Regulating Routine Flaring: Theory and Evidence

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Abstract

Emissions typically arise as waste by-products from economic activities, lacking inherent value or established markets. Standard policy interventions, such as carbon pricing or cap-and-trade systems, aim to create artificial markets to incentivize emission reductions. However, natural gas emissions from oil extraction differ uniquely, because these emissions already possess an inherent economic value and established market. Given this inherent market, routine flaring and venting of valuable gas seem economically puzzling. We demonstrate that routine and persistent flaring arises primarily due to the joint production nature of oil and gas and the insufficient market demand for gas relative to oil, rather than technological or infrastructure constraints alone. Using a conceptual framework and empirical evidence from Alberta, Canada, we show that higher gas prices reduce emissions, whereas higher oil prices increase flaring. Through a regulatory experiment in Alberta, we uncover two forms of emissions leakage. First, regulating venting alone leads to increased flaring. Second, restricting both venting and flaring effectively reduces local emissions but shifts oil production—and associated emissions—to unregulated areas. While immediate oil revenue losses explain industry resistance to regulations, we also find that production declines predominantly occur in legacy facilities, whereas new capital investments can adapt efficiently with minimal output loss. Our findings highlight that effective emissions reduction strategies in oil extraction must integrate oil market dynamics and production management, not merely enhance conditions in the gas market.

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1 Introduction

Emissions are commonly understood as negative externalities resulting from economic production activities. In a typical context, these emissions are considered waste because they have no inherent economic value or market. Economists typically propose regulatory solutions—such as carbon pricing or cap-and-trade systems—that artificially create markets for these emissions to incentivize firms to reduce their environmental footprint. However, the context of natural gas emissions in upstream oil production provides a uniquely challenging contrast: these emissions already possess their own inherent economic value and an established market. Natural gas associated with oil extraction ("associated gas") can either be sold in gas markets or released via flaring or venting. Given that this gas has intrinsic value, one might expect minimal or even zero emissions in this context. Yet, persistent routine flaring and venting still occur worldwide. Why do firms choose to flare or vent valuable gas?

This paper presents a conceptual and empirical investigation into the economics underlying ***routine and persistent*** flaring and venting, focusing on the joint production nature of oil and gas and the relative insufficiency of natural gas demand (relative to oil demand). In upstream oil extraction, natural gas is produced as an unavoidable by-product. When the demand and economic value for this associated gas are limited relative to oil, firms face economic incentives to routinely flare or vent gas, even when infrastructure exists to capture and sell it. We demonstrate that the fundamental reason for routine flaring is neither purely technological nor infrastructure-constrained, as previously argued in the literature (Lyon et al., 2021; Agerton, Gilbert and Upton Jr, 2023; Lade and Rudik, 2020), but rather a fundamental economic mechanism driven by joint production and differential market demands. Consequently, the economic impacts of flaring regulations primarily manifest in oil markets rather than gas markets, a distinction with important policy implications.

We formalize this mechanism with a conceptual framework illustrating how both oil and gas prices affect flaring, but in opposite directions. Higher natural gas prices incentivize gas capture and reduce flaring, whereas higher oil prices—reflecting strong oil demand—promote more oil extraction, thus increasing associated gas emissions. We empirically validate this model using detailed, facility-level data from Alberta, Canada from 2002 to 2023.[1] Exploiting exogenous variation in monthly U.S. commodity prices as instrumental variables for regional Alberta prices, we show that a 10%

[1] In 2023, Alberta accounted for 84% of Canada's crude oil production, while Canada was the world's fourth-largest oil producer (Energy Institute, 2024).

increase in oil prices leads to a 2.7% increase in flaring, while a 10% increase in gas prices reduces flaring by 3.3%.

The economic logic of joint production also shapes the impacts of regulations aimed at reducing flaring and venting. Because oil drives production decisions, regulating gas emissions significantly affects oil rather than gas markets. We illustrate this by examining a regulatory experiment in Alberta's Peace River region, where odor-related complaints prompted regulators to ban venting and restrict flaring starting in 2014. While these regulations effectively reduced emissions locally, we uncover two notable forms of leakage. First, regulations targeting only venting caused unintended substitution towards flaring, highlighting the ineffectiveness of partial emissions bans. While previous literature and policy reports acknowledge the possibility of substitution (Calel and Mahdavi, 2020), our analysis provides the first empirical confirmation of venting-to-flaring substitution. This implies that effective regulation must comprehensively address all forms of emission releases simultaneously.

Second, we identify geographical leakage due to oil market incentives. Regulated facilities reduced oil extraction and associated emissions, but this reduction was partly offset by increased oil production—and consequently higher flaring—in neighboring unregulated areas. The existence of geographical leakage demonstrates the immediate economic costs of emissions regulations borne by producers, explaining their strong resistance to flaring and venting restrictions.

Nevertheless, we uncover promising evidence for policy design from new capital responses. Legacy operations experienced most output losses from emissions regulations, while new facilities built after the regulations took effect successfully reduced emissions without substantial production losses. This suggests that long-term regulatory compliance and emissions reductions can be achieved cost-effectively through technology investment.

Our paper contributes to a growing but limited literature on methane emissions regulation in the oil and gas sector. Prior studies primarily attribute flaring to technological constraints and midstream infrastructure limitations (Lyon et al., 2021; Agerton, Gilbert and Upton Jr, 2023). By highlighting the joint production and relative demand mechanism, we emphasize the importance of integrating oil market considerations into emissions reduction strategies, rather than solely improving natural gas market conditions. Furthermore, 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—a finding consistent with Lade and Rudik (2020) and Marks (2022)—any regulatory framework must comprehensively target all emission pathways and account for potential leakage to achieve genuine emissions reductions.

2 Natural Gas Flaring in Alberta and the Puzzle of Persistent and Routine Flaring Even After Being Connected with Collection Infrastructure

We study the case of natural gas flaring and venting in the Canadian province of Alberta. The data was collected by the Alberta Energy Regulator. Through an FOI request, we received historical data dating back to 2002. Our sample covers the period 2002–2023 and includes volumes of flaring, venting, and oil and gas production at the month-battery level for crude oil and bitumen batteries in Alberta. A battery consists of one or more clustered wells within a field. Batteries are the typical connection point for midstream infrastructure and represent the most consistent reporting entity for flaring.

In Alberta, the flaring rate has been consistently low. Figure 1 shows the flaring and venting rates in Alberta from 2002 to 2023. Total emissions peaked at 6% of associated gas but have leveled off at approximately 3% for the 2015-2023 period. 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%. This flaring rate is very closed to the world's average flaring rate. Table 1 compares flaring rates across selected countries in 2022.[2] Emission rates vary significantly worldwide, but the globally flaring rates are relatively modest at 3.3%.[3] The low flaring rate in Alberta implies that our analyses on the joint production nature and the demand for oil provide a main mechanism to explain the routine and persistent flaring. Regulations aiming to further reduce flaring and venting in a region like Alberta must account for this mechanism to target the tail of the phenomenon, those last few percent of flared and vented gas.

Our analysis also highlights that significant flaring and venting persist even in locations where gas capture infrastructure is already available. Figure 2 categorizes

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

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

Figure 1: Flaring and Venting Rates

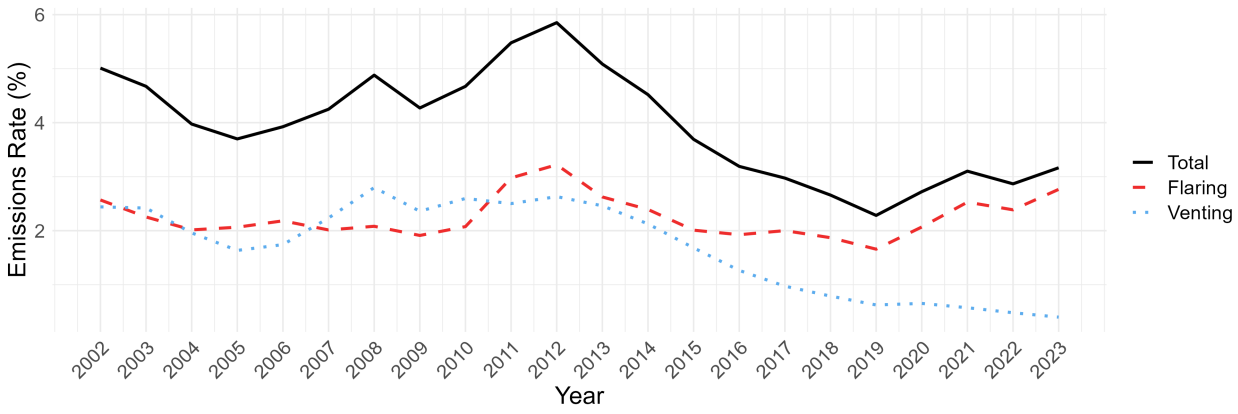


Table 1: Global Flaring Rates - 2022

	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.

gas emissions in Alberta based on infrastructure connection status and the proportion of associated gas sold relative to production.[4] Remarkably, less than half of the total emissions originate from sites lacking connection, and these emissions have remained stable over the entire period from 2002 to 2023. Conversely, connected sites—particularly those selling the majority of their gas (more than 75%)—have seen emissions steadily increase. This pattern, indicative of infrastructure adequacy alone being insufficient to eliminate flaring and venting, aligns with similar observations documented in the Bakken and Permian basins in the U.S. (Agerton, Gilbert and Upton Jr, 2023).

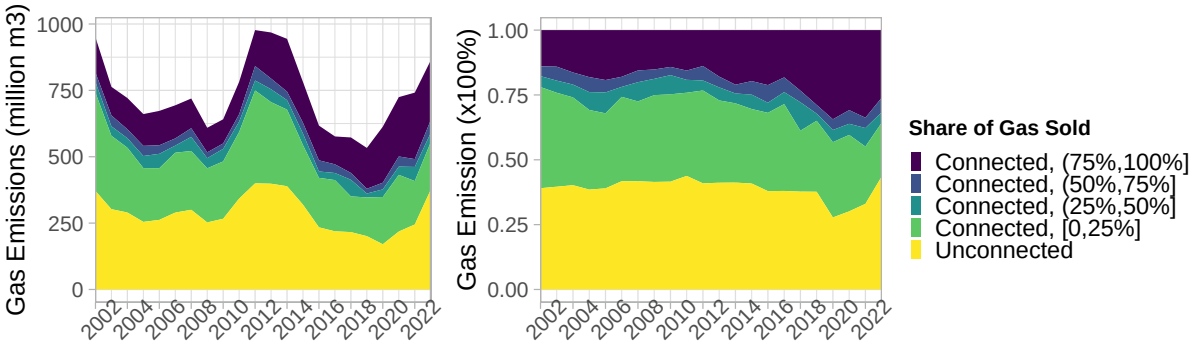
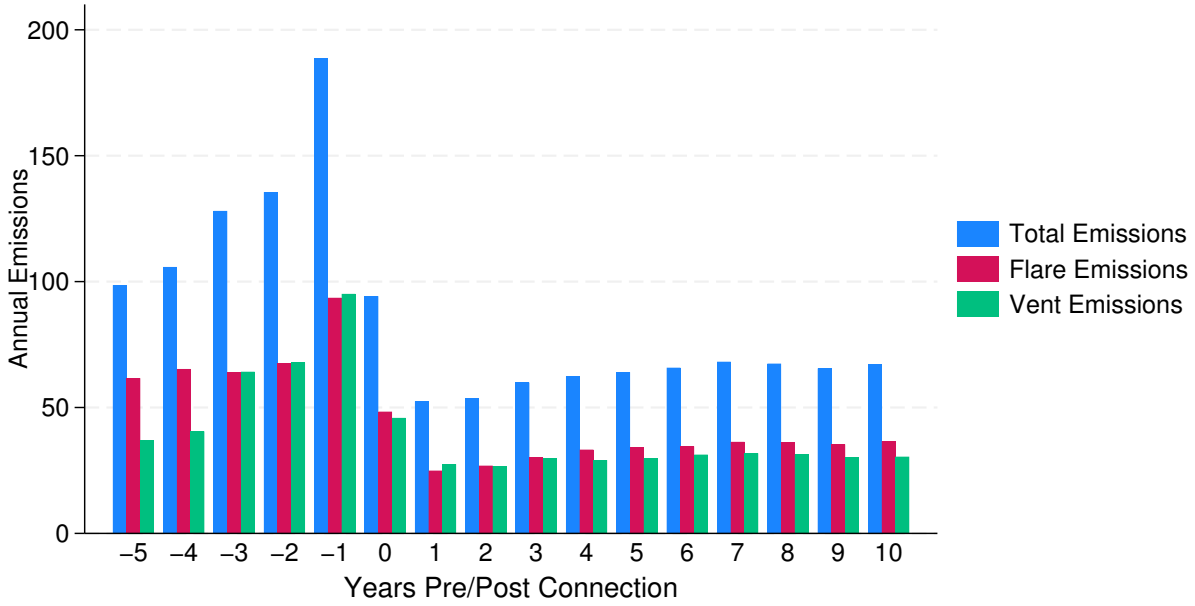


Figure 2: Gas emissions by share of gas sold

The puzzle becomes clearer when examining the immediate effects of connecting batteries to gas infrastructure. As illustrated in Figure 3, connecting batteries to midstream infrastructure did not lead to the complete cessation of flaring and venting. Rather, emissions sharply declined initially but quickly stabilized at a persistent positive level in subsequent years. This phenomenon underscores that routine flaring and venting persist even when midstream infrastructure constraints are effectively removed. Our paper aims to resolve this puzzle by introducing a conceptual framework and empirical evidence emphasizing the joint production nature of oil and gas and the relatively insufficient demand for natural gas compared to oil. Understanding this fundamental economic mechanism is crucial for designing more effective policy interventions to eliminate these persistent emissions.

[4]Connected locations refer to batteries that have sold associated gas either in the same year or previously (dating back to January 2002). Unconnected locations refer to batteries that have never sold associated gas (since January 2002). For connected sites, we further classify batteries according to their gas sold as a share of total associated gas production within the same year.



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

Oil reservoirs frequently have associated gases 'in solution.'[5] Upstream firms extract crude oil and simultaneously obtain natural gas as a lower value by-product because gas is located alongside, i.e., 'associated' with, oil in the geological formations.[6] That is to say, oil and natural gas are joint products, produced in fixed proportions according to the geological characteristics of the resource.[7] 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 the 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.

Firms facing joint production make decisions based on the dominant product and manage – sell or dispose of – by-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

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

[6]In 2022, for example, 96% of batteries in Alberta, Canada, the setting for our empirical analysis, produced both gas and oil.

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

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:

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

where Q_1^* solves the operator's profit maximization problem for oil, the high-value product and the second line merely substitutes the fixed proportion equality, $Q_2 = \alpha Q_1^*$. Likewise, 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.[8]

There is ample global demand for oil with prices set internationally. Firms take the price of oil, P_1, as given. Unlike the demand for oil, 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). These market characteristics lead to an inverse demand for natural gas given by:

$$P_2 = \begin{cases} D(Q_2) & \text{if} \quad Q_2 \leq \hat{Q}_2 \\ 0 & \text{if} \quad Q_2 > \hat{Q}_2 \end{cases} \tag{1}$$

where $\hat{Q}_2$ is the quantity at which the natural market is saturated and price equals zero. Importantly, demand, (1) is asymmetric at the saturation point.

Without regulation, operators will not sell gas at negative prices because free disposal the disposal of excess gas via flaring. Thus, if $Q_2 > \hat{Q}_2$, producers optimally flare an amount equal to:

$$\begin{aligned}\text{Flared Excess Gas} = F &= Q_2 - \hat{Q}_2 \\ &= \alpha Q_1^* - \hat{Q}_2\end{aligned} \tag{2}$$

where the fixed proportions constraint is used in the second line. Excess production of natural gas equals $\alpha Q_1^* - \hat{Q}_2$. This difference, F, is flared, converting methane, an especially potent greenhouse gas, into CO2, and producing fires visible from space. Routine flaring occurs, however, because there is insufficient demand for a by-product

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

in a joint production problem: the quantity of gas produced exceeds the saturation point.

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. The marginal cost of gas is assumed equal to zero.

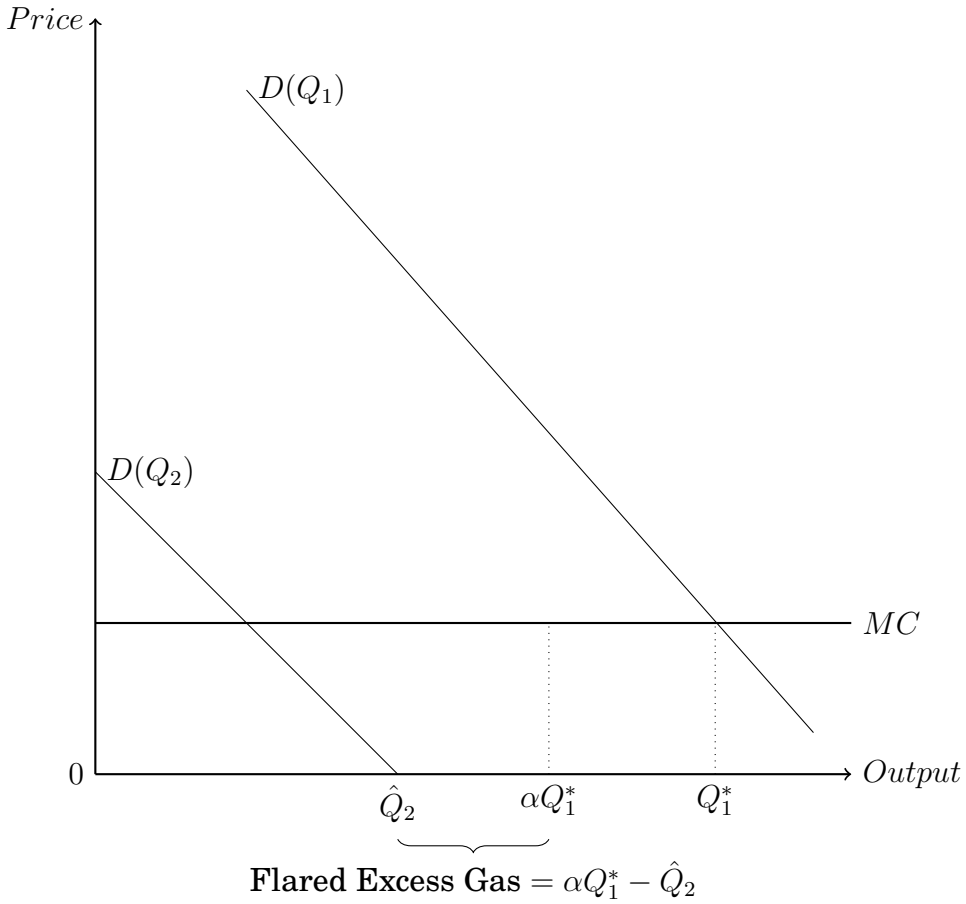


Figure 4: Joint Production of Oil and Natural Gas with Flaring

Because routine flaring is permitted, firms maximizes profits by selecting Q_1^* at the point where price equals marginal production costs. Because 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. 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 $\alpha Q_1^* - \hat{Q}_2$ in the figure.

Flaring due to insufficient demand is a market outcome. Thus, flaring volumes will vary with market conditions, specifically changes in demand for the commodity.

Empirically, we study this by employing an instrumental variable strategy to estimate how flaring responds to commodity prices. Given this conceptual framework, straightforward predictions emerge from the model. Totally differentiate (2) to observe how flaring, F, responds to oil and gas prices, P_1 and P_2, respectively:

$$dF = \underbrace{\alpha \frac{\partial Q_1^*}{\partial P_1} dP_1}_{(A)} - \underbrace{\frac{\partial \hat{Q}_2}{\partial P_2} dP_2}_{(B)} \tag{3}$$

where, for simplicity, we assume independent market demands for oil and gas. The first term, (A), shows the effect of changes in oil demand on flaring volumes. If demand increases – e.g., the demand curve shifts right in Figure 4 – then, holding other variables constant, flaring volumes are expected to increase. Similarly, 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 $\hat{Q}_2$. An increase in $\hat{Q}_2$ decreases flaring F, because of the negative sign leading term (B) in (3).

Oil and gas prices have an intuitive relationship to flaring. Yet, the conceptual framework makes plain the causes of routine flaring. Routine flaring is due (i) the joint production of oil and natural gas combined with (ii) differences in demand between the primary and by-products. That is, routine flaring is caused by an insufficient demand for natural gas (relative to demand for oil).

Further, the differential, (3), illustrates how the relative elasticities of oil and natural gas demand explain variation in flaring volumes. We empirically address the relationship between market prices and flaring volumes in section 4, yet, as an initial approximation, estimates from the literature help guide our empirical analysis. As an example, Kilian (2022) suggests that a reasonable short-run estimate of global oil demand is -0.30. This corresponds to term (A) in (3). Arora (2014) estimates the elasticity of U.S. natural gas demand equals -0.25. This is reflected in term (B) of (3). Combining these estimates enables us to make a prediction on the prospective magnitudes of the direct effect of prices on flaring volumes. As the elasticities of oil and gas are roughly equivalent, we expect and find that routine flaring volumes respond roughly proportionally to comparably sized oil and gas price shocks (with a different sign, of course).

4 Empirical Evidence of the Joint Production Mechanism

4.1 Empirical Strategy

Our conceptual framework of the joint production of oil and natural gas predicts routine flaring that is caused by fluctuations in oil and natural gas prices. Specifically, the model predicts higher oil prices increase flaring, whereas higher gas prices decrease it. We test these predictions by estimating the response of battery-level emissions to changes in provincial market prices. The formal specification is

$$y_{imt} = \tilde{\beta}_g \text{ln(Gas Price)}_{mt} + \tilde{\beta}_o \text{ln(Oil Price)}_{mt} + \lambda_i + \zeta_m + \xi_t + e_{imt}, \tag{4}$$

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, $\text{ln(Oil Price)}_{mt}$, in Alberta in month m and year t. We control for battery fixed effects, λ_i, to ensure Equation 4 captures changes in prices faced by a given battery over time. We also include month fixed effects, ζ_m, to account for seasonality in prices and extraction and year fixed effects, ξ_t, to account for prevailing trends common across all batteries in the province.

The coefficients of interests are $\tilde{\beta}_g$ and $\tilde{\beta}_o$, which show the change in emission levels given a 1% increase in natural gas and oil prices, respectively.

Though oil and gas are traded commodities, 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, the coefficients of interest in Equation 4 are potentially biased due to simultaneity. To address this bias, we instrument for provincial prices with their US counterparts.[9] Monthly variation in US prices directly affects prices in Alberta. However, they are independent of shipping constraints because international pipeline and shipping capacity is slow to adjust (Janzwood, Neville and Martin, 2023). As a result, US prices serve as valid instruments for these short-run changes in provincial prices.

The nature of joint production varies across batteries, according to resource char-

[9] We instrument for Alberta's natural gas price with prices reported at the Henry Hub in Louisiana. We instrument for Western Canadian Select prices (Alberta's benchmark oil price) with West Texas Intermediate prices.

acteristics. Thus, the relationship between prices and flaring will likewise vary cross-sectionally. Indeed, natural gas accounted for just 20% of revenues for the average battery in Alberta in 2022, but accounted for the majority of revenues for over 10% of active batteries. Further, the importance of natural gas in joint production exhibits considerable heterogeneity across regions too. To capture this heterogeneity, we include interactions between gas prices (and oil 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 ($\left[\frac{\text{Gas Rev.}}{\text{Total Rev.}}\right]_i$). We demean $\left[\frac{\text{Gas Rev.}}{\text{Total Rev.}}\right]_i$ and scale by 100. The formal specification is:

$$\begin{aligned} y_{imt} =& \beta_g \ln(\text{Gas Price})_{mt} + \gamma_g \left[\frac{\text{Gas Rev.}}{\text{Total Rev.}}\right]_i \times \ln(\text{Gas Price})_{mt} \\ &+ \beta_o \ln(\text{Oil Price})_{mt} + \gamma_o \left[\frac{\text{Gas Rev.}}{\text{Total Rev.}}\right]_i \times \ln(\text{Oil Price})_{mt} \\ &+ \lambda_i + \zeta_m + \xi_t + e_{imt}, \end{aligned} \tag{5}$$

In Equation 5, the coefficients β_g and β_o show the change in emission levels given a 1% increase in natural gas and oil prices, respectively, holding the battery's gas intensity fixed at the average. The coefficients γ_g and γ_o show 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 show results of estimates for coefficients in Equation (4). Columns (1)-(2) contain the ordinary least squares estimates, while columns (3)-(4) show the instrumental variable results. While both specifications recover point estimates with the appropriate sign, our preferred results are the instrumental variable parameters. Our discussion, therefore, focuses on column (3)-(4).

To start, US prices are strong predictors of Alberta prices. The first-stage Kleibergen-Papp F-statistic equals 33.44, generally greater than conventional rules of thumb. More importantly, the estimates in column (3) shows that higher oil prices lead batteries to increase flaring and venting releases. Higher oil prices increase operator's incentive to extract oil. More oil extraction leads to greater production of associated gas. Thus, higher oil prices yield more flaring. A 10% increase in oil price causes a significant 2.7% increase in flaring rates.

Next, as predicted, increasing gas prices causes a decrease in flaring. Higher

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 Equations 4. Monthly battery gas emissions are regressed on provincial monthly gas and oil prices. Emissions are measured in 1000 m^3. Prices are measured in USD per gigajoule of energy. All regressions include battery, year, and month fixed effects. Column (1) shows results of OLS regressions. Column (2) 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.

prices, holding constant supply, are a consequence of increased demand for gas. A 10% increase in the price of natural gas leads to a 3.3% reduction in flaring. Stated otherwise, higher gas prices alleviate the insufficient demand problem as more demand for gas increases the opportunity cost of wasting, i.e., not selling, the by-product. Moreover, the appendix demonstrates that this is primarily driven by joint production. Higher gas prices do not have a statistically significant effect on gas extraction volumes, whereas oil prices significantly affect oil and gas volumes.

The key implications of Table 2 is that both gas and oil prices affect flaring and venting releases, but they do so in opposing directions. Higher gas prices lead to lower releases, even for gas-intensive batteries that increase extraction rates in response to higher prices. In contrast, higher oil prices lead to higher releases, regardless of the battery's dependence on gas.

5 The Impacts of Regulating Routine Flaring

5.1 Empirical Strategy

Regulating routine flaring imposes additional costs on firms. Firms must balance costs across production, wastage, and sales. Because oil extraction and its joint production with gas drives routine flaring, restrictions on venting and flaring would primarily impact oil rather than gas markets. We demonstrate this using regulatory changes in a region within Alberta. Our evidence from a policy experiment in Alberta shows that firms reduce major product output to prevent oversupply of by-product.

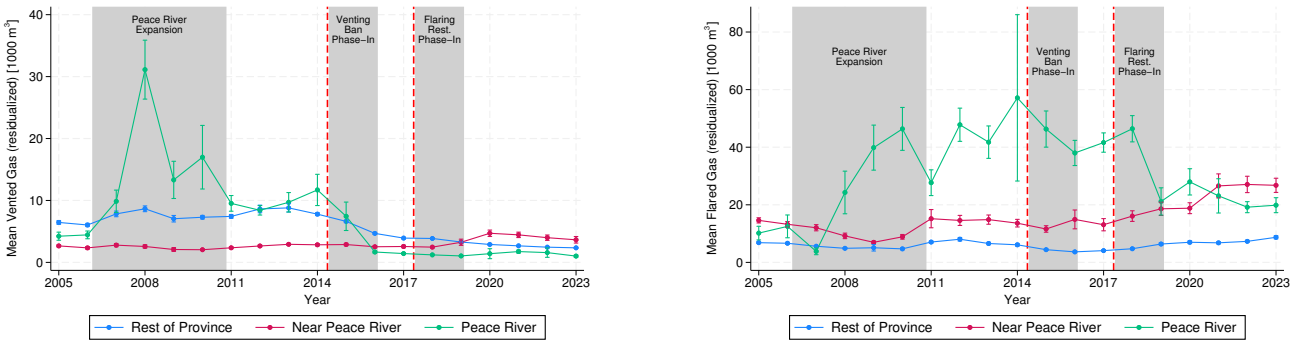
In 2014, Alberta implemented phased venting and flaring regulations in the Peace River region, enabling comparisons with unregulated areas. The venting ban started in May 2014 and was fully in place by 2016, with additional flaring restrictions introduced in April 2017 and phased in over two years. This staggered rollout allows us to examine the effects of the venting ban alone and in combination with flaring restrictions.

Figures showing trends in battery level outcomes across three regions: batteries 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 (either the Grande Prairie office or the St. Albert/Slave Lake office).[10] The idea is that nearby batteries are likely competing over same pipelines. So, they should be 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 variable of interest on section and battery-type by date fixed effects. The 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. We present deviance residuals (McCullagh and Nelder, 1989) from these regressions in Figure 5.

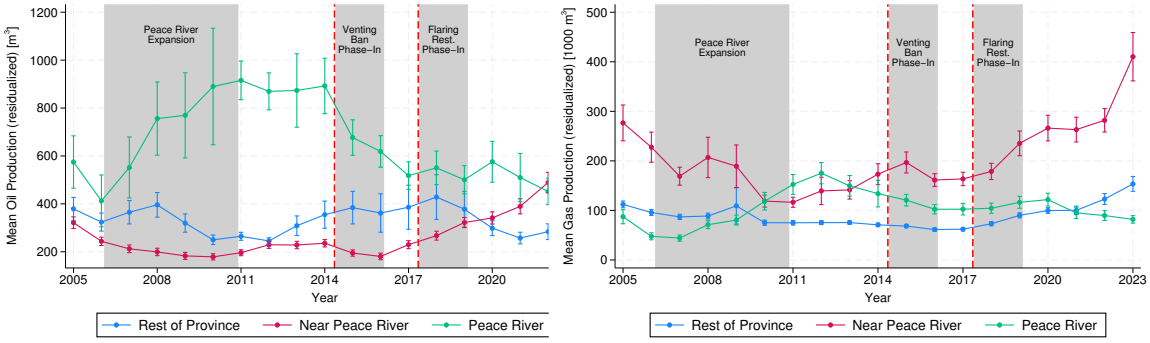
There are four time periods highlighted in Figure 5. Between 2006 and 2010, production expanded in Peace River due to the rise of SAGD technology. Production (and emissions) leveled out in 2011, before the introduction of regulation. The venting ban was phased in from late 2014 through 2016 (initially regulating batteries in the Three Creeks and Reno sub-regions, followed by regulation of the Seal Lake and Walrus sub-

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



(a) Venting Emissions

(b) Flaring Emissions



(c) Oil Production

(d) Gas Production

Figure 5: Trends at regulated and unregulated batteries

regions). The flaring ban 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 5 clearly show a reduction in emissions, and suggest this may have been accompanied by production losses. To estimate the causal effects of the Peace River regulation, we turn to the non-linear difference in difference estimator of Wooldridge (2023). The challenge in estimating the causal effects of the Peace River regulation arise 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. We apply the pooled quasi-maximum likelihood estimator developed by Wooldridge (2023). This estimator offers some notable advantages. Though it is a pooled estimator, as Wooldridge (2023) shows, it is equivalent to a a two-way fixed effect estimator. Fully saturating the regression eschews the need for high dimensional fixed effects. As a result, while it is equivalent to a two-way fixed effect regression, it is not subject to the heterogeneity bias raised in the recent causal inference literature. It is consistent even when the linear paral-

lel trend assumption is violated. Point estimates and cluster-robust standard errors can be easily computed for several relevant treatment effects, including the Average Treatment Effect on the Treated that allows for a non-linear counterfactual. Lastly, the presence of pre-trends can also be tested. This all requires that an appropriate link function is adopted that matches the linear exponential family used by the quasi-maximum likelihood estimator. Here, we use the exponential conditional mean link function paired with the Poisson LEF density.

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 in 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 on (when the additional flaring restrictions first became binding).

5.2 Evidence of Leakage

Table 3 shows the impacts of venting ban and flaring restrictions on vented and flared gas amount. We find evidence for two forms of leakage. First, we find that venting and flaring are emitting substitutes; restricting releases of one led to greater releases of the other. Columns (1)-(2) show that the venting ban in Peace River region removed venting while increased flaring in this area. Once the additional restrictions on flaring were introduced, the regulations effectively reduce both venting and flaring in the Peace River; see columns (3)-(4).

However, emissions reduction in the regulated area may be offset by the second type of leakage—emissions increase in the unregulated. Table 3 shows that batteries nearby the Peace River area increased both venting and flaring, after the sole venting ban and its combination with the flaring restrictions.

5.3 Oil Extraction and Joint Production Nature as Explanation for Leakage

As mentioned, oil extraction and its joint production nature with gas drives routine flaring. As a result, restrictions on venting and flaring would primarily impact oil

Table 3: Flaring and Venting Regulation and Emissions

	Vent Ban		Additional 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. Significance at the 1%, 5%, and 10% levels are denoted by ^{a}, ^{b}, and ^{c}, respectively.

rather than gas markets. Table 4 shows that venting ban and flaring restrictions in Peace River region significantly reduced oil production rather than gas production in batteries in this region. On the other hand, batteries in the nearby unregulated area substantially increased oil production, generating emissions leakage as seen above.

Table 4: Flaring and Venting Regulation and Production

	Vent Ban		Additional 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. Significance at the 1%, 5%, and 10% levels are denoted by ^{a}, ^{b}, and ^{c}, respectively.

5.4 New Capital Adapts to Regulations to Avoid Output Loss

The oil extraction and its joint production nature with gas explains why firms may strongly oppose regulations on flaring and venting. The reason is that flaring and

venting restrictions will strongly affect the output of the higher-valued main product, oil. Collecting the less-valued by-product, gas, may be not enough to compensate for this loss. So, regulations can come at the loss of output and revenue of the main product. However, this can be short term. In long term, firms may adapt with new capital. We find that new batteries built under regulations flare less without significant oil output loss.

Table 5 shows the regulation impacts on legacy batteries, those that were built by 2014, before the Peace River venting ban. Similarly to the previous analyses, we use non-linear difference in difference estimator (Wooldridge, 2023) to compare outcomes among batteries in three areas: regulated Peace River region, region nearby Peace River but unregulated, and the rest of the Alberta province. We restrict the sample to only batteries that were built by 2014, before the Peace River venting ban. Results similar patterns to the ones the analyses on all batteries. The legacy batteries in Peace River switched to flaring after the venting ban, but reduced both flaring and venting after the additional restrictions on flaring were imposed. To cut the emissions, these batteries cut oil production rather than gas production. Meanwhile, legacy batteries in the nearby unregulated area increased oil production and venting after the Peace River regulations were introduced.

Table 6 explores the regulation impacts on new batteries that were built after the venting and flaring regulations were introduced. We explore how the regulatory environment affects new capital decisions made by operators. We compare characteristics of new batteries opened after the Peace River regulations became fully enforced both in and outside the regulated region. We perform two sets of regressions. The first focuses on the period when only venting was regulated, covering batteries that began operating between June 2014 and March 2019. Results are in Panel A. The second regression focuses on the period when both flaring and venting were regulated, including batteries that began operating after the additional flaring restrictions took effect (March 2019); see Panel B.

Results show that new batteries in the regulated Peace River region effectively comply with the venting ban and additional flaring restrictions without cutting oil production. In contrast, these new batteries significantly increased gas production. For new batteries in the unregulated nearby region, they significantly increased both oil and gas output, even more substantial than the legacy batteries, suggesting the flaring leakage in the unregulated area mainly induced by the emissions increase at new capital than legacy one.

Table 5: Flaring Regulations and Emissions at Pre-2014 Batteries

	Vent Ban		Additional 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. Significance at the 1%, 5%, and 10% levels are denoted by ^{a}, ^{b}, and ^{c}, respectively.

6 Conclusion

We study the economic mechanism for routine flaring that goes beyond the technological limitations and infrastructure constraints suggested in the literature. We highlight that it is the joint production nature of oil and gas and the demand for oil that explains the routine and persistent flaring. Regulations on flaring and venting primarily affected oil production rather gas production, thereby generating flaring leakage in the unregulated areas. We demonstrate this using regulatory changes in a region within Alberta, Canada. We find that batteries in the regulated area cut oil production to effectively reduced flaring and venting, highlighting the key trade-off between oil production and flaring and venting and the private costs of flaring regulations. However, new capital that is built under the regulation periods does not have this trade-off; they effectively reduced emissions without cutting oil production. On the other hand, new batteries in the nearby unregulated area substantially increased oil extraction and emissions, explaining the flaring leakage in the unregulated area. These results emphasize the need to account for leakage when designing an effective regulations on

Table 6: The Impacts of Flaring Regulations in New Batteries

Outcome:	Venting	Flaring	Oil Output	Gas Output
	(1)	(2)	(3)	(4)
Panel A: Outcomes after Venting Ban				
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
R^2	0.035	0.056	0.492	0.122
Panel B: Outcomes after Venting Ban and Additional Flaring Restrictions				
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
R^2	0.034	0.132	0.208	0.140

This table shows estimates of the effects of the venting ban and its combination with the flaring restrictions in the Peace River region on the characteristics of new batteries. The regression compares characteristics among new batteries built after the venting ban (Panel A) and additional flaring restrictions (Panel B) in the Peace River region and nearby regions to characteristics of 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) shows 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 data on monthly battery operations are restricted to the same date range. 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.

routine flaring.

References

Agerton, Mark, Ben Gilbert, and Gregory B Upton Jr. 2023. "The Economics of Natural Gas Flaring and Methane Emissions in US Shale: An Agenda for Research and Policy." *Review of Environmental Economics and Policy*, 17(2): 251–273.

Arora, Vipin. 2014. "Estimates of the price elasticities of natural gas supply and demand in the United States."

Calel, Raphael, and Paasha Mahdavi. 2020. "The unintended consequences of antiflaring policies—and measures for mitigation." *Proceedings of the National Academy of Sciences*, 117(23): 12503–12507.

Coburn, Timothy C. 2020. "Oil and Gas Infrastructure." *The Oxford Handbook of Energy Politics*, 99.

Energy Institute. 2024. "2024 Statistical Review of World Energy Data." {https://www.energyinst.org/statistical-review}[Accessed:2024-10-20].

Hausman, Catherine, and Lucija Muehlenbachs. 2019. "Price regulation and environmental externalities: Evidence from methane leaks." *Journal of the Association of Environmental and Resource Economists*, 6(1): 73–109.

Janzwood, Amy, Kate J. Neville, and Sarah J. Martin. 2023. "Financing energy futures: the contested assetization of pipelines in Canada." *Review of International Political Economy*, 30(6): 2333–2356.

Kilian, Lutz. 2022. "Understanding the estimation of oil demand and oil supply elasticities." *Energy Economics*, 107: 105844.

Lade, Gabriel E, and Ivan Rudik. 2020. "Costs of inefficient regulation: Evidence from the Bakken." *Journal of Environmental Economics and Management*, 102: 102336.

Lyon, David R, Benjamin Hmiel, Ritesh Gautam, Mark Omara, Katherine A Roberts, Zachary R Barkley, Kenneth J Davis, Natasha L Miles, Vanessa C Monteiro, Scott J Richardson, et al. 2021. "Concurrent variation in oil and gas methane emissions and oil price during the COVID-19 pandemic." *Atmospheric Chemistry and Physics*, 21(9): 6605–6626.

Marks, Levi. 2022. "The abatement cost of methane emissions from natural gas production." *Journal of the Association of Environmental and Resource Economists*, 9(2): 165–198.

Mason, Charles F, and Gavin Roberts. 2018. "Price elasticity of supply and productivity: an analysis of natural gas wells in Wyoming." *The Energy Journal*, 39(1_suppl): 79–100.

McCullagh, P., and J. A. Nelder. 1989. *Generalized Linear Models. 2nd ed.* London: Chapman Hall/CRC.

Salmon, Ryan, and Andrew Logan. 2013. "Flaring up: North Dakota natural gas flaring more than doubles in two years." *Ceres*, 1.

Schaufele, Brandon, and Jennifer Winter. 2023. "Production Controls in Heavy Oil and Bitumen Markets: Surplus Transfer Due to Alberta's Curtailment Policy." *Energies*, 16(3): 1–24.

Wooldridge, Jeffrey M. 2023. "Simple approaches to nonlinear difference-in-differences with panel data." *Econometrics Journal*, 26(3): C31–C66.

A Appendix

A.1 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.1 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.1: 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.