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Modeling market power in the U.S. shale gas market

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Abstract Natural gas is becoming a fuel of choice for many energy consumption markets. In the United States, both the production and consumption of natural gas has recently increased with the advent of shale gas. This has result in markets where players who produce and sell shale gas can potentially exercise market power. In this paper, we compare two different methods of analyzing market power in energy markets with the United States natural gas market as an example. We show that these two methods yield different results, which imply that domain knowledge of markets is essential when deciding on the modeling paradigm. While both methods present an extreme in modeling market power, the results nevertheless provide relevant bounding scenarios for analyzing the future of shale gas in the United States.

Keywords Market power · MPEC · Cournot · Natural gas · Infrastructure

1 Introduction

The abundance of natural gas in certain parts of the world and its relative environmental advantage over other fossil fuels makes it an important fuel for today's energy markets. One part of the rising importance of natural gas, at least in

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the United States, is the abundance of shale gas. This type of unconventional gas, made available in part by horizontal drilling and hydraulic fracturing (“fracking”) is projected to play a big role in the U.S. energy future (Holz et al. 2015; Richter 2015). Indeed, according to the U.S. Energy Information Administration (EIA) shale gas provided the largest share of US natural gas production in 2013 (EIA 2014). EIA also predicts that by 2040 shale gas will make up over 55 % of the total U.S. natural gas production (EIA 2015). There are environmental concerns with hydraulic fracturing, including possible contamination of the water table and induced earthquakes. At present, these issues are being discussed in the public and private sectors in order to come up with a reasonable solution.

In this paper, we explore scenarios modeling the U.S. shale gas market from two perspectives on market power. The first is a perspective of a Stackelberg leader–follower game (Luo et al. 1996) expressed more generally as a mathematical program with equilibrium constraints (MPEC). The second is the perspective of Cournot market power, wherein market power is exercised over consumers by setting a price relative to oligopolistic behavior (Hobbs and Rijkers 2004; Gabriel et al. 2013). The first perspective gives the producer market power, while the second method allows the trader (one of many intermediary players between the producer and consumer) the ability to behave strategically.

For the MPEC model, there is one leader in the U.S. shale gas market considered as a dominant player in the Stackelberg leader–follower game. The decisions of this player typically involve strategic decisions, which are then fixed for the lower-level players that constitute the rest of the natural gas market. MPECs have been widely used to simulate this multi-level player situation in the marketplace (Marcotte and Savard 2001), where the Stackelberg leader can anticipate the reaction of the followers.

The intent of this paper is to see counterfactually how important the role of a leader in the U.S. shale gas market could be. The leader is assumed to be a dominant producer in the South Louisiana region as described in more detail below. We have also assumed that the rest of the market can be described as a non-cooperative game. This paper uses the World Gas Model (Gabriel et al. 2012) restricted to North American nodes with the analysis focused on the United States.

Mathematically speaking, an MPEC can be written in general form as the following:

$$\begin{aligned} &\min_{x,y} f(x,y) \\ &s.t. \\ &(x,y) \in \Omega \\ &y \in SOL(x) \end{aligned} \tag{1}$$

where x is the vector of decision variables at the upper level (leader), y is the vector of decision variables at the lower level (followers), Ω is the joint feasible region for x and y, $SOL(x)$ is the solution set of the lower-level problem when x is fixed.

This last constraint which involves the solution set $SOL(x)$ is the source of computational difficulty for MPECs. The principal reason is that this set is generally not known in closed form when the lower-level problems are optimization or game theory models. Consequently, some sort of characterization of this solution set, via for example the Karush–Kuhn–Tucker (KKT) optimality conditions of the lower-level players' problems, is needed as well as some more readily computable transformation of these conditions (e.g., via SOS1 constraints as in Siddiqui and Gabriel (2013) and Siddiqui and Christensen (2016)).

In the MPEC to be described in the next section, the shale gas producer for census region 7 (South Louisiana) is modeled as the Stackelberg leader with the rest of the U.S. nodes for conventional, unconventional (shale or other) constituting the followers. This MPEC is built from the World Gas Model (WGM) (Gabriel et al. 2012) which is a single-level, Nash-Cournot model of global gas markets. For this paper, the WGM has been reduced in size to include North America.

The second perspective on market power is assigning the shale producer for census region 7 a dedicated "trader" charged with exporting the gas to the demand sector. This trader maximizes profits like the producer, except that it has the ability to set the price. This price setting behavior has two extremes: perfectly competitive behavior and perfect Nash-Cournot oligopolistic behavior. The following formulation studies cases where this trader varies between these two extremes. Note that perfect Nash-Cournot oligopolistic behavior in a setup like this does not necessarily imply the highest market power (Ulph and Folie 1980). We need to be very careful in selecting how the trader operates between these extremes, as this can lead to counter-intuitive results where perfectly competitive behavior can be more profitable than any price-setting behavior (Huppmann 2013). Nevertheless, this technique has widespread use in the literature, as it has proven to be a useful calibration tool and a convenient way to model strategic behavior (Huppmann and Egging 2014).

The rest of this paper is organized as follows. In Sect. 2 we present the various optimization problems faced by the market participants. The resulting Karush–Kuhn–Tucker (KKT) optimality conditions for these problems combined with market-clearing conditions form the lower-level mixed complementarity problem can also be found in the Appendix of Gabriel et al. (2012).[1] Section 3 provides numerical analysis under consideration of several tax regimes and the ensuing market results. Lastly, in Sect. 4 we conclude the paper and summarize the findings.

2 World gas model

The World Gas Model is a large-scale complementarity problem (Gabriel et al., 2012) which has been used in a number of studies for the U.S. and European governments. It models many aspects of the natural gas supply chain starting with producers. The next players are the traders, which are the export arm of the producers. The traders send gas to other traders in different locations (e.g., countries or local nodes) as well as nominating injections and extractions into/out of storage to the storage operators. Next are the transmission operators who handle

[1] See Gabriel et al. (2013) for details on complementarity and other equilibrium problems in energy.

transportation of gas by pipeline or liquefied natural gas (LNG) boats. Lastly, the consumers are modeled by demand functions.

2.1 Producers

Producers in the WGM are modeled as maximizing their profits discounted over the time horizon considered. The producers are responsible for getting the gas out of the ground and the sales, storage, and transport are taken care of respectively, by the traders, storage operators, and transmission system operators. [To avoid unnecessary notation, a simplified version of the optimization problem for producers (and other players) is given in this paper. The full version of the model can be found in the Appendix of Gabriel et al. (2012)].

The key decision variable of for each producer is how much gas to produce and then sell in a given node n (e.g., country or sub-country), season s and year y. Without loss of generality, but a gain in ease of presentation, we assume that there is just one producer per node. The overall optimization problem for a typical producer is thus the following:

$$\begin{aligned}
&\max \sum_{y} \gamma_y \left\{ \pi_{nsy} days_s SALES_{nsy} - days_s c_n\left(SALES_{nsy}\right)\right\} \\
&s.t. \\
&days_s SALES_{nsy} \le days_s PR_n, \ \left(\alpha_{nsy}\right) \forall sy \\
&\sum_{y} days_s SALES_{nsy} \le RES_n \ (\beta_n) \\
&SALES_{nsy} \ge 0
\end{aligned} \tag{2}$$

where[2] $SALES_{nsy}$ is the decision variable representing cubic feet/day of sales (production) at node n, in season s, year y, $days_s$ is the number of days in season s (two seasons considered), $c_n(\bullet)$ is the production cost function in dollars/day (taken to be convex and increasing), π_{nsy} is the wellhead price of gas in dollars/cubic feet (determined outside of the producer optimization problem), γ_y is a discount factor, PR_n is the maximum production rate (cubic feet/day).

RES_n is the maximum amount of the resource that can be extracted over the time horizon (cubic feet).

Note that the dual variables for each constraint are listed in parentheses to the right of the associated constraint. Clearly more complicated engineering details of the gas production process could be modeled, but for tractability and usefulness the above is sufficient. The KKT conditions for the producer optimization problem are necessary since the constraints are linear. These conditions are sufficient for optimality as long as the production cost function is convex which will make the objective function concave. These KKT conditions are thus the following.

Find primal variables $SALES_{nsy}$ and dual variables α_{nsy}, β_n such that:

[2] Note that the production rate constraint includes the number of days in season s so that the associated multiplier has the same units as the other one and the objective function.

$$
\begin{aligned}
&0 \leq days_s \gamma_y \left\{ \frac{d\, c_n\left(SALES_{nsy}\right)}{d\, SALES_{nsy}} - \pi_{nsy} + \alpha_{nsy} + \beta_n \right\} \perp SALES_{nsy} \geq 0\, \forall sy \\
&0 \leq days_s \left\{ PR - SALES_{nsy} \right\} \perp \alpha_{nsy} \geq 0 \forall sy \\
&0 \leq RES_n - \sum_y days_s SALES_{nsy} \perp \beta_n \geq 0
\end{aligned}
\tag{3}
$$

where the notation $0 \leq x \perp y \geq 0$ means that both vectors x and y are nonnegative and their inner product is zero (i.e., complementarity between these two vectors).

If the sales variable is positive and the production is below the daily limit as well as the resource limit, then by complementarity, the wellhead price equals the marginal cost. When either of these constraints is binding, then the associated multiplier gets added to the wellhead price showing the cost of increasing capacity.

2.2 Market-clearing conditions for production

To calculate the wellhead price π_{nsy} market-clearing conditions of the following form are used:

$$
0 = days_s SALES_{nsy} - \sum_{t \in T(n)} days_s PURCH^T_{tnsy}\left(\pi_{nsy}\right) \tag{4}
$$

where $PURCH^T_{tnsy}$ is the amount of gas in cubic feet/day purchased by trader t, $T(n)$ is the set of traders from all the producers located at node n and π_{nsy} the dual price of these market-clearing conditions.

Note that the superscript "T" for the purchasing variables is used to differentiate purchases by the traders from purchases by the other players (e.g., storage operators).

2.3 Trader's optimization problem

The traders are modeled as agents that procure gas from producers and sell to markets who in turn sell the gas to consumers. These traders are modeled as profit-maximizers, with conservation of gas constraints by node and time period, including injections and extractions from storage.

The trader's selling price is a weighted combination of the wellhead price (perfect competition) and an inverse demand price allowing for strategic behavior. This weighted combination of prices, as opposed to a more standard Nash-Cournot approach using just the inverse demand function, allows for the modeling of mitigation of actual market power (e.g., in the presence of gas contracts) as well as helping as a calibration tool. This weight given as δ^C_{tn} is a value in [0,1] with 0 meaning a perfectly competitive price and 1 a Cournot price. In previous studies (e.g., Gabriel et al., 2012)), values in [0,1] have been used for some traders in some regions (e.g., Russia). However, for this study restricted to North America, only the trader dedicated to the producer at census region has been given a value of 1, with all other traders behaving consistently with perfect competition. We have numerically verified this value as giving the trader the highest profit, but this may not always be the case. Lastly, the traders maintain contractual obligations for gas between nodes using these amounts as lower bounds on the flow.

2.4 Other players' optimization problems

The optimization problems for the other players (with the exception of the consumers) are similar in structure to that of the producers. The players maximize net profit subject to engineering-related constraints and conservation of gas. For example, the storage operators make money by selling injection and extraction capacity to the traders and they incur costs in determining how much storage capacity to add subject to injection, extraction, and working gas volumetric constraints.

The transmission system operator problem involves an economic mechanism to efficiently allocate transport capacity to the various traders where a general "arc" is used for either pipelines or LNG. These players make revenue from selling this capacity at a congestion fee and incur possible expansion costs. Lastly, there are market-clearing conditions in the storage injection, extraction and arc capacity markets that yield dual prices embedded in various players' problems. Taking the KKT conditions for each of the players in combination with the market-clearing conditions gives rise to a large-scale complementarity problem whose solution is a market equilibrium.

3 Scenarios and results

The WGM restricted to the North American nodes has 30 producers, of which seven are for shale gas and seven for unconventional (non-shale) gas production in the United States. The rest produce conventional gas. There are a total of 15 production nodes, of which nine correspond to the census region for the lower-48 states. There are also three traders (one each for United States, Canada, and Mexico, the three countries in the model), along with eight periods from 2005 to 2040 (the last two five-year periods are not reported to avoid end-of-horizon bias), and two seasons (high and low demand) in each period. The decision variables are operating levels (production, storage injection, etc.) as well as investment levels (pipeline, liquefaction capacity, etc.). Prices are set to 2005 US$.

The MPEC scenario of the WGM restricted to North America was formulated with the shale gas producer in census region 7 as the top-level player. Census region 7 contains both the Barnett and Haynesville shale plays, two of the most important ones in the United States.

The Cournot market power scenario of the WGM restricted to North America was formulated with an additional trader (taking the total number of traders up to 4) who exercised market power in selling gas downstream from the shale gas producer at node 7. Thus, in the Cournot market power version, the shale gas producer at node 7 sells only to this dedicated trader and not to the United States trader. Note that in this scenario, it is the trader as opposed to the producer that behaves strategically.

The following five scenarios were considered, with the first (Base Scenario) modeled as a complementarity problem and the rest as one of the two scenarios of market power for purposes of comparison:

Base The Base Scenario for the WGM restricted to North America formulated as a complementarity problem and calibrated according to the Annual Energy Outlook (April 2009 ARRA version) and the World Energy Outlook (IEA, 2008).

MPEC The MPEC version of the Base Scenario. The shale producer in census region 7 was placed at the upper level and all other players at the lower level.

MPECTax All shale-producing firms are taxed \$0.39/MCF (39 cents for every thousand cubic feet of natural gas produced) from 2015 to 2040. This is in line with the tax proposed for Pennsylvania shale production in the Marcellus shale play, which was later overturned (Barnes 2010). No other value for a shale tax has so far been found. This scenario is modeled based on the MPEC Scenario.

Cournot Like the Base Scenario, but with a fourth trader added who exercises market power and buys exclusively from the shale gas producer at node 7.

CournotTax All shale-producing firms are taxed \$0.39/MCF (39 cents for every thousand cubic feet of natural gas produced) from 2015 to 2040. This scenario is modeled based on the Cournot Scenario.

The following table compares all scenarios, and provides further clarity on their formulation (Table 1):

The following figures display the results. Note that it is important to keep in mind that under both market power scenarios, node 7 is the shale production region which is the focus. Also note that the MPEC and MPECTax scenarios are referred to jointly as the "MPEC scenarios" and "MPEC market power scenarios" below and the Cournot and CournotTax cases are referred to jointly as the "Cournot scenarios" and "Cournot market power scenarios".

In the case of natural gas production, as shown by Fig. 1, the type of market power studied matters for node 7. Production at this node goes up when MPEC market power is modeled when compared to the Base scenario, but down when Cournot market power is modeled (for the trader) compared to the Base scenario. Production across other regions remains relatively stable, except node 8 where there is a slight change from the Base scenario. The increase in natural gas production in the MPEC scenarios is consistent with microeconomic theory, in that the Stackelberg leader will attempt to increase profits by increasing production

Table 1 Scenarios of market power and taxation

Scenario	MPEC market power?	Cournot market power?	Tax on shale production?
Base	No	No	No
MPEC	Yes	No	No
MPECTax	Yes	No	Yes
Cournot	No	Yes	No
CournotTax	No	Yes	Yes

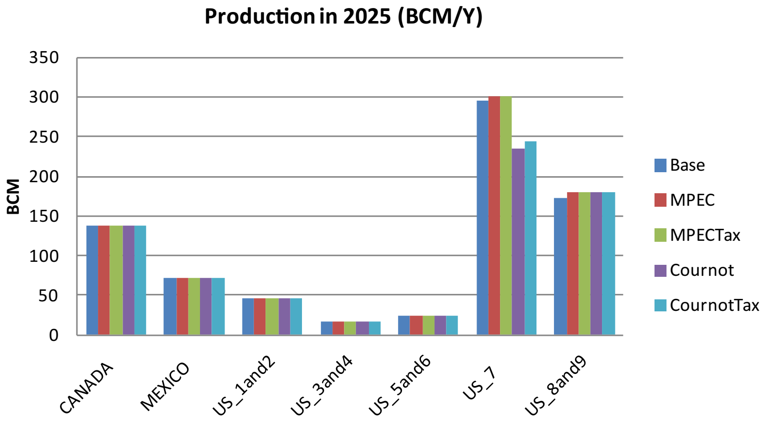

Fig. 1 Natural gas production in 2025 (note that US_1 and 2 signifies US census region 1 and 2)

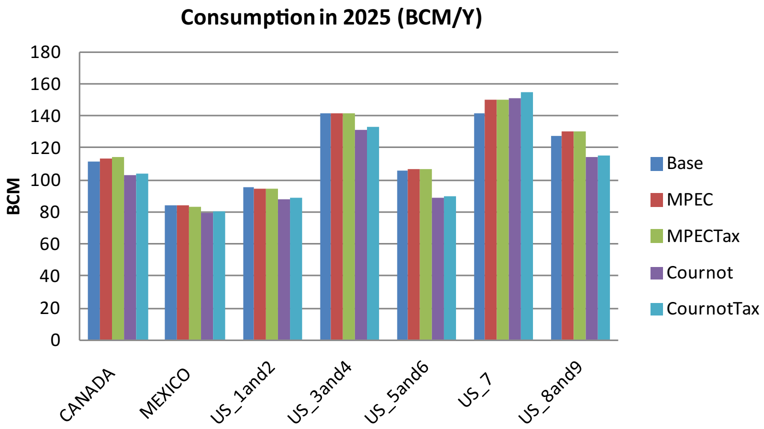

Fig. 2 Consumption of natural gas in 2025

(Gibbons 1996). Production in the MPEC scenarios is unchanged by a tax, signifying that by moving first the producers are passing the tax along downstream.

Alternatively, in the Cournot market power scenarios, production at node 7 goes down because the trader buying from this node exercises market power. The producer at node 7 sells directly to this trader, and the trader buys (and sells) this gas for a higher price than the competitive equilibrium price. Under a tax, the producer has to actually increase production to maximize profits, and is not able to pass the tax along as in the MPEC scenarios.

Figure 2 shows that consumption increases in all scenarios in node 7 when compared to the Base scenario. Having a producer as a Stackelberg leader in the MPEC scenarios, or a trader exercising Cournot market power as in the Cournot scenarios helps node 7 have a supply of cheap natural gas compared to the Base

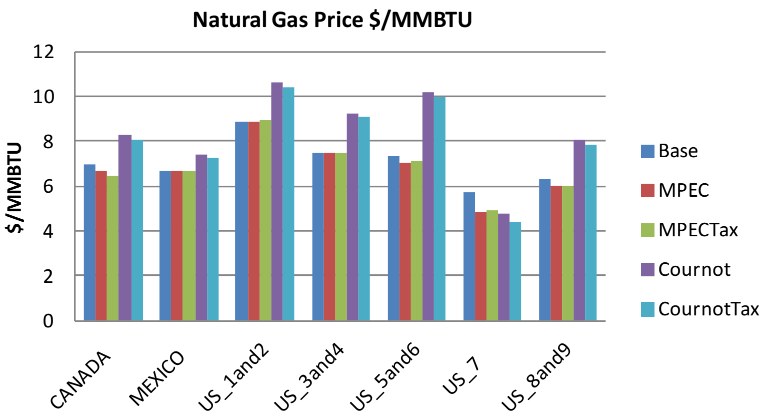

Fig. 3 Natural gas prices in 2025

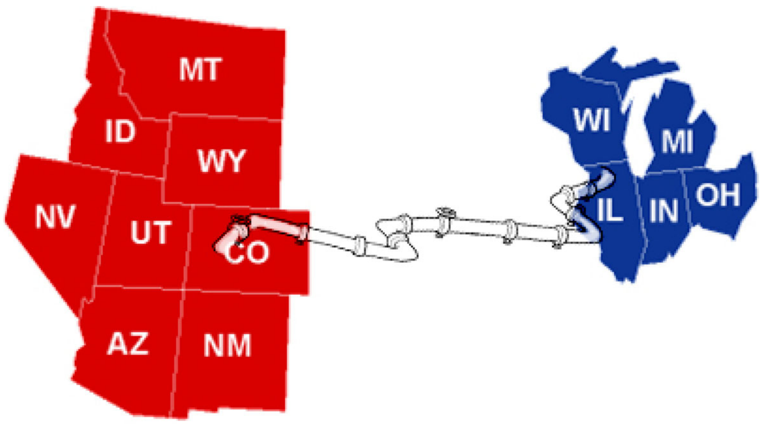

Fig. 4 The new pipeline capacity constructed in the MPEC market power scenarios

scenario, which is also shown in Fig. 3 for the prices. Consumption doesn't change much in other regions under the MPEC scenarios and neither do prices when compared to the Base scenario. However, consumption drops in other regions in the Cournot scenarios, and prices go up signifying that the trader at node 7 is exerting market power when selling gas to regions other than node 7. Under a tax, the MPEC scenarios show a slight increase in price, showing that the producer passes the tax downstream. However, prices actually drop in the Cournot scenarios under a tax. The explanation for this lies in the fact that an imposition of tax on the producer, along with a market power exerting trader, results in the optimal decision to produce more natural gas, and lose profits. However, the production of this extra gas lowers prices and increases production.

The US natural gas model also helps study the development of infrastructure. One such interesting occurrence is the expansion of pipeline capacity between node 4 and node 8 under the MPEC scenarios. When a producer at node 7 exercises

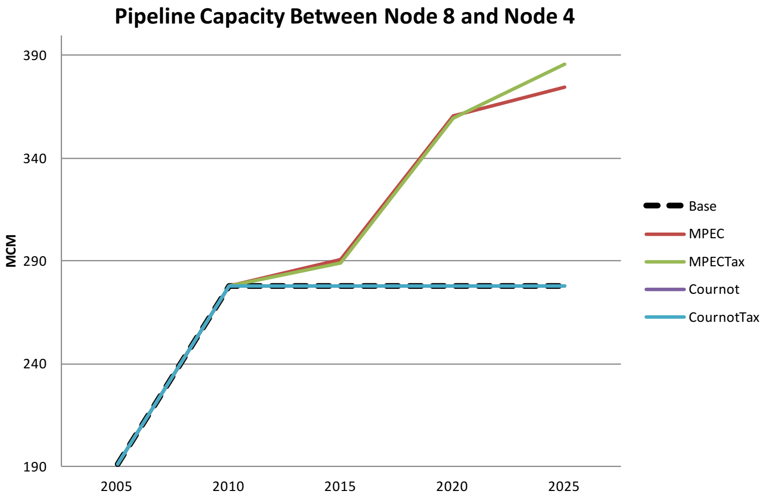

Fig. 5 Pipeline capacity in the scenarios (note that Base, Cournot, and CournotTax overlap)

market power, the other market players need to come up with alternatives to the Stackelberg leader's dominating strategy. Therefore, in the presence of expensive gas, the construction of a pipeline becomes profitable for the pipeline operator. Node 4, which had to buy gas from node 7, now has an alternative in node 8. Note that under a tax, the pipeline expands slightly more than it did without the tax in the MPEC scenarios (Figs. 4, 5). This signifies the fact that under a tax, the Stackelberg leader tries to pass more cost downstream, thus necessitating alternative sources of natural gas.

4 Conclusions

This paper has looked at two different ways to model market power: one by allowing the producer to move first as in a Stackelberg game and the other in allowing a trader to exert market power downstream to the consumer. The advent of shale gas has changed the market structure of natural gas in the US, and these modeling platforms helped us get insight into the changes that can be expected.

The MPEC scenarios worked best for the producer. The shale producer at node 7 had the highest increase in profits, when compared to the Base scenario, which was expected as this player was the Stackelberg leader. The US trader, who was sold gas from the Stackelberg leader under the MPEC scenarios, was most affected by the Stackelberg leader strategy.

The scenarios with Cournot market power were different, with the advantage lying with the traders and consumers of node 7. While in the MPEC scenarios the producer extracted extra profits from the one US trader, the Cournot scenarios saw the trader on node 7 extract profits from both the producer as well as consumers in other regions. Another big difference was the pipeline built between node 4 and node 8, which did not show up in either of the Cournot market power scenarios.

The advantage of modeling market power using MPECs is clearly shown in this example. The player who acts strategically receives the rents, and we can clearly define the strategic behavior as first-mover advantage. Cournot market power is not straightforward, and there is no real way to define how to choose the Cournot parameter δ. Many situations exist in the literature where the best choice of this parameter is in hindsight after doing the analysis rather than before. Moreover, there is little flexibility on who can exercise this form of market power, as we had to add an extra trader for this analysis.

While the jury is still out on how exactly shale gas will affect the US natural gas market, the two types of market power presented here give us an indication of how producers and traders might act. Moreover, the scenarios also show that response to taxation will be mostly passed along to the consumers under the MPEC scenarios. The producers and regions without a trader with market power will bear the brunt of the tax under the Cournot scenarios. In the MPEC scenarios, producers will try their best to extract rent using the presence of abundant shale resources to their advantage. Conversely in the Cournot scenarios, the trader with market power will take advantage of the producer as well as consumers.

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