Relieving Midstream Constraints in Natural Gas Flaring

Wint Myat Thu*

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Abstract

Flaring releases carbon dioxide, methane, and other toxic air pollutants that are harmful to the environment and human health. Natural gas extracted from the ground cannot be sold in the markets unless there is sufficient capacity to process the gas. I theoretically derive a subsidy to offset the flaring damages that stem from insufficient processing capacity. The subsidy depends on the economic relationship between capacity and flaring, which I quantify using an instrumental variable model and new data from North Dakota. I find that processing capacity bottlenecks are indeed an important driver of flaring. I estimate that each gas processing plant requires an ex-ante capacity subsidy of $396 per thousand cubic feet to ensure that flaring emissions remain at the socially optimal levels. Back of the envelope calculations suggest that the subsidy would have reduced flaring by 1.4 billion cubic feet across the state, offsetting roughly $5 million in flaring damages per year.

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*Department of Economics, Rensselaer Polytechnic Institute. Email: thuw@rpi.edu

1 Introduction

Every year, U.S. oil and gas producers burn off billions of cubic feet of natural gas. This is a longstanding practice known as flaring, and it poses three significant problems for the environment and human health. First, flaring emits carbon dioxide, the primary greenhouse gas that drives climate change, without generating useful energy for heating or electricity. Second, defective flares are simply venting out methane, which holds a greater heat trapping potential than carbon dioxide despite its shorter half life in the atmosphere. Lastly, flaring releases toxic pollutants into the air, endangering the health of nearby communities, most of whom are low-income and non-white (Cushing et al., 2021).

Many states have implemented policies that aim to reduce natural gas flaring. However, flaring emissions continue to soar over the years. For instance, in 2019, approximately 500 billion cubic feet of natural gas were burned off in the U.S. (EIA, 2020). Given that natural gas is a priced commodity, much of the flaring is unwarranted and driven by bottlenecks along the supply chain. Unlike oil, the extracted natural gas cannot be transported via trucking. Instead, it must be delivered by pipelines to gas processing facilities to produce clean, "dry"[1] gas for sale. In this paper, I show that midstream bottlenecks play an important role in natural gas flaring and examine how these constraints can be relieved to curb the associated emissions.

I quantify the role of insufficient processing capacity in natural gas flaring and use the empirical estimates to derive a capacity subsidy that offsets the flaring damages. I use novel data from North Dakota that enables me to connect all oil and gas wells to their respective gas processing plants in the state. Over the last decade, North Dakota has experienced a sharp increase in total production of oil due to recent breakthroughs in hydraulic fracturing. While the producers drill for oil, the existing infrastructure for gas processing has struggled to keep up with the production of associated gas from the oil wells. As a result, producers

[1] Dry natural gas is free from impurities and heavier hydrocarbons such as natural gas liquids.

in North Dakota have contributed to a significant share of total gas flared in the U.S. in the recent years (EIA, 2020). I empirically demonstrate that flaring decreases as processing capacity increases and theoretically derive a subsidy which depends on the estimated economic relationship between processing capacity and the quantity of natural gas flared.

In an optimal setting, a regulator would tax flaring emissions. However, it is important to examine the extent to which policies targeting midstream bottlenecks can affect the incentives to flare. Policies targeting midstream capacity constraints merit consideration for two reasons. First, flaring efficiency varies with environmental conditions such as wind and precipitation (Leahey et al., 2001). Recent studies using aerial surveys have reported that most flares in the Permian Basin are unlit, releasing five times more methane than previously estimated (Plant et al., 2022). As a result, producers may evade emissions taxes by leveraging hard-to-detect unlit flares. Second, although well operators may be let off the emissions taxes by state regulators due to lax enforcement (Lade and Rudik, 2020), gas plants would want to claim the processing capacity subsidy which directly incentivizes producers to capture and market the gas.

I formally show that gas processing plants require an upfront capacity subsidy to ensure that emissions from flaring remain at the socially optimal levels. The profit maximizing decisions of gas plants at the equilibrium do not account for damages they cause by forcing wells to flare when capacity is insufficient. In contrast, the social planner determines the total processing capacity to maximize social welfare accounting for all costs, including total damages from flaring. Therefore, gas plants underinvest in processing capacity compared to the social optimum. To correct this, I propose a capacity subsidy that reconciles the market incentives with the social planner's equilibrium conditions.

I estimate the relationship between the processing capacity available to a well and the quantity of natural gas flared. Estimating the causal effect of capacity on flaring is complicated by shocks that can impact both variables of interest in any given month. For instance, pipeline extensions from plants to new wells take up a higher share of the available capacity.

This contributes to increased flaring by other wells connected to the same plant. Wells may also engage in repeated fracking to increase the reservoir pressure that drives up production, which then affects processing capacity at the plant, as well as how much gas gets flared from increased congestion in the gathering networks. To address the endogeneity problem posed by the unobservables, I construct an instrument for processing capacity using novel data that connects all wells and plants in North Dakota from 2012 to 2019.

I instrument for each well's share of capacity at the plant using total natural gas production of all other wells connected to the same plant, located away from the well of interest. Changes in gas production from a given well are random, driven by the reservoir pressure, and changes in the total wells are also random, driven by oil profits. Natural gas production of connected wells drive fluctuations in available processing capacity at the plant, which in turn affects flaring. However, given that the wells included in the instrument are located away from the gathering network of the well of interest, the only way their production affects flaring by the well of interest is via the shared processing capacity.

I find that on average, an additional 1 thousand cubic feet (mcf) of processing capacity at a plant decreases flaring by 200 cubic feet (cf) among all the wells connected to the plant. This relationship isn't exactly one-to-one given that constraints beyond processing capacity, such as congestion, may also drive flaring. However, my results show that constrained processing capacity plays an important role in natural gas flaring, and that relieving the midstream bottlenecks can reduce the emissions from flaring.

Combining my theoretical analysis with the estimated economic relationship between capacity and flaring, I show that on average, gas plants require an ex-ante subsidy of $396 per thousand cubic feet of processing capacity to ensure that flaring emissions remain at the socially optimal levels. This accounts for approximately 40% of the per unit capacity construction costs.[2] Back of the envelope calculations suggest that the proposed subsidy

[2] Capacity costs, lifted from the gas plant siting permits submitted to the regulators, are roughly $1000 per thousand cubic feet (mcf).

would reduce monthly flaring by 120 million cubic feet, offsetting roughly $5 million in flaring damages per year. I also show suggestive evidence that flaring reductions from additional capacity likely vary by the size of the plants.

The environmental, health, and economic consequences of the U.S. shale revolution have been extensively studied in recent literature. Existing work contends that the fracking boom led to positive wage and consumption benefits from increased oil and gas production (Feyrer et al., 2017; Bartik et al., 2019; Jacobsen, 2019), as well as negative impacts on housing prices in locations that rely on groundwater contaminated by fracking operations (Gopalakrishnan and Klaiber, 2014; Muehlenbachs et al., 2015). In addition, natural gas production accompanied by the fracking boom has driven producers to burn off the natural gas that cannot be captured due to cost and capacity constraints.

The negative externalities associated with natural gas flaring are well-documented. Communities that live near flare sites experience higher respiratory hospitalization rates as total emissions from flaring increase (Blundell and Kokoza, 2022), and symptoms for pediatric asthma tend to worsen with increased drilling and natural gas production nearby (Willis et al., 2020). In addition to health impacts, flaring emissions translate to millions of dollars in lost natural gas revenue (Rabe et al., 2020), as well as climate damages from greenhouse gas emissions (Agerton et al., 2023). To reduce flaring emissions, it is crucial to understand why producers burn off a valuable commodity, which begins with investigating the production constraints throughout the natural gas supply chain.

To date, the most comprehensive review on mechanisms that drive flaring comes from Agerton et al. (2023), which summarizes the economics surrounding producers' decision to drill and flare. How much gas gets flared versus captured is often influenced by the profitability of natural gas given oil production from the same well sites: on average, oil prices are much higher than gas, and the additional investment required to capture and sell the gas may be too costly (Gilbert and Roberts, 2020; Agerton et al., 2023). Mandates that restrict the share of production flared can reduce flaring by encouraging wells to connect to gathering pipelines faster (Lade and Rudik, 2020), but the majority of flaring in shale reservoirs still stem from connected wells facing constraints along the supply chain (Agerton et al., 2023). To my knowledge, the present paper is the first to formally examine the economic relationship between processing capacity constraints and natural gas flaring, and also the first to propose a policy solution for flaring through relieving the midstream capacity constraints in natural gas production.

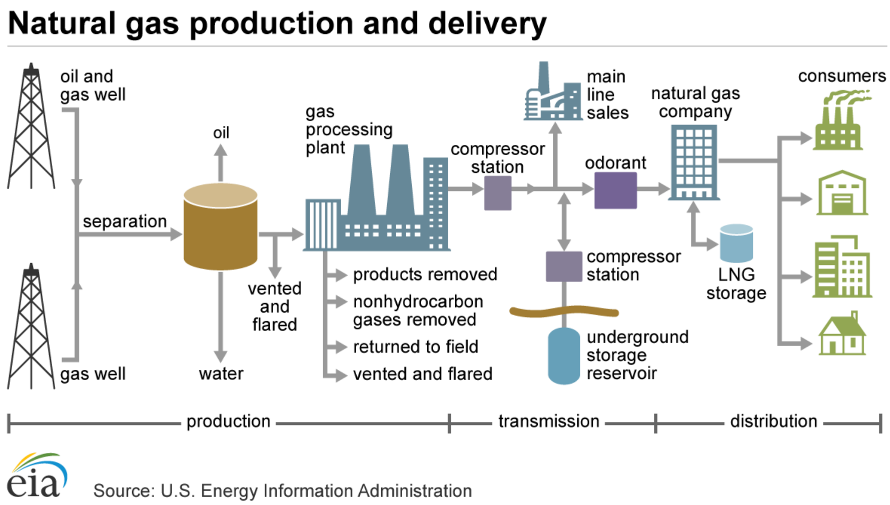
In the next section, I discuss the background on natural gas production and outline the existing flaring regulations in North Dakota. In Section 3, I formally derive the optimal subsidy on processing capacity using a theoretical model that will motivate my empirical estimation. In Section 4, I provide summary statistics on the data used in my analysis. In Section 5, I describe the empirical model, threats to identification, and instrument. In Section 6 I present the results along with policy implications of my estimates. Section 7 concludes and provides directions for future research.

2 Institutional Background

2.1 Natural Gas Extraction and Processing

The oil and gas industry is divided into upstream, midstream, and downstream segments. The upstream sector of the industry drills and operates the wells, where the production is primarily determined by the reservoir pressure. The extracted hydrocarbons are then processed and transported by the midstream segment of the industry to the downstream markets. Figure 1 demonstrates the process of production and delivery of natural gas. Unlike oil, natural gas extracted from the wells cannot be transported via trucking. Wellhead gas must be delivered to nearby processing plants to remove heavier hydrocarbons and produce dry, market-grade natural gas fit to be transported through distribution pipelines.

Figure 1: Natural Gas Production and Delivery



Most of the wells in North Dakota are drilled for tight oil in the Bakken shale formation using fracking technologies. More often that not, natural gas is an associated product of the oil wells. Hence, the drilling decision is exogenous to natural gas production. Upon completion of the wells, producers are unlikely to wait for the gas gathering infrastructure to be built in order to begin production, and hence flaring can occur when wells are unconnected to the gathering network. In this paper, I only consider flaring from wells that have sold gas during the sample period (2012-2019) and therefore must be connected to gas processing infrastructure, to better understand the role of processing capacity constraints in flaring.

Oil and natural gas are separated at the extraction site and processed at different facilities. Oil is transported via liquids pipelines or trucks to refineries, and natural gas is delivered to gas processing plants via gas gathering pipelines. Producers generally do not construct the gathering network themselves. Instead they purchase gathering services from midstream firms that directly invest in pipeline construction. Some of these midstream firms also own gas processing facilities, but not all processing plants provide gathering services. Producers generally enter into long-term contracts with gas processing plants.

The primary term of the contracts can be anywhere from 7 to 15 years and can be renewed on a year by year basis afterwards. These contracts typically require producers to dedicate the entire stream of production from an area to the processing plant, meaning that a well cannot deliver their production to other plants during the contract term. Acreage dedication agreements are often accompanied by the minimum delivery requirement: producers are required to pay for an agreed upon minimum volume to be delivered to the plant, regardless of whether this volume is actually delivered.

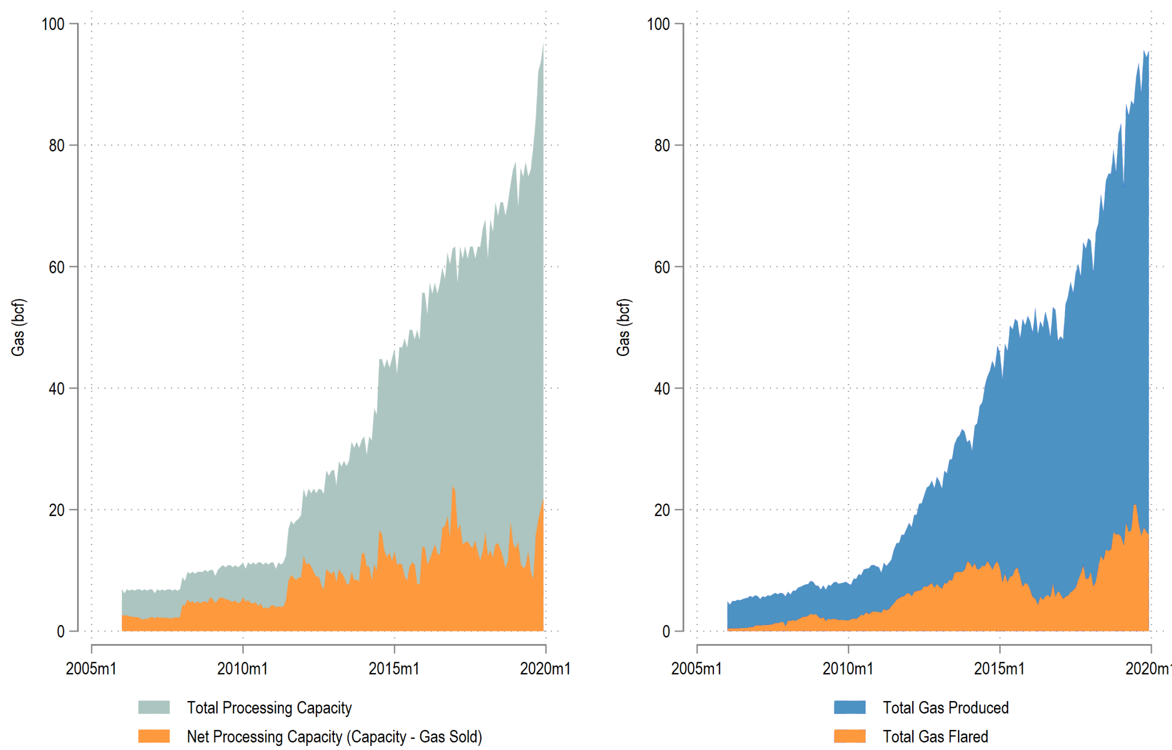
More often than not, wells and plants will agree on a banking mechanism. Well operators will bank the obligated minimum volume fees if the plant is at capacity for when the minimum volume cannot be delivered due to unexpected changes in production (Howe, 2016). The plant, on the other hand, does not need to guarantee processing capacity unless the contract specifies otherwise. When the processing capacity is fully utilized, producers will flare the gas that cannot be processed. Upon facing capacity constraints, natural gas transmitted through gathering pipelines will flow back to producers who then burn off the gas at the well site.

Despite the growth of unconventional tight oil developments in North Dakota, the existing infrastructure to gather and process the gas co-produced has been insufficient. Consequently, flaring levels have been increasing over the years, at least until 2019 before the pandemic. Figure 2 shows that over time, flaring has increased and capacity has barely kept up with production. It also highlights that flaring occurs even in years with capacity availability, indicating the importance of the spatially differentiated nature of constraints where spare capacity might exist across the network but cannot accommodate producers far away.

2.2 Regulatory Setting in North Dakota

North Dakota bans venting of natural gas and requires that gas be burned through a flare with the estimated volume flared reported to the North Dakota Industrial Commission

Figure 2: Gas Processing Capacity in North Dakota



(NDIC). Prior to 2014, the only existing flaring regulation was that the operators pay royalties on flared gas after the first year of production. In 2014, North Dakota passed its first flaring regulation which requires all oil and gas well operators in the state to capture a minimum share of all gas produced. The gas capture target specified in the regulation is intended to increase over time to encourage producers to flare less. However, gas capture goals have remained constant at 91% of total production since 2018 given insufficient infrastructure along the natural gas supply chain.

North Dakota's gas capture rules are inefficient for three reasons. First, the mandate is essentially an intensity standard that combines an implicit tax on flaring with an implicit subsidy for drilling new wells (Helfand, 1991). The rules imply that operators are allowed to increase the quantity of gas flared as long as the total production increases, which can be achieved by repeated re-fracturing of the wells. Second, the gas capture rule applies uniformly across all operators regardless of their abatement costs. Existing research shows that this results in misallocation of flaring abatement driven by hetereogeneity in compliance costs across firms (Lade and Rudik, 2020). Lastly, operators facing gathering and processing constraints are exempt from the gas capture requirement (NDIC, 2014). Considering the inefficiency of current flaring regulations, it becomes crucial to examine policies that target the production bottlenecks by encouraging investment in infrastructure necessary to capture the gas.

3 Theoretical Model

I present a theoretical model that formalizes the decisions of (1) the social planner seeking to maximize welfare, and (2) gas processing plants maximizing profit. Using the first order conditions at the market equilibrium and the social optimum, I derive the ex-ante capacity subsidy that optimally offsets the damages from flaring.

Suppose that there are $j = 1, 2, 3, ..., J$ gas processing plants and $i = 1, 2, 3, ..., N$ natural gas producing wells connected to each plant in any given month t. Let $q^P_{i,j,t}$ be the monthly natural gas produced by each well i connected to plant j. Total gas produced by all wells connected to the plant is the sum of production across all wells, $Q^P_{j,t} = \sum_i q^P_{i,j,t}$. I assume that $Q^P_{j,t}$ is continuously distributed over $[0, \overline{Q}_{j,t}]$ in each month and is $i.i.d$ across all j and t.

In month $t = t_1$, gas plants set new processing capacity K_j that will last indefinitely given monthly discount rate $\delta > 0$. This decision can represent either the construction of a new plant, or new capacity at the existing plant. In t_1, plants incur a fixed cost of capacity construction $C(K_j)$ where $C(\cdot)$ is positive, strictly increasing, and strictly convex, as well as a constant marginal cost $c_t \geq 0$ to process the gas delivered to them each month.

Let $Q_{j,t}$ be the quantity of gas processed by plant j in month t. Plants earn monthly profits $\pi(Q_{j,t}) = (p_t - c_t)Q_{j,t}$ where p_t is the exogenous market price of natural gas. Damages from gas left unprocessed or flared are $D_j(Q_{j,t}) = \gamma_j(Q^P_{j,t} - Q_{j,t})$, where $\gamma_j > 0 \quad \forall j \in \{1, 2, 3, ..., J\}$ is the per unit social cost of flaring. Although climate damages do not vary by j, external health costs from particulate pollution likely vary by plant depending on density and characteristics of the population nearby. Natural gas processed by all gas plants in each month, $Q_t = \sum_j Q_{j,t}$, is delivered to households via transmission pipelines.

The representative household gains utility $u(Q_t)$ from consumption of the processed natural gas in each month. Suppose that the household's marginal utility of natural gas consumption is greater than the marginal processing cost over the relevant domain, i.e. $u'_{Q_{j,t}}(Q_t) > c_t \; \forall Q_t \leq \sum_j \overline{Q}_{j,t}$. This implies that all of the natural gas processed by the plants is eventually consumed in the market.

In each month, the total quantity of gas processed by each plant must be less than the total monthly production of all connected wells, i.e. $Q_{j,t} \leq Q^P_{j,t}$. Moreover, total gas processed cannot exceed the total available capacity at the plant, i.e. $Q_{j,t} \leq K_j$.

3.1 The Social Planner's Problem

I first derive the optimal quantity of monthly gas processed conditional on available capacity. I then derive the conditions for setting the optimal capacity.

For a given vector of plant capacity $\{K_1, K_2, K_3, ..., K_J\}$ in each month, the social planner seeks to maximize the utility of consuming the natural gas processed by all plants, net of processing costs and damages from flaring:

$$\begin{aligned} \max_{\{Q_{j,t}\}_{j=1}^{J}} \quad & \Big\{u(Q_t) - c_t Q_t - D_j(Q_t)\Big\} \\ \text{s.t.} \quad & Q_{j,t} \leq K_j, \\ & Q_{j,t} \leq Q^P_{j,t} \quad \forall j \in \{1, 2, 3, ..., J\}. \end{aligned} \tag{1}$$

The solution to the optimization problem is symmetric across all periods. Therefore the following Lagrangian solves equation (1) in each t:

$$\mathcal{L} = \max_{\{Q_{j,t}\}_{j=1}^{J}} \Big\{ u(Q_t) - c_t Q_t - D_j(Q_t) - \Big[\sum_{j=1}^{J} \lambda_{j,t}^{1}(Q_{j,t} - K_j)\Big] - \Big[\sum_{j=1}^{J} \lambda_{j,t}^{2}(Q_{j,t} - Q_{j,t}^{P})\Big]\Big\}.$$

Per the first order conditions, the marginal utility net of associated monthly costs is equal to the shadow value of relaxing the constraints for each $Q_{j,t}$:

$$u'(Q_t) - c_t + \gamma = \lambda_{j,t}^{1} + \lambda_{j,t}^{2}.$$

Following the assumption that $u'(Q_t) > c_t \ \forall Q_t \leq \sum_j \overline{Q}_{j,t}$, it must be that $u'(Q_t) - c_t > 0$. Given that $\lambda_{j,t}^{j}, \lambda_{j,t}^{j} \geq 0$, and $\gamma > 0$, the equilibrium conditions are satisfied.

From the inequality constraints in equation (1), the following complementary slackness conditions arise for each $Q_{j,t}$:

$$\lambda_{j,t}^{1}(Q_{j,t} - K_j) = 0 \text{ and } \lambda_{j,t}^{2}(Q_{j,t} - Q_{j,t}^{P}) = 0.$$

The capacity and production constraints cannot both with equality hold unless total capacity just happens to be equal to the total production delivered each month, i.e. $K_j = Q_{j,t}^{P}$. As a result, the optimal quantity of gas processed in each month for each plant is

$$Q_{j,t}^{*} = \min\{K_j, Q_{j,t}^{P}\}.$$

This implies that all of the natural gas produced by the wells must be processed as long as there is sufficient capacity at the plant. The total optimal quantity of natural gas processed across all plants is $Q_t^{*} = \sum_{j=1}^{J} Q_{j,t}^{*}$.

Now consider the planner solving for the optimal processing plant capacity as follows:

$$\max_{\{K_j\}_{j=1}^{J}} \quad \Big\{\sum_{t=t_1}^{\infty} \frac{1}{(1+\delta)^t}\,\mathbb{E}[u(Q_t^*) - c_t Q_t^* - D_j(Q_t^*)] - C(K_j)\Big\}. \tag{2}$$

Per the first order necessary conditions for each K_j, we have that

$$\sum_{t=t_1}^{\infty} \frac{1}{(1+\delta)^t} \frac{\partial\,\mathbb{E}[u(Q_t^*)]}{\partial K_j} = \sum_{t=t_1}^{\infty} \frac{1}{(1+\delta)^t} \Big\{ \frac{\partial\,\mathbb{E}[D_j(Q_t^*)]}{\partial K_j} + c_t \frac{\partial\,\mathbb{E}[Q_{j,t}^*]}{\partial K_j} \Big\} + \frac{\partial C(K_j)}{\partial K_j} \qquad \forall j \in \{1,2,3,...,J\}. \tag{3}$$

At social optimum, the present value of marginal utility from additional capacity must be equal to the marginal costs of capacity setting and processing, plus the present value of marginal damages from natural gas left unprocessed or flared.

The expected marginal damages in equation (3) for each j can be decomposed as:

$$\mathbb{E}\Big[\frac{\partial D_j(Q_t^*)}{\partial K_j}\Big] = \underbrace{\mathbb{E}\Big[\frac{\partial D_j(Q_t^*)}{\partial Q_t^*}\Big]}_{\text{social cost of flaring, } \gamma_j} \cdot \mathbb{E}\Big[\frac{\partial Q_t^*}{\partial K_j}\Big],$$

where $\mathbb{E}\Big[\frac{\partial Q_t^*}{\partial K_j}\Big] \neq 0$ if and only if the capacity constraint can bind in some state of the world. When total production exceeds total processing capacity at each plant, unprocessed gas is burned off at the extraction site and the marginal damages from flaring are non-zero. The expected marginal damages then depend on changes in total gas flared with respect to changes in total processing capacity at each plant.

3.2 Market Equilibrium

Now, consider the market for natural gas. The price of processed gas p_t is exogenous and determined nationally. In each month t, the representative household maximizes their utility from consuming the natural gas processed by gas plants as follows:

$$\max_{\{Q_{j,t}\}_{j=1}^{J}} \quad \Big\{u\Big(\sum_j Q_{j,t}\Big) - p_t \sum_j Q_{j,t}\Big\}. \tag{4}$$

At market equilibrium, the marginal utility of consuming the processed gas is equal to the market price of natural gas $\forall j \in \{1, 2, 3, ..., J\}$:

$$\frac{\partial u(\sum_j Q_{j,t})}{\partial Q_{j,t}} = p_t. \tag{5}$$

For given capacity in each month t, gas plants choose the optimal quantity of natural gas to process, accounting for the market price and processing costs:

$$\begin{aligned} \max_{Q_{j,t}} \quad & \Big\{(p_t - c_t)Q_{j,t}\Big\} \\ \text{s.t.} \quad & Q_{j,t} \le K_j, \\ & Q_{j,t} \le Q^P_{j,t}. \end{aligned} \tag{6}$$

The solution satisfies the following Lagrangian in each period:

$$\mathcal{L} = \max_{Q_{j,t}} \quad \Big\{p_t Q_{j,t} - c_t Q_{j,t} - \eta^1_{j,t}(Q_{j,t} - K_j) - \eta^2_{j,t}(Q_{j,t} - Q^P_{j,t})\Big\}.$$

Per the first order conditions, we have that at equilibrium, $p_t - c_t = \eta_{j,1} + \eta_{j,2} \quad \forall j \in \{1, ..., J\}$. From the household's consumption problem in equation (6), the marginal utility of consuming the processed gas is equal to the price of natural gas. Hence, plants' marginal profit of processing each unit of gas is strictly positive, or $p_t - c_t > 0$, following the assumption that the marginal utility is greater than the marginal cost of processing. Given that $\eta_{j,1}, \eta_{j,2} \ge 0$ $\forall j$, the equilibrium conditions are satisfied.

Note that both of the inequality constraints in equation (6) cannot hold except in knife-edge cases where the plant's capacity happens to be exactly equal to the total production of all connected wells. At equilibrium, each plant must then process all of the gas produced so long as the capacity does not exceed total production:

$$Q^*_{j,t} = \min\{K_j, Q^P_{j,t}\}.$$

Comparing to equation (1) from the social planner's problem, we achieve efficiency conditional on capacity K_j for each plant.

Now consider the processing capacity chosen in the market. Given the optimal quantity of gas processed each month, plants set their capacity to be operational in $t = t_1$ by solving

$$\max_{K_j} \quad \Big\{ \sum_{t=t_1}^{\infty} \frac{1}{(1+\delta)^t} \mathbb{E}[\underbrace{\pi(Q^*_{j,t})}_{(p_t - c_t)Q^*_{j,t}}] - C(K_j) \Big\}, \tag{7}$$

where each plant maximizes the present value of expected monthly profits net of processing and capacity construction costs. The first order necessary conditions imply that at equilibrium, the present value of marginal profits must be equal to the marginal cost of capacity construction,

$$\sum_{t=t_1}^{\infty} \frac{1}{(1+\delta)^t} \frac{\partial \, \mathbb{E}[\pi(Q^*_{j,t})]}{\partial K_j} = \frac{\partial C(K_j)}{\partial K_j}. \tag{8}$$

Compared to the social optimum in equation (3), gas plants underinvest in processing capacity due to the external damages from flaring that are unaccounted for.

Consider a corrective capacity subsidy that reconciles market incentives with the social planner's equilibrium conditions. Comparing equations (3) and (8), the capacity at market equilibrium would be efficient if each plant j were offered the following per unit capacity subsidy:

$$s_j = \sum_{t=t_1}^{\infty} \frac{1}{(1+\delta)^t} \frac{\partial \, \mathbb{E}[D_j(Q^*_t)]}{\partial K_j}. \tag{9}$$

Here, I recover a first-best capacity subsidy that varies by each plant given that damages from flaring may be heterogeneous across plants.

3.3 Optimal Subsidy

The subsidy s_j derived in the previous section requires the regulator to offer a different subsidy to each plant, depending on plant characteristics. For instance, health related damages from flaring may likely vary by plant, depending on the density of the population nearby. However, the regulator may realistically only be able to offer a single subsidy for all plants, which I formally examine below.

The regulator chooses a single subsidy s across all plants $j = 1, 2, 3, ..., J$ that maximizes the utility of consuming all processed gas, net of associated costs including damages from total gas flared:

$$\max_{s} \quad \Big\{\sum_{t=t_1}^{\infty} \frac{1}{(1+\delta)^t} \Big\{\mathbb{E}\Big[u(\sum_j Q^*_{j,t}) - c_t \sum_j Q^*_{j,t} - D(\sum_j Q^*_{j,t})\Big]\Big\} - \sum_j C(K_j)\Big\}. \tag{10}$$

The following proposition characterizes the optimal single subsidy offered to all gas processing plants.

Proposition 1. *The optimal subsidy the regulator offers to all plants is*

$$s^* = \sum_{t=t_1}^{\infty} \frac{1}{(1+\delta)^t} \Big(\sum_j \gamma_j w_j \, \mathbb{E}\Big[\frac{\partial Q^F_{j,t}}{\partial K_j}\Big]\Big), \tag{11}$$

where

$$w_j = \frac{\frac{\partial K_j}{\partial s}}{\sum_j \frac{\partial K_j}{\partial s}},$$

such that $w_j \in [0, 1]$, *and* $\sum_j w_j = 1$.

Proof. See Appendix A. □

The regulator's optimal subsidy is the weighted average of the marginal flaring damages with respect to capacity across all plants, where the weights are determined by how each plant's processing capacity responds to the subsidy. If the effect of subsidy on processing capacity is homogeneous across plants, the weight then becomes $\frac{1}{J}$, and the subsidy is the present value of discounted average damages from insufficient capacity across all plants. However, under heterogeneity, the subsidy in (11) depends on the weighted average over marginal damages from flaring. As a result, the size of the subsidy will vary depending on the responsiveness of plant capacity to the subsidy. For example, the optimal subsidy will likely be larger if plants located in areas with higher population density respond strongly to the subsidy.

In my empirical application, I assume that the effect of subsidy on processing capacity is homogeneous across all plants, so that $w_j = \frac{1}{J}$. I also assume that the social cost of flaring is symmetric across plants, i.e. $\gamma_j = \gamma \quad \forall j \in \{1, 2, 3, ..., J\}$, given that the geographical attributes surrounding plants are relatively homogeneous in my application. Using an instrumental variable model, I estimate the average changes in flaring with additional processing capacity across all gas plants $\sum_{j=1}^{J} \frac{1}{J}\, \mathbb{E}\left[\frac{\partial Q^F_{j,t}}{\partial K_j}\right]$, and calculate the optimal single subsidy that offsets flaring damages driven by insufficient processing capacity.

4 Data

4.1 Oil and Gas Wells

The data on well-level monthly oil and gas produced, sold, and flared for 2012-2019 are obtained from North Dakota Industrial Commission (NDIC). I exclude wells that have never sold gas during the sample period, since they may not be connected to gas processing plants. There are 13,901 active wells in my sample, all of which co-produce natural gas along with oil. Among them, 95% are horizontally drilled, which is a common technology used in hydraulic fracturing. This aligns with the industry outlook in the Bakken that most wells are drilled primarily to extract tight oil in the shale formation, and that natural gas is an associated product. Moreover, the disparity in the revenue from oil and gas sales in the sample indicates that producers are motivated by the profitability of oil. On average, gas sales contribute to only 7% of the total monthly revenue for the wells.

Although some of the oldest wells in the sample were drilled in the 1950s, the median age of wells is around 30 months or 2.5 years. Generally, reservoir pressure declines with age and production diminishes over time. Figure 8 plots the distribution of average monthly natural gas production for wells above and below the median age in the sample. As expected, younger wells tend to be more productive compared to the older wells drilled in earlier decades. Figure 9 presents the relationship between well tenure and monthly gas production in the sample, which shows that production declines with a well's age. Similarly, monthly gas flared tends to decrease with tenure, which is likely to be driven by the diminishing production.

4.2 Gas Processing Plants

The data on gas processing plants are obtained from the North Dakota Industrial Commission (NDIC) and North Dakota Pipeline Administration (NDPA). I obtain plant locations from the NDIC's geographic information systems (GIS) server, and I fill in for missing location data via Environmental Protection Agency's record of gas processing plants across the country. Plant capacity data are provided by NDPA on an annual basis measured as millions of cubic feet per day, and I multiply this measure with total number of days in a month to obtain total monthly capacity. I obtain plant expansion permits submitted to the North Dakota Public Service Commission to determine the exact month of the expansion in the years capacity changes and adjust for monthly capacity accordingly.

Figure 10 shows the total capacity along with plant entries and exits over the sample period. Total gas processing capacity is increasing over the years– in 2019, it stood at approximately 3 billion cubic feet per day. The number of gas processing plants is also increasing over time starting at 17 in 2012 and growing to 27 by 2019. Over the sample period, two gas plants shut down in 2014 and 2017. Consequently, total processing capacity appears to remain stagnant during the exit years. However, flaring increased in those same years, even though production didn't experience a significant spike, as seen in Figure 2. This suggests that reduction in processing capacity may potentially drive the upsurge in natural gas flaring.

4.3 Connecting Wells and Plants

To connect gas processing plants and wells, I use monthly gas plant receipts obtained from North Dakota Industrial Commission (NDIC). These receipts are submitted by gas plants recording the total gas processed for each well in each month. Figure 11 shows an example of the receipts scanned and provided by the NDIC. I extract the data from these receipts using optimal character recognition (OCR). Almost all the wells in the sample are connected to the same one plant throughout their lifetime. A total of 12 wells reconnected to a different plant when one of the plants shut down in 2017, and no well in the sample switched plants more than once. This aligns with personal accounts by plant managers in North Dakota[3] that it is customary for wells to maintain a relationship with one processing plant over their lifetime since the construction of gathering pipelines requires lengthy permitting procedures and high costs.

Figure 13 shows that wells connected to constrained processing plants tend to flare higher quantities of natural gas. The location of wells and plants are shown in figure 12, where the same relationship between constrained capacity and flaring is observed. Natural gas flows from the wells to gas plants along the gathering network, and when processing capacity is constrained, gas sent by the wells flow back to the producers. There is a possibility that wells located closer to plants may be able to utilize the capacity sooner than those located farther

[3] According to the manager of Red Wing Creek gas plant in McKenzie County, ND via phone interview in 2023 March.

Table 4.1: Well Characteristics and Heterogeneity in Flaring

	(1) % of Months Flared	(2) p-Value	(3) Mean
Density of Gathering Network (meters)	-0.0002	0.162	99,279.5
Avg. Monthly Oil Sales (bbl)	0.0074***	0.000	1,956.17
Avg. Gas Production (mcf)	-0.0009**	0.022	3,193.2
Distance to Plant (km)	0.1243**	0.015	40.54
Avg. Tenure (months)	-0.0086	0.675	56.4
Owned by the Plant	-1.0816	0.841	.10
Owned by Large Operators	-6.5202	0.042	.72
Owned by Publicly-traded Operators	7.586	0.208	.72
Observations	13,901	13,901	13,901
Plant FE	YES	-	-
Std. Errors Clustered by	Plant	-	-

away. Figure 14 shows that wells farther away may flare slightly more of their production compared to their closer counterparts.

I examine the heterogeneity in flaring across wells in table 4.1, where I regress the share of months that a well flares at least some of their production on its distance to the processing plant, average monthly production, average monthly oil sales, average tenure, density of gathering network around the well, whether the well is owned by the same operator as the plant, whether the well is owned by operators above $2 billion market capitalization, and whether the well is owned by publicly traded operators. I include plant fixed effects to analyze the variation in flaring among the wells that share the processing capacity. Standard errors are clustered at the plant level given that the fluctuations in flaring are likely to be correlated among the wells connected to the same plant.

It appears that density of the gathering network reduces the share of months a well flares: the more pipelines a well is surrounded by, the more likely that the congestion will be lower within its own gathering line. Distance also seems to matter, as well as the size and type of the operating firm. However, whether the wells are owned by the same operators as the gas plant does not appear to affect flaring, which suggests that market power may not be a concern. There may still be differences in flaring among the wells connected to differently sized plants, which I explore in Section 6.3. In my estimating equation, I control for time-varying characteristics of the wells that drive flaring and include well fixed effects to account for the time-invariant well attributes such as distance to processing plants.

5 Empirical Model

In each month, the natural gas extracted from oil and gas wells is transported via gathering lines to gas processing plants in order to produce dry natural gas ready for sale. If the capacity available at the plant is constrained, the share of production that cannot be processed gets flared off at the extraction site. To offset the damages from flaring that stems from insufficient processing capacity, I propose a subsidy that depends on the economic relationship between processing capacity at the plants and the quantity of natural gas flared at the wells.

The data on total processing capacity at the plants are at the annual level. Hence, the monthly variation in available capacity for each well is primarily driven by changes in production of all other wells connected to the same plant. Using well-level monthly data on natural gas flared, I quantify the relationship between available capacity and the amount of natural gas flared by each well. I then use this estimate to calculate changes in flaring from fluctuations in total processing capacity, which serve as a basis for the derivation of the capacity subsidy outlined in Section 3.3.

5.1 Ordinary Least Squares Model

Consider the following ordinary least squares (OLS) specification:

$$q^F_{i,j,t} = \alpha_0 + \alpha_1 K^R_{i,j,t} + X_{i,j,t}\Theta + \gamma_i + \zeta_m + \eta_y + \varepsilon_{i,j,t}, \tag{12}$$

where $q^F_{i,j,t} = q^P_{i,j,t} - q_{i,j,t}$ is the total gas flared by well i connected to plant j in month t, which is the difference between total gas produced ($q^P_{i,j,t}$) and total gas processed ($q_{i,j,t}$). $K^R_{i,j,t}$ is the residual or share of capacity available at plant j to process gas produced by well i in a given month, calculated as:

$$K^R_{i,j,t} = K_{j,t} - (Q_{j,t} - q_{i,j,t}),$$

where $K_{j,t}$ is the total capacity at plant j in month t, $Q_{j,t} = \sum_{i=1}^{N} q_{i,j,t}$ is the total gas processed by plant j in month t, and $q_{i,j,t}$ is the total gas delivered by well i to plant j in month t. In other words, the residual capacity for well i is the space available at plant j to process well i's monthly natural gas production, conditional on the total production of all other wells connected to the plant.

I control for time-varying well attributes that affect total gas production and flared, such as monthly oil and water production, well tenure and well tenure squared. In addition, the quantity of gas flared can be affected by nearby natural gas production and sales. Therefore, I control for total gas processed and sold by the neighboring wells. To account for time-invariant well-specific characteristics that can affect flaring, I include well fixed effects. I also include year and month-of-year fixed effects to control for potential shocks that may have occurred during the sample period. The standard errors are clustered over the shared gathering pipelines among the wells, since flaring is likely to be correlated across wells in the same gathering network.

The coefficient of interest is $\hat{\alpha}_1$ which captures the marginal effect of residual capacity on the quantity of natural gas flared by each well. This is identified by the idiosyncratic shocks to residual capacity, relative to the average flaring for that well in a given month. There are two main threats to the identification of $\hat{\alpha}_1$. First is the presence of unobserved shocks that can affect how much gas is captured and flared, which are likely to be correlated with the primary independent variable of interest, $K^R_{i,j,t}$. For example, pipeline extensions from the plant to new wells contribute to the total gas delivered at the plant for processing. This takes up the residual capacity available for each well connected to the plant. Meanwhile, new drilling activities may affect the geological components that drive production and flaring of nearby wells.

Congestion in the gathering lines can also drive flaring among the wells. The pressure in the gathering pipelines is primarily determined by (1) total production of the wells connected, and (2) compressor stations along the pipelines that maintain the pressure at a desired rate. First, stochastic changes in the compressor station operations can drive congestion among the wells that share the gathering network, affecting how much gas gets flared by the wells using the pipelines. At the same time, changes in the amount of gas delivered to the plants directly translate to fluctuations in each well's residual capacity. Second, increased production from re-fracturing the wells can drive congestion in the gathering network and drive up flaring of nearby wells that share the pipeline. At the same time, more gas is delivered by re-fracked wells to processing plants, reducing the share of capacity available to nearby wells connected to the same plant.

Lastly, the variation in residual capacity for each well is driven by (1) the amount of gas captured by the well, and (2) total gas sold by all other wells connected to the plant. As such, when plants are at capacity, each well's reduction in flaring, $q^F_{i,j,t}$, increases the residual capacity, $K^R_{i,j,t}$, by occupying a higher share of the available capacity at the plant. Hence, when the capacity constraint binds, residual capacity is a function of the quantity of gas flared. This indicates that the OLS estimation suffers from the simultaneity bias.

To address both the endogeneity and simultaneity concerns, I construct an instrument for $K^R_{i,j,t}$, to infer a causal relationship between natural gas flaring and processing capacity available to each well.

5.2 Instrumental Variable Model

I estimate the following two-stage least square specification using an instrument $z_{i,j,t}$ to infer a causal relationship between residual capacity for each well and the quantity of natural gas flared:

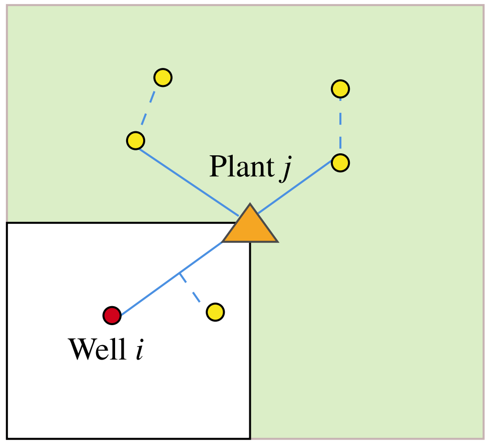
$$\begin{aligned} K^R_{i,j,t} &= \beta_0 + \beta_1 z_{i,j,t} + X_{i,j,t}\Psi + \rho_i + \kappa_m + \phi_y + \mu_{i,j,t}, \\ q^F_{i,j,t} &= \alpha_0 + \alpha_1 \widehat{K^R_{i,j,t}} + X_{i,j,t}\Theta + \gamma_i + \zeta_m + \eta_y + \varepsilon_{i,j,t}. \end{aligned} \tag{13}$$

The goal of the IV specification is to eliminate the concerns addressed in Section 5.1, by utilizing an instrument that affects each well's flaring only through the residual capacity available at the plant. The issues of endogeneity are specific to the well's geographical location: expected and realized changes in drilling, production, flaring, and pipeline pressure nearby affect both the residual capacity and the quantity of gas flared. The construction of the instrument ensures that the localized unobservables are excluded in the variation.

Figure 3 depicts the construction of the instrument $z_{i,j,t}$ for each well's monthly residual capacity. Suppose that well i is connected to plant j in month t. In each month, total natural gas produced by all other wells connected to the plant directly affects well i's residual capacity. However, production of wells adjacent to well i also contributes to congestion and potential geological determinants of flaring. To address this, I draw "exclusion boundaries" on both sides of well i to ensure that neighboring wells are excluded in calculation of the instrument, which is total natural gas production of all wells on the opposite side of the plant in the green area. The exclusion boundaries create a 90 degree quadrant around well i that includes all other wells nearby connected to plant j. I then instrument for the residual capacity for well i using monthly gas production of all other wells connected to plant j located outside the exclusion boundary.

Pipeline extensions from plant j to additional wells outside the exclusion boundary increase the total quantity of gas delivered to the plant. As a result, $z_{i,j,t}$ is correlated with the residual capacity, and the instrument is relevant. As the production increases for the

Figure 3: Construction of the Instrument



wells included in the instrument, the residual capacity for well i decreases. My first-stage results confirm this relationship in Section 6.2.1.

Wells outside the exclusion boundary are sufficiently far enough that their production is unlikely to affect the geological factors that drive flaring by well i. In addition, pipeline connections to these wells don't interfere with well i's gathering network, and as a result, the instrument affects well i's flaring only through the available processing capacity at plant j. Hence, the instrument exhibits exogeneity, which is reinforced by two key facts: (1) producers drill for oil, and (2) production is primarily determined by the underground pressure.

As the area of the exclusion boundary increases, fewer wells are included in the calculation of the instrument. This reduces the power of the instrument but makes it more likely that the exclusion restriction is fully satisfied. I vary the 90 degree perimeter of the exclusion boundary in Section 6.2.3, and find that my results are robust to changes in the number of wells included in the calculation of the instrument.

6 Results

Here I present the results for the OLS and IV models. I examine the direction of the bias induced by threats to identification discussed in Section 5.1 and verify the robustness of the instrument. Using the estimates from the IV model, I then calculate the capacity subsidy formally derived in Section 3.3, and present back-of-the-envelope analysis of the proposed subsidy.

6.1 Ordinary Least Squares Results

The results for the OLS specification in equation (12) are presented in table 6.1 column (3). I find that on average, an additional 1 thousand cubic feet (mcf) of residual capacity at the plant decreases the quantity of gas flared by approximately 0.01 cubic feet (cf) per well per month. The estimated coefficient lacks statistical significance, and the magnitude is diminutive. This can be attributed to the threats to identification discussed in Section 5.1.

First, estimating the causal effect of processing capacity on flaring is complicated by local market and geological shocks that can affect both variables of interest in any given month. These shocks are likely to be concentrated around each well's gathering and production network. For instance, the pressure in the gathering pipelines, $p_{i,j,t}$, is generally determined by (1) the number of compressor stations along the pipeline, and (2) total production of the wells in the network.

If there are stochastic equipment failures that cause any of the compressor stations to malfunction, $p_{i,j,t}$ decreases in the gathering pipelines. This lowers the amount of gas each well can send to the plant, driving flaring up. Consequently, the residual capacity at the plant for each well increases since wells affected by lower pressure are delivering less of their production to the plant. Hence, $Cov(p_{i,j,t}, q^F_{i,j,t}) > 0$, and $Cov(p_{i,j,t}, K^R_{i,j,t}) > 0$, which biases the coefficient downwards. Second, the OLS estimate is further biased towards zero due to the simultaneity of residual capacity and flaring by each well when plants are at capacity. In contrast, the IV estimation results in table 6.1 demonstrate that the instrumental variable model corrects the bias.

6.2 Instrumental Variable Analysis

6.2.1 First Stage Results

Column (1) of table 6 reports the first-stage results for the IV specification. I find that on average, an increase in total production of all other wells on the opposite side of the plant by 1 thousand cubic feet (mcf) lowers the plant's residual capacity for the well of interest by 70 cubic feet (cf) per month. The coefficient is statistically significant at the 1 % level, and the F-statistic exceeds the widely recognized threshold of 10. This suggests that the instrument is sufficiently strong for the second-stage analysis of the IV model.

Table 6.1: The Effect of Excess Capacity on Total Gas Flared

	(1) Residual Capacity (mcf)	(2) Gas Flared (mcf)	(3) Gas Flared (mcf)
Model	**IV First Stage**	**IV Second Stage**	**OLS**
Residual Capacity (mcf)	-	-0.000409***	-0.00001
		(0.000085)	(0.000006)
Gas Production Outside Gathering Network (mcf)	-0.07131***	-	-
	(0.00321)		
Gas Sold in Vicinity (mcf)	-0.0808***	-0.0001***	-0.0001***
	(0.0089)	(0.0000)	(0.0000)
Oil Sold (bbl)	4.239***	0.380***	0.370***
	(1.132)	(0.010)	(0.010)
Water Prod. (bbl)	9.161***	0.026***	0.024***
	(1.015)	(0.007)	(0.006)
Well Tenure (Months)	-16396.821***	-7.258***	-1.729***
	(617.639)	(1.566)	(0.487)
Well Tenure Sq.	2.917***	0.006***	0.005***
	(0.616)	(0.001)	(0.000)
Gas Price ($/mcf)	-1.330e+05***	-14.55	40.62***
	(3.508e+03)	(12.98)	(5.73)
Oil Price ($/bbl)	1.035e+04***	4.80***	0.72*
	(160.87)	(0.95)	(0.37)
Observations	955,131	955,131	955,131
F-Stat	492.44	492.44	-
Year FE	YES	YES	YES
Well FE	YES	YES	YES
Month-Of-Year FE	YES	YES	YES
Std. Clustered By	2019 Gathering Network	2019 Gathering Network	2019 Gathering Network

6.2.2 Second Stage Results

I report the IV second stage results in table 6 column (2). I find that on average, an additional 1 thousand cubic feet (mcf) of residual capacity decreases flaring by 0.4 cubic feet (cf) per well per month. The coefficient is statistically significant at the 1% level. Compared to the OLS estimate in column (3), the magnitude of the coefficient is larger: the instrumental variable approach corrects the potential biases discussed in Section 6.1.

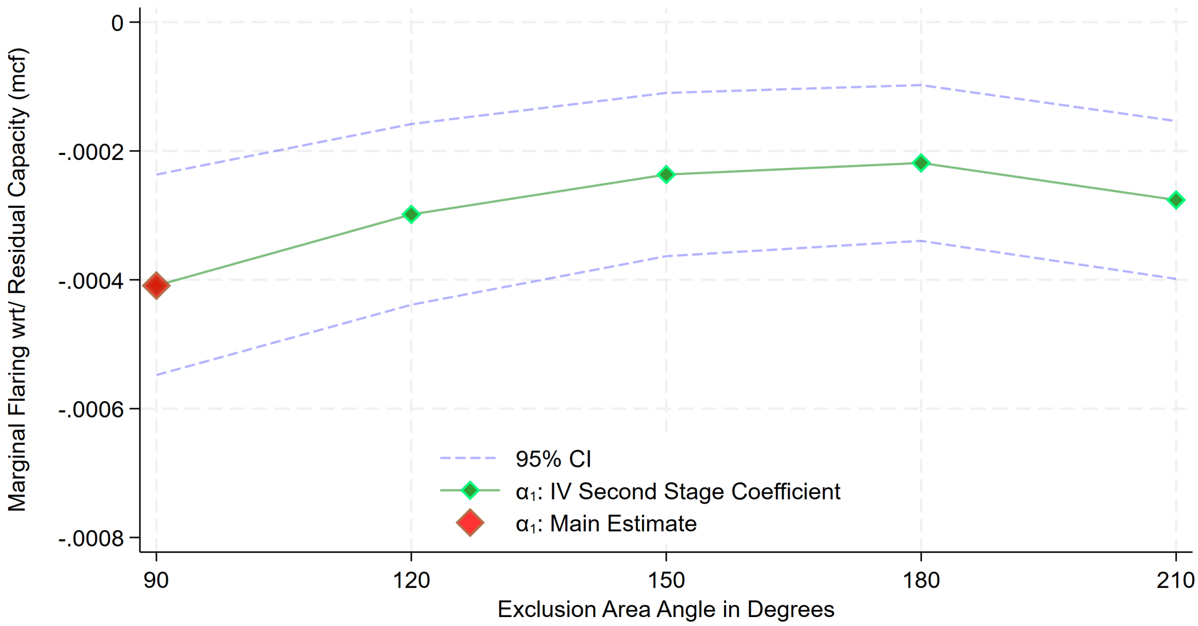
I control for time-varying well-specific attributes that can affect flaring in my model. I find that as total gas sold by wells in the vicinity increases, flaring decreases. This aligns with the expectation that the production and market shocks that drive the incentives to flare are likely to be localized. I also find that flaring increases with monthly oil sales and oil prices. As gas prices increase, however, the quantity of gas flared decreases.

Given that the monthly average number of wells connected to plants in my sample is 523, the average flaring reduction per plant per month is 209 cubic feet (cf) for every 1 thousand cubic feet increase in the residual capacity for all wells connected to the plant. The results indicate that capacity constraints in fact drive natural gas flaring. Therefore, policies that encourage investment in processing capacity can reduce flaring emissions that stem from insufficient capacity.

6.2.3 Robustness of the Instrument

I vary the 90 degree angle perimeter of the exclusion boundary described in Figure 3. This affects the number of wells included in the calculation of the instrumental variable, which is total gas production of wells located on the opposite side of the plant ($z_{i,j,t}$). As I increase the size of the exclusion boundary, fewer wells are included in the calculation of $z_{i,j,t}$, which reduces the power of the instrument, as shown in Figure 4. Despite the decrease in magnitude of the coefficient $\hat{\alpha}_1$ as the size of the instrument decreases, my results are robust to this

Figure 4: Robustness of the Instrumental Variable



variation– the relationship between flaring and residual capacity is consistently negative, and the estimates are significant.

6.3 Heterogeneity

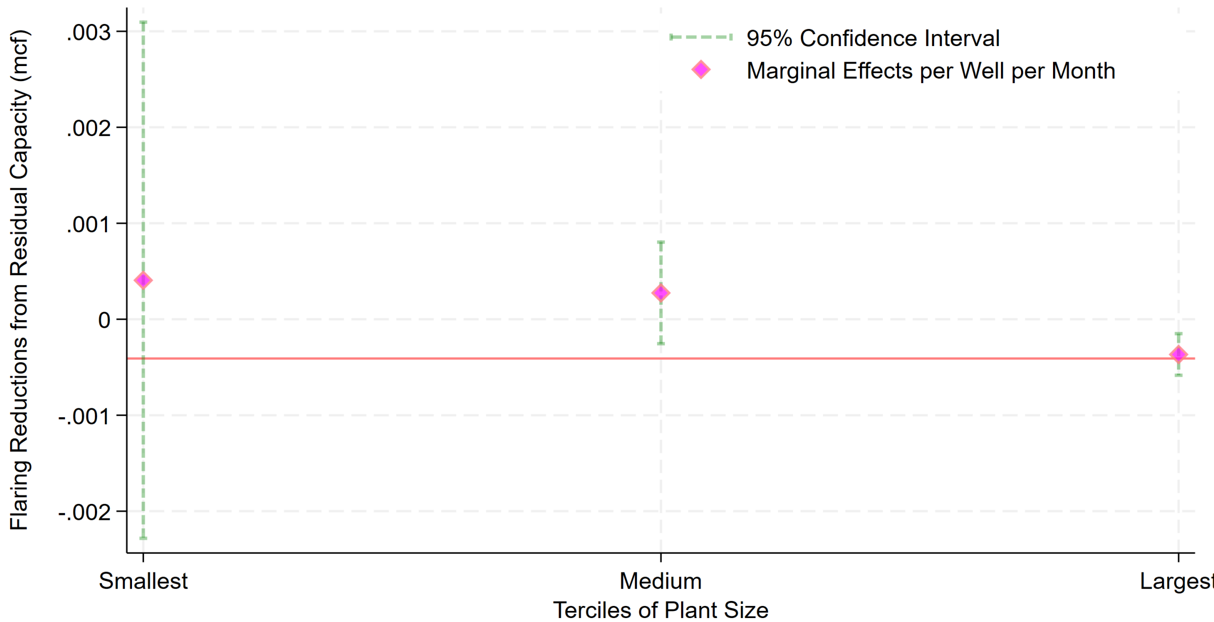
Extending the primary analysis in Section 5.2, I estimate

$$K^R_{i,j,t} = \beta_0 + \beta_1 z_{i,j,t} + \beta_2 z_{i,j,t} \times D_2 + \beta_3 z_{i,j,t} \times D_3 + X_{i,j,t}\Psi + \rho_i + \kappa_m + \phi_y + \mu_{i,j,t}, \tag{14}$$

$$q^F_{i,j,t} = \alpha_0 + \alpha_1 \widehat{K}^R_{i,j,t} + \alpha_2 \widehat{K^R_{i,j,t} \times D_2} + \alpha_3 \widehat{K^R_{i,j,t} \times D_3} + X_{i,j,t}\Theta + \gamma_i + \zeta_m + \eta_y + \varepsilon_{i,j,t}, \tag{15}$$

where D_j is an indicator for whether the plants' average capacity over the sample period lies in the j^{th} tercile of the sample distribution $\forall j = 2, 3$. Interacting the tercile indicators with $\widehat{K}^R_{i,j,t}$ allows me to estimate the differential effects of residual capacity on flaring based on plant attributes.

Figure 5: Heterogeneity in Flaring Reduction by Plant Size



Note: Plant size is measured as average monthly processing capacity over the sample period 2012-2019. The red line plots the benchmark estimate of flaring reductions from additional residual capacity per well per month.

I find suggestive evidence that the flaring reductions from additional residual capacity are heterogeneous across wells connected to plants of different sizes. Figure 5 shows that the primary estimation results in Section 6.2.2 are driven by reduction in flaring from wells connected to the largest plants in the sample.

6.4 Capacity Subsidy

The subsidy derived in Section 3.3 depends on the expectations over the marginal effect of processing capacity on flaring, which can be decomposed as follows using the estimated $\hat{\alpha}_1$ for each of the wells i connected to plant j:

$$\mathbb{E}\left[\frac{\partial q^F_{i,j,t}}{\partial K_{j,t}}\right] = \underbrace{\mathbb{E}\left[\frac{\partial q^F_{i,j,t}}{\partial K^R_{i,j,t}}\right]}_{\hat{\alpha}_1} \cdot \mathbb{E}\left[\frac{\partial K^R_{i,j,t}}{\partial K_{j,t}}\right] + Cov\left(\frac{\partial q^F_{i,j,t}}{\partial K^R_{i,j,t}}, \frac{\partial K^R_{i,j,t}}{\partial K_{j,t}}\right). \tag{16}$$

Suppose that the treatment effect of increasing processing capacity on flaring are homogeneous across all wells connected to each plant in the sample. This implies that there is no correlation between changes in residual capacity from plant expansions and how much each well flares from fluctuations in the residual capacity:

$$\mathbb{E}\Big[\frac{\partial q^F_{i,j,t}}{\partial K_{j,t}}\Big] = \hat{\alpha}_1 \cdot \mathbb{E}\Big[\frac{\partial K^R_{i,j,t}}{\partial K_{j,t}}\Big]\,. \tag{17}$$

Having estimated $\hat{\alpha}_1$, the calculation of marginal flaring with respect to capacity in equation (17) now depends on $\mathbb{E}\Big[\frac{\partial K^R_{i,j,t}}{\partial K_{j,t}}\Big]$, which can be derived from the definition of residual capacity for each well. Recall that residual capacity is defined as the difference between total monthly capacity and total gas processed for all other wells connected to the plant:

$$\begin{aligned} K^R_{i,j,t} &= \overbrace{K_{j,t}}^{\text{capacity}} - \overbrace{(Q_{j,t} - q_{i,j,t})}^{\text{gas processed from all wells except } i} \\ &= K_{j,t} - \underbrace{Q^P_{-i,j,t}}_{\text{gas produced by all wells except } i} + \underbrace{Q^F_{-i,j,t}}_{\text{gas flared by all wells except } i}. \end{aligned}$$

Given (1) the homogeneous treatment assumption above, and (2) the exogeneity of the drilling decision discussed in Section 2, we have that

$$\begin{aligned} \frac{\partial K^R_{i,j,t}}{\partial K_j} &= 1 + \frac{\partial Q^F_{-i,j,t}}{\partial K_j} \\ &= 1 + (N-1)\frac{\partial q^F_{i,j,t}}{\partial K_j}, \end{aligned}$$

where N is the total number of wells connected to the plant.

Hence, changes in the quantity of gas flared for each well with respect to total capacity can be expressed in terms of the estimated $\hat{\alpha}_1$ as follows:

$$\mathbb{E}\Big[\frac{\partial q^F_{i,j,t}}{\partial K_j}\Big] = \frac{\hat{\alpha}_1}{1 - \hat{\alpha}_1(N-1)}.$$

Note that well i's residual capacity is partly determined by the share of capacity used by all other wells connected to the same plant. Consequently, accounting for the reduction in flaring by other wells takes up the available capacity for well i. This adjustment brings the estimate closer to 0 when flaring decreases with additional residual capacity (i.e. $\hat{\alpha}_1 < 0$).

The average flaring reduction from changes in capacity per plant per month can then be aggregated as

$$\sum_j \frac{1}{J}\,\mathbb{E}\Big[\frac{\partial Q^F_{j,t}}{\partial K_j}\Big] = \Big\{\frac{\hat{\alpha}_1}{1-\hat{\alpha}_1(N-1)}\Big\} N \approx -0.2 \text{ mcf},$$

where $N = 523$ is the average number of wells connected to all processing plants in my sample. This indicates that an additional 1 thousand cubic feet (mcf) of processing capacity reduces flaring by 200 cubic feet (cf) per plant per month. The relationship isn't 1-to-1 given that flaring can be driven by constraints beyond processing capacity. However, my results show that processing capacity plays an important role in natural gas flaring, and relieving these constraints can reduce flaring that stems from insufficient processing capacity.

Recall that the capacity subsidy derived in Section 3.3 depends on the present value of marginal flaring with changes in total processing capacity and the social cost of flaring:

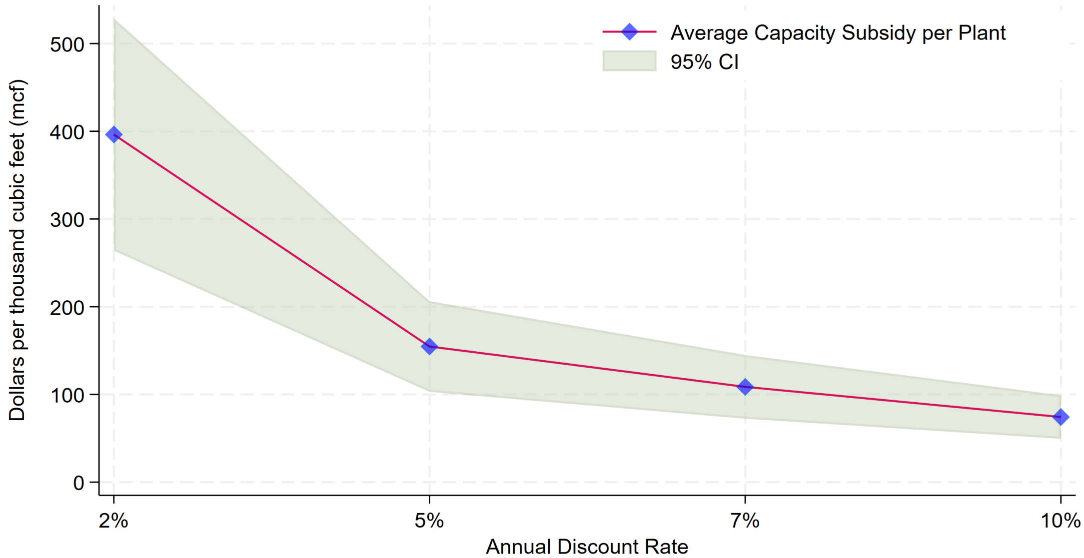
$$\gamma \sum_{t=t_1}^{\infty} \frac{1}{(1+\delta)^t} \sum_j \frac{1}{J}\,\mathbb{E}\Big[\frac{\partial Q^F_{j,t}}{\partial K_j}\Big].$$

Using the calculation of $\sum_j \frac{1}{J}\,\mathbb{E}\Big[\frac{\partial Q^F_{j,t}}{\partial K_j}\Big]$ above, we can now derive the capacity subsidy that will offset the damages from flaring emissions.

The external costs of natural gas flared[4] is estimated to be \$1.64 per thousand cubic feet (mcf) in hospitalization expenditures ((Blundell and Kokoza, 2022)). In addition, climate costs are estimated to be \$3.23 per thousand cubic feet of natural gas flared at the EPA-assumed 98% efficiency (Agerton et al., 2023). Taken together, I consider γ to be \$4.87 per unit of natural gas flared. On average, gas plants are operational in a year from construction,

[4] Note that the external costs do not include the forgone value of the natural gas flared since it is not considered an externality at the market equilibrium.

Figure 6: Average Capacity Subsidy per Thousand Cubic Feet (mcf)



so I take t_1 to be 12.

In Figure 6, I present the average capacity subsidy at different discount rates. At the annual social discount rate of 2% (or monthly discount rate of 0.17%), the capacity subsidy that offsets the damages from flaring is approximately \$396 per thousand cubic feet for each plant given that treatment effects are assumed to be constant. It should be noted that flaring reductions are heterogeneous across plants of different sizes in Section 6.3, which suggests that the optimal capacity subsidy likely varies by plant attributes.

Now consider a back-of-the-envelope approximation of the implications of the subsidy for flaring. I gather data on capacity and construction costs from gas plant siting applications submitted to the North Dakota Public Service Commission and estimate a logarithmic relationship between total capacity and total estimated costs. Assuming a constant elasticity of capacity investment with respect to costs, I find that reducing capacity costs by 1% would lead to an increase of 0.8% in processing capacity.[5]

According to processing plant construction and expansion permits submitted to the North Dakota Industrial Commission (NDIC), the cost of capacity construction is roughly

[5] I regress $log(K_j) = \zeta_0 + \zeta_1 log(C_j) + \phi_j$ for 10 plants.

\$1000 per thousand cubic feet (mcf). Given that the calculated average capacity subsidy is \$396 per thousand cubic feet, this lowers the per unit capacity costs by approximately 40%. The average monthly processing capacity among all plants in the sample period is 1.9 billion cubic feet. This means that the calculated subsidy would increase the average monthly capacity by roughly 600 million cubic feet.

The empirical estimates indicate that an increase in 1000 cubic feet of processing capacity reduces flaring by 200 cubic feet per plant per month. This implies that the subsidy would reduce monthly flaring by 120 million cubic feet on average. This is roughly $\$480,000$ saved in total damages per month, offsetting about \$5 million in flaring damages per year.

7 Conclusion

In this paper, I quantify the role of insufficient processing capacity in natural gas flaring by leveraging novel data from North Dakota where midstream constraints are especially relevant (Lade and Rudik, 2020) due to producers primarily drilling for oil. Using an instrumental variable model, I empirically demonstrate that flaring decreases as processing capacity increases and theoretically derive a subsidy which depends on the estimated economic relationship between processing capacity and the quantity of natural gas flared.

I find that on average, each gas processing plant requires an ex-ante subsidy of \$396 per thousand cubic feet (mcf) of processing capacity to ensure that flaring emissions remain at the socially optimal level. The subsidy is derived from the estimated marginal flaring with changes in processing capacity, which indicates that on average, an additional 1 thousand cubic feet (mcf) of processing capacity at a plant decreases flaring by 200 cubic feet (cf) among all the wells connected to the plant.

My results show that constrained processing capacity does in fact drive natural gas flaring, and that damages can be offset by subsidizing the processing capacity necessary to capture the gas. Back of the envelope calculations suggest that investment in additional processing capacity would offset the damages from flaring emissions by roughly \$5 million per year across the state. Future research should explore empirically testing the heterogeneous responses of plant capacity to the subsidy derived in the theoretical model, relaxing the homogeneity assumption in the application.

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A Proof of Proposition 1

Proof. The first order conditions for the regulator gives us

$$0 = \sum_{t=t_1}^{\infty} \frac{1}{(1+\delta)^t} \Big\{ \sum_j \Big(\frac{\partial K_j}{\partial s} \cdot \Big(\mathbb{E}\Big[\frac{\partial u(\sum_j Q^*_{j,t})}{\partial Q^*_{j,t}} \cdot \frac{\partial Q^*_{j,t}}{\partial K_j} \Big] - c_t \, \mathbb{E}\Big[\frac{\partial Q^*_{j,t}}{\partial K_j} \Big] + \gamma_j \, \mathbb{E}\Big[\frac{\partial Q^*_{j,t}}{\partial K_j} \Big] \Big) \Big) \Big\} - \sum_j \Big(\frac{\partial K_j}{\partial s} \cdot \frac{\partial C(K_j)}{\partial K_j} \Big). \tag{18}$$

Adjust the first order conditions for the capacity setting problem of gas processing plants at market equilibrium in equation (8) as each plant being offered a constant subsidy s:

$$\sum_{t=t_1}^{\infty} \frac{1}{(1+\delta)^t} \frac{\partial \, \mathbb{E}[\pi(Q^*_{j,t})]}{\partial K_j} = \frac{\partial C(K_j)}{\partial K_j} + s.$$

Given that $\pi(Q^*_{j,t}) = p_t Q^*_{j,t} - c_t Q^*_{j,t}$ where p_t is the exogenous market price of natural gas, observe that

$$\frac{\partial \, \mathbb{E}[\pi(Q^*_{j,t})]}{\partial K_j} = \mathbb{E}\Big[\underbrace{\frac{\partial u(\sum_j Q^*_{j,t})}{\partial Q^*_{j,t}}}_{p_t} \cdot \frac{\partial Q^*_{j,t}}{\partial K_j} \Big] - c_t \, \mathbb{E}\Big[\frac{\partial Q^*_{j,t}}{\partial K_j} \Big],$$

since $p_t = \frac{\partial u(\sum_j Q^*_{j,t})}{\partial Q^*_{j,t}}$ following equation (5). Therefore, it must be that

$$s = \sum_{t=t_1}^{\infty} \frac{1}{(1+\delta)^t} \Big\{ \mathbb{E}\Big[\frac{\partial u(\sum_j Q^*_{j,t})}{\partial Q^*_{j,t}} \cdot \frac{\partial Q^*_{j,t}}{\partial K_j} \Big] - c_t \, \mathbb{E}\Big[\frac{\partial Q^*_{j,t}}{\partial K_j} \Big] \Big\} - \frac{\partial C(K_j)}{\partial K_j}.$$

Plugging this expression into equation (18) further simplifies the regulator FOC to:

$$0 = \sum_j \Big(\frac{\partial K_j}{\partial s} \cdot \Big(s + \gamma_j \sum_{t=t_1}^{\infty} \frac{1}{(1+\delta)^t} \Big\{ \mathbb{E}\Big[\frac{\partial Q^*_{j,t}}{\partial K_j} \Big] \Big\} \Big) \Big). \tag{19}$$

Since $Q^*_{j,t} = Q^P_{j,t} - Q^F_{j,t}$, and $Q^P_{j,t}$ is exogenous to K, this is equivalent to

$$0 = \sum_j \Big(\frac{\partial K_j}{\partial s} \cdot \Big(s - \gamma_j \sum_{t=t_1}^{\infty} \frac{1}{(1+\delta)^t} \Big\{ \mathbb{E}\Big[\frac{\partial Q^F_{j,t}}{\partial K_j} \Big] \Big\} \Big) \Big). \tag{20}$$

Hence, the optimal subsidy derived in Proposition 1 directly follows from rearranging the above expression to obtain s^*. □

B Figures

Figure 7: Distribution of Average Monthly Percent of Production Flared

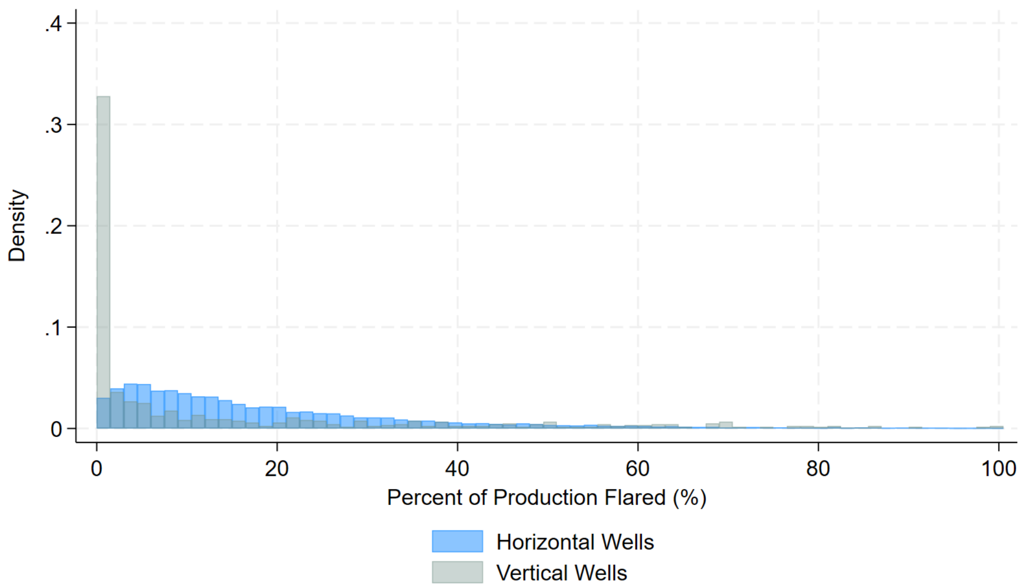

Figure 8: Distribution of Average Monthly Gas Production

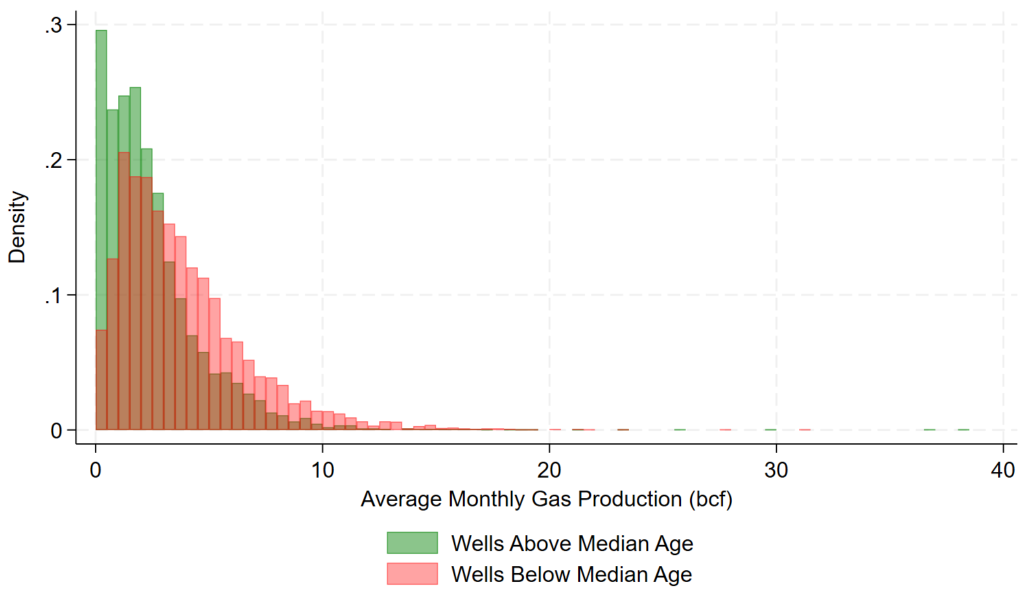

Figure 9: Relationship between Gas Produced, Flared, and Tenure

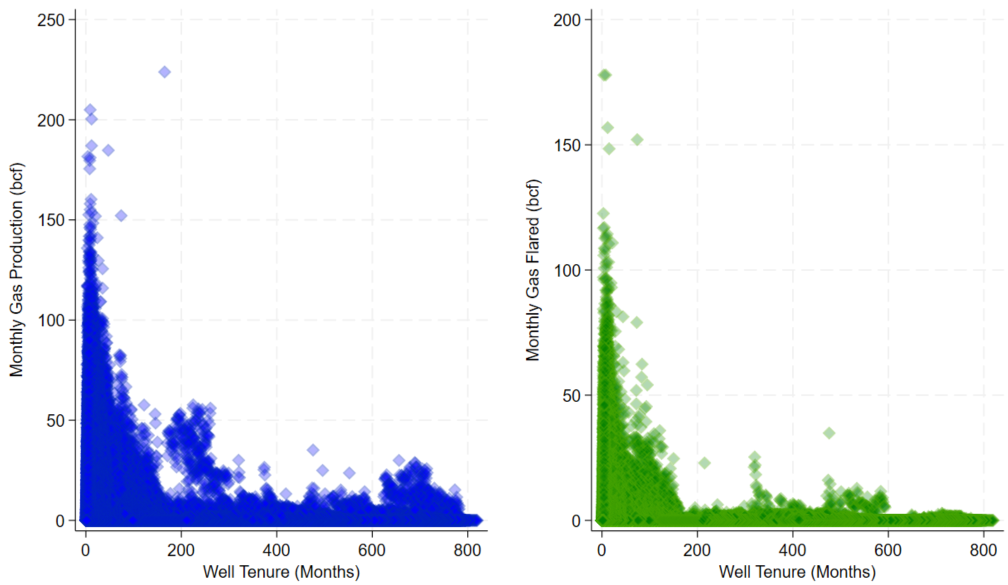

Figure 10: Variation in Gas Processing Capacity Over the Years

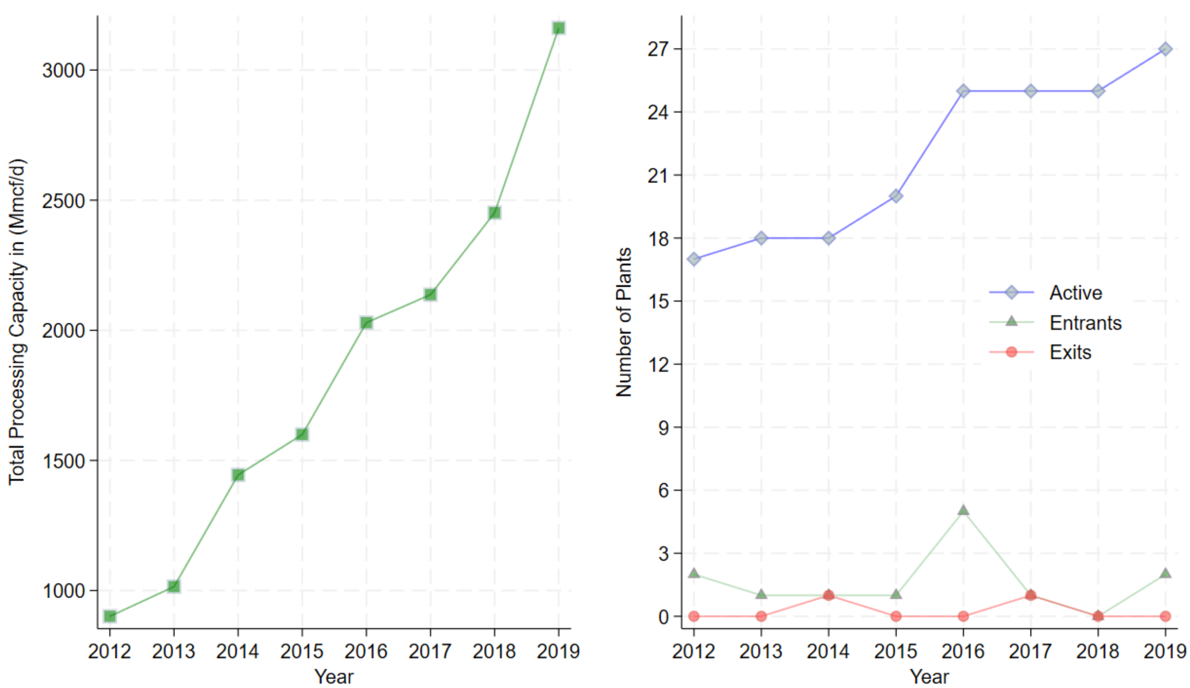

Figure 11: An Example of Scanned Monthly Gas Plant Receipts

GAS PROCESSING PLANT REPORT OF RECEIPTS FROM WELLS - FORM 12A

INDUSTRIAL COMMISSION OF NORTH DAKOTA
OIL AND GAS DIVISION
600 EAST BOULEVARD DEPT 405
BISMARCK, ND 58505-0840
SFN 18671 (04-2000)

☐ **Amended**

PLEASE READ INSTRUCTIONS BEFORE FILLING OUT FORM.
PLEASE SUBMIT THE ORIGINAL.
THIS REPORT SHALL BE ACCOMPANIED BY A GAS PROCESSING PLANT REPORT - FORM 12.

For Month/Year: **12/1/2018**

Gas Plant Name: **Arrow Bear Den Gas Plant**

Gas Plant Operator: **Arrow Midstream Holdings**

Telephone Number: **832.519.2232**

Operator	Well Name and Number	Well File No. or NDIC CTB No.	Take (MCF)
WPX ENERGY WILLISTON, LLC	ALISIA FOX 16-9H	117943	149
WPX ENERGY WILLISTON, LLC	NATHAN HALE 3-18H	117658	947
WPX ENERGY WILLISTON, LLC	CROSS 2-13H	118128	625
WPX ENERGY WILLISTON, LLC	PATRICIA CHARGING 4-15H	118166	257
WPX ENERGY WILLISTON, LLC	CLARA 14-17H	118564	2184
WPX ENERGY WILLISTON, LLC	BIRDSBILL 14-16H	118520	320
WPX ENERGY WILLISTON, LLC	TAT {1922} 14-2H	118007	0
WPX ENERGY WILLISTON, LLC	TAT 15-1H	118396	462
WPX ENERGY WILLISTON, LLC	NATHAN HALE 4-25H	117978	419
WPX ENERGY WILLISTON, LLC	HIGH HAWK 4-9H	118729	77
WPX ENERGY WILLISTON, LLC	MORSETTE 35-26H	218803	1477
WPX ENERGY WILLISTON, LLC	MORSETTE 35-26HD	218803	949
WPX ENERGY WILLISTON, LLC	MORSETTE 35-26HX	218803	1075
WPX ENERGY WILLISTON, LLC	MORSETTE 35-26HZ	218803	1475
ERPLUS RESOURCES USA CORPORATION	TAT {714A} 2-1H	117975	0
RIMROCK OIL & GAS WILLISTON LLC	TWO SHIELDS BUTTE 16-8-7H	117981	777
RIMROCK OIL & GAS WILLISTON LLC	TWO SHIELDS BUTTE 16-8-16H	118022	254
QEP ENERGY COMPANY	MHA 1-06-31H-150-92	118322	424
RIMROCK OIL & GAS WILLISTON LLC	TWO SHIELDS BUTTE 14-33-6H	118107	74
RIMROCK OIL & GAS WILLISTON LLC	TWO SHIELDS BUTTE 14-33-28H	118051	390
WPX ENERGY WILLISTON, LLC	KYW 27-34H	118948	0
WPX ENERGY WILLISTON, LLC	WELLS 32-29H	219246	1108
WPX ENERGY WILLISTON, LLC	WELLS 32-29HD	219246	4624
WPX ENERGY WILLISTON, LLC	WELLS 32-29HY	219246	4157
WPX ENERGY WILLISTON, LLC	WELLS 32-29HZ	219246	2089
WPX ENERGY WILLISTON, LLC	HELENA RUTH GRANT 33-34HA	229081	2400

Figure 12: Location of Gas Plants and Wells in North Dakota

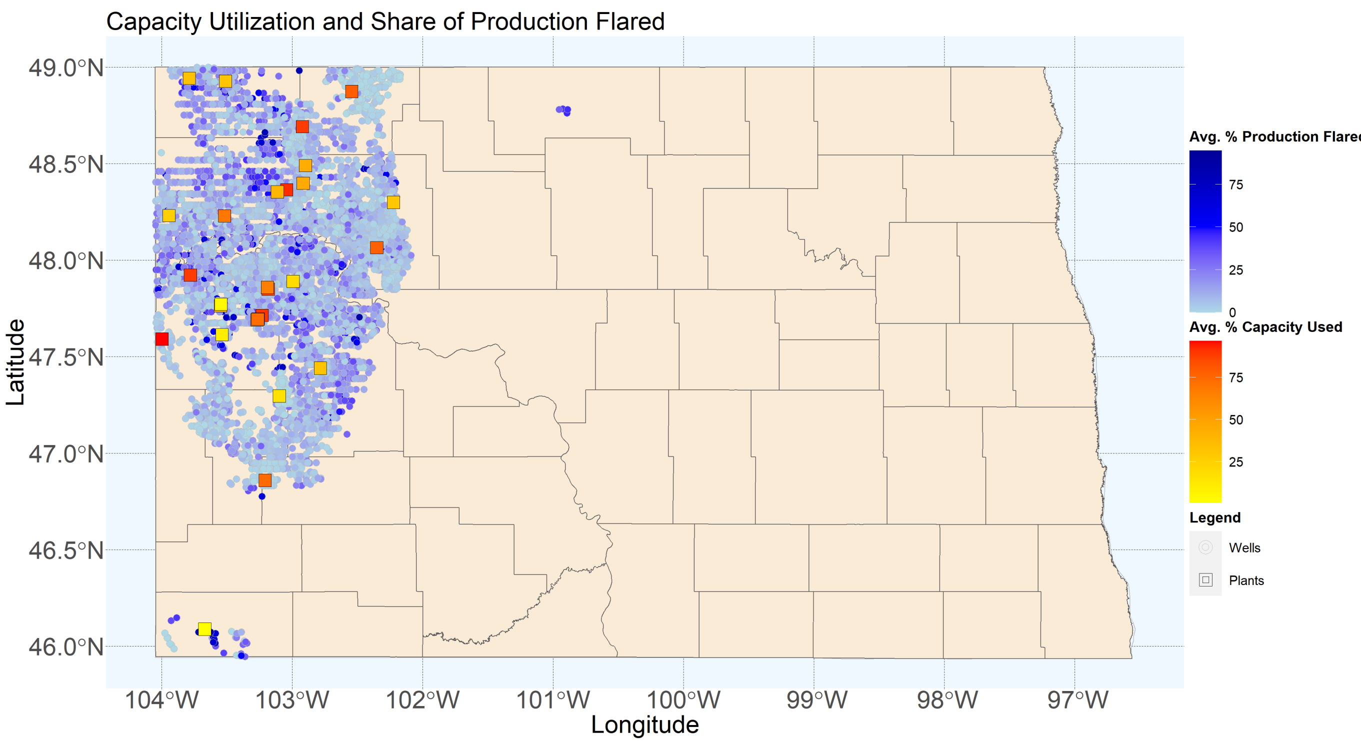

Figure 13: Monthly Gas Flared and Processing Capacity Utilization

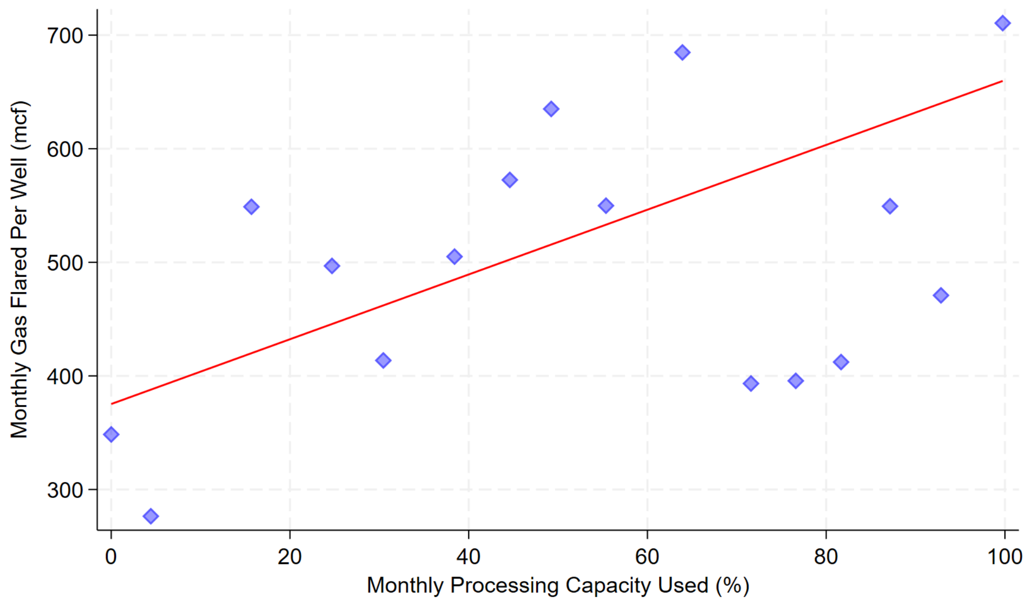

Figure 14: The Relationship Between Share of Production Flared and Distance to Plants