Regulating Routine Flaring: Theory and Evidence

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Abstract

Flaring, the practice of burning excess natural gas obtained during oil extraction, is common across oil producing countries. Several multilateral agencies are working to ban routine flaring and economically important jurisdictions have proposed new regulations on the activity. We develop a price-theoretic model demonstrating that routine flaring fundamentally results from economic incentives, specifically, insufficient demand for a lower-valued by-product in a joint production process. This interpretation contrasts with prevailing engineering-based explanations of the practice built into regulatory assessments. Using rich battery-level data from Alberta, Canada, we test the model's predictions and find that a 10% increase in oil prices leads to a 3.1% increase in flaring, while a 10% increase in gas prices reduces flaring by 3.6%. We then exploit a natural experiment, where venting and flaring regulations were imposed on a small region in Alberta, to estimate the causal effects of flaring restrictions. We demonstrate that regulations effectively reduced local emissions; however, we find virtually 100% leakage to unregulated areas. More importantly, we show that the regulations, although nominally on natural gas emissions, primarily impact oil production rather than gas output. This conclusion has important implications for understanding the costs and benefits of regulating methane in the oil and gas sector.

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1 Introduction

Many industrial processes yield multiple products, a high-value main product and a lower-value co-product or by-product. Further, when free disposal is available, the lower-value co-product often becomes a source of pollution, even when markets exist for the output. This is because the costs associated with marketing the co-product exceeds expected revenues, so “wasting” it – i.e., free disposal – is optimal for firms. The dual nature of co-products as both waste and marketable output means that regulating them as pollutants presents unique challenges. This paper evaluates a situation where an otherwise valuable co-product, natural gas, becomes a source of pollution because there is insufficient demand in local markets. We demonstrate, both conceptually and empirically, that imposing regulations on natural gas flaring, the preferred method to dispose of excess gas, effectively imposes regulations on the output of the main, high-value product, crude oil in our setting.

Our focus is oil and gas markets, but joint production and free disposal are features of many industries. Thus, understanding the implications of regulating jointly produced by-products is important beyond the energy sector. For example, blast furnace slag in steel production can be used in cement production, yet a non-negligible share ends up in landfills. Titanium dioxide production yields iron sulfate and iron oxide, potentially marketable products which are typically wasted because of weak industrial demand. Ethanol production generates distillers grains, which can be fed to livestock. However, when there is insufficient local demand, they are simply wasted. Each of these cases represents a situation where there is strong demand for a higher-value product, ethanol, for example, and weak or negligible demand for a lower-value product, distillers grains. Each of these cases also represents a scenario where excess production of the by-product must be managed. The prevalence of joint production underscores the need for estimates of the costs of how regulation trades-off market impacts while maintaining environmental standards.

A feature of our context is that oil producers jointly recover both crude oil and natural gas from drilled wells. When there is insufficient demand for the less valuable co-product, natural gas, relative to the main product, oil, natural gas becomes a pollutant. Excess natural gas is typically freely disposed of via *flaring* or *venting* at the wellhead. Flaring is the combustion of methane and other gases, while venting is the direct release of gas into the atmosphere.[1] Because natural gas is a valuable energy

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[1] While methane, i.e., natural gas, is the dominant co-product from oil extraction, “associated gases” typically include a wide array of other gases, including hydrogen sulfide, pentane, ethane, etc.

source, flaring and venting frequently seem inefficient and uneconomical, especially to non-economists.[2] As such, flaring regulation has garnered widespread attention as a strategy to reduce emissions linked to climate change while bolstering energy security and affordability (European Parliament, 2023; World Bank, 2024; Gordon, 2025).

Flaring regulations are economically important. A recent impact assessment in Canada, for example, pegged regulatory compliance costs at more than CAD$15.4 billion (Canada, 2023). Yet, high compliance costs contrast with the International Energy Association's assessment of the industry. They argue that, even without regulations, "around 30% of the industry's emissions today could be *avoided with measures offering rates of return of more than 25% – well above the usual returns sought by oil and gas companies when considering new capital investment*" (IEA, 2025, pg. 11, *emphasis added*). The contradictory positions appear to be a puzzle: On the one hand, flaring regulations require substantial resource to mitigate the activity; on the other hand, there are opportunities to earn large returns from capturing a valuable co-product, avoiding the "inherently wasteful" practice. This paper reconciles these perspectives by using detailed data on more than 35,000 facilities between 2002-2023 in the Canadian province of Alberta. We measure the implications of regulations by exploiting a natural experiment where a surprise venting ban and flaring restrictions were imposed in a small region within the province. We illustrate that the costs of flaring and venting regulations far exceed existing estimates.

Our analysis starts by developing a price-theoretic model of routine flaring. We emphasize two key ingredients: the joint production of oil and gas and the *extent of the market* limitations for the co-product, natural gas. The novelty of the analysis is that we explicitly incorporate *insufficient demand* into a joint production scenario. When free disposal is available, excess natural gas is wasted whenever the costs of conservation exceed revenues. We then study what happens when free disposal becomes costly. We demonstrate that, when there is joint production and a limited extent of the market, the main effect of regulations nominally targeting the by-product are actually observed as a binding on in the he high-value output.

Three policy-relevant predictions follow from this set-up. The first two illustrate how the conceptual framework links the existing literature on taxing methane emissions from Lade and Rudik (2020) and Marks (2022) to conventional market elasticities estimated by energy economists (e.g., Mason and Roberts, 2018; Arora, 2014, among many others). The third prediction is counter-intuitive, is absent from the literature,

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[2] Salmon and Logan (2013), for example, estimate that flaring in the North Dakota's Bakken formation causes roughly $3.6M in "lost" revenue per day.

and is the main focus of this paper.[3] In contrast to the prevailing engineering characterization of flaring by regulatory agencies (e.g., IEA, 2025; Canada, 2023), the model highlights that firms have *an economic incentive* to flare, even when infrastructure exists to capture and sell natural gas. That is, the fundamental reason for routine flaring is not technological or infrastructure constraints, as previously argued (Lyon et al., 2021; Agerton, Gilbert and Upton Jr, 2023). Rather, a fundamental economic mechanism, insufficient demand for a co-product, driven by joint production and the limited extent of local natural gas markets causes an otherwise valuable output to become a pollutant.

We test the two initial using rich data from Alberta, Canada for the 2002-2023 period. Exploiting exogenous variation in monthly U.S. commodity prices as instrumental variables for regional Alberta prices, we show that a 10% increase in oil prices leads to a 3.1% increase in flaring, while a 10% increase in gas prices reduces flaring by 3.6%. Importantly, as expected, the magnitudes matches expected emission rates derived from previous structural estimates from the North American oil and gas market.

The main prediction of our conceptual framework is that the economic consequences of flaring regulations primarily manifest in oil markets rather than gas markets. Put differently, even though flaring regulations are nominally target natural gas, counterintuitively, compliance primarily occurs by adjusting oil output. Our main contribution involves estimating the direct economic effects of regulating flaring and venting. To do this, we exploit unanticipated changes in local regulations in Alberta. In 2013, Alberta's Peace River region experienced an inordinate number of local odor complaints.[4] These complaints led the provincial regulator, the Alberta Energy Regulator (AER), to impose region-specific venting and flaring restrictions starting in 2014 (AER, 2014). Flaring rules in the rest of the province remained unchanged. We combine this regulatory change with a difference-in-differences research design to estimate the causal effects of flaring and venting regulation at the oil battery level.

To isolate the causal effect of the regulations, we need to overcome two main empirical challenges. First, our analysis is at the battery-level. Thus, our main dependent variables, flaring and venting emissions, are non-negative and contain zeros. Conventional two-way fixed effect estimators may yield biased parameters, when the dependent variable has a skewed distribution. Second, as is well-known, conven-

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[3] Indeed, to the best of our knowledge, the prediction is missing from the discussion of joint production more generally.

[4] Flaring and venting are common with "sour" natural gas, gas with a high concentration of hydrogen sulfide. Hydrogen sulfide has a strong rotten eggs smell.

tional difference-in-differences maintains a *linear* parallel trends assumption. Our data illustrate distinctly non-linear pre-trends. We address these issues in two steps. First, we adopt the *non-linear difference-in-differences* design suggested in Wooldridge (2023). Specifically, we use Wooldridge's (2023) Poission link function to deal with the zeros in measured flaring and venting and formulate an index supporting the common trends assumption. Second, we are fastidious with respect to control windows and groups with which we construct counterfactuals. For example, we want to distinguish between direct and leakage effects. To do this, we separate the batteries into three groups: regulated, nearby unregulated, and the rest of the province. Making different comparisons across these three groups enables us to infer different effects of the regulations.

Several important results emerge from this analysis. First, regulations that ban venting and restrict flaring are effective in achieving their goals. Unsurprisingly, the AER venting ban effectively eliminated venting emissions, while the flaring restrictions curtailed flaring. However, these regulations generated a series of unintended consequences. To start, during a period when the venting regulations were binding but the flaring restrictions were not, there was a large switch from venting to flaring. Previous literature and policy reports acknowledge the possibility of substitution (Calel and Mahdavi, 2020), yet our analysis provides the first empirical confirmation of venting-to-flaring substitution. Subsequently, when both the venting and flaring regulations were binding, as expected, venting and flaring emissions in the regulated region decreased. This decrease was fully offset by an increase in emissions in the proximate, nearby region. That is, flaring leakage was virtually 100%.

Finally, our conceptual framework predicts that the effects of flaring regulations will be principally observed in the oil market. We demonstrate that regulated facilities reduce oil extraction and that the magnitudes are large. The per battery reductions in output equal 1308m^3 of oil per month, roughly equivalent to the average output of active batteries in the province. Further, these output reductions are offset by increased oil production – and higher flaring – in neighboring unregulated areas. We also uncover suggestive evidence of the role of new capital in response to the policy. Legacy operations experienced the most output losses from emissions regulations, while new facilities built after the regulations were implemented reduced emissions and had smaller output reductions.

Several studies address methane regulation in the energy sector.[5] Our paper con-

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[5] Hausman and Muehlenbachs (2019) study methane leaks in regulated the natural gas distribution system. They show how a regulatory system that emphasizes a return on capitalized assets distorts

tributes to a small but growing literature on methane emissions regulation in the upstream oil and gas sector. Flaring, to date, has primarily been attributed to technological constraints or midstream infrastructure limitations (Lyon et al., 2021; Agerton, Gilbert and Upton Jr, 2023). By highlighting the joint production and insufficient demand mechanism, we emphasize the importance of integrating extent of the market considerations into emissions reduction strategies. Spillovers are common in markets characterized by joint production. Further, the existing literature on flaring regulation mainly considers emissions taxes and price-based instruments (Lade and Rudik, 2020; Marks, 2022). We extend this discussion by empirically analyzing non-price regulatory measures such as direct bans and operational restrictions, offering crucial evidence on their impacts and limitations. Our results indicate that while emissions regulations might effectively reduce flaring, at least locally – a finding consistent with Lade and Rudik (2020) and Marks (2022). Effective regulatory frameworks, however, typically comprehensively target all emission pathways and account for potential leakage to achieve genuine emissions reductions.

Finally, joint production has long been recognized as important for understanding overcompliance with environmental regulation (Shimshack and Ward, 2008). We further contribute by considering a situation where the regulated output is sometimes inherently valuable and sometimes a pure pollutant.

2 Natural Gas Flaring in Alberta, Canada

Canada is the world's fourth-largest oil producer (Energy Institute, 2024) and the Canadian province of Alberta accounts for more than 84% of Canadian crude oil production. We study flaring and venting regulations in Alberta. Alberta was among the first oil and gas producing jurisdictions to enact restrictions on emissions from flaring, introducing rules in the late 1990s. Our analysis is at the oil battery level. A battery is defined as one or more wells clustered within a field and operated by the same company. Batteries are the typical connection point for midstream infrastructure and represent the most consistent reporting entity for flaring. Via a Freedom of Information request submitted to the AER, we obtained rich battery-level data on flaring and venting volumes combined with output of oil and gas. Our sample covers the period from 2002 through to the end of 2023. Data are at the month-battery level

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firm incentives to minimize leaks. Mason and Roberts (2018) demonstrate that well-level natural gas production is driven by geological factors.

for 38,500 unique crude oil and bitumen facilities.[6]

Table 1 shows selected summary statistics for the sample. The average oil battery produces 266.9 m^3 per month. However, output declines over the life of an oil well. Eventually, wells are shut-in and recorded at producing zero output. Thus, simple averages understate expected battery output. Panel B shows average output, for wells that are producing non-zero volumes. The mean oil output per producing battery equals 1,313.7 m^3 per month. Further, there is substantial variation at the battery-level. The standard deviation equals 641.5 m^3 in Panel A, increasing to 2,029.4 m^3 for producing wells in Panel B. To convert m^3 to more familiar barrels of oil, note that 1,313.7 m^3 is equivalent to 8262.9 barrels of oil. Assuming an average price of crude oil equal to $60 CAD per barrel, the average producing battery in Alberta yields nearly $500,000 in revenue per month.

Table 1: Summary Statistics on Output and Emissions at the Crude Battery-level, 2002-2023

Panel A: All observations				
	Mean	Std. Dev.	Min	Max
Oil production	266.9	641.5	0.0	6,759.7
Gas production	88.8	232.9	0.0	2,702.6
Gas flared	2.1	7.8	0.0	86.5
Gas vented	1.6	4.5	0.0	43.3
Panel B: Non-zero observations				
Oil production	1,313.7	2,029.4	0.1	6,759.7
Gas production	466.6	804.3	0.1	2,702.6
Gas flared	20.1	25.6	0.1	86.5
Gas vented	4.1	8.4	0.1	43.3

Oil volumes are measured in m^3. Gas volumes are measured in thousand m^3. Data trimmed at the 99% level, dropping the top 1% of batteries.

Oil batteries in Alberta also produce significant volumes of natural gas. The average oil battery in the province produces 88,000 m^3 of natural gas. Producing batteries, as shown in Panel B, yield over 466,600 m^3 per month. The prevailing price of natural gas in Alberta over the 2018-2023 period was approximately $0.10/m^3.[7] Thus, oil

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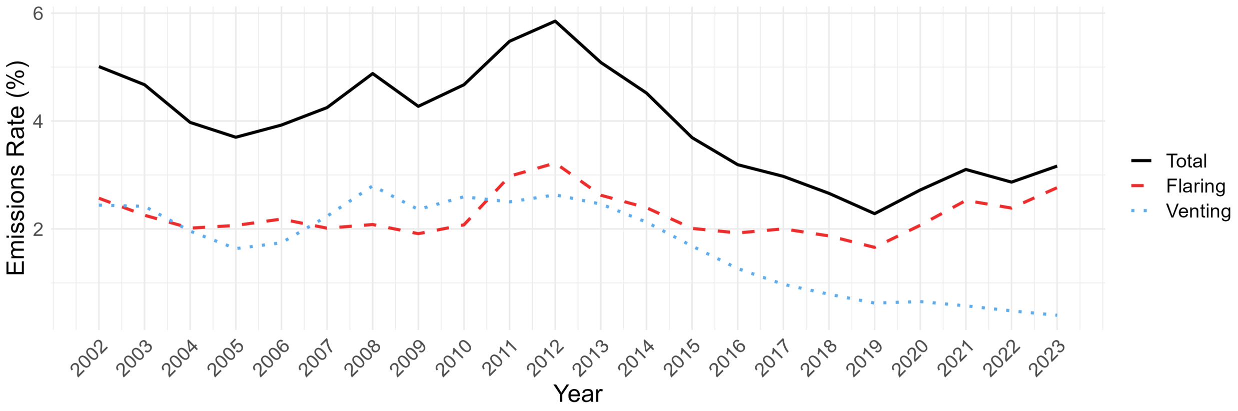
[6] Select "confidential" facitilies are excluded, representing less than 2% of emissions and production in the province.

[7] The annual average price in Alberta over the 2018–2023 period was $2.61/GJ (Government of Alberta, 2024). When converted from GJ to volumes, this equals: $\frac{\$2.61/GJ}{26.3m^3/GJ} \approx \$0.099/m^3$.

batteries earn an additional ~\$50,000 per month on average from selling jointly produced natural gas. As with oil, there is substantial variation around the mean, with a standard deviation equal to more than 800,000 m^3 per month. Panel B also demonstrates another interesting fact. More than 24,000 m^3 of gas is wasted each month. Approximately 20,000 m^3 of gas is flared, while an additional 4,100 m^3 is vented. Assuming a price of \$0.10/m^3, this is equivalent to "burning" \$2,500 per battery-month. Expressed differently, at the battery level, flared and vented gas, if it were not wasted, would equal roughly 0.5% of the revenue earned from selling oil.

Figure 1 adds context to the summary statistics. Figure 1 shows the flaring and venting rates in Alberta over time. As mentioned, Alberta was among the first major hydrocarbon producers to implement flaring and venting rules, initially regulating the practices in the 1990s. This is an important reason why, over our sample period, the flaring rate has been consistently low. Figure 1 shows that total emissions peaked at 6% of associated gas but have leveled off at approximately 3% since 2015. Further, while the venting rate dropped from a peak of 3% in 2008 to about 0.5% in 2023, the flaring rate remained relatively steady at 2-3%. Table A.1 in the Appendix shows flaring rates across selected countries in 2022.[8] Emission rates vary significantly worldwide, but globally flaring rates are reasonably modest at 3.3%, reflecting the dual nature of natural gas as both a valuable product and potential pollutant.[9]

Figure 1: Flaring and Venting Rates



The raw data also highlight the limitations of infrastructure-based explanations of

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[8] Replicating comparable time series for most countries is not possible due to the lack of data on venting volumes and associated gas production. Table A.1 only reports the flaring rates for a set of representative countries in 2022. Venting volumes, which could be substantial, are also not reflected in the table.

[9] Note that this does not account for venting, which may be substantial.

flaring. Flaring and venting persist even in locations where gas capture infrastructure is readily available. Figure 2 categorizes gas emissions in Alberta based on two dimensions. First is a battery's infrastructure connection status. A battery is "connected" if there is a natural gas pipeline that links the battery to a gas processing plant. Second is the proportion of associated gas (i.e., jointly produced gas) marketed relative to total gas production at the battery-level. Figure 2 suggests that we should be skeptical of infrastructure-based explanations for flaring. Less than half of the total flaring and venting emissions are from sites that are unconnected to the natural gas pipeline network. Moreover, the emission shares of connected batteries have remained stable over the sample period, even though batteries come into and fall out of production. These patterns are difficult to reconcile with infrastructure gap explanations for flaring (e.g., Agerton, Gilbert and Upton Jr, 2023).

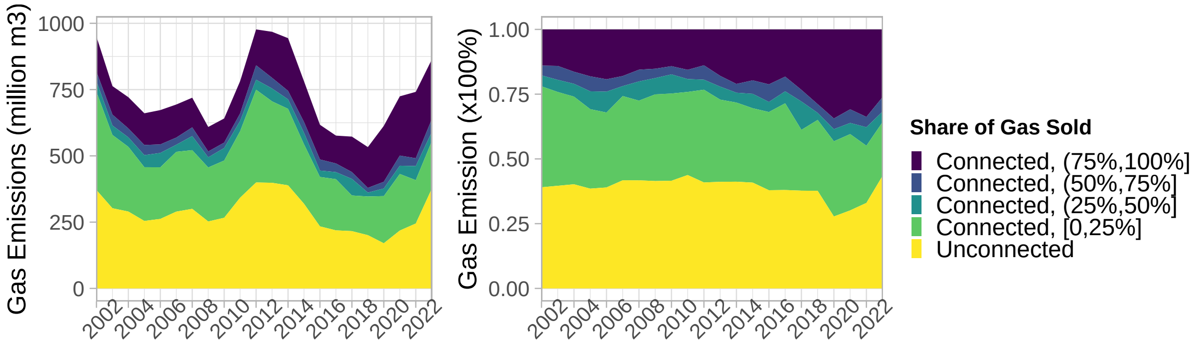
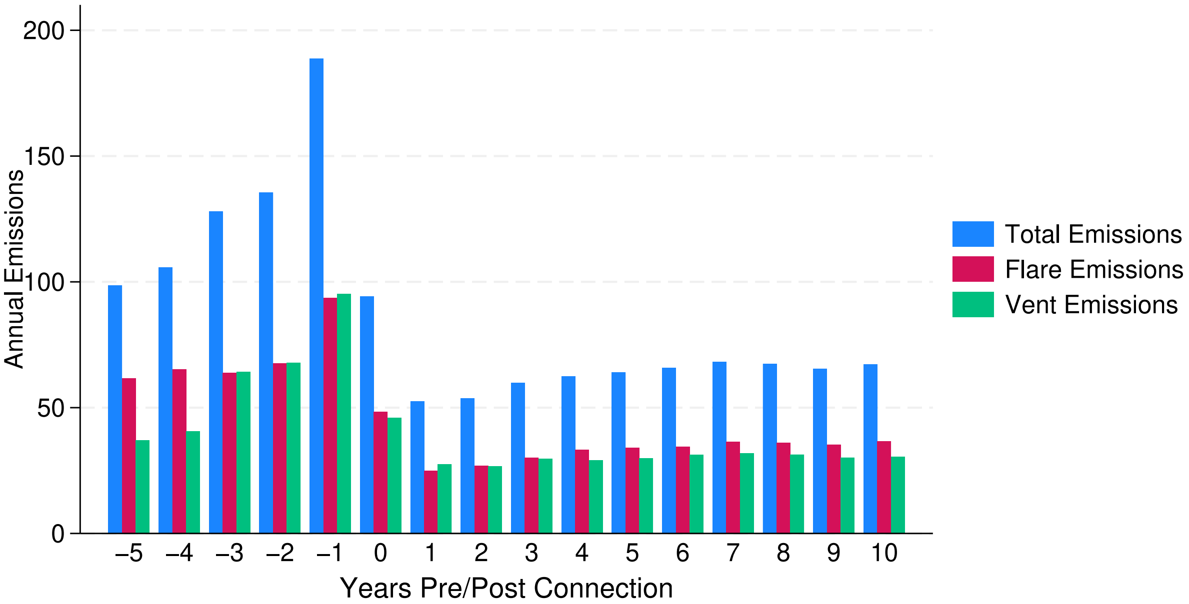


Figure 2: Gas emissions by share of gas sold

Figure 3 expands on Figure 2, offering persuasive evidence against infrastructure-based explanations of flaring. Figure 3 shows per battery flaring and venting emissions before and after they connect to the natural gas network. When a battery connects to the network, emissions decline and more gas is marketed. This is expected and aligns with our conceptual framework. However, connecting a battery to midstream infrastructure does not eliminate flaring and venting. Emissions decline but remain persistent in subsequent years. This underscores the fact that routine flaring is common irrespective of midstream infrastructure constraints. Put differently, forward-looking firms would reasonably right-size infrastructure if the net present value of these expenditures were positive. Our paper contributes to explanations for flaring and venting by moving beyond mere infrastructure hypotheses. We emphasize that an economic mechanism, joint production and insufficient demand, is the primary explanation of flaring and venting. Understanding these economic incentives is important for designing effective regulations.



Notes: Plot includes all batteries connected to a pipeline between 2002 and 2023. Emission units are 1000 cubic meters. Emissions variables have been purged of the following fixed effects in regressions including all operating batteries: battery–type by year, township by year, and age by year.

Figure 3: Gas emissions by share of gas sold

3 Conceptual Framework: Routine Flaring due to Insufficient Demand

Oil reservoirs frequently have associated gases 'in solution.'[10] Upstream firms extract crude oil and simultaneously obtain natural gas as a lower value by-product because gas occurs alongside, i.e., is 'associated' with, oil in the geological formations.[11] That is to say, oil and natural gas are joint products, produced in fixed proportions according to the geological characteristics of the resource.[12] We present a price-theoretic framework that encapsulates these essential characteristics and enables us to formulate three important predictions about the implications of regulating flaring.

Let Q_1 represent oil, the high-value product, and Q_2 be natural gas, the by-product. Joint production implies $Q_2 = \alpha Q_1$ at all production levels. For any volume of oil extracted, an operator obtains αQ_1 of gas. Let P_1 be the price of oil and P_2 of natural gas. The oil market is large and oil is easy to transport internationally. Natural gas

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[10] Associated gases include methane, heavier hydrocarbons and other compounds mixed into or sitting atop oil pools.

[11] In 2022, for example, 96% of batteries in Alberta produced both gas and oil.

[12] Strictly, fixed proportions is unnecessary for our analysis; however, it is a very good approximation for the context we are studying.

markets tend to be more regional, with more limited extent.

Firms facing joint production make decisions based on the dominant product and manage – sell or dispose of – co-products. Insufficient demand for natural gas, as exists in this scenario, means that an operator's marginal revenue from capturing and marketing associated natural gas equals zero. Free disposal implies that operators will optimally "waste" the excess gas via flaring. To see how insufficient demand causes routine flaring, start with a representative operator's optimized profit function, where optimization occurred over the high-value product:

$$\begin{aligned}\Pi^* &= P_1 Q_1^* + P_2(Q_2)Q_2 - C(Q_1^*, Q_2)\\ &= P_1 Q_1^* + P_2(Q_2)(\alpha Q_1^*) - C(Q_1^*)\end{aligned}$$

where Q_1^* solves the operator's profit maximization problem for oil and the second line merely substitutes the fixed proportion equality, $Q_2 = \alpha Q_1^*$. Given joint production, it makes little sense to ask which portion of the drilling costs were the result of oil and which are from natural gas as there is no unique way of allocating costs to the separate products. Thus, $C(Q_1^*, Q_2) = C(Q_1^*)$ is the joint, pre-splitoff cost of production for both oil and natural gas.[13]

There is ample global demand for oil with prices set internationally. Firms take the price of oil, P_1, as given. By contrast, which is large, the demand for natural gas, the less valuable by-product, is more limited and regional. Natural gas is also subject to a series of infrastructure and storage constraints that are assumed non-binding in the oil market (Coburn, 2020).

Given that the firm obtains associated gas αQ_1^*, they decide how much to conserve by solving:

$$\max_{Q_2} P_2(Q_2)Q_2 - \tilde{C}_2(Q_2) \text{ subject to } Q_2 \leq \alpha Q_1^*$$

where $\tilde{C}_2(Q_2)$ is the post-splitoff cost of marketing the associated gas. A firm's optimal volume of gas conserved, Q_2^*, is determined by the first-order condition:

$$P_2'(Q_2^*)Q_2^* + P_2 = \tilde{C}_2'(Q_2) + \lambda \tag{1}$$

where $\lambda \geq 0$ is the shadow price of associated gas due to the joint production process. (Below, when we impose regulations on flaring, a very similar expression, but for oil,

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[13] The splitoff point is the stage in a joint production process where products become separately identifiable. After the splitoff point, costs are also separable.

Q_1, rather than gas, Q_2, will be derived.)

The left-hand side of Eq.(1) is the additional revenue earned by the firm from selling the natural gas. The right-hand side of Eq.(1) is the "full" marginal cost of producing natural gas. It is comprised of two parts. First, there is the marginal cost of marketing gas, $\tilde{C}_2'$. Importantly, this is the marginal cost that is incurred after the splitoff point of the joint production process. The second element is λ. We dwell on the interpretation of λ because an analogous constraint arises when we consider regulating flaring. λ represents the opportunity cost of gas shortages. When demand for natural gas is robust, firms will sell all available gas and flaring will not occur. λ, the shadow price on gas availability, measures how much more gas the firm would be willing to sell if it were a standalone product. Yet, because gas is jointly produced alongside oil, λ captures the willingness of the firm to *deviate from optimal oil production* during the first stage of the decision problem in order to obtain compensating revenue in the gas market. That is, λ connects the two disparate revenue streams for the firm. When there is ample demand for natural gas, the joint production constraint binds, λ is positive and all gas is conserved. When there is insufficient demand, i.e., the extent of the market is too small, $\lambda = 0$ and flaring occurs.

Next, we introduce demand for natural gas faced by the firm (i.e., the residual demand for gas). The inverse demand for natural gas is given by:

$$P_2 = \begin{cases} D(Q_2) & \text{if} \quad Q_2 \leq \hat{Q}_2 \\ 0 & \text{if} \quad Q_2 > \hat{Q}_2 \end{cases} \tag{2}$$

where $\hat{Q}_2$ is the quantity at which the natural market is saturated. At that level, price equals zero and firms would need to subsidize buyers to take additional gas.

Without regulation, operators will not market unprofitable gas when they have access to free disposal. Free disposal means that firms are flaring excess gas. Thus, producers optimally flare an amount equal to:

$$\begin{aligned} \text{Flared Excess Gas} = F &= Q_2 - Q_2^* \\ &= \alpha Q_1^* - Q_2^* \end{aligned} \tag{3}$$

where the fixed proportions constraint is used in the second line. Excess production of natural gas equals $\alpha Q_1^* - Q_2^*$ and the flared difference is denoted as F. To restate, flaring occurs because there is insufficient demand for a co-product in a joint production problem when the firm optimally chooses its output and there is free disposal. In this case, the quantity of gas produced exceeds the firm's full cost of conserving gas.

Figure 4 illustrates a stylized depiction of this market. The demand for oil is given by $D(Q_1)$. The demand for natural gas is $D(Q_2)$. MC is the marginal cost of oil production (i.e., the pre-splitoff point marginal cost, $C_1'(Q_1)$). To reduce clutter, the marginal cost of gas, $\tilde{C}_2'$, is set equal to zero.

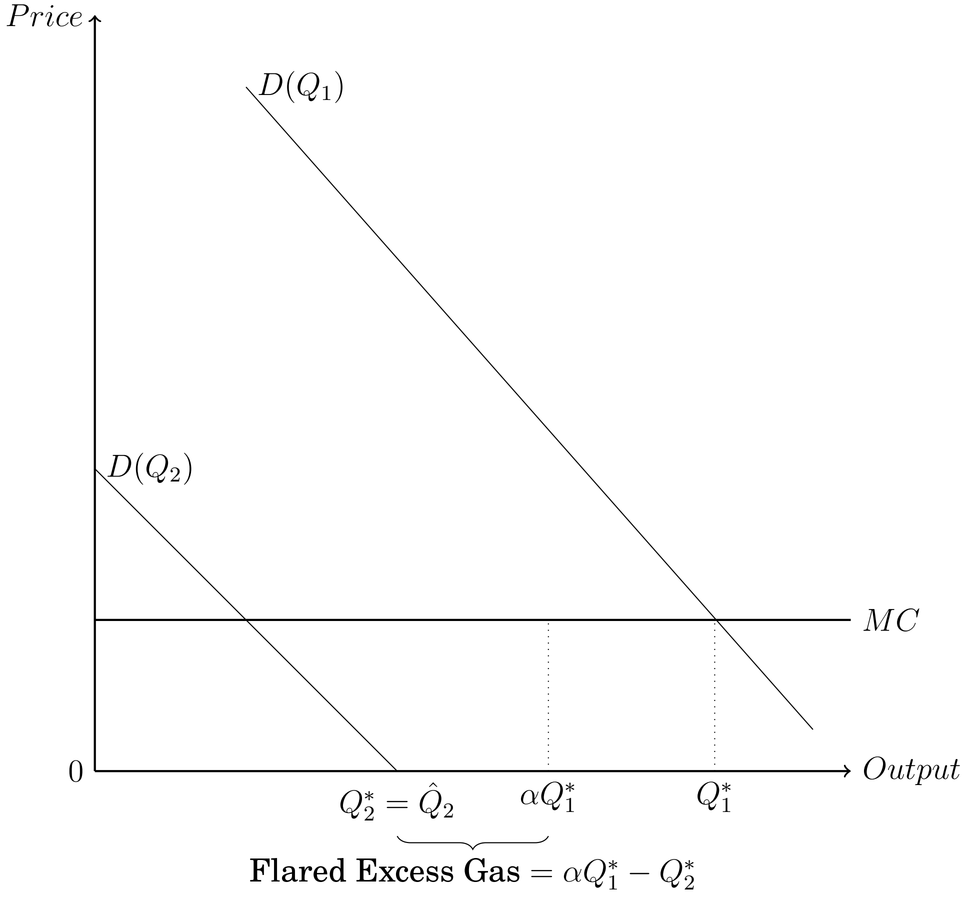

Figure 4: Joint Production of Oil and Natural Gas with Flaring

Because routine flaring is permitted, firms maximizes profits by selecting Q_1^* at the point where price equals marginal production costs. But oil and natural gas are joint products. At the optimal oil production level, the firm obtains a quantity of αQ_1^* of natural gas. Figure 4 depicts a scenario where αQ_1^*, the volume of gas produced, exceeds the market saturation point, $\hat{Q}_2$. There is insufficient demand for natural gas. The extent of the market is too small. Because there is free disposal, the firm will not sell its excess gas at negative prices. Instead, it will opt to flare the excess gas, an amount equal to $\alpha Q_1^* - Q_2^*$ in the figure.

Flaring is a market outcome. Thus, flaring volumes will vary with market conditions, specifically changes in demand for the commodity. By totally differentiating

Eq.(3) with respect to oil and gas prices, two immediate predictions emerge from the model:

$$dF = \underbrace{\alpha \frac{\partial Q_1^*}{\partial P_1} dP_1}_{(A)} - \underbrace{\frac{\partial Q_2^*}{\partial P_2} dP_2}_{(B)} \tag{4}$$

where we assume independent market demands for oil and gas.[14] The first term, (A), represents our first prediction. It captures the oil market effect, namely the effect of changes in oil demand on flaring volumes. If demand for oil increases – e.g., the oil demand curve shifts right in Figure 4 – then, holding other factors constant, equilibrium oil output increases. As the quantity of oil produced, Q_1 increases, so does the volume of associated gas, αQ_1. Flaring volumes thus increase. Similarly, term (B) shows a gas conservation effect. Holding oil demand constant, an increase in natural gas demand – i.e., a rightward shift in $D(Q_2)$ in Figure 4 – yields an increase in Q_2^*. An increase in Q_2^* decreases flaring, F, because of the negative sign leading term (B) in (4).

Oil and gas prices have an intuitive relationship to flaring even as the conceptual framework makes plain the economic causes of routine flaring. Routine flaring is due the joint production of oil and natural gas combined with differences in the level of demand between the primary and by-products. Routine flaring is caused by an insufficient demand for natural gas. Empirically, we evaluate the validity of this model by employing an instrumental variable strategy to test these two "intuitive" predictions with respect to how flaring responds to commodity prices.

3.1 Implications of Regulating Flaring

Next, we consider the implications of regulating flaring when oil and gas are jointly produced. Therein, we obtain our third, counter-intuitive prediction: the effects of regulating flaring, nominally a rule on natural gas emissions, are primarily observed in oil markets.

As above, assume firms maximize profits with joint production characterized by the relationship $Q_2 = \alpha Q_1^*$ and that the joint cost function $C(Q_1, Q_2) = C(Q_1)$ encapsulates all production expenses up to the split-off point, beyond which gas and oil incur separable costs. Regulatory constraints are represented through the imposition of a

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[14] There is substantial evidence that North American gas and oil prices are "decoupled" or independent (Ramberg and Parsons, 2012; Hartley and Medlock III, 2014; Zhang and Ji, 2018).

binding restriction on flaring:

$$F = \alpha Q_1^* - Q_2^* \leq \bar{F},$$

where $\bar{F}$ denotes maximum allowable flaring volume at the battery-level. Setting $\bar{F} = 0$, for example, implies that all gas produced must be conserved, effectively eliminating the option for free disposal via flaring. Allowing $\bar{F} > 0$ implies that the firm is allowed to flare some portion of its associated gas.

Given this regulatory constraint, the firm's first-sage optimization problem becomes:

$$\max_{Q_1} P_1 Q_1 - C(Q_1) \text{ subject to } \alpha Q_1 - Q_2 \leq \bar{F}.$$

which, given the assumption that oil producers are price takers, leads to the optimal level of oil production given by the condition:

$$P_1 = C_1'(Q_1) + \phi\alpha \tag{5}$$

where ϕ is the shadow price of the flaring regulation and $C_1'(Q_1)$ is the marginal cost of joint oil and gas production when optimizing over oil production. Eq.(5) is analogous to Eq.(1), where λ has been swapped with the product $\phi\alpha$.

Similar to above, the regulatory constraint induces a direct link between the markets for oil and gas. In particular, Eq.(5) shows that regulating flaring is equivalent to increasing the marginal cost of producing oil. Specifically, ϕ represents the implicit value *in the oil market* associated with ensuring that the firm complies with the flaring regulation on natural gas.

Whenever there is insufficient demand for a co-product, the excess co-product becomes a pollutant. Free disposal is tantamount to setting $\phi = 0$.[15] When the extent of the gas market is small, flaring regulations lead to $\phi > 0$.

The third prediction of our model then is that, when the extent of the natural gas market is small, there will be insufficient demand for gas. Thus, regulating flaring is equivalent to imposing higher marginal costs on oil production. Higher marginal costs entail less oil production. Put differently, regulating flaring – even though the rules nominally target natural gas emissions – reduces output of the primary commodity, oil, due to the joint production process and insufficient demand for natural gas.

Figure 5 offers a graphical illustration, starting from the initial situation shown in

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[15] Likewise, if the extent of the gas market is large, there will be positive demand for associated gas, such that market demand ensures that $\phi = 0$ and there is no flaring.

Figure 4. Gas sales are limited by the extent of the market, so the flaring constraint binds at $\bar{F}$. This constraint on flaring spillover into the firm's oil production decision through $\phi\alpha$, an amount equal to the shadow cost of the regulation scaled by the joint production proportionality coefficient. The main effect of flaring regulations is to increase the marginal cost of producing oil for the firm. In the figure, this is shown as the marginal cost curve without regulations, $MC_{\text{No Reg}}$, shifting up. The new, effective marginal cost curve is $MC_{\text{w/ Reg}}$. Optimal output, determined by Eq.(5), gives oil output equal to $\tilde{Q}_1$ and corresponding gas output of $\alpha\tilde{Q}_1$. Compared with Figure 4, both flaring and oil production are lower.

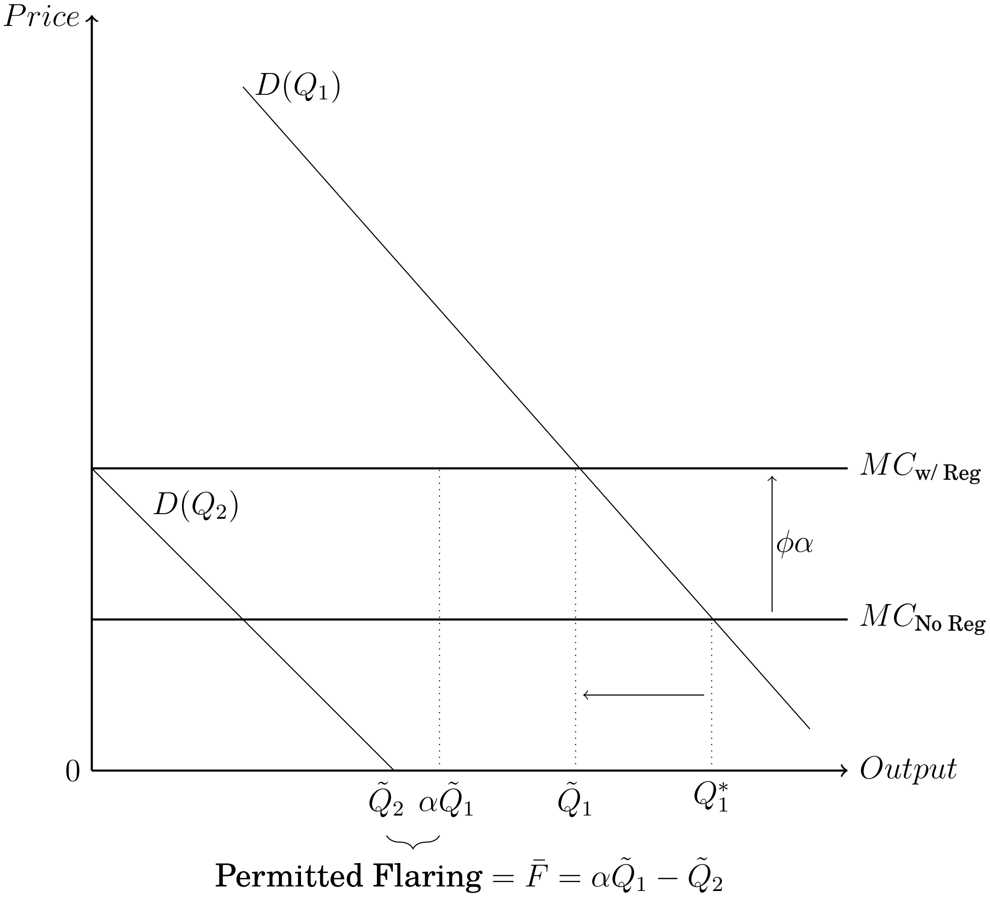

Figure 5: Joint Production of Oil and Natural Gas with Binding Flaring Regulations

Empirically, Figure 5 shows two observable implications of flaring regulations that we test using a natural experiment in Alberta. First, unsurprisingly, there is less pollution. Flaring now equals $\bar{F}$ which is less than F. The regulations ensure that a larger share of the co-product is conserved. In the alternative, less of the co-product is wasted. The more interesting consequence is that oil production decreases by an amount equal to $Q_1^* - \tilde{Q}_1$, where Q_1^* is the level of production in the no regulation state of the world and $\tilde{Q}_1$ is output with regulations. The main contribution of this paper is to empirically estimate the magnitude of this oil market effect.

4 Empirical Evidence of Joint Production and Insufficient Demand Mechanisms

Our conceptual model makes two predictions regarding the effect of oil and gas prices on routine flaring. We test these predictions by estimating the response of battery-level emissions to changes in provincial market prices. This section describes our econometric setup, including how we identify prices effects, followed by a discussion of the results.

4.1 Empirical Strategy

Our model predicts that higher oil prices increase flaring, whereas higher gas prices reduce it. We test these predictions by estimating the response of battery-level emissions to changes in provincial market prices. Our main specification takes the form:

$$y_{imt} = \tilde{\beta}_g \text{ln(Gas Price)}_{mt} + \tilde{\beta}_o \text{ln(Oil Price)}_{mt} + \lambda_i + \zeta_m + \xi_t + e_{imt}, \tag{6}$$

where y_{imt} is the total volume of natural gas flared or vented for battery i in month m of year t. Flaring volumes are regressed on the natural log of market-wide natural gas prices, ln(Gas)$_{mt}$, and the natural log of market crude oil prices, ln(Oil Price)$_{mt}$, in month m and year t. We control for battery fixed effects, λ_i, to capture geological variation in resource plays, month fixed effects, ζ_m, to account for seasonality in prices, and year fixed effects, ξ_t, to accommodate common shocks across batteries in the province.

Eq.(6) has two coefficients of interest: $\tilde{\beta}_g$ and $\tilde{\beta}_o$. $\tilde{\beta}_g$ shows how battery-level emissions (i.e., flaring and venting) change for each a 1% increase in natural gas price. Similarly, $\tilde{\beta}_o$ is an estimate of the effect of oil price fluctuations on emissions.

Testing the predictions of the conceptual framework requires unbiased estimates of $\tilde{\beta}_g$ and $\tilde{\beta}_o$. Oil and gas are widely traded commodities and are frequently believed to be exogenous to any particular producer in any specific market. Yet, local oil and gas activity in Alberta has the potential to directly affect provincial prices because of pipeline and shipping constraints that limit the ability of producers to serve export markets (Schaufele and Winter, 2023). As a result, there is the prospect that flaring and venting are jointly determined with the equilibrium price in Alberta. Put differently, the coefficients in Eq.(6) may be biased due to simultaneity. To address this, we instrument for provincial prices with their U.S. counterparts. We use the Henry Hub price of natural gas to instrument for Alberta's natural gas price and instrument for Western Canadian Select prices, Alberta's benchmark oil price, with West Texas Intermediate prices. Monthly variation in U.S. prices directly affect prices in Alberta; however, they are independent of local shipping constraints, at least in the short-run (Janzwood, Neville and Martin, 2023). Thus, U.S. prices plausibly satisfy the exclusion restriction for local prices.

In addition to our main specification, we explore heterogeneity across geological conditions. The nature of joint outputs varies across batteries. In section 3, the volume of gas produced per unit oil output is determined by α. In reality, α varies across batteries as it is determined according to resource characteristics. Thus, the relationship between prices and flaring will vary in the cross-section. To capture this heterogeneity, we include interactions between prices and a battery's dependence on natural gas, measured by the median share of natural gas revenues to total revenues for battery i observed over our sample ($\left[\frac{\text{Gas Rev.}}{\text{Total Rev.}}\right]_i$). Natural gas accounts for a small share of revenues for the average battery in Alberta, but represents the majority of revenue (i.e., $\geq 50\%$) for over $\sim$10% of active batteries. We demean $\left[\frac{\text{Gas Rev.}}{\text{Total Rev.}}\right]_i$ and scale by 100. We then estimate:

$$\begin{aligned} y_{imt} =& \beta_g \ln(\text{Gas Price})_{mt} + \gamma_g \left[\frac{\text{Gas Rev.}}{\text{Total Rev.}}\right]_i \times \ln(\text{Gas Price})_{mt} \\ &+ \beta_o \ln(\text{Oil Price})_{mt} + \gamma_o \left[\frac{\text{Gas Rev.}}{\text{Total Rev.}}\right]_i \times \ln(\text{Oil Price})_{mt} \\ &+ \lambda_i + \zeta_m + \xi_t + e_{imt}, \end{aligned} \tag{7}$$

As in Eq.(6), the coefficients β_g and β_o show the change in emission levels given a 1% change in natural gas and oil prices, respectively, holding the battery's gas intensity fixed at the average. The new coefficients γ_g and γ_o, then, capture how these relationships change as the battery's gas share increases by one percentage point relative to the average battery.

4.2 Results

Table 2 shows the results of estimates for the first two predictions from our conceptual framework. Coefficients from Eq.(6) are in columns (1) and (3). Corresponding estimates for Eq.(7) are in columns (2) and (4). The first two columns show values estimated via least squares, while the latter two columns are the instrumental variable results.

Table 2: Responsiveness of Gas Emissions to Natural Gas and Oil Prices

	OLS		IV	
	(1)	(2)	(3)	(4)
ln(Gas Price)	-0.121	-0.125	-0.360	-0.339
	(0.122)	(0.122)	(0.192)	(0.192)
ln(Gas Price) x Gas Share		-0.027		-0.028
		(0.002)		(0.002)
ln(Oil Price)	0.385	0.390	0.305	0.305
	(0.105)	(0.105)	(0.134)	(0.135)
ln(Oil Price) x Gas Share		-0.001		0.001
		(0.002)		(0.003)
Obs.	2,113,735	2,113,735	2,113,735	2,113,735
R^2	0.336	0.336	-	-
F-Stat (1st Stage)	-	-	66.896	33.438

This table presents results of Eqs(6) and (7). Monthly battery gas emissions are regressed on provincial monthly gas and oil prices. Emissions are measured in thousands m^3. Prices are measured in USD per gigajoule of energy. All regressions include battery, year, and month fixed effects. Columns (1) and (2) show results of OLS regressions. Columns (3) and (4) show results of instrumental variable regressions, in which US gas and oil prices are used as instruments for Albertan prices. The analysis is restricted to the years for which Albertan oil prices are available from 2005-2023. Standard errors, shown in parentheses, are clustered by month-year.

Table 2 provides compelling empirical support for the paper's theoretical framework. The signs of all coefficients have the correct sign and magnitudes are in line with expectations. The differential, Eq.(4), illustrates how the relative elasticities of oil and natural gas demand explain variation in flaring volumes. Estimates from the literature help guide which values we expect from these estimates. As an example, Kilian (2022) suggests that a reasonable short-run estimate of global oil demand is -0.30 with a negligible one-month elasticity of supply. This corresponds to term (A) in Eq.(4). Arora (2014) estimates the elasticity of U.S. natural gas demand to be -0.25, while Farag (2024) estimates a short-run elasticity of supply of 0.02. These elasticities are reflected in term (B) of Eq.(4). As the total elasticities of oil and gas are roughly equivalent, we would expect that flaring volumes respond roughly proportionally to comparably sized oil and gas price shocks (with a different sign, of course).

Least squares estimates from column (1) show that increasing gas prices by 10% reduces flaring and venting emissions by 1.21%. A 10% increase in oil prices, in contrast, increases flaring by 3.85%. Both coefficients match the predictions of our conceptual model. Column (2) shows very similar main effects but adds interactions with a battery's gas revenue share. These results show how flaring and venting change as natural gas becomes more important to the battery. The interaction between gas price and gas share demonstrates that gas prices are especially important for batteries that obtain a higher than average share of revenues from marketing natural gas. The same cannot be claimed for the oil price-gas share interaction. Flaring does not differentially respond to oil prices in batteries that have above average revenues from gas sales compared to the average. The coefficient is a statistically insignificant -0.001. This finding further supports a key assumption in the conceptual framework, viz., that oil producers optimize over oil output and take jointly produced gas as given.

The results from the least squares models carry over to the instrumental variable regressions in columns (3) and (4). The instrumental variable models address potential simultaneity between local Alberta prices and flaring activity. These estimates also reveal relationships that align with the model's predictions. The negative coefficient on natural gas prices equals -0.360 in the baseline specification. This demonstrates the "gas conservation effect." When gas prices rise by 10%, flaring and venting emissions decrease by approximately 3.6%. This occurs because higher gas prices reflect increased demand for the by-product, making it more economically attractive for operators to capture and sell gas rather than waste it through flaring. This finding challenges infrastructure-based explanations for flaring, as it shows that even when pipeline infrastructure exists, economic incentives drive disposal decisions.

The positive coefficient of 0.305 on oil prices in column (3) confirms the "oil market effect" of Eq.(4). A 10% increase in oil prices leads to roughly a 3.1% increase in emissions. Higher oil prices incentivize greater oil extraction, which mechanically produces more associated gas. When the extent of the local gas market is such that demand remains insufficient to absorb this additional supply, excess gas is flared.

The interaction terms in column (4) are nearly identical to those in column (2). The negative interaction between gas prices and gas share of -0.028 indicates that flaring at gas-dependent operations are responsive to gas price signals. As in column (2), gas revenue share has no additional explanatory value when interacted with oil price.

Table 2 demonstrates that both gas and oil prices affect flaring and venting releases, matching the predictions of the model. Higher gas prices lead to lower releases.

Higher oil prices lead to more flaring.

5 Direct Effect of Regulating Routine Flaring

We next estimate the causal effect of flaring and venting regulations by exploiting a policy experiment in Alberta. Alberta's Peace River region phased in a venting ban over the 2014-2016 period and then subsequently introduced flaring restrictions between 2017 and 2019.

5.1 Empirical Strategy

To quantify the causal effects of Alberta's venting ban and subsequent flaring regulations, we adopt a *non-linear* difference-in-differences estimator that is robust to skewed, non-negative flaring and venting data and accommodates non-linear pretrends. Specifically, we follow the "fully saturated" Poisson quasi–maximum-likelihood framework of Wooldridge (2023), which extends the traditional two-way fixed-effects difference-in-differences set-up to the exponential family. A Poisson panel yields consistent estimates under weaker assumptions that the conditional mean is correctly specified, regardless of the true distribution of the dependent variable.

Let y_{it} denote monthly emissions (e.g., flaring, venting, or combined releases) for battery i in calendar month t. Define $\mathbb{1}\{g = i\}$ as an indicator that battery i belongs to one of three groups, $g \in \{\text{Peace River}, \text{Near Peace Region}, \text{Rest}\}$. The idea behind these three groups is that we want to isolate a leakage effect as distinct from the direct regulatory effect. The step facilitates a series of comparisons. For instance, we compare the regulated Peace River region to nearby unregulated regions. We also compare Peace River batteries to batteries that are far from Peace River, excluding unregulated batteries spatially proximate to Peace River. These are distinct estimands that offer different insights into the consequences of regulating flaring. Next, let $\mathbb{1}\{p = t\}$ indicate whether month t falls into policy phase $p \in \{\text{Pre-Period}, \text{Venting Ban}, \text{Flaring Restrictions}\}$, so that we can distinguish between the phases of regulatory stringency. As with groups, we make a series of intertemporal comparisons that omit data from key periods to avoid contaminating our estimands of interest. Based on this set-up, our estimating equation is the multiplicative mean:

$$
\begin{aligned}
E[Y_{it} \mid G_i, T_t, X_{it}] = \exp\Big(\alpha_0 &+ \sum_{g \neq \text{Rest}} \alpha_g \, \mathbb{1}\{g = i\} + \sum_{p \neq \text{Pre}} \tau_p \, \mathbb{1}\{p = t\} \\
&+ \sum_{g \neq \text{Rest}} \sum_{p \neq \text{Pre}} \delta_{gp} \, \mathbb{1}\{g = i\} \, \mathbb{1}\{p = t\} + X'_{it}\beta\Big)
\end{aligned}
\tag{8}
$$

where X_{it} includes the price controls, $\ln P_t^g$ and $\ln P_t^o$, along with battery, month-of-year, and calendar-year fixed effects. The price terms absorb short-run demand and supply shocks highlighted in the price-theoretic model. We use the exponential conditional mean link function paired with the Poisson density.

The coefficients of interest are the δ_{gp}'s. These coefficients identify average treatment effects on the treated in a non-linear setup, such that $\exp(\delta_{gp}) - 1$ is the percentage change in expected emissions for batteries in group g during policy phase p relative to the same batteries in the pre-policy era, net of contemporaneous changes for the rest-of-province batteries (i.e., both the near and rest groups). Specifically, $\delta_{\text{Peace,VentingBan}}$ captures the proportional change in emissions when the venting ban is binding but flaring restrictions are not. A positive $\delta_{\text{Peace,VentingBan}}$ for flaring, coupled with a negative one for venting, indicates the substitution across the practices. Next, $\delta_{\text{Peace,FlareRestrict}}$ measures the incremental effect once the flaring standard becomes binding. Comparing this treatment effect with the same coefficient for *Near*-Peace-River batteries quantifies the extent of spatial leakage.

Eq.(8) nests all group, period, and group–period interactions.[16] Identification comes from within-battery variation in the treatment dummies, conditional on price controls and the saturated set of calendar dummies. Standard errors are heteroskedasticity-robust and clustered at the geographic section level to allow arbitrary spatial correlation across batteries sharing local infrastructure. Further, because Eq.(8) is fully saturated, we can perform placebo tests by interacting group indicators with lead dummies for each policy phase and testing the joint significance of the corresponding $\delta_{gp}^{\text{lead}}$ coefficients. Violations of parallel trends, in context, however, allows for nonlinear transformations of the mean, $E[Y_{it} \mid \cdot]$ and holds indices inside the link function (i.e., the $\exp(\cdot)$ transformation (Wooldridge, 2023)). Failure to reject these pre-trends tests supports the identifying assumption that, absent the policy, the evolution of emissions in Peace River would have paralleled changes elsewhere. As mentioned, we use distinct control groups to support the parallel trends assumption. Similarly, as (Wooldridge, 2023,

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[16] In staggered treatment designs, this eliminates the heterogeneity bias that plagues conventional two-way fixed-effects estimators.

pg.C34) describes, the no anticipation assumption means that the "treated group [has] ... no anticipatory changes that affect the potential outcomes prior to the intervention." In essence, no anticipation holds if firms do not change behaviour at existing batteries before they are required to do so. Based on conversations with regulators and operators in the province, we understand this to be plausible. Taken together, this nonlinear difference-in-differences design aligns the rich, non-negative emissions data with the predictions of our conceptual model while delivering consistent, easily interpretable treatment effects of Alberta's venting ban and flaring restrictions.

In practical terms, we perform two separate regressions to estimate the effects of each regulation. In both regressions, we drop data prior to 2011, as this captures the Peace River region's expansion period. To estimate the effects of the venting regulation, we restrict the treatment period to the dates during which the venting regulation was in place but the flaring restrictions were not (September 2014 to April 2018). We drop all observations post April 2018. To estimate the effects of the additional flaring restrictions, we drop observations between September 2014 to April 2018 and define the treatment period from May 2018 forward (when the additional flaring restrictions first became binding).

5.2 Background and Initial Graphical Results

Starting in 2014, Alberta's energy regulator began regulating venting and flaring emissions at batteries located in the Peace River region of the province. Batteries in this region were subject to regulations not imposed elsewhere in Alberta. This policy experiment is instructive for several reasons. First, it unexpectedly introduced new rules, following a provincial panel investigating odor complaints in the province's Peace River region.[17] The panel's deliberations took less than a year, and, based on conversations with parties involved, neither the regulator nor local operators anticipated the outcome. Second, the rules exclusively applied to a relatively small region, allowing for comparisons with both proximate and distant unregulated areas. Finally,

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[17] The process to enact these regulations is instructive. In 2013, the AER established a panel of Hearing Commissioners to investigate odor complaints in the Peace River region. The panel's report, issued in March of 2014, recommended banning venting and restricting flaring in the region AER (2014). In April 2014, the AER announced its intention to accept the panel recommendations. The AER subsequently amended Directive 060, the province-wide regulations on flaring and venting, in May 2014. The initial update banned venting in the region. While the venting ban was being phased-in, the AER began working on a new regulation, Directive 084, to replace the Peace River-specific regulatory clauses in Directive 060. Directive 084 was released in February 2017 and became effective as of April 2017. Directive 084, in addition to maintaining the venting ban, added the restrictions to flaring that were omitted from the April 2014 amendments.

this region was singled out because of odor complaints arose from a small set of special interests in the local community, not because of any economic or technical aspects related to flaring or venting (AER, 2014).

The venting ban began in May 2014. The additional limits on routine flaring, equal to no more than 5% of the facility's natural gas production for routine flaring and 3% on non-routine flaring, came into force in April 2017. Figure 6 shows trends in battery level outcomes across three regions: in Peace River, batteries near Peace River, and batteries in the rest of the province. We define regions close to Peace River as those located in the same field centre area as defined by AER (either the Grande Prairie office or the St. Albert/Slave Lake office).[18] The motivation for the three regions is that nearby batteries likely compete over the same pipelines. So, nearby batteries are the ones to "pick up the slack" if the Peace River batteries reduce production. In contrast, the rest of the province should be relatively unaffected by a reduction in output from Peace River.

We produce these figures by running a Poisson regression of the variables of interest – venting emissions, flaring emissions, oil production and gas production – on section and battery-type-by-date fixed effects. A section represents a square mile (2.5 km^2); section fixed effects account for regional level differences in outcomes. The battery-type-by-date fixed effects account for differential trends by battery type. The figure shows deviance residuals (McCullagh and Nelder, 1989) from these regressions in Figure 6.

Four time periods are highlighted in Figure 6. Between 2006 and 2010, the first gray area in the figure, production expanded in Peace River due to the rise of a new technology designed for bitumen extraction.[19] Production (and emissions) stabilized in 2011, before the introduction of regulation. The venting ban was phased in from late 2014 through 2016, shown as the second gray area. Initial venting regulations only applied to batteries in the Three Creeks and Reno sub-regions, but these were shortly followed by identical restrictions in the Seal Lake and Walrus sub-regions. The flaring ban, shown as the third gray section, was phased in from 2017 to 2019. Existing operators were given until 2018 to reduce flaring, while regulations on new operators didn't take effect until 2019.

The trends in Figure 6 clearly show a reduction in emissions. The green line in Figure 6 shows the downward trend in venting at the outset of the venting ban, in Panel (a), and a decline in flaring upon the implementation of the flaring rules, in

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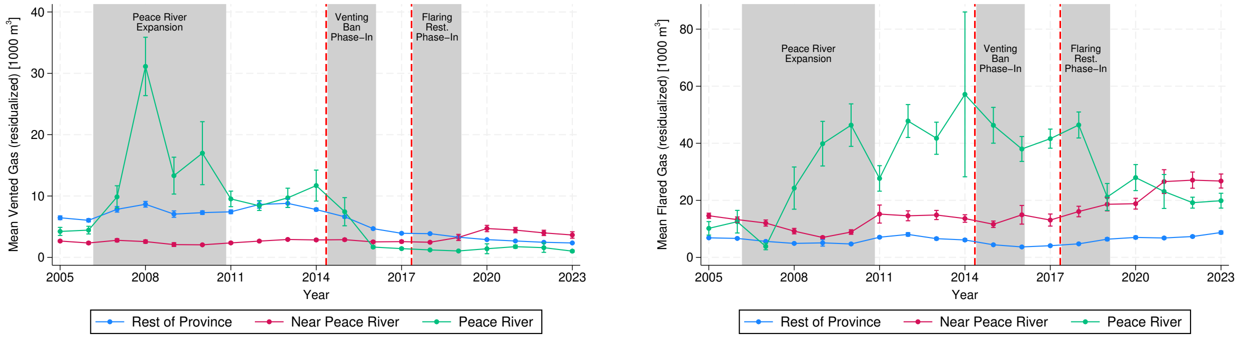
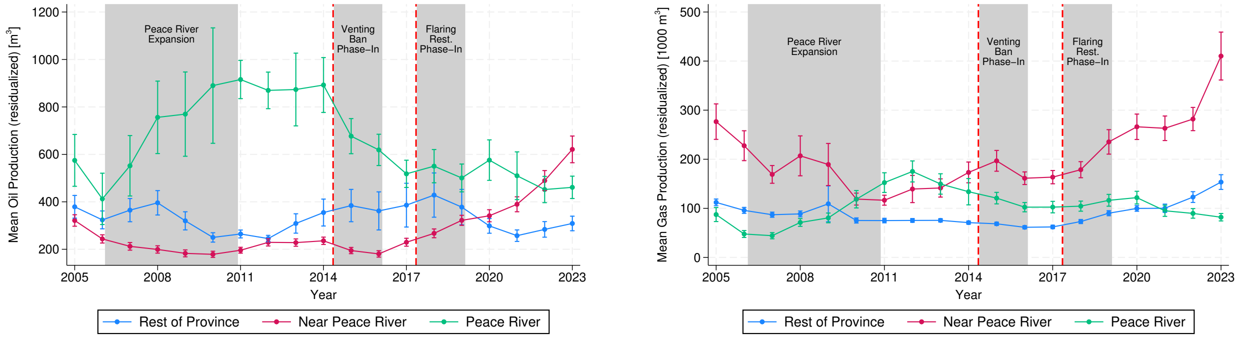
[18] The St. Albert office closed in 2018 and was replaced by the Slave Lake office.

[19] This is known as steam-assisted gravity drainage, or SAGD, technology.



(a) Venting Emissions

(b) Flaring Emissions



(c) Oil Production

(d) Gas Production

Figure 6: Trends at regulated and unregulated batteries

Panel (b). The bottom panels also suggest differential trends in output suggesting that these rules may have been accompanied by production losses. The challenge in estimating the causal effects of the Peace River regulation arises because outcomes are highly non-linear and right skewed. As there are potentially many zeros, log transformations are not appropriate. Moreover, assuming linear parallel trends is potentially problematic. To obtain the appropriate counterfactuals, we apply Wooldridge's (2023) pooled quasi-maximum likelihood estimator.

5.3 Effect of Regulations on Venting and Flaring Volumes

Table 3 shows the impacts of venting and flaring regulations on vented and flared emissions. The results reveal clear evidence of two forms of emissions leakage, as well as confirmation of the model's predictions.

Regulations on venting have two effects. First, Table 3 shows that venting and flaring are substitutes. The venting ban caused producers to increase flaring in the Peace River region. This is evident by comparing columns (1) and (2). The coefficient on venting ban for the Peace River region, in column (1) where the dependent variable is venting emissions, is -0.555, implying an almost complete removal of vented volumes. The venting ban was completely effective at eliminating venting emissions, except for emergency releases. In response to these rules, however, operators significantly increased flaring as seen in column (2). Column (2) shows a positive effect of the venting ban on flared gas volumes. The estimate equals 71.08, suggesting that much of the gas that would have been vented was instead burned off. Firms substituted flaring for venting when venting alone was prohibited. The second form of leakage is the spatial displacement of emissions. Column (1) of Table 3 shows that producers shifted pollution to nearby unregulated regions to evade the Peace River constraints. In the proximate unregulated region, the "Near Peace River" region, both venting and flaring increased significantly following the policy changes. After the venting ban, vented volumes in the neighboring area rose by about 964 m^3 per battery. Flared volumes increased by 1,200 m^3 per battery.

Table 3: Flaring and Venting Regulation and Emissions

	Vent Ban		Flare Restric.	
	(1)	(2)	(3)	(4)
Dep. Var.:	Vent	Flare	Vent	Flare
Peace River batteries	-0.555	71.08	-0.322	-11.00
	(0.165)	(38.03)	(0.145)	(7.623)
Near Peace River	0.964	1.200	2.630	12.43
	(0.129)	(0.656)	(0.617)	(2.682)
Obs.	822,448	822,448	943,795	943,795

Standard errors are clustered by geographic section.

Columns (3) and (4) of Table 3 show the effect of the flaring restrictions. The regulated, Peace River region saw further declines in venting. Venting fell by an additional 322 m^3. To reiterate, this comparison is made to the pre-venting ban counterfactual. Flaring, as expected, also dramatically fell with a point estimate of 11,000 m^3. These within-region patterns underscore that the initial a narrowly targeted venting regulation led to intertemporal leakage, whereby firms simply shifted the timing and method of release until the comprehensive flaring rules eventually forced an overall reduction.

The interregional leakage is even more pronounced with the flaring restriction. Nearby, unregulated batteries increased venting by roughly 2,630 m^3 and flaring by

12,430 m^3 relative to the no-regulation counterfactual. These represent very large surges in emissions outstripping the reductions in the regulated region. The magnitudes imply that essentially every unit of emissions avoided in Peace River was offset by a new unit of venting or flaring elsewhere. There was nearly 100% leakage. Together, the within- and outside-region results highlight the challenge of partial regulation: firms respond by either changing the form of the externality or relocating it to jurisdictions with laxer rules.

5.4 Effect of Regulations on Oil and Gas Production

We next examine production outcomes to understand the mechanism behind these leakage patterns. In line with the joint production nature of oil and gas, the flaring regulations – though nominally targeting natural gas disposal – primarily affected oil output. Table 4 reports the impacts on monthly oil and gas production in Peace River and the surrounding area. In the regulated region, the venting ban caused oil extraction to drop substantially, by about 1021 m^3 per battery per month. Gas output, in contrast, was largely unchanged. This asymmetry increases when looking at the flaring regulations in columns (3) and (4). Oil production in Peace River fell by $\sim$1308 m^3, whereas gas production was not significantly affected. In other words, operators complied with the tighter flaring and venting rules by scaling back oil production, rather than by curtailing gas output. Moreover, increased gas production does not compensate for the reduced oil volumes. These estimates validate the counterintuitive prediction of our model: because gas disposal constraints bind during oil extraction, a regulation on routine flaring effectively acts as a tax on oil production. Producers cannot easily increase gas market sales in the short run due to insufficient demand, so the immediate method to reduce waste gas emissions is to pump less oil. Importantly, we see no analogous decline in gas marketed volumes inside the regulated region.

These output effects are large in magnitude. The average producing battery in Alberta yields 1,313 m^3. So the lost output due to the flaring ban, relative to the pre-vent ban counterfactual, is equivalent to losing an average battery. These results help explain why the industry was so resistant to the flaring regulations. Flaring regulations force a cut in the higher-valued joint product for the sake of abating emissions of the lower-valued product. Further, the costs of foregone oil production are typically not counted in regulatory assessments of flaring rules (e.g., Canada, 2023; IEA, 2025).

Table 4 also shows interesting leakage patterns for nearby, unregulated regions. Despite the large reduction in Peace River oil output following the implementation of

Table 4: Flaring and Venting Regulation and Production

	Vent Ban		Flare Restric.	
	(1)	(2)	(3)	(4)
Dep. Var.:	Oil	Gas	Oil	Gas
Peace River batteries	-1020.9	85.14	-1308.2	34.75
	(229.9)	(44.79)	(328.4)	(45.57)
Near Peace River	112.3	56.84	1052.8	417.6
	(113.1)	(31.25)	(429.7)	(126.5)
Obs.	822,448	822,448	943,795	943,795

Standard errors are clustered by geographic section.

the venting ban, the increase in proximate regions was muted. Column (1) shows the oil output only increased by an imprecisely estimated 112 m^3. This can be contrasted with the coefficient in column (3). Once Peace River was subject to flaring regulations, oil production spiked in nearby regions, increasing by 1,052 m^3 per battery-month. Thus, the emissions leakage from Table 3 is attributable to the production leakage.

5.5 Effect on Legacy and New Batteries

To provide context to these results, we next investigate heterogeneity between legacy wells, those that were in operation before the policy, and new entrants, wells drilled after the policy. Table 5 focuses on legacy batteries. Panel A shows estimates for emissions, while Panel B is the impact on production. The patterns in Table 5 mirror the main findings. Legacy sites in Peace River sharply reduced venting and switched to flaring when the vent ban took effect. They then cut back on flaring once the additional restrictions were in place. These reductions were chiefly achieved by reducing oil output. For example, pre-2014 wells in the regulated region increased flaring by about 53,000 m^3 after venting was banned and subsequently reduced flaring by 10,800 m^3 once flaring limits hit. Correspondingly, these legacy wells' oil production dropped significantly under both regulatory regimes, while gas production remained relatively stable. Meanwhile, legacy wells in the unregulated neighboring area responded by expanding output. They show modest increases in oil production in response to the vent ban, but large 1611 m^3 per battery-month increases in production under the flaring restrictions. The additional output further led to significantly more venting. Vented gas at unregulated facilities increased by 3,844 m^3 per battery per month once the flaring regulations were implemented.

Table 5: Effect of Flaring Regulations on Batteries Built before 2014

	Vent Ban		Flare Restric.	
	(1)	(2)	(3)	(4)
Panel A: Impacts on Emissions				
Dep. Var.:	Vent	Flare	Vent	Flare
Peace River batteries	-0.486	53.46	-0.336	-10.80
	(0.171)	(29.09)	(0.144)	(6.336)
Near Peace River	0.678	-0.0262	3.844	-1.747
	(0.0720)	(0.501)	(1.804)	(1.533)
Panel B: Impacts on Production Output				
Dep. Var.:	Oil	Gas	Oil	Gas
Peace River batteries	-1136.1	93.48	-1741.3	-6.862
	(252.5)	(50.06)	(461.6)	(41.49)
Near Peace River	42.88	51.33	1610.9	340.3
	(126.7)	(34.85)	(1201.0)	(163.9)
Obs.	783,900	783,900	795,396	795,396

Standard errors are clustered by geographic section.

Table 6 shows the consequences of the regulations on new batteries, those that were built after the policies were implemented. Batteries built after the introduction of the regulations do not have a pre-period with which to make comparisons, so caution is required in interpreting the results. Specifically, Table 6 shows estimates of the effects of the venting ban and flaring restrictions in the Peace River region by comparing the characteristics of newly built batteries in Peace River to new batteries built in the same periods in the rest of the province. Columns (1) and (2) show average venting and flaring releases. Columns (3) and (4) show average oil and natural gas production. In Panel A, the sample is restricted to batteries that begin operating after June 1st, 2014 and before March 1st, 2019. In Panel B, the sample is restricted to batteries that began operating after March 1st, 2019 and before December 31st, 2023.

The results suggest that new oil developments in the regulated region were better able to comply with the rules with smaller losses in oil production. New Peace River batteries essentially vented no gas and flared at the strictly limited levels, yet their oil output was statistically indistinguishable from new wells built elsewhere in the

Table 6: Effect of Flaring Regulations on Newly Constructed Batteries

Outcome:	Venting (1)	Flaring (2)	Oil Output (3)	Gas Output (4)
Panel A: Batteries Built Between June 1, 2014 and March 1, 2019				
Peace River Batteries	-4.211	65.428	-41.817	147.792
	(0.093)	(4.686)	(120.758)	(8.444)
Near Peace River	-0.285	14.779	281.491	312.995
	(0.098)	(1.829)	(18.095)	(17.741)
Obs.	84,349	38,426	84,349	84,349
Panel B: Batteries Built After March 1, 2019				
Peace River Batteries	-2.028	-16.712	-18.087	155.011
	(0.111)	(2.906)	(66.897)	(16.826)
Near Peace River	0.657	30.990	1170.401	640.020
	(0.131)	(1.905)	(38.351)	(32.133)
Obs.	48,185	48,185	48,185	48,185

All regressions include date-of-opening and battery-type fixed effects and control for the natural log of both monthly crude and natural gas prices in Alberta. Standard errors are clustered at the geographic section level.

province. Moreover, these new wells significantly increased their gas production relative to baseline, suggesting that operators invested in gas capture infrastructure so that more of the associated gas could be sold or used instead of emitted. In short, new capital was built to fit the regulatory environment. Firms adopted technologies and practices that allowed continued oil extraction under a no-venting and minimal-flaring regulatory regime. In contrast to the Peace River results, new batteries in the nearby, unregulated area expanded both oil and gas output dramatically -— even more than the legacy wells did. Moreover, they did so while flaring or venting freely. This disparity implies that a sizable leakage driven by new investment moving outside the regulated region. Rather than the regulations simply stranding existing assets in Peace River, it appears firms redirected their growth to jurisdictions without flaring rules, while within Peace River only compliant facilities were added.

6 Conclusion

Our analysis demonstrates that regulating routine flaring in oil production fundamentally represents an economic issue driven by joint production and insufficient demand for the co-product, natural gas, rather than purely technological or infrastructure limitations. Using detailed battery-level data from Alberta, we provide robust empirical support for our theoretical model. Specifically, we find that a 10% increase in oil prices results in approximately a 3.1% rise in flaring, whereas a 10% increase in natural gas prices reduces flaring by 3.6%. These findings substantiate the intuitive predictions of our conceptual framework, emphasizing the critical role market dynamics play in flaring activities.

Further, exploiting a natural experiment involving regulatory changes in Alberta's Peace River region, we reveal significant unintended consequences of flaring restrictions. Regulations effectively eliminated venting and substantially curtailed flaring within the regulated area; however, they resulted in nearly complete emissions leakage to unregulated neighboring regions. Critically, our results underscore that the primary economic impact of these regulations manifests through reduced oil production rather than diminished natural gas output. Indeed, regulated facilities experienced substantial declines in oil extraction, equivalent to losing production from an average-sized battery, illustrating the implicit and overlooked cost of stringent flaring controls.

Finally, we identify notable heterogeneity between legacy facilities and new investments. Legacy operations incurred substantial output losses, whereas newly constructed batteries integrated gas capture infrastructure effectively to comply with regulations, minimizing oil production losses. This pattern emphasizes the importance of aligning regulatory measures with market incentives to promote economically efficient and environmentally beneficial outcomes. Overall, these insights highlight the need for comprehensive regulatory frameworks that account for economic incentives and potential leakage to ensure genuine reductions in emissions.

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A Appendix

A.1 Background Data: Additional Tables and Figures

Table A.1: Global Flaring Rates - 2022

	Flaring Rate	Global Volume Rank
Russia	4.1%	1
Iran	6.5%	3
United States	0.8%	6
Mexico	18.0%	8
Nigeria	13.3%	9
China	1.1%	10
Saudi Arabia	1.5%	14
India	4.7%	18
Brazil	3.9%	28
Australia	0.5%	31
Global	3.4%	-

Table presents flaring rates and global flaring volume rank for ten countries, listed in descending order by emitter rank. Flaring rate is the total volume flared divided by the total volume of natural gas extracted. Countries are ranked by the total volume flared in 2022. The final row shows the total global flaring rate.

A.2 Effect of Gas and Oil Prices on Gas and Oil Volumes

The main analysis shows that oil price, in addition to gas price, significantly affect flaring, demonstrating the joint production mechanism. Table A.2 shows the impacts of gas and oil prices on gas and oil output, further supporting the joint production mechanism. Results show that the gas prices do *not* have a statistically significant effect on gas and oi extraction volumes. It is the oil price that drives the gas and oil production, highlighting oil as the main product and thus, the factor of flared gas releases.

Table A.2: Responsiveness of Production to Natural Gas and Oil Prices

	Panel A: OLS				Panel B: IV			
Outcome:	Oil		Gas		Oil		Gas	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
ln(Gas Price)	-1.558	-1.138	-0.803	0.077	-8.942	-12.168	1.010	-0.536
	(11.869)	(11.892)	(2.292)	(2.312)	(15.171)	(15.370)	(3.937)	(4.042)
ln(Gas Price) x Gas Share		3.956***		2.246***		3.710***		2.905***
		(0.366)		(0.206)		(0.433)		(0.219)
ln(Oil Price)	32.743***	32.133***	2.397	1.636	28.366*	28.024*	2.076	2.478
	(10.142)	(10.220)	(2.498)	(2.648)	(14.697)	(14.903)	(3.114)	(3.068)
ln(Oil Price) x Gas Share		0.597		-1.419***		1.108**		-1.926***
		(0.453)		(0.296)		(0.517)		(0.332)
Obs.	2,113,735	2,113,735	2,113,735	2,113,735	2,113,735	2,113,735	2,113,735	2,113,735
R^2	0.804	0.804	0.667	0.667	-	-	-	-
F-Stat (1st Stage)	-	-	-	-	66.896	33.438	66.896	33.438

This table presents estimates of the effect of gas and oil prices on gas and oil production. Columns (1) and (3) show results show the effect of changes in provincial monthly gas and oil prices on monthly battery oil production. Columns (2) and (4) show results show the effect of changes in provincial monthly gas and oil prices on monthly battery gas production. Battery gas production is measured in 1000 m^3. Battery oil production is measured in m^3. Prices are measured in USD per gigajoule of energy. All regressions include battery, year, and month fixed effects. Panel A shows results of OLS regressions. Panel B shows results of instrumental variable regressions, in which US gas and oil prices are used as instruments for Albertan prices. The analysis is restricted to the years for which Albertan oil prices are available, 2005-2023. Standard errors, shown in parentheses, are clustered by month-year.