

Co-Product Pollution: Theory and Evidence from Oil and Gas Flaring*

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Abstract

Many commercial processes yield a lower-value co-product alongside a high-value main product. Under free disposal and weak demand, co-products are frequently discharged as air, water, or land pollution. We provide the first formal treatment of co-product pollution regulation, showing that regulating the co-product is equivalent to taxing the main product. We corroborate the theory using data and a policy change from Canada's oil sector, where excess co-produced natural gas is flared. Flaring regulation caused a 55% reduction in oil production and substantial leakage. Our results suggest regulating the \$54 billion worth of gas flared globally could have significant unintended consequences.

Keywords: Joint production; oil and gas; flaring and venting; methane pollution

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1 Introduction

Many commercial processes yield multiple products, a high-value main product and a lower-value co-product. When free disposal is available, however, the lower-value co-product often becomes a by-product – a source of pollution or waste – even when markets exist for the output. This is because the costs associated with marketing the co-product exceed expected revenues, so “wasting” the co-product is optimal for firms.

Co-product pollution is both widespread and consequential. The flaring of natural gas that is co-produced during oil extraction releases harmful local air pollutants, creates \$85 billion in climate damages globally each year, and wastes over \$50 billion worth of gas annually (World Bank, 2026a).¹ Agricultural crop residues that could be used for bioenergy or fodder and are jointly produced with grain are often burned. This creates air pollution that has been shown to cause tens of thousands of premature deaths annually in India alone (Lan et al., 2022). Phosphoric acid production (used in fertilizer and detergents) creates phosphogypsum, a substitute for mined gypsum. The use and release of phosphogypsum is tightly controlled in many countries, as its trace radioactive elements decay into radon, a key risk factor for lung cancer among non-smokers (Environmental Protection Agency, 2026). Many other examples underscore the extent of harm and waste created by co-product pollution.²

Despite its prevalence, there is surprisingly little work on the economics of managing co-product pollution. We provide the first such formal treatment, evaluating one of the most pervasive examples: the disposal of natural gas through flaring (burning) or venting (releasing) during oil extraction. We develop a tractable theory of co-product pollution regulation and test its predictions using oil battery-level data and a policy change from Alberta, Canada. Our analysis shows that regulating co-product pollution, including gas flaring and venting, is more complex than is accounted for in current policy discussions and than standard theory suggests.

¹This is adopting a \$200 social cost of carbon and the World Bank’s estimate that 429 million metric tonnes of carbon dioxide equivalent was flared globally in 2025 (World Bank, 2026b).

²Examples of co-product pollutants with meaningful damages exist across many sectors and regions. Whey from cheese production can be used for various products, including protein powder, but is often disposed of in wastewater. Whey constitutes roughly 85% of milk volume. Its biological and chemical oxygen demand give it pollutant potential up to 100 times that of domestic sewage. Untreated discharge causes severe oxygen depletion in receiving waters. Alumina refining creates bauxite residue, which is a highly caustic slurry. Containment failures can be lethal, as in the case of Ajka, Hungary in 2010 in which ten people died, 406 were injured, and a river system was sterilized for 70 km. Gold mining creates arsenic trioxide, which is used in chemical, electronic, and glass manufacturing. If not collected, arsenic trioxide dust can be poisonous to humans and ecosystems through air and water. The Giant Mine arsenic trioxide remediation project in Yellowknife is Canada’s most expensive federal environmental cleanup at an estimated \$3.16 billion USD.

Our setting, as is the case with many co-product waste problems, is characterized by two key ingredients: joint production of a main product and a co-product and *extent-of-the-market* limitations for the co-product. Here, oil producers jointly recover both crude oil (the main product) and natural gas (the co-product) from drilled wells. When the extent of the natural gas market is low relative to oil, natural gas becomes a pollutant. This insufficient demand may arise because of shipping costs or constraints, or more perniciously, insufficient global demand attributed to absent shipping infrastructure. This 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.³

What unites the various forms of co-product pollution is not the physical form of the waste but their economic structure. In each, the co-product is generated in near-fixed proportion to the main product, disposal is free or nearly free to the firm, and a market for the co-product exists but is too small to absorb the volumes generated (or the price is insufficient to warrant marketing). The dual nature of co-products as both waste and marketable output means that regulating them as pollutants presents unique challenges. Our analysis shows formally, and verifies empirically, that adopting a standard model of pollution in these settings will lead to inaccurate policy conclusions along two dimensions. First, treating the polluting co-product as independent of the main product results in an incomplete assessment of the costs of (and potential leakage from) regulation because regulating the co-product acts as a *de facto* tax on the main product. Second, treating the co-product as the main product’s effluent and ignoring its potential market misses the possible efficiency gains from expanding the extent of the co-product market (which alleviates the tax on the main product) and the downstream environmental effects of using the co-product (which can be significant).

Our analysis starts by developing a price-theoretic model of routine flaring.⁴ The novelty of the analysis is that we explicitly incorporate *insufficient demand* into a joint production scenario. With free disposal, excess natural gas is wasted whenever the costs of conservation exceed revenues. We then study what happens when free disposal becomes costly due to the implementation of a ban on routine flaring.

Three policy-relevant predictions follow from this. The first prediction is that increases in oil prices will cause an increase in flaring due to a rise in production of the main product. The second prediction is that an increase in natural gas prices, that

³While 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.

⁴For simplicity, we jointly refer to flaring and venting as flaring in much of the rest of this paper.

is, the price of the co-product, will create a conservation effect that decreases flaring. These first two illustrate how the conceptual framework links to conventional energy market elasticities (e.g., Mason and Roberts, 2018; Arora, 2014, among others).⁵ The third prediction, the main focus of the paper, is counter-intuitive and absent from the literature.⁶ That prediction is that when the extent of the natural gas market is small relative to oil, regulation of natural gas acts as a de facto tax on oil extraction. We further show that this tax on the main product can only be alleviated when regulation is paired with a sufficient expansion in the extent of the co-product market.⁷

We test the two initial predictions using battery-level data from Alberta, Canada for the 2005-2023 period. Using 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 thousand cubic meter (MCM) increase in flaring, while a 10% increase in gas prices reduces flaring by 3.6 MCM.

Our main empirical contribution involves assessing the validity of our model’s third prediction by 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.⁸ 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.

We must overcome a tricky empirical challenge to isolate the causal effect of these regulations. Our analysis is at the battery-level (a collection of one or more wells at which oil and gas is extracted). Batteries make both extensive- and intensive-margin decisions with respect to emissions. Thus, our main dependent variables, flaring and venting emissions, are highly skewed, non-negative, and contain many zeros. The potential extensive margin selection effect makes these outcomes non-linear. Conventional two-way fixed effect estimators may yield biased estimates in such a setting. We address this issue in two steps. First, we adopt the *non-linear difference-in-differences* design suggested in Wooldridge (2023), using a Poisson link function to deal with the

⁵This follows from early analysis by Houck (1964).

⁶Indeed, we believe the prediction is missing from the discussion of joint production more generally.

⁷Although we do not model this explicitly, an interesting implication of our model is that a flaring tax would always create an effective tax on oil extraction, even if the natural gas market also expands.

⁸Flaring and venting are common with “sour” natural gas, gas with a high concentration of hydrogen sulfide. Hydrogen sulfide has a strong rotten egg smell.

zeros in measured flaring and venting. Second, we are fastidious with respect to control windows and groups with which we construct counterfactuals. In particular, to distinguish between direct and leakage effects we separate batteries into three groups: regulated, nearby unregulated, and the rest of the province. This involves invoking a conditional parallel trends assumption for both the treated and leakage batteries, in the vein of Jetsupphasuk, Li and Hudgens (2025).⁹ As we explain in detail, this stratification of treatment intensities is driven by pipeline geography, differences in geology, and regional input markets (Canada Energy Regulator, 2020). Comparisons across these three groups and non-continuous time periods enables us to infer the effects of regulation, while accounting for spillovers to proximate batteries.

Several important results emerge from this analysis. First, regulations that ban venting and restrict flaring locally are effective in achieving their goals locally. Unsurprisingly, in the regulated region, the 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, venting and flaring emissions in the regulated region decreased when both the venting and flaring regulations were binding. However, these decreases were more than fully offset by increases in emissions in the nearby unregulated region. That is, flaring leakage was greater than 100%. We show that this large degree of leakage was caused by “crowding in” of new and relatively dirty producers in the nearby unregulated region.

Finally, our conceptual framework predicts that the effects of flaring regulations will be principally observed in the oil market. We demonstrate that regulated facilities reduced oil extraction and that the magnitudes are large. Oil output fell by 55% per battery, on average. Further, these output reductions were offset by increased oil production in neighboring unregulated areas. We also uncover suggestive evidence that new batteries and those that expanded the extent of their co-product markets through new pipeline connections experienced smaller output losses.

This paper contributes to three active research areas. While it is common to model pollution as a “bad” output that is jointly produced with another good (e.g., Fowlie,

⁹Jetsupphasuk, Li and Hudgens (2025) discuss how causal indirect effects can be inferred provided that, in absence of treatment, both the treated and spillover units would have followed the same expected trend conditional on covariates and spatial location.

Reguant and Ryan (2016)), ours is the first to consider the class of pollutants that are themselves also marketable products. This paper thus extends the large literature on the effects of pollution regulation on output and emissions (see, e.g., Greenstone (2002); Fowlie, Reguant and Ryan (2016); Najjar and Cherniwchan (2021)) to the case of co-product pollution.¹⁰ We show that regulating co-product pollution is conceptually distinct from regulating a standard effluent.

We also contribute to the literature studying natural gas flaring and venting (Blundell and Kokoza, 2022; Guerin, Najjar and Schaufele, 2024; Agerton, Gilbert and Upton Jr, 2023). The most relevant analytical counterpart to our paper is that of Lade and Rudik (2020), who examine flaring regulations in North Dakota. We complement this work by analyzing regulation in a different jurisdiction and by incorporating venting – a critical yet often neglected aspect of gas waste. Our primary contribution, however, is to provide a new explanation for flaring and venting (joint production paired with insufficient demand) that is distinct from the infrastructure-based mechanisms previously offered by researchers (Lade and Rudik, 2020; Agerton, Gilbert and Upton Jr, 2023) and regulatory agencies (e.g., IEA, 2025; Canada, 2023). By acknowledging that firms have *an economic incentive* to flare, even when infrastructure exists to capture and sell natural gas, our framework provides a more complete economic foundation for understanding producers’ responses to flaring and venting regulation. This has important implications for an active policy debate, as the global push to regulate flaring (World Bank, 2024) has prompted planned or enacted regulations in many jurisdictions, including the US (the Environmental Protection Agency’s 2024 Methane Rule, or 89 FR 16820), EU (Regulation (EU) 2024/1787), and Canada (SOR/2025-280).

Finally, we contribute to the broader literature on methane regulation in the energy sector, of which flaring regulation is a subset. Hausman and Muehlenbachs (2019) study methane leaks in the regulated natural gas distribution system. They show how a regulatory system that emphasizes a return on capitalized assets distorts firm incentives to minimize leaks. Mason and Roberts (2018) demonstrate that well-level natural gas production is driven by geological factors. Aldy, Reinhardt and Stavins (2025) review methane abatement cost estimates for oil and gas. Our results show that while flaring regulations might effectively reduce flaring locally, their use as a tool to mitigate global methane emissions must comprehensively target all emission pathways and account for potential leakage to achieve genuine emissions reductions.

The rest of the paper is organized as follows. Section 2 provides an overview of our

¹⁰A useful counterpart is Shimshack and Ward (2008) who study regulation when multiple pollutants are jointly discharged.

setting and data. We then outline our model of co-production pollution in Section 3. We test the relationship between prices and emissions in Section 4. We examine the effects of the Peace River regulations, the primary empirical contribution of our paper, in Section 5. A short conclusion follows.

2 Overview of Data and Role of Infrastructure

We study flaring and venting regulations in Alberta, Canada. Canada is the world’s fourth-largest oil producer (Energy Institute, 2024) and the province of Alberta accounts for more than 84% of Canadian crude oil production. More significantly, Alberta, in the late 1990s, was among the first oil and gas producing jurisdictions to enact rules and mandate monitoring of flaring and venting. This longstanding regulatory system makes it an especially interesting jurisdiction to investigate.

Our empirical analysis is at the oil battery level. Batteries are the typical connection point for midstream infrastructure and represent the most consistent reporting entity for flaring. They are defined as one or more wells clustered within a field and operated by the same company. We obtained rich monthly battery-level data on flaring and venting volumes and oil and gas production via a Freedom of Information request submitted to the Alberta Energy Regulator (AER). Our sample runs from 2005-2023, and represents virtually all batteries in the province, containing 31,103 unique batteries and 2,097,163 observations.^{11,12}

Table 1 shows selected summary statistics for the sample. The average oil battery produces 712.4 m³ of oil and 172.5 thousand m³ of gas per month. Our analysis maintains the units in the data, m³ for oil and thousand m³ for gas. However, for oil, barrels are likely more familiar to most readers. To fix intuition, 712.4 m³ is equivalent to 4,480.9 barrels of oil per month. Further, assuming an average price of crude oil equal to \$60 CAD per barrel, the average battery in Alberta yields nearly \$270,000 CAD in revenue per month. The prevailing price of natural gas in Alberta over the recent 2018-2023 period was approximately \$0.10/m³.¹³ Thus, oil batteries earn an

¹¹“Confidential” facilities are excluded, representing less than 2% of emissions and production.

¹²The data are self-reported but vetted by an “audit group” within the AER. The audit group ensures data accuracy and regulatory compliance. Firms must submit information on oil production, gas production, water use and gas flared and vented on a monthly basis. Each submission is reviewed and compared with automated systems which issue flags for changes in expected trends and when variables cross pre-specified thresholds. Field inspections also occur regularly by each of seven field offices, with audit probabilities determined according to a risk prioritization framework.

¹³The annual average price in Alberta over 2018–2023 was \$2.61/GJ (Government of Alberta, 2024). When converted from GJ to volumes, this equals: $\frac{\$2.61/\text{GJ}}{26.3\text{m}^3/\text{GJ}} \approx \$0.099/\text{m}^3$.

additional $\sim \$17,000$ per month on average from selling jointly produced natural gas. There is substantial variation around the mean for both oil and gas production, as both operation size and gas content varies across sites.

Table 1: Summary Statistics at the Crude Battery-level, 2005-2023

<i>Panel A: All observations</i>				
	Mean	Std. Dev.	Min	Max
Oil production	712.4	12,216.6	0.0	1,278,849.0
Gas production	172.5	1,800.3	0.0	574,554.6
Gas flared	3.9	32.4	0.0	12,433.5
Gas vented	2.0	11.7	0.0	4,444.0
<i>Panel B: Non-zero observations</i>				
Oil production	840.7	13,267.2	0.1	1,278,849.0
Gas production	205.0	1,960.7	0.1	574,554.6
Gas flared	27.5	82.7	0.1	12,433.5
Gas vented	4.5	17.2	0.1	4,444.0

Oil volumes are measured in m^3 . Gas volumes are measured in thousand m^3 .
Sample contains 2,097,163 monthly observations across 31,103 batteries.

The average battery also flares 3.9 thousand m^3 of gas and vents 2.0 thousand m^3 of gas each month. As with oil and gas production, there is significant variation in flaring and venting across observations. However, the source of this variation differs for releases; in addition to size and site-specific conditions, many batteries do not flare or vent each month. If we restrict to observations that report positive values (Panel B), monthly average flaring releases increase to 27.5 thousand m^3 of gas and venting releases increase to 4.5 thousand m^3 of gas. This amounts to roughly 1% of battery revenues being wasted in months in which batteries flare and vent.¹⁴ As we discuss in Section 5.2, an important component of our research design is in accounting for the extensive margin pollution decisions that populate our data with many zeros.

Figure 1 shows the flaring and venting rates in Alberta over time to add context to the summary statistics. 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 5% of associated gas but have leveled off at approximately 3% since 2016.¹⁵ Further, while

¹⁴This adds positive flaring and venting volumes and assumes a natural gas price of $\$0.10/\text{m}^3$.

¹⁵For comparison, Lade and Rudik (2020) discuss how North Dakota's Order 24,665, required wells to conserve 77% of produced gas starting in January 2015, rising in steps to 91% by November 2020.

the venting rate dropped from a peak of 2% in 2012 to about 0.5% in 2023, the flaring rate remained relatively steady at 2-3%. 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 (Guerin et al., 2025).¹⁶

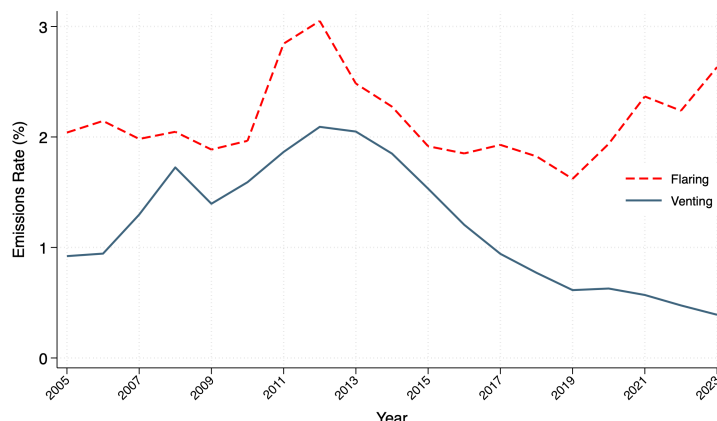


Figure 1: Alberta Flaring and Venting Rates, 2005-2023

The raw data also highlight why moving beyond infrastructure-based explanations of flaring is important. This can be seen in Figure 2, which shows average annual per battery flaring and venting emissions before and after they connect to the natural gas network.¹⁷ To start, Figure 2 confirms the results from Lade and Rudik (2020). Connecting a previously unconnected battery to natural gas collection infrastructure reduces flaring and venting. Here, annual emissions drop by approximately 50% once a battery is connected to the midstream pipelines system.¹⁸ This is expected and aligns with our conceptual framework. Indeed, the magnitude of the effect is larger than found in Lade and Rudik (2020). The more interesting point, however, is that connecting a battery to midstream infrastructure does not eliminate flaring and venting. Emissions decline but remain persistent in subsequent years.¹⁹ This underscores

¹⁶Note the global estimates do not account for venting, which may be substantial.

¹⁷The bars plot the residuals from regressions of flaring and venting emissions on battery-type-by-year, township-by-year, and age-by-year fixed effects.

¹⁸The Alberta regulations include a series of special provisions with respect to new batteries. For example, there is a six month grace period prior to adhering to the existing flaring and venting regulations. Also, companies must meet net present value thresholds with respect to natural gas flaring and venting (i.e., they are not permitted to waste gas above a specific economic level). This threshold is viewed as largely non-binding. Finally, batteries are classified as connected starting with the first date that they market gas via pipeline infrastructure.

¹⁹We caution that Figure 2 does not offer a credible estimate of the causal effect of connection due to the fact that firms can self select into connecting. We simply use this figure to underscore the fact that connection appears insufficient to eliminate flaring and venting.

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.

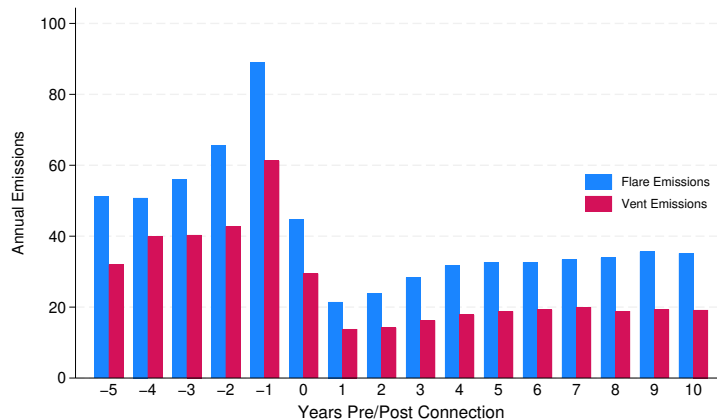


Figure 2: Flaring and Venting Emissions by Pipeline Connection Status

Our paper contributes to explanations for flaring by moving beyond infrastructure hypotheses. We emphasize that an economic mechanism, the co-product nature of natural gas, as discussed next, is the primary explanation of flaring and venting. Understanding these economic incentives is important for designing effective regulations.

3 Conceptual Framework: Joint Production and Insufficient Demand Cause Co-Product Pollution

We present a simple theory of co-product pollution. We frame the theory around our empirical setting – the flaring of natural gas during oil production – however, we stress that the framework applies more generally to the issue of co-product pollution.

Oil reservoirs frequently have associated gases ‘in solution.’ Upstream firms seeking to extract crude oil simultaneously obtain natural gas as a lower value by-product because gas occurs alongside, i.e., is ‘associated’ with, oil in the geological formations.²⁰ That is to say, oil and natural gas are joint products, produced in fixed proportions according to the geological characteristics of the resource.²¹ We present a price-theoretic framework that encapsulates joint production alongside extent-of-the-market limits, yielding three important predictions about the implications of regulating co-product

²⁰In 2022, for example, 96% of batteries in Alberta produced both gas and oil.

²¹Strictly, fixed proportions is unnecessary for our analysis. However, it is a very good approximation for the context we are studying and that of many other co-products.

pollution. We begin by establishing firms' economic motivation for flaring and then show how joint production and insufficient demand interact with flaring regulations.

3.1 Economics of Natural Gas Flaring

Let Q_1 represent oil, the high-value product, and Q_2 be natural gas, the co-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 the price of natural gas. The oil market is large and oil is easy to transport internationally. Natural gas markets tend to be fractured and regional, with more limited extent.

Firms obtaining joint products 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.²²

There is ample global demand for oil with prices set internationally. Firms take the price of oil, P_1 , as given. By contrast, the demand for natural gas, the less valuable product, is more limited and regional. Natural gas is also subject to infrastructure and storage constraints that are assumed non-binding in the oil market (Coburn, 2020). In Section 3.3, we relax this asymmetry by allowing for expansion in the natural gas market (i.e., pipeline construction).

²²The splitoff point is the stage in a joint production process where products become separately identifiable. After the splitoff point, costs are also separable.

The firm decides how much of the associated gas, αQ_1^* , 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:²³

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

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

The left-hand side of Eq.(1) is the firm's additional revenue from selling 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 , which represents the opportunity cost of gas shortages. We dwell on the interpretation of λ because an analogous constraint arises when we consider regulating flaring. 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:

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

where $\hat{Q}_2$ is the quantity at which the natural market is saturated. At that level, price

²³Lade and Rudik (2020) derive a virtually identical first-order condition. Their paper and ours offer distinct interpretations, however.

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 optimally flare excess gas:

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

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.

Figure 3 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.

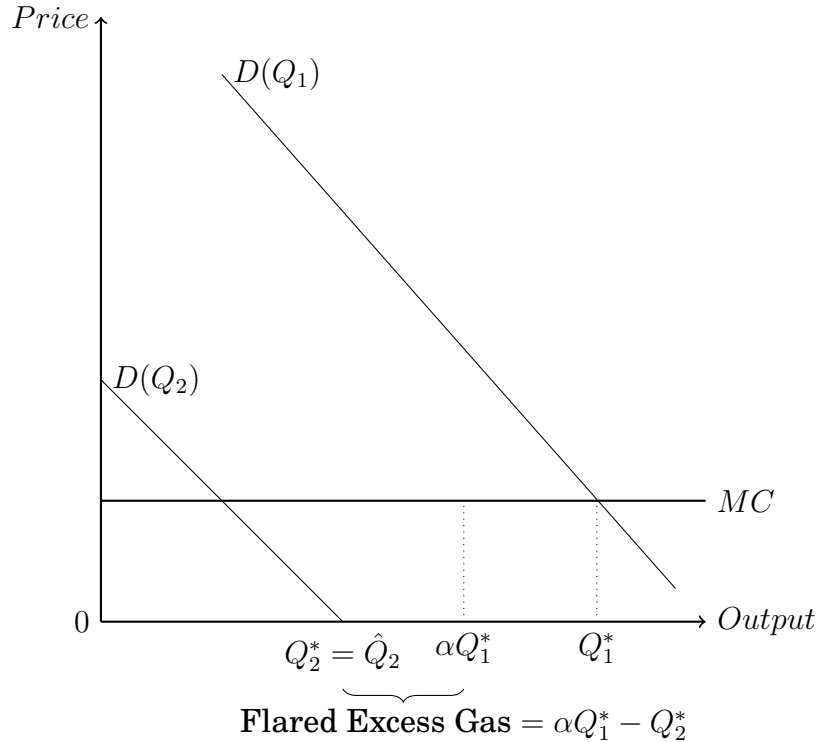


Figure 3: Joint Production of Oil and Natural Gas – Unregulated

Because routine flaring is permitted, firms maximize 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 nat-

ural gas. Figure 3 depicts a scenario where αQ_1^* , the volume of gas produced, exceeds the market saturation point, $\hat{Q}_2$. This is the interesting case in which 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 $\alpha Q_1^* - Q_2^*$ of excess gas.

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:

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

where we assume independent market demands for oil and gas.²⁴ 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 3) 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 3 – yields an increase in Q_2^* . An increase in Q_2^* decreases flaring, F , because of the negative sign leading term (B) in Eq.(4).

Eq.(4) further provides a direct connection between market elasticities and flaring levels. Variation in flaring explained by variation in commodity prices is proportional to variation in output explained by prices. This correspondence acts as a litmus test for our point estimates in Section 4 and provides a means to connect our regressions to other results on oil and gas markets.

Oil and gas prices have an intuitive relationship to flaring and the conceptual framework makes plain an additional economic cause of routine flaring. 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. Specifically, 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 initial predictions with respect to how flaring responds to commodity prices.

²⁴There 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).

3.2 Implications of Regulating Flaring

Next, we consider the implications of regulating flaring when oil and gas are jointly produced and there is insufficient demand for natural gas. Therein, we obtain our third, counter-intuitive prediction: the economic consequences 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 costs are separable. Regulatory constraints are represented through a 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 (e.g., as in North Dakota and Alberta).

Given this regulatory constraint, the firm's first-stage optimization problem is:

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

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 the oil analogue to Eq.(1), where λ has been swapped with the product $\phi \alpha$. 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 $\phi = 0$.²⁵ When the extent of the gas market is small, flaring regulations lead to $\phi > 0$.

²⁵Likewise, 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.

The third prediction of our model then is that, when the extent of the natural gas market is small, 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, the co-product.

Figure 4 offers a graphical illustration, starting from the Figure 3 baseline. Gas sales are limited by the extent of the market, so the flaring constraint binds at $\bar{F}$. This constraint on flaring spills over 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 to $MC_{\text{w/ Reg}}$. Optimal output, determined by Eq.(5), gives oil production equal to $\tilde{Q}_1$ and corresponding gas yield of $\alpha\tilde{Q}_1$. Compared with Figure 3, both flaring and oil production are lower.

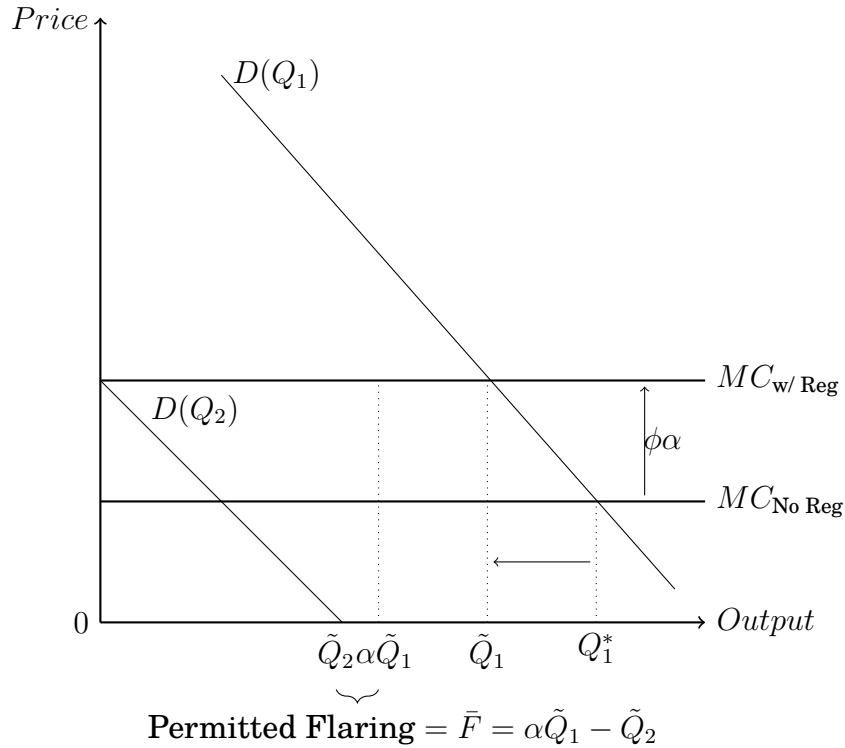


Figure 4: Joint Production of Oil and Natural Gas – Regulated Flaring

Figure 4 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 free disposal level (e.g., as illustrated in Fig.

3). The regulations ensure that 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 empirical contribution of this paper is to estimate the magnitude of this oil market effect. This prediction is new to the literature: a regulation nominally on the co-product has first-order economic consequences for the high-value product when there is a limited extent of the market for the co-product.

While obviously highly stylized, there are two immediate extensions of the model worth discussing. First, α , the co-production rate, may be endogenous. In particular, new batteries, especially if regulated, may adopt different extraction technologies than their legacy counterparts. We explore this possibility empirically. Second, $D(Q_2)$ is in reality endogenous, as firms could make pipeline investments to connect to new markets. We explore the consequences of relaxing this constraint next.

3.3 Consequences of Extending the Market

Next, we extend the model to allow firms to respond to flaring regulation by investing to expand the extent of the co-market.²⁶ This might correspond to building more natural gas pipelines, increasing natural gas processing capacity, or expanding liquefied natural gas processing in the region. This extension offers a useful connection to previous work that has explored the role of infrastructure constraints as a cause of flaring (Agerton, Gilbert and Upton Jr, 2023; Lade and Rudik, 2020).

Consider a discrete investment decision given by $I \in \{0, 1\}$. If the firm invests ($I = 1$), it pays a fixed cost $K > 0$ and gains access to a market with a larger saturation point $\hat{Q}_2^H > \hat{Q}_2$. The inverse demand for natural gas from Eq.(2) is modified so that the saturation point depends on the investment choice:

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

where $\hat{Q}_2(I) = \hat{Q}_2$ if $I = 0$ and $\hat{Q}_2(I) = \hat{Q}_2^H$ if $I = 1$.

The firm now faces three choices: 1) how much oil to extract, 2) how much gas to market, given the level of oil extraction, and 3) whether to invest in market-expanding

²⁶We model this as the regulated firm making the investment. In practice, it could be a third party.

infrastructure. The firm's problem becomes:

$$\max_{Q_1, Q_2, I \in \{0,1\}} P_1 Q_1 + P_2(Q_2) Q_2 - C(Q_1) - \tilde{C}_2(Q_2) - K \cdot I$$

subject to the joint production constraint $Q_2 \leq \alpha Q_1$, the market extent constraint $Q_2 \leq \hat{Q}_2(I)$, and the flaring regulation $\alpha Q_1 - Q_2 \leq \bar{F}$.

Because I is discrete, the firm compares profits under each choice and selects the investment level yielding the higher payoff. Let $\Pi^*(I)$ denote the firm's optimal profit conditional on investment choice I . The firm invests if and only if:

$$\Pi^*(I = 1) - \Pi^*(I = 0) \geq K. \quad (6)$$

The left-hand side of Eq.(6) captures two distinct benefits of investment. First, the firm earns additional revenue from selling gas in the expanded market. Second, and more importantly for our purposes, investment (weakly) reduces the shadow price ϕ of the flaring regulation. Let ϕ^I denote this shadow price when the firm invests. This lower shadow price means the effective marginal cost of oil production is lower when the firm invests. Compared with the no investment scenario, oil profits are higher under regulation with investment.²⁷

This extension yields another notable prediction: extending the market lowers output losses in the primary product by reducing the effective tax faced by producers. This implies that the effect of regulation on oil output will be heterogeneous across firms depending on their fixed cost of investment K . In our setting, K is correlated with proximity to infrastructure, firm capital, and battery vintage, among other slow moving stock variables. Newly-constructed batteries, in particular, can integrate infrastructure decisions into facility design and therefore face lower effective K , while legacy batteries face higher retrofit costs and are more likely to opt out of investment. We examine this heterogeneity in the empirical analysis that follows.

Figure 5 shows the implications of allowing firms to expand the co-product market, relative to the regulatory example shown in Figure 4. If the firm invests following regulation, then the oil marginal cost curve shifts up by less than without investment. As a result, oil output falls to $\tilde{Q}_1^I$, a smaller drop in production than when the firm is regulated without investment ($\tilde{Q}_1$). The investment expands the co-product market, shifting the residual demand curve for natural gas to the right to $D(Q_2|I = 1)$, with a

²⁷To see this, note that by construction investment relaxes the market saturation point $\hat{Q}_2$. By necessity, either market saturation is never reached, in which case the Lagrange multiplier ϕ is unchanged, or the constraint becomes less binding, and $\phi \geq \phi^I$.

market saturation point of $\hat{Q}_2^H$. Flaring becomes $F^I = \alpha\tilde{Q}_1^I - \hat{Q}_2^H \leq \bar{F}$.

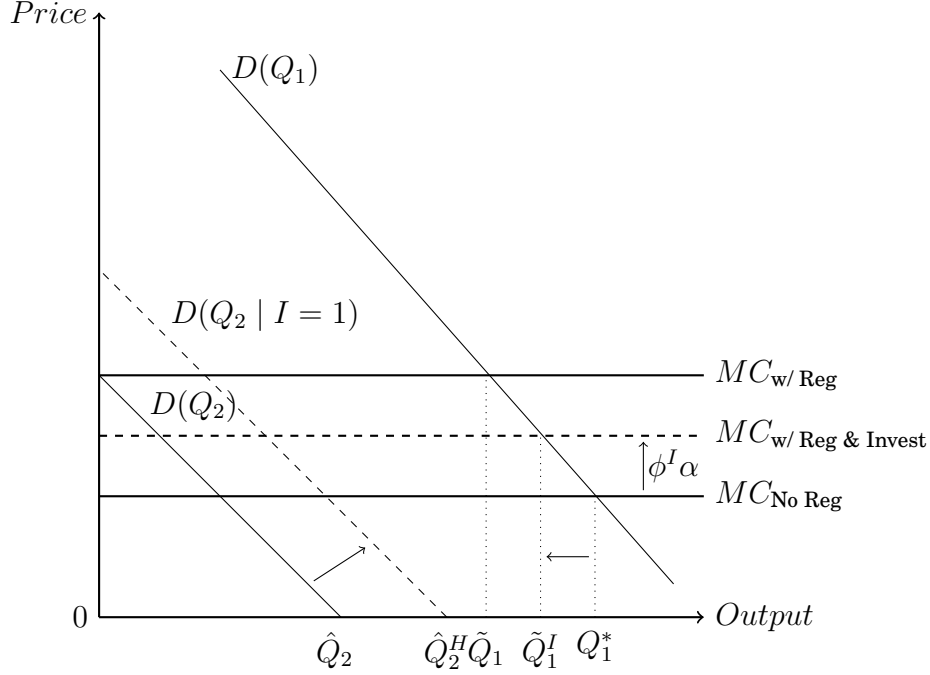


Figure 5: Joint Production of Oil and Natural Gas – Regulated Flaring with Pipeline Expansion

This extension has two important implications. First, for the general issue of co-product waste regulation, the effective tax on the high-value product resulting from co-product regulation can be reduced through costly investment that extends the secondary market. This, of course, is only possible if there is sufficient demand globally to support this extension.

Second, in the specific case of flaring regulation, pipeline expansion would lessen the regulatory effects on oil production. However, it also directly undermines the main emission reduction objective of the policy. This occurs because the newly conserved natural gas would be combusted downstream, releasing virtually identical levels of emissions. Thus, if flaring regulation were paired with (or met by) pipeline expansion, the only climate benefit would occur through the conversion of vented emissions to downstream combusted emissions. Flaring reductions would have no climate benefit.

4 Empirical Evidence of the Joint Production and Insufficient Demand Mechanism

Our conceptual model makes two predictions bridging variation in oil and gas prices to changing flaring volumes: oil prices and flaring should be positively correlated, while natural gas prices and flaring should be negatively correlated. We test these predictions by estimating the response of battery-level emissions to changes in Albertan market prices. This highlights the empirical content of the conceptual set-up before we move to the regulatory analysis. This section describes our econometric setup, including how we identify price effects, followed by a discussion of the results.

4.1 Empirical Strategy

Our main specification for testing the model’s price theoretic predictions is:

$$y_{imt} = \tilde{\beta}_g \ln(\text{Gas Price})_{mt} + \tilde{\beta}_o \ln(\text{Oil Price})_{mt} + \lambda_i + \zeta_m + \xi_t + e_{imt}, \quad (7)$$

where y_{imt} is the total volume of all natural gas released (summing flaring and venting) for battery i in month m of year t . Release volumes are regressed on the natural log of market-wide natural gas prices, $\ln(\text{Gas})_{mt}$, and the natural log of market crude oil prices, $\ln(\text{Oil Price})_{mt}$, 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, and year fixed effects, ξ_t , to accommodate common shocks across batteries.

Eq.(7) has two coefficients of interest: $\tilde{\beta}_g$ and $\tilde{\beta}_o$.²⁸ $\tilde{\beta}_g$ shows how battery-level emissions change in response to 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, the coefficients in Eq.(7) may be biased due to simultaneity. To address this, we instrument for provincial prices with their U.S. counterparts. We instrument for Alberta’s natural gas prices with Henry Hub prices and for Western Canadian Select prices, Alberta’s benchmark oil price,

²⁸Appendix A, Table A.2 includes separate regressions including gas and oil prices separately.

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 of oil output is determined by an arbitrary coefficient of proportionality, α . In reality, α varies across batteries as it is determined by 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 approximately 10% of active batteries. We demean $\left[\frac{\text{Gas Rev.}}{\text{Total Rev.}}\right]_i$ and scale by 100. We then estimate:

$$\begin{aligned}
y_{imt} = & \beta_g \ln(\text{Gas Price})_{mt} + \gamma_g \left[\frac{\text{Gas Rev.}}{\text{Total Rev.}} \right]_i \times \ln(\text{Gas Price})_{mt} \\
& + \beta_o \ln(\text{Oil Price})_{mt} + \gamma_o \left[\frac{\text{Gas Rev.}}{\text{Total Rev.}} \right]_i \times \ln(\text{Oil Price})_{mt} \\
& + \lambda_i + \zeta_m + \xi_t + e_{imt},
\end{aligned} \tag{8}$$

As in Eq.(7), 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 coefficients γ_g and γ_o capture how these relationships change as the battery's gas share increases by one percentage point relative to the average.

4.2 Results

Table 2 shows the estimates testing the first two predictions from our conceptual framework. Coefficients from Eq.(7) are in columns (1) and (3). Corresponding estimates for Eq.(8) are in columns (2) and (4). The first two columns show values estimated via least squares. The last two columns show the instrumental variable results.

Table 2 provides compelling empirical support for the paper's theoretical framework. All coefficients have the predicted sign and magnitudes are in line with expectations. Before presenting the results we provide some context guided by Eq.(4), which illustrates how the relative market elasticities of oil and natural gas explain varia-

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

	<u>OLS</u>		<u>IV</u>	
	(1)	(2)	(3)	(4)
ln(Gas Price)	-0.121 (0.122)	-0.125 (0.122)	-0.360 (0.192)	-0.339 (0.192)
ln(Gas Price) x Gas Share		-0.027 (0.002)		-0.028 (0.002)
ln(Oil Price)	0.385 (0.105)	0.390 (0.105)	0.305 (0.134)	0.305 (0.135)
ln(Oil Price) x Gas Share		-0.001 (0.002)		0.001 (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 Eq.(7) and (8). Monthly battery gas emissions are regressed on provincial monthly gas and oil prices. Emissions are measured in thousands m³. Prices are measured in USD per gigajoule of energy. All regressions include battery, year, and month fixed effects. Columns (2) and (4) include an interaction between the battery's share of revenues from gas and each price variable. 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.

tion in flaring volumes, and related literature. 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).

The instrumental variable results in columns (3) and (4) of Table 2 match these theoretical predictions closely. 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 MCM.²⁹ 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 MCM increase in emissions.³⁰ 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.

Column (4) 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.

Table 2 demonstrates that both gas and oil prices affect flaring and venting releases. We interpret these results as corroborating evidence that limited extent of the natural gas market leads firms to waste an otherwise valuable co-product. Additional evidence that further supports this claim is presented in Online Appendix A. We show that only oil prices have a statistically significant effect on oil and gas production, consistent with oil as the main product. We also show that the results are robust to including gas and oil prices separately.

We next explore the consequences of co-pollution regulation.

²⁹The average monthly log change in Alberta gas prices is -0.0005 with a standard deviation of 0.18.

³⁰The average monthly log change in Alberta oil prices is -0.008 with a standard deviation of 0.23.

5 The Effects of Regulating Co-Product Pollution

5.1 Institutional Background and Initial Graphical Results

We study the causal effect of flaring and venting regulations by exploiting an unexpected policy change in Alberta. In 2014, Alberta introduced Directive 084. This created regulations that applied exclusively to batteries in a small region of the province, the Peace River region. These regulations were not imposed elsewhere in Alberta. The regulatory order phased in a venting ban over the 2014-2016 period and then subsequently introduced flaring restrictions between 2017 and 2019.

This policy experiment is instructive for several reasons. First, the regulations were the product of a provincial panel created to investigate odor complaints in the province's Peace River region. According to anecdotal accounts, the regulations were a surprise to both the region's oil producers and even the complainants.³¹

Second, this region was singled out because of odor complaints that 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).

Finally, the rules exclusively applied to a relatively small and clearly defined region. Spatial spillovers represent an important challenge, as the regulated region shares infrastructure and geological conditions with the surrounding areas. However, both the regulated and proximate regions are relatively distinct from further producers. Thus, properly comparing regulated and proximate areas with distant unregulated areas allows us to estimate both the direct and spillover effects of policy.

The venting ban was introduced in May 2014, first became binding for some producers in September 2014, and extended to all producers by 2016.³² Additional limits on flaring, of 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. These first became

³¹The 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.

³²Initial venting regulations only applied to batteries in the Three Creeks and Reno sub-regions. These were shortly followed by identical restrictions in the Seal Lake and Walrus sub-regions. Together the four sub-regions comprise the broader Peace River area.

binding in April 2018, with the last provisions taking effect in March 2019.

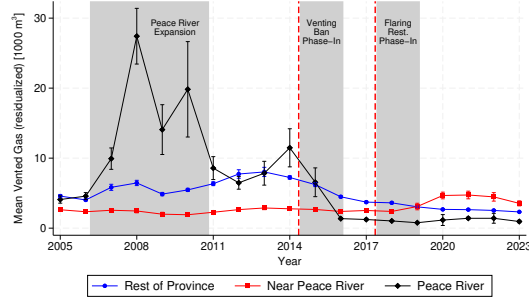
Restricted access to natural gas gathering pipelines, a small number of exit points to long-haul transmission infrastructure, common regional input markets, and shared geological formations effectively generate three levels of treatment intensity for the Peace River regulations. The first tier comprises batteries directly bound by the regulation — those located in the Peace River area. The second tier comprises batteries that are not directly regulated but share regional conditions with Peace River operations along three dimensions. First, they feed the same constrained Upstream James River leg of the natural gas gathering network (Canada Energy Regulator, 2020) and therefore compete with Peace River batteries for scarce gas takeaway capacity (Oliver, Mason, and Finnoff, 2014). Second, they operate in proximate regional labor and services markets, drawing on a common pool of drilling rigs, servicing contractors, and skilled labor. Third, some producers in both areas target the same underlying geological formations — principally the Bluesky and Gething formations of the Peace River Arch — using similar extraction technologies. 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), as this captures access to the upstream James River leg of the gas gathering network and encompasses an area with proximate input markets and similar geography.³³ The third tier comprises batteries in the rest of the province, which feed separate gas gathering legs, operate in different regional labor markets, and target geologically distinct formations. As a result, they do not directly compete with Peace River batteries along any of these three dimensions.

Figure 6 shows trends in battery level outcomes across these three different groups of batteries. The figure plots the residuals from running a Poisson regression of the variables of interest – venting emissions, flaring emissions, oil production, and gas production – on section and oil-type-by-date fixed effects. Sections represent a square mile (2.5 km²); section fixed effects account for regional level differences in outcomes. The oil-type-by-date fixed effects account for differential trends by type of oil produced (bitumen vs. other lighter crude). The figure plots average deviance residuals from these regressions (McCullagh and Nelder, 1989).

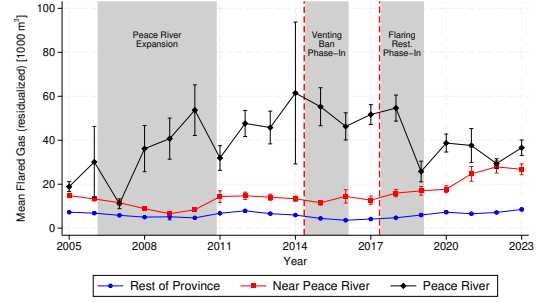
Four time periods are highlighted in Figure 6. Between 2006 and 2010, the first gray area in the figure, production expanded in Peace River due to the rise of a new technology designed for bitumen extraction.³⁴ Production (and emissions) stabilized in 2011 prior to the introduction of regulation. The venting ban was phased in from

³³The St. Albert office closed in 2018 and was replaced by the Slave Lake office.

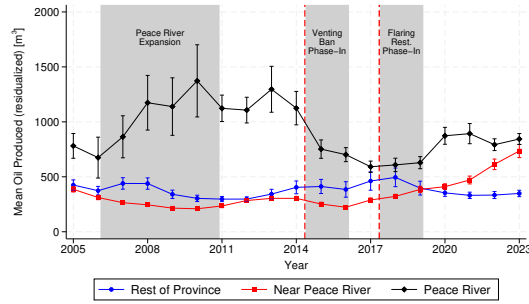
³⁴This is known as steam-assisted gravity drainage, or SAGD, technology.



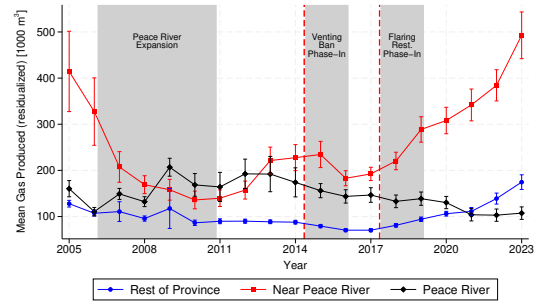
(a) Venting Emissions



(b) Flaring Emissions



(c) Oil Production



(d) Gas Production

Figure 6: Trends at regulated and unregulated batteries

Notes: Each panel plots deviance residuals (McCullagh and Nelder, 1989) from a Poisson regression of the outcome on region (section) and oil-type-by-date fixed effects, averaged annually within each treatment group. The three groups are Peace River (regulated), Near Peace River (potential spillover batteries), and Rest of Province (unregulated, distant batteries). Vertical bars denote 95% confidence intervals. Venting and flaring emissions and gas are measured in thousands of m^3 per battery-month; oil is measured in m^3 .

late 2014 through 2016, shown as the second gray area. 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 new operators were given until 2019.

The trends in Figure 6 are suggestive of the effects of regulation. The black line in Figure 6 shows a sharp reduction 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 Panel (b). The bottom panels show diverging trends in output suggesting that these rules may have been accompanied by production losses. The figures also indicate potential leakage to batteries close to Peace River, for whom output and emissions increased following the Peace River regulations.

While suggestive evidence is visible in simply detrended data, there is one issue that makes quantifying the causal effects challenging. Venting and flaring are char-

acterized by frequent zeros; these zeros vary both across and within batteries. That is, batteries make both extensive- and intensive-margin decisions with respect to emissions. These decisions are highlighted in Figure 7, which shows the share of batteries reporting zero venting or flaring emissions in each year across each treatment group.³⁵ The extensive margin varies systematically across groups and over time. This means that outcomes are potentially non-linear due the extensive margin selection. In addition, data are extremely right skewed with many zeros. So, a log transformation with an OLS-based regression is also ill-suited to the data. As we explain next, to obtain the appropriate counterfactuals and make causal claims about the effects of the regulations, we apply Wooldridge’s (2023) pooled quasi-maximum likelihood estimator with an exponential (i.e., Poisson) link function.

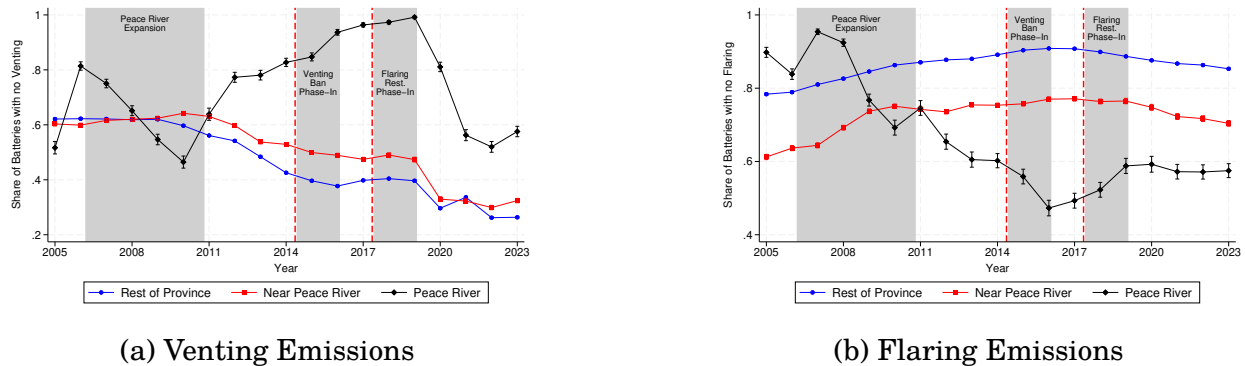


Figure 7: Extensive margin at regulated and unregulated batteries

Notes: Figure plots the share of batteries reporting no venting emissions (panel (a)) and no flaring emissions (panel (b)) averaged annually within each treatment group. The three groups are Peace River (regulated), Near Peace River (potential spillover batteries), and Rest of Province (unregulated, distant batteries). Vertical bars denote 95% confidence intervals.

5.2 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 pre-trends. Specifically, we follow the “fully saturated” Poisson quasi-maximum-likelihood framework of Wooldridge (2023), which extends the traditional two-way fixed-effects

³⁵The share of zero-venting batteries fell sharply in 2020 due to a small change in venting reporting requirements. This does not affect our research design, as it applied to all batteries.

difference-in-differences set-up to the exponential family. A Poisson panel yields consistent estimates under weaker assumptions when the conditional mean is correctly specified, regardless of the true distribution of the dependent variable. This fits our setting well as we seek to account for both the extensive- and intensive-margins jointly.

Let y_{it} denote monthly outcomes (e.g., flaring, venting, or oil extraction) for battery i in calendar month t . Define $\mathbb{1}\{g = i\}$ as an indicator that battery i belongs to one of three groups, $g \in \{\text{Peace River, Near Peace River, Rest}\}$. These three groups allow for a series of comparisons that identify distinct estimands. We compare changes in the regulated Peace River region to changes at batteries in the rest of the province to construct the first counterfactual, excluding unregulated batteries spatially proximate to Peace River. This shows the direct consequences of regulating flaring. We also compare changes at batteries “close enough” to Peace River to share significant oil and gas infrastructure with regulated batteries to changes at batteries in the rest of the province, excluding directly regulated batteries. We then interpret this difference as leakage.³⁶ Our identifying assumption is still conditional parallel (non-linear) trends, where in the absence of treatment both the directly treated and indirectly treated batteries would have followed the same expected relative trends as control batteries, conditional on covariates and spatial position (Jetsupphasuk, Li and Hudgens, 2025).

In addition to paying attention to spatial interference, we are careful with respect to which temporal periods we use to formulate counterfactuals. Specifically, we distinguish between regulatory phases. Let $\mathbb{1}\{p = t\}$ indicate whether month t falls into policy phase $p \in \{\text{Pre-Period, Venting Ban, Flaring Restrictions}\}$. 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:

$$E[Y_{it} \mid G_i, T_t, X_{it}] = \exp\left(\alpha_0 + \sum_{g \neq \text{Rest}} \alpha_g \mathbb{1}\{g = i\} + \sum_{p \neq \text{Pre}} \tau_p \mathbb{1}\{p = t\} + \sum_{g \neq \text{Rest}} \sum_{p \neq \text{Pre}} \delta_{gp} \mathbb{1}\{g = i\} \mathbb{1}\{p = t\} + X'_{it}\beta\right) \quad (9)$$

where X_{it} includes price controls $\ln P_t^g$ and $\ln P_t^o$, month-of-year fixed effects, an indicator for whether the battery extracts bitumen, and interactions between bitumen, region, and period. We do not include battery fixed effects in this specification to ensure we capture the joint intensive and extensive margin effects of this policy. Battery fixed

³⁶This can be thought of as jointly estimating two distinct difference-in-difference regressions.

effects are incorporated in additional analyses in Section 5.4. 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. We follow Wooldridge (2023) and convert estimates to reflect the average treatment effect on the treated (i.e., we adjust for the observed covariate distribution in each regulated group) and express these in natural logs.

The coefficients of interest are the δ_{gp} 's. These coefficients identify the causal effects of regulation 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 batteries in the same group in the pre-policy era, net of contemporaneous changes for the rest-of-province batteries. For example, $\delta_{\text{Peace}, \text{VentingBan}}$ captures the proportional change in emissions in the Peace River region when the venting ban is binding but flaring restrictions are not. A positive $\delta_{\text{Peace}, \text{VentingBan}}$ for flaring, coupled with a negative one for venting, would indicate substitution from venting to flaring at batteries in Peace River. Likewise, $\delta_{\text{Peace}, \text{FlareRestrict}}$ measures the joint effect of both the venting ban and the flaring standard becoming binding. The same coefficient for *Near-Peace-River* batteries quantifies the extent of spatial leakage.

Eq.(9) nests all group, period, and group–period interactions, which eliminates the heterogeneity bias that plagues conventional two-way fixed-effects estimators (Wooldridge, 2023). Identification comes from within-group variation in treatment, conditional on price controls and the saturated set of treatment-time dummies. Standard errors are robust to heteroskedasticity and clustered at the geographic section level to allow arbitrary spatial correlation across batteries sharing very localized infrastructure.

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). These provide clean comparisons with immediate regulatory relevance.³⁷ We also estimate an event-study variant of Equation 9 to examine pre-

³⁷Alternatively, we could include both regulatory phases in the same regression. This would slightly change the counterfactual estimate, as the fixed effects would be fit across both regulatory periods. We have opted for this cleaner specification. Results are robust to adopting this approach, however.

trends and dynamic responses within each regulatory period.

5.3 The Main Effects of Venting and Flaring Regulation

5.3.1 Effect of Regulations on Venting and Flaring Volumes

Table 3 begins by examining the impacts of venting and flaring regulations on vented and flared emissions. Columns (1) and (2) show the effects of the venting ban in isolation on venting and flaring releases, respectively. Columns (3) and (4) show the effects of the venting ban and flaring restrictions combined. The first row shows the direct effect of regulation on Peace River batteries. The second row estimates the spillover effects on the nearby batteries.

The results demonstrate that the venting ban had three consequences. First, the ban was effective at reducing venting. The coefficient in the first row of column (1) shows that the ban decreased venting releases by 53%. Second, venting and flaring are substitutes. When the venting ban was applied in isolation, this caused producers to more than double flaring volumes relative to the previous period at the average Peace River battery. That flaring increased more than venting declined indicates that gas capture efficiency actually decreased due to the venting ban.³⁸ Firms, due to both cross-emissions substitution and a reduction in gas recovery, more than offset their venting reductions through extra flaring when venting was prohibited. Third, the ban may have caused some spatial leakage, but the effects are small and not statistically significant. The estimate for Near Peace River in column (1) of Table 3 shows that venting increased at batteries in nearby unregulated regions by 12%.

Columns (3) and (4) of Table 3 show the effect of the flaring restrictions paired with the venting ban. The regulated region saw further declines in venting. Relative to the period with no venting ban or flaring restrictions, venting fell by 88%. Flaring, as expected, also dramatically fell with a 44% reduction relative to the unregulated period. These within-region patterns underscore that the initial narrowly targeted venting regulation led to intertemporal leakage, whereby firms simply shifted the timing and method of release until the comprehensive rules forced an overall reduction.

Next, the inter-regional leakage from the combined venting and flaring restrictions was substantial. Nearby, unregulated batteries increased venting by 34% and flaring by 72% relative to the no-regulation counterfactual. These represent large surges in emissions, with the flaring leakage outstripping the reductions in the regulated

³⁸Indeed, in unreported analyses, we find gas conservation rates fell by almost 6% among Peace River batteries during the venting ban.

Table 3: Regulation and Emissions

Dep. Var.:	<u>Vent Ban</u>		<u>Flare Restrict.</u>	
	(1) Vent	(2) Flare	(3) Vent	(4) Flare
Peace River	-0.748 (0.350)	0.793 (0.169)	-2.110 (0.310)	-0.580 (0.217)
Near Peace River	0.115 (0.072)	-0.019 (0.081)	0.296 (0.104)	0.540 (0.109)
Obs.	929,530	929,530	1,069,412	1,069,412

Notes: Table reports log-scale average treatment effects on the treated for venting and flaring emissions, estimated using the Wooldridge (2023) Poisson difference-in-differences estimator. Dependent variables are monthly battery-level emissions (thousands of m³). The first row shows the effect on directly regulated batteries in Peace River; the second row shows the leakage effect on nearby unregulated batteries. All effects are estimated relative to batteries in the rest of Alberta. Columns (1) and (2) isolate the venting ban’s effect by restricting the sample to before the flaring restrictions became binding (May 2018). Columns (3) and (4) reflect the combined effect of both the venting ban and flaring restrictions by excluding the transition period (September 2014–April 2018). All regressions control for oil and gas prices, whether the battery produces bitumen, and month fixed effects. Each sample begins in 2011. Standard errors in parentheses are clustered at the geographic section level.

region. As there are more batteries in the near Peace River region, these magnitudes imply substantial leakage. Accounting for the higher level of both venting and flaring in Peace River prior to the regulations, our estimates imply that in aggregate leakage was 95% for venting and over double for flaring.³⁹ In Section 5.4, we show that this large degree of leakage occurred because the regulation inadvertently “crowded-in” new, but dirtier, producers in the nearby unregulated area. The counterfactual for both these regions is determined by using distant unregulated batteries.

In one sense, the venting and flaring regulations were effective. The rules reduced emissions in the treated region. However, the within- and outside-region results highlight the classic challenge of partial regulation: the market responded by either changing the form of the externality or relocating the harm to jurisdictions with laxer rules.

³⁹We arrive at these figures by using our estimates to compute the average change in emissions due to the combined flaring and venting regulations relative to 2014, and multiply this by the number of active batteries in each region in 2023.

5.3.2 Effect of Regulations on Oil and Gas Production

We next examine production outcomes to understand the mechanism behind the emissions patterns. Our model of joint production predicts that flaring regulations – though nominally targeting natural gas disposal – primarily affect oil output. We find that the reallocation of production rationalizes the estimated change in flaring and venting.

Table 4 reports the consequences of the flaring and venting regulations 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 roughly 30%. In contrast, there was no statistically significant change in gas output (at conventional levels). This oil-gas asymmetry is even more pronounced when looking at the flaring regulations in columns (3) and (4). When both venting and flaring were regulated, there was still no significant change in gas production, whereas oil production in Peace River fell by 55%. In other words, operators complied with the tighter flaring and venting rules primarily by scaling back oil production, rather than by substantively increasing gas conservation.

Table 4: Regulation and Production

Dep. Var.:	<u>Vent Ban</u>		<u>Flare Restrict.</u>	
	(1) Oil	(2) Gas	(3) Oil	(4) Gas
Peace River	-0.351 (0.079)	0.196 (0.180)	-0.804 (0.123)	0.257 (0.182)
Near Peace River	0.042 (0.051)	0.450 (0.078)	0.466 (0.122)	1.386 (0.174)
Obs.	929,530	929,530	1,069,412	1,069,412

Notes: Table reports log-scale average treatment effects on the treated for oil and gas production, estimated using the Wooldridge (2023) Poisson difference-in-differences estimator. Dependent variables are monthly battery-level production (in m³ for oil and thousands of m³ for gas). The first row shows the effect on directly regulated batteries in Peace River; the second row shows the leakage effect on nearby unregulated batteries. All effects are estimated relative to batteries in the rest of Alberta. Columns (1) and (2) isolate the venting ban’s effect by restricting the sample to before the flaring restrictions became binding (May 2018). Columns (3) and (4) reflect the combined effect of both the venting ban and flaring restrictions by excluding the transition period (September 2014–April 2018). All regressions control for oil and gas prices, whether the battery produces bitumen, and month fixed effects. Each sample begins in 2011. Standard errors in parentheses are clustered at the geographic section level.

These estimates support the third prediction of our model. When disposal con-

straints bind during a joint production process, a regulation on co-product pollution effectively acts as a tax on the main product. In this context, producers cannot easily increase gas sales in the short run due to insufficient demand, so the mechanism to reduce gas-related emissions is to pump less oil. Importantly, we see no analogous decline in gas marketed volumes inside the regulated region. Regulatory design with joint production and free disposal, particularly with respect to flaring and venting, is more nuanced than conventionally believed.

These estimates go a long way to explain why industry so fiercely resists flaring regulations (Rabe, Kaliban and Englehart, 2020): they force cuts to the higher-valued product for the sake of abating emissions of the lower-valued product. Moreover, from a regulatory assessment perspective, the costs of foregone oil production are typically not counted in impact assessments of flaring rules (e.g., Canada, 2023; IEA, 2025).

Table 4 also shows the mechanism behind leakage. The reduction in Peace River oil production following flaring regulations is offset by increases at nearby batteries. As column (3) shows, oil production in the region near Peace River increased by 59%. That is, production at the average nearby battery increased the same degree (in percentage terms) as production declined for regulated batteries.⁴⁰

5.3.3 Robustness

We probe the sensitivity of these results along several dimensions. We document these robustness checks here and relegate the details to Online Appendix B. First, we examine whether there is evidence of pre-trends by estimating an event-study analogue to Eq.(9). We find no evidence of any meaningful pre-trends for any of the outcomes for batteries located in Peace River. For the batteries located near Peace River, there are no pre-trends for venting, flaring, and oil production. These batteries show a potential pre-trend for gas production. However, a clear break in trend occurs once the flaring regulations are phased in. Adjusting the gas spillover estimate for the largest pre-trend value suggests an increase in gas production among the nearby Peace River batteries in the final six months of our sample of around 0.5 log points, nearly identical to the estimate for the oil spillover.

We next reproduce our main results restricting the analysis to bitumen producing batteries. We do this to ensure our results are not biased by the compositional dif-

⁴⁰Gas production also significantly increased. We draw caution around this result, however, as we show in the next section that there is a statistically significant pre-trend in gas production among the near Peace River batteries. Accounting for these pre-trends indicates gas and oil production increased to similar degrees. No other groups or outcomes show evidence of pre-trends.

ferences in the type of oil extracted across regions. Our main analysis accounts for this by allowing for differential trends across bitumen and non-bitumen batteries (in addition to differential slopes by region). However, as the composition varies considerably across regions (the bitumen share is roughly 98% in Peace River, 12% near Peace River, and 21% in the rest of the province) we adopt this sample restriction out of added caution. The results of this exercise mirror those in the main analysis closely, with an even larger spillover for bitumen batteries near Peace River.

Finally, we perform the near-opposite exercise, omitting bitumen batteries from outside the Peace River region. As most batteries in Peace River produce bitumen, omitting them from this region would not be sensible. However, we want to assess whether the main effects and spillover results are robust to comparing outcomes in Peace River to non-bitumen outcomes elsewhere. We find very similar results to our main analysis. This suggests that the leakage effects, though strongest among nearby bitumen producers, are not restricted to bitumen batteries.

5.4 Effect on Legacy and New Batteries

The preceding results demonstrate how regulating a joint production process when there is insufficient demand for the co-product acts as an implicit tax on the high value output. The results further show that this implicit tax creates increased opportunities for leakage to unregulated producers. However, because our policy intervention was largely a surprise to operators, their ability to adapt their production technologies may have been limited. Curtailing oil production was the only (or least cost) method to comply with regulation in the short-run. Had the regulations allowed for grandfathering or more lead time, outcomes may have differed. To explore the role of technology choice, we investigate heterogeneity between legacy batteries, those in operation before the policy, and new entrants that opened after the policy. We include this analysis to further probe the mechanisms of this particular setting and generalize our results, as other settings of co-product pollution may have more flexible technological choices.

Tables 5 and 6 focus on emissions and production from legacy batteries, respectively. For this analysis we restrict to batteries opened prior to the venting ban's first introduction. We then estimate a variant of Eq.(9) that includes battery fixed effects, to isolate within-battery changes among this group.⁴¹

Though subtle coefficient differences emerge relative to our main analysis, the

⁴¹Note that including battery fixed effects leads to large changes in observations across regressions. This occurs because batteries with zero venting or flaring across our sample are necessarily dropped.

Table 5: Regulation and Emissions at Legacy Batteries

Dep. Var.:	<u>Vent Ban</u>		<u>Flare Restric.</u>	
	(1) Vent	(2) Flare	(3) Vent	(4) Flare
Peace River	-0.079 (0.406)	0.401 (0.147)	-1.808 (0.427)	-0.993 (0.213)
Near Peace River	-0.096 (0.072)	-0.252 (0.070)	-0.283 (0.083)	-0.462 (0.116)
Obs.	703,895	285,419	775,714	318,179

Notes: Table reports log-scale average treatment effects on the treated for venting and flaring emissions from legacy batteries in operation before regulation, estimated using the Wooldridge (2023) Poisson difference-in-differences estimator. Dependent variables are monthly battery-level emissions (thousands of m³). The first row shows the effect on directly regulated batteries in Peace River; the second row shows the leakage effect on nearby unregulated batteries. All effects are estimated relative to batteries in the rest of Alberta. Columns (1) and (2) isolate the venting ban’s effect by restricting the sample to before the flaring restrictions became binding (May 2018). Columns (3) and (4) reflect the combined effect of both the venting ban and flaring restrictions by excluding the transition period (September 2014–April 2018). All regressions control for oil and gas prices, whether the battery produces bitumen, and battery and month fixed effects. Each sample begins in 2011. Within each analysis sample, sample sizes vary across regressions because batteries that never emit are dropped. Standard errors in parentheses are clustered at the geographic section level.

headline results for directly regulated batteries remain unchanged. The combined venting and flaring regulations reduced emissions at legacy batteries substantially. This was accomplished by curtailments in oil extraction. In contrast, a very different story emerges for the legacy batteries near Peace River relative to our main analysis. Emissions and oil production actually fell at these legacy batteries, indicating negative – not positive – leakage within this restricted sample.

These results suggest that new and legacy batteries were very differently affected by regulation. By definition there is no pre-treatment period for new batteries, our ability to probe the sub-sample of new batteries is limited. Nevertheless, we add a descriptive analysis of these new batteries to more directly explore the role of new capital. For this analysis, we restrict the sample to batteries built after the policy’s introduction in 2014 and estimate a Poisson regression of battery outcomes (venting, flaring, oil, or gas) on a regulatory group indicator (Peace River, near Peace River, or the rest of the province) and month-by-year, entry month-year, and oil-type (through

Table 6: Regulation and Production at Legacy Batteries

Dep. Var.:	<u>Vent Ban</u>		<u>Flare Restrict.</u>	
	(1) Oil	(2) Gas	(3) Oil	(4) Gas
Peace River	-0.638 (0.089)	0.095 (0.149)	-1.148 (0.158)	0.094 (0.106)
Near Peace River	-0.215 (0.051)	0.091 (0.073)	-0.342 (0.096)	0.196 (0.128)
Obs.	872,030	866,197	893,589	888,059

Notes: Table reports log-scale average treatment effects on the treated for oil and gas production from legacy batteries in operation before regulation, estimated using the Wooldridge (2023) Poisson difference-in-differences estimator. Dependent variables are monthly battery-level oil and gas production (in m³ for oil and thousands of m³ for gas). The first row shows the effect on directly regulated batteries in Peace River; the second row shows the leakage effect on nearby unregulated batteries. All effects are estimated relative to batteries in the rest of Alberta. Columns (1) and (2) isolate the venting ban's effect by restricting the sample to before the flaring restrictions became binding (May 2018). Columns (3) and (4) reflect the combined effect of both the venting ban and flaring restrictions by excluding the transition period (September 2014-April 2018). All regressions control for oil and gas prices, whether the battery produces bitumen, and battery and month fixed effects. Each sample begins in 2011. Within each analysis sample, sample sizes vary across regressions because batteries that never produce gas are dropped. Standard errors in parentheses are clustered at the geographic section level.

a bitumen indicator) fixed effects. The results allow us to compare the average log-difference in each outcome at newly-built treated batteries (or batteries near Peace River) relative to newly-built control batteries, net of included fixed effects. Tables 7 and 8 show the results of these comparisons. For reference, Appendix Figure B.2 shows the number of batteries built in each time-period and region.

Table 7 compares Peace River and near Peace River batteries built during the venting ban, which was binding on new entrants in June 2014, but before the flaring regulations were introduced on March 2019, i.e., when flaring regulations became binding on new plants. Batteries built in Peace River during this period vent less but flare more than those built during the same period in the rest of the province. Batteries built near Peace River both vent and flare more than new batteries built elsewhere. There is no difference in oil production at Peace River batteries, but gas production is much higher. Batteries near Peace River produce both more oil and gas.

Table 8 compares Peace River and near Peace River batteries built once the flaring

Table 7: New Batteries Built – Venting Ban Period

Dep. Var.:	(1) Vent	(2) Flare	(3) Oil	(4) Gas
Peace River	-2.030 (0.199)	3.090 (0.252)	0.145 (0.287)	1.715 (0.294)
Near Peace River	0.330 (0.087)	1.279 (0.172)	0.729 (0.236)	1.540 (0.195)
Obs.	200,966	200,966	200,966	200,966

Table reports average outcomes for batteries built during the venting ban period in Peace River (first row) and regions near Peace River (second row) relative to those built in the rest of the province. Column (1) compares venting emissions (thousands of m³). Column (2) compares flaring emissions (thousands of m³). Column (3) compares oil production (m³). Column (4) compares gas production (thousands of m³). Comparisons are derived from a Poisson regression with bitumen, month-by-year, and month-year of opening fixed effects. Standard errors in parentheses are clustered at the geographic section level.

regulations became binding (March 2019). The batteries built in Peace River vent and flare less (although the latter is imprecisely estimated), but have no significant difference in oil or gas production. The batteries built near Peace River vent and flare more and produce more oil and gas.

Table 8: New Batteries Built – Venting and Flaring Regulation Period

Dep. Var.:	(1) Vent	(2) Flare	(3) Oil	(4) Gas
Peace River	-3.273 (0.454)	-0.828 (0.605)	0.330 (0.223)	0.161 (0.357)
Near Peace River	0.499 (0.169)	1.722 (0.159)	1.622 (0.117)	1.409 (0.182)
Obs.	53,879	53,879	53,879	53,879

Table reports average outcomes for batteries built during the flaring regulation period in Peace River (first row) and regions near Peace River (second row) relative to those built in the rest of the province. Column (1) compares venting emissions (thousands of m³). Column (2) compares flaring emissions (thousands of m³). Column (3) compares oil production (m³). Column (4) compares gas production (thousands of m³). Comparisons are derived from a Poisson regression with bitumen, month-by-year, and month-year of opening fixed effects. Standard errors in parentheses are clustered at the geographic section level.

We draw the following conclusions from the legacy and new battery analyses. First,

directly regulated legacy batteries complied with regulation by reducing output and shifting vented emissions to flaring when only venting was regulated. Second, regulated new capital took on emission profiles consistent with the relevant regulatory regime, with lower venting but higher flaring when only venting was regulated. However, the new capital did so without sacrificing output. Third, legacy batteries near Peace River decreased emissions and output. However, they did so by much less than the directly regulated legacy batteries. Finally, new capital in the near Peace River region was built with higher emissions (both venting and flaring) and output.

This analysis reveals the role of new capital in facilitating leakage. Leakage occurred through new batteries that were built subject to weaker environmental constraints, but larger expected market opportunities due to reduced output in Peace River. This allowed them to produce at higher levels than even the unregulated legacy batteries. The new batteries out-competed legacy batteries in both Peace River and their own region, causing negative leakage to legacy batteries in the region near Peace River. This suggests the “crowding in” of new, unregulated, batteries is what allowed leakage to exceed the emission reductions among regulated batteries.

5.5 Regulation and the Extent of the Market

Our model shows how limits on the extent of the co-product market causes regulation of co-product pollution to act as a tax on the main product. In our setting, the main mechanism to increase the extent of the co-product market is to build more natural gas pipeline capacity. While no major transmission pipeline expansions occurred in the province since the regulations came into place, as Figure 1 shows, batteries routinely connect to the existing gathering pipeline network. That is, they build small pipelines that connect to the larger transmission infrastructure.

We use new battery connections to examine the role of an expanded market extent on the implications of flaring regulations. As we do not have exogenous pipeline expansion decisions, we caution that this analysis is merely suggestive.

We focus on the period in which both venting and flaring regulations are in place. We proceed by identifying any battery that first connected to the gas gathering network after the original venting ban came into place in September 2014. We then estimate a version of Eq.(9) that allows the effect of treatment for the Peace River batteries to vary by whether the battery connected to the gathering system post regulation.⁴²

⁴²We do not let treatment vary for the near Peace River batteries. We also restrict the analysis to legacy batteries built before 2015, to ensure the comparison doesn’t reflect the role of new capital.

The results are shown in Table 9 for each of the four outcomes. The first row shows the effect of the combined venting and flaring regulations for Peace River batteries that do not connect to the gathering system following regulation (note that they may already be connected to this system). The second row shows the effect of the regulations for Peace River batteries that first connect to the gathering system after the regulation was enacted. We do not show the treatment coefficients for the near Peace River batteries, as they effectively replicate the results in Section 5.3.1.

Table 9: Effects of Regulation with and without Pipeline Expansion

Dep. Var.:	<u>Emissions</u>		<u>Production</u>	
	(1) Vent	(2) Flare	(3) Oil	(4) Gas
Peace River - No New Connection	-3.137 (0.321)	-1.098 (0.232)	-0.836 (0.188)	0.295 (0.181)
Peace River - New Connection	-0.738 (0.167)	-1.780 (0.399)	-0.345 (0.545)	-0.084 (0.304)
Obs.	908,340	908,340	908,340	908,340

Notes: Table reports log-scale average treatment effects on the treated for venting and flaring emissions (columns (1) and (2)) and oil and gas production (columns (3) and (4)). Effects are estimated using the Wooldridge (2023) Poisson difference-in-differences estimator. Regressions estimate the combined effect of both the venting ban and flaring restrictions by excluding the transition period (September 2014-April 2018). Only the effects on directly regulated batteries in Peace River are shown. The first row shows the effects on batteries that do not built a new pipeline connection after regulation. The second row shows the effects on batteries that built a new pipeline connection after regulation. All regressions control for oil and gas prices, whether the battery produces bitumen, and month fixed effects. Each sample begins in 2011. Standard errors in parentheses are clustered at the geographic section level.

Table 9 suggests that the extent of the market constraints meaningfully alter the effects of regulation. Batteries that do not form a new connection reduce flaring and venting significantly, which is driven by a large and significant drop in oil production. In contrast, batteries that establish a new pipeline connection reduce emissions, but experience a smaller (although statistically insignificant) decrease in oil production. For the newly connected batteries, the reduction is less than half of that for unconnected observations.

6 Conclusion

When a lower-value co-product is jointly produced with a higher-value main product, the co-product is often wasted. This is particularly true when disposal is free and relative demand for the co-product is weak. Under these conditions, the co-product becomes a pollutant rather than a marketable output. Examples of co-product pollution exist in many industries, including oil, mining, manufacturing, and agriculture.

We provide the first formal treatment of the economics of regulating co-product pollution. Our theory shows that treating co-product waste as a standard form of pollution is incorrect: regulating co-product pollution acts as a *de facto* tax on the main product. As a result, these regulations could have important unintended effects, including an increased scope for leakage through both goods markets.

We explore this problem empirically in the context of one of the largest examples of co-production pollution: the flaring and venting of natural gas during oil extraction. We test our model's predictions using detailed battery-level data and a policy change from Alberta, Canada. We find that a 10% increase in oil prices results in a 3.1 thousand cubic meter (MCM) increase in flaring, whereas a 10% increase in natural gas prices reduces flaring by 3.6 MCM. Next, exploiting a natural experiment involving regulatory changes, we reveal significant unintended consequences of co-product regulation. Regulations effectively eliminated venting and substantially curtailed flaring within the regulated area. However, they resulted in significant leakage to unregulated neighboring regions. Our results underscore that the primary economic impact of these regulations manifests through reduced oil production rather than in the natural gas market. Indeed, regulated facilities experienced a 55% decline in oil production, illustrating an implicit, but overlooked, component of stringent flaring controls.

Finally, we identify important heterogeneity along two margins: 1) comparing legacy facilities to new investments, and 2) comparing facilities that invested in new pipeline connections to those that did not. The results suggest new capital and batteries that formed new pipeline connections had lower output losses associated with the regulations. Legacy batteries that did not connect to the gas gather network faced substantial reductions in oil production. Identifying adaptation according to technology choices emphasizes the importance of designing regulatory measures to allow markets to adapt and promote economically efficient and environmentally beneficial outcomes.

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Online Appendix for Co-Product Pollution: Theory and Evidence from Oil and Gas Flaring

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A Additional Results to Support Prediction 1 and 2

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 oil 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.

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Table A.1: Responsiveness of Production to Natural Gas and Oil Prices

Outcome:	Panel A: OLS				Panel B: IV			
	<u>Oil</u>		<u>Gas</u>		<u>Oil</u>		<u>Gas</u>	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
ln(Gas Price)	-1.558 (11.869)	-1.138 (11.892)	-0.803 (2.292)	0.077 (2.312)	-8.942 (15.171)	-12.168 (15.370)	1.010 (3.937)	-0.536 (4.042)
ln(Gas Price) x Gas Share		3.956 (0.366)		2.246 (0.206)		3.710 (0.433)		2.905 (0.219)
ln(Oil Price)	32.743 (10.142)	32.133 (10.220)	2.397 (2.498)	1.636 (2.648)	28.366 (14.697)	28.024 (14.903)	2.076 (3.114)	2.478 (3.068)
ln(Oil Price) x Gas Share		0.597 (0.453)		-1.419 (0.296)		1.108 (0.517)		-1.926 (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 m³. Battery oil production is measured in m³. Prices are measured in USD per gigajoule of energy. All regressions include battery, year, and month fixed effects. Columns (2), (4), (6), and (8) include an interaction between the battery's share of revenues from gas and each price variable. 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.

A.2 Table 2, including Oil and Gas Prices Independently

Table A.2: Including Natural Gas and Oil Prices Separately

	OLS		IV	
	(1)	(2)	(3)	(4)
ln(Gas Price)	-0.028 (0.129)		-0.250 (0.199)	
ln(Oil Price)		0.368 (0.104)		0.205 (0.132)
Obs.	2,113,735	2,113,735	2,113,735	2,113,735
R ²	0.336	0.336		
F-Stat (1st Stage)			199.379	136.130

This table presents estimates of the effect of gas and oil prices on monthly battery gas emissions. Emissions are measured in thousands m³. 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.

B Peace River Analysis Robustness

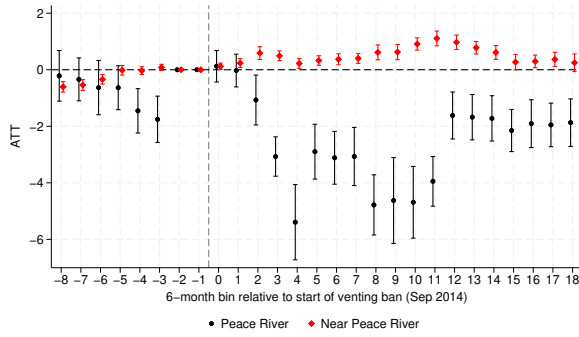
This section contains details of the robustness exercises performed for the main Peace River regulatory analysis.

First, we examine whether there is evidence of pre-trends by estimating an event-study analogue to Equation 9. To do so, we estimate leads and lags of the treatment effects for both the directly regulated batteries and those near Peace River (relative to the rest of the province). We estimate these leads and lags in six month bins, starting treatment in September 2014 (when the venting ban was first introduced).¹ We omit the year prior to treatment and convert estimates to reflect the average treatment effect on the treated at observed covariate values and express these in natural logs.

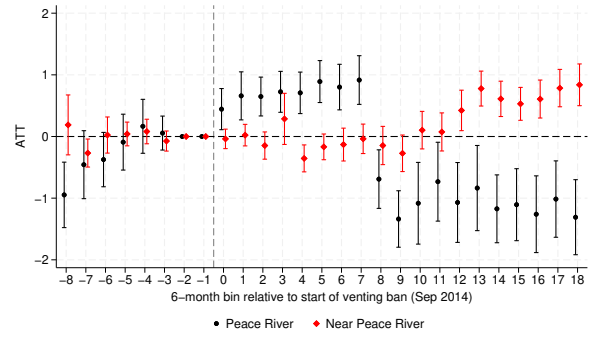
The event study results are shown in Figure B.1. The results for both venting and flaring emissions are noisy, as one would expect, but show no meaningful pre-trend

¹Recall the venting ban was phased in across different batteries from September 2014 becoming binding on all batteries in 2016. Similarly, the flaring restrictions were phased in from 2017 to 2019.

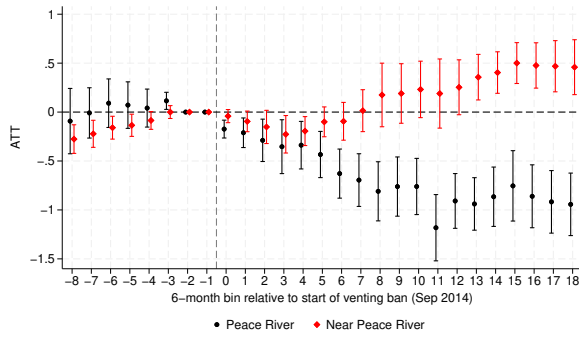
patterns.² Oil production is flat prior to regulation among regulated batteries, then begins to fall once regulation is implemented. Oil production falls in each six-month bin, leveling off in 2019 once all regulations are fully implemented. Among the batteries near Peace River, oil production is flat until the flaring ban is phased in, which led to a significant increase in production. Gas production is flat across all periods for the directly regulated batteries. The one notable concern is that of a pre-trend in gas production among the batteries close to Peace River. There is still a break in trend once the flaring regulations are phased in, however. Adjusting the gas spillover estimate for the largest pre-trend value suggests an increase in gas production among the nearby Peace River batteries in the final six months of our sample of around 0.5 log points, nearly identical to the estimate for the oil spillover.



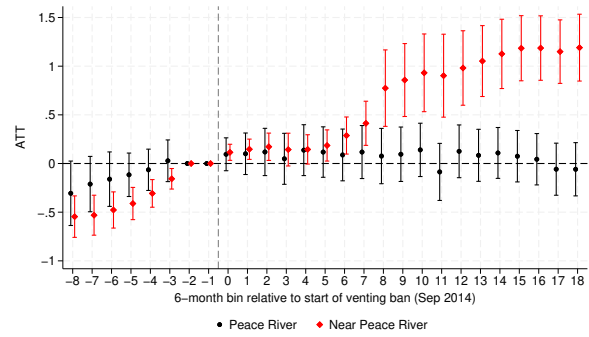
(a) Venting Emissions



(b) Flaring Emissions



(c) Oil Production



(d) Gas Production

Figure B.1: Event Study

In Tables B.3 and B.4 we reproduce our main results, restricting the analysis to bitumen producing batteries only. We do this to ensure our results are not biased by

²Venting emissions in Peace River appear to have fallen in 2012 relative to 2013, but rebounded to normal levels at the start of the regulatory period. Emissions then fell dramatically (and rebounded slightly once the reporting requirements on venting change).

the compositional differences in the type of oil production that occurs across regions. Our main analysis accounts for this to the extent possible, by allowing for differential trends across bitumen and non-bitumen batteries (in addition to differential slopes by region). However, as the composition varies considerably across regions (the bitumen share is roughly 98% in Peace River, 12% near Peace River, and 21% in the rest of the province) we adopt this sample restriction to ensure our results are unchanged.

The results in both tables mirror those in the main analysis closely with two notable exceptions. First, the leakage effect to bitumen batteries close to Peace River is even larger than in our main analysis. This is sensible, as bitumen batteries close to Peace River likely extract from the same oil field as those in Peace River. Thus, the scope for leakage is very large. Second, the effect on oil production at nearby batteries is also larger than in our main analysis, but there is no effect on gas once both venting and flaring restrictions are incorporated.

Table B.3: Flaring and Venting Regulation and Emissions; Bitumen Batteries Only

Dep. Var.:	<u>Vent Ban</u>		<u>Flare Restrict.</u>	
	(1) Vent	(2) Flare	(3) Vent	(4) Flare
Peace River	-0.620 (0.352)	0.754 (0.208)	-2.351 (0.333)	-0.623 (0.221)
Near Peace River	2.457 (0.836)	0.320 (0.718)	3.178 (0.574)	3.464 (0.543)
Obs.	199,400	199,400	223,170	223,170

Standard errors are clustered by geographic section.

Finally, we perform the near-opposite exercise, omitting bitumen batteries from outside the Peace River region. As most batteries in Peace River produce bitumen, omitting them from this region would not be sensible. However, we want to assess whether the main effects and spillover results are robust to comparing outcomes in Peace River to non-bitumen outcomes elsewhere. To do so, we drop any bitumen producing battery located outside of Peace River from our sample and then estimate Equation 9. The results are shown in Tables B.5 and B.6.

Dropping bitumen batteries from outside of Peace River produces very similar results to our main analysis. This suggests that the leakage effects, though strongest

Table B.4: Flaring and Venting Regulation and Production; Bitumen Batteries Only

Dep. Var.:	Vent Ban		Flare Restric.	
	(1) Oil	(2) Gas	(3) Oil	(4) Gas
Peace River	-0.383 (0.081)	0.164 (0.178)	-0.844 (0.143)	0.240 (0.201)
Near Peace River	0.614 (0.547)	-1.037 (0.611)	2.732 (0.621)	0.322 (0.536)
Obs.	199,400	199,400	223,170	223,170

Standard errors are clustered by geographic section.

Table B.5: Flaring and Venting Regulation and Emissions; Non-Peace River Bitumen Batteries Excluded

Dep. Var.:	Vent Ban		Flare Restric.	
	(1) Vent	(2) Flare	(3) Vent	(4) Flare
Peace River	-0.800 (0.355)	0.834 (0.170)	-1.943 (0.311)	-0.570 (0.216)
Near Peace River	0.040 (0.073)	-0.022 (0.081)	0.405 (0.101)	0.402 (0.113)
Obs.	745,713	745,713	867,301	867,301

Standard errors are clustered by geographic section.

among nearby bitumen producers, are not restricted to bitumen batteries.

The following figure illustrates the number of batteries constructed during each regulatory phase.

Table B.6: Flaring and Venting Regulation and Production; Non-Peace River Bitumen Batteries Excluded

Dep. Var.:	Vent Ban		Flare Restric.	
	(1) Oil	(2) Gas	(3) Oil	(4) Gas
Peace River	-0.243 (0.077)	0.245 (0.180)	-0.685 (0.109)	0.345 (0.182)
Near Peace River	0.089 (0.047)	0.458 (0.077)	0.451 (0.105)	1.375 (0.167)
Obs.	745,713	745,713	867,301	867,301

Standard errors are clustered by geographic section.

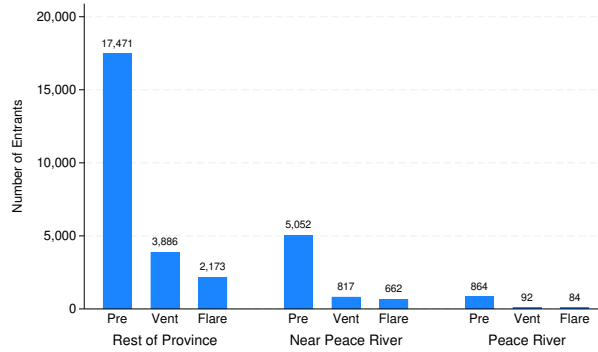


Figure B.2: Number of newly built batteries by time-period and region

Notes: Figure plots the number of new batteries opened across each treatment group in each of three different periods. The “Pre” period includes batteries built between 2005 and May 2014. The “Vent” period includes batteries built between June 2014 and February 2019. The “Flare” period includes batteries built between March 2019 and December 2023. The three groups are Peace River (regulated), Near Peace River (potential spillover batteries), and Rest of Province (unregulated, distant batteries).