The World Oil Market and OPEC: A Structural Econometric Model*

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Abstract

We develop and estimate a structural econometric model of the dynamic game among petroleum-producing firms making production and investment decisions in the world oil market. Our parsimonious model of the notoriously complex world oil market fares fairly well in assessments of model validity and model fit, particularly for oil producers; and also generates results that align with economic theory and previous assessments of the industry. To further gauge the validity of our parsimonious model and its plausibility for use in approximating the effects of counterfactual scenarios on the short-run evolution of industry, and also to enhance our understanding of OPEC behavior, we use the structural econometric model to analyze the effects of a hypothetical change in OPEC membership on the petroleum industry. Although we do not assume or impose that OPEC producers collude to maximize joint profits, but instead infer the strategy and payoffs for OPEC firms from the data, results show that OPEC behaves in such a way that is consistent with its mission and also with cartel behavior. We find evidence of cost synergies between oil and natural gas production. Our results also suggest that the high fossil fuel subsidies observed in many oil-rich countries may result from state-owned firms maximizing profits and then redistributing some of the profits that they have maximized, rather than from state-owned firms maximizing a weighted sum of profits and consumer surplus in a mixed oligopolistic setting.

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1 Introduction

Fossil fuels supply more than 80 percent of the energy consumed in the world (U.S. Energy Information Administration, 2013). Oil and natural gas provide a large share of energy consumption, and getting access to secure sources of oil and natural gas is of huge importance for any economy (Finley, 2012). The production and consumption of oil and natural gas raise concerns about air pollution, fossil fuel price volatility, energy security, climate change, and fossil fuel scarcity.

The world oil market is not only highly important, but also notoriously complex – many observers regard the world oil market as a puzzle (Smith, 2009); detailed data, particularly from state-owned firms, is difficult to obtain; and OPEC strategy and whether OPEC behaves as a cartel remains a mystery (Baumeister and Kilian, 2016, 2017; Lin Lawell, 2020; Parnes, 2019). The objective of our paper is to develop and estimate a parsimonious model of the notoriously complex world oil market that generates results that align with economic theory and previous assessments – anecdotal, qualitative, empirical, or otherwise – of the industry, and that enables us to assess the effects of counterfactual scenarios on the short-run evolution of industry.

To do so, we develop and estimate a structural econometric model of the dynamic game among petroleum-producing firms in the world petroleum market. Our model incorporates the dynamic behavior and strategic interactions that arise as petroleum-producing firms make their production and investment decisions. We apply our model to annual firm-level panel data on oil and gas exploration, development, production, mergers, acquisitions, and reserves along with data on oil and gas prices to study the behavior of the top 50 oil and natural gas producing companies in the world. To gauge the validity of our parsimonious model and its plausibility for use in approximating the effects of counterfactual scenarios on the short-run evolution of industry, and also to enhance our understanding of OPEC behavior, we use the structural econometric model to analyze the effects of a hypothetical change in OPEC membership on the petroleum industry.

A dynamic model is important for modeling the decisions of petroleum-producing firms for several reasons. First, the production decisions of oil and gas producers are dynamic because petroleum is a nonrenewable resource; as a consequence, current extraction and production affect the availability of reserves for future extraction and production (Hotelling, 1931). Second, the investment decisions of petroleum producers are dynamic because they are at least partially irreversible, because their payoffs are uncertain, and because petroleum producers have leeway over the timing of these investment decisions. Since the profits from investment and production decisions depend on market conditions such as the oil price that vary stochastically over time, an individual firm operating in isolation that hopes to make dynamically optimal decisions would need to account for the option value to waiting before making these irreversible investments (Dixit and Pindyck, 1994).

We model the petroleum industry as a dynamic game because petroleum producers consider not only future market conditions but also their competitors' investment and production activities when making their current decisions. Since the production decisions of other firms affect the prices of oil and natural gas, and therefore affect a firm's current payoff from production; and since the investment and production decisions of other firms affect future values of state variables which affect a firm's future payoff from producing and investing, petroleum-producing firms must anticipate the production and investment strategies of other firms in order to make a dynamically optimal decision. As a consequence, there are strategic interactions between petroleum-producing firms. In addition, the uncertainty over the production and investment strategies of other firms is another reason there is an option value to waiting before investing (Dixit and Pindyck, 1994).

Our parsimonious model of the notoriously complex world oil market fares fairly well in assessments of model validity and model fit, particularly for oil producers; and also generates results that align with economic theory and previous assessments of the industry. We find evidence of cost synergies between oil and natural gas production, which may include joint production and other supply-side links in oil and gas (Roberts and Gilbert, 2020). Our results also suggest that the high fossil fuel subsidies observed in many oil-rich countries (Ross et al., 2017; Kheiravar and Lin Lawell, 2020) may result from state-owned firms maximizing profits and then redistributing some of the profits that they have maximized, rather than from state-owned firms maximizing a weighted sum of profits and consumer surplus in a mixed oligopolistic setting.

As OPEC strategy and whether OPEC behaves as a cartel remains a mystery (Baumeister and Kilian, 2016, 2017; Lin Lawell, 2020; Parnes, 2019), we do not assume or impose that OPEC producers collude to maximize joint profits, but instead infer the strategy and payoffs for OPEC firms from the data. Nevertheless, we find that the oil production strategy for OPEC firms depends less on oil reserves and more on cumulative (or historical) oil output than does the oil production strategy for non-OPEC firms, which is possibly consistent with a strategy that supports collusion over time. In addition, results from our counterfactual OPEC membership scenario show that including all firms in OPEC causes firms to decrease oil production, leading to increases in the average firm payoff, increases in oil prices, and decreases in consumer surplus. Thus, although we do not assume or impose that OPEC producers collude to maximize joint profits, we find that OPEC behaves in such a way that is consistent with its mission and also with cartel behavior.

The balance of our paper proceeds as follows. Section 2 reviews the previous literature. Section 3 presents our structural econometric model. We describe our data in Section 4. We present our results in Section 5. We validate our model and assess model fit in Section 6. Section 7 presents our counterfactual simulations. Section 8 concludes.

2 Literature Review

2.1 Models of the world petroleum market

We build on the empirical literature on the world petroleum market, much of which is from over three decades ago (Adelman, 1962; Kennedy, 1974; Nordhaus, 1980; Gately, 1984; Griffin, 1985; Lin, 2011; Kilian and Murphy, 2014; Espinasa et al., 2017; Zhou, 2020). Cremer and Salehi-Isfahani (1991) provide a survey of models of the oil market. Many previous empirical studies of world petroleum market use a static model; one exception is Lin Lawell (2020). Unlike previous empirical studies of the petroleum market that use a static model, we estimate a dynamic model of the world petroleum market.

We also build on the literature analyzing strategic behavior in the world petroleum market, and particularly the behavior of OPEC (Cremer and Weitzman, 1976; Griffin, 1985; Matutes, 1988; Golombek et al., 2014; Gulen, 1996; Farzin, 1985; Alhajji and Huettner, 2000a,b; Kaufmann et al., 2004; Almoguera et al., 2011; Fang et al., 2014; Hochman and Zilberman, 2015; Okullo and Reynès, 2016; Baumeister and Kilian, 2017; Genc, 2017; Ghoddusi et al., 2017; Asker et al., 2019; Branger et al., 2019; Lin Lawell, 2020). For detailed background information on the world energy industry, see the classic text by Dahl (2015). For a detailed review of the literature on oil market modeling and OPEC's behavior, see Al-Qahtani et al. (2008).

Our dynamic model of oil production builds on the theoretical model of optimal nonrenewable resource extraction that was first examined by Hotelling (1931), and then expanded upon by many others (see e.g., Solow and Wan (1976); Hanson (1980); Pesaran (1990); Pindyck (1978, 1980); Farzin (1992, 1995); Young and Ryan (1996); Lin and Wagner (2007); Livernois (2009); Lin (2009b); Slade and Thille (2009); Lin et al. (2009); Gao et al. (2009); Leighty and Lin (2012); Almansour and Insley (2016); Zhang and Lin Lawell (2017); Brown et al. (2017); Ghandi and Lin Lawell (2020); Anderson et al. (2018); van Veldhuizen and

Sonnemans (2018)).

2.2 Models of mixed oligopoly and state-owned firms

The second strand of literature upon which we build is that on mixed oligopoly and state-owned firms. A mixed oligopoly is defined as an oligopolistic market structure in which the objective of at least one firm differs from that of other firms (de Fraja and Delbono, 1990), as opposed to a private oligopoly in which all firms have the objective of profit maximization. Usually in a mixed oligopoly there is a public firm competing with a multitude of profit-maximizing firms (Poyago-Theotoky, 2001). A market in which there are both private and public firms is then a mixed oligopoly because the firms owned by private agents aim to maximize profits, whereas the publicly owned firms are interested in optimizing social targets (de Fraja and Delbono, 1990). There is a burgeoning theoretical literature analyzing mixed oligopoly (de Fraja and Delbono, 1989; Fjell and Pal, 1996; White, 1996; Poyago-Theotoky, 2001; de Fraja and Valbonesi, 2009; Lutz and Pezzino, 2014; Bennett and La Manna, 2012; Haraguchi and Matsumura, 2016). We build on this theoretical literature by empirically modeling the world petroleum market as a mixed oligopoly consisting of private firms and firms that are at least partially state-owned, and by allowing firms that are at least partially state-owned to have objectives other than profit maximization alone.

In comparing private and state-owned oil firms, Ohene-Asare et al. (2017) find that private oil companies outperform state-owned oil companies and that state-owned firms suffer from scale inefficiencies. Cabrales et al. (2017) assess the impact of domestic fuel subsidies and employment on the performance of national oil companies by developing a model that clarifies the trade-offs among non-commercial objectives and the market value, production, and reinvestment of national oil companies.

A related literature is that on the objectives of state-owned firms. Chen and Lin Lawell (2020) develop and estimate a random coefficients mixed oligopolistic differentiated products model to analyze supply, demand, and the effects of government policy in the Chinese automobile market, a market that includes both private and state-owned firms. Their structural econometric model of a mixed oligopolistic differentiated products market allows different consumers to vary in how much they like different car characteristics on the demand side, and state-owned automobile companies to have different objectives than private automobile companies on the supply side.

Ghandi and Lin (2012) model the dynamically optimal oil production on Iran's offshore Soroosh and Nowrooz fields, which have been developed by Shell Exploration through a buy-back service contract. In particular, they examine the National Iranian Oil Company's (NIOC) actual and contractual oil production behavior and compare it to the production profile that would have been optimal under the conditions of the contract. They find that the contract's production profile is different from optimal production profile for most discount rates, and that the NIOC's actual production rates have not maximized profits.

2.3 Dynamic structural econometric models

Structural econometric models of dynamic behavior have been applied to bus engine replacement (Rust, 1987), nuclear power plant shutdown decisions (Rothwell and Rust, 1997), water management (Timmins, 2002), air conditioner purchase behavior (Rapson, 2014), wind turbine shutdowns and upgrades (Cook and Lin Lawell, 2020), copper mining decisions (Aguirregabiria and Luengo, 2016), long-term and short-term decision-making for disease control (Carroll et al., 2020a), the adoption of rooftop solar photovoltaics (Feger et al., 2017; Langer and Lemoine, 2018), supply chain externalities (Carroll et al., 2020b), vehicle scrappage programs (Li and Wei, 2013), vehicle ownership and usage (Gillingham et al., 2016), agricultural productivity (Carroll et al., 2019), organ transplant decisions (Agarwal et al., 2019), and the spraying of pesticides (Sambucci et al., 2020).

Structural econometric models of dynamic games include the model developed by Pakes et al. (2007), which has been applied to the multi-stage investment timing game in offshore petroleum production (Lin, 2013), to ethanol investment decisions (Thome and Lin Lawell, 2020), and to the decision to wear and use glasses (Ma et al., 2020); a model developed by Aguirregabiria and Mira (2007), which has been applied to entry, exit, and growth in oligopoly retail markets Aguirregabiria et al. (2007); a model developed by Bajari et al. (2015), which has been applied to ethanol investment (Yi and Lin Lawell, 2020a,b); and models developed by Pesendorfer and Schmidt-Dengler (2008) and Srisuma and Linton (2012). Structural econometric models of dynamic games have also been applied to fisheries (Huang and Smith, 2014), dynamic natural monopoly regulation (Lim and Yurukoglu, 2018), Chinese shipbuilding (Kalouptsidi, 2018), the market for smartphones and tablets (Kehoe et al., 2018), industrial policy (Barwick et al., 2019), horizontal mergers (Benkard et al., 2019), and coal procurement (Jha, 2019).

Lin (2013) develops and estimates a structural model of the multi-stage investment timing game in offshore petroleum production. When individual petroleum-producing firms make their exploration and development investment timing decisions, positive information externalities and negative extraction externalities may lead them to interact strategically with their neighbors. If they do occur, strategic interactions in petroleum production would lead to a loss in both firm profit and government royalty revenue. The possibility of strategic interactions thus poses a concern to policy-makers and affects the optimal government policy. Lin (2013) examines whether these inefficient strategic interactions take place on U.S. federal lands in the Gulf of Mexico. In particular, she analyzes whether a firm's production decisions and profits depend on the decisions of firms owning neighboring tracts of land. The empirical approach is to estimate a structural econometric model of the firms' multi-stage investment timing game. Lin (2009a) uses a reduced-form model to examine whether strategic interactions take place during petroleum exploration.

In this paper, we apply the structural econometric model of a dynamic game that was developed by Bajari et al. (2007). This model has been applied to the cement industry (Ryan, 2012; Fowlie et al., 2016), to the production decisions of ethanol producers (Yi et al., 2020), to migration decisions (Rojas Valdés et al., 2018, 2020), to the global market for solar panels (Gerarden, 2019), to the digitization of consumer goods (Leyden, 2019), to calorie consumption (Uetake and Yang, 2018), and to climate change policy (Zakerinia and Lin Lawell, 2020).

3 Structural Econometric Model

To model the world oil market, we model the dynamic game among the top 50 petroleum producers in the world and their decisions regarding oil production and investment in exploration and development. Exploration and development are important components of the petroleum production process. Exploration entails making capital expenditures to invest in drilling rigs needed for exploratory drilling. Development entails making capital expenditures to invest in production platforms needed to develop and extract the reserve (Dixit and Pindyck, 1994; Lin, 2013).

As our primary concern is to model the world oil market, we focus primarily on modeling the decisions of petroleum-producing firms regarding oil production and investment in exploration and development. Nevertheless, we include natural gas production in our model because of joint production and other supply-side links in oil and natural gas (Roberts and Gilbert, 2020). Similarly, as petroleum-producing firms also engage in mergers and acquisitions, we also include mergers and acquisitions in our model. Thus, our intent in including a parsimonious and stylized model of natural gas and of mergers and acquisitions is to enable us to better model the world oil market, rather than to fully model and capture all the complexities of the natural gas market and of mergers and acquisitions.

Each period, each petroleum producer decides how much oil and natural gas to produce; how much to spend on investments (capital expenditure) in exploration, development, and acquisition; whether to acquire another firm or be acquired by another firm; and whether to merge with another firm. The actions a_i of each firm i are assumed to be functions of a set of state variables and private information:

$$a_i = \sigma_i(s, \varepsilon_i), \tag{1}$$

where s is a vector of publicly observable state variables and ε_i is a vector of private information shocks to firm i which are not observed by either other firms or the econometrician. These private information shocks include idiosyncratic firm-specific shocks to merger and acquisition costs.

We include the following firm-specific state variables: oil and natural gas reserves; cumulative oil and natural gas output; cumulative investments (capital expenditure) in exploration, development, and acquisition; percentage of state ownership; whether the firm is a member of OPEC; whether the firm merged in the previous year; and whether the firm acquired another firm in the previous year. We include the following global state variables: average industry rate of return on capital for mining and quarry; average capital compensation on other machinery and equipment; world population; world GDP; world motor vehicles; world road sector gasoline fuel consumption; and world electricity production from oil and natural gas sources.

The production, investment, merger, and acquisition decisions of a petroleum-producing firm i affect firm i's own per-period payoff $\pi_i(s, a, \varepsilon_i; \theta)$; the per-period payoff of other firms; and the distribution of future state variables, including firm-specific state variables such as firm i's own oil and natural gas reserves, as well as global state variables that affect all firms.

In addition to firm-specific state variables, our model allows for several other sources of heterogeneity among firms, as explained in more detail below. To make a dynamic game among 50 players tractable, however, we abstract away from the particular identity of each firm, and model the strategic interactions as arising from the dependence of each firm's strategy on the aggregate actions of firms in the market, rather than on particular actions undertaken by any particular firm. Nevertheless, although we abstract away from the particular identity of each firm, we include firm-specific state variables and allow for other sources of heterogeneity among firms, as explained in more detail below.

The firm-specific state variables and the global state variables evolve endogenously as controlled first-order Markov processes with transition density $Pr(s'|s,a)$. The firm-specific state variables for whether the firm merged in the previous year, and for whether the firm acquired another firm in the previous year evolve deterministically as a function of the firm's merger and acquisition decisions in the previous year. The transition densities for each of the remaining state variables are stochastic.

For the transition densities $Pr(s'|s,a)$ for oil and natural gas reserves, we allow the distribution of reserves the next period to depend on the reserves, production, exploration, development, and merger and acquisitions this period. We do not assume any fixed finite amount for the reserves, but instead allow reserves to increase or decrease as a result of production, exploration, development, mergers, and acquisitions. This is consistent with the common practice in the natural resource economics literature of modeling potential reserves as infinite; potential reserves are probably infinite, although the amount that is economical to extract is finite, and technological progress and new discoveries will always make more reserves available and feasible for extraction (Farzin, 1992; Lin, 2009b).

We model the oil market as a world market. World oil demand $D_{oil}(p_{oil})$ is a function of world oil price p_{oil}. The world oil price p_{oil} is therefore given by the inverse of the world demand for oil evaluated at world oil quantity Q_{oil}:

$$p_{oil} = D_{oil}^{-1}(Q_{oil}). \tag{2}$$

While our primary concern is to model the world oil market, we include natural gas production and natural gas reserves in our model because of joint production and other supply-side links in oil and natural gas (Roberts and Gilbert, 2020). Thus, our intent in including a parsimonious and stylized model of natural gas is to enable us to better model the world oil market, rather than to fully model and capture all the complexities of the natural gas market. Unlike the oil market, the natural gas market is not necessarily a world market. Due to the lack of a global pipeline network, the market for natural gas is mostly defined by proximity to supply sources and the availability of a pipeline. In our parsimonious and stylized model of natural gas, we consider 6 separate regional markets r for natural gas: Africa; Asia and Oceania; Eurasia; Europe; the Middle East; and the Americas. The regional demand $D_{ng_r}(p_{ng_r})$ for natural gas in region r is a function of the natural gas price p_{ng_r} in region r. The natural gas price p_{ng_r} in region r is therefore given by the inverse of the regional demand for natural gas in region r evaluated at the regional natural gas quantity Q_{ng_r} in region r:

$$p_{ng_r} = D_{ng_r}^{-1}(Q_{ng_r}). \tag{3}$$

We assume the costs of oil and natural gas production for each firm i are given by the following production cost functions:

$$c_{i,oil}(q_{i,oil}, z_{i,oil}; \delta_{11}, \delta_{12}, \delta_{13}, \delta_{14}) = \delta_{11} q_{i,oil} + \delta_{12} q_{i,oil}^2 + \delta_{13} z_{i,oil} + \delta_{14} q_{i,oil} \cdot z_{i,oil} + \delta_{15} q_{i,oil} \cdot q_{i,ng} \tag{4}$$

$$c_{i,ng}(q_{i,ng}, z_{i,ng}; \delta_{21}, \delta_{22}, \delta_{23}, \delta_{24}) = \delta_{21} q_{i,ng} + \delta_{22} q_{i,ng}^2 + \delta_{23} z_{i,ng} + \delta_{24} q_{i,ng} \cdot z_{i,ng} + \delta_{25} q_{i,ng} \cdot q_{i,oil}, \tag{5}$$

where $q_{i,oil}$ and $q_{i,ng} = \sum_{r=1}^{6} q_{i,ng_r}$ are firm i's oil and natural gas production output, respectively; $z_{i,oil}$ and $z_{i,ng}$ are firm i's oil and natural gas reserves, respectively; and δ_{11}, δ_{12}, δ_{13}, δ_{14}, δ_{21}, δ_{22}, δ_{23}, δ_{24}, and $\delta_5 \equiv (\delta_{15} + \delta_{25})$ are among the parameters θ to be estimated.

We allow for nonlinearities with respect to both output and reserves in the oil and natural gas production costs in equations (4) and (5) so that oil and natural gas production may exhibit increasing or decreasing returns to scale, or both. We allow the costs and marginal costs of production to potentially depend on the stock of reserves remaining in the ground, a dependence natural resource economists refer to as 'stock effects', by including oil and natural gas reserves and their interactions with oil and natural gas output in the respective production cost functions. There are several possible reasons why marginal production costs may increase when there are fewer reserves remaining in the ground. First, oil (or natural gas) extraction costs may increase as less oil (or natural gas) reserve remains in the ground if the resource needs to be extracted from greater depths as it is being depleted. Second, costs may increase if well pressure declines as more of the reserve is depleted. Third, since different grades of oil (or natural gas) may differ in their extraction costs, and since production may move towards more expensive grades as the stock of cheaper grades diminishes, the marginal cost of extraction may increase as the stock of cheaper grades and therefore the total stock decreases (Lin, 2009b; Zhang and Lin Lawell, 2017).

Since we cannot separately identify the coefficient δ_{15} on the interaction between oil and natural gas output in the oil production cost from the coefficient δ_{25} on the interaction between oil and natural gas output in the natural gas production cost, we estimate one coefficient on the interaction between oil and natural gas output in the oil and natural gas production cost: $\delta_5 \equiv (\delta_{15} + \delta_{25})$, which represents any cost synergies from joint production and other supply-side links in oil and natural gas (Roberts and Gilbert, 2020).

The per-period production profit $\bar{\pi}_i(s, a; \theta)$ for firm i from the production of oil and natural gas is thus given by:

$$
\begin{aligned}
&\bar{\pi}_i\left(s, a; \theta\right) \\
&= \underbrace{\left(D_{oil}^{-1}(Q_{oil})\, q_{i,oil} - \delta_{11} q_{i,oil} - \delta_{12} q_{i,oil}^2 - \delta_{13} z_{i,oil} - \delta_{14} q_{i,oil} \cdot z_{i,oil} - \delta_{15} q_{i,oil} \cdot q_{i,ng}\right)}_{\text{Profit from production of oil}} \\
&+ \underbrace{\left(\sum_{r=1}^{6} D_{ng_r}^{-1}(Q_{ng_r})\, q_{i,ng_r} - \delta_{21} q_{i,ng} - \delta_{22} q_{i,ng}^2 - \delta_{23} z_{i,ng} - \delta_{24} q_{i,ng} \cdot z_{i,ng} - \delta_{25} q_{i,ng} \cdot q_{i,oil}\right)}_{\text{Profit from production of natural gas}}.
\end{aligned}
\tag{6}
$$

In addition to producing oil and natural gas, firms can invest in capital using three forms of capital expenditure (capex): exploration $x_{i,exp}$, development $x_{i,dvp}$, and acquisition $x_{i,acq}$ capital expenditure.[1] The investment decisions of a petroleum-producing firm i affect firm i's own per-period payoff $\pi_i(s, a, \varepsilon_i; \theta)$; firm i's own current and future production, investment, merger and acquisitions decisions; the current and future production, investment, merger and acquisitions decisions of other firms; and the distribution of firm i's own oil and natural gas reserves next period.

In addition to production and investment, petroleum-producing firms that are not members of OPEC and that are not 100% state-owned also make decisions about mergers and acquisitions.[2] While our primary concern is to model the world oil market, and while we focus primarily on modeling the decisions of petroleum-producing firms regarding oil production and investment in exploration and development, we include mergers and acquisitions in our model because petroleum-producing firms also engage in mergers and acquisitions. Thus, our intent in including a parsimonious and stylized model of mergers and acquisitions is to enable us to better model the world oil market, rather than to fully model and capture all the complexities of mergers and acquisitions in the petroleum industry.

In our parsimonious model of oil production and investment in the world oil market, we do not explicitly model the merger and acquisitions game nor do we model any matching between firms that wish to engage in mergers and acquisitions, for several reasons. First, our data set includes all acquisitions made by the top 50 firms, even if the firm being acquired by a top 50 firm is itself not among the top 50 firms. Thus, our model better accounts for the possibility that a top 50 firm in our model may acquire a firm that is not in the

[1] Acquisition capital expenditures include expenditures for acquiring machinery and any other type of asset.

[2] OPEC firms and firms that are 100% state-owned never merge or acquire other firms.

top 50 than would a model that requires acquiring firms to be matched with an acquired firm from among the 50 firms in the model. Second, to make a dynamic game among 50 players tractable, we abstract away from the particular identity of each firm, and model the strategic interactions as arising from the dependence of each firm's strategy on the aggregate actions of firms in the market, rather than on particular actions undertaken by any particular firm. As we abstract away from the particular identity of each firm, we do not model any matching that arises from merger and acquisition decisions of particular firms either. Third, as our primary concern is to model the world oil market, and as we focus primarily on modeling the decisions of petroleum-producing firms regarding oil production and investment in exploration and development, our intent in including a parsimonious and stylized model of mergers and acquisitions is to enable us to better model the world oil market, rather than to fully model and capture all the complexities of mergers and acquisitions in the petroleum industry.

Instead, our structural model of the dynamic game among petroleum producing firms incorporates the interdependence of petroleum-producing firms' value functions that arises from the possibility of mergers and acquisitions. When one firm merges with or acquires another firm, the value of the other firm with which it merges or acquires is given by the other firm's value function, which is the present discounted value of the entire stream of per-period payoffs of the other firm, and which accounts for the options that the other firm has to explore, develop, produce, merge, and acquire. Thus, a firm's value function depends on the expected value of other firms with which it has the option to merge or acquire. Our structural model of the dynamic game among petroleum producing firms incorporates this interdependence of petroleum-producing firms' value functions.

There are several possible reasons for mergers and acquisitions in the petroleum industry that are captured by our model. First, owing to nonlinearities with respect to both output and reserves in the production profit function in equation (6), oil and natural gas production may exhibit increasing or decreasing returns to scale, or both. As a consequence, firms may benefit from changing their scale via mergers and acquisitions. Second, there may be other synergies between firms as well, including cost synergies, knowledge synergies, organizational synergies, and management synergies. As we explain below, these additional synergies are captured in our policy functions and transition densities. Third, firms may benefit from any increase in market power as a result of a merger or acquisition. Market power motivations are captured in part by the inverse demand function and any resulting markup from market power. Fourth, some firms may be particularly well suited for mergers and acquisitions, as captured in our model by idiosyncratic private information shocks to the costs and benefits of mergers and acquisitions that firms receive.

In particular, firm i's payoffs $\Phi_i(s, a_i, \sigma_{-i}, \varepsilon_i; \theta)$ from mergers and/or acquisition are given by:

$$\Phi_i(s, a_i, \sigma_{-i}, \varepsilon_i; \theta) = \begin{cases} -\Gamma_i^B + EV_j(s; \sigma, \theta) \cdot \eta_1 & \text{if firm } i \text{ acquires firm } j \\ \Gamma_i^S & \text{if firm } i \text{ is acquired by firm } j \\ -\Lambda_i + EV_j(s; \sigma, \theta) \cdot \eta_2 & \text{if firms } i \text{ and } j \text{ merge into one firm,} \end{cases}$$

where σ_{-i} are the strategies played by all firms other than firm i; Γ_i^B is the fixed cost to firm i of acquiring other firm; Γ_i^S is the fixed benefit to firm i from being acquired; Λ_i is the fixed cost to firm i of merging; and $EV_j(s; \sigma, \theta)$ is the expected value of the value function $V_j(s; \sigma, \theta)$ for firm j, which depends on the strategies σ played by all firms. Firm i's idiosyncratic fixed payoffs Γ_i^B, Γ_i^S, and Λ_i of acquiring, being acquired, and merging, respectively, are private information to firm i, and are thus included in the vector ε_i of private information shocks to firm i. The coefficients η_1 and η_2 on the expected value $EV_j(s; \sigma, \theta)$ of the other firms that firm i may acquire or with which firm i may merge are among the parameters we estimate.

A coefficient η_1 on the expected value $EV_j(s; \sigma, \theta)$ of the other firms that firm i may acquire that is less than 1 may reflect in part the possibility that firm i may acquire a firm that is not in the top 50, and therefore that firm i may acquire a firm that may have a lower expected value than firms in the top 50 do; as well as any transactions costs that may lead to firm i to anticipate receiving less than the expected value of other firms that firm i may acquire. Similarly, a coefficient η_2 on the expected value $EV_j(s; \sigma, \theta)$ of the other firms with which firm i may merge that is less than 0.5 may reflect in part any bargaining or transactions costs that may lead to firm i to anticipate receiving less than half the expected value of other firms with which firm i may merge.

While we do not explicitly model the merger and acquisitions game and the matching between firms that wish to engage in mergers and acquisitions, our model nevertheless incorporates the interdependence of petroleum-producing firms' value functions that arises from the possibility of mergers and acquisitions. Despite the very parsimonious nature by which we incorporate mergers and acquisitions, we find in our assessment of model fit and model validity below that whether a firm merged with another firm in the previous year and whether it acquired another firm in the previous year do not appear to be significant characteristics of firms whose behavior our model does less well in explaining.[3]

[3] In future work we hope to further model additional complexities of mergers and acquisitions, building

We model the world petroleum market as a mixed oligopoly consisting of private firms and firms that are at least partially state-owned, and allow firms that are at least partially state-owned to have objectives other than profit maximization alone. In particular, we assume that private firms care solely about profit, while we allow firms that are at least partially state-owned to possibly put some weight on the consumer surplus faced by that firm as well.

The consumer surplus from oil and natural gas consumption, CS_{oil} and CS_{ng_r} respectively, are given by:

$$CS_{oil} = \int_0^{Q_{oil}} D_{oil}^{-1}(x)dx - p_{oil}Q_{oil} \tag{7}$$

$$CS_{ng_r} = \int_0^{Q_{ng_r}} D_{ng_r}^{-1}(x)dx - p_{ng_r}Q_{ng_r}. \tag{8}$$

Total consumer surplus CS from oil and natural gas consumption is therefore given by:

$$CS = CS_{oil} + \sum_{r=1}^{6} CS_{ng_r}. \tag{9}$$

We define the consumer surplus for oil faced by firm i as the world consumer surplus for oil times firm i's oil production as a fraction of world oil production (where world oil production is total oil production over the top 50 firms). For each natural gas region, we define consumer surplus for natural gas in that region faced by firm i as the world consumer surplus for natural gas in that region times firm i's natural gas production in that region as a fraction of total natural gas production in the region (where total natural gas production in a region is the natural gas production in that region summed over the top 50 firms). The consumer surplus CS_i faced by firm i is therefore given by the following weighted sum of the consumer surplus from oil and the consumer surplus from natural gas in each region, where the weights are given by firm i's respective share in the total production of oil and regional natural gas:

$$CS_i = CS_{oil}\frac{q_{i,oil}}{Q_{oil}} + \sum_{r=1}^{6} CS_{ng_r}\frac{q_{i,ng_r}}{Q_{ng_r}}. \tag{10}$$

on the stochastically alternating-move game of dynamic oligopoly of mergers the hard disk drive industry developed by Igami and Uetake (2019) as well as the empirical model of dynamic mergers by Jeziorski (2015). We also hope in future work to complement our analysis of mergers and acquisitions by further analyzing other forms of cooperation between firms, including production sharing or service-type contracts between state-owned oil companies and international oil companies (Ghandi and Lin, 2012, 2014; Ghandi and Lin Lawell, 2020).

The per-period payoff $\pi_i(s, a, \varepsilon_i; \theta)$ for each firm i is therefore as follows:

$$\pi_i(s, a, \varepsilon_i; \theta) = (1 - O_{i,state}) \underbrace{\bar{\pi}_i(s, a; \theta)}_{\text{production profit}} + O_{i,state} \left((1 - \rho_{CS}) \underbrace{\bar{\pi}_i(s, a; \theta)}_{\text{production profit}} + \rho_{CS} CS_i \right)$$
$$+ \omega_1 O_{i,state} + \omega_2 O_{i,OPEC} + \underbrace{\Phi_i(s, a_i, \sigma_{-i}, \varepsilon_i; \theta)}_{\text{M\&A}} - \underbrace{x_{i,exp} + x_{i,dvp} + x_{i,acq}}_{\text{investment}} + \delta_0, \tag{11}$$

where $O_{i,state}$ denotes the fraction of state ownership in firm i; ρ_{CS} is the weight that a firm that is at least partially state-owned puts on consumer surplus; $O_{i,OPEC}$ denotes a dummy variable for whether firm i is an OPEC member; and δ_0 is a constant.

Identification of the weight ρ_{CS} that a state-owned firms put on consumer surplus comes from variation in the fraction of state ownership among firms. Identification of the cost parameters comes from the realized firm behavior, including the realized behavior of private firms which care solely about profit.

The expected present discounted value $V_i(s; \sigma, \theta)$ of the entire stream of per-period payoffs for firm i as a function of its strategy σ_i is given by:

$$V_i(s; \sigma_i, \sigma_{-i}, \theta) = \mathbb{E}\left[\sum_{t=0}^{\infty} \beta^t \pi_i(s, a, \varepsilon_i; \theta) \right], \tag{12}$$

We cannot directly estimate the parameters in the unconditional distributions for the idiosyncratic firm-specific fixed payoffs Γ_i^B, Γ_i^S, and Λ_i to each firm i of acquiring, being acquired, and merging, respectively, since firms only undertake actions of acquiring, being acquired, and merging when the respective firm-specific fixed payoffs are sufficiently favorable.

Thus, we instead estimate the conditional expectations of the idiosyncratic firm-specific fixed payoffs Γ_i^B, Γ_i^S, and Λ_i to each firm i of acquiring, being acquired, and merging as functions of the probabilities p_B, p_S, and p_M of acquiring another firm, being acquired by another firm, and merging with another firm. Since these strategy probabilities capture the relevant information faced by a firm at a specific state, the conditional distributions of the fixed payoffs of acquiring, being acquired, and merging are also each a function of these probabilities (Ryan, 2012); if another alternative becomes more attractive, which would be reflected in a higher choice probability for this alternative, the draw of the fixed payoffs of acquiring, being acquired, and merging should represent such preference. In particular, we estimate the conditional expectations of the idiosyncratic firm-specific fixed payoffs Γ_i^B, Γ_i^S, and Λ_i to each firm i of acquiring, being acquired, and merging each as second-order polynomials of the probabilities p_B, p_S, and p_M of acquiring another firm, being acquired by another firm, and merging with another firm.

We assume that each firm chooses its production, investment, and merger and acquisition strategy to maximize the expected present discounted value $V_i(s; \sigma_i, \sigma_{-i}, \theta)$ of its entire stream of per-period payoffs, conditional on the current state variables, other firms' strategies, and its own private shocks, which results in a Markov perfect equilibrium (MPE). The optimal strategy $\sigma_i^*(s)$ for each firm i should therefore satisfy the following condition that, for all state variables s and alternative strategies $\tilde{\sigma}_i(s)$, the optimal strategy $\sigma_i^*(s)$ yields an expected present discounted value of the entire stream of per-period payoffs at least as high as the expected present discounted value of the entire stream of per-period payoffs from any alternative strategy $\tilde{\sigma}_i(s)$:

$$V_i(s; \sigma_i^*(s), \sigma_{-i}, \theta, \varepsilon_i) \geq V_i(s; \tilde{\sigma}_i(s), \sigma_{-i}, \theta, \varepsilon_i). \tag{13}$$

Although the mission of OPEC is to 'coordinate and unify the petroleum policies of its Member Countries' (Organization of Petroleum Exporting Countries [OPEC], 2017), it is unclear whether OPEC behaves as a cartel (Baumeister and Kilian, 2016, 2017; Lin Lawell, 2020; Parnes, 2019). We therefore do not assume or impose that OPEC producers collude to maximize joint profits, nor do we explicitly model any particular repeated game strategy, trigger strategy, or other strategy that might support collusion. We instead allow the strategies and payoffs for OPEC and non-OPEC firms to differ, and infer the strategy and payoffs for OPEC firms from the data. In particular, we estimate the oil and natural gas policy functions for OPEC firms and non-OPEC firms separately, allow the Markov state-space strategy of OPEC firms to depend on aggregated and cumulative measures of historical play, and include a dummy variable $O_{i,OPEC}$ for whether firm i is an OPEC member in the per-period payoff function. By allowing the Markov state-space strategy of OPEC firms to depend on aggregated and cumulative measures of historical play, our model may capture and therefore allow for the reduced-form implications of a number of repeated game strategies, trigger strategies, or other strategies that might support collusion (Fudenberg and Tirole, 1998; Maskin and Tirole, 2001; Doraszelski and Escobar, 2010). Similarly, while we remain agnostic in this paper as to what the dummy variable for being an OPEC member represents in the per-period payoff, what it captures may include some measure of the joint per-period payoffs to OPEC firms and/or some measure of transfers or benefits from joint profit maximization among OPEC firms.[4]

In our dynamic game, a firm's decisions may depend on the decisions of other firms through several channels. First, aggregate output of oil and natural gas affect the prices of oil and natural gas faced by each firm; as a consequence, owing to market power, each firm's production decisions affect the prices faced by all firms. Second, aggregate output, aggregate reserves, and aggregate capital expenditures affect each firm's policy functions. Thus, each firm's decisions depend on the aggregate output and capital expenditure of all other firms, and on the aggregate reserves of all other firms. Third, aggregate output affects the transition densities for the global state variables. Thus, production decisions of each firm affect future values of the state variables, which then affect the payoffs and decisions of all firms.

There are several sources of heterogeneity among firms in our model of the dynamic game between petroleum producers in the world petroleum market. First, firms differ in whether they are private or at least partially state-owned. We allow firms that are at least partially state-owned to have objectives other than profit maximization alone. Second, firms differ in their values of firm-specific state variables, the evolution of which may depend in part on previous actions they have taken. These firm-specific state variables include oil and natural gas reserves; cumulative oil and natural gas output; cumulative exploration, acquisition, and development expenditure; percentage of state ownership; whether the firm is a member of OPEC; whether the firm merged in the previous year; and whether the firm acquired another firm in the previous year. Third, firms differ in their idiosyncratic firm-specific fixed payoffs Γ_i^B, Γ_i^S, and Λ_i of acquiring, being acquired, and merging, respectively. Fourth, firms differ in their idiosyncratic draws from the mixed strategies given by their policy functions.

There are several sources of uncertainty in our model of a dynamic game. First, future values of the state variables are stochastic. Second, there are shocks to oil demand and regional natural gas demand. Third, merger and acquisition costs are private information to each firm i, and are not observed by either other firms or the econometrician. Fourth, the actual actions drawn from the mixed strategies given by the policy functions are stochastic.

[4] We hope in future work to develop techniques for estimating dynamic games to allow for more complicated repeated game strategies, trigger strategies, or other strategies that might support collusion, including tit-for-tat strategies whose reduced-form implications may not be fully captured by a Markov state-space strategy that depends on aggregated and cumulative measures of historical play rather than the entire history of past play. Nevertheless, as we explain in more detail below, even though we do not assume or impose that OPEC producers collude to maximize joint profits, but instead infer the strategy and payoffs for OPEC firms from the data, our results show that OPEC behaves in such a way that is consistent with its mission and also with cartel behavior.

The structural parameters θ to be estimated include the parameters in the per-period payoff function; and the distributions of the fixed payoffs to merging, acquiring, and being acquired.

Finding a single equilibrium is computationally costly even for problems with a simple structure. In more complex problems – as in the case of our dynamic game between petroleum producers in the world petroleum market, where many agents and decisions are involved – the computational burden is even more important, particularly if there may be multiple equilibria. Bajari et al. (2007) propose a method for recovering the dynamic parameters of the payoff function without having to compute any single equilibrium. The crucial mathematical assumption to be able to estimate the parameters in the payoff function is that, even when multiple equilibria are possible, the same equilibrium is always played. We reduce the number of potential multiple equilibria in our parsimonious dynamic game by modeling the strategic interactions and the dependence of each firm's payoffs and decisions on other firms as arising through the aggregate behavior of other firms in the market, rather than through the individual behavior of each of the other individual firms in the market.

We estimate the structural econometric model in two steps. In the first step, we characterize the equilibrium policy functions for the firms' decisions regarding exploration, development, production, merger, and acquisition as functions of state variables by using reduced-form regressions correlating actions to states. We also estimate the transition density for the state variables. We then calculate value functions using forward simulation following methods in Hotz et al. (1994) and Bajari et al. (2007). In the second step, using the condition for a Markov perfect equilibrium in equation (13), we find the parameters θ that minimize any profitable deviations from the optimal policy as given by the policy functions estimated in the first step.

An innovation we make in our econometric method arises since a firm's own value function $V_i(s;\sigma,\theta)$ depends on the expected value of the value function $EV_j(s;\sigma,\theta)$ of other firms that the firm may acquire or with which the firm may merge. We address the endogeneity of value functions using a fixed point algorithm.

4 Data

We construct an annual firm-level panel data set of the top 50 oil and natural gas producing companies each year. The original source of data is the Petroleum Intelligence Weekly (PIW). Known as the 'bible' of the international oil industry (Baer, 2004; Rubino, 2008), the Petroleum Intelligence Weekly is published by Energy Intelligence Group, and reports annual information on different operational criteria as well as financial and other measures of size for each of the top 50 oil and natural gas producing companies. This data set includes firm-level data on oil and natural gas output; oil and natural gas reserves;[5] investment (capital expenditures) in exploration, development, and acquisition;[6] and percentage of state ownership. Each year, the top 50 firms are determined by production as reported in the Petroleum Intelligence Weekly.

The top 50 oil and natural gas producing firms supply a significant share of global supply of oil. As seen in Figure A.1 in Appendix A, on average over 70% of the global supply is produced by the top 50 oil and natural gas producing firms.

We use membership information from the Organization of Petroleum Exporting Countries (OPEC) to construct a dummy variable that takes the value of 1 for a firm if it is a state-owned company owned by an OPEC member country.

We obtain annual oil and natural gas prices from the U.S. Energy Information Administration. We obtain average hourly earning of workers in oil and gas extraction industry from the U.S. Bureau of Labor Statistics.

We also use data on financial indicators averaged over 10 OECD countries as reported in the EU KLEMS database. These indicators include industry rate of return on capital in mining and quarry; average capital compensation on transport equipment in mining and quarry; average capital compensation on other machinery and equipment in mining and quarry; average capital compensation on total non-residential investment in mining and quarry; and average capital compensation on other assets in mining and quarry. Capital compensation is the price of capital times the quantity of capital, which under constant returns to scale is the value added minus labor compensation. We use capital compensation as our measure of capital costs, including costs of drilling rigs and production platforms, in the oil and gas industry.

We use data on world GDP, world population, world electricity production from oil and natural gas, world road sector fuel consumption, and world motor vehicles from the World Bank.

Our data set includes all acquisitions made by the top 50 firms, even if the firm being

[5] The reserves data reflect 'proved reserves', which U.S. Energy Information Administration (2018a) defines as 'volumes of oil and natural gas that geologic and engineering data demonstrate with reasonable certainty to be recoverable in future years from known reservoirs under existing economic and operating conditions'.

[6] Acquisition capital expenditures include expenditures for acquiring machinery and any other type of asset.

acquired by a top 50 firm was itself not among the top 50 firms. In addition, during the time period of our data set, any top 50 firms that were acquired were only ever acquired by other top 50 firms. We therefore observe and model all acquisition activity of the top 50 firms, even if the acquiree was not a top 50 firm.

Our data also includes all mergers between top 50 firms. During the time period of our data set, there were 3 mergers among the top 50 firms. Conoco and Phillips merge in 2000 to become ConocoPhillips. Exxon and Mobil merge in 1998 to become ExxonMobil. Sidanco and Tyumen Oil merge in 2002, after which they drop out of the top 50 firms.

Although our data includes all mergers between top 50 firms, we do not observe and therefore do not explicitly model mergers between a top 50 firm and a firm that is not among the top 50 firms. Nevertheless, we do observe and model the resulting effects of these unobserved mergers on the state variables (including reserves) and actions of the top 50 firm involved in the merger. In particular, unobserved mergers with non-top 50 firms are captured by the error terms in our policy functions and transition densities, and their effects on state variables and actions are therefore accounted for in our model. Although mergers with a firm that is not among the top 50 firms are not directly included in our per-period payoff function, but only indirectly through their effects on state variables and actions, this is justified by our assumption that, conditional on the state variables and actions we do observe, the expected value of the opportunity to merge with a non-top 50 firm is negligible relative to the other terms we include in the per-period payoff function, as the expected value of non-top 50 firms is smaller than those of top 50 firms, and, when weighted by the probability of merging with a non-top 50 firm, is even smaller still.

There are 65 firms that appear in the top 50 oil and natural gas producing companies for at least 1 year over the period 2000 to 2005. For firms that appear in the top 50 in some but not all years over the period 2000 to 2005, we treat the observations for these firms in years in which they are not in the top 50 (and therefore years for which we do not have data) as missing, and we use data from the non-missing years over the period 2000 to 2005 for all 65 firms that appear in the top 50 oil and natural gas producing companies for at least 1 year over the period 2000 to 2005 to estimate the policy functions and transition densities. For the structural econometric estimation, when forward simulating over many paths of play to calculate the expected present discounted value of the entire stream of per-period payoffs for each of the 50 players in the game, for each path of play we randomly draw a year from our data set and use values of the state variables from that year as our initial state variables and the top 50 firms in that year as the 50 firms for that simulated path of play, and then average over multiple simulated paths of play. Because the composition of the 50 petroleum-producing firms in our data set may change from year to year, and to make a dynamic game among 50 players tractable, we abstract away from the particular identity of each firm, and model the strategic interactions as arising from the dependence of each firm's strategy on the aggregate actions of firms in the market, rather than on particular actions undertaken by any particular firm.

As our primary concern is to model the world oil market, our intent in including a parsimonious and stylized model of natural gas is to enable us to better model the world oil market, rather than to fully model and capture all the complexities of the natural gas market. Unlike the oil market, the natural gas market is not necessarily a global market. Due to the lack of a global pipeline network, the market for natural gas is mostly defined by proximity to supply sources and the availability of a pipeline. In order to estimate separate natural gas demand functions for 6 different regional markets, we collect and construct regional natural gas prices using data from the EIA, and regional population and GDP data from the World Bank. Our 6 regional natural gas markets are Africa; Asia and Oceania; Eurasia; Europe; the Middle East; and the Americas. We describe the 6 regional natural gas markets in more detail in Appendix B.

Summary statistics for the action variables, firm-level state variables, and price variables over the years 2000-2005 are presented in Tables 1 to 3; summary statistics for the same variables over the entire period of the data set are in Tables A.1 to A.3 in Appendix A. Summary statistics for the regional and global state variables are in Table 4.

5 Results

5.1 Oil and natural gas demand

We estimate a simple econometric model of oil demand as an input to our structural model. As the price elasticity of oil demand is an input to rather than the primary output of our structural model, the price elasticity of oil demand that we input into our structural model need not necessarily be one that we estimate ourselves. Nevertheless, as described in detail in Appendix B, we estimate a parsimonious model of oil demand using our data set, and find that our estimated price elasticity of oil demand is in the range of previous estimates of price elasticity of oil demand in the literature. The results of our structural model are therefore robust to whether the price elasticity of oil demand we use for our structural model was chosen based on previous estimates of price elasticity of oil demand in the literature, or instead based on our own estimate of the price elasticity of oil demand.

We similarly estimate a simple econometric model of regional natural gas demand as an input to our structural model. Our natural gas demand model and results are described in Appendix B. Once again, the price elasticities of regional natural demand are inputs to rather than the primary output of our structural model. While our primary concern is to model the world oil market, we include natural gas in our model because of joint production and other supply-side links in oil and natural gas (Roberts and Gilbert, 2020). Our intent in including a parsimonious and stylized model of regional natural gas demand is therefore to enable us to better model the world oil market, rather than to fully model and capture all the complexities of the natural gas market. In future work we hope to better incorporate and model additional complexities of the natural gas industry.

5.2 Policy functions

Each period, each petroleum producer decides how much oil and natural gas to produce and how much to spend on each type of capital expenditure. Using our panel data on the top 50 petroleum producers, we estimate policy functions for these decision variables which correlate actions to states. We include dummies for having merged or acquired in the previous year as regressors to capture any synergies or returns to scale in production and/or investment resulting from mergers and acquisitions. The estimation results are reported in Table A.4 in Appendix A.

Although the mission of OPEC is to 'coordinate and unify the petroleum policies of its Member Countries' (Organization of Petroleum Exporting Countries [OPEC], 2017), it is unclear whether OPEC behaves as a cartel (Baumeister and Kilian, 2016, 2017; Lin Lawell, 2020; Parnes, 2019). Thus, rather than assume or impose that OPEC producers collude to maximize joint profits, we instead allow the strategies and payoffs for OPEC and non-OPEC firms to differ, and infer the strategy and payoffs for OPEC firms from the data. Thus, since OPEC firms may have different production policies from non-OPEC firms, we estimate the oil and natural gas production policy functions for OPEC firms separately; these results are reported in Table A.5 in Appendix A.

Comparing the oil production policy functions for non-OPEC firms in Table A.4 in Appendix A with those for OPEC firms in Table A.5 in Appendix A, we find that the magnitude of the coefficient on oil reserves is smaller for OPEC firms than for non-OPEC firms, while the magnitude of the coefficient on cumulative oil output is larger for OPEC firms than for non-OPEC firms. Thus, oil reserves has a smaller marginal correlation with oil production for OPEC firms than for non-OPEC firms, while cumulative oil output has a larger marginal correlation with oil production for OPEC firms than for non-OPEC firms. This suggests that the oil production strategy for OPEC firms depends less on oil reserves and more on cumulative (or historical) oil output than does the oil production strategy for non-OPEC firms.

In addition to production and investment, each firm also decides whether to acquire another firm or be acquired by another firm, and whether to merge with another firm. In order to estimate the policy function for merger and acquisition decisions, we define a merger and acquisition action variable which takes the value of 1 for merger, 2 when a firm acquires another firm, and 0 otherwise. We use a multinomial logit regression model to estimate this policy function. Since OPEC firms and firms that are 100% state-owned never merge or acquire, we exclude these firms from the estimation. Estimation results for policy function on merger and acquisition are reported in Table A.6 in Appendix A. We use specification (4) in the structural estimation.

For firms that do not merge or acquire, these firms may choose to be acquired by another firm. We use a logit regression model to estimate this policy function, once again excluding OPEC firms and firms that are 100% state-owned, since they are never acquired by others, and also excluding firms that merge or acquire. Estimation results for policy function for being acquired are reported in Table A.7 in Appendix A. We use specification (2) in the structural estimation.

5.3 Transition densities

The firm-specific state variables for whether the firm merged in the previous year, and for whether the firm acquired another firm in the previous year evolve deterministically as a function of the firm's merger and acquisition decisions in the previous year. The transition densities for each of the remaining state variables are stochastic, and depend on the lagged value of that state variable and also potentially on the lags of other state variables and lagged actions.

We model the remaining firm-specific variables as controlled Markov processes. We estimate the transition densities for firm-level oil reserves and natural gas reserves by regressing reserves on lagged reserves, lagged output, lagged capital expenditures in exploration, lagged capital expenditures in development, lagged percent state ownership, lagged dummy for merger, and lagged dummy for acquisition, all at the firm level. Similarly we estimate a transition density for percentage of state ownership. The results are presented in Table A.8

in Appendix A.

In our transition densities for oil and natural gas reserves, we do not assume any fixed finite amount for the reserves, but instead allow the distribution of reserves the next period to depend on the reserves, production, investment, and merger and acquisitions this period, and we let the data tell us what the transition density is. This is consistent with the common practice in the natural resource economics literature of modeling potential reserves as infinite; potential reserves are probably infinite, although the amount that is economical to extract is finite, and technological progress and new discoveries will always make more reserves available and feasible for extraction (Farzin, 1992; Lin, 2009b).

Thus, for the transition densities for oil and natural gas reserves, we regress reserves on lagged reserves, lagged output, lagged exploration capital expenditure, lagged development capital expenditure, lagged percent state ownership, lagged dummy for merger, and lagged dummy for acquisition, and we let the data tell us what the transition density is. Our econometric model allows for reserves to increase or decrease over time.

We allow the energy-related global state variables to evolve endogenously as controlled Markov processes as well. The transition densities for average industry rate of return on capital, average capital compensation on other machinery and equipment, average capital compensation on total non-residential investment, world road sector gasoline fuel consumption, world motor vehicles, world electricity production from natural gas sources, and world road sector gasoline from oil sources are in Tables A.9 to A.15, respectively, in Appendix A. For each of these state variables, we regress the state variable on the lagged value of the state variable, as well as on the lagged values of other relevant state variables and lagged values of aggregate reserves and aggregate production variables. In some cases, relevant state variables were dropped due to collinearity.

The lagged values of aggregate reserves and aggregate production are significant in most transition densities, which means that the investment and production decisions of other firms affect the future values of state variables that affect a firm's future payoff from producing and investing, and therefore that firms must anticipate the production and investment strategies of other firms in order to make a dynamically optimal decision. There is thus an important strategic component in firms' production and investment decisions.

The results for the transition density for world population, which depends on lagged world population, are presented in Table A.16. The results for the transition density for world GDP per capita, which depends on lagged world GDP per capita, are presented in Table A.17 in Appendix A. The results for the transition density for regional population, which depends on lagged regional population, for each of the 6 regions of the world are presented in Table A.18. The results for the transition density for regional GDP, which depends on lagged regional GDP, for each of the 6 regions of the world are presented in Table A.19 in Appendix A.

5.4 Structural parameters

The structural parameters θ we estimate include the parameters in the per-period payoff function, and the distributions of the fixed payoffs to merging, acquiring, and being acquired. We set the discount factor β to 0.9.

Our estimates of the parameters in the per-period payoff function are presented in Table 5. Our estimated parameters in the per-period payoff function show that there are nonlinearities with respect to both output and reserves in the production profit function. Thus, oil and natural gas production may exhibit increasing or decreasing returns to scale, or both. As a consequence, firms may benefit from changing their scale via mergers and acquisitions.

The coefficient δ_5 in oil and natural gas production cost on the interaction between oil and natural gas output is significant and negative, which is evidence of cost synergies between oil and natural gas production, which may include joint production and other supply-side links in oil and gas (Roberts and Gilbert, 2020).

Both the percentage of state ownership and being an OPEC member have a significant positive effect on the per-period payoff. While our model allows firms that are at least partially state-owned to have different objectives from private firms, we find that state-owned firms do not put any weight on consumer surplus, as we estimate ρ_{CS} to be a precise zero.

The coefficient η_1 on the expected value $EV_j(s;\sigma,\theta)$ of the other firms that firm i may acquire is less than 1, which may reflect in part the possibility that firm i may acquire a firm that is not in the top 50, and therefore that firm i may acquire a firm that may have a lower expected value than firms in the top 50 do; as well as any transactions costs that may lead to firm i to anticipate receiving less than the expected value of other firms that firm i may acquire. The coefficient η_2 on the expected value $EV_j(s;\sigma,\theta)$ of the other firms with which firm i may merge that is less than 0.5, which may reflect in part any bargaining or transactions costs that may lead to firm i to anticipate receiving less than half the expected value of other firms with which firm i may merge.

Our estimates of the distribution of fixed payoffs to merger and acquisition are presented in Table 6. The fixed benefits from being acquired, the fixed costs of acquiring another firm, and the fixed costs of merging each have a significant and positive mean, but a large significant standard deviation as well. Thus, the idiosyncratic fixed payoffs to merger and acquisition vary greatly by firm and year.

Welfare statistics, including firm payoffs for all firms, OPEC firms, and non-OPEC firms; and consumer surplus are presented in Table A.20 in Appendix A. The expected firm payoff is significant and positive on average, but can be negative for some firms in some years. Expected total consumer surplus is several orders of magnitude larger than expected total firm payoff.

6 Model Validation

To assess the goodness of fit of our structural econometric model, we compare the actual values of the action variables observed in the data with the action variables predicted by our structural econometric model for the period 2000-2005. Summary statistics of the actual values of the action variables observed in the data over the period 2000-2005 are presented in Table 1. Summary statistics of the action variables predicted by our structural econometric model for the period 2000-2005 are presented in Table A.21 in Appendix A. When comparing the summary statistics of the actual and model predicted action variables, it appears that our structural econometric model does a fairly good job matching the actual data.

Our econometric estimation entails finding the parameters θ that minimize any profitable deviations from the optimal strategy as given by the estimated policy functions. Table 7 presents each firm's probability of having an economically significant profitable deviation from their estimated optimal strategy under our estimated structural parameters. We define and calculate a firm's probability of having an economically significant profitable deviation as the fraction of alternative strategies simulated that would yield a payoff, as evaluated using our estimated structural parameters, more than one billion dollars per year higher than would the optimal strategy as given by our estimated policy functions. One billion dollars per year is roughly 7% of the expected maximum firm payoff.

There are 65 firms that appear in the top 50 oil and natural gas producing companies for at least 1 year over the period 2000 to 2005. As seen in Table 7, most of the firms do not have any economically significant profitable deviations from their estimated optimal strategy under our estimated parameters, which suggests that our parsimonious model does a fairly good job explaining the behavior of these firms. The probability of having an economically significant profitable deviation is statistically significant at a 5% level and greater than 0.1

for only a few firms: Chevron, ExxonMobil, Gazprom, and the Iraq National Oil Company (INOC).

To examine how a firm's probability of having an economically significant profitable deviation relates to observable firm characteristics, we analyze the firm-level determinants of any statistically significant non-zero probability of having an economically significant profitable deviation. To do so, we regress the probabilities of having an economically significant profitable deviation that are significant at a 5% level on whether the firm is an OPEC member, its state ownership, its initial oil reserves, its initial natural gas reserves, whether it merged with another firm in the previous year, and whether it acquired another firm in the previous year. In this regression, the value of the dependent variable is zero for firms whose probability of an economically significant profitable deviation is not significant at a 5% level.

As seen in Table 8, a firm's probability of having an economically significant profitable deviation is not significantly correlated with whether the firm is an OPEC member, its state ownership, its initial oil reserves, whether it merged with another firm in the previous year, or whether it acquired another firm in the previous year. Thus, whether the firm is an OPEC member, its state ownership, its initial oil reserves, whether it merged with another firm in the previous year, or whether it acquired another firm in the previous year do not appear to be significant determinants of a firm's probability of having an economically significant profitable deviation, and therefore do not appear to be significant characteristics of firms that our model does less well explaining.

On the other hand, as seen in Table 8, a firm's probability of having an economically significant profitable deviation is positively correlated with the firm's natural gas reserves. Thus, our model does not perfectly explain the behavior of firms with large natural gas reserves, and therefore may better explain the world oil market than natural gas markets.

While our primary concern is to model the world oil market, we include natural gas production and natural gas reserves in our model because of joint production and other supply-side links in oil and natural gas (Roberts and Gilbert, 2020). Thus, our intent in including a parsimonious and stylized model of natural gas is to enable us to better model the world oil market, rather than to fully model and capture all the complexities of the natural gas market. It is therefore reassuring that, while our model does not perfectly explain the behavior of firms with large natural gas reserves, it appears to do a fairly heroic and remarkable job of modeling the notoriously complex world oil market. In future work we hope to better incorporate and model additional complexities of the natural gas industry, and to obtain more recent data to enable us to include shale as well.

Our measure of profitable deviations might be a conservative upper bound, since some of the alternative strategies that we find to yield profitable deviations for a firm might not actually be feasible for the firm, for example owing to capital or liquidity constraints that we do not observe, assume, impose, or explicitly model.[7] Thus, our parsimonious model appears to do a fairly heroic and remarkable job of modeling the notoriously complex world oil market.

7 Counterfactual Simulations

To further gauge the validity of our parsimonious model and its plausibility for use in approximating the effects of counterfactual scenarios on the short-run evolution of industry, and also to enhance our understanding of OPEC behavior, we use the structural econometric model to analyze the effects of a hypothetical change in OPEC membership on the petroleum industry over the period 2000-2005. In particular, we simulate a counterfactual OPEC membership scenario in which all firms are members of OPEC. We compare the production, investment, mergers and acquisitions, firm payoffs, and consumer surplus under that counterfactual scenario with those under the base-case status quo simulation of no counterfactual change using two-sample t-tests.

There are several channels through which the counterfactual change in OPEC membership may affect firm payoffs, consumer surplus, and welfare. First, the counterfactual change in OPEC membership may affect firm payoffs directly. Second, the counterfactual change may affect production, investment, and merger and acquisition decisions which affect firm payoffs and consumer surplus. Third, changes in actions and/or state variables resulting from the counterfactual change may affect future values of the state variables, which may affect future actions and/or welfare. Our estimates of the changes in firm payoffs, consumer surplus, and welfare that arise in each counterfactual simulation capture all channels through which the counterfactual scenario may affect firm payoffs, consumer surplus, and welfare.

In analyzing the short-run effects of the counterfactual OPEC membership scenario, we

[7] The alternative strategies $\tilde{\sigma}_i(s)$ we simulate are pertubations to the optimal strategy $\sigma_i^*(s)$ that shift the estimated production or investment policy function upwards or downwards by up to two times the observed standard deviation of the respective production or investment action variable in the data; and that shift the estimated policy functions for the merger and acquisition probabilities upwards or downwards by up to 0.20. Not all of these alternative strategies might actually be feasible for a firm. It may not be feasible, for example, for some firms to increase their oil production by two times the standard deviation of oil production over all top 50 firms. Similarly, as another example, it may not be feasible for some firms to increase their exploration capital expenditure by two times the standard deviation of exploration capital expenditure over all top 50 firms.

assume that the counterfactual change we simulate is one that firms and consumers neither anticipate nor expect to be permanent; and that the counterfactual scenario does not change which equilibrium is played. Adapting the policy invariance assumption and approach of Benkard et al. (2019), we therefore assume that the oil and natural gas demand functions, policy functions, transition densities of unaffected state variables, and structural parameters we estimate themselves do not change under the counterfactual scenario. In particular, when simulating the effects of counterfactual changes in OPEC membership, we assume that the oil and natural gas demand functions; the policy functions for OPEC and non-OPEC firms as a function of state variables; the evolution of state variables as a function of lagged state variables and lagged actions; and parameters in the per-period payoff function for OPEC and non-OPEC do not change when OPEC membership changes, but instead that what changes is whether a particular firm is an OPEC firm or not, and therefore whether the appropriate policy function that governs a particular firm's decision-making is that for an OPEC or non-OPEC firm, and whether the appropriate per-period payoff is that for an OPEC or non-OPEC firm.

Table 9 presents results of two-sample t-tests comparing the welfare from the counterfactual OPEC membership scenario to the welfare from the base-case status quo simulation. Table 10 presents results of two-sample t-tests comparing each of the action variables (output, investment, and mergers and acquisitions) from the counterfactual OPEC membership scenario to the action variables from the base-case status quo simulation.

According to the results, including all firms in OPEC causes firms to decrease oil production, leading to increases in the average firm payoff, increases in oil prices, and decreases in consumer surplus.

Our result that including all firms in OPEC increases average firm payoff is consistent with OPEC's mission to 'coordinate and unify the petroleum policies of its Member Countries and ensure the stabilization of oil markets in order to secure an efficient, economic and regular supply of petroleum to consumers, a steady income to producers and a fair return on capital for those investing in the petroleum industry' (Organization of Petroleum Exporting Countries [OPEC], 2017).

Our result that including all firms in OPEC causes firms to decrease oil production, leading to increases in the average firm payoff, increases in oil prices, and decreases in consumer surplus is also consistent with the assessment of the U.S. Energy Information Administration (2018b) that 'Crude oil production by the Organization of the Petroleum Exporting Countries (OPEC) is an important factor that affects oil prices. This organization seeks to actively manage oil production in its member countries by setting production targets. Historically, crude oil prices have seen increases in times when OPEC production targets are reduced. OPEC member countries produce about 40 percent of the world's crude oil. Equally important to global prices, OPEC's oil exports represent about 60 percent of the total petroleum traded internationally. Because of this market share, OPEC's actions can, and do, influence international oil prices.'

8 Discussion and Conclusions

In this paper, we develop and estimate a structural econometric model of the dynamic game among petroleum-producing firms that enables us to assess the effects of counterfactual scenarios on the short-run evolution of industry. Our parsimonious model does a fairly heroic and remarkable job of modeling the notoriously complex world oil market and generating results that align with economic theory and/or previous assessments – anecdotal, qualitative, empirical, or otherwise – of the industry.

According to the results of our structural econometric model, oil and natural gas production may exhibit increasing or decreasing returns to scale, or both. As a consequence, firms may benefit from changing their scale via mergers and acquisitions. In addition, we find evidence of cost synergies between oil and natural gas production, which may include joint production and other supply-side links in oil and gas (Roberts and Gilbert, 2020).

While our model allows firms that are at least partially state-owned to have different objectives from private firms, we find that state-owned firms do not put any weight on consumer surplus. The high fossil fuel subsidies observed in many oil-rich countries in the Middle East and North Africa that are economically dependent on oil and gas exports are motivated in large part by a desire to distribute resource revenues, perhaps due to political pressure to do so (Ross et al., 2017; Kheiravar and Lin Lawell, 2020). A zero weight on consumer surplus is consistent with a model in which state-owned firms maximize the present discounted value of the entire stream of profits, and then use some of the profits to subsidize domestic consumers. Thus, our results suggest that fossil fuel subsidies in oil-rich countries arise from state-owned firms maximizing profits and then redistributing some of the profits that they have maximized, rather than from state-owned firms maximizing a weighted sum of profits and consumer surplus in a mixed oligopolistic setting.

Although the mission of OPEC is to 'coordinate and unify the petroleum policies of its Member Countries' (Organization of Petroleum Exporting Countries [OPEC], 2017), it is unclear whether OPEC behaves as a cartel (Baumeister and Kilian, 2016, 2017; Lin Lawell, 2020; Parnes, 2019). Thus, rather than assume or impose that OPEC producers collude to maximize joint profits, we instead allow the strategies and payoffs for OPEC and non-OPEC firms to differ, and infer the strategy and payoffs for OPEC firms from the data. In particular, we estimate the oil and natural gas policy functions for OPEC firms and non-OPEC firms separately, and we include a dummy variable for whether the firm is an OPEC member in the per-period payoff function.

Our results for the oil production policy functions for OPEC and non-OPEC firms suggest that the oil production strategy for OPEC firms depends less on oil reserves and more on cumulative (or historical) oil output than does the oil production strategy for non-OPEC firms. While we do not assume or impose that OPEC producers collude to maximize joint profits, nor do we explicitly model any particular repeated game strategy, trigger strategy, or other strategy that might support collusion, our result that the oil production policy function for OPEC firms depends more on cumulative (or historical) oil output than does the oil production strategy for non-OPEC firms is possibly consistent with a repeated game strategy that depends on a long history of play. By allowing the Markov state-space strategy of OPEC firms to depend on aggregated and cumulative measures of historical play, our model may capture and therefore allow for the reduced-form implications of a number of repeated game strategies, trigger strategies, or other strategies that might support collusion (Fudenberg and Tirole, 1998; Maskin and Tirole, 2001; Doraszelski and Escobar, 2010). We hope to allow for more complicated repeated game strategies, trigger strategies, or other strategies that might support collusion, including tit-for-tat strategies whose reduced-form implications may not be fully captured by a Markov state-space strategy that depends on aggregated and cumulative measures of historical play rather than the entire history of past play, and to develop techniques for estimating dynamic games that allow for such strategies, in future work.

Our estimated structural parameters show that being an OPEC member has a significant positive effect on the per-period payoff. While we remain agnostic in this paper as to what this dummy variable for being an OPEC member represents in the per-period payoff, it is possible that what is captured in this significant positive effect may include some measure of the joint per-period payoffs to OPEC firms and/or some measure of transfers or benefits from joint profit maximization among OPEC firms.

As our primary concern is to model the world oil market, we focus primarily on modeling the decisions of petroleum-producing firms regarding oil production and investment in exploration and development. Nevertheless, we include natural gas production in our model because of joint production and other supply-side links in oil and natural gas (Roberts and Gilbert, 2020). Similarly, as petroleum-producing firms also engage in mergers and acquisitions, we also include mergers and acquisitions in our model. Thus, our intent in including a parsimonious and stylized model of natural gas and of mergers and acquisitions is to enable us to better model the world oil market, rather than to fully model and capture all the complexities of the natural gas market and of mergers and acquisitions.

In our assessment of the validity of our model and model fit, it is therefore reassuring that, while our model does not perfectly explain the behavior of firms with large natural gas reserves, it appears to do a fairly heroic and remarkable job of modeling the notoriously complex world oil market. Whether the firm is an OPEC member, its state ownership, its initial oil reserves, whether it merged with another firm in the previous year, or whether it acquired another firm in the previous year do not appear to be significant characteristics of firms that our model does less well explaining. Most of the firms do not have any economically significant profitable deviations from their estimated optimal strategy under our estimated parameters, which suggests that our parsimonious model does a fairly good job explaining the behavior of these firms.

To further gauge the validity of our parsimonious model and its plausibility for use in approximating the effects of counterfactual scenarios on the short-run evolution of industry, and also to enhance our understanding of OPEC behavior, we use the structural econometric model to analyze the effects of a hypothetical change in OPEC membership on the petroleum industry. According to the results from our counterfactual OPEC membership scenario, including all firms in OPEC increases the average firm payoff. This result is consistent with OPEC's mission to 'coordinate and unify the petroleum policies of its Member Countries and ensure ... a steady income to producers' (Organization of Petroleum Exporting Countries [OPEC], 2017). Our result that including all firms in OPEC causes firms to decrease oil production, leading to increases in the average firm payoff, increases in oil prices, and decreases in consumer surplus is also consistent with the assessment of the U.S. Energy Information Administration (2018b) that OPEC 'seeks to actively manage oil production in its member countries by setting production targets' and that 'Historically, crude oil prices have seen increases in times when OPEC production targets are reduced.'

Thus, although it is unclear whether OPEC behaves as a cartel (Baumeister and Kilian, 2016, 2017; Lin Lawell, 2020; Parnes, 2019), and even though we do not assume or impose that OPEC producers collude to maximize joint profits, but instead infer the strategy and payoffs for OPEC firms from the data, we find that OPEC behaves in such a way that is consistent with its mission to increase the average firm payoff of its member countries, and that is also consistent with cartel behavior of decreasing oil production in order to increase oil price. It is important to note that we generated outcomes for production, firm payoffs, oil prices, and consumer surplus that were consistent with cartel behavior without assuming joint profit maximization, but rather with a dummy variable for being an OPEC member in the per-period payoff function and with policy functions that differed between OPEC and non-OPEC firms. Thus, while our results may be consistent with cartel behavior, they may also be consistent with alternative non-collusive stories for why the strategies and payoffs for OPEC and non-OPEC firms differ and may lead to outcomes that are beneficial to OPEC firms, harmful to consumers, and consistent with cartel behavior.

There are several potential avenues for future work that we hope to pursue. First, in future work we hope to further analyze the strategies and behavior of OPEC and OPEC firms. For example, as mentioned, we hope in future work to develop techniques for estimating dynamic games to allow for more complicated repeated game strategies, trigger strategies, or other strategies that might support collusion, including tit-for-tat strategies whose reduced-form implications may not be fully captured by a Markov state-space strategy that depends on aggregated and cumulative measures of historical play rather than the entire history of past play, building on a model of collusion in a dynamic oligopoly by Doraszelski et al. (2019).

To make a dynamic game among 50 players tractable, we abstract away from the particular identity of each firm, and model the strategic interactions as arising from the dependence of each firm's strategy on the aggregate actions of firms in the market, rather than on particular actions undertaken by any particular firm. In a second avenue for future work, we hope to develop techniques for estimating dynamic games in which all firms may care about the individual states and actions of certain firms, such as certain individual OPEC firms, in addition to the aggregate actions of firms, building on the notion of a partially oblivious equilibrium (POE) developed by Benkard et al. (2015), which allows for there to be a set of strategically important firms (the 'dominant' firms), whose firm states are always monitored by every other firm in the market.

Third, in future work we hope to incorporate and model additional complexities of the natural gas industry, and to obtain more recent data to enable us to include shale gas and shale oil as well. Fourth, in future work we hope to further model additional complexities of mergers and acquisitions, building on the stochastically alternating-move game of dynamic oligopoly of mergers the hard disk drive industry developed by Igami and Uetake (2019) as well as the empirical model of dynamic mergers by Jeziorski (2015). We also hope in future work to complement our analysis of mergers and acquisitions by further analyzing other forms of cooperation between firms, including production sharing or service-type contracts between state-owned oil companies and international oil companies (Ghandi and Lin, 2012, 2014; Ghandi and Lin Lawell, 2020).

Fifth, in future work we hope to develop techniques for analyzing counterfactual scenarios that might change the equilibrium being played. Sixth, in future work we hope to analyze the effects of demand shocks, including those that arise due to disruptive technologies, such as shale oil and gas and new batteries for electric vehicles, on the world petroleum market. Seventh, in future work we hope to obtain international data on annual firm-level crude oil and natural gas storage to enable us to analyze the role of crude oil and natural gas storage on price dynamics, including the possible role of crude and natural gas storage as a buffer to demand shocks (Williams and Wright, 1991; Kilian and Murphy, 2014). Eighth, as we found that firms that are at least partially state-owned do not put any weight on consumer surplus, we hope to further analyze other alternative objectives for state-owned firms, as well as alternative means of calculating the consumer surplus for the set of consumers each state-owned firm may care about, in future work.

Last but not least, in future work we hope to extend our model to incorporate environmental externalities arising from oil and natural gas production and consumption, which would then enable us to simulate and analyze sophisticated counterfactual scenarios regarding global environmental policy, and subsequently to design environmental policies that maximize net benefits to society, and that best benefit both firms and consumers with minimal adverse distributional consequences.

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Table 1: Summary statistics for action variables (2000-2005)

Variable	# Obs	Mean	Std. Dev.	Min	Max
Oil output (KBD)	300	1214.441	1466.5487	11	11035
Natural gas output (MCFD)	300	3445.546	7242.888	44	53135
Exploration capex (million 2005 US$)	94	595.9822	453.5993	-13.232	1828.14
Development capex (million 2005 US$)	94	2640.832	2268.744	0	9045
Acquisition capex (million 2005 US$)	93	1133.271	2651.709	-142.899	17625
Dummy for M&A at time t					
merging with another firm	300	0.0133	0.1149	0	1
acquiring another firm	300	0.0233	0.1512	0	1
being acquired by another firm	300	0.0167	0.1282	0	1
OPEC firms' production only					
Oil output (KBD)	67	2445.269	2324.396	135	11035
Natural gas output (MCFD)	67	3419.313	2687.751	112	8485
Non-OPEC firms' production only					
Oil output (KBD)	233	860.5119	819.4949	11	3754
Natural gas output (MCFD)	233	3453.09	8096.542	44	53135

Table 2: Summary statistics for firm level state variables (2000-2005)

Variable	# Obs	Mean	Std. Dev.	Min	Max
OPEC membership at time t (dummy)	300	0.2233	0.4171	0	1
State ownership (in percentage)	300	48.48641	45.74817	0	100
Oil reserves (million barrels)	300	19820.82	44090.61	50	264200
Natural gas reserves (BCF)	300	85529.82	207369.9	420	1320000

Table 3: Summary statistics for prices of oil and natural gas (2000-2005)

Variable	# Obs	Mean	Std. Dev.	Min	Max
Crude oil price, Brent (2005 US$/bbl)	6	35.98517	9.791585	28.7883	54.4341
Natural gas price, US (2005 US$/mmbtu)	6	5.756597	1.755797	3.97939	8.91567
Regional natural gas price (2005 US$/mmbtu)					
Africa	5	5.643	2.4304	3.3171	9.679
Asia & Oceania	5	9.7815	1.4431	8.2034	11.764
Eurasia	5	0.9509	0.2714	0.7106	1.3715
Europe	5	7.1918	1.8749	5.1571	9.7842
Middle East	5	6.263	1.0773	5.3768	8.1295
America	5	5.8928	1.8119	3.9221	8.5541

Table 4: Summary statistics for regional and global state variables

Variable	# Obs	Mean	Std. Dev.	Min	Max
Avg capital compensation (million 2005 US$)					
on transport equipment	24	132.322	57.204	21.891	243.422
on other machinery and equipment	24	2086.081	870.891	415.203	4141.958
on total non-residential investment	24	4078.227	2371.123	847.457	10639.06
Average industry rate of return on capital	24	0.144	0.04	0.08	0.232
World GDP per capita (2005 US$)	25	6475.482	691.679	5456.522	7642.35
World population (million people)	25	5970.799	575.621	4985.892	6942.765
World electricity production (kWh)					
from oil sources	25	1.04e+12	1.02e+11	8.08e+11	1.19e+12
from natural gas sources	25	2.71e+12	1.17e+12	8.28e+11	4.85e+12
World road sector gasoline					
fuel consumption (kt of oil equivalent)	18	827537.6	50057.57	730584	898004
World motor vehicles (per 1,000 people)	10	156.73	11.225	142.4	180.18
Average weekly earnings (2005 US$)					
for oil and gas extraction	25	892.2796	65.31246	803.238	1023.57
for supporting activities in oil and gas	22	789.4748	92.58307	681.1732	978.1636
Regional GDP (trillion 2005 US$)					
Africa	25	0.817	0.507	0.408	2.13
Asia and Oceania	25	9.19	4.3	3.81	20.7
Eurasia	25	0.871	0.691	0.0722	2.6
Europe	25	11.9	4.68	5.59	20.8
Middle East	25	0.885	0.622	0.304	2.52
Americas	25	13.3	5.15	6.1	23.2
Regional population (million people)					
Africa	25	797	144	578	1050
Asia and Oceania	25	3340	321	2780	3820
Eurasia	25	287	2.548955	281	291
Europe	25	574	18.6	540	604
Middle East	25	168	30.2	120	221
Americas	25	823	80.3	689	948

Table 5: Estimated parameters in per-period payoff function

Description		Estimated parameters
Coefficient in oil production cost on:		
Oil production (KBD*1e-4)	δ_{11}	-20.0970 ***
		(1.1779)
Oil production squared	δ_{12}	-0.1591 ***
		(0.0093)
Oil reserves (bbl)	δ_{13}	1.1744 ***
		(0.0688)
Oil production × Oil reserves	δ_{14}	-0.7277 ***
		(0.0426)
Coefficient in natural gas production cost on:		
NG production (MCF*1e-4)	δ_{21}	0.0200 ***
		(0.0012)
NG production squared	δ_{22}	-0.0140 ***
		(0.0008)
NG reserves (KCF)	δ_{23}	-0.2700 ***
		(0.0158)
NG production × NG reserves	δ_{24}	-0.0772 ***
		(0.0045)
Coefficient in oil and natural gas production cost on:		
Oil production × NG production	δ_5	-11.4587 ***
		(0.6716)
Coefficient in per-period payoff on:		
Percentage of state ownership	ω_1	0.3787 ***
		(0.0222)
OPEC member (dummy)	ω_2	2.8945 ***
		(0.1696)
EV of other firm if acquire (billion $)	η_1	0.1710 ***
		(0.0100)
EV of other firm if merge (billion $)	η_2	0.3976 ***
		(0.0233)
Percent state ownership × Consumer surplus (billion $)	ρ_{CS}	0.0000 ***
		(0.0000)
Constant	δ_0	0.0000 ***
		(0.0000)

Notes: Per period payoffs are in billion dollars. Standard errors in parentheses.
Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 6: Estimated distribution of fixed payoffs to merger and acquisition

		Mean	Standard Deviation
Fixed costs of acquiring another firm	Γ_i^B	0.1037 ***	0.1401 ***
		(0.0062)	(0.0083)
Fixed benefits from being acquired	Γ_i^S	0.0487 ***	0.0724 ***
		(0.0031)	(0.0048)
Fixed costs of merging	Λ_i	0.0588 ***	0.0767 ***
		(0.0035)	(0.0045)

Note: Per period payoffs are in billion dollars. Standard errors in parentheses.
Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 7: Probability of an economically significant profitable deviation by firm

Company	Probability of an economically significant profitable deviation
ADNOC	0.0250 ***
Anadarko	0.0000
Apache	0.0000
BG	0.0000
BHP	0.0000
BP	0.0166 ***
Burlington	0.0000
Canadian Natural (CNR)	0.0000
Chevron	0.1166 ***
CNPC	0.0500 ***
CPC (Taiwan)	0.0500 ***
Conoco Phillips	0.0000
Devon Energy	0.0000
Ecopetrol	0.0000
EGPC	0.0000
El Paso Energy	0.0000
Encana	0.0000
Eni	0.0083 ***
ExxonMobil	0.2083 ***
Gazprom	0.2416 ***
Hess Corporation	0.0500 ***
INOC	0.1083 ***
KazMunayGas	0.0000
KPC	0.1000 ***
Libya NOC	0.0000
Lukoil	0.0166 ***
Marathon Oil	0.0166 ***
NIOC	0.0083 ***
Nippon Mitsubishi	0.0500 ***
NNPC	0.0416 ***
Norsk Hydro	0.0333 ***
Occidental	0.0000
OMV	0.0000
ONGC	0.0000
PDO	0.0000
PDV	0.0666 ***
Pemex	0.0083 ***
Pertamina	0.0583 ***
Petro-Canada	0.0000
Petrobras	0.0500
Petroecuador	0.0000
Petronas	0.0333 ***
Phillips	0.0000
QP	0.0750 ***
Repsol	0.0083 ***
Rosneft	0.0333 ***
Royal Dutch Shell	0.0916 ***

Saudi Aramco	0.0416 ***
Sibneft	0.0000
Sidanco	0.0000
Sinopec	0.0000
Slavneft	0.0000
SOCAR	0.0000
Sonatrach	0.1166 ***
SPC	0.0000
Statoil	0.0000
Surgutneftegas	0.0000
Talisman Energy	0.0000
Tatneft	0.0000
Texaco	0.0000
TNK-BP	0.0000
Total	0.0000
Tyumen Oil	0.0000
Unocal Corporation	0.0000
Yukos	0.0000

Notes: We define and calculate a firm's probability of having an economically significant profitable deviation as the fraction of alternative strategies simulated that would yield a payoff, as evaluated using our estimated structural parameters, more than one billion dollars per year higher than would the optimal strategy as given by our estimated policy functions.
Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 8: Determinants of a firm's probability of an economically significant profitable deviation

	Dependent variable is: Statistically significant probability of an economically significant profitable deviation
OPEC membership (dummy)	0.0235
	(0.0196)
State ownership (in percentage)	-0.000170
	(0.000155)
Oil reserves (million barrels)	-0.000000032
	(0.000000157)
Natural gas reserves (BCF)	0.000000105 ***
.	(0.000000029)
Lagged dummy for merger	-0.0298
	(0.0937)
Lagged dummy for acquiring another firm	-0.0179
	(0.0362)
Constant	0.0281 **
	(0.0086)
N	283
R^2	0.068

Notes: The value of the dependent variable is zero for firms whose probability of an economically significant profitable deviation is not significant at a 5% level. We define and calculate a firm's probability of having an economically significant profitable deviation as the fraction of alternative strategies simulated that would yield a payoff, as evaluated using our estimated structural parameters, more than one billion dollars per year higher than would the optimal strategy as given by our estimated policy functions. Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 9: Changes in welfare from base case when all firms are members of OPEC

	All firms
Expected total firm payoff	53.6844 ***
Expected avg firm payoff	1.0737 ***
Min firm payoff	0.0620 ***
Max firm payoff	0.1101
Expected total consumer surplus	-4.90e+09 ***

Notes: Table reports the difference between the value of the respective welfare statistic under the counterfactual scenario in which all firms are members of OPEC, and the value of the respective welfare statistic under the base-case status quo simulation of no counterfactual change. Firm payoffs and consumer surplus are in billion dollars per year. Significance codes from two-sample t-tests comparing the welfare from the counterfactual OPEC membership scenario to the welfare from the base-case status quo simulation: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 10: Change in action variables from base case when all firms are members of OPEC

	All firms
Oil output (KBD)	-317.1271 ***
Natural gas output (MCFD)	-1728.641 ***
Exploration capex (2005 US$)	-138.822 ***
Development capex (2005 US$)	-392.5024 ***
Acquisition capex (2005 US$)	-261.2711 ***

Notes: Table reports the difference between the respective action variable under the counterfactual scenario in which all firms are members of OPEC, and the respective action variable under the base-case status quo simulation of no counterfactual change. Significance codes from two-sample t-tests comparing the action variables from the counterfactual OPEC membership scenario to the welfare from the base-case status quo simulation: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Appendix A. Supplementary Tables and Figures

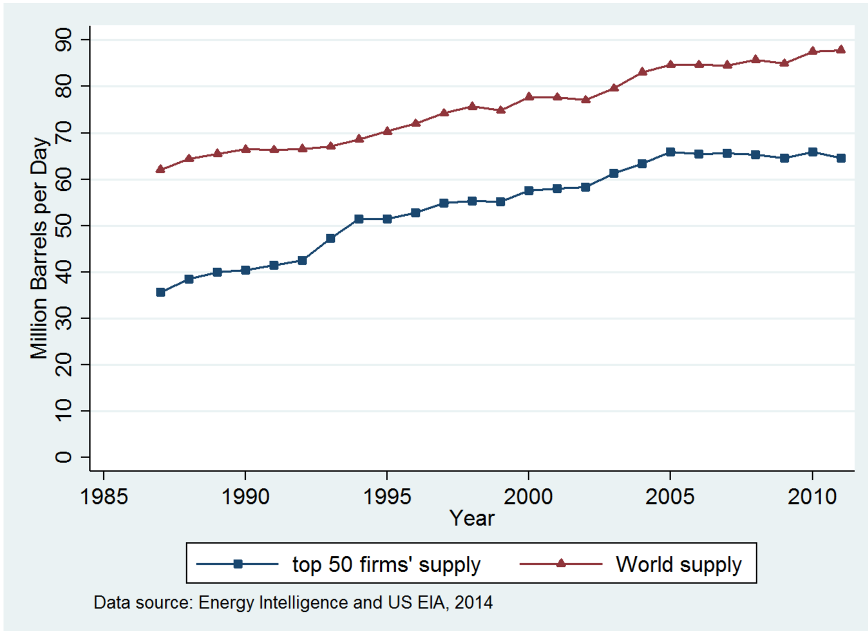

Figure A.1: World oil supply vs top 50 producers supply in MMBD

Table A.1: Summary statistics for action variables

Variable	# Obs	Mean	Std. Dev.	Min	Max
Oil output (KBD)	1250	1089.934	1407.45	4	11035
Natural gas output (MCFD)	1250	2951.507	6528.964	0	55901.06
Exploration capex (million 2005 US$)	300	520.385	596.664	-13.232	2760.085
Development capex (million 2005 US$)	300	1743.55	2043.468	0	9045
Acquisition capex (million 2005 US$)	295	531.016	1720.282	-142.899	17625
Dummy for M&A at time t					
merging with another firm	1296	0.005	0.067	0	1
acquiring another firm	1296	0.012	0.11	0	1
being acquired by another firm	1296	0.009	0.095	0	1

Table A.2: Summary statistics for firm level state variables

Variable	# Obs	Mean	Std. Dev.	Min	Max
OPEC membership at time t (dummy)	1316	0.211	0.408	0	1
State ownership (in percentage)	1316	49.858	46.344	0	100
Oil reserves (million barrels)	1250	19473.12	45401.37	22	296501
Natural gas reserves (BCF)	1250	72399.95	177989.3	0	1320000

Table A.3: Summary statistics for prices of oil and natural gas

Variable	# Obs	Mean	Std. Dev.	Min	Max
Crude oil price, Brent (2005 US$/bbl)	25	35.6445	23.3058	13.6616	90.5464
Natural gas price, US (2005 US$/mmbtu)	25	3.6833	2.14151	1.5439	8.9157
Regional natural gas price (2005 US$/mmbtu)					
Africa	9	6.0782	2.2554	3.3171	9.6790
Asia & Oceania	9	12.1561	3.2825	8.2034	18.1676
Eurasia	9	1.3760	0.5569	0.7106	2.1370
Europe	9	10.2351	4.0633	5.1570	16.6824
Middle East	9	8.8214	3.4490	5.3768	15.1544
America	9	6.8508	2.2628	3.9221	10.7228

Table A.4: Estimation results for policy functions

	Dependent variable is:				
	Oil output	Natural gas output	Exploration capex	Development capex	Acquisition capex
Avg capital compensation (million 2005 US$)					
on transport equipment	0.761	4.030	2.246	7.716	10.85
	(2.655)	(7.666)	(5.110)	(14.23)	(21.58)
on other machinery and equipment	0.0934	0.491	0.177	0.520	0.546
	(0.172)	(0.496)	(0.331)	(0.921)	(1.397)
on total non-residential investment	0.131	0.549	0.219	0.162	0.127
	(0.208)	(0.602)	(0.401)	(1.117)	(1.694)
on other assets	0.0225	-0.148	-0.190	-0.810	0.0379
	(0.238)	(0.688)	(0.459)	(1.278)	(1.938)
Oil reserves (million Barrels)	0.102***	-0.0298*	0.000859	-0.00840	-0.0380
	(0.00475)	(0.0137)	(0.00914)	(0.0254)	(0.0386)
Natural gas reserves (BCF)	0.0111***	0.0996***	0.0205***	0.0490***	0.0184
	(0.00163)	(0.00470)	(0.00313)	(0.00872)	(0.0132)
Avg weekly earning (2005 US$)					
on oil and gas extraction	1.260	5.709	3.450	4.734	-6.329
	(2.339)	(6.753)	(4.501)	(12.53)	(19.01)
on supporting activities in oil and gas	0.874	4.311	3.434	7.274	-0.546
	(2.373)	(6.852)	(4.567)	(12.72)	(19.29)
Cumulative oil output (KBD)	0.0113*	-0.0779***	0.0101	0.0408	-0.00104
	(0.00474)	(0.0137)	(0.00912)	(0.0254)	(0.0385)
Cumulative gas output (MCFD)	-0.000100	0.0240***	-0.00340	-0.00831	0.00561
	(0.00167)	(0.00481)	(0.00321)	(0.00893)	(0.0135)

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table A.4: (continued)

	Dependent variable is:				
	Oil output	Natural gas output	Exploration capex	Development capex	Acquisition capex
Aggregate oil output (KBD)	-0.00424	-0.0315	-0.00614	0.000890	-0.0116
	(0.0252)	(0.0727)	(0.0485)	(0.135)	(0.205)
Aggregate gas output (MCFD)	-0.000200	0.00737	0.00407	0.00377	-0.0120
	(0.00625)	(0.0180)	(0.0120)	(0.0335)	(0.0508)
Cumulative					
exploration capex (2005 US$)	0.0340	-0.0343	0.186***	0.0371	0.109
	(0.0183)	(0.0528)	(0.0352)	(0.0980)	(0.149)
development capex (million 2005 US$)	-0.00169	0.0727***	-0.0547***	0.0487	-0.0420
	(0.00608)	(0.0176)	(0.0117)	(0.0326)	(0.0495)
acquisition capex (million 2005 US$)	0.00137	0.0315**	-0.0186*	0.0191	0.0314
	(0.00404)	(0.0117)	(0.00778)	(0.0217)	(0.0329)
Aggregate					
exploration capex (million 2005 US$)	0.0143	0.0732	-0.0168	0.0104	0.181
	(0.0733)	(0.212)	(0.141)	(0.393)	(0.596)
development capex (million 2005 US$)	0.00849	0.0224	0.00821	-0.0103	0.00210
	(0.0114)	(0.0329)	(0.0219)	(0.0611)	(0.0926)
acquisition capex (million 2005 US$)	-0.00572	-0.0300	-0.00720	0.00700	-0.0250
	(0.0109)	(0.0315)	(0.0210)	(0.0584)	(0.0886)
Aggregate oil reserves (million barrels)	-0.00480	-0.0198	-0.00717	-0.00923	-0.00395
	(0.00553)	(0.0160)	(0.0106)	(0.0296)	(0.0449)
Aggregate gas reserves (BCF)	0.000108	0.000539	0.000304	0.000799	0.000647
	(0.000218)	(0.000630)	(0.000420)	(0.00117)	(0.00177)

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table A.4: (continued)

	Dependent variable is:				
	Oil output	Natural gas output	Exploration capex	Development capex	Acquisition capex
World GDP per capita (2005 US$)	-1.234	-6.065	-3.163	-5.290	7.063
	(2.275)	(6.567)	(4.377)	(12.19)	(18.49)
Percentage of state ownership	1.158**	-7.148***	-3.318***	-6.515**	-2.339
	(0.426)	(1.230)	(0.820)	(2.283)	(3.463)
Lag dummy for merger	204.3	1617.3***	-145.3	-421.1	-234.9
	(161.0)	(464.7)	(309.7)	(862.5)	(1308.1)
Lag dummy for acquiring another firm	177.2	414.5	-119.1	-122.6	4035.3***
	(92.10)	(265.9)	(177.2)	(493.5)	(748.5)
Constant	9036.9	42039.7	17489.3	25295.1	-33943.4
	(14302.4)	(41292.6)	(27522.5)	(76637.4)	(116237.7)
N	252	252	252	252	252
R^2	0.933	0.950	0.617	0.748	0.255
Root MSE	206.94	597.46	398.22	1108.9	1681.8

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table A.5: Oil and natural gas production policy functions for OPEC firms

	Dependent variable is:	
	Oil output	Natural gas output
Avg capital compensation (million 2005 US$)		
on transport equipment	-4.065	-10.62
	(34.87)	(42.65)
on other machinery and equipment	-0.204	-0.834
	(1.402)	(1.715)
on total non-residential investment	-0.0981	-0.0783
	(0.304)	(0.372)
on other assets	0.459	1.415
	(2.110)	(2.581)
Oil reserves (million Barrels)	0.0176***	0.000415
	(0.00144)	(0.00176)
Natural gas reserves (BCF)	0.000524	0.00186***
	(0.000266)	(0.000326)
Avg weekly earning (2005 US$)		
on supporting activities in oil and gas	-0.586	-2.412
	(7.484)	(9.155)
Cumulative oil output (KBD)	0.0386***	-0.00133
	(0.00537)	(0.00657)
Cumulative gas output (MCFD)	0.0119***	0.103***
	(0.00346)	(0.00423)
Aggregate oil output (KBD)	0.0282	0.0148
	(0.122)	(0.149)
Aggregate gas output (MCFD)	-0.00801	-0.00309
	(0.0344)	(0.0421)
Aggregate oil reserves (million barrels)	0.000392	0.00662
	(0.0149)	(0.0182)
Aggregate gas reserves (BCF)	-0.0000213	-0.000514
	(0.00187)	(0.00229)
World GDP per capita (2005 US$)	2.316	1.402
	(7.867)	(9.624)
World population	-8.492	-8.726
	(38.08)	(46.58)

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table A.5: (continued)

	Dependent variable is:	
	Oil output	Natural gas output
Aggregate exploration capex (million 2005 US$)	-0.00534	0.00711
	(0.226)	(0.277)
Aggregate development capex (million 2005 US$)	0.0110	0.0203
	(0.101)	(0.123)
Aggregate acquisition capex (million 2005 US$)	0.00231	0.0196
	(0.0643)	(0.0787)
Constant	30697.6	36317.5
	(205966.5)	(251941.4)
N	173	173
R^2	0.900	0.863
Root MSE	725.51	887.45

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table A.6: Multinomial logit regression of decisions on merger and acquisitions for non-OPEC firms that are not 100% state-owned

	(1)	(2)	(3)	(4)†	(5)
0: Base outcome					
1: Merge					
Oil reserves (million barrels)	-0.000969	-0.0184	-0.000678	-0.000692	-0.0241
	(0.00115)	(16.30)	(0.000923)	(0.000915)	(38.84)
Natural gas reserves (BCF)	0.000171	0.00623	0.000106	0.0000843	0.00625
	(0.000191)	(2.830)	(0.000155)	(0.000147)	(8.071)
Cumulative oil output (KBD)	0.000629	0.00901	0.000477	0.000389	0.0142
	(0.000749)	(15.23)	(0.000681)	(0.000558)	(20.92)
Cumulative natural gas output (MCFD)	-0.0000306	0.00313	-0.0000275	-0.0000449	
	(0.000259)	(10.78)	(0.000215)	(0.000151)	
Avg industry rate of return on capital	-95.99		-65.55		
	(64.26)		(41.02)		
Avg capital compensation (million 2005 US$)					
on other machinery and equipment		-0.964			-0.901
		(212.1)			(133.0)
on total non-residential investment	0.00105	0.00532		0.000208	0.00519
	(0.00119)	(4.109)		(0.000715)	(2.559)
Percentage of state ownership	-3.835	-5.975	-3.905	-3.359	-5.160
	(601.5)	(2604.6)	(627.0)	(464.2)	(1581.6)
Lag dummy for merger	-14.09	222.8	-15.09	-15.77	210.2
	(308979.2)	(1682718.4)	(213014.2)	(126734.6)	(1829812.3)
Lag dummy for acquiring another firm	-20.97	-7.690	-20.86	-19.15	-14.89
	(46820.3)	(399914.3)	(54990.4)	(37619.4)	(564250.7)

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.
† Specification used in structural model.

Table A.6: (continued)

	(1)	(2)	(3)	(4)†	(5)
Cumulative exploration capex (million 2005 US$)	-0.00174	-0.0825	-0.00138	-0.000288	-0.0694
	(0.00175)	(42.33)	(0.00148)	(0.000939)	(22.40)
Cumulative development capex (million 2005 US$)	0.000363	0.0163	0.000314	0.0000469	0.0152
	(0.000457)	(4.922)	(0.000438)	(0.000327)	(4.906)
Cumulative acquisition capex (million 2005 US$)	-0.000364	-0.00801	-0.000204	-0.000237	-0.00782
	(0.000451)	(2.525)	(0.000413)	(0.000368)	(1.918)
Constant	4.092	1377.3	4.216	-4.408	1290.8
	(4.837)	(310162.1)	(4.736)	(2.483)	(177846.4)
2: Acquire another firm					
Oil reserves (million barrels)	-0.000999	-0.000756	-0.00102	-0.00108*	-0.000132
	(0.000571)	(0.000500)	(0.000570)	(0.000533)	(0.000384)
Natural gas reserves (BCF)	-0.000236*	-0.000483*	-0.000234*	-0.000224*	-0.0000764
	(0.000109)	(0.000197)	(0.000108)	(0.000101)	(0.0000697)
Cumulative oil output (KBD)	0.0000650	0.000553	0.0000465	-0.0000236	-0.000295
	(0.000293)	(0.000395)	(0.000282)	(0.000245)	(0.000218)
Cumulative natural gas output (MCFD)	-0.000350*	-0.000708**	-0.000343*	-0.000331*	
	(0.000151)	(0.000273)	(0.000146)	(0.000138)	
Avg industry rate of return on capital	-41.81		-37.44		
	(34.26)		(25.80)		
Avg capital compensation (million 2005 US$)					
on other machinery and equipment		-0.0109*			-0.00257
		(0.00513)			(0.00199)
on total non-residential investment	0.000173	-0.000193		-0.000366	-0.000747
	(0.000826)	(0.000640)		(0.000586)	(0.000513)

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.
† Specification used in structural model.

Table A.6: (continued)

	(1)	(2)	(3)	(4)†	(5)
Percentage of state ownership	-0.0203	-0.0880	-0.0148	-0.0129	-0.00616
	(0.0534)	(0.0583)	(0.0459)	(0.0448)	(0.0382)
Lag dummy for merger	-23.17	-25.86	-22.41	-21.00	-26.71
	(139116.7)	(1075955.0)	(95709.8)	(52089.2)	(1071192.3)
Lag dummy for acquiring another firm	-22.49	-29.56	-21.74	-20.94	-27.23
	(53086.1)	(369831.2)	(37340.2)	(26521.0)	(503787.3)
Cumulative exploration capex (million 2005 US$)	0.00136	0.00127	0.00142	0.00162*	0.00170
	(0.000854)	(0.00101)	(0.000802)	(0.000792)	(0.000945)
Cumulative development capex (million 2005 US$)	0.0000737	0.000293	0.0000560	0.0000163	-0.000403
	(0.000291)	(0.000423)	(0.000276)	(0.000259)	(0.000305)
Cumulative acquisition capex (million 2005 US$)	0.000314*	0.000376*	0.000329*	0.000326*	0.000186
	(0.000146)	(0.000162)	(0.000133)	(0.000141)	(0.000103)
Constant	0.817	15.15	0.822	-2.402	2.439
	(2.967)	(8.012)	(2.964)	(1.901)	(3.743)
N	244	244	244	244	244
pseudo R^2	0.484	0.724	0.474	0.420	0.553

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.
† Specification used in structural model.

Table A.7: Logit regression of decisions on selling (being acquired) for non-OPEC firms that are not 100% state-owned

	(1)	(2)†	(3)	(4)	(5)
Oil reserves (million barrels)	-0.000225	-0.000217	-0.000198	-0.000110	-0.000262
	(0.000239)	(0.000239)	(0.000239)	(0.000231)	(0.000173)
Natural gas reserves (BCF)	-0.0000643	-0.0000640	-0.0000706	-0.0000816	-0.0000576
	(0.0000702)	(0.0000704)	(0.0000733)	(0.0000761)	(0.0000644)
Cumulative oil output (KBD)	0.0000341	0.0000391	0.0000279	0.00000187	0.0000868
	(0.000193)	(0.000203)	(0.000204)	(0.000182)	(0.0000807)
Cumulative natural gas output (MCFD)	0.0000140	0.0000151	0.0000234	0.0000277	
	(0.0000566)	(0.0000587)	(0.0000597)	(0.0000543)	
Avg industry rate of return on capital	-41.99**		-31.07*		
	(15.79)		(12.13)		
Avg capital compensation (million 2005 US$)					
on other machinery and equipment		-0.00365*			-0.00367*
		(0.00159)			(0.00159)
on total non-residential investment	0.000364	-0.000117		-0.0000388	-0.000112
	(0.000256)	(0.000201)		(0.000146)	(0.000200)
Percentage of state ownership	-0.00456	-0.00743	-0.00152	-0.00413	-0.00904
	(0.0158)	(0.0155)	(0.0153)	(0.0145)	(0.0143)
Constant	0.947	3.846	0.908	-3.035***	3.909
	(1.546)	(2.757)	(1.507)	(0.703)	(2.747)
N	574	600	574	600	600
pseudo R^2	0.158	0.171	0.138	0.057	0.171

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.
† Specification used in structural model.

Table A.8: Estimated transition densities for oil and natural gas reserves and state ownership

	Dependent variable is:		
	Oil reserves (million barrels)	Natural gas reserves (BCF)	percentage of state ownership
Lag oil reserves (million barrels)	0.774***	-0.789***	-0.000521
	(0.0590)	(0.127)	(0.000424)
Lag natural gas reserves (BCF)	-0.00558	0.941***	0.000337**
	(0.0175)	(0.0378)	(0.000125)
Lag oil output (KBD)	1.785***	7.502***	0.00379
	(0.460)	(0.993)	(0.00331)
Lag natural gas output (MCFD)	-0.142	-0.585*	-0.00237*
	(0.129)	(0.278)	(0.000924)
Lag exploration capex (million 2005 US$)	-0.353	-1.077	-0.00263
	(0.304)	(0.655)	(0.00218)
Lag development capex (million 2005 US$)	-0.0513	0.0464	0.000445
	(0.113)	(0.244)	(0.000814)
Lag acquisition capex (million 2005 US$)	-0.0206	-0.0896	-0.000134
	(0.0492)	(0.106)	(0.000354)
Lag Percentage of state ownership	-4.954	-5.762	0.868***
	(3.254)	(7.024)	(0.0233)
Lag dummy for merger	4199.2***	13760.5***	-0.0118
	(995.3)	(2148.5)	(7.160)
Lag dummy for acquiring another firm	1147.0*	6993.3***	-2.989
	(540.3)	(1166.3)	(3.886)
Constant	319.1	30.32	1.372
	(184.2)	(397.6)	(1.307)
N	249	249	252

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table A.8: (continued)

	Dependent variable is:		
	Oil reserves (million barrels)	Natural gas reserves (BCF)	percentage of state ownership
R^2	0.913	0.968	0.920
Root MSE	1381.7	2982.8	9.9398

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table A.9: Estimated transition density for avg industry rate of return on capital

	Dependent variable is: Avg industry rate of return on capital for mining and quarry
Lag avg industry rate of return on capital for mining and quarry	-1.005***
	(0.0295)
Lag aggregate oil reserves (million Barrels)	0.000000987***
	(2.86e-08)
Lag aggregate natural gas reserves (BCF)	-5.80e-08***
	(2.11e-09)
Lag avg capital compensation (million 2005 US$)	
on other machinery and equipment	-0.0000540***
	(0.00000144)
on total non-residential investment	0.00000925***
	(0.00000105)
Lag world road sector gasoline fuel consumption (kt of oil equivalent)	0.00000241***
	(0.000000115)
Lag world population (million people)	-0.000926***
	(0.0000281)
Lag world GDP per capita (2005 US$)	-0.0000776***
	(0.00000757)
Lag world electricity production (kWh)	
from natural gas sources	2.98e-13***
	(9.28e-15)
from oil sources	-1.03e-12***
	(2.45e-14)
Lag aggregate output of all firms	
Oil (KBD)	0.000000341
	(0.000000325)
Natural gas (MCFD)	-0.00000177***
	(0.000000121)
Constant	4.296***
	(0.0779)
N	750
R^2	0.970
Root MSE	0.00613

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table A.10: Estimated transition density for avg capital compensation on other machinery and equipment

	Dependent variable is: Avg capital compensation on other machinery and equipment
Lag avg industry rate of return on capital	
for mining and quarry	1365.0***
	(348.4)
Lag aggregate oil reserves (million barrels)	0.0196***
	(0.000348)
Lag aggregate natural gas reserves (BCF)	-0.00105***
	(0.0000287)
Lag avg capital compensation (million 2005 US$)	
on other machinery and equipment	0.0439*
	(0.0188)
on total non-residential investment	-0.0155
	(0.0129)
Lag world road sector	
gasoline fuel consumption (kt of oil equivalent)	0.0479***
	(0.00123)
Lag world population (million people)	-12.85***
	(0.288)
Lag world GDP per capita (2005 US$)	-4.037***
	(0.103)
Lag world electricity production (kWh)	
from natural gas sources	5.33e-09***
	(1.26e-10)
from oil sources	-3.48e-09***
	(2.70e-10)
Lag aggregate output of all firms	
Oil (KBD)	-0.100***
	(0.00431)
Natural gas (MCFD)	-0.00540***
	(0.00152)
Constant	48009.7***
	(1023.5)
N	799
R^2	0.984
Root MSE	84.461

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table A.11: Estimated transition density for avg capital compensation on total non-residential investment

	Dependent variable is: Avg capital compensation on total non-residential investment
Lag avg industry rate of return on capital for mining and quarry	-9793.8***
	(1027.7)
Lag aggregate oil reserves (million barrels)	0.0238***
	(0.00103)
Lag aggregate natural gas reserves (BCF)	-0.00133***
	(0.0000847)
Lag avg capital compensation (million 2005 US$) on other machinery and equipment	-1.862***
	(0.0554)
on total non-residential investment	0.288***
	(0.0382)
Lag world road sector gasoline fuel consumption (kt of oil equivalent)	0.0913***
	(0.00363)
Lag world population (million people)	-18.10***
	(0.850)
Lag world GDP per capita (2005 US$)	2.459***
	(0.303)
Lag world electricity production (kWh) from natural gas sources	2.57e-09***
	(3.73e-10)
from oil sources	-2.77e-08***
	(7.96e-10)
Lag aggregate output of all firms Oil (KBD)	-0.221***
	(0.0127)
Natural gas (MCFD)	-0.0479***
	(0.00447)
Constant	52944.6***
	(3018.8)
N	799
R^2	0.988
Root MSE	249.12

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table A.12: Estimated transition density for world road sector gasoline fuel consumption

	Dependent variable is: World road sector gasoline fuel consumption (kt of oil equivalent)
Lag avg industry rate of return on capital for mining and quarry	-67174.8***
	(7757.0)
Lag aggregate oil reserves (million barrels)	0.0681***
	(0.00774)
Lag aggregate natural gas reserves (BCF)	-0.00510***
	(0.000639)
Lag avg capital compensation (million 2005 US$) on other machinery and equipment	-3.795***
	(0.418)
on total non-residential investment	1.360***
	(0.288)
Lag world road sector gasoline fuel consumption (kt of oil equivalent)	0.656***
	(0.0274)
Lag world population (million people)	125.3***
	(6.413)
Lag world GDP per capita (2005 US$)	-40.56***
	(2.286)
Lag world electricity production (kWh) from natural gas sources	-5.56e-08***
	(2.81e-09)
from oil sources	-8.99e-08***
	(6.01e-09)
Lag aggregate output of all firms Oil (KBD)	2.995***
	(0.0960)
Natural gas (MCFD)	0.378***
	(0.0338)
Constant	-226225.2***
	(22785.8)
N	799
R^2	0.998
Root MSE	1880.3

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table A.13: Estimated transition density for world motor vehicles

	Dependent variable is: World motor vehicles (per 1,000 people)
Lag aggregate oil reserves (million barrels)	-0.000708***
	(0.000154)
Lag avg capital compensation (million 2005 US$) on total non-residential investment	0.0283**
	(0.0102)
Lag world road sector gasoline fuel consumption (kt of oil equivalent)	0.000419*
	(0.000200)
Lag world motor vehicles (per 1,000 people)	1.232***
	(0.341)
Lag world electricity production (kWh) from natural gas sources	-1.25e-10***
	(3.35e-11)
from oil sources	7.30e-11
	(1.53e-10)
Lag aggregate oil output of all firms (KBD)	0.0144***
	(0.00355)
Constant	-375.4
	(384.0)
N	432
R^2	0.847
Root MSE	4.2212

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table A.14: Estimated transition density for world electricity production from natural gas sources

	Dependent variable is: World electricity production from natural gas sources (kWh)
Lag avg industry rate of return on capital for mining and quarry	-1.00546e+12***
	(5.49455e+10)
Lag aggregate oil reserves (million barrels)	667398.1***
	(54844.7)
Lag aggregate natural gas reserves (BCF)	-1946.8
	(4529.8)
Lag avg capital compensation (million 2005 US$) on other machinery and equipment	-137198427.2***
	(2959959.6)
on total non-residential investment	-38581285.1***
	(2040441.5)
Lag world road sector gasoline fuel consumption (kt of oil equivalent)	-958016.6***
	(193818.5)
Lag world population (million people)	1.23760e+09***
	(45427800.1)
Lag world GDP per capita (2005 US$)	447240369.9***
	(16189014.5)
Lag world electricity production (kWh) from natural gas sources	-0.391***
	(0.0199)
from oil sources	-2.678***
	(0.0425)
Lag aggregate output of all firms Oil (KBD)	27159110.5***
	(680113.6)
Natural gas (MCFD)	11117179.1***
	(239226.4)
Constant	-6.26490e+12***
	(1.61399e+11)
N	799
R^2	1.000
Root MSE	1.3e10

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table A.15: Estimated transition density for world electricity production from oil sources

	Dependent variable is: World electricity production from oil sources (kWh)
Lag avg industry rate of return on capital	
for mining and quarry	-1.29705e+12***
	(4.12199e+10)
Lag aggregate oil reserves (million barrels)	-554911.8***
	(41144.2)
Lag aggregate natural gas reserves (BCF)	48747.4***
	(3398.2)
Lag avg capital compensation (million 2005 US$)	
on other machinery and equipment	21049440.2***
	(2220549.6)
on total non-residential investment	22978949.9***
	(1530730.9)
Lag world road sector	
gasoline fuel consumption (kt of oil equivalent)	-116019.6
	(145401.9)
Lag world population (million people)	-70654784.0*
	(34079749.4)
Lag world GDP per capita (2005 US$)	127831765.8***
	(12144932.3)
Lag world electricity production (kWh)	
from natural gas sources	-0.186***
	(0.0150)
from oil sources	-0.0661*
	(0.0319)
Lag aggregate output of all firms	
Oil (KBD)	10355770.0***
	(510218.5)
Natural gas (MCFD)	-555873.4**
	(179466.7)
Constant	1.18372e+12***
	(1.21081e+11)
Observations	799
R^2	0.988
Root MSE	1.0e10

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table A.16: Estimated transition density for world population

	Dependent variable is: World population (million people)
Lag world population (million people)	0.994***
	(0.000149)
Constant	116.8***
	(0.890)
N	1203
R^2	1.000
Root MSE	2.8701

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table A.17: Estimated transition density for GDP per capita

	Dependent variable is: World GDP per capita (2005 US$)
Lag world GDP per capita (2005 US$)	1.003***
	(0.00411)
Constant	71.11**
	(26.59)
N	1203
R^2	0.980
Root MSE	95.064

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table A.18: Estimated transition densities for regional population

	Dependent variable is: Regional population					
	Africa	Asia and Oceania	Eurasia	Europe	Middle East	Americas
Lag regional population	1.022***	0.982***	0.815***	0.979***	1.014***	0.991***
	(0.000793)	(0.000535)	(0.0797)	(0.0192)	(0.00553)	(0.00132)
Constant	2377399.5**	102604406.2***	53407212.6*	14702775.6	1865626.2	18512826.5***
	(632438.5)	(1781063.3)	(22869701.1)	(11008355.2)	(927779.4)	(1082268.0)
N	24	24	24	24	24	24
R^2	1.000	1.000	0.826	0.992	0.999	1.000
Root MSE	5.2e5	8.0e5	9.8e5	1.6e6	7.6e5	4.9e5

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table A.19: Estimated transition densities for regional GDP

	Dependent variable is: Regional GDP (2005 US$)					
	Africa	Asia and Oceania	Eurasia	Europe	Middle East	Americas
Lag regional GDP	1.153***	1.151***	1.062***	1.005***	1.146***	1.041***
	(0.0439)	(0.0379)	(0.0862)	(0.0520)	(0.0597)	(0.0221)
Constant	-4.48941e+10	-6.11064e+11	5.56731e+10	5.59495e+11	-3.05928e+10	1.92957e+11
	(3.83697e+10)	(3.56436e+11)	(8.55987e+10)	(6.42472e+11)	(5.78489e+10)	(3.03131e+11)
N	24	24	24	24	24	24
R^2	0.969	0.977	0.873	0.944	0.944	0.990
Root MSE	9.2e10	6.6e11	2.5e11	1.1e12	1.5e11	5.1e11

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table A.20: Welfare

Variable	All firms	OPEC firms	Non-OPEC firms
Expected total firm payoff	63.0721 ***	37.0672 ***	26.0049 ***
	(11.2308)	(4.4646)	(6.7669)
Expected avg. firm payoff	1.2614 ***	3.3048 ***	0.6719 ***
	(0.2246)	(0.3960)	(0.1749)
Min firm payoff	-3.9834 ***	-3.9834 ***	-0.6357 *
	(0.2105)	(0.2105)	(0.2554)
Max firm payoff	14.3074 ***	14.3074 ***	10.3077 ***
	(0.9821)	(0.9821)	(0.9953)
Expected total consumer surplus	3.12e+10 ***		
	(6.48e+09)		

Notes: Firm payoffs and consumer surplus are in billion dollars per year.

Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table A.21: Summary statistics for action variables predicted by structural model (2000-2005)

	All firms		OPEC firms		Non-OPEC firms	
Variable	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Oil output (KBD)	1503.514 ***	1796.073 ***	2512.852 ***	2562.346 ***	1028.842 ***	967.779 ***
	(43.788)	(71.594)	(160.515)	(113.881)	(11.299)	(8.659)
Natural gas output (MCFD)	3874.760 ***	7502.254 ***	3336.468 ***	3383.802 ***	4135.609 ***	8784.601 ***
	(155.890)	(103.774)	(231.449)	(141.766)	(122.972)	(124.555)
Capital expenditure on						
Exploration (million 2005 US$)	679.122 ***	897.901 ***	1126.927 ***	1139.218 ***	466.955 ***	657.581 ***
	(19.319)	(9.175)	(35.132)	(10.234)	(20.062)	(11.838)
Development (million 2005 US$)	1832.241 ***	2577.189 ***	3091.026 ***	3421.532 ***	1232.528 ***	1766.299 ***
	(22.778)	(21.113)	(84.241)	(28.691)	(15.390)	(18.242)
Acquisition (million 2005 US$)	776.833 ***	1376.407 ***	499.663 ***	954.628 ***	908.868 ***	1517.305 ***
	(19.530)	(26.413)	(8.003)	(8.435)	(27.168)	(32.139)
Dummy for M&A at time t						
merging	0.174 ***	0.379 ***			0.225 ***	0.418 ***
	(0.002)	(0.001)			(0.001)	(0.001)
acquiring another firm	0.048 ***	0.212 ***			0.062 ***	0.240 ***
	(0.004)	(0.009)			(0.005)	(0.010)
being acquired by another firm	0.003 ***	0.036 ***			0.003 ***	0.041 ***
	(0.000)	(0.002)			(0.000)	(0.003)

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Appendix B. Oil Demand and the Natural Gas Market

B.1 Oil demand

We estimate a simple econometric model of oil demand as an input to our structural model. As the price elasticity of oil demand is an input to rather than the primary output of our structural model, the price elasticity of oil demand that we input into our structural model need not necessarily be one that we estimate ourselves. Nevertheless, we estimate a parsimonious model of oil demand using our data set, as detailed below, and find that our estimated price elasticity of oil demand is in the range of previous estimates of price elasticity of oil demand in the literature. The results of our structural model are therefore robust to whether the price elasticity of oil demand we use for our structural model was chosen based on previous estimates of price elasticity of oil demand in the literature, or instead based on our own estimate of the price elasticity of oil demand.

To estimate a simple econometric model of oil demand as an input to our structural model, we use annual oil production data of the top 50 producers over the period 1987-2011 along with oil price data to estimate the oil demand equation (**??**). Because observed equilibrium prices and quantities are simultaneously determined in the supply-and-demand system, instrumental variables are needed to address the endogeneity problem (Manski, 1995; Goldberger, 1991; Angrist et al., 2000; Lin, 2011). We instrument for oil price using either real average weekly earnings for support activities in oil and gas extraction or lagged real average weekly earnings for support activities in oil and gas extraction. These variables are supply shifters that affect the costs of producing oil but not the demand for oil, and therefore serve as good instruments for oil price. The first-stage F-statistics are over 12 in both specifications of oil demand, and the instruments pass tests of underidentification and weak-instrument-robust inference.

Estimation results for oil demand are reported in Table B.1. The coefficient on crude oil price is significant and negative in both specifications of the model, which makes sense as it indicates a downward sloping demand curve for crude oil. Demand for oil is increasing with world GDP per capita, which has a significant coefficient in both specifications of the model.[8]

Our estimated price elasticity of oil demand ranges from -0.18 to -0.32, which is in the

[8] When included, natural gas prices do not have any significant effect on oil demand. Thus, because we are limited in the number of regressors we can include owing to our small sample size, we do not include natural gas prices in our specification of oil demand.

range of previous estimates of price elasticity of oil demand in the literature. For example, Cooper (2003) estimates that the long-run price elasticity of oil demand falls within the range -0.18 to -0.45 for the G7 group of countries: Canada, France, Germany, Italy, Japan, the United Kingdom, and the United States. As expected, since we estimate the price elasticity for the residual demand for oil sold by the top 50 producers, our estimated price elasticity of this residual oil demand is more elastic than global demand. For example, Caldara et al. (2019) derive VAR-consistent elasticities of of -0.14 for global oil demand.

We use specification (2) for our structural model, since using the lagged real average weekly earnings for support activities in oil and gas extraction as an instrument may more convincingly satisfy the exclusion restriction, since the realized oil price and oil market in one year is unlikely to have had an effect on real average weekly earnings for support activities in oil and gas extraction in the previous year.

Notwithstanding our simplistic econometric model of oil demand, whose estimated parameters are an input to rather than the primary output of our structural model, the price elasticity of oil demand we use for our structural model is in the range of previous estimates of price elasticity of oil demand in the literature. The results of our structural model are therefore robust to whether the price elasticity of oil demand we use for our structural model was chosen based on previous estimates of price elasticity of oil demand in the literature, or instead based on our own estimate of the price elasticity of oil demand.

B.2 Natural gas market

As our primary concern is to model the world oil market, our intent in including a parsimonious and stylized model of natural gas is to enable us to better model the world oil market, rather than to fully model and capture all the complexities of the natural gas market. Unlike the oil market, the natural gas market is not necessarily a global market. Due to the lack of a global pipeline network, the market for natural gas is mostly defined by proximity to supply sources and the availability of a pipeline. In order to estimate separate natural gas demand functions for 6 different regional markets, we collect and construct regional natural gas prices using data from the EIA, and regional population and GDP data from the World Bank. Our 6 regional natural gas markets are Africa; Asia and Oceania; Eurasia; Europe; the Middle East; and the Americas.

Africa accounts for about 2.8% of global natural gas consumption, the lowest natural gas consumption share out of all our 6 regions. We use data from Algeria, Egypt, Equatorial Guinea, Libya, Mozambique, and Nigeria to construct an average natural gas price for Africa.

The Asia and Oceania region accounts for just below 15% of global natural gas consumption. We use data from Australia, Brunei, Burma, China, Indonesia, and Malaysia to construct an average natural gas price for Asia and Oceania.

Eurasia accounts for over 20% of global natural gas consumption and is home to a significant share of the world's natural gas resources, which makes this region a net natural gas exporter. We use data along from Azerbaijan, Georgia, Kazakhstan, Russia, Turkmenistan, Ukraine, and Uzbekistan to construct an average natural gas price for Eurasia.

European Union (EU) countries account for about 20% of global natural gas consumption. Russia is the major supplier of EU natural gas imports. We use data from EU members and Turkey to construct an average natural gas price for Europe.

The Middle East accounts for just below 10% of global natural gas consumption, but is home to a significant share of the world's natural gas resources, which makes the region a net exporter of natural gas. We use data from Iran, Iraq, Oman, Qatar, UAE, and Yemen to construct an average natural gas price for the Middle East.

North and South America together account for about 32% of global natural gas consumption, and aside from the insignificant liquefied natural gas imports from outside of the continent, it is disconnected from natural gas markets in other parts of the world. Over the last decade, the North American natural gas market has been experiencing a boom as a result of the boost in shale gas extraction in the United States. We use data from Canada, Mexico, United States, Argentina, Bolivia, Brazil, Colombia, Peru, and Trinidad and Tobago to construct an average natural gas price for the Americas.

Since we only observe total annual natural gas production for each firm, but do not observe each firm's natural gas production in each of the 6 regional natural gas markets, we make the following assumptions about each firm's share of natural gas production in each regional market. First, we assume that oil and gas companies that are not state-owned divide up their total natural gas production each year to each region according to each region's average share of total natural gas consumption. Second, for oil and gas companies that are at least partially state-owned, if the state-owned company is in a country that does not export natural gas, then we assume that the state-owned company only sells to its own regional market. Third, for oil and gas companies that are at least partially state-owned and are in a country that exports natural gas, we assume that each year these state-owned companies allocate the production that is not already allocated to their own region to all regions (including their own) according to the respective region's average natural gas import shares. The regional average natural gas import shares are calculated as follows: for each region-year, we calculate what fraction of total natural gas imports (over all regions in the world) that year is imported into that region. We then average each region's annual fraction of imports over all years.

Thus, we assume that a state-owned company that is in a country that exports natural gas allocates a portion (equal to one minus its export share) of its natural gas production to its own region, and then allocates the remaining export share to all regions (including its own) according to the 6 regional natural gas import shares. The state-owned company's own region is double counted because the company may be exporting to another country in its own region.

B.3 Regional natural gas demand

We estimate a simple econometric model of regional natural gas demand as an input to our structural model. Once again, the price elasticities of regional natural demand are inputs to rather than the primary output of our structural model. Moreover, as our primary concern is to model the world oil market, our intent in including a parsimonious and stylized model of natural gas is to enable us to better model the world oil market, rather than to fully model and capture all the complexities of the natural gas market.

Unlike the global market for oil, natural gas markets are more regional due to lack of a global natural gas pipeline networks and natural gas prices change regionally. We estimate regional natural gas demand functions for 6 regions: Africa; Asia and Oceania; Eurasia; Europe; the Middle East; and the Americas. We use data on regional natural gas prices and quantity along with regional GDP and population to estimate the regional natural gas demand equation (**??**) for each region.

We instrument for natural gas prices using average capital compensation and lagged real average weekly earnings for oil and gas extraction as well as support activities in oil and gas extraction, and total natural gas reserves. These variables are supply shifters that affect the costs of producing natural gas but not demand for natural gas, and therefore serve as good instruments for natural gas price.

Tables B.2- B.7 report the estimated results for regional natural gas demand for each region respectively. The first-stage F-statistics as well as the p-values for underidentification, weak-instrument-robust inference, and overidentification tests are also reported. The specifications used in our structural model are indicated with a dagger (†).

While regional natural gas demand is weakly downward sloping for each region, there is variation in the demand parameters across regions, which provides support for our estimating separate regional natural gas demand functions for each of the 6 regions. As seen in the first column of Table B.4, the coefficient for natural gas price is negative and significant for the Eurasian natural gas market. The coefficient on regional GDP is also positive and significant for all regions.

The weak instrument robust inference tests test whether the coefficient on price (the endogenous regressor) is significant. The null hypothesis tested is that the coefficient on price in the structural equation is equal to zero, and, in addition, that the overidentifying restrictions are valid. Thus, when we pass both the weak instrument robust inference test (p-value ≤ 0.05) and the overidentification test (p-value > 0.05), as is the case with Eurasia, the Middle East, and the Americas, the coefficient on price is significant.[9]

Taken together, our results show that regional natural gas demand is weakly downward sloping for each region, and that there is a significant negative elasticity of demand for regional natural gas in Eurasia, the Middle East, and the Americas. While our primary concern is to model the world oil market, we include natural gas in our model because of joint production and other supply-side links in oil and natural gas (Roberts and Gilbert, 2020). Our intent in including a parsimonious and stylized model of regional natural gas demand is therefore to enable us to better model the world oil market, rather than to fully model and capture all the complexities of the natural gas market. In future work we hope to better incorporate and model additional complexities of the natural gas industry.

[9] When included, oil price does not have any significant effect on natural gas demand. Thus, because we are limited in the number of regressors we can include owing to our small sample size, we do not include oil price in our specifications of regional natural gas demand.

Table B.1: Estimated demand function for oil

	Dependent variable is: Oil quantity (KBD)	
	(1)	(2)†
Crude oil price, Brent (2005 US$/bbl)	-274.6**	-495.3*
	(102.1)	(205.8)
World GDP per capita (2005 US$)	17.66*	36.69*
	(8.427)	(16.35)
World population (million people)	1.936	-19.40
	(9.522)	(18.09)
World electricity production from oil sources (kWh)	-1.11e-08	-4.02e-08
	(1.60e-08)	(2.89e-08)
Constant	-50081.5	-7019.2
	(27851.5)	(45755.7)
Instruments used:		
Average weekly earning		
for support activities in oil and gas extraction	Y	
for support activities in oil and gas extraction (lagged)		Y
First stage F-statistic	21.62	12.44
p-value of underidentification test	0.0035	0.0488
p-value of weak-instrument-robust inference tests	0.0092	0.0002
Price elasticity of oil demand	-0.1796**	-0.3240*
	(0.0668)	(0.1346)
N	22	21
R^2	0.951	0.888
Root MSE	1810	2516

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.
† Specification used in structural model.

Table B.2: Estimated regional demand function for natural gas for Africa

	Dependent variable is: Regional natural gas consumption (MCFD)			
	(1)†	(2)	(3)	(4)
Natural gas regional price,(US$/mmbtu)	-2.213	-7.540	-14.97	-5.894
	(20.03)	(19.93)	(20.66)	(21.04)
Regional GDP (US$)	1.14e-09***	1.15e-09***	1.17e-09***	4.64e-10
	(1.14e-10)	(1.13e-10)	(1.15e-10)	(5.66e-10)
Regional population				0.00000456
				(0.00000355)
Constant	1688.1***	1706.9***	1732.9***	-1742.0
	(133.4)	(133.0)	(135.4)	(2713.4)
Instruments used:				
Lagged average weekly earnings (2005 US$)				
for oil and gas extraction	N	Y	Y	Y
for supporting activities in oil and gas	Y	Y	Y	N
Avg capital compensation (million 2005 US$)				
on other machinery and equipment	Y	N	Y	N
on transport equipment	Y	Y	N	N
on total non-residential investment	Y	Y	Y	Y
Avg industry rate of return on capital	Y	Y	Y	Y
Aggregate gas reserve (BCF)	Y	Y	Y	N
First stage F-statistic	17.61	74.20	2.60	5.38
p-value of underidentification test	0.1777	0.1746	0.2017	0.0478
p-value of weak-instrument-robust inference tests	0.3282	0.0001	0.0068	0.3675
p-value of Sargan-Hansen overidentification test	0.5603	0.2362	0.3701	0.3350
Price elasticity of natural gas demand	-0.0047	-0.0160	-0.0318	-0.0125
	(0.0425)	(0.04228)	(0.0438)	(0.0446)
N	9	9	9	9
R^2	0.932	0.932	0.931	0.945
Root MSE	114.8	114.5	115.7	103.4

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.
† Specification used in structural model.

Table B.3: Estimated regional demand function for natural gas for Asia and Oceania

	Dependent variable is: Regional natural gas consumption (MCFD)				
	(1)†	(2)	(3)	(4)	(5)
Natural gas regional price,(US$/mmbtu)	-76.94	-30.18	-195.4	-22.75	-355.8
	(189.6)	(206.8)	(304.2)	(178.2)	(353.0)
Regional GDP (US$)	5.77e-10*	5.46e-10*	6.56e-10*	5.41e-10*	7.63e-10*
	(2.53e-10)	(2.52e-10)	(3.20e-10)	(2.41e-10)	(3.81e-10)
Regional population	0.0000135*	0.0000129*	0.0000151	0.0000129*	0.0000171
	(0.00000637)	(0.00000625)	(0.00000772)	(0.00000608)	(0.00000922)
Constant	-39914.4	-37989.0	-44790.6	-37683.5	-51393.2
	(20404.5)	(20014.5)	(24743.0)	(19447.4)	(29540.3)
Instruments used:					
Avg capital compensation (million 2005 US$)					
on other machinery and equipment	N	N	Y	N	N
on transport equipment	N	N	N	Y	N
on total non-residential investment	N	N	N	N	Y
Avg industry rate of return on capital	Y	Y	N	Y	N
Aggregate gas reserve (BCF)	Y	N	Y	Y	N
First stage F-statistic	2.67	2.38	0.71	1.79	1.31
p-value of underidentification test	0.0437	0.0275	0.2103	0.0906	0.0667
p-value of weak-instrument-robust inference tests	0.8001	0.8813	0.6690	0.2002	0.0939
p-value of Sargan-Hansen overidentification test	0.6459	NA	0.7563	0.2290	NA
Price elasticity of natural gas demand	-0.0651	-0.0255	-0.16543	-0.0193	-0.3012
	(0.1605)	(0.1751)	(0.2575)	(0.1509)	(0.2989)
N	9	9	9	9	9
R^2	0.984	0.985	0.979	0.985	0.970
Root MSE	337	323.8	381.5	322	459.8

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.
† Specification used in structural model.

Table B.4: Estimated regional demand function for natural gas for Eurasia

	Dependent variable is: Regional natural gas consumption (MCFD)	
	(1)†	(2)
Natural gas regional price,(US$/mmbtu)	-5960.0***	-6039.3***
	(420.7)	(482.2)
Regional GDP (US$)	4.99e-09***	5.06e-09***
	(3.57e-10)	(4.07e-10)
Regional population	-0.00135***	-0.00135***
	(0.0000574)	(0.0000581)
Constant	408719.2***	409082.8***
	(16435.4)	(16636.3)
Instruments used:		
Lagged average weekly earnings (2005 US$)		
for supporting activities in oil and gas	Y	Y
for oil and gas extraction	Y	N
Avg capital compensation on transport equipment (million 2005 US$)	Y	Y
Avg industry rate of return on capital	N	Y
First stage F-statistic	13.23	1.76
p-value of underidentification test	0.0350	0.0826
p-value of weak-instrument-robust inference tests	0.0000	0.0000
p-value of Sargan-Hansen overidentification test	0.2582	0.0755
Price elasticity of natural gas demand	-0.3857***	-0.3909***
	(0.0272)	(0.0312)
N	9	9
R^2	0.990	0.990
Root MSE	126.9	128.2

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.
† Specification used in structural model.

Table B.5: Estimated regional demand function for natural gas for Europe

	Dependent variable is: Regional natural gas consumption (MCFD)	
	(1)†	(2)
Natural gas regional price,(US$/mmbtu)	-169.9	-344.7
	(165.2)	(185.5)
Regional GDP (US$)	5.15e-10***	6.11e-10***
	(1.44e-10)	(1.55e-10)
Regional population	-0.0000783	-0.0000361
	(0.0000679)	(0.0000730)
Constant	59235.9	34714.0
	(38457.1)	(41355.9)
Instruments used:		
Lagged average weekly earnings (2005 US$)		
for supporting activities in oil and gas	Y	N
for oil and gas extraction	Y	Y
Avg capital compensation (million 2005 US$)		
on total non-residential investment	N	Y
Avg industry rate of return on capital	Y	N
Aggregate gas reserve (BCF)	Y	N
First stage F-statistic	9.36	7.63
p-value of underidentification test	0.0738	0.0243
p-value of weak-instrument-robust inference tests	0.0000	0.0014
p-value of Sargan-Hansen overidentification test	0.0451	0.1406
Price elasticity of natural gas demand	-0.0899	-0.1824
	(0.0874)	(0.0982)
N	9	9
R^2	0.833	0.817
Root MSE	331	346.8

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.
† Specification used in structural model.

Table B.6: Estimated regional demand function for natural gas for the Middle East

	Dependent variable is: Regional natural gas consumption (MCFD)		
	(1)†	(2)	(3)
Natural gas regional price,(US$/mmbtu)	-12.14	-38.25	-37.77
	(47.81)	(50.26)	(50.23)
Regional population	0.000146***	0.000152***	0.000152***
	(0.0000126)	(0.0000132)	(0.0000132)
Constant	-18265.8***	-19250.5***	-19232.7***
	(2027.4)	(2118.4)	(2117.0)
Instruments used:			
Lagged average weekly earnings (2005 US$) for oil and gas extraction	Y	Y	N
Avg capital compensation (million 2005 US$) on total non-residential investment	Y	Y	Y
Avg industry rate of return on capital	Y	N	N
First stage F-statistic	49.67	57.38	103.23
p-value of underidentification test	0.0478	0.0241	0.0063
p-value of weak-instrument-robust inference tests	0.0019	0.4334	0.4296
p-value of Sargan-Hansen overidentification test	0.0612	0.3753	NA
Price elasticity of natural gas demand	-0.0112	-0.0352	-0.0348
	(0.0441)	(0.0463)	(0.0463)
N	9	9	9
R^2	0.99	0.989	0.989
Root MSE	177.1	180.7	180.6

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.
† Specification used in structural model.

Table B.7: Estimated regional demand function for natural gas for the Americas

	Dependent variable is: Regional natural gas consumption (MCFD)				
	(1)†	(2)	(3)	(4)	(5)
Natural gas regional price,(US$/mmbtu)	-85.00	-67.54	-80.89	-74.39	-39.23
	(85.49)	(86.38)	(85.30)	(84.32)	(108.8)
Regional GDP (US$)	3.17e-10***	3.08e-10***	3.15e-10***	3.12e-10***	2.37e-10
	(6.64e-11)	(6.65e-11)	(6.63e-11)	(6.58e-11)	(3.12e-10)
Regional population					0.00000594
					(0.0000288)
Constant	26750.5***	26792.2***	26760.3***	26775.8***	22518.3
	(849.0)	(844.7)	(847.4)	(844.9)	(20904.6)
Instruments used:					
Lagged average weekly earnings (2005 US$)					
for supporting activities in oil and gas	N	N	N	Y	Y
for oil and gas extraction	Y	Y	Y	Y	N
Avg capital compensation (million 2005 US$)					
on other machinery and equipment	N	N	N	N	Y
on transport equipment	N	N	N	N	Y
on total non-residential investment	Y	N	Y	Y	Y
Avg industry rate of return on capital	Y	Y	Y	Y	Y
Aggregate gas reserve (BCF)	N	Y	Y	Y	N
First stage F-statistic	16.65	10.48	10.13	8.36	4.15
p-value of underidentification test	0.0369	0.0418	0.0750	0.1236	0.1305
p-value of weak-instrument-robust inference tests	0.0135	0.0001	0.0000	0.0000	0.0000
p-value of Sargan-Hansen overidentification test	0.1309	0.0426	0.0727	0.1195	0.0614
Price elasticity of natural gas demand	-0.0184	-0.0146	-0.0175	-0.0161	-0.0085
	(0.0185)	(0.0187)	(0.0185)	(0.01829)	(0.0236)
N	9	9	9	9	9
R^2	0.785	0.787	0.785	0.786	0.788
Root MSE	386.6	384.3	385.9	385	383

Notes: Standard errors in parentheses. Significance codes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.
† Specification used in structural model.