" (Hoel, 1996, pg.13). Ambiguity arises because of potential heterogeneity in the emissions profiles due to extraction. For instance, if a low cost barrel with commensurately low extraction emissions is replaced with a high cost barrel that has high extraction emissions, the benefits of conserving the low cost barrel are less. In the extreme, it is possible, although exceedingly unlikely, that the differential on extraction emissions could offset the net-of-leakage savings from the initial conservation activity.

[14] To provide a comparison to the Alberta experience, Fæhn et al. (2017) find that the net global reduction in emissions from reduced Norwegian extraction equals 51% in the oil market.

[15] This means that, for this example, even if leakage were 100%, there is a 0.105 tCO_2 per barrel benefit from swapping oilsands for EPA barrels.

[16] Choosing where barrels leak to only matters for determining the adjustment to the emissions factor. As is evident from Table 1, these adjustments tend to be small.

[17] Gross of leakage emissions mitigated equal 4.7M tCO_2, implying that roughly 1.4M tCO_2 leak due to market forces.

[18] Elasticities are not invariant to price, as an example. Thus, the leakage rates will also vary with prices.

[19] That is, $\tilde{q}$ is the change in the market from the initial equilibrium position.

[20] There are several methods to derive similar expressions for the leakage rate. As one example, the leakage rate can be determined from a sufficient statistic framework via a model set-up from a social planner's perspective. This formulation is based on Prest and Stock (2021), who build on Hoel (1996), Holland (2012) and Fæhn et al. (2017).

Let total fuel consumed be the sum of quantity in credit, C, and non-credit, NC markets: $Q = Q^{C} + Q^{NC}$. As in the main text, credit refers to a market with production removed via an easement while non-credit markets do not sell any carbon credits. Consumer utility is an increasing function of fuel: $U(Q)$. Emissions, E, are proportional to consumption $E = eQ$ with e representing the tonnes of CO_2 emitted per unit fuel. Damages from CO_2 emissions are given by $D(E)$.

A social planner optimizes the following social welfare function by choosing how much quantity, $\tilde{q}$, to permanently set-aside in the fuel market (measured in units of emissions) (i.e., the planner is choosing how much $\tilde{q}$ to remove from the market to balance marginal benefits and costs from CO_2 emissions):

$$max_{\tilde{q}} W(Q) = U(Q) - C^{C}(Q^{C}, \tilde{q}) - C^{NC}(Q^{NC}) - D(E) + \theta \tilde{q} E^{C}$$

where $\theta = \frac{dD}{dE}$ is marginal damages due to CO_2 emissions (alternatively, it is the marginal benefit from abating a tonne of emissions), $C^{C}(Q^{C}, \tilde{q})$ is the cost of producing fuel in the covered market and $C^{NC}(Q^{NC})$ is the cost function in the uncovered market. The first-order condition is:

$$\frac{\partial U}{\partial Q}\left(\frac{\partial Q^{C}}{\partial \tilde{q}} + \frac{\partial Q^{NC}}{\partial \tilde{q}}\right) - \frac{\partial C^{C}(Q^{C}, \tilde{q})}{\partial Q^{C}}\frac{\partial Q^{C}}{\partial \tilde{q}} - \frac{\partial C^{C}(Q^{C}, \tilde{q})}{\partial \tilde{q}} - \frac{\partial C^{NC}(Q^{NC}, \tilde{q})}{\partial Q^{NC}}\frac{\partial Q^{NC}}{\partial \tilde{q}} - \theta\frac{\partial E}{\partial \tilde{q}} + E^{C} + \theta\tilde{q}\frac{\partial E^{C}}{\partial \tilde{q}} = 0$$

Market clearing implies $\frac{\partial U}{\partial Q} = \frac{\partial C^{C}}{\partial Q^{C}} = \frac{\partial C^{NC}}{\partial Q^{NC}}$ and the envelope theorem implies $\frac{\partial C^{C}}{\partial \tilde{q}} = E^{C}$. Thus, the first-order condition simplifies to:

$$\tilde{q} = \frac{\partial E / \partial \tilde{q}}{\partial E^{C} / \partial \tilde{q}}$$

This expression should be interpreted as follows. A social planner would optimally set-aside $\frac{\partial E / \partial \tilde{q}}{\partial E^{C} / \partial \tilde{q}}$ units of fuel reserves where $(1 - \lambda) = \frac{\partial E / \partial \tilde{q}}{\partial E^{C} / \partial \tilde{q}}$. λ is less than 1 because the change in global emissions, E is less than the change in emissions in the credit market, E^{C}. λ is the leakage rate.

See Murray (2008), Harstad (2012), Phaneuf and Requate (2016), Fowlie and Reguant (2018), Fæhn et al. (2017) for alternative expressions for leakage, each of which has a similar form.

[21] This is leakage due to the price effect. It excludes leakage due to the inclusion or exclusion attributable to buffer pools.

[22] There are a range of methods to estimate elasticities and calculate leakage. Rystad, as an example, has a detailed model that includes information on specific assets. Other methods include estimating a reduced-form elasticities (e.g., Fowlie and Reguant, 2018), building structural vector autoregression models as in Baumeister and Hamilton (2019) and Kilian (2008) or developing computable general equilibrium models (see Carbone and Rivers, 2017). Each of these approaches has distinct advantages and drawbacks.

[23] Kilian (2020) presents a recent overview.

[24] Of note, Bordoff and Houser (2015) suggest that increasing US production by 1.2 million barrels per day would increase global emissions by -57 to 168 $MtCO_2$. Erickson and Lazarus (2018) find that cutting 820,000 barrels per day of US production, via leasing restrictions on federal lands, would reduce emissions by 110 $MtCO_2$. The implied leakage rates from these results typically range for approximately 35% to 65%.

[25] A common question is how fluctuations in, say, gasoline or aviation fuel prices influence the price (and, hence, quantity supplied) of oil. Straightforward expressions can be derived to make the relationships precise, however, a good "rule of thumb" is that a one percent change in the price of gasoline translates into a one percent change in the price of oil. The following, derivation is based on Gardner (1975), makes this "rule of thumb" more precise.

Assume competitive product and factor markets. Assume a model with one product, gasoline (x), and two inputs, oil (a), and refining (b). A constant returns to scale refining production function is:

$$x = f(a, b)$$

Demand for gasoline is:

$$x = D\,(\,p_x,\, N\,)$$

where p_x is the price of gasoline and N is a retail demand shifter.

Refiners will buy profit-maximizing amounts of a and b, where the marginal value product equals price:

$$p_b = p_x * f_b$$
$$p_a = p_x * f_a$$

The input supply equations are:

$$p_b = g(b,\, T\,)$$
$$p_a = h(a,\, W\,)$$

where T and W are exogenous shifters.

This gives six equations in six unknowns (x, b, a, p_x, p_b, p_a). Assume normal conditions such as a unique equilibrium and given, exogenous values. Solving for the percent change in the price of oil given a one percent change in the price of gasoline (i.e., via an application of Cramer's rule) gives:

$$E_{p_a \bar{p}_x} = \frac{\sigma + s_a e_b + s_b e_a}{\sigma + e_b}$$

where σ is the elasticity of substitution between oil and refining inputs, s_a is the factor share of oil in the production of gasoline, $s_b = 1 - s_a$ is the factor share of refining inputs in the production of gasoline and $\{\, e_a,\, e_b\}$ are the price elasticities of input demands. As an initial approximation, in the short-run, it is reasonable to assume that $\sigma \rightarrow 0$ and $e_a \approx e_b$. Thus, a one percent change in the price of gasoline leads to a one percent change in the price of oil.

[26] Hughes et al. (2008) suggest that short-run gasoline demand is becoming increasingly inelastic in recent decades, suggesting smaller values (in absolute value) may be more accurate.

[27] Oil producers may anticipate this and actually extract at a faster than otherwise pace. This is known as the "green paradox".

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