Econometric Modeling of the World Oil Market as a Dynamic Game

Khaled H. Kheiravar, University of California at Davis
C.-Y. Cynthia Lin Lawell, Cornell University

Abstract

The decisions made by petroleum producers in the world oil market are both dynamic and strategic, and are thus best modeled as a dynamic game. In this chapter, we review the literature on the world oil market and discuss our research on econometric modeling of the world oil market as a dynamic game. Our research on econometric modeling of the world oil market as a dynamic game research builds on the previous literature by combining three erstwhile separate dimensions of modeling the world oil market: dynamic optimization, game theory, and econometrics. Our results show that dynamic behavior and strategic interactions are important aspects of the world oil market that must be accounted for in empirical analyses of the world oil market.

Keywords: structural econometric model; dynamic game; world oil market; petroleum production; dynamic; strategic; dynamic optimization; game theory; OPEC; econometrics

1. Introduction

The decisions made by petroleum producers in the world oil market are both dynamic and strategic, and are thus best modeled as a dynamic game. In this chapter, we review the literature on the world oil market and discuss our research on econometric modeling of the world oil market as a dynamic game. Our research on econometric modeling of the world oil market as a dynamic game research builds on the previous literature by combining three erstwhile separate dimensions of modeling the world oil market: dynamic optimization, game theory, and econometrics.

In Lin Lawell [2017], we develop and estimate an empirical dynamic model of the world oil market based on optimal control theory, and use this model to test for market power.

In Kheiravar *et al.* [2017], we develop and estimate a structural econometric model of the dynamic game among petroleum-producing firms based on dynamic programming and game theory, and we apply this model to firm-level panel data on oil and gas exploration, development, production, mergers, acquisitions, and reserves. We then use the structural econometric model to analyze the effects of government policies, changing geopolitical landscapes, and new technologies on the petroleum industry.

Our results show that dynamic behavior and strategic interactions are important aspects of the world oil market that must be accounted for in empirical analyses of the world oil market.

The balance of this chapter proceeds as follows. In Section 2, we explain why the world oil market should be modeled as a dynamic game. We review the related literature in Section 3. In Section 4, we discuss our research in Lin Lawell [2017], in which we develop an empirical dynamic model of the world oil market based on optimal control theory. In Section 5, we discuss our research in Kheiravar *et al.* [2017], in which we develop and estimate a structural econometric model of the dynamic game among petroleum-producing firms based on dynamic programming and game theory. Section 6 concludes.

2. The world oil market as a dynamic game

The decisions made by petroleum producers in the world oil market are both dynamic and strategic. 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. The exploration, development, merger, and acquisition decisions of petroleum producers are dynamic because they are irreversible investments, 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].

The decisions of petroleum-producing firms are not only dynamic but strategic as well. 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.

Because the decisions made by petroleum producers in the world oil market are both dynamic and strategic, they are best modeled as a dynamic game. In our previous work in Lin [2011], we show that assuming the world oil market is static and perfectly competitive yields unrealistic empirical results, and therefore that econometric models of the world oil market should incorporate the dynamic and strategic dimensions of the world oil market.

3. Related literature

Economists have long been interested the world oil market. The theoretical model of optimal nonrenewable resource extraction was first examined by Hotelling [1931], who developed the insight that dynamic optimization and dynamic behavior are critical for analyzing the world oil market.

The dynamic optimization model and framework for the world oil market developed by Hotelling [1931] has since been expanded upon by many others to allow for such features as stock effects in extraction costs (Solow and Wan, 1976; Hanson, 1980; Farzin, 1992); exploration (Pindyck, 1978; Pesaran, 1990); market imperfections (Stiglitz, 1976; Khalatbari, 1977; Sweeney, 1977; Crémer and Salehi-Isfahani, 1991); technological progress (Farzin, 1992, 1995; Lin *et al.*, 2009; Lin and Wagner, 2007); outward-shifting demand (Chapman, 1993; Chapman and Khanna, 2000); uncertainty (Hoel, 1978; Pindyck, 1980); risk (Young and Ryan, 1996); drilling activity (Anderson, Kellogg and Salant, forthcoming); stochastic and volatile output price and production cost (Almansour and Insley, 2016); tax policy (Leighty and Lin, 2012); and oil contracts (Ghandi and Lin, 2012; Ghandi and Lin Lawell, 2017).

Gaudet [2007] provides a recent review of factors that can potentially help bridge the gap between the basic Hotelling rule of natural resource exploitation and the historical behavior resource prices. Lin [2009] shows that even the most basic Hotelling model yields insights.

Recognizing the importance of strategic interactions in addition to dynamic behavior in the world oil market, the dynamic optimization model and framework for the world oil market developed by Hotelling [1931] has also been expanded upon to allow for such features as Nash-Cournot behavior (Salant, 1976; Ulph and Folie, 1980) and OPEC behavior (Hnyilicza and Pindyck, 1976; Pindyck, 1976; Crémer and Weitzman, 1976).

Until recently, much of the empirical literature on the world petroleum market was from over three decades ago (Adelman, 1962; Kennedy, 1974; Nordhaus, 1980; Gately, 1984; Griffin, 1985; Lin, 2011; Espinasa *et al.*, 2017). Crémer 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. Lin [2011] shows that assuming the world oil market is static and perfectly competitive yields unrealistic empirical results, and therefore that econometric models of the world oil market should incorporate the dynamic and strategic dimensions of the world oil market.

There is also a literature analyzing strategic behavior in the world petroleum market, and particularly the behavior of OPEC (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; Hochman and Zilberman, 2015; Okullo and Reynès, 2016; Baumeister and Kilian, 2017; Genc, 2017; Asker *et al.*, 2017; Ghoddusi *et al.*, 2017). 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].

4. An empirical dynamic model of the world oil market

The mission of OPEC is to "coordinate and unify the petroleum policies of its Member Countries" [OPEC, 2017]; however, it is unclear whether OPEC behaves as a cartel. As a step towards better understanding and modeling the world oil market and OPEC in particular, our work in Lin Lawell [2017] estimates a Hotelling model of the world oil market and tests whether OPEC countries colluded and whether non-OPEC countries behaved as price takers or oligopolists over the period 1970-2004.

Our research in Lin Lawell [2017] makes several important contributions to the existing literature. First, it takes to data the theoretical model of optimal nonrenewable resource extraction that was first examined by Hotelling [1931], and later expanded upon by many others [see e.g., Pindyck, 1976; Cremer and Weitzman, 1976; Solow and Wan, 1976; Pindyck, 1978; Hanson, 1980; Pindyck, 1980; Pesaran, 1990; Farzin, 1992; Farzin, 1995; Lin, 2009; Lin *et al.*, 2009; Lin and Wagner, 2007; Leighty and Lin, 2012; Ghandi and Lin, 2012; Anderson, Kellogg and Salant, forthcoming; Ghandi and Lin Lawell, 2017).

Unlike many previous empirical studies of the petroleum market, which use a static model, in Lin Lawell [2017] we estimate a Hotelling model of the world petroleum market, which is a dynamic model. The dynamics in Lin Lawell [2017] arise from the nonrenewable nature of the resource.

A second contribution is that our work in Lin Lawell [2017] builds upon existing empirical studies of nonrenewable resource markets by addressing the identification problem that arises in empirical analyses of supply and demand. Because the observed equilibrium prices and quantities are simultaneously determined in the supply-and-demand system, instrumental variables are needed to address the endogeneity problem [Lin, 2011].

The third contribution is that our work in Lin Lawell [2017] develops a Hotelling model that enables one to test for the market conduct of OPEC and non-OPEC producers.

Our empirical dynamic model in Lin Lawell [2017] is based on taking an optimal control theory-based Hotelling model to data. In particular, we use the first-order conditions from an optimal control theory model of optimal nonrenewable resource extraction under different market conditions to formulate a general supply-side first-order condition that we then estimate with data.

According to our results in Lin Lawell [2017], results of the analysis by decade support OPEC countries colluding as the dominant cartel producer and non-OPEC countries behaving as an oligopolistic fringe. Market demand has become more inelastic over time over the period of study. The estimated shadow prices are jointly significant, which is consistent with the hypothesis that a Hotelling model, which accounts for the nonrenewable nature of the resource, is a more appropriate model for the world oil market than a static model is.

Our results in Lin Lawell [2017] therefore show that dynamic behavior and strategic interactions are important aspects of the world oil market that must be accounted for in empirical analyses of the world oil market.

5. A structural econometric model of the dynamic game among petroleum-producing firms

In Kheiravar *et al.* [2017], we develop and estimate a structural econometric model of the dynamic game among petroleum-producing firms in the world petroleum market. Our model allows firms that are at least partially state-owned to have objectives other than profit maximization alone. We apply this model to panel data on firm-level 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.

We then use the parameters estimated from our structural econometric model to simulate counterfactual scenarios to analyze the effects of changes in OPEC membership, the privatization of state-owned oil companies, a ban on mergers, and demand shocks on the petroleum industry.

There are several advantages to using a dynamic structural model to analyze the investment, production, merger, and acquisition decisions of petroleum-producing firms. First, unlike reduced-form models, a structural approach explicitly models the dynamics of these decisions. 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. The exploration, development, merger, and acquisition decisions of petroleum producers are dynamic because they are irreversible investments, 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].

A second advantage of our model of the dynamic game between petroleum producers is that it models the strategic nature of the decisions of petroleum-producing firms. 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.

A third advantage of our structural model is that it enables us to estimate the effect of each state variable on the expected payoffs from exploration, development, production, merger, and acquisition decisions, and therefore enables us to estimate parameters that have direct economic interpretations. Our dynamic model accounts for the continuation value, which is the expected value of the value function next period. With the structural model we are able to estimate parameters in the payoffs from exploration, development, production, merger, and acquisition, since we are able to structurally model how the continuation values relate to the payoffs from each of these decisions.

A fourth advantage of our structural model is that we are able to model the interdependence of petroleum-producing firms' value functions. When one firm merges with or acquires another firm, the value of the other firm with which it merges or acquires is given by that other firm's value function, which is the present discounted value of the entire stream of per-period payoffs of that other firm, and which accounts for the options that that 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. Therefore, the firms' value functions are interdependent.

A fifth advantage of our structural model is that we can use the parameter estimates from our structural model to simulate various counterfactual scenarios. We use our estimates to simulate counterfactual scenarios to analyze the effects of changes in OPEC membership, the privatization of state-owned oil companies, a ban on mergers, and demand shocks on the petroleum industry.

We build on the literature on structural econometric models of dynamic games. In Lin [2013], we develop and estimate 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. In Lin [2013], we examine whether these inefficient strategic interactions take place on U.S. federal lands in the Gulf of Mexico. In particular, we analyze whether one 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.

In our model of the dynamic game among petroleum-producing firms in the world petroleum market in Kheiravar *et al.* [2017], 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 uncertainty in our model of a dynamic game in Kheiravar *et al.* [2017]. First, future values of the state variables are stochastic. Second, each player receives private information shocks. Third, there are shocks to oil demand and regional natural gas demand.

Fourth, merger and acquisition costs are private information to each firm, and are not observed by either other firms or the econometrician.

We assume that each firm optimizes its behavior conditional on the current state variables, other firms' strategies and its own private shocks, which results in a Markov perfect equilibrium (MPE). In a Markov perfect equilibrium, the optimal strategy for each firm should therefore yield 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.

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, we find the parameters 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 depends on the expected value of the value function 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.

We use the structural econometric model to analyze the effects of changes in OPEC membership, the privatization of state-owned oil companies, a ban on mergers, and demand shocks on the petroleum industry.

The results of our research in Kheiravar *et al.* [2017] will be of interest to academics, policy-makers, entrepreneurs, and business practitioners, including oil companies, alike. Our modeling outcomes can be used to help inform decision-making and policy design. This model will also help petroleum firms better respond to government policies, and will help policy-makers better design sustainable energy policies.

6. Conclusion

The decisions made by petroleum producers in the world oil market are both dynamic and strategic, and are thus best modeled as a dynamic game. In this chapter, we review the literature on the world oil market and discuss our research on econometric modeling of the world oil market as a dynamic game. Our research on econometric modeling of the world oil market as a dynamic game research builds on the previous literature by combining three erstwhile separate dimensions of modeling the world oil market: dynamic optimization, game theory, and econometrics.

Our results show that dynamic behavior and strategic interactions are important aspects of the world oil market that must be accounted for in empirical analyses of the world oil market.

In ongoing and future work, we hope to use our structural econometric model to better understand how government policies, changing geopolitical landscapes, and disruptive technologies, such as shale oil and gas, and new batteries for electric vehicles, impact future business models, the competition of fuels, and the composition of future energy demand. We would also like to use our structural econometric model to analyze how industry will respond to regulatory and/or societal demands for reduced greenhouse gas emissions and improved environmental quality; to examine how the oil industry might transition to more sustainable fuels; and to better understand what is required for early alternative fuel transitions to succeed.

In future work, we hope to use our structural econometric model modeling outcomes to help inform decision-making and policy design. In particular, we hope to help petroleum firms better respond to government policies, and to help policy-makers better design sustainable energy policies.

The results of our research will be of interest to academics, policy-makers, entrepreneurs, and business practitioners, including oil companies, alike.

7. References and Citations

Adelman, M. A. (1962). Natural gas and the world petroleum market. *Journal of Industrial Economics*, 10, pp. 76-112.

Alhajji, A., and Huettner, D. (2000a). OPEC and other commodity cartels: A comparison. *Energy Policy*, 28, pp. 1151-1164.

Alhajji, A., and Huettner, D. (2000b). OPEC and world crude oil markets from 1973 to 1994: Cartel, oligopoly or competitive? *Energy Journal*, 21(3), pp. 31-60.

Almansour, A., and Insley, M. (2016). The impact of stochastic extraction cost on the value of an exhaustible resource: An application to Alberta oil sands. *Energy Journal*, 37 (2), pp. 61-88.

Almoguera, P., Douglas, C. and Herrera, A. (2011). Testing for the cartel in OPEC: Noncooperative collusion or just noncooperative? *Oxford Review of Economic Policy*, 27, pp. 144-168.

Al-Qahtani, A., Balistreri, E., and Dahl, C. (2008). Literature review on oil market modeling and OPEC's behavior. Working paper, Colorado School of Mines.

Anderson, S. T., Kellogg, R., and Salant, S. W. (forthcoming). Hotelling under pressure. *Journal of Political Economy*.

Asker, J., Collard-Wexler, A., and De Loecker, J. (2017). Market power, production (mis)allocation and OPEC. NBER Working Paper No. 23801.

Bajari, P., Benkard, C. L., and Levin, J. (2007). Estimating dynamic models of imperfect competition. *Econometrica*, 75 (5), pp. 1331-1370.

Baumeister, C., and Kilian, L. (2017). Understanding the decline in the price of oil since June 2014. *Journal of the Association of Environmental and Resource Economists*, 3 (1), pp. 131-158.

Chapman, D. (1993). World oil: Hotelling depletion or accelerating use? *Natural Resources Research*, 2 (4), pp. 331-339.

Chapman, D., and Khanna, N. (2000). World oil: The growing case for international policy. *Contemporary Economic Policy*, 18 (1), pp. 1-13.

Crémer, J., and Salehi-Isfahani, D. (1991) *Models of the Oil Market* (Harwood Academic Publishers, New York).

Crémer, J., and Weitzman, M. L. (1976). OPEC and the monopoly price of world oil. *European Economic Review*, 8, pp. 155-164.

Dahl, C. A. (2015) *International Energy Markets: Understanding Pricing, Policies, and Profits*, 2nd Ed. (Pennwell Press, USA).

Dixit, A. K., and Pindyck, R. S. (1994) *Investment under Uncertainty* (Princeton University Press, Princeton).

Espinasa, R., ter Horst, E., Guerra Reyes, S., Manzano, O., Molina, G., and Rigobon, R. (2017). A micro-based model for world oil market. *Energy Economics*, 66, pp. 431-449.

Farzin, Y. H. (1992). The time path of scarcity rent in the theory of exhaustible resources. *Economic Journal*, 102, pp. 841-851.

Farzin, Y. H. (1995). Technological change and the dynamics of resource scarcity measures. *Journal of Environmental Economics and Management*, 29, pp. 105-120.

Gately, D. (1984). A ten-year retrospective: OPEC and the world oil market. *Journal of Economic Literature*, 22, 1100-1114.

Gaudet, G. (2007). Natural resource economics under the rule of Hotelling. *Canadian Journal of Economics*, 40, pp. 1033-1059.

Genc, T.S. (2017). OPEC and demand response to crude oil prices. *Energy Economics*, 66, pp. 238-246.

Ghandi, A., and Lin, C.-Y. C. (2012). Do Iran's buy-back service contracts lead to optimal production? The case of Soroosh and Nowrooz. *Energy Policy*, 42, pp. 181-190.

Ghandi, A., and Lin Lawell, C.-Y. C. (2017). On the economic efficiency of oil production contracts: A dynamic model of the Rumaila oil field in Iraq. Working paper, Cornell University.

Ghoddusi, H., Nili, M., and Rastad, M. (2017). On quota violations of OPEC members. *Energy Economics*, 68, pp. 410-422.

Golombek, R., Irarrazabal, A. A., and Ma, L. (2014). OPEC's market power: An empirical dominant firm model for the oil market. CESifo Working Paper Series 4512, CESifo Group Munich.

Griffin, J. M. (1985). OPEC behavior: A test of alternative hypotheses. *American Economic Review*, 75, 954-963.

Gulen, S. G. (1996). Is OPEC a cartel?: Evidence from cointegration and causality tests. *Energy Journal*, 17, pp. 43-57.

Hanson, D. A. (1980). Increasing extraction costs and resource prices: Some further results. *Bell Journal of Economics*, 11 (1), pp. 335-342.

Hnyilicza, E. and Pindyck, R .S. (1976). Pricing policies for a two-part exhaustible resource cartel: The case of OPEC. *European Economic Review*, 8, pp. 139-154.

Hochman, G., and Zilberman, D. (2015). The political economy of OPEC. *Energy Economics*, 48, pp. 203-216.

Hoel, M. (1978). Resource extraction, uncertainty, and learning. *Bell Journal of Economics*, 9 (2), pp. 642-645.

Hotelling, H. (1931). The economics of exhaustible resources. *Journal of Political Economy*, 39 (2), pp. 137-175.

Hotz, V. J., Miller, R. A., Sanders, S., and Smith, J. (1994). A simulation estimator for dynamic models of discrete choice. *Review of Economic Studies*, 61, pp. 265-289.

Kaufmann, R. K., Dees, S., Karadeloglou, P., and Sánchez, M. (2004). Does OPEC matter?: An econometric analysis of oil prices. *Energy Journal*, 24 (4), pp. 67-90.

Kennedy, M. (1974). An economic model of the world oil market. *Bell Journal of Economics and Management Science*, 5, pp. 540-577.

Khalatbari, F. (1977). Market imperfections and the optimum rate of depletion of natural resources. *Economica*, 44 (176), pp. 409-414.

Kheiravar, K. H., Lin Lawell, C.-Y. C., and Jaffe, A. M. (2017). A structural econometric model of the dynamic game between petroleum producers in the world petroleum market. Working paper, Cornell University.

Leighty, W., and C.-Y. C. Lin. (2012). Tax policy can change the production path: A model of optimal oil extraction in Alaska. *Energy Policy*, 41, pp. 759-774.

Lin, C.-Y. C. (2009). Insights from a simple Hotelling model of the world oil market. *Natural Resources Research*, 18 (1), pp. 19-28.

Lin, C.-Y. C. (2011). Estimating supply and demand in the world oil market. *Journal of Energy and Development*, 34 (1), pp. 1-32.

Lin, C.-Y. C. (2013). Strategic decision-making with information and extraction externalities: A structural model of the multi-stage investment timing game in offshore petroleum production. *Review of Economics and Statistics*, 95 (5), pp. 1601-1621.

Lin, C.-Y. C., Meng, H., Ngai, T. Y., Oscherov, V., and Zhu, Y. H. (2009). Hotelling revisited: Oil prices and endogenous technological progress. *Natural Resources Research*, 18 (1), pp. 29-38.

Lin, C.-Y. C. and Wagner, G. (2007). Steady-state growth in a Hotelling model of resource extraction. *Journal of Environmental Economics and Management*, 54 (1), pp. 68-83.

Lin Lawell, C.-Y. C. (2017). Market power in the world oil market: Evidence for an OPEC cartel and an oligopolistic non-OPEC fringe. Working paper, Cornell University.

Matutes, C. (1988). The center of OPEC: An econometric analysis. Working paper, University of California at Berkeley.

Nordhaus, W. (1980). Oil and economic performance in industrial countries. *Brookings Papers on Economic Activity*, 11, pp. 341-400.

Okullo, S. J., and Reynès, F. (2016). Imperfect cartelization in OPEC. *Energy Economics*, 60, pp. 333-344.

Organization of Petroleum Exporting Countries [OPEC]. (2017). Our Mission. URL: http://www.opec.org/opec_web/en/about_us/23.htm

Pesaran, M. H. (1990). An econometric analysis of exploration and extraction of oil in the U.K. Continental Shelf. *Economic Journal*, 100 (401), pp. 367-390.

Pindyck, R. S. (1976). Gains to producers from the cartelization of exhaustible resources. MIT Energy Lab working paper (No. MIT-EL 76-012WP).

Pindyck, R. S. (1978). The optimal exploration and production of nonrenewable resources. *Journal of Political Economy*, 86 (5), pp. 841-861.

Pindyck, R. S. (1980). Uncertainty and exhaustible resource markets. *Journal of Political Economy*, 88 (6), pp. 1203-1225.

Salant, S. W. (1976). Exhaustible resources and industrial structure: A Nash-Cournot approach to the world oil market. *Journal of Political Economy*, 84 (5), pp. 1079-1094.

Solow, R. M., and Wan, F. Y. (1976). Extraction costs in the theory of exhaustible resources. *Bell Journal of Economics*, 7 (2), pp. 359-370.

Stiglitz, J. E. (1976). Monopoly and the rate of extraction of exhaustible resources. *American Economic Review*, 66 (4), pp. 655-661.

Sweeney, J. L. (1977). Economics of depletable resources: Market forces and intertemporal bias. *Review of Economic Studies*, 44 (1), pp. 124-141.

Ulph, A. M., and Folie, G. M. (1980). Exhaustible resources and cartels: An intertemporal Nash-Cournot model. *Canadian Journal of Economics*, 13 (4), pp. 645-658.

Young, D., and Ryan, D. L. (1996). Empirical testing of a risk-adjusted Hotelling model. *Resource and Energy Economics*, 18, pp. 265-289.

Short bios of all coauthors

Khaled Kheiravar is a Ph.D. candidate in Economics at the University of California at Davis; as well as a Graduate Research Associate at Cornell University DEEP-GREEN-RADAR and at Cornell University TREESPEAR. Khaled has won several prestigious awards for his research, including the 2013 ExxonMobil Corporate Affiliate Fellowship, the 2016 ExxonMobil Corporate Affiliate Fellowship, the Henry A. Jastro Graduate Research Award, the USAEE Student Registration Fee Scholarship, the OPEC Fund for International Development IAEE Support Fund Scholarship; the UC-Davis Fellowship for Excellence in Graduate Research, and the UC-Davis Economics Department Job Market Fellowship. Khaled has presented his research at USAEE conferences; at Columbia University; and at AERE @ WEAI.

C.-Y. Cynthia Lin Lawell is Associate Professor and the Rob Dyson Sesquicentennial Chair in Environmental, Energy and Resource Economics in the Charles H. Dyson School of Applied Economics and Management at Cornell University. She is the Director of Cornell DEEP-GREEN-RADAR and the Director of the Cornell University TREESPEAR. Professor Lin Lawell has received numerous awards for her research, including the Harvard University Stone Fellow Award. Her research has also been featured in such media outlets as the *New York Times*, the *Washington Post*, the *Guardian*, Platt's blog, and *Bloomberg View*. Professor Lin Lawell received her bachelor's degree, *summa cum laude*, in Environmental Science and Public Policy from Harvard College in 2000 and her Ph.D. in Economics from Harvard University in 2006.