TIGHT-OIL PRODUCTION TECHNOLOGY EFFECTS ON THE

U.S. PETROLEUM INDUSTRY'S VERTICAL INTEGRATION

by

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DISSERTATION

Presented to the Faculty of

The University of Texas at Dallas

in Partial Fulfillment

of the Requirements

for the Degree of

DOCTOR OF PHILOSOPHY IN

ECONOMICS

THE UNIVERSITY OF TEXAS AT DALLAS

May 2020

ACKNOWLEDGMENTS

I would like express my deep gratitude to the following for assisting me with my research:

My academic advisor, Dr. Donald Hicks, for his guidance through each stage of the process,

The following companies for their assistance:

Enverus – Drillinginfo, who provided crude production data, which made this research possible,

Baker & O’Brien Inc., for their support with detailed refinery information, and

Netherland, Sewell & Associates, who provided technical assistance concerning tight-oil technology.

I would also like to thank Greg Wright, Connie Brittelli, Melody Ramirez, Mary Brown, Jesse Wrisley, and Heather Varner for their assistance in preparing the documents.

March 2020

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The University of Texas at Dallas, 2020

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The introduction of tight-oil technologies into the U.S. petroleum industry's supply chain has triggered a revolution with wide commercial, economic, and geopolitical impacts. While these *upstream* technologies have increased proven reserves, reduced the unsuccessful well incident rate, and increased individual well productivity, they have also increased per well costs. Concurrently, the U.S. petroleum industry expanded and modernized its *downstream* refining sector with a different suite of technologies, including "digital oilfield" technologies and advanced refinery processes. Moreover, while these innovations were being introduced, the U.S. petroleum industry's long-standing vertically-integrated structure has undergone a steady disintegration, in which the dominance of large integrated companies has been weakened. This study explores whether – and to what extent -- these two industrial developments may be related, and, if so, what is the nature of this relationship?

The introduction of tight-oil technology in U.S. crude oil production provides an

opportunity to study a new technology's measurable deployment into the upstream portion of a supply chain and its potential influence on an industry's industrial organization. Tight-oil deployments were largely unanticipated, and any biases introduced by the reciprocal relationships between organizational changes and technological progress are likely minimized. Due to the nature of these innovations, the production from wells utilizing the tight-oil technologies can be segregated from that of other wells using more conventional technologies. Because this study measures directly the adoption and implementation of innovative technologies on an industry's discrete operations, it can assess more accurately the impact of technological innovation on an industry's evolving organizational structure. As a result, this study seeks to provide insight into the essential nature of a technological innovation and how its insertion into key locations in an industry's supply chain can influence directly and substantially the organizational structure of the linked industries that compose it.

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CHAPTER 1

INTRODUCTION

"It has been said that a special Providence watches over children, drunkards, and the United States."

— *Harper's New Monthly Magazine*[1]

Though it is the richest most powerful nation in history, the United States (U.S.) has been blessed with billions of additional barrels of crude oil and natural gas in the last two decades that were previously thought to be beyond reach. Surprisingly, American crude oil production, which had previously been in a long slow decline, experienced a dramatic turnaround due to a technological revolution that made it possible to extract crude oil and natural gas from shale formations that exist in many parts of the country. The technique is popularly called "fracking," but this description is somewhat inaccurate because "hydrofracturing" is only a part of the suite of technologies that were married together to bring about this revolution. In this study, I will use the term "tight-oil" technology. Much has been written about the broad and disparate effects it has had on the nation and world – politically, strategically, and financially – adding as much as 1 percent to the U.S. Gross Domestic Product (GDP) growth during the 2010 -2015 period.[2] Tight-oil technology is

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[1] "Editor's Drawer," December 1856, *Harper's New Monthly Magazine*, pg. 135, col. 2.

[2] Yucel, M. and Plante M.D., August 20, 2019, *GDP Gain Realized in Shale Boom's First 10 Years*, Federal Reserve Bank of Dallas.

still in its infancy. However, even as it continues to be improved upon, and despite facing mounting challenges over its environmental impact, it already accounted for the majority of U.S. production of crude oil and natural gas by 2016.

For most of the 20th century, the U.S. was a major energy producer and exporter, but also an early exploiter of its own petroleum resources. U.S. production peaked in the early 1970's, and the nation transitioned from the being the world's leading oil exporter to the world's largest crude oil importer, importing 10 million barrels a day by 2000.[3] The combination of horizontal drilling technology, hydrofracturing, and advanced computer-aided geoscience and navigation comprised a suite of technologies that began to be deployed commercially in the late 1990's in the Barnett Shale near Fort Worth, Texas. Curiously, the individual technologies that comprised this suite were not well protected by patents, and the usage spread rapidly to other companies and into other production fields – the Permian Basin in South Texas, the Bakken Formation in North Dakota, and the Marcellus Formation in the Appalachian Basin along the East Coast, among others. U.S. crude production rose exponentially until by 2018 the U.S. was again a net energy exporter, with approximately tight-oil wells accounting for 60 percent of that production. The U.S. Energy Information Agency (E.I.A.) reported that the U.S. had shale formation proven reserves[4] of 23 billion barrels of crude oil and 342 trillion cubic feet of natural gas in

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[3] https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=MTTNTUS2&f=M.

[4] Proven reserves are only those reserves that a company estimates have a 90 percent probability of being economically extracted using current technology and prices.

2018,[5] reserves that did not exist in 2000 in an economic and financial sense.[6] Without a doubt, this is a major shock to the industry. It is a shock that has affected its very industrial organization.

The petroleum industry supply chain spans an extended sequence of linked industrial activities, including the exploration, production, refining, transportation, and marketing of petroleum products, such as gasoline, diesel, lubricants, and petrochemicals.[7] Though it is a complex supply chain[8] supplying massive daily amounts of consumption throughout the world, fuel costs to U.S. consumers are comparable to bottled water on a volume basis, which speaks well of the efficiency of the enterprise. A part of the reason for the industry's efficiency is its highly-vertical organizational structure. Simply put, vertical integration exists when a firm has operations at more than one location along a supply chain. Petroleum companies, such as ExxonMobil, Chevron,[9] and other well-known firms are well known to have large operations in all stages of the supply chain. Past research and investigations have generally determined that petroleum market conditions encouraged

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[5] U.S. Energy Information Administration, Form EIA-23L, Annual Report of Domestic Oil and Gas Reserves, 2017 and 2018.

[6] In accordance with Security and Exchange Commission (SEC) regulations companies cannot count oil and gas reserves as proven reserves unless they can be exploited economically using current technology. The introduction of tight-oil technology allowed these reserves to be considered "proven" and enter the balance sheets of firms.

[7] Deutsche Bank Market Research publishes a good introduction to the petroleum industry which can be found at https://drive.google.com/file/d/0B8QPsQ-9eAMBcTBRZXpoYXRaYTQ/edit.

[8] The term "supply chain" or "value chain" is a system of organizations, transactions, and transformations involved in moving a finished product, or service, from raw materials to the consumer.

[9] https://corporate.exxonmobil.com/, www.chevron.com.

the formation of these large vertically-integrated companies. These organizations are generally efficient and promote the general welfare, or are at least benign.

This organizational structure has existed for the better part of a century, surviving two world wars, periods of economic expansion and contraction, and across a globe experiencing persistent industrialization. Cracks in this organization began to appear with the rise of national oil companies (NOCs) and their reclamation of national oil reserves from a cabal of major international oil companies (IOCs), long known as the "Seven Sisters."[10] In response to this, the IOCs lost much of their control over global petroleum reserves,[11] with a number of new companies coming into global prominence, such as ENI and Marathon.[12] Oilfield service companies, such as Schlumberger and Halliburton,[13] among many others, became major providers of various production and refining support services, weakening the motivation for firms to remain vertically-integrated. Despite this, U.S. production and refining were still largely controlled by large vertically-integrated oil companies at the end of the twentieth century. In the past two decades, this vertically-integrated structure has undergone a quiet but unprecedented disintegration in the United States, concurrent with the introduction of tight-oil technology into the upstream stage of

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[10] British Petroleum, Gulf, Royal Dutch Shell, Texaco, Standard Oil of California, Standard Oil of New Jersey, and Standard Oil of New York.

[11] Reserves commonly refer to the amount of crude oil and natural gas still in the ground that can be technically recovered at a financially feasible cost at the present market price.

[12] www.eni.com, www.marathonoil.com.

[13] www.slb.com, www.halliburton.com.

the supply chain. This research will examine whether – and, if so, how – this upstream technological revolution has affected the petroleum industry's long standing highly vertically-integrated industrial organization.

Literature on vertical integration has mostly dealt with the subject of whether – and under what conditions – firms replace market transactions with internal transactions within their own organization. The literature is sparse on the subject of why, or why not, an already integrated firm would want to disintegrate its already existing vertically-organized structure. In many respects this study focuses on a mirror image of the original question, so lessons must be drawn from the founding literature with care. Neo-classical microeconomics, found in most textbooks, addresses vertical integration based on what is mathematically most efficient, including issues such as monopolies, oligopolies, foreclosure, and price theory. Most research in industrial organization and vertical integration has been conducted in the context of Ronald Coase's groundbreaking, *The Nature of the Firm* (1937), wherein he contended that a firm's boundaries are largely determined by the balance between market costs and bureaucratic costs in conducting transactions. Where it is less expensive to conduct transactions through market processes, these transactions will generally be done outside the firm's boundaries. Where it is less expensive to conduct transactions internally, transactions generally will be done within the firm's boundaries. O.E Williamson (1975, 1980, 1985, 1989) expanded this perspective with his Transaction Cost Economics (TCE) theory that argues that the risks associated with transaction costs, asset specificity,[14] incomplete contracts,[15] and opportunistic behavior[16] are balanced against an organization's internal costs and benefits in a firm's decisions concerning the organization's vertical integration. Sanford Grossman and Oliver Hart (1986), and Oliver Hart and John Moore (1990) refined TCE with their Property Rights Theory (PRT) which is also based on the problem of incomplete contracts and the importance of property rights which confer residual rights of control[17] in *ex post* negotiations. PRT also examines residual rights with regard to a firm's efficient investments in its assets.[18] A new paradigm of vertical disintegration started to gain attention in the 1980's in work by researchers, such as Hicks (1988, 1996, 2001), who related emergent industrial configurations to investment dynamics in technical advance across in a number of U.S. industries.

On a more specific level, substantial research on the relationship between technological

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[14] "Asset specificity" refers to investments in assets that a firm would need to spend in order to support a specific transaction and how easily that asset can be redeployed to other transactions if necessary. In one sense, oil refineries have high asset specificity because their only use is processing crude oil that is purchased from producers. They cannot be easily redeployed for other uses. In another sense asset specificity may not be high in all cases since crude oil is a commodity with producers and refiners having some alternatives as to where to buy and sell. The assets are contract specific in those cases.

[15] "Incomplete contracts" is the notion that no contract can be written so thoroughly that all states of nature, or contingencies, are foreseen and covered in the contract language. If any of these unforeseen events appear post ante, this can lead to one, or both, parties taking undue advantage of the other.

[16] "Opportunistic behavior" is motivated by the maximization of economic self-interest by a party within a contract or transaction typically at the expense of the other party.

[17] As an example, a plumber can contract a reasonable amount of his time to an owner to repair a faucet. The plumber's time is her property. Her time outside of that reasonable amount of time to complete the work under the contracts are her "residual rights" to her property.

[18] If the plumber books most of his time and has little remaining residual rights may not be motivated to spend effort to take courses to keep his skills sharp would be an example of inefficient investment.

innovation and vertical integration exists, with much of it conducted within the framework of TCE and PRT theories. There are a number of known competing determinants, or factors, that a firm must continuously evaluate in order to determine its optimal level of vertical organization. Of the known determinants, technology could be described as the most mercurial, as innovations can transform industries in both large and small ways and in rapid time frames. Depending on its nature, technological innovation within a market and/or supply chain can have differing effects on any number of consequential organizational changes. How and where along a supply chain a technological breakthrough occurs can also affect its impact on an industry's organization structure. Technological innovation and its consequent impact can affect organizational structure, and, conversely, an existing organizational structure can affect a firm's innovative climate. Curiously, most research that I discovered examined the effects of one upon the other, without discussing any potential simultaneous cross effects between innovation and vertical integration, which could inject unwanted biases into results and conclusions.

The introduction of tight-oil technology and how it came about provides an excellent opportunity to examine how the introduction of an upstream technology can affect vertical disintegration in a mature industry. Since the technology was developed by somewhat peripheral players in the industry (small companies, service providers, government) there is less risk that the industry had previously managed its organization to bring about the technology. As a result, this sequence lessens the chances of simultaneous effects that would bias research results. The primary question being examined here is whether – and if so, how – a technological innovation in the upstream of a supply chain can influence an industry's organizational structure, including its degree of vertical integration. A secondary question is whether other technological changes taking place on or in other locations along the supply chain can also influence organizational structure; in this case, downstream technology at the petroleum refining stage.

Much research on technological innovation in industrial settings is disadvantaged by being unable to measure technological innovation directly within the supply chain. As a result, such research is forced to rely on secondary methods to identify, locate, and measure the level of technological innovation. By contrast, in the present technology research, the innovation is in a precise supply chain location, in an identifiable manner, and the level and impact of its insertion is measurable.

Data on the U.S. petroleum industry is relatively rich in comparison to other industries.[19] Energy costs still account for a significant portion of household budgets and changing prices, some of which can be quite dramatic as commodity prices wax and wane, and are a considerable periodic concern to consumers. Consequently, there is recurring interest in examining the petroleum industry by society and government. There exists a comparatively large amount of information publicly available, in comparison to other U.S.

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[19] The U.S. government has an entire agency, Energy Information Agency (E.I.A.) dedicated to collecting and dispensing information.

industries, largely due to these investigations and ensuing reporting requirements.

This present study is organized as follows. Chapter 2 presents the theoretical background and literature on vertical integration and disintegration. It continues with a literature review of the relationship of technological innovation and vertical integration. Chapter 3 provides an overview of the role of technological innovation on the U.S. petroleum industry and the evolution of its organization over the past century. It then provides an introduction to tight-oil technology and its development. Chapter 4 describes the data and model development of this study and how vertical disintegration, technological innovation, and other covariates were selected, measured, and incorporated into the analyses. Chapter 5 presents the main findings of the analyses and offers an interpretation of the results. Chapter 6 presents the study's conclusions and observations regarding their contributions to the body of literature from which the main research questions were derived

CHAPTER 2

CONCEPTUAL AND THEORETICAL BACKGROUND

For the past two hundred years, the primary industries of manufacturing and transportation used Industrial Revolution-Era technologies and mass production to expand dramatically the economies of scale for goods and services which involved large investments in expensive specialized equipment and assets. These capital bases and assets became important to the firms by their very nature and were necessary to maximize their utilization and minimize disruptions. In order to optimize the investment in expensive equipment, firms needed to be operational as much as possible in order to maximize revenues and justify their investments. Many firms evolved into large vertically-integrated organizational forms to control and mitigate sources of disruption by bringing multiple stages of their supply chains under common corporate control to be efficiently managed. For example, it is important that petroleum refiners have reliable sources of crude oil feedstock because of the large, long-lived[20] and specialized nature of refining equipment. Feedstock shortages would be disruptive, and maintaining significant crude oil inventories to mitigate supply shortages is not economically feasible for extended periods. In this situation, refiners may backward vertically integrate[21] as a risk mitigation strategy by

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[20] Typically, major refining processing equipment is expected to be in service for decades in order to justify their investment. It is not unusual for U.S. refineries to operate with some processing units that are several decades old, being kept in service with turnarounds, upgrades, and modernizations.

[21] Backward integration is when a firm acquires upstream assets that provide its supply chain inputs. This can also mean developing its own upstream supply assets.

investing in crude oil production to assure supplies of its primary feedstock and to guard against opportunistic behavior. Alternatively, a crude oil producer may forward integrate[22] by purchasing pipelines or refining assets in order to assure a market for its product. In all, a petroleum company may desire to have assets in multiple stages of its supply chain to smooth the effects of the business cycle.

In the past few decades, a number of U.S. industries have experienced periods of rapid technological innovation, representing significant investment. However, in contrast to earlier periods, these industries have trended toward less vertical integration (disintegration) in their industrial organization. Hicks (1996, 2001) studied vertical disintegration in the face of rapid innovation in the semiconductor and telecommunications industries and found that rapid investment in technical advance to retain a competitive advantage was often financially unsustainable. Companies in those industries recognized that they could not adequately maintain the rapid pace of creating cutting-edge process and product technologies and still remain economically. As a result, the entire industry evolved their organizational structures into smaller, specialized, and less vertically-integrated organizations, creating more collaborative supply chain relationships within industrial ecosystems. Their industrial organization evolved from

[22] Forward integration is when a firm acquires downstream assets in its supply chain, such as its downstream distributors. This can also mean developing its own downstream distribution assets.

large integrated firms, both horizontally and vertically,[23] into a large number of smaller firms cooperating and competing in "*complex adaptive systems*" that provided operational and financial flexibility while exploiting the competitive advantages of continuing technical advance.

Besides semiconductors and telecommunications others, such as the steel, automobile, and petroleum industries, have also become less integrated (Hicks, 1988) than the classic Chandler (1977) industrial organizational model that dominated the twentieth century. Oilfield service companies, such as Haliburton, Schlumberger, and Cameron, have grown to become integral parts of the petroleum industry in the past few decades, expanding significantly into a number of production and refining support functions (Beyazay, 2015). The major petroleum companies have reduced much of their in-house research and development (R&D) efforts, with the large R&D centers for ExxonMobil, Chevron, and other operating companies being significantly reduced, and instead depending on oilfield service and engineering companies for much of their continuing technical advance.

2.1 Vertical Integration: A Closer Look

Vertical integration, or more specifically when a firm is vertically integrated, is difficult to define due to the vast number of transactions undertaken by each individual firm in the

[23] Whereas vertical integration refers to ownership or control of more than one function along a supply chain, horizontal integration refers to the market share of a company has a particular stage of the supply chain. For example, a monopolist would be 100 percent horizontally integrated, while a market with many competitors would have little horizontal integration.

normal course of business and the multitudes of ownership arrangements that firms have at their disposal to govern transactions. The fundamental concept of vertical integration is the substitution of market transactions between firms for internal transactions within a firm's boundaries. Product supply chains (or value chains) are composed of transformations and transactions to move products from commodity suppliers to consumers, from upstream to downstream. Transformations occur when something is changed into something else, such as when crude oil is processed into gasoline precursors and then into gasoline within a refinery. Transactions are the steps of transferring one group to the next, either *inter* or *intra*-organizationally. These transaction steps can be done within one company's organization (vertically-integrated) or between two, or more, companies under contractual arrangements. In a strict manner, a transaction step should be viewed as fully vertically integrated if one firm owns both the upstream and downstream processes where *all* of the upstream process goes into the downstream process, or if the firm's downstream process gets *all* of one, or more, of its feedstocks from the same firm's upstream process. This strict criterion of vertical integration is typically only found within single locations or plants where engineering considerations determine the number of process steps to be undertaken within an organization. [24] Beyond this, most vertically-integrated transactions in actual commerce and industry fall into the "partially

[24] A firm may vertically integrate due to engineering or process technology reasons, such as integrated chemical steps within an oil refinery to conserve energy. These are important determinants for vertical integration within industry, but fall outside of the economic reasons.

integrated" category, where one firm owns upstream and downstream processes where *some* of the upstream process goes into the downstream process, or the downstream process gets *some* of one, or more, of its feedstocks from the upstream process.   This is true of virtually all ongoing interactions between production and refining stages within vertically-integrated petroleum companies. The production businesses within integrated petroleum companies do not go out of their way to ship their crude oil to affiliated refineries. The refineries within those companies do not limit themselves to only processing crude oil from affiliated producers. Since crude oil is essentially a commodity, both businesses ship or buy their crude oil from the most economical source available. In fact, it is possible that most integrated oil companies would not even have an accounting for how much of their own crude oil is processed by their own refineries.

A single firm can have several supply chains running through it with varying degrees of vertical integration across a continuum of its transactions, from conducting spot market[25] transactions between independent agents to conducting these transactions within a single organization. In other words, a firm can buy a good or service or they could decide to produce it themselves internally. Between these two extremes, there are an infinite number of possible contractual arrangements. Exchanges between independent agents or firms can be governed by contracts specifying various terms, conditions, and pricing that

[25]Spot markets are transactions between independent agents for goods, commodities, securities, or other assets for cash payments and immediate deliveries. Most retail transactions, such as a grocery store, would be considered spot market transactions.

restricts or compels behaviors by the parties. They are typically referred to as "vertical restrictions" or "vertical restraints" under U.S. antitrust law. Examples of these include sales territories, minimum marketing requirements, minimum inventories, franchise contracts, pricing arrangements, delivery time requirements, and others. These contracting arrangements may be perfect or imperfect alternatives to vertical integration, depending on the individual exchange circumstances. Unfortunately for research purposes, these contracts are typically private with little publicly available information, making it difficult to obtain any usable statistics. Consequently, research on vertical integration and disintegration has been, for the most part, restricted to observations of only the two extreme cases.

The difficulty in defining vertical integration gives an, "*I can't define it, but I know it when I see it*," feeling to the subject, with compromises manifesting themselves in data collection and measurement problems. Academic researchers have used a variety of metrics to measure the level of vertical integration of firms, none of which appears to be universally accepted. Since available information is provided by private firms, sometimes with motivations to be less than truthful, this makes the reliability of the information somewhat doubtful in some cases. Fortunately, U.S. petroleum companies are required to report a good deal of information to state and federal authorities, increasing their motivations for accuracy.

The ratio of the input value to sales appears to be the most common metric when individual company structures are examined and measured for their degree of vertical integration. Mitchel (1976) named this ratio the *"self-sufficiency ratio"* in his extensive research on the root causes of the petroleum industry's industrial organization. Other studies of individual industries sometimes evaluate individual firms and make dichotomous evaluations, either firms are, or are not, vertically integrated. Stuckey's (1983) study of the aluminum industry is a good example of this, but he also uses industry-wide metrics to measure the degree of forward and backward integration in the industry as a whole. All three of these metrics are used in this research.

The dominant theories of vertical integration and firm boundaries generally start with the understanding that markets are not perfectly competitive. This reality provides firms' primary motivations to expand from "unit" economic entities, providing only one step in the supply chain, to entities that execute several steps in that chain. There is not one encompassing theory that is universally accepted among economists, but a number of them are more prevalent than others. This likely reflects reality since decisions on firms' industrial organizations are undertaken considering many competing factors over forward-looking time periods. Neo-classical economics approaches vertical integration by focusing on firms' market power and profit optimization of upstream or downstream relationships within its supply chain and integrating transactions within a firm's boundaries, or not. Transaction Cost Theory (TCE) argues that firm boundaries are determined by a balance between market transaction costs versus internal bureaucratic costs. TCE states that firms within a supply chain that make transaction-specific investments are exposed to uncertainty due to the issue of incomplete contracts and resulting opportunistic behavior risk, balanced against the benefits and costs of internalizing transactions. Property Rights Theory (PRT) focuses on ownership of assets and how control of "residual rights" *ex-post* contracts can alter the efficiency of transactions. Contracts between firms cannot be written to cover all contingencies. Residual rights determine which party has the upper hand in any subsequent negotiations. Vertical integration means that the acquiring party gains control of all of the residual rights.

There are other theories on vertical integration which do not directly deal with the relationship to technological well, so they will not be discussed in detail. These include Stigler (1951), who refers to Adam Smith's theorem that an industry's division of labor or labor specialization is determined by the extent of the market. Stigler states that infant industries will begin as vertically-integrated because their economic scale is typically too small to have intermediate markets. As an industry grows and matures, some tasks are spun off as specialized firms in order to increase the efficiency of the core industry, leading to a trend of vertical disintegration. Lastly, a declining industry will lead to vertical integration as demand declines and intermediate markets become smaller and less efficient to support. Another approach utilizes game theory methods, such as Lafontaine and Slade's (1996, 2007) principal/agent argument. The principal/agent models, or moral hazard, pit a principal (a franchisor) against an agent (franchisee) in a model set up to determine whether it is advantageous to vertically integrate. These models can be used to understand the various factors that lead to vertical integration or other contractual arrangements.

Some earlier research on vertical integration uses data across a number of industries, typically within a single nation. Another popular method of studying vertical integration has been in the context of single industries, such as this research of the petroleum industry. Stuckey's (1983) excellent book studied the structure of the international aluminum industry from 1955-1979. Since the aluminum and petroleum industries share some similar attributes, namely that they are both extraction industries that also require extensive downstream refining, some of the quantitative methods used to understand the aluminum industry organization are borrowed from that study. Other studies include Joskow's (1987) study of the coal/electrical generating industry, Ohanian's (1994) analysis of the pulp and paper industry, and Hortaçsu's (2007) study of the U.S. cement industry, among a number of others.

The highly vertical structure of the petroleum industry has been the subject of several studies over time. McLean and Haigh (1954) provided an exhaustive study of the history and development of vertical integration within the petroleum industry in the first half of the twentieth century in response to government concerns of excessive market power by the integrated petroleum companies. That book found that several determinants characteristic of the industry favored a high level of integration, and that its integrated structure generally increased the social welfare. Mitchell (1976) and Greening (1976) conducted detailed studies, and both came to similar conclusions that the industry's structure was due to the nature of its competitive market, and that any forced divestures would most likely reduce social welfare.

2.2 Neo-classical Economics Approach to Vertical Integration

The fundamental premise of Neo-classical economics is that firms exist, make decisions, and allocate their resources to maximize their profits. The firm is a production function or simply a set of inputs and outputs. Vertical integration is principally viewed as a market power strategy between upstream and downstream firms in an imperfectly competitive market. Motivations to vertically integrate can be divided into three categories: 1) to remove market inefficiencies by internalizing transactions between stages; 2) to extract rents from an otherwise competitive stage; and/or 3) to obtain the ability to price discriminate (Perry, 1989). Neo-classical theory has typically ignored market transaction costs, or increasing bureaucratic costs, as firms grow larger and more complex, so these are not taken into account in a firm's decision to vertically integrate or not (Joskow, 2010). This obviously is not a realistic assumption and tends to cause these models to show that vertical integration is favorable, or neutral, for firm welfare in almost all cases. The theory does not answer why all commerce is not just conducted under the roof of one company. Though there are shortcomings, Neo-classical models using interactions between monopolies and monopsonies provide insight and motivations to vertically integrate in order to extract additional rents. These lessons can be applied to oligopolistic cases and to less-than-perfectly competitive market cases.

2.2.1 ''Double Marginalization'' and the Two-Monopoly Case

The first motivation to take advantage of market inefficiencies can be demonstrated using

1) an extreme model comparing two monopolies in series supplying a market to 2) an integrated monopoly that encompasses both stages. In the first instance, the two monopolies both charge their monopoly prices, adding their combined markups to the consumer's price into what is called "double marginalization." The model shows that shifting to an integrated monopoly of only one firm will result in only one monopoly price which will translate to lower prices to the consumer, and will also increase the monopolist's profits due to higher quantities, increasing welfare for both (Perloff & Carlton, Chapter 12, 2005). Again, the weakness of this model is that it ignores any contract or market transaction costs or integration bureaucratic costs that firms would bear. If contracting costs are ignored, the features of this vertical integration can be perfectly substituted with vertical restraint arrangements, such as linear transfer pricing, tying contracts, two-part tariffs, franchise fees, minimum quantity contracts, and resale price maintenance (RPM) with the same welfare results for the firms and consumers.

2.2.2 The Monopoly-Competitive Firm Scenario

The second motivation to vertical integration can be demonstrated by modeling a downstream firm that can substitute, to some degree, from an input supplied by a monopoly to a competitive supplier. As a result, the monopolist's high price will induce the downstream firm to shift inefficiently their input mix away from the monopolist. This will then induce the monopolist to forward-vertically integrate into the downstream market. This integration can result in a more efficient use of inputs and increase profits to the integrated firm and may increase consumer welfare (Tirole, 4.2, 1988).[26] As in the model above, this model also ignores any costs associated with market transactions or internal bureaucracy costs. This motivation could also be vertical integration in order to foreclose another firm from either its inputs or downstream markets, or to erect market entry barriers for upstream, downstream, or entering firms. It should be noted that these motivations would be considered anticompetitive and, most likely, illegal by U.S. Federal authorities.

Market inefficiencies caused by uncertainty or private information can also induce firms toward vertical integration. A good example is the coordination involved in the knowledge of when, where, and what petroleum pipelines should be built to support new production and/or refining. The assumption is that information flows are faster and more efficient within firms than between independent firms, even if there is no reason to withhold information. Therefore, when production, pipeline, and refining planners are all in the same firm, projects can be executed in parallel and more efficiently than would be the case if different companies were attempting to coordinate in some manner. Government regulations, price controls, and taxes can also introduce market imperfections, all with the potential to affect the motivations to vertically integrate.

[26] Note that this example is not particularly applicable for the petroleum industry since there is no substitute for crude oil.

2.2.3 The Monopoly-Forward Integration Scenario

The third motivation is exhibited by a number of major petroleum companies, which have forward-integrated into retail sales in order to differentiate their petroleum products and price discriminate among different types of customers. Though crude oils are differentiated by various quality specifications, crude oil is essentially a commodity. As a result, that stage of the supply chain is not particularly susceptible to price discrimination beyond some quantity discounting and other long-term contract provisions. This motivates petroleum companies to forward integrate into retail in order to differentiate their products. Examples of this are marketing campaigns to differentiate brands of motor fuels and lubricants, such as Chevron's "Techron"™ branding of gasoline additives, and price discrimination by location of service stations.

While models primarily using monopolies and oligopolies may not be particularly realistic, these lessons are still applicable in real-world cases involving imperfect competition. Double marginalization and market power problems are present within small and/or localized markets. These create incentives for vertical integration or vertical restraint arrangements, though these actions may make social welfare effects even more uncertain. Neo-classical economics describes a fairly rich array of inducements to vertical integration, but again its weakness is that it ignores market transaction costs or bureaucratic costs associated with internal organizations. Consequently, by itself Neo-classical microeconomics will tend to call for more vertical integration to increase social welfare under any market imperfection. For this reason, it is best to apply Neoclassical theory in combination with other theoretical frameworks.

Neo-classical microeconomics' treatment of technological innovation is approached in terms of the introduction of changes in the conditions within a supply chain, such as costs, or cost reductions, or product differentiation in cases of new product lines. These changes can impact the balances between parties, modifying strengths and weaknesses within the relationships. Additionally, a technologically-innovative climate can increase the level of uncertainty among firms. Various neo-classical models and studies, such as Perry (1982) and Carlton (1979), show that firms vertically integrate in response to increasing uncertainty or risk in their supply chains. Technological innovation can either increase or decrease uncertainty for different parties within a supply chain depending on its location and/or its nature. The possibility of obsolescence of older technology can introduce supply chain risks, potentially decreasing asset usefulness and value. On the other hand, technological innovation may increase a firm's upstream supply options or downstream markets, thus reducing its uncertainty.

2.3 Capital Costs Savings of Vertical Integration

The petroleum industry is capital-intensive with high expenses incurred to explore, produce, and refine petroleum, so that the cost of capital is a major factor in a firm's competitive position. Diversification is a well-known investing strategy to reduce financial portfolio risk. In order to reduce their earnings risk, Mitchell (1976) stated that petroleum companies have commonly vertically integrated as a portfolio diversification strategy to reduce period earnings variations. Due to exogenous shifts in crude oil supply and demand, returns in the upstream petroleum production and downstream refining stages are not correlated. By diversifying the uncorrelated returns of production and refining by vertically integrating, petroleum companies can reduce their return variance between periods, reducing portfolio risk and reducing their cost of capital financing. By investing in related businesses in which it may have some expertise by backward or forward integrating, a petroleum company reduces its risk of making bad investment and managerial decisions, further reducing its portfolio risk. Additionally, assurance of markets or supplies can influence a firm's financial risk level. Standard Oil of Ohio (Sohio) was initially a marketing and retailing firm after the 1911 breakup of Standard Oil with no crude production operations. Because of this, its financing costs were higher than competitors with more integrated structures, contributing to its profitability struggles for many years until it eventually gained its own crude oil supplies. (McLean & Haigh, 1954)

2.4 Transactional Cost Economics (TCE)

Ronald Coase (1937), argued that the Neo-classical focus on production relationships between firms were not the key to understanding the motivations for firms to vertically integrate, but that vertical integration and market exchanges, or transactions, were the primary substitutes, or alternatives, in firms' organizational decisions.

> *"Outside the firm, price movements direct production, which is coordinated through a series of exchange transactions on the market. Within a firm, these market*

transactions are eliminated and in place of the complicated market structure with exchange transactions is substituted the entrepreneur-coordinator, who directs production. It is clear that these are alternative methods of coordinating production."
Ronald Coase (1937: pp 388)

All economic exchanges incur transaction costs, whether the exchange is conducted externally within a commercial market or internally inside a firm. Coase argued that a firm will expand its boundaries until the internal bureaucratic costs balance with market costs. These concepts did not gain wide acceptance until O.E. Williamson (1975, 1985, and 1989) and others developed what is now called, Transaction Costs Economics (TCE). [27] Williamson explained market transaction costs to include the costs to search for and identify trading partners, bargaining and negotiating, contract writing, and enforcement (Williamson, 1975, pp 4,7). This theory utilizes the concept of human "bounded rationality" and the problem of incomplete contracts. Bounded rationality refers to the limits of people's capacity to solve complex problems within a limited time frame. Incomplete contract problems arise when transactions become more complex than simple spot purchases can accommodate, and become increasingly more difficult – and therefore costly – due to this bounded rationality to find and negotiate contracts that cover all *ex-post* circumstances. This results in uncertainty in market exchanges and gives parties the ability to "behave opportunistically," meaning generally to take unfair advantage of another

[27] The term "Transaction Cost Economics" was not popularized until Williamson's treatments.

contractual party when the opportunity arises. If market contracts between independent firms are necessarily complex enough so that bargaining costs outweigh the cost of alternative bureaucratic costs, industries will increasingly tend toward vertical integration.

A simple example of opportunistic behavior would be a repair contractor taking the opportunity to not show at the designated time after you have already paid him. This uncertainty increases the homeowner's transaction costs. All buyers and sellers have different, sometimes conflicting, interests when conducting a transaction through market contracts. In an ongoing contractual arrangement, or trading relationship, opportunistic behavior may arise because it is advantageous for the parties to stay locked in a relationship rather than seek out new partners.

> *"If parity among suppliers is upset by first-mover advantages, so that winners of original bids subsequently enjoy nontrivial cost advantages over nonwinners..."* (Williamson, 1975, p28)

In these cases, a party may engage in opportunistic behavior to extract additional "*appropriable quasi-rents*"[28] from the other party (Klein, Crawford, and Alchain, 1978) (Goldberg, 1976). The resulting bargaining and conflict can affect the profitability of both parties and the relationship's expected value and economic performance. This uncertainty

[28]Klein, Crawford and Alchain (1978) defines, "*The quasi-rent value of the asset is the excess of its value over its salvage value, that is, its value in its next best use to another renter. The potentially appropriable specialized portion of the quasi rent is the portion, if any, in excess of its value to the second highest-valuing user."*

can also discourage the efficient investment of transaction specific assets, "hold-up," by the parties.

If costs, complexity, and/or uncertainty are high in a circumstance, it may be too difficult – and costly – for a firm to use market exchanges through contracting with other firms. If market choices are limited (i.e., small market) and the risk of opportunistic behavior is high, firms may decide to produce an intermediate product internally, that is, through vertical integration. Vertically integrating the transaction into one organization could potentially allow for efficient management of the conflicting interests and efficient allocation of investments. In the same manner, one may decide to do their own home repairs rather than dealing with a contractor. This comes with its own internal or organizational costs. As organizations grow, they become more unwieldy and bureaucratic, increasing the internal costs. Firms weigh these alternative costs over the many transactions it executes to determine the extent of its vertical integration and boundaries. A firm (or firms within an industry) chooses the degree of vertical integration along a product supply chain to minimize costs and to mitigate risks.

Caves and Bradbury (1988) identified a number of common determinants affecting the balance between market transaction costs and organizational costs. These included market concentration, asset specificity, supplier importance, relationship complexity, advertising, R&D expenditures, and risk and uncertainty, with asset specificity having the highest correlation with vertical integration. Technological innovation could potentially affect any of these determinants with varying influence on the market transaction and internal cost balance.

2.4.1 Asset Specificity

The concept of asset specificity within TCE requires a particular discussion. Transactions in many cases require transaction or relationship-specific upstream and/or downstream asset investments to enhance its economic efficiency. Asset specificity increases firm commercial risk because if a contract is terminated, or reduced, it may be left with assets that are now significantly less valuable, such as a producer terminating a crude supply contract with a refiner. Industries that tend to be vertically-integrated also tend to have higher asset specificity in its commercial relationships. Lieberman (1991) stated that asset specificity of transaction related investments is the most important determinant in a firm's decision to integrate vertically. There are a number of characteristics that can limit an asset's utility so that it is specific to a particular transaction.

1) Assets might be built at specific locations, such as building a coal mine near a coal powered electrical generating plant. As a result, it may be difficult to move assets or service other customers from that location.

2) Specific equipment, such as petroleum production wells and refineries, may not be suited for other purposes.

3) Specific human capital, such as technicians trained for a particular client's

requirements or human relations and experience developed during a contract may not be completely transferable to another client.

4) Dedicated capital assets, such as investments may be made for a specific contract that would not have been made otherwise.

5) Intangible assets are likely to be less valuable to other clients, such as brand names.

6) Risk of capital losses may occur in the event of obsolescence due to technological innovation.

2.5 Property Rights Theory (PRT)

TCE was substantially formalized by Grossman and Hart (1986) and Hart and Moore (1990) with their Property Rights Theory (PRT). PRT addresses vertical integration through the issue of incomplete contracts, but also engages property rights economics and the concept of residual rights. PRT differs from TCE by focusing on the ownership and control of assets and *ex ante* investments and how these alter trading relation power rather than *ex-post* transaction problems. In real business, contracts are incomplete because it is impossible to consider all possible states of the world. PRT uses the concept of *residual rights*, which are those property rights that a party has over assets that are not contractually controlled by others. A party to a contact can have property rights over an asset without being the actual owner, such as in the case of a lease agreement. The residual rights of control of property left outside of the contract language determine each party's negotiating leverage when unforeseen contingencies develop. PRT states that the residual rights over assets affect a party's ability to engage in opportunistic behavior. As does TCE, PRT is also concerned with the potential of firms being locked into contracts, resulting in potential opportunistic behavior by other parties. These considerations will also determine upstream and downstream parties' incentives to efficiently invest, or not, in assets. This problem of inefficient, or insufficient, investments is called "hold-up."

In the case of backward integration, the control rights of an upstream supplier's assets are entirely transferred to the downstream firm, giving the downstream firm the incentive to increase investment in itself due to reduced risk. The loss of all asset rights would reduce the upstream suppliers bargaining power and the motivation to invest in its upstream assets. Consequently, a higher importance or intensity of the downstream buyer's technology would be positively correlated with backward integration.   The importance or intensity of the upstream supplier's technology would have the opposite effect.

2.6 Technical Innovation and Vertical Integration

How a technical innovation affects the supply chain can also affect the optimum industrial organization and whether existing organizations require change themselves. Technological innovations affecting different parts of supply chains, or in different ways, may require different industrial organizational responses. The concept of technical innovation and what it constitutes can mean many things. It could be a physical technology, such as computers and automation or organizational innovations, such as the building a production infrastructure around an assembly line. Consequently, innovation is difficult to measure in any uniform manner that would make it easily comparable from study to study. Technical innovation has come in many varieties over the past two centuries, affecting products, production processes, and their supply chains. Organizational innovations, such as the development of the modern corporate structure, are also overlaid across this period. These factors are interrelated with business, political, and other inputs making the entire subject of cause-and-effect between technology and industrial organization somewhat murky.

Chandler (1977), Chandler & Daems (1979), Jones (1987), Landes (2003), and other industrial historians provide a number of examples of nineteenth and twentieth century technological innovations that are correlated with increased vertical integration of corporations. As it became increasingly technologically intensive in its early years, the petroleum industry also evolved into a highly vertically-integrated industry in the nineteenth and throughout the twentieth century. In such cases, these correlations were commonly explained as the result of increasing asset specificity and uncertainty along with the industries' efforts to mitigate against production disruptions. Different lessons have been noted in recent interplays between innovation and industrial organization.

How technological innovation affects a supply chain and its organization depends on the nature of the innovation and on the location, that is, precisely where along the supply chain a technical advance can register an economic (or other) effect, including effects on competing or complimentary supply chains. For example, an innovation that decreases the cost of production in the development of assembly line operations can be expected to have an effect different from an innovation that decreases transaction costs, such as improved telecommunications. Tight-oil technology increased the supply potential of crude oil and natural gas into the market, decreased the rate of unsuccessful wells, but increased the cost per well drilled. It is doubtful that its effects on the petroleum industry would be the same as an innovation that, for example, simply reduced production costs.

Williamson argues that tracing how technological change effects firm organizational changes is determined by how it affects future transaction costs. He argues that technologies do not determine organizational changes, but they may create circumstances that have the potential to alter the cost of market-based contracting. Technology and internal industrial organization are not independent, but the most efficient mode for transactions depends on the properties of bounded rationality, transaction costs, and opportunism risks, not necessarily the technologies available to the firm.

> *"…tight linkages among processes are technologically determined only if technological inseparabilities are significant. Otherwise, decisions to forge linkages reflect transaction-cost savings rather than technological imperatives."* (Williamson, 1980, p.195)

PRT becomes more helpful in predicting the effect of technological innovation on vertical integration when transaction costs are not necessarily affected. Technological innovation that affects the value of property residual rights can thereby affect the motivations for vertical integration and disintegration. Acemoglu (2010) and Cainelli (2009) built both theoretical and empirical models based on the PRT approach, using R&D as a proxy for technological intensity over a number of industries in United Kingdom and Italy, respectively. Acemoglu's found that, consistent with PRT predictions, vertical integration was more prevalent when the downstream buyers were more technologically-intensive. By contrast, upstream suppliers were less motivated toward vertical integration with increased technological intensity. These correlations increased as the upstream firm's contribution to the downstream firm's cost structure increased. Cainelli 's (2009) findings were similar in that the downstream buyers' technological intensity was positively correlated with vertical integration, although they found no statistically significant relationship with the upstream supplier's intensity.

Measuring the introduction of technological innovation into the marketplace often has proven to be quite difficult. Most studies have depended on the use of proxies operating indirectly, such as R&D expenditures, patents, and average plant age, rather than the more direct measurement of the insertion of a specific technology into a supply chain. R&D expenditures and patents are at least one step removed from market and/or supply chain innovations. While they would be positively correlated, different firms' experiences with transitioning R&D and/or patents into actual product and process improvements would likely introduce biases into any measurement. Additionally, even precise and accurate measurement of R&D or patents does not take into account how any resulting innovation registers their effects in market dynamics or supply chain operations explicitly. The use of plant age assumes that innovative industries have newer plants; a plausible idea but one for which there is no direct evidence of a positive correlation to be found in the literature. Indeed, Dunne (1994) found no evidence of a correlation between plant age and the use of advanced manufacturing in the United States.

Technical innovation can affect a supply chain in at least three general ways, singly or in some combination. First, innovations can be introduced into the supply chain in the form of a new product concept. Such an innovation may well necessitate the creation of an entirely new supply chain. Every product used by consumers was a technical innovation at some point in time. This type of innovation can also take the form of an intermediate product, such as the supplanting of metal with carbon products for automobile and aircraft bodies. Secondly, an innovation can take the form of a new type of production process that transforms or eliminates one or more stages in a supply chain. Tight-oil exploration and production technology falls into this category. The history of the petroleum industry offers many other examples over the years, such as the refining industry's migration from batch to continuous processing. The third category of effect includes innovations affecting the cost or efficiency of transactions within a supply chain. Examples of this would include advances in telecommunications, introduction of block chain accounting, or other communication advances that are capable of dramatically accelerating transaction velocity while reducing costs. Technical innovations can affect one or a combination of these three varieties. The computer and communication revolutions – and especially their convergence – are examples of innovations affecting the supply chain within and across all three categories. While PCs were primarily a new consumer product, their adoption and implementation in industry dramatically increased efficiencies in transactions and transformed information flows across all locations along the supply chain. Technological innovations in complementary or competing supply chains can also register the same or similar industrial organizational consequences.

TCE theory explains how the Industrial Revolution's technological innovations led to highly vertical corporate organizational forms due to increased asset specificity. Greater investments, however, do not always lead to higher vertical integration. Balakrishnan (1986) advanced an argument, utilizing TCE, that technological innovation can also lead to vertical disintegration. If an industry experiences a period of technological innovation, existing capital becomes more exposed to the risk of obsolescence and consequently becomes less valuable. Even newly-introduced assets can have diminished value because they can also be rendered obsolete by even newer technology. Capital life expectancy is reduced with potentially lower realized profits from existing assets. This reduces the value of bargaining involving the use of these assets and their attendant costs, leading to lower transaction costs and reduced motivation to vertically integrate. If this is taken to a limit where industry profits are reduced to only competitive rates of return, there is little need either to bargain or to vertically integrate. Balakrishnan (1986) constructed a simple theoretical model that concluded (1) vertical integration is reduced by technological innovation, especially in highly competitive industries, and (2) the optimum level of vertical integration was negatively dependent on the degree of industry competition. He also developed an empirical model supporting his conclusions using Federal Trade Commission data for 1973-1977 over a large number of industries, using the average age of plants as a proxy on whether an industry was experiencing technical innovation.

Likewise, Hicks' (1996, 2001) illustrated the role of TCE dynamics at work in his analyses of the transformation of the semiconductor and telecommunications industries. He found that the financial pressures associated with rising internal R&D investments in order to stay competitive led to internal bureaucratic costs increasing at rates faster than market exchange transaction costs. As a result, both industries responded by assuming new organizational forms that reflected patterns of vertical disintegration to better accommodate those financial pressures.

2.7 Simultaneous Effects of Innovation and Organizational Structure

Another issue that is not commonly addressed in past studies is the possibility that technical innovation may unleash countervailing pressures along a supply change or across an industrial landscape to vertically integrate *or* disintegrate simultaneously. This would be evident in the circumstance where firm A has an effect on firm B at the same time that firm B has an effect on firm A? This simultaneous effect certainly could lead to bias if not properly addressed in econometric models.

A consensus around the actual effects of technological innovation on vertical integration, and the reverse, has yet to be reached among economists. Nearly all studies can be placed in two categories. The first category analyzes the effects of vertical integration on technical innovation, particularly what types of industrial organization foster innovation most efficiently and effectively. Prominent studies include Armour (1980), who studied the U.S. petroleum industry and found that the extent of vertical integration within a particular industry is positively correlated with the extent of R&D expenditures. Freeman (1982) argued that vertically-integrated organizations were more efficient at R&D primarily because of the likely complementary applications of new technology among the various stages in an integrated firm's supply chain. This encouraged a higher level of R&D (innovation) in larger vertically-integrated firms. Piore (1984) argued the opposite noting that smaller, less integrated, companies are more flexible, an attribute that engenders better innovation environments. He qualified his findings that large firms were perhaps better suited to bringing existing ideas to fruition, while smaller firms seemed to be better at developing new ideas ab initio. Robertson (1995) concluded that neither a vertically-integrated nor a decentralized industrial organization is necessarily the optimum to enhance technological innovation. Rather, the most efficient structure depends on the nature of the technological change and the particular product life cycle. Acemoglu (2003) found that the advantages of a firm's level of vertical integration are negatively correlated with its proximity to its industry's centers of innovation, with firms located far from the technological frontier tending to be more vertically integrated. Since the center of innovation in the petroleum industry is arguably in the U.S. – particularly in the Greater Houston region – Acemoglu would most likely argue that American domestic petroleum companies should be less vertically integrated than firms in other countries.

The second category is studies of the effects that technical innovation has had on vertical integration in industries. These studies include Balakrishnan (1986), who found that high rates of technological change within an industry lead to less vertical integration, with the optimum level determined by the degree of competition. Hicks (1988) found evidence of technological and competitive disruptions associated with vertical disintegration within several broad industry categories, including the machine tool, automobile manufacturing, and steel industries which were under technological pressure from a variety of sources. Brynjolfsson (1994) studied the degree of information technology (IT) investment within firms and found that the greater the adoption of information technology (IT) in an industry, the smaller the average firm size and, presumably, the less integration within the industry. As stated earlier, Acemoglu (2010) found that technology intensity in upstream industries is negatively correlated with vertical integration, while downstream technical intensity is positively correlated.

There is a rich literature on vertical integration and its relationship with technology and innovation. The dominant economic theoretical frameworks examine this relationship from different perspectives, mirroring the various competing considerations firms must weigh in determining their industrial organization. These considerations include a firm's market power and status relative to their competition, as well as their transaction costs, property rights, and investments. As in most economic research, studies under laboratory conditions are not feasible. This sets limits on experimentation, data gathering, and eliminating bias from results. Consequently, opportunities must be found in the real world where bias can be minimized even as measurable data can be gathered. In light of the theoretical discussion in this chapter, the next chapter will introduce the real-world opportunity presented to examine the effects of the introduction of a technological innovation into the U.S. petroleum industry, a massive and mature vertically-integrated industrial organization.

CHAPTER 3

THE IMPACT OF TECHNOLOGY INNOVATION ON THE STRUCTURE AND OPERATIONS OF THE U.S. PETROLEUM INDUSTRY

The petroleum industry is one of the world's most important industries due to its economic and geopolitical influence. The ever-widening variety of uses of petroleum products has vastly accelerated human progress since the time of Col. Drake[29] when most useful energy was supplied from draft animals and manual labor. Today the world's work and leisure are powered by massive amounts of energy provided, in a large part, by petroleum and other hydrocarbons. The world demand for crude oil is approximate 100 million barrels per day (BPD), with the U.S. demand being about 12 million BPD. The industry is notoriously capital-intensive with high levels of investment uncertainty and operational hazards. The supply chain for petroleum products is organized into three principal stages: crude oil production, petroleum refining, and customer-facing marketing, with transportation bridges in between. Crude oil production involves the extraction of crude oil and natural gas from geological deposits[30] located in porous rock thousands of feet below the surface, with many of these deposits below the ocean. It requires very sophisticated expertise and technology to find, develop, and produce crude oil and natural gas. The production stage involves significant financial risk due to the large variety of unknowns involved in

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[29] Col. Edwin Drake was the first American to successfully drill for oil in 1859. The drill site was in Titusville, Pennsylvania.

[30] Crude oil and natural gas are separated close to the production site. Natural gas is then sent through a different supply chain to its consumers.

prospecting for petroleum, with many exploration wells proving to be unsuccessful, producing little or even no petroleum or natural gas after considerable investments. Once petroleum is produced, it must be transported to specialized refineries to be processed into the various petroleum products, including fuels, lubricants, and chemical feedstocks. Petroleum refineries can contain billions of dollars' worth of production and processing equipment, with those in the United States being more complex on average than those found in other countries. The wholesale and retail stages distribute and market these products to consumers. Connecting these stages is a large specialized transportation system, including storage tanks, pipelines, railroad tankers, trucks, ships, and barges. [31]

The U.S. petroleum industry's historically highly vertical-integrated organization reflects a number of factors, particularly its asset specificity, its risks, and its complexity. Crude production and refining equipment are expensive and cannot be readily used for other tasks. Crude oil has no other market other than petroleum refiners, and crude oil is a major input cost for refiners which have no substitutes. Crude oil contracts can be complicated, increasing bargaining and searching costs and incomplete contract risk. On the other hand, crude oil is a commodity, so production and refining equipment are not typically locked into a single specific contract.

Though crude oil is a commodity traded on a world market, not all crude oil is the same.

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[31] Deutsche Bank, Oil & Gas for Beginners - A Guide to the Oil & Gas Industry, January 25, 2013. This guide provides an in-depth description of the petroleum industry but is written for readers without experience in that industry.

Wells from different fields produce crude oil and natural gas in varying compositions and varying proportions. The crude oil and natural gas are separated near the production field and afterward routed into different supply chains.[32] Assays for crude oil vary over a number of specifications; the most important being API gravity[33] and sulfur compound content.[34] Individual refinery designs are limited to process a crude slate within the bounds of certain assay specifications, with the more complex refineries having some additional flexibility. A refinery's engineering design is based on the available crude oil, as well as access to pipelines, harbors, and other logistical considerations. The U.S. crude oil logistics system is extensive and provides refineries flexibility in their supply sources, but refiner and crude oil supplier bargaining relationships can be one of small numbers locally, giving rise to opportunistic behaviors. [35]

The industry has experienced a number of significant shocks and changes throughout its history. Early on petroleum products were primarily used as an illuminant (kerosene), replacing whale oil and essentially saving those species from extinction. At the time,

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[32] In order to simplify the analysis, this research concentrates on the crude oil supply chain.

[33] API gravity is a measure of the density of crude oil and other liquid petroleum products. API gravity was devised by the American Petroleum Institute (API) and the National Institute of Standards and Technology (NIST).

[34] The amount of sulfur compounds contained in a crude oil assay can significantly affect its market price and limit the refineries that are capable of processing it. Crude oil with greater than 0.5 percent sulfur is considered "sour," and can contain poisonous hydrogen sulfide. These types of crude oil can only be processed in refineries that have made the investment of equipment that can handle them. "Sweet" crudes contain much less sulfur compounds and can command significantly higher prices in the world market because of higher demand. Crude oil from U.S. tight-oil reservoirs are almost all sweet crude oil.

[35] This has been a significant challenge for tight-oil producers who operate in new basins in many cases. These new basins lack the necessary logistical infrastructures until they are built. This has forced producers to discount their crude oil prices below market sometimes. The crude oil from the Bakken basin in North Dakota has been a good example of this situation.

gasoline was an unwanted byproduct and was dumped with little or no regard to environmental considerations. Thomas Edison's electric light bulb and distributed electricity technology displaced kerosene as a source of lighting starting in the last part of the nineteenth century. Fortunate for the industry, the introduction of the automobile turned the previously unwanted by-product, gasoline, into a valuable commodity, resulting in a major new market. Other petroleum fuels also became widely used, such as diesel, ship bunker fuel, heating fuels, and aviation fuels. The petrochemical and plastic industries, both petroleum-based, rose throughout the twentieth century to provide innumerable products in modern life. (Yergen, 1990)

Firms such as Standard Oil, British Petroleum, and Shell dominated the industry since the late-nineteenth century through today, both internationally and domestically. John D. Rockefeller's Standard Oil Company became a virtual U.S. monopoly and also controlled much of the international petroleum market. In 1911, Standard was forced by a U.S. federal court to divest itself under the Sherman Anti-Trust Act into 34 still large successor companies, including those that eventually became Exxon, Mobil, Chevron, Amoco (BP), Conoco, Atlantic, and Marathon.

The United States was the world's leading crude oil producer during World War II and overwhelmed its enemies with its energy and materials. During the two decades following

World War II, the international market was controlled by the "Seven Sisters,"[36] and in combination with the French company Compagnie Francaise des Petroles (CFP, later Total) produced 100 percent of the crude oil outside of North America and the Communist Bloc in 1950. During that time, an increasing share of this crude oil was being produced in the Middle East, Indonesia, Africa, Venezuela, and other third world countries. The international oil companies (IOCs) colluded in ways, large and small, to keep international oil market prices artificially low in order to develop and expand the petroleum world market, particularly in the Western world. Consequently, the producing countries were receiving below-market value for the crude oil they produced. (Yergen, 1990)

The rise of national oil companies (NOCs) and the Organization of Petroleum Exporting Countries (OPEC) was a direct response to these low market prices. Over a quarter century most crude oil exporting national governments retook ownership of their crude oil resources by various means and established their own NOCs to manage their production fields. Petroleum prices rose dramatically, particularly in the 1970's, leading to economic stagnation throughout the world. This turmoil provided room for more independent petroleum companies, such as Unocal, Occidental,[37] and ENI, to enter the international

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[36] Standard Oil Company of California (SoCal, now Chevron);
Standard Oil Company of New Jersey (Esso, Exxon, now ExxonMobil);
Standard Oil Company of New York (Socony, Mobil, now ExxonMobil);
Texaco (merged with Chevron);
Gulf Oil (acquired by Chevron);
Royal Dutch Shell; and
Anglo-Iranian Oil Company (now BP).

[37] www.unocal.com, Unocal has since been acquired by Chevron, www.oxy.com.

market (Brock, 2015). From essentially no production in 1950, the NOCs claimed about 10 percent of crude oil reserves in the 1970's, and then 90 percent of proven crude oil reserves and 75 percent global crude oil production by 2010 (Bain & Company, 2012). The NOCs have been successful in increasing the prices they receive to near market levels. However, their performances triggered a concerted effort throughout the Western nations to achieve greater energy efficiency and to pursue an enhanced strategy of exploration for energy alternatives, such as solar and nuclear power, both of which continue to this day. The loss of control over foreign fields caused the IOCs to intensify the search for new petroleum sources resulting in new discoveries in places such as the Gulf of Mexico, the North Sea, and offshore Brazil. The loss of reserves to the NOCs also eventually caused the need for the IOCs to reorganize themselves to cut operating costs, resulting in a wave of mergers in the late 1990's and early 2000's, that resulted in Exxon-Mobil, BP-Amoco-Sohio-ARCO, Chevron-Texaco-Gulf-Unocal, Conoco-Phillips, and Total-Petrofina–Elf Aquitaine. These mergers were horizontal in nature since the players were all vertically-integrated companies. Figure 3.1 shows pictorially the basic evolution of the major integrated oil companies over the last century.

The IOCs continue to provide technical and operational support to the NOCs to a considerable, but declining, extent as the NOCs acquired their own expertise. Today the IOCs still control much of the production throughout the world and still retain control over most international refining and marketing. However, increasingly NOCs have been forward integrating into those stages of the supply chain. One example of this is Saudi Aramco's refineries which operate in North America under the name Motiva.

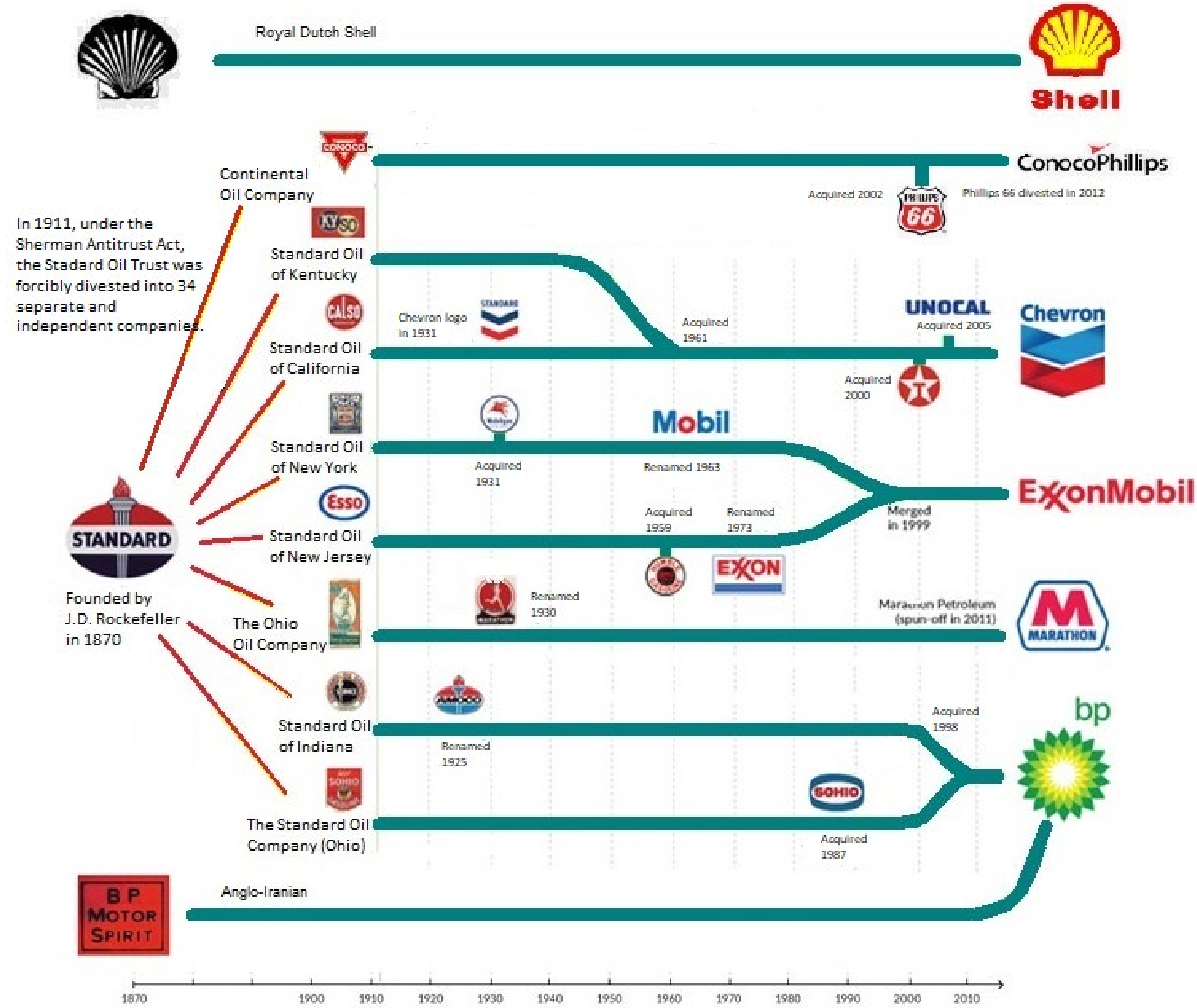

Figure 3.1: Evolution of Major International Integrated Oil Companies

A unique aspect of the American petroleum industry is that mineral rights on private property are not controlled by the government, but by private companies or individuals. Consequently, there are hundreds of crude oil production companies in the U.S. market, but large integrated companies still dominate the American petroleum industry. McLean and

Haigh (1954) found that large vertically-integrated companies operated 92 percent of the refining capacity in the United States in 1950. Teece (1976) found that major integrated oil companies produced between 50-90 percent of U.S. crude at the time, stating high asset specificity as a major determinant for this widespread level of vertical integration in the industry. Mitchell (1976) reported that the top 20 refiners, all integrated oil companies, operated 88 percent of the refining capacity in the United States in 1972.

Oilfield service companies (OSCs) play a vital role in the petroleum sector, both domestically and internationally. Through the first half of the twentieth century, petroleum companies commonly possessed their own equipment and expertise to explore, develop and produce crude oil on their leased or owned properties. Major companies had their own engineering and project capabilities to execute major capital projects in pipelines and refineries. Many of these functions have been divested over the years. As a result, both small production companies and major integrated companies have become dependent on OSCs for many production and refining operation tasks, including geo-surveying, drilling, well servicing, engineering, fabrication, construction among others. (Beyazay, 2015)

The *Deepwater Horizon* accident of 2010 on a Gulf of Mexico offshore well illustrates the extent to which OSCs are instrumental in production operations. Typically, drilling and production operations are private and all of the companies involved are not publicly announced. The *Deepwater Horizon* accident investigations provided an in-depth view of off-shore operations well beyond what had previously been revealed.[38,39,40] The subsea well itself was jointly leased by BP, Anadarko, and MOEX Offshore.[41] The semisubmersible vessel, *Deepwater Horizon*, was owned by Transocean,[42] along with the drilling equipment and crew. It had been designed and built by Hyundai Heavy Industries.[43] Halliburton and Schlumberger provided cement, drilling mud, and other drilling fluid services plus technical and testing services. Cameron and Weatherford provided specialized drilling and safety equipment.[44] Additionally, there were several companies providing logistical support, such as shipping, air transportation, and other supplies and services.

The petroleum industry has always been technology-driven, but in recent years increasing computer power and connectivity – referred to as the "Digital Oilfield" – has been introduced throughout the petroleum supply chain.[45] These technology advances have been gradual, but significant, and are likely contributing to changes in vertical integration

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[38] BP, Deepwater *Horizon Accident Investigation Report*, September 8, 2010.

[39] U.S. Chemical Safety and Hazard Investigation Board, *Investigation Report Executive Summary Drilling Rig Explosion and Fire at the Macondo Well*, Report No. 2010-10-I-OS 04/12/2016, April 20, 2010.

[40] National Commission on the Deepwater Horizon Oil Spill and Offshore Drilling, *Deepwater, the Gulf Coast Disaster and the Future of Offshore Drilling, Report to the President, January* 2011.

[41] https://www.bp.com, www.anadarko.com, Anadarko has since been acquired by Occidental Petroleum, MOEX USA is a subsidiary of Mutsui Oil Exploration Co. moeco.co.jp.

[42] www.deepwater.com.

[43] english.hhi.co.kr.

[44] www.slb.com/companies/cameron, Cameron has since been acquired by Schlumberger, www.weatherford.com.

[45] Digital Oilfield refers to the sections of the petroleum industry which have incorporated advanced hardware, software, and data analysis techniques into their operations so as to provide better efficiencies and profitability of the production processes.

within the organization of the industry by reducing operating, communication, and transaction costs.

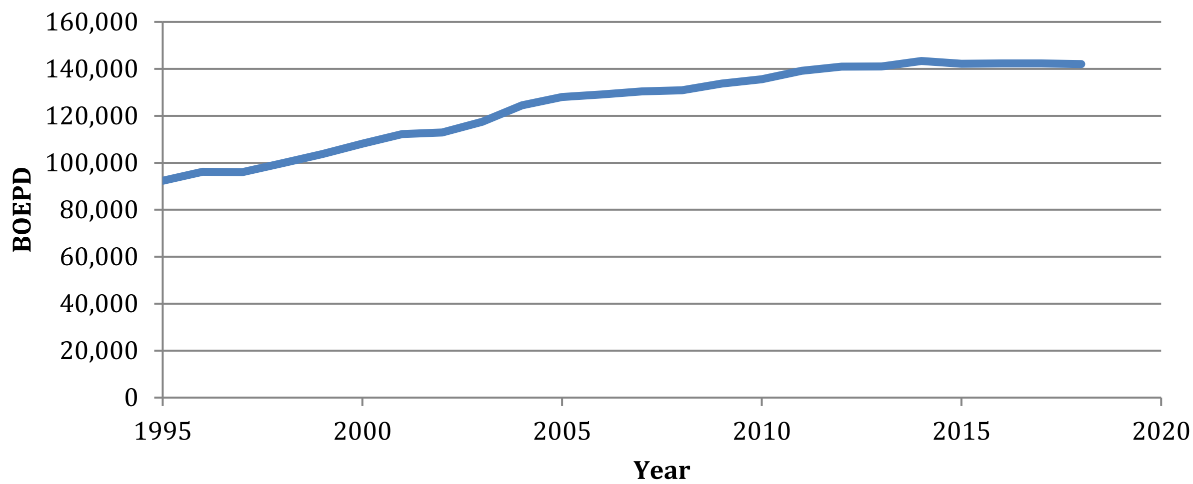

Figure 3.2: Average U.S. Refinery Capacity[46]

The United States deregulated many parts of the petroleum products market under the Carter and Reagan administrations. Similar to other industries undergoing transitions described by Hicks (1985, 1988), the U.S. refining industry has experienced a renaissance since that time, as small obsolete refineries were shut down and other refineries organized around new infrastructures, production/process technologies and business models were enlarged, upgraded, and modernized. Overall, U.S. refining capacity grew while the number of refineries decreased from 168 in 1995 to 129 in 2018 (Figure 3.2). In addition to

[46] Baker & O'Brien *PRISM*, and Oil & Gas Journal *Annual Refining Survey*, Barrels of oil equivalent per day (BOEPD).

growing

larger in capacity, the processing complexity of refineries also increased (Figure 3.3) allowing refineries to process less expensive crude oils and increase their product slates. Despite this, U.S. refineries increased their heat efficiency, meaning they now use less heat per barrel of crude oil processed (Figure 3.4). This turnaround was largely due to significant technological advances in chemical processing methods, industrial automation, and digital controls. Similar advances in industrial automation can be found throughout the petroleum supply chain increasing inventory control and flexibility while reducing transaction costs. The U.S. entered the twenty-first century with arguably the most

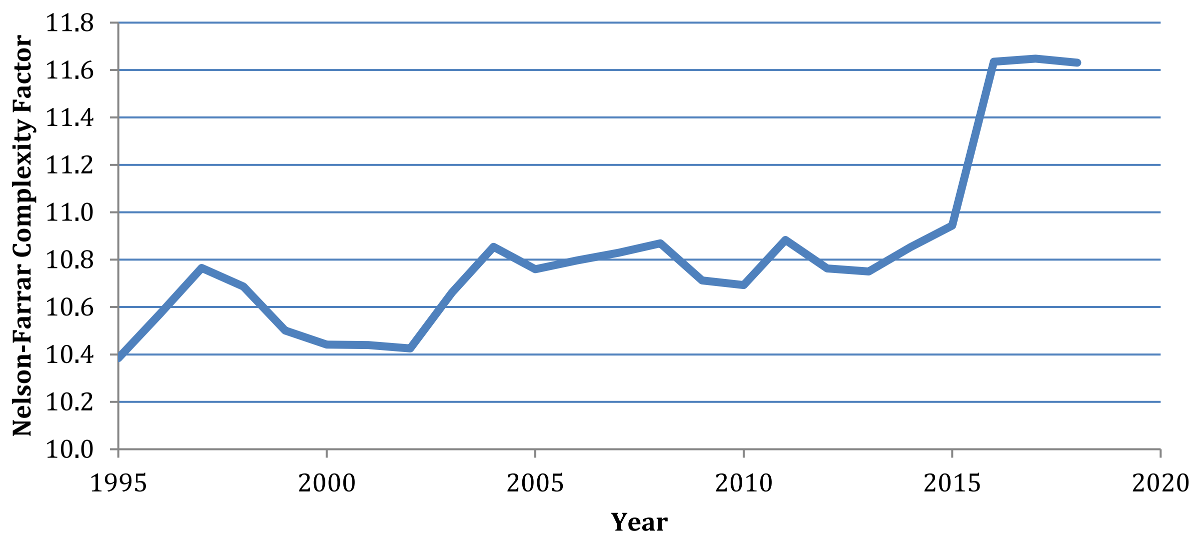

Figure 3.3: Average Weighted Nelson Farrar Complexity of U.S. Refineries[47]

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[47] Oil & Gas Journal's *Annual Refining Survey*, Baker & O'Brien's *PRISM*. The complexity factor for refineries is derived from

competitive petroleum refining industry in the world, accounting for a significant share of U.S. exports and wreaking havoc among other refiners, and especially among the less economical refiners in Latin America.[48]

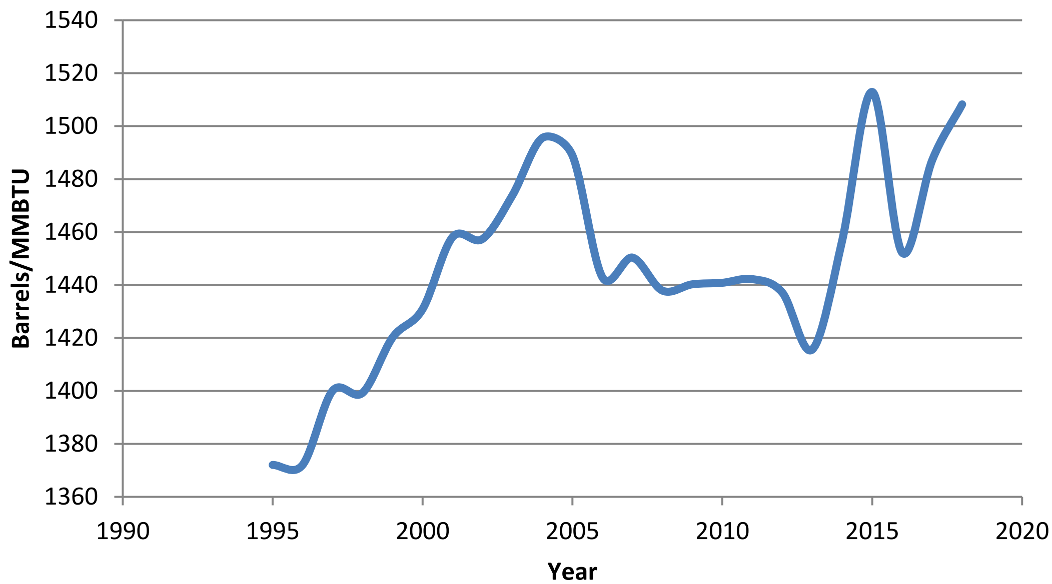

Figure 3.4: U.S. Refinery Energy Efficiency[49]

As stated above, the United States was once the leading source of exported crude oil in the world, but later became ever more depleted with production peaking in 1970 and entering a long downward trend. M. K. Hubbert developed the "*peak oil*" theory, which had

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a standard formula developed by Wilbur Nelson and Gerald Farrar, PennWell Corporation. It is based on the processing unit types and capacities of subunits within a refinery. This formula allows for the caparison of the capabilities between different facilities and is *commonly* used in the petroleum industry. A more detailed explanation of how this value is calculated can be found in Johnston, D. (1996). Complexity Index Indicates Refinery Capability, Value*. Oil and Gas Journal,* 94(12), 74-80.

[48] https://oilprice.com/Energy/Energy-General/US-Refineries-Respond-to-Latin-American-Shortfall.html.

[49] Energy Information Agency.

significant political impact. While this perspective was based on extant engineering and technical foundations of the time, it largely ignored the prospects for future technological progress as well as the primacy of economic supply and demand which anticipates that higher prices will motivate additional supply. Hubbert accurately predicted that U.S. crude oil would peak in approximately 1970, but his estimate of the rate of decline was well off the mark given that U.S. production in 2010 was four times higher than his estimate. (Yergen, Chapter 11, 2011) Hubbert's theories would take further beatings when the turn of the century ushered in a resurgence in U.S. petroleum and natural gas production.

3.1 The Introduction of "Tight-Oil Technology"

Large deposits of shale rock, a very hard rock that contains petroleum and natural gas trapped within its porous structure, are located in the United States. Shale is present in thin wide layers throughout many parts of the country, but it was thought that it was too technically difficult and uneconomic to exploit. The shale would have to be fractured thousands of feet below the surface in large amounts in order feasibly to extract these trapped hydrocarbons. Conventional well technology cannot profitably exploit these formations because of simple geometry, since the well pipes are effectively vertical and shale deposits are horizontal. It would be like trying to use a stationary straw on a wide and shallow plate of water. Most industry insiders assumed that this crude oil and natural gas would remain in the ground forever. The dramatic development of three primary technologies, hydraulic fractionation, horizontal drilling, and advanced computer technologies, such as 3-D seismic modelling and data mining, would prove to be the magic synergy that would add billions of barrels of new hydrocarbon reserves and trillions of dollars to the nation's wealth. While this suite of technology is popularly known as "fracking," this is somewhat misleading since the technique involves a combination of component technologies. This research uses the term "tight-oil technology" in referring to this technology combination.

3.1.1 Hydraulic Fractionation

Well fractionation is almost as old as the U.S. petroleum industry. It is a well-stimulation technique where either an explosion – shooting a projectile, and/or a high-pressure liquid – is used to fracture the oil-containing rock to allow the crude oil and gas to escape out of the well more easily. Edward Roberts first patented a technique of this type in the 1860's, using explosive "torpedoes" that were dropped into wells to fracture the rock formations below.[50] Floyd Farris and J.B. Clark, scientists at Stanolind Oil Company, developed the first hydraulic fractionation (hydrofracturing) techniques in the late 1940's.[51] (Clark, 1949) Hydrofracturing uses high-pressure liquid that is forced down into the well to hydraulically fracture the rock, squeezing the rock until it shatters. The U.S. Department of Energy conducted further hydrofracturing research to discover methods to exploit shale deposits in its Energy Eastern Gas Shales Project during the 1970's. This research developed the

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[50] U.S. Patent No. 59,936, November 20, 1866, E.A.L. Roberts Torpedo.

[51] Montgomery, C. T., & Smith, M. B. (2010). Hydraulic fracturing: history of an enduring technology. *Journal of Petroleum Technology*, *62*(12), 26-40.

concept of hydrofracturing fluids which contain proppants, such as sand, and other agents to clean and hold the cracks open once the rocks shatter, allowing the hydrocarbons to flow out. [52] Hydrofracturing has been a common well stimulation technique in conventional wells ever since, commonly used in conventional wells as one method to stimulate well production to higher levels. Though useful in conventional wells, the fluids were not sufficient in the much more difficult shale rock application.

George Mitchell and the engineers at Mitchell Energy Partners developed new fractionation fluids and hydrofracturing techniques in the late 1990's that first enabled shale gas wells to be economically viable in the Barnett Shale natural gas basin near Ft. Worth, Texas. This set off a small oil boom in the Barnett and then another in North Dakota's Bakken basin. (Golden 2010) It would take the fusion of George Mitchell's engineer's innovations with other developments to start a revolution.

3.1.2 Horizontal Directional Drilling:

H. John Eastman and Roman W. Hines of Long Beach, California,[53] and George Failing of Enid, Oklahoma were the first known pioneers in directional drilling in the 1930's, allowing wells to be drilled at a slanted angle rather than at a vertical.[54] The Sperry Corporation,

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[52] Trembath, A., Jenkins, J., Nordhaus, T., & Shellenberger, M. (2012). Where the shale gas revolution came from. *The Breakthrough Institute*, *23*.

[53] "Slanted Oil Wells Work New Marvels" *Popular Science*, May 1934.

[54] "Technology and the Conroe Crater". *American Oil & Gas Historical Society.* Retrieved 23 September 2014.

now a part of Halliburton, developed the first gyroscopic compass, which has been developed further over the years and is necessary to determine the location of the bore thousands of feet below the surface.[55] Downhole drilling motors, such as mud motors, were the next major advance. Conventional wells are drilled by spinning the entire drill pipe stack from the surface. Drilling motors removed the need to rotate the drill pipe, but allowed the cutting face at the bottom of the drill pipe to still work. [56] Several companies advanced measurement equipment to send directional and location information from the cutting tool to the surface on a real time basis. Between 1985 and 1993, the Naval Civil Engineering Laboratory (NCEL) combined these developments to produce a truly controllable horizontal drilling technology capable of reaching 10,000–15,000 ft. and possibly 25,000 ft.,[57] a very adequate capability to reach shale rock deposits.

3..1.2 Geoscience, Navigation, and 3-D Seismic Imaging and Modeling

The task of choosing the correct location to explore for hydrocarbons has been part science, part art by geologists since the industry started. The primary tool today is "reflection seismology" that utilizes a load noise from the surface using a "thumper truck" or an explosion to generate sound waves into the ground. The return echoes from the

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[55] U.S. Patent 1,279,471: issued September, 1918, "*Gyroscopic compass*" by E. A. Sperry.

[56] A simple example of a wire spun between your fingers demonstrates that the wire must be straight for the other end to remain in the same position. The opposite end moves in a circle if the wire is bent. In the same manner, a spinning drill pipe must be straight, otherwise the cutting end will want to rotate in a wide circle.

[57] Naval Civil Engineering Lab Port Hueneme Ca, Horizontal Drilling System (HDS) Operations Theory Report, 1993.

geologic conditions below are measured in a similar way that radar and sonar work. These seismic surveys are conducted on land and sea.

A reflection seismograph, invented and first successfully commercialized for petroleum exploration by John Clarence Karcher,[58] is used to capture the reflected sound vibrations. The outputs are charts of many squiggly lines that are interpreted by geoscientists.[59] Prior to adequately powerful computers capable of data mining, their interpretation was an art form, but resulted in less than optimal success in confidently identifying hydrocarbon deposits. The advent of massively faster computers in the 1990's and 2000's introduced 3-D seismic imaging and modeling techniques and data mining, improving geologic analysis, and yielding dramatically better results in identifying deposits. The instances of operating companies drilling dry holes or unsuccessful wells decreased dramatically. These techniques were turned to accurately map shale deposits.

3.1.3 Putting It Together

Devon Energy Corp., an early user of horizontal drilling techniques, acquired Mitchell Energy in 2001 and combined its horizontal drilling technology and 3-D seismic modeling

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[58] John Clarence Karcher and Eugene McDermont founded Geophysical Services Incorporated (GSI) in 1930 to provide seismic exploration services for petroleum exploration. GSI eventually became Texas Instruments Incorporated (TI), in an effort to develop engineers, scientists, and other technologically qualified people in the Dallas -Fort Worth area. The owners of TI established the Graduate Research Center of the Southwest in the 1960's, which eventually developed into the University of Texas at Dallas.

[59] The seismic surveys are typically conducted by OSCs. The interpretation is almost always done by geologists and scientists in the operating company. Each operating company considers its methods and procedures highly proprietary and their competitive advantage over the competition.

with Mitchell's hydrofracturing methods to create a revolutionary exploration and drilling method that could economically exploit shale rock formations.[60] Soon after, other companies were drilling using these techniques in basins around the country, including some small companies that rapidly became very large, such as Chesapeake Energy and Continental Resources. Using the three technologies in combination, drillings could be accurately steered horizontally into and through relatively thin shale layers, with the hard shale rock being economically fractured and exploited as shown in Figure 3.5.

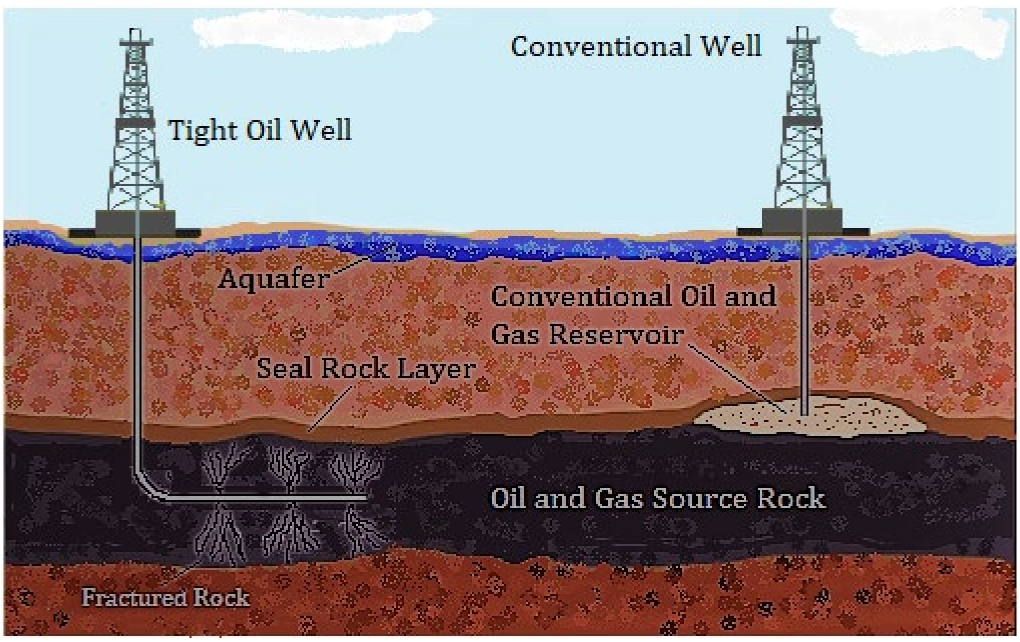

Figure 3.5: Simple Illustration of Tight-Oil Well and Conventional Well

Eagle Ford and Permian basins in Texas, the Bakken around North Dakota, the Marcellus

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[60] Other technologies were also instrumental in improving and optimizing the technology, including improved drill bits, flexible coiled tubing, and more mobile drilling rigs.

centered on Pennsylvania, and others soon experienced an oil boom. Indicative of a technological revolution, in the past decade there has been exponential increase in the share of U.S. crude production coming from wells utilizing tight-oil technology as shown in Figure 3.6.

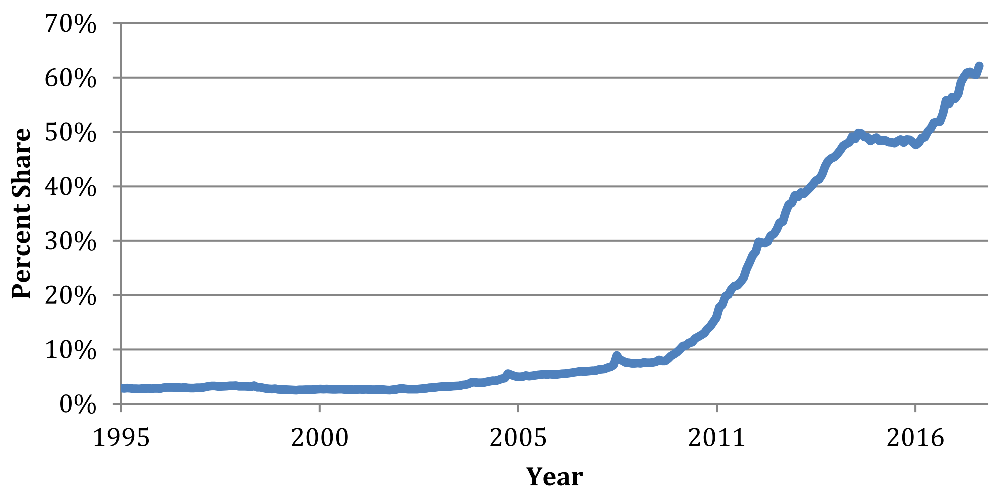

Figure 3.6: Percent of U.S. Crude Oil Production Utilizing Horizontal Production Technology[61]

This surge of new crude oil and gas production in the U.S. has had major economic and geopolitical effects around the world and had been the subject of many books and articles [O'Sullivan (2017)]. In a matter of a few years, the U.S. has gone from the world's largest

[61] Enverus - Drillinginfo Inc.

crude oil importer to an energy exporter and the largest crude oil producer as shown in Figure 3.7.

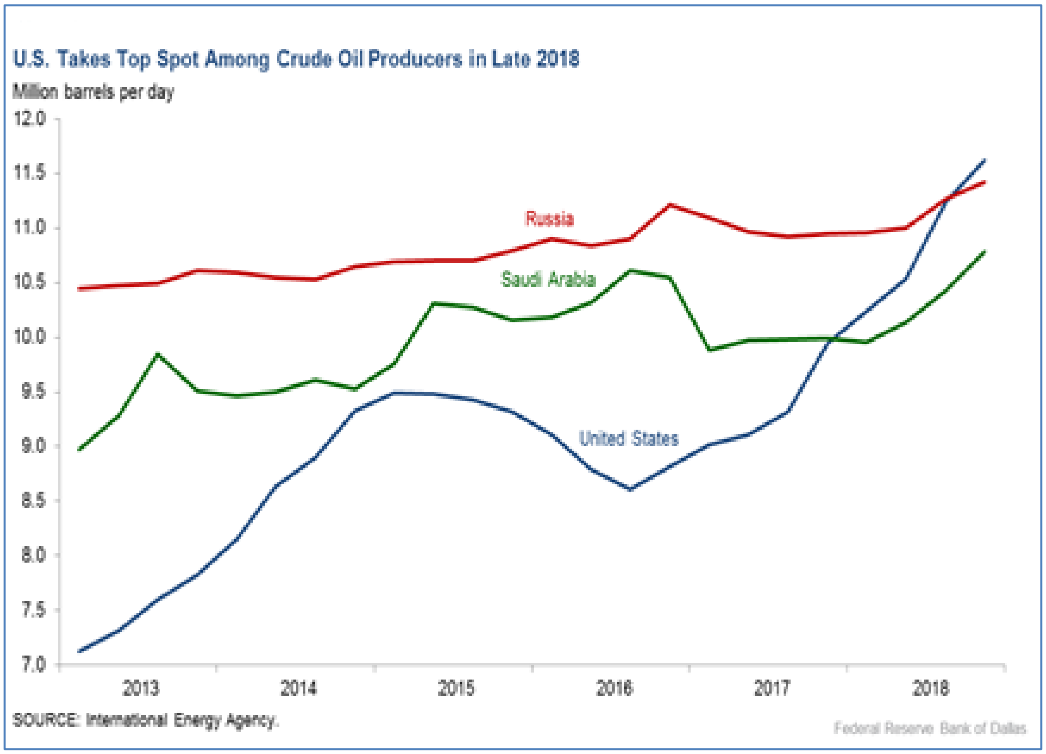

Figure 3.7: U.S. Becomes Largest Crude Oil Producer[62]

The introduction of this technology and its effects has most likely not reached equilibrium. A case in point, the midstream pipelines for moving crude oil from new shale rock production fields, such as those in North Dakota and West Texas, to refineries have not kept up with demand and are still being installed in many locations around the country.

[62] Plante M.D. and Patel K., February 14, 2019, *Dallas Fed Energy Survey Suggests Oil Price Drop Won't Cause Sector Collapse in 2019,* Federal Reserve Bank of Dallas.

Until pipeline completion reaches a higher level, this situation creates major logistical bottlenecks that could possibly bias the data in some fashion.

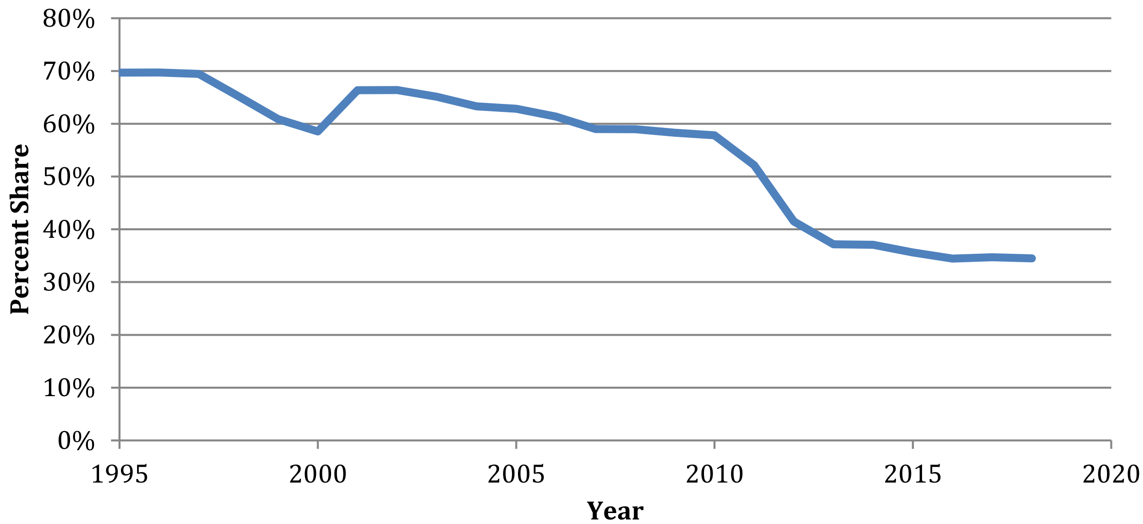

Figure 3.8: Integrated Petroleum Companies' Share of U.S. Refining Capacity[63]

Concurrent with the rapid introduction of technology was an unravelling of the vertically integrated nature of the petroleum industrial organization. In 1995, Oil & Gas Journal's *Annual Refining Survey* reported vertically integrated companies operated 70 percent of U.S. refinery capacity. By 2018, this had declined to about 34 percent, as depicted in Figure 3.8. In 1995, the largest U.S. refiners by capacity were all large integrated companies. By 2018, the three largest U.S. refiners had no crude oil production capacity – Valero, Marathon Petroleum, and Phillips 66. See Table 4.1.

[63] Oil & Gas Journal's *Annual Refining Survey*, Baker & O'Brien's *PRISM*, individual petroleum company annual reports and webpages.

The share of overall U.S. crude oil production by integrated companies has declined significantly as shown in Figure 3.9.

This decline in the presence of integrated oil companies in the U.S. market is unprecedented. The increasing importance of OSCs certainly has played a role in this change, but their increased presence was mostly witnessed in the 1980's and 1990's. Their relative market capitalization since 2000 has been relatively steady. Could an upstream production innovation, such as tight-oil technology, have such an outsized effect on the petroleum industry's organization structure?

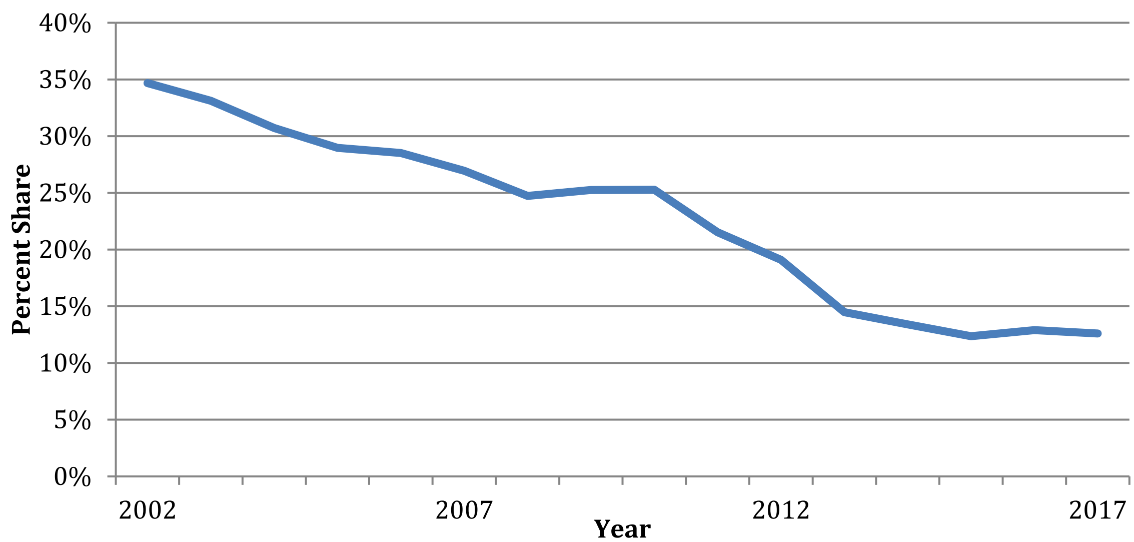

Figure 3.9: Integrated Petroleum Company Share of U.S. Crude Production [64]

Tight-oil technology is an innovation that affects the petroleum supply chain in the

[64] Bloomberg Finance L.P. and individual petroleum company annual reports.

upstream production stage. Its important value is the increase of crude oil reserves available to be economically exploited, but it has little to no effect on transaction costs between firms, or bureaucratic costs within an integrated firm. Tight-oil technology is more complex and costly than drilling an onshore conventional well, but the risks of unsuccessful wells has been reduced. Individual horizontal wells also tend to be more productive than conventional wells on average. The crude oil that is typically produced from shale rock is light sweet crude, so it demands a premium price over heavier sour crudes, assuming no distribution constraints,[65] but it is not a new crude oil product. Petroleum products to the consumer from this crude oil are the same as from other crude oil. Natural gas from shale has not changed the natural gas that is supplied to consumers. Tight-oil technology has not made conventional drilling and production techniques obsolete, but it has reduced the value of those types of equipment. Offshore U.S. operations activity, where little shale rock is found, [66] has been negatively affected in the short term by the interest in tight-oil plays, reducing the present value of that technology and equipment.

Neo-classical theory predicts that downstream refiners would be less motivated to backward integrate into crude oil production since tight-oil technology has opened new sources of feed stock and lessened the risk of supply interruptions. Integrated companies

[65] Crude prices from some basins have suffered a discount due to infrastructure bottlenecks, such as lack of adequate pipelines. Bakken crude has consistently sold for a discount to other similar crudes, due to the inability to transport it by pipeline to Midwest and Gulf Coast refineries. The Dakota Access and Keystone XL pipelines are solutions to this problem.

[66] There are no known economic shale reservoirs in U.S. territorial waters.

may have the same motivation to disintegrate since refiners have a more competitive feedstock supply. Crude oil producers may have a motivation to forward integrate into downstream refining since the increased crude oil supply would reduce prices and increase competition, but there are no actual examples of this. Crude producers would have less incentive to be acquired in a backward integration since the value of their property is increased. It is likely that producers judged that their returns on capital for investment in upstream production would be higher than downstream refinery assets. There are a number of examples of crude producers horizontally integrating through mergers and acquisitions of other production companies and investing in transportation assets, such as pipelines. Occidental's 2019 acquisition of Anadarko is a recent example of horizontal integration.[67] Pipeline investments by producers have been justified as either cost reduction moves or to ensure market access.[68] No U.S. non-integrated refiner, such as Valero, has invested in upstream assets in any significant manner since the introduction of tight-oil technology. Currently, three Canadian production companies (Cenovus, Husky, and Suncor) are the only North American production companies that have taken new equity positions in any U.S. refinery operations since 2000.

Though TCE could arguably be considered the leading theory on the determinants of vertical integration, it does not provide a clear prediction in this case. It is not readily

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[67] Bloomberg, https://www.bloomberg.com/press-releases/2019-08-08/occidental-completes-acquisition-of-anadarko.

[68] Commonly, crude oil pipeline companies do not take possession of the crude oil they transport but, rather, charge a tolling cost.

apparent that tight-oil technology affects the transaction costs between upstream producers and downstream refiners. The up-front capital costs to develop and drill a production well using tight-oil technology are significantly higher than conventional techniques, increasing risk and uncertainty in that respect, but the risk of unsuccessful wells has been demonstrated to be significantly less. Additionally, there is good evidence that individual horizontal wells are much more productive than conventional vertical wells. (Waters, *et al*, 2006)

PRT predicts that an increase in the technological intensity of upstream production, such as that brought on by tight-oil technology, will increase the motivation of the producer business within an integrated firm to vertically disintegrate from its downstream refining business, so as to concentrate investments in the upstream business. ConocoPhillips, a major integrated company, divested its downstream assets into a new company called Phillips 66 in 2012, turning itself into the largest domestic pure play upstream exploration and production (E&P) company. The CEO of ConocoPhillips stated that the divestiture would allow each company to focus on its individual businesses and create better value for its shareholders, making an almost exact PRT explanation for their divestment.

> *"The new Phillips 66 will offer a unique approach to downstream integration, comprising segment-leading refining and marketing, midstream and chemicals businesses. ConocoPhillips will continue as the industry's largest and most diverse global pure-play exploration and production company.*

The repositioning will help grow the value of both companies for our shareholders by unlocking the potential of their assets and employees." [69]

The various parts of an integrated firm compete for larger shares of the investment pie. Much of ConocoPhillips' North American production assets were located in the large Bakken and Eagle Ford basins, areas being developed using tight-oil technology. ConocoPhillips investment balance in 2012 was heavily tilted toward its upstream business with only a small portion being targeted toward its downstream.[70] Any investment in the downstream sector at the expense of the upstream sector was not in ConocoPhillips interest, meaning that the refining side of their business had to go to maximize shareholder value.

"This 2012 ConocoPhillips annual report is our first to you, our shareholders, as a newly independent company focused solely on our core business of exploration and production. We began the year midway through preparations for the separation of our downstream operations into a stand-alone company, Phillips 66.

We successfully completed this repositioning on April 30, becoming the world's largest independent E&P company based on production and proved reserves. We have since

[69] ConocoPhillips 2011 Annual Report.

[70] Helman C., April 30, 2012. *As ConocoPhillips Spins Off Refining Assets, Think Twice Before Buying the New Phillips 66*, Forbes Magazine.

moved forward through a transformation and upgrading of our asset base…"[71]

Marathon Oil spun off its downstream refining business into a company called Marathon Petroleum in 2011 for similar reasons. One major difference in this case, at the time, was Marathon did not have particularly strong assets in tight-oil basins around the U.S. but rather in more conventional areas. Since the divestiture, Marathon Oil has divested all its production assets in Canada (oil sands), UK (North Sea), and Kurdistan and invested heavily into the Permian basin in Texas, a major play where tight-oil technology is being utilized.

The development and introduction of tight-oil technology had significant economic and political influence throughout the world. Little has been published concerning the concurrent trend of disintegration of the U.S. petroleum industry's vertical integration. The next chapter will describe how this research identified a link between these important developments.

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[71] ConocoPhillips 2012 Annual Report.

CHAPTER 4

RESEARCH DESIGN, DATA SELECTION AND MODEL DEVELOPMENT

How technological innovation manifests itself can significantly affect how it influences a firm's decision to vertically integrate its industrial organization. As discussed earlier, past research has identified major determinants influencing a firm's or industry's tendency to vertically integrate its industrial organization, including technological innovation. The introduction of tight-oil technology and the concurrent vertical disintegration provides an opportunity to explore the possibility of a more interdependent relationship evident in this mature industry. The detailed nature of the tight-oil technology suite allows it to be measured as it is being introduced, rather than relying on less direct measurements or proxies, as has been the norm in the extant literature. Data at the level of individual well types and their production volumes is available, allowing for the tracking of a new production technology's adoption and implementation. The introduction of tight-oil technology was generally unexpected and initially was driven primarily by smaller independent firms. As a result, the aggregate industry's overall industrial organization likely would not have been influenced by the advent of tight-oil innovation. Moreover, measurement of tight-oil's effects on the petroleum industry's industrial organization should only be minimally biased by any simultaneous counteracting influences of the industry's organizational structure on the development and maturation of tight-oil production arrangements.

The petroleum market is international and its defining performance metrics have the capacity to generate ripple effects around the world. This research is limited to the United States, since the adoption of tight-oil technologies is at this writing largely a domestic U.S. phenomenon. Consequently, this research either ignores or treats as fixed effects any scattered and rare nondomestic data. Currently, the U.S. domestic market orientation of tight-oil technology is evident in both development and deployment. The fact that tight-oil technology has not been widely utilized in other countries is due to a variety of more localized political and technical issues. As such, while limiting the study to the United States may introduce some biases, their influence can likely be considered minimal. Previous studies have found that asset specificity is one of the most important determinants in the tendency to vertically integrate. (Lieberman, 1991). However, because such studies have sought to explain the phenomenon across different industries, the U.S. domestic focus of this research permits us to treat any potential influence of asset specificity as a fixed effect.

Data for the years 1995 – 2018 is utilized. This interval captures the initial introduction of tight-oil technology and its subsequent rapid and widespread employment in U.S. petroleum production. The year 1995 was approximately five years prior to any significant tight-oil production coming on stream. And it was not until approximately 2008 that this tight-oil production had become a defining feature of significant portions of the industry (see Figure 3.6). The primary data used in this study are from official U.S. petroleum industry sources. Other data enabling detailed model specification with variables introduced as controls in model testing have been drawn from official government sources as well as public macroeconomic and/or licensed industry data archives. All model testing utilized STATA 15.1 software for effect estimation, model development and related econometric analysis.

This study utilizes panel data to build and test models of the hypothesized influence of the tight-oil technology suite on the U.S. petroleum industry's industrial organization. Five metrics that purport to capture the essence of vertical integration are either drawn from published research or have been created to leverage the detailed circumstances of the U.S. petroleum industry in years preceding and following the introduction of tight-oil technologies. They serve as dependent variables in this study. In addition, a sequence of varying model specifications is proposed and tested that explicitly control for potential alternative explanations of variation in vertical integration dynamics over time. The selections of these sources of systematic variance are introduced as control variables. The selection of each control variable has been guided both by theory, extant research and the author's own professional experience in the industry.

The dependent variables ($*VI*_{it}$) are representations of the relationship between individual U.S. petroleum companies' upstream crude production and petroleum refining capacity on an annual basis. This research will use barrels of oil equivalent (BOE) as the unit of measure of both upstream and downstream volumes.[72] For individual well sites, crude

[72] Natural gas production is included in production volume data with 5,800 cubic feet of natural gas or 58 CCF equivalent to one barrel of oil equivalent (BOE).

production data is used rather than capacity given the nature of petroleum wells. Maximum capacities of production wells are only estimations, at best, and depend on technical considerations and the inevitability of diminished capacity over time as a well becomes depleted. Enhanced recovery techniques can also revive well production, but likely only for a period of time. By contrast, at the refinery stage in the supply chain, aggregate capacities are used rather than annual refinery production because capacity data is more reliable. Refinery production levels are typically close to full utilization, with maintenance and turnaround outages being the largest cause of refinery downtime.

The independent variables of most interest in this research are upstream technological innovation and, secondarily, downstream industry attributes that reflect the capacity for enabling and exploiting ongoing technological innovation. Upstream technical innovation is represented by the share of total annual crude oil production of individual petroleum companies accounted for by tight-oil technology. Downstream innovation is represented by three metrics of refinery technology: 1) refinery capacity (firm-level), 2) average refinery complexity (firm-level), and 3) energy efficiency (industry-level). Other covariates included as controls include market concentration, product pricing, oilfield service company effects, macro-level interest rates, inflation, and GDP growth.

The research advances separate hypotheses for each dependent variable to enable valid inferences and from which to draw its conclusions. The basic model is as follows:

$$*VI*_{it} = \alpha_i + \beta_1[T_{it}] + \beta_2[R_{it}] + \beta_3[X_{it}] + \beta_4[Z_t] + \mu_{it}$$

**VI*: Vertical integration metric*

T: Upstream technical innovation

R: Downstream refinery technology

X, Z: Other covariates

α: Unobserved time-invariant individual effects

μ: error term

The resulting panel data set includes annual data on each term in the basic model for each individual petroleum company.

I: Individual petroleum company

t: Year

4.1 Dependent Variables

In the industrial organization literature, the typical way to identify the degree of vertical integration is to measure the relationship between a firm's upstream and downstream production. For petroleum companies this would entail modeling the relationship between industry-specific metrics: a producer's crude oil equivalent production [73] and a refiner's petroleum refining capacity. For this study, a database of U.S. crude production data for individual companies was compiled utilizing three sources covering the years 1995 to 2018. The primary sources for total domestic production for individual public companies are annual reports and Security and Exchange Commission (S.E.C.) 10-K filings. This

[73] Most production wells produce both natural gas and petroleum liquids at varying ratios largely depending on the basin and its unique geology. The liquids and gases are typically separated in the production field and sent into different supply chains. This total production is measured in "barrels of oil equivalent" (BOE) with 1 barrel of oil equaling 5,800.6 cubic feet of natural gas in equivalent energy.

information was supplemented by Bloomberg Professional Services when SEC filings for some years were not available for individual companies.[74] Production information for private companies and individual company ratios of conventional and tight-oil production was obtained from a private company – Enverus (formerly, Drillinginfo).[75] This database includes production data from approximately 82 of the largest production companies (varies by year) – including all integrated companies – accounting for approximately 60 percent of all domestic crude oil equivalent production.

Capacity data on individual U.S. petroleum refineries was obtained from the *Oil & Gas Journal's (OGJ) Annual Refining Survey* [76] for the years 1995-2018. This information was supplemented by data extracted from Baker & O'Brien Inc.'s *PRISM*™ database[77] where some OGJ refinery information was incomplete. Together, the two sources covered over 95 percent of all domestic refinery operations and all major facilities.[78] Refinery nameplate capacity was used in this research rather than annual throughput because refineries are highly capital-intensive assets. Owners' attempt to maximize throughput, so annual variations are typically a function of technical factors, such as maintenance outage

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[74] Bloomberg financial data was accessed from the Bloomberg terminal located on the campus of the University of Texas at Dallas.

[75] Enverus is a web-based platform providing information for the U.S. upstream oil and gas industry utilizing open source information. Enverus' subscriber network consists of petroleum and gas companies, consultants, service providers, financial institutions, and regulatory and governmental agencies, including the U.S. Energy Information Agency (E.I.A.). The company was formally called Drillinginfo. https://www.enverus.com/.

[76] Oil and Gas Journal is a leading petroleum industry publication from the PennWell Corporation.

[77] A trademark of Baker & O'Brien Inc.

[78] The missing facilities consist of some small and simple refiners such as local asphalt suppliers. When known, these facilities were included in the research database.

frequencies, rather than due to supply or commercial factors. The data show that on occasion the capacity of individual refineries tends to change in a step-wise manner as capital projects are completed.

This research utilized five different dependent variables, each measuring vertical integration in a different manner and from different perspectives.

4.1.1 Self-Sufficiency Ratio (SIVI)

The dependent variable of the ratio between upstream crude production and downstream refinery capacity is essentially the metric utilized in several earlier studies. Mitchell (1974) used this ratio of a company's crude production and refinery "*stills*" capacity (refinery capacity), calling it a "*Self Sufficiency Ratio*" (SIVI).

$$SIVI_{it} = \frac{Crude\ Equivalent\ Production\ (BPD)}{Petroleum\ Refinery\ Capacity\ (BPD)} x100\ percent$$

Analysis using SIVI panel data is limited to the extent that it only covers large integrated companies[79] with significant refinery capabilities. Companies without refining assets are excluded since they would only have undefined SIVI values (∞). Appendix A lists the companies in the SIVI sample.

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[79] Only integrated companies with significant total refinery capacity (>25 thousand barrels per day total refining capacity) and production rates (>100 barrels per day) were included the sample. The excluded companies were small independent companies with SIVI values near zero and unchanging over the sample period or were extremely high with large value swings. Their inclusion in the sample masked the econometric trends within the large integrated companies.

Figure 4.1 shows a declining average SIVI value among the large integrated companies during the 1995-2018 time frame. This pattern is consistent with a persistent vertical disintegration occurring among the petroleum's dominant producers that plateaued beginning around 2005. Similarly, Table 4.1 depicts the self-sufficiency ratios of the twelve largest petroleum company operations, by volume,[80] in 1995 and 2018. With the exception of Mobil and Texaco, all the integrated producers registered a dramatic

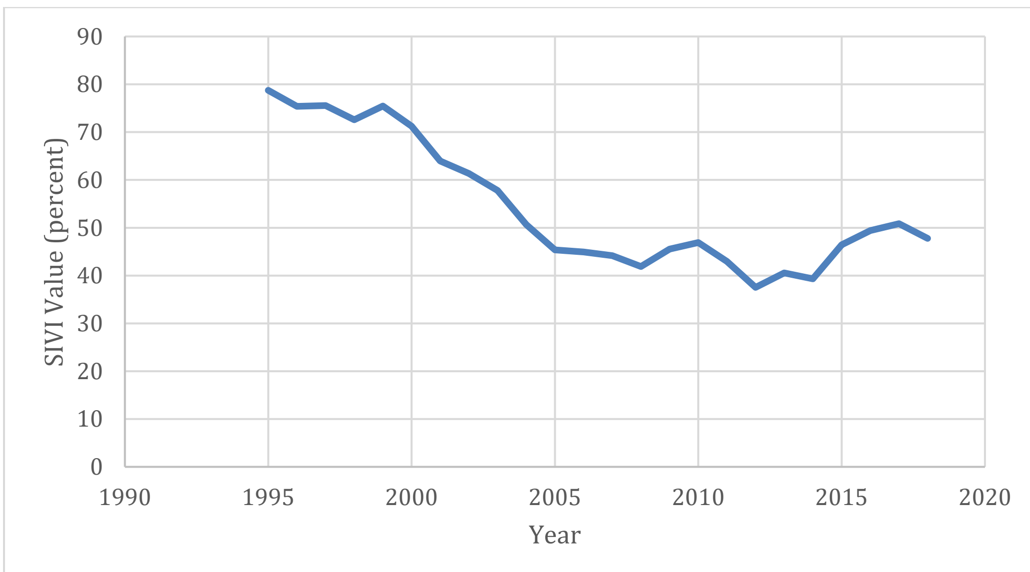

Figure 4.1: Average Weighted Self Sufficiency Ratio (SIVI) Among Large U.S. Integrated Petroleum Companies

decline in their SIVI ratios, even as the volumes of their production increased across all these producers (except Shell and Arco). As a result of these shifts, while the 1995 ranking

[80] Volume = annual crude production plus refinery capacity.

is dominated by integrated companies with both significant production and refining, the 2018 ranking is dominated by non-integrated companies with either production-only profiles (SIVI = ∞) or refinery-only profiles (SIVI = 0 percent). The transformation depicted in Table 4.1 is consistent with the underlying premise of this study, namely that the U.S. petroleum industry has been experiencing a decisive shift away from its traditional vertically-integrated industrial organization. This shift is most pronounced during the 1995-2005 decade, after which the organization structure of the industry appears to have stabilized.

Table 4.1: Self-Sufficiency Ratio of 12 Largest U.S. Petroleum Operations

1995			2018		
	Size**	SIVI (%)		Size**	SIVI (%)
Exxon	1,946	96	Marathon Petroleum	2,882	0
Chevron	1,733	63	ExxonMobil	2,701	58
Amoco	1,727	71	Valero	2,177	0
Shell	1,585	74	Phillips	1,826	0
Mobil	1,501	55	Chevron	1,697	87
Texaco	1,338	95	BP	1,492	107
BP	1,276	84	Shell	1,418	37
ARCO	1,204	168	Chesapeake	967	∞
Marathon	772	45	PBF Holdings	879	0
Citgo*	750	*	EOG	838	∞
Phillips	717	124	EQT	795	∞
Conoco	695	55	Citgo*	764	*

* Foreign Owned Company with Crude Production Operations

** Refinery Capacity + Crude Oil Production (MBOE/Day)

4.1.2 Balance Index (BIVI)

A variation to Self-Sufficiency Ratio is a metric that measures how balanced each individual firm is between the crude output it produces and its capacity for refining that output. The Balanced Index (BIVI) measure is calculated as follows:

$$BIVI_{it} = \left(1 - \frac{Max\ (refining, production) - Min\ (refining, production)}{Max\ (refining, production)}\right) x\ 100\ percent$$

This calculation of each company's crude/refining balance results in a bounded scale metric in which values range from 0 to 100 percent. Companies that only produce crude oil or only refine petroleum, would have a BIVI value of 0. Companies with exactly equal values of crude production and refining capacity would have a value of 100 percent. I found no earlier research that used this method to measure the degree of firm-level vertical integration. The advantage of this measure is that unlike the SIVI measure, the BIVI metric is able to include crude oil production-only companies in an analysis. At the same time, the

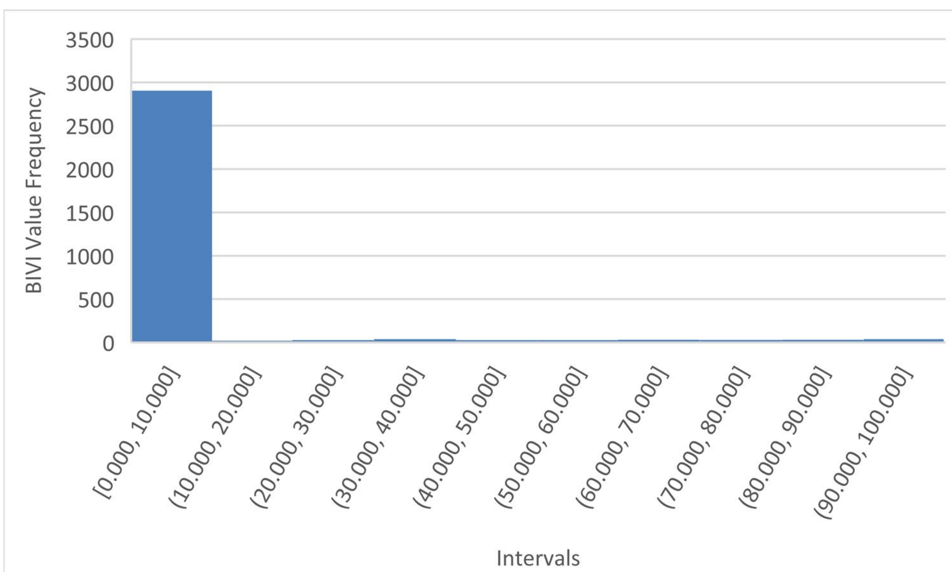

Figure 4.2: Histogram of Balance Index Values of All U.S. Petroleum Companies

histogram of this metric for petroleum companies over the period 1995-2018 weighs heavily toward one extreme (Figure 4.2), revealing clearly that the vast majority of petroleum companies are not integrated. While there are comparatively few integrated companies in the industry, they all tend to be very large and account for an equally large share of both upstream crude production and downstream refinery capacity.

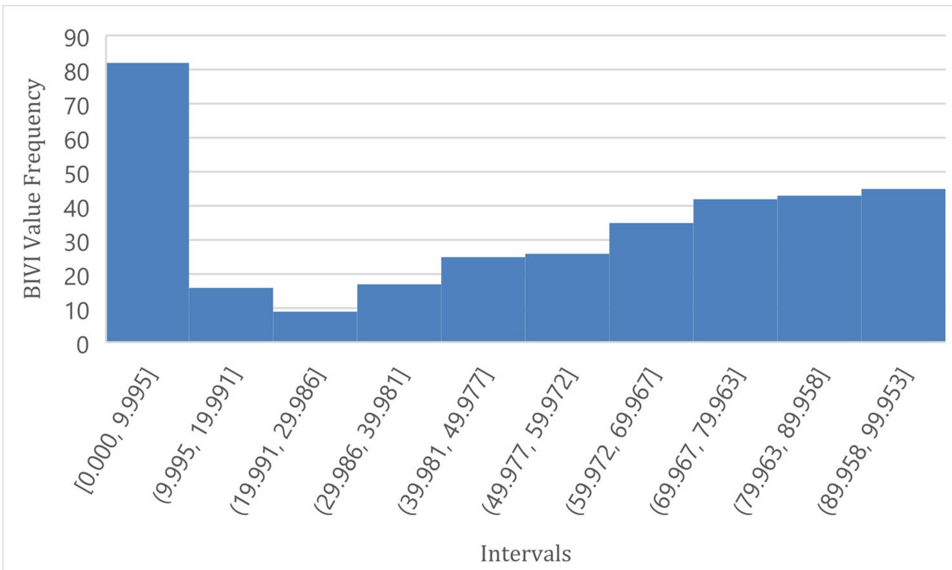

Figure 4.3: Histogram of Balance Index (BIVI) Values of Large Integrated Firms

A histogram of BIVI values for only large integrated companies in the data sample, the (Figure 4.3) provides a much more interesting pattern. The BIVI model was run for both databases, resulting in fairly similar results. The BIVI values for both databases declined over the sample period as depicted in Figure 4.4, revealing an even broader pattern of vertical disintegration in the U.S. petroleum industry that was underway between 1995 and approximately 2012.

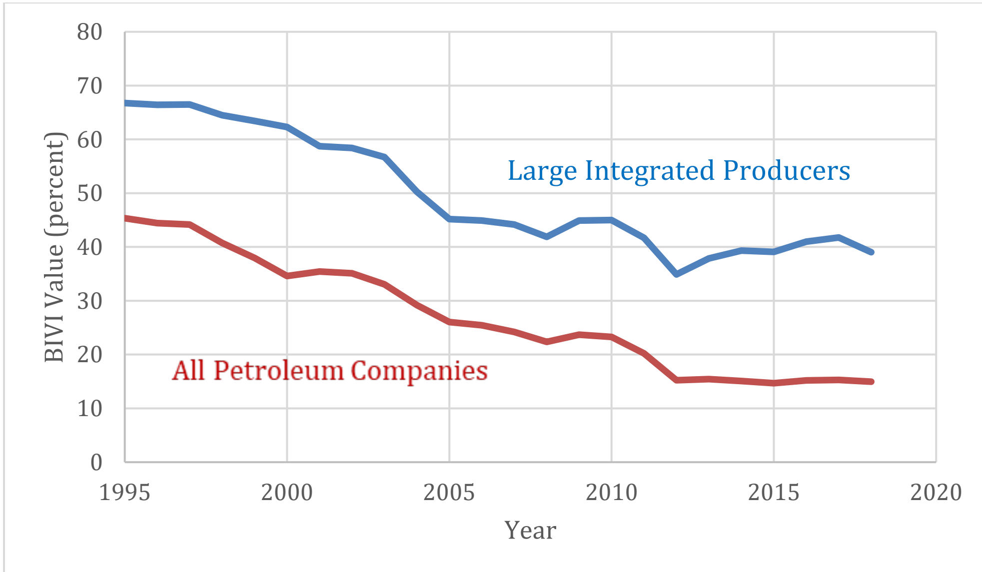

Figure 4.4: Balance Index Change Over Time

4.1.3 Probit Integration Index (VIL)

A fixed-effects Probit model using the sample panel data constitutes a third dependent variable metric. The measure is a dummy variable in which each firm is identified simply as being either an "integrated" firm or a "not-integrated" firm.

$$VIL_{it} = \begin{cases} 1 & \textit{if firm I owns both significant production and refining capabilities} \\ 0 & \textit{otherwise.} \end{cases}$$

The model compares each firm's refining capacity to its crude production volume for each period. If the smaller of the two volumetric values was at least 50 percent as large as the larger operation, the firm was deemed to be "vertically-integrated." Moreover, such a firm could be assumed to have an industrial profile that included significant commitments to both refining and production capabilities. A firm with a value below the 50 percent threshold could be presumed to be oriented primarily to one or the other stages in the supply chain.

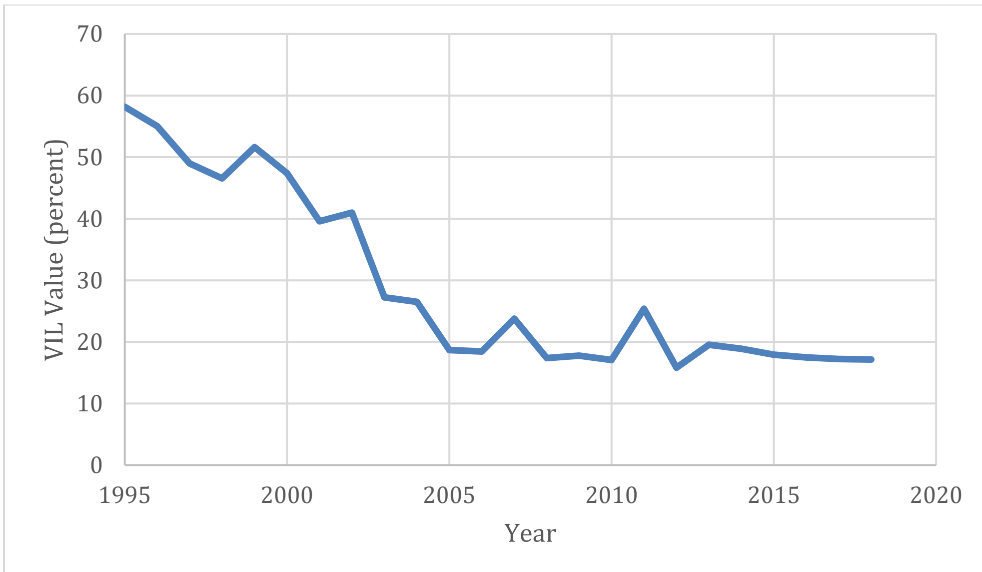

Figure 4.5: Weighted Average Probit Integration Index (VIL)

4.1.4 U.S. Industry Integration Indices

The next two dependent variable metrics are derivative of those used by Stuckey (1983) and modified for the petroleum industry as a whole. These are metrics that measure vertical integration at the industry level, rather than firm level as do the previous three (SIVI, BIVI, and VIL) metrics. The Forward Integration Index (CVIC) measures the share of domestic crude production that could potentially be transferred within the same firm to be processed by affiliated refineries. The CVIC metric, then, measures the forward integration capacity of each firm annually as follows:

$$CVIC_t = \frac{\sum RC_{it} + \sum CP_{jt}}{Total\ Crude\ Production}$$

RC: *Refinery capacity.*

CP: *Crude production.*

i: *Firms where refinery capacity is less than crude production*

j: *Firms where refinery capacity is greater than crude production*

t: *Year*

Similarly, Backward Integration Index (RVIC) measures the maximum amount of U.S. refinery capacity that could theoretically be supplied from a firm's own crude oil production through intra-corporate transfers. This metric then provides a measure of backward integration capacity for petroleum firms annually. [81] The RVIC Index is calculated as follows:

$$RVIC_t = \frac{\sum RC_{it} + \sum CP_{jt}}{Total\ Refinery\ Capacity}$$

Taken together, the CVIC and RCIV metrics are correlated and are shown in Figure 4.6 to have declined steadily over the 1995 – 2018 period, with the exception of a slight cessation apparent in the RVIC trend occurring around 2012. The larger significance of these trends, of course, is that they offer further evidence of the long-term vertical disintegration that

[81] There are no publicly available data on the amount of crude oil produced by integrated petroleum companies that is processed in their own refineries. It is very possible that companies themselves do not keep track of this kind of data. The actual production is only transported to affiliated refinery facilities if that is the most economical alternative. Because of this, no petroleum company's supply chain is a true vertically integrated unit under its strict definition.

has characterized the U.S. petroleum industry since 1995.

The analysis model is modified so that the dependent variable is only time dependent.

$$(RVIC\ or\ CVIR)_t = \alpha_i + \beta_1\,[T_{it}] + \beta_2\,[R_{it}] + \beta_3\,[X_{it}] + \beta_4\,[Z_t] + \mu_{it}$$

T: *Upstream technical innovation*

R: *Downstream refinery technology*

X, Z: *Other covariates*

α: *Unobserved time-invariant individual effect*

μ: *error term*

i: *Individual petroleum company*

t: *Year*

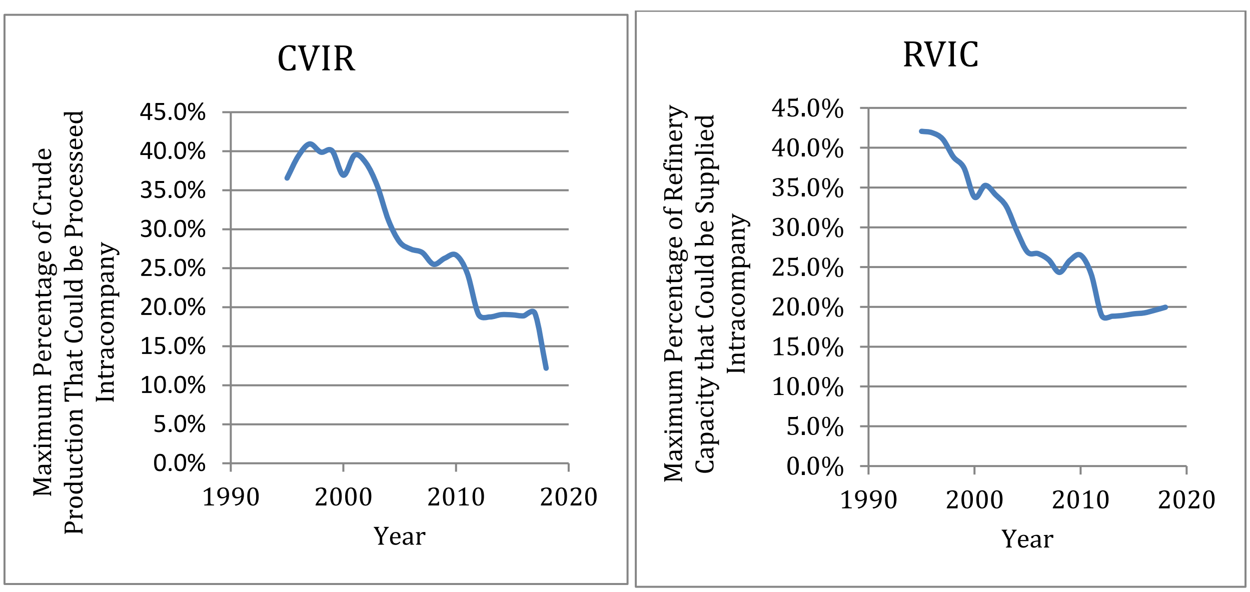

Figure 4.6: Forward and Backward Integration Indices Over Time

Table 4.2: Conceptual and Operational Definitions of Dependent Variables

Variable	Conceptual Definition	Description	Operational Definition	Population	Model Type	Potential Range	Actual Range
$SIVI_{it}$	Self Sufficiency Ratio (Individual Company Metric)	Index of how sufficient individual petroleum refiner is in intracompany crude oil production	$SIVI = \frac{Crude\ Equivalent\ Production\ (BPD)}{Petroleum\ Refinery\ Capacity\ (BPD)}$	Major integrated petroleum companies. See Appendix _ of for list of companies	Regression, Panel Data	0% to ∞	0 to 340 for the large integrated company data set
$BIVI_{it}$	Balance Index (Individual Company Metric)	Index of balance between crude production (p) and refinery capacity (r)	$BIVI = (1 - \frac{Max\ (refining, production) - Min\ (refining, production)}{Max\ (refining, production)}) x\ 100\%$	Integrated petroleum companies with significant US crude production and refining capacity	Regression, Panel Data	0 to 100%	0 to 100%
VIL_{it}	Company Integration Status (Individual Company Metric)	Status on whether company was integrated or not for time period t	*1 if firm i owns both significant production and refining capabilities,* *0 otherwise.*	All petroleum companies in database	Probit Panel Data	0 and 1	0 and 1
$CVIR_t$	Forward Integration Index (Industry Metric)	Maximum possible petroleum industry intracompany crude transfers as a percentage of total crude oil production	$CVIC = \frac{\sum RC_{it} + \sum CP_{jt}}{Total\ Crude\ Production}$	All petroleum companies in database	Regression, Panel Data	0 to 100%	12.2 to 40.9%
$RVIC_t$	Backward Integration Index (Industry Metric)	Maximum possible petroleum industry intracompany crude transfers as a percentage of total refinery capacity	$RVIC = \frac{\sum RC_{it} + \sum CP_{jt}}{Total\ Refinery\ Capacity}$	All petroleum companies in database	Regression, Panel Data	0 to 100%	18.8 to 42.0%

4.2 Independent Variables and Research Hypotheses to Be Tested

We turn now to the variables that will be introduced in the model development to follow.

Primary Research Hypothesis

Hypothesis 1: T*he introduction of tight-oil technology into U.S. petroleum production has caused a change in the U.S. petroleum industry's vertical integration structure.*

4.2.1 Tight-Oil Share of Upstream Production

Firms that deploy horizontal-drilling methods, by definition, can be said to have adopted and implemented tight-oil technologies as an operational innovation. Therefore, the independent variable of primary interest in this study is the share of a firm's total output that is produced using a tight-oil production regime. For this data we consulted with Enverus – (formerly, Drillinginfo) which maintains a database on North American crude production. This data source is particularly valuable since it has information on individual production wells, including the drilling methods used at the site. With such highly-granular data available, this primary independent variable could be measured with great precision. Therefore, the crude oil production volumes from horizontal wells as a share of the total production from all wells is the metric used to measure the introduction and diffusion of tight-oil technology into the petroleum industry supply chain.[82] This variable is depicted in Figure 3.6, showing the percentage of U.S. crude oil production coming from horizontal wells.

Additional Research Hypotheses to Be Tested

Beyond the primary hypothesis which tests whether the adoption and implementation of tight-oil technology has influenced the industrial organization of the U.S. petroleum industry, there are several other hypotheses we can test using the panel data assembled. Let us consider them in turn.

4.2.2 Downstream Technological Innovation

Downstream technology innovation can also be presumed to exert an influence on an industry's organizational structure. The petroleum industry has always been heavily shaped by the evolution of its technological origins and infrastructures. Oil refineries, particularly those in the United States., represent massive legacy investment in industrial infrastructure that leverages a wide variety of advanced technologies. Transportation logistics among the oil pipelines, ships, barges, trucks, railways, and storage facilities represent an extended and extremely complicated enterprise infrastructure requiring the

[82] All horizontal wells utilize hydrofracturing and geoscience technology in their drilling process. Some or all of these three principle technologies are used in some conventional wells. As a conservative assumption, only wells classified as horizontal wells are considered those using tight-oil technology in this research. Nicholas M. Gnyra, Netherland, Sewell & Associates, Inc. provided guidance on tight-oil technology and verified that this assumption was valid.

integration of all manner of complex technologies. Petroleum industry facilities all along the supply chain are continually being upgraded with ever newer technologies and equipment. The consulting firm, Accenture, and General Electric have published a number of articles describing automation and communications innovations today arrayed across the petroleum supply chain and which constitute the "Digital Oilfield." Additionally, all manners of new petroleum processing technologies are being developed and deployed on an ongoing basis.

To represent technological advances downstream of the production stage, this research now focuses on improvements in refinery technology. We propose to measure the innovative potential at this stage of the supply chain using three separate independent variables: 1) firm-level refinery capacity; 3) firm-level average refinery complexity; and 3) industry-level refinery energy efficiency. Refinery capacity and complexity data are gathered from the Oil & Gas Journal's *Annual Refining Survey* and Baker & O'Brien's *PRISM* database. Refinery size is measured by total crude oil input capacity. This is an accepted metric within the industry to describe refinery size, but it does simplify the matter somewhat since various refineries can have more complicated feed arrangements, such as the intermediate (partially processed) feedstocks being fed into downstream processing units from other refineries.

Petroleum refineries are typically a collection of processing units within one facility, as illustrated in Figure 4.7. These units are interconnected with each other to perform process steps in the overall process of converting crude oil into petroleum products. The diagram below reveals the potential complexity of a typical refinery complex. Though refineries may have similar units within, ultimately, each refinery is unique and has been

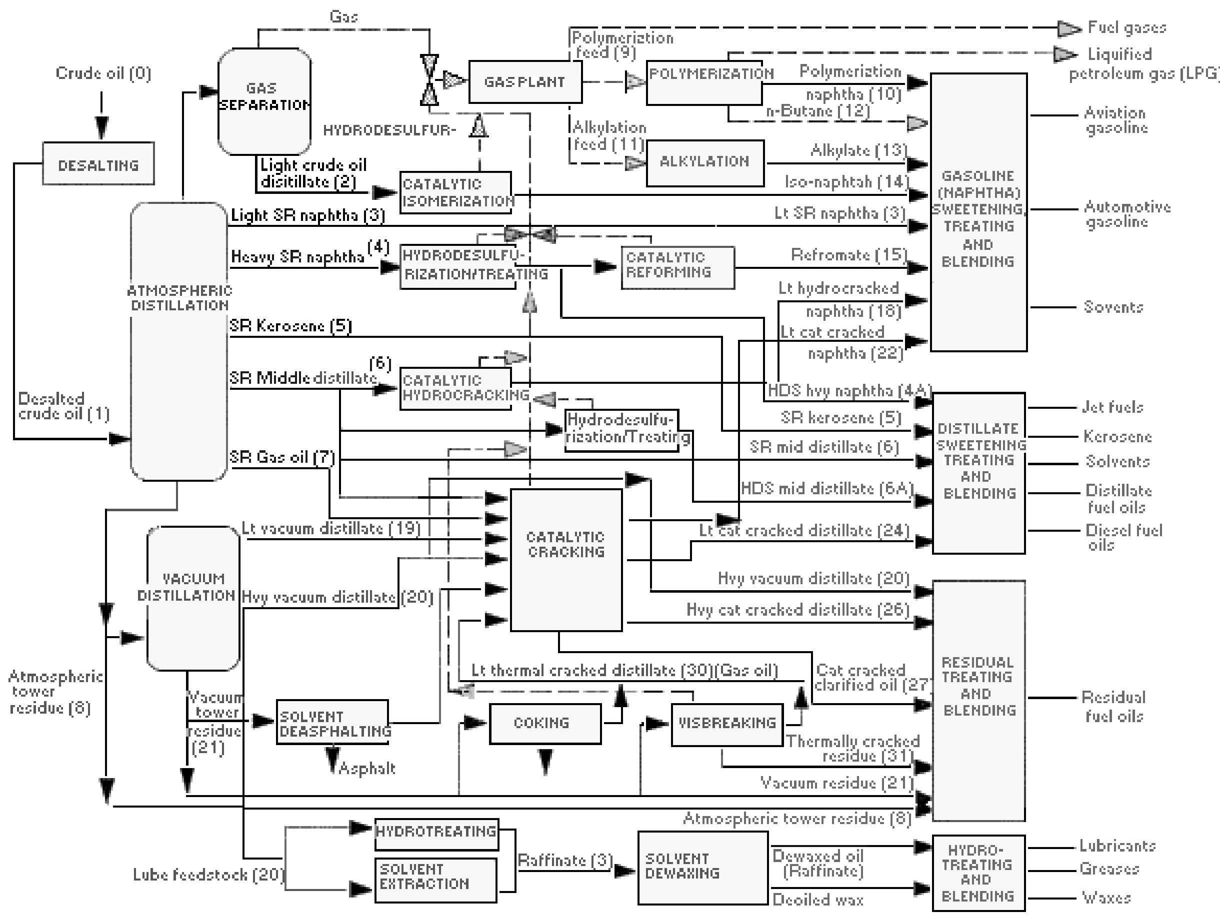

Figure 4.7: Typical Complex Petroleum Refinery Block Flow Diagram[83]

custom-built to handle its own particular feedstocks, address its own targeted markets, and exploit its own commercial opportunities. Each type of product winds its way through the

[83] Occupational Safety and Health Administration, *Petroleum Refining Process,* https://www.osha.gov/dts/osta/otm/otm_iv/otm_iv_2.html.

refinery along different path(s). All crude oils are a mixture of different hydrocarbons, from light gases (methane) to heavy – and solid – hydrocarbons (coke). The first step in the refining process involves separating different hydrocarbons using their different boiling points. This is done by sending the crude oil through a desalter and on to an atmospheric distillation unit. The intermediate streams from the atmospheric distillation unit are then sent to various units for further processing.

The lightest gases are sent through gas separation and then on to a gas plant to further separate the different types of petroleum gases, methane, ethane, propane, and butane for commercial sale.

The next lightest product is gasoline, which is a blend of a number of streams that move through the refinery. The major streams for gasoline come from alkylation, catalytic reforming, catalytic hydrocracking, catalytic cracking, and other sources. Each of these streams has different characteristics, such as octane level and vapor pressure, which must be blended with the correct properties in order to produce gasoline that combusts properly in today's complex engines.

Other processing streams produce distillates, such as jet fuels, diesel, kerosene, and heating fuels. The heaviest hydrocarbons are either cracked in coker or visbreaking units to convert them to lighter hydrocarbons or processed into asphalt products or ship fuel oils. Residuals from cokers and visbreakers are sold as petroleum coke. Some refineries also produce non-fuel products, such as petrochemical feedstocks and lubricating products.

In order to provide a simple method to compare the processing capabilities of refineries, the petroleum industry uses the "*Nelson Complexity Index*" [84, 85]("*NCI*") to provide a numerical value to describe the complexity of refineries in order to compare their building costs and their processing capabilities. The formula used is:

$$NCI_t = \frac{\sum_{i=1}^{N} F_i \cdot C_{it}}{C_{CDUt}}$$

F_i: *complexity factor assigned for each unit by type*[86]

C_{it}: *throughput capacity for unit i at time t*

C_{CDUt}: *capacity of the refinery's crude distillation unit(s) at time t.*

N: *number of individual processing units for that refinery*

I: *individual refinery processing unit*

The higher an NCI value that characterizes a refinery, the more varied its product line. Because North American refineries are most often designed to maximize gasoline production, they tend to be more complex than refineries found elsewhere. All refineries are designed to process a limited range of crude oil types based primarily on API gravity and sourness, but other assay characteristics can be significant.

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84 The Nelson Farrar Complexity Index was developed by Wilbur L. Nelson in *Oil and Gas Journal* in issues from 1960, 1960, and 1976.

85 Johnston, D. (1996). Complexity index indicates refinery capability, value. *Oil and Gas Journal,* 94(12), 74-80.

86 Each processing unit has a standard complexity value based on the type of unit (F). For example, crude units have a value of 1.0, while catalytic cracking units have a value of 6.0. The values for different types of refinery units can be found in the referenced articles above.

One point of interest to note is that shale crude oil is almost uniformly sweet and light. In contrast, many U.S. refineries are designed to run sour and heavy crude, since these crude types are less expensive to purchase. The onset of large new domestic sources of light sweet crude has caused some refineries problems, requiring the blending of different crude feedstocks together in order to properly process these shale crude oils.[87]

Over the time period of this study, U.S. refineries have increased their average size and complexity. Though the number of U.S. refineries has declined significantly, their overall output has increased and become more diverse. The increased size of refineries is due largely to efforts to identify locations or equipment that hinder the flow of feedstocks through the refining process. Attempts to remedy these issues are known as "de-bottlenecking," and typically include deploying advanced processing technology improvements.

> Hypothesis 2: T*he change in average size of U.S. petroleum refineries* has *caused a change in the U.S. petroleum industry's average vertical integration.*

Refineries have also added new processing units that increased their NCI and their processing abilities. This includes the ability to process heavier crude oils in order to run less expensive crude oil. Other additions have increased refineries' ability to process a

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[87] Strickler, G and Plante M.D., April 9, 2019, *Modern Refineries, Shale Boom Upend Traditional Oil Price Relationships*, Federal Reserve Bank of Dallas.

wider product line and to process more valuable product lines.

> Hypothesis 3: T*he change in the average NCI* has *caused a change in the U.S. petroleum industry's average vertical integration.*

Adding additional units and equipment would result in higher energy usage per barrel of oil processed if refinery technology had remained static. Though refineries are larger and more complex, the average energy usage has become more efficient. This is due to the Digital Oilfield technology increasing the automation, controls, and other processing technologies to improve refining processes. The Energy Information Agency (E.I.A.) provided pooled U.S. heat efficiency data for all U.S. refineries on an annual basis.[88]

> Hypothesis 4: T*he improvement in energy efficiency among U.S. refineries has caused a change in the U.S. petroleum industry's average vertical integration.*

4.2.3 Covariates

Previous research has identified other significant determinants that influence the level of vertical integration an industry or companies undertake. These include asset specificity, firm demographics, market relationship complexity, market concentration, the value of feedstock in relation to product price, and macroeconomic considerations.

Asset specificity and relationship complexity have been identified as important

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[88] Energy Information Agency, https://www.eia.gov/dnav/pet/pet_pnp_capfuel_dcu_nus_a.htm.

determinants, if not the most important, in the tendency to vertically integrate in a number of studies. This has typically been measured in studies that have looked across different industries. The petroleum industry requires a large amount of specialized capital, increasing its level of asset specificity as an industry. Petroleum production transportation, refining, and marketing equipment do not have readily identifiable alternate uses. The relationships between crude oil producers and refiners are complex and intertwined. Conversely, crude oil is a commodity with many buyers and sellers. Crude producers' and refiners' assets are not typically specific to a single supply contract. All this said, there is no indication the level of asset specificity has appreciably changed and is treated as part of the fixed effects in this research.

Market Concentration

Past research has shown that there is a positive correlation between market concentration and vertical integration. This research will include two metrics for market concentration. The first will measure refined product concentration by tracking the percentage of total U.S. refining capacity owned by the top 15 refiners. The second metric will measure the market concentration of the crude oil market by the percentage of production capacity by the top 15 producers. Figures 4.8 and 4.9 show that crude production market concentration has decreased while refinery concentration has increased. The introduction of tight-oil technology and the opening of new production basins and fields have encouraged many new companies to enter the market. The refinery market experienced a concentration in the late 1990's and 2000's as several major companies went through a

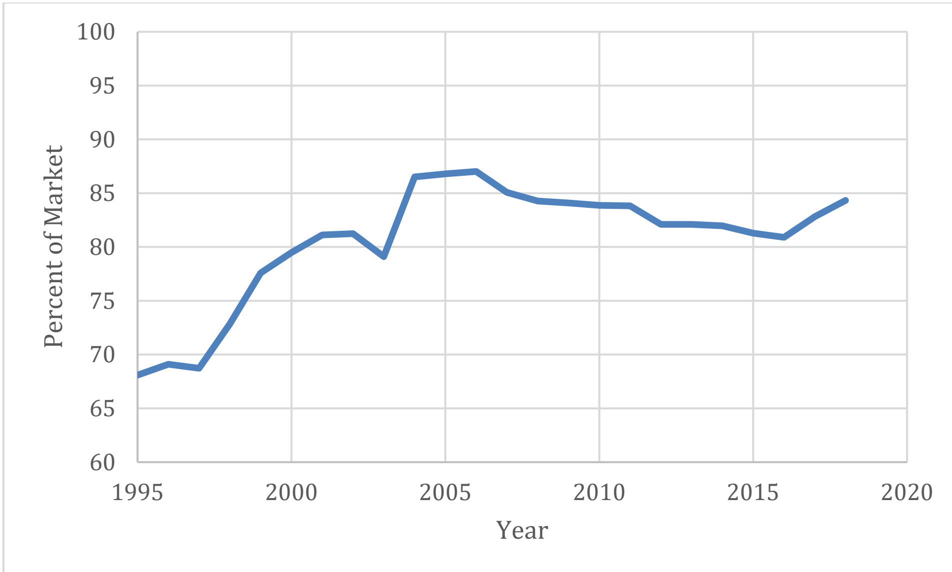

Figure 4.8: Market Concentration of Refinery Industry, Percentage Controlled by 15 Largest Refiners

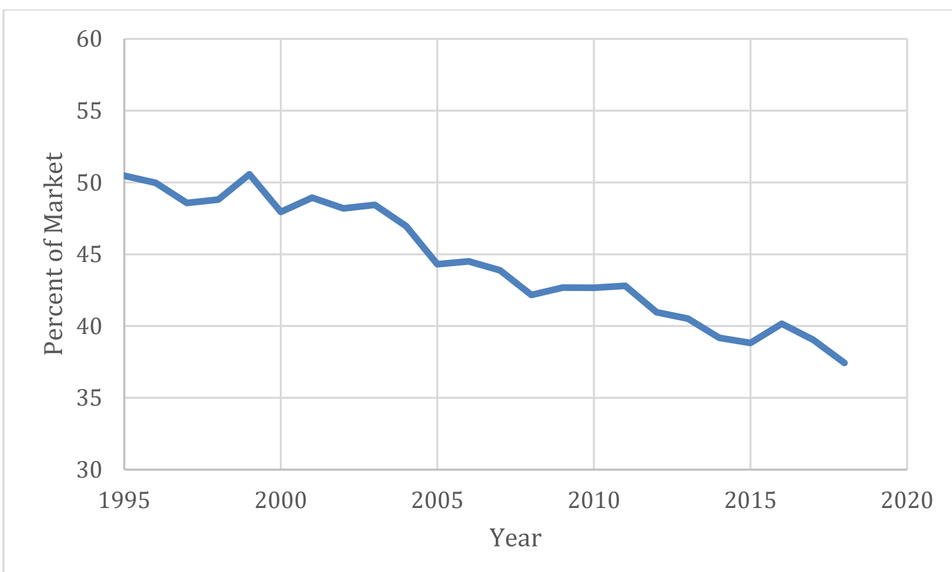

Figure 4.9: Market Concentration of Crude Production, Percentage Controlled by 15 Largest Producers

round of mergers and acquisitions. Concentration has been relatively constant since that period.

Oilfield Service Company Penetration

Oilfield service companies (OSC) have played an increasing role in the production and processing of petroleum in the past few decades. The comparative market capitalizations of oilfield service companies, in comparison to operations companies, peaked in the 1990's but has retreated and leveled to some degree during the sample period, as shown in Figure 5.12. This data was derived from Bloomberg Profession Services comparing global oilfield services to petroleum operating companies' market capitalizations.

Cracking Spread and Oil Pricing

The importance of a feed input to a final product has been found to have a positive correlation with vertical integration in earlier research. The more important an input is to the production of a final product, such as crude oil is to a refinery, the more important it is to avoid supply disruptions. One mitigation is to backward integrate the sources of the input. The cracking spread is a well know petroleum industry metric that measures the value of crude in comparison to product pricing. The New York Mercantile Exchange's (NYMEX) 3-2-1 Crack Spread is one of the most widely used, comparing the spot prices of two parts gasoline and one part diesel to three parts West Texas Intermediate (WTI). These are all posted benchmark pricing available in financial publications. This gives a value in nominal dollars. In order to remove inflationary influences, the crack spread formula was converted to a ratio.

$$\left. \mathit{Crude\ Price} \middle/ \mathit{Product\ Price} \right. = \frac{3\ X\ WTI\ Price}{2\ X\ Gasoline\ Price + Diesel\ Price}$$

This formula uses the same NYMEX posted pricing as the Crack Spread. WTI is a benchmark crude oil price, similar to Brent in Europe. Many crude oil contracts in the Western Hemisphere use WTI as the pricing benchmark in their contract language. Product prices are based in New York Harbor. WTI price is based in Cushing, OK.

Firm Demographics

Firm size and age have been identified in earlier research to have positive correlation with vertical integration. Average firm size is measured as the sum of crude oil equivalent production and refinery capacity for each company. Longevity is the number of years since incorporation.

Macroeconomic Metrics

The petroleum market is international and generally well developed, with events having ripple effects around the world. Macroeconomic considerations for GDP growth, interest rates, and inflation were included in the research. Average annual nominal GDP growth was obtained from the U.S. Bureau of Economic Analysis. The annual average U.S. Treasury 10-year yield is the metric to represent interest rates. This information was obtained from Bloomberg Professional Services. Inflation rates are measured from the U.S. Bureau of Labor Statistics average annual consumer price index (CPI).

Table 4.3: Conceptual and Operational Definitions of Independent Variables

Variable	Type	Conceptual Definition	Description	Operational Definition	Units	Range in Sample
Percent Tight Oil	Primary	Percent of Company Crude Oil Production Utilizing Tight Oil Technology (Horizontal Drilling)	Industry Introduction of Tight Oil Technology	$Percent\ Tight\ Oil\ Technology = \frac{Horizontal\ Crude\ Production}{Total\ Crude\ Production}$	Percent	0 to 100% for individual companies; 2 to 59% for U.S. Industry
Total Refinery Capacity	Secondary	Petroleum Company Total Refinery Capacity	Petroleum Company Total Refinery Capacity	$Average\ Refining\ Capaity = \frac{Total\ Refinery\ Capacity}{Number\ of\ Refineries}$	Thousands of Barrels/ Day (MBPD)	0 to 2,881 MBPD
Average Refinery Complexity	Secondary	Petroleum Company Average Complexity of its Refineries	Average Product Capability and Flexibility of Petroleum Company Refineries	$NCI_t = \frac{\sum_{i=1}^{N} F_i \cdot C_{it}}{C_{CDUt}}$	Unitless	1 to 57
Refinery Energy Usage	Secondary	Average Energy Usage in Refineries per Barrel of Crude Oil Processed	Technology Growth in Downstream Processing	*U.S. Average Energy Usage per Crude Oil Barrel Refined*	British Thermal Units (BTU) per Barrel	660 to 730 BTU/BBl
Market Concentration - Crude Production	Covariate	Percent of Total U.S. Refinery Capacity Controlled by Ten Largest Refining Companies	Market Concentration of Crude Production	$Market\ Concentration = \frac{Crude\ Production\ of\ 10\ Largest}{Total\ U.S. Crude\ Production}$	Percent	37 to 50%

Table 4.3 (cont.): Conceptual and Operational Definitions of Independent Variables

Variable	Type	Conceptual Definition	Description	Operational Definition	Units	Range in Sample
Market Concentration - Refining	Covariate	Percent of Total Crude Oil Equivalent Production Controlled by Ten Largest Production Companies	Market Concentration of Refining Industry	$Market\ Concentration = \frac{Total\ Refinery\ Capacity\ of\ 10\ Largest\ Refiners}{Total\ U.S.\ Refinery\ Capacity}$	Percent	68 to 87%
Oil Service Company Penetration	Covariate	Total U.S. Oil Service Company Revenues as a Percentage of Operating Petroleum Company Revenue	Growth of Oil Service Company Input to Product Supply Chain	$Oil\ Service\ Company\ Penetration = \frac{Oil\ Service\ Company\ Market\ Capitalization\ (Global)}{Operating\ Company\ Market\ Capitalization\ (Global)}$	Percent	4 to 17%
Crude Price vs Product Price	Covariate	NYMEX 3-2-1 Cracking Spread	Final Product Margin	$\frac{Crude}{Product} = \frac{3\ x\ WTI\ Price/Bbl}{2x\ Gasoline\ Price/Bbl + Diesel\ Price/Bbl}$	Percent	72 to 91%
WTI Pricing	Covariate	Annual Average NYMEX Posted West Texas Intermediate (WTI) Posted Price	Final Product Pricing	*Annual Average Daily NYMEX Posted Price*	Dollars ($)	$14.40 to $97.89

Table 4.3 (cont.): Conceptual and Operational Definitions of Independent Variables

Variable	Type	Conceptual Definition	Description	Operational Definition	Units	Range in Sample
Company Size	Covariate	Petroleum Company Total Crude Oil Equivalent Production plus Refinery Capacity	Company Size	*Company Size = Annual Crude Oil Equivalent Production + Refinery Capacity*	Thousands of Barrels per Year (MBPY)	0 to 3,225 MBPY
Company Age	Covariate	Petroleum Company Years since Incorporation	Company Longevity in Industry	*Years since incorporation*	Years	0 to158 years
Average 10-Year Treasury Rate	Covariate	Average Annual 10-Year Treasury Yield	Interest Rate	*Annual Average U.S. Treasury Yield*	Percent	1.8 to 6.6%
U.S. G.D.P. Growth	Covariate	Annual U.S. Gross Domestic Product Growth	Macroeconomic Growth	*Annual G.D.P. Growth*	Percent	-1.8 to 6.3%
CPI Annual Inflation	Covariate	Annual Consumer Price Index Inflation	Inflation	*Annual C.P.I.*	Percent	-.4 to 3.7%

4.2.4 Model Assumptions

This study is limited to the U.S. and, as such, will largely ignore, or treat as fixed effects, all international information. Currently, tight-oil technology is primarily an American phenomenon in both development and deployment, having not been widely utilized in other countries due to a variety of political and technical issues. As such, limiting the research to the U.S. may introduce some biases, but these biases should be limited due to the unique nature of American exploitation of this technology.

The introduction of this technology and its effects has most likely not reached equilibrium. A case in point, the midstream pipelines for moving crude oil from new fields to refineries are still being installed in many locations around the country. Until pipeline completion reaches a higher level, this situation creates major logistical bottlenecks that could possibly bias the data in some fashion. Additionally, tight-oil technology is still in its infancy in many respects and is still being constantly improved. Output from individual wells and basins are still be optimized.

Alternative Fuels

This research gathered information concerning the introduction of alternative fuels, but their market share is still relatively insignificant compared to all transportation fuels. Their introduction may be having an effect on the structure of the petroleum industry, but it would be due to market share projections of the future rather than current conditions. Consequently, this data was not included in the research.

Unbalanced Panel Data

The panel data in this research is unbalanced since companies are going in and out of the business during the research time frame. Additionally, some data is not firm specific but reflects national annual averages. STATA automatically detects and corrects for this.

Multicollinearity, Autocorrelation and Heteroscedasticity

The variables are measured as annual averages and represent time series for individual companies and will likely be autocorrelated. One of the Gauss–Markov theorem assumptions of the classical linear regression model is that there is no, or little, heteroscedasticity. Breaking this assumption means that regression estimators are not the Best Linear Unbiased Estimators (BLUE) and does not represent the lowest variance of all other unbiased estimators. Tests for heteroscedasticity will be performed and evaluated on the analysis results. Multicollinearity exists when three or more variables are collinear even if pairs of variables have little correlation. This means that there is redundancy between predictor variables. The solution of the regression model becomes unstable if multicollinearity is present. Since data in this research is derived from one industry, multicollinearity is a good possibility. To compensate for these sources of bias, STATA clustered robust standard errors are used in these analyses. As can be observed in the results tables below, the model's most efficient method varied from fixed effects, random effects, and Ordinary Least Squares (OLS), depending on results from the Durbin-Wu-

Hausman and Breusch Pagen Lagrangian multiplier tests, which were applied after each STATA analysis.

Trend Data and Possible Spurious Correlations

The primary focus of this research is to characterize the relationship between upstream technological innovation and vertical disintegration. During the 1995-2018 period under study both measures experienced strong trends, which raises the question whether any measured correlations are only spurious. I do not believe this is the case here. Past research discussed in this study found evidence of causal relationships between technological intensity and innovation with organizational vertical integration. There are solid theoretical explanations for the empirical results and conclusions drawn in this research. The research accounts the known factors from earlier research in its regressions, the sample period encompassed 24 years and included the majority of U.S. petroleum companies, including all integrated ones.

CHAPTER 5

MODEL TEST RESULTS AND INTERPRETATION

This chapter reports the model development and test results for each of the five dependent variable measures discussed in the previous chapter. Each of these metrics captures a specific aspect of the vertical integration long associated with the U.S. petroleum industry. Taken together they offer the possibility of detecting, heretofore, unanticipated development stages in the ongoing maturation of the industry. As has been demonstrated in previous chapters, since the mid-1990's the U.S. petroleum industry has endured a precipitous unravelling of its legendary vertical integration. In this chapter we report the results of detailed analyses seeking to test whether there is evidence that these disintegration dynamics might be related to the industry's adoption and implementation of tight-oil technologies that also began in the mid-1990's. If so, it could be presumed that the technology suite referred to as "tight-oil" production has gradually transformed the industry's operations and did so by pressuring – or enabling – key portions of the production operations to be relocated to new locations along the extended supply chain.

The results reported in this chapter also include those obtained for the several covariates that were assigned roles in the five sets of model specifications that were tested. As these specifications and tests are introduced, the results will be interpreted with relevant consideration of the results of the data diagnostics used to guide the respective tests.

Analysis Strategy: Effect Estimates and Interpretation

In each analysis below, we begin by testing a simple bivariate model. The main independent variable representing the volume percentage of crude production from horizontal wells is regressed against the dependent variable representing the introduction of tight-oil technology for both the U.S. and firm level. The estimated effect for this initial specification will be found in Column 1 of each of the Tables 5.1 to Table 5.6. The results from this simple initial test for each of dependent variable model sets will serve as a baseline against which more elaborated models can be judged. Each model is tested for one- and two-year leads on the dependent variable with the effect estimate yielding the highest significance being reported in the respective tables.

Following the initial bivariate model reported in Column 1, a sequence of models is tested with each successive model elaborated by introducing an additional set of covariates as controls. In all five tables, a second model specification includes effect estimates for three Downstream Technology factors, with the results reported in Column 2. A third specification includes effect estimates for two Firm Demographics Factors, with the results reported in Column 3. A fourth specification includes effect estimates for five Market Factors, with the results reported in Column 4. A fifth specification includes effect estimates for three Macroeconomic Factors, with the results reported in Column 5. In each case the model specification is tested using one- and two-year leads, with the effect estimate yielding the highest significance being reported in the respective tables. The results for each of these progressively elaborated models are reported in Tables 5.1 to 5.6.

By testing this sequence of increasingly-elaborated models we are subjecting the original hypothesis to a sort of stress test. As a succession of controls is introduced into these models, we are most interested in whether the original negative effect (col. 1) on the dependent variable by the introduction of tight-oil technology is replicated. This stress-testing across increasingly elaborated models permits us to discover whether the original relationship might be spurious. We find that the tight-oil effect is indeed replicated in three of the five models, with special significance associated with its replication in the most fully specified fifth model.

We begin by analyzing a model set that uses the Self-Sufficiency Ratio (SIVI) as the dependent variable metric. Econometric results are reported in Table 5.1 and graphical representations of relationships involving key covariates.

5.1 Self-Sufficiency Ratio (SIVI)

As discussed earlier, the Self Sufficiency Ratio (SIVI) is a simple ratio between all crude equivalent production volume and refining capacity.

$$\mathrm{SIVI} = \frac{\text{Crude Equivalent Production (BOEPD}^{89}\text{)}}{\text{Petroleum Refinery Capacity (BOEPD)}}$$

[89] Barrels of oil equivalent per day (BOEPD).

The SIVI metric, or variations of it, have been used in earlier research, particularly those that were focused on backward integration.[90] Again, the data set for testing this model only included large integrated companies, as listed in Appendix A, in order to avoid undefined SIVI values. With this limitation, the influence of all "crude production only" or "pure-play" companies which would have had excessively high SIVI values approaching ∞ was eliminated.

Introduction of Tight-Oil Technology

The adoption of horizontal crude oil production using tight-oil technologies has increased

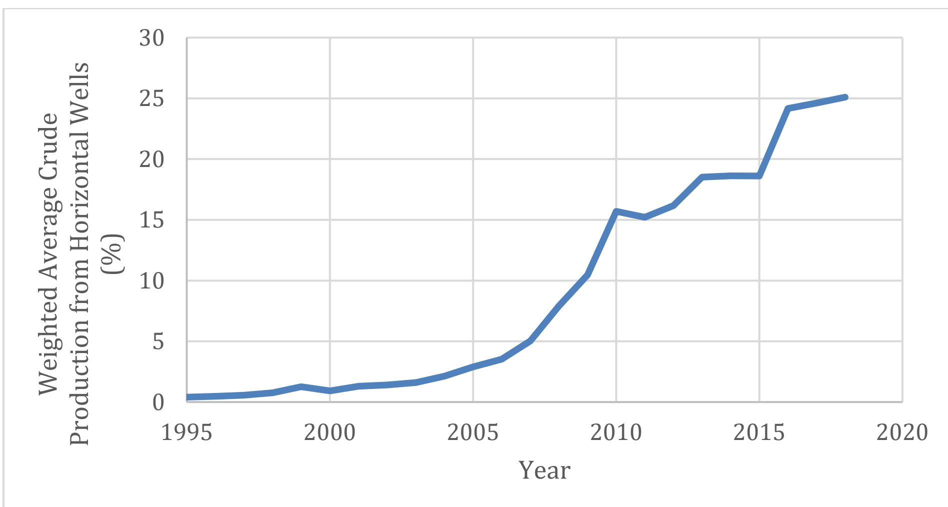

Figure 5.1: Weighted Average Horizontal Crude Production Percentage Among Large U.S. Integrated Petroleum Companies

[90] The term self-sufficiency ratio was used in Mitchel (1976).

dramatically over the 1995-2018 study period (See Figure 5.1). Figure 5.2 depicts graphically the relationship between the introduction of tight-oil technology and SIVI.

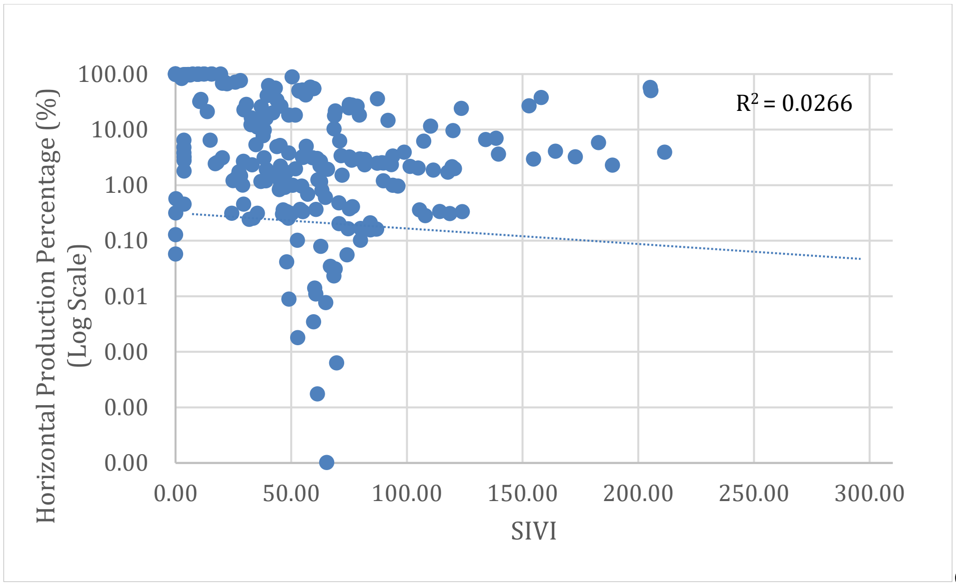

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Figure 5.2: Self Sufficiency Ratio (SIVI) vs. Natural Log of Company Crude Volume Percentage from Horizontal Wells

While Figure 5.2 justifies our hypothesis that the introduction of tight-oil technology likely has a negative effect on the degree of vertical integration in the U.S. petroleum industry, we can now begin to test that hypothesis econometrically in a sequence of increasingly elaborated models. The first trial results are reported in Table 5.1 (column 1). When we regress upstream technology against SIVI, the results yield a statistically significant negative correlation (-3.137). This outcome is consistent with Property Rights Theory (PRT) predictions.

Table 5.1: Self Sufficiency Ratio Model Trials

Dependent Variable: SIVI Master Data- Majors.xlsx

Green cells indicate significant effect in that trial.

t or z test value is in parenthesis.

	Trial	1	2	3	4	5
	Best Estimator	RE*	FE**	RE*	RE*	OLS***
	Observations	211	192	192	192	192
	R-sq	0.0266 overall	0.0002 overall	0.7348 overall	0.7123 overall	0.7658
	Prob > F	0.0000	0.0000	0.0000	0.0000	0.0000
	Constant	58.811 (5.19)	99.547 (1.34)	60.429 (1.46)	81.756 (1.14)	80.346 (0.76)
Upstream Introduction of Tight Oil Technology	**Natural Log Company Horizontal Production Percentage**	-3.137 (-4.69)	-2.675 (-3.99)	-1.577 (-1.39)	-1.888 (-1.64)	-1.161 (-2.58)
Downstream Technology	**Refinery Complexity**		-0.109 (-0.45)	-0.505 (-1.55)	-0.701 (-1.80)	-0.796 (-5.12)
	Refinery Capacity		-0.023 (-1.99)	-0.118 (-6.34)	-0.122 (-5.61)	-0.139 (-20.99)
	Refinery Energy Efficiency		-0.018 (-0.33)	-0.019 (-0.77)	0.008 (0.41)	-0.006 (-0.08)
Firm Demographics	**Size**			0.075 (5.35)	0.078 (4.92)	0.095 (22.34)
	Age			0.285 (0.99)	0.112 (0.45)	0.161 (2.62)
Market Factors	Refinery Concentration				-0.375 (-1.39)	-0.240 (-0.44)
	Production Concentration				-0.833 (-1.16)	-1.209 (-1.75)
	WTI Price				0.007 (0.20)	(0.071) (-0.68)
	Crude Price / Product Price				0.296 (1.77)	0.365 (0.82)
	Oilfield Service Capitalization				0.039 (1.14)	0.022 (0.03)
Macroeconomic Factors	Treasury Rate					2.262 (1.00)
	GDP Growth					0.655 (0.69)
	Inflation					-0.126 (-0.07)

* Random Effects estimator with cluster robust standard error
Hausman Test >.05
** Fixed Effects estimator with cluster robust standard error
Hausman Test <.05
*** OLS Linear Regression, Breusch-Pagan LM test for random effects versus OLS: Prob > chibar2 = 1.0000
Grey cells are industry or nationla level variables.

When downstream technology control factors are added to the model in the second trial, the negative coefficient on the main independent variable (-2.675) remains statistically significant. That the original negative effect in the first trial is replicated serves as evidence that the addition of controls for downstream technology do not account for the initial negative effect reported in the first specification. Of the three downstream technology factors, only refinery capacity yields a statistically significant independent negative effect, in contrast to PRT and TCE expectations that vertical integration would be associated with increased refinery capacity.

The third trial further elaborates the model with the addition of firm size and firm age as demographic controls. While firm size alone has a positive independent effect on SIVI, as would be consistent with theoretical expectations, it counts for enough to the variation in SIVI to cause the tight-oil effect to lose significance. Finally, the fourth and fifth trials further elaborate the original model by adding controls for market factors and macroeconomic factors, respectively. The results in both columns four and five reveal that while neither of these sets of control factors have independent effects on SIVI, more importantly, when both sets are included in the fully specified model (column 5), the negative effect (-1.161) of the introduction of tight-oil technology regains its statistical significance.

By testing this sequence of increasingly-elaborated we are subjecting the original hypothesis to a sort of stress test. As a succession of controls is introduced into these models, we are most interested in whether the original negative effect (col. 1) on SIVI by the introduction of tight-oil technology is replicated. This stress-testing across increasingly elaborated models permits us to discover whether the original relationship might be spurious. We find that the tight-oil effect is indeed replicated in three of the five models, with special significance associated with its replication in the most fully specified fifth model.

Downstream Technology

When downstream technology control factors are added to the model in the second trial, the negative coefficient on the main independent variable (-2.675) remains statistically significant. That the original negative effect in the first trial is replicated serves as evidence that the addition of controls for downstream technology do not account for the initial negative effect reported in the first specification.

The large integrated companies increased both their refinery capacities and complexities during the sample period, as shown in Figure 5.3 and 5.4. Of the three downstream technology factors, only refinery capacity yields a statistically significant independent negative effect, in contrast to PRT and TCE expectations that vertical integration would be associated with increased refinery capacity. The negative regression coefficients β in conjunction with these increases indicate that refineries becoming larger and more complex contributed to firm vertical disintegration. Neoclassical microeconomics and TCE would have predicted a positive effect on vertical integration as refinery investments increased and asset specificity rose.

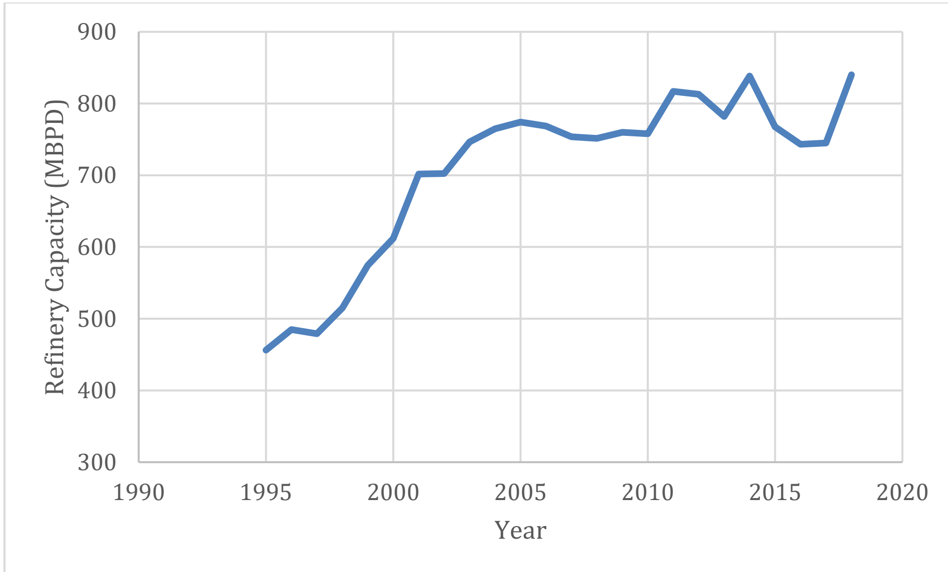

Figure 5.3: Average Total Refinery Capacity Among Large U.S. Integrated Petroleum Companies

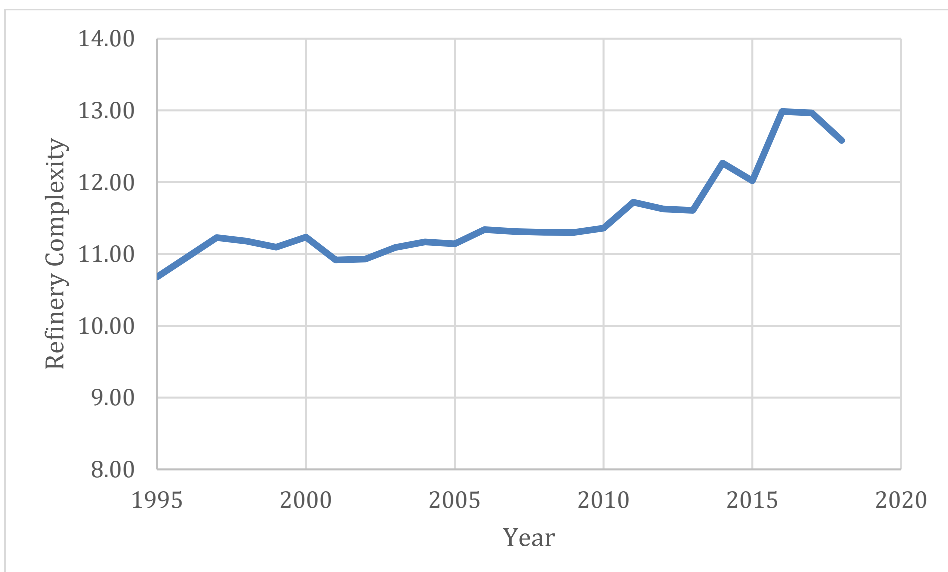

Figure 5.4: Weighted Average Refinery Complexity Among Large US Integrated Petroleum Companies

Refinery energy efficiency has an insignificant correlation with SIVI in this model. Data at the refinery level is only available publicly at the industry level through the E.I.A., providing only pooled data for this analysis. The comparison of firm level SIVI to industry level energy efficiency would likely increase the data scatter pattern, decreasing statistical significance. The availability of individual refinery level energy efficiency data may yield different results.

Firm Demographics

The third trial further elaborates the model with the addition of firm size and firm age as demographic controls. While firm size alone has a positive independent effect on SIVI, as would be consistent with theoretical expectations, it counts for enough of the variation in SIVI to cause the tight-oil effect to lose significance.

Market Factors

The SIVI model did not produce any significant results regarding market concentration, or horizontal integration, and vertical integration. Figures 4.8 and 4.9 showed that refinery market concentration increased while crude production market concentration steadily declined during the sample period. Neo-classical economics predicts that vertical integration would be positively correlated with market concentration.

Market concentration data is at the U.S. industry level, rather than at local market level. As will be discussed below, production market concentration for the U.S. industry level (RVIC and CVIR) models show production concentration to have a positive correlation with vertical integration.

Macroeconomic Factors

Macroeconomic covariates in the model are all found to be insignificant, but they do have an effect on the coefficients and significance of other covariates. This may be a case of data quality in regard to the macroeconomic factors. The data available for interest rates and growth are U.S. economy wide, while the SIVI value is specific to each firm for each period. Better results would more likely have been achieved with interest rates and growth information for individual companies, such as weighted average cost of capital (WACC) and revenue or gross margin growth in the U.S. market for each firm. Publicly available data of this granularity would only be available for U.S. public companies. Finally, the fourth and fifth trials further elaborate the original model by adding controls for market factors and macroeconomic factors, respectively. The results in both columns four and five reveal that while neither of these sets of control factors have independent effects on SIVI, more importantly when both sets are included in the fully specified model (column 5), the negative effect (-1.161) of the introduction of tight-oil technology regains its statistical significance. The model also found, unsurprisingly, that older and larger companies tended to be more vertically integrated. The regression coefficients β on both size and age are small, but statistically significant. The large petroleum companies in the sample were about 43% larger in refinery capacity in 2018, as compared to 1995.[91] It is unlikely that company size was a factor in management decisions on vertical integration.

These results are consistent with the Property Rights Theory (PRT) that states that producers are more motivated to retain property residual rights as their upstream businesses increase in technological sophistication. The change in the percentage of crude production from horizontal wells controlled by large integrated companies (Figure 5.2) shows that they were not early users of tight-oil technology, lagging behind the industry as a whole (see Figure 5.2 in comparison to Figure 3.6), but their reliance on the technology continues to grow briskly to the present.

This large increase in crude oil production from horizontal wells depicted in Figure 5.1, in conjunction with the fairly large β coefficient from the SIVI regression analysis, supports the hypothesis that technology innovation significantly contributed to the disintegration of the petroleum industry's vertical structure. The STATA output for SIVI Trial 5 is contained in Appendix B.

5.2 Balance Index (BIVI)

The Balance Index (BIVI) model measures the balance between the two supply chain functions of crude production and refinery capacity. As stated earlier, the formula for BIVI

[91] Size being the summation of crude production plus refinery capacity.

is calculated as follows:

$$BIVI = \left(1 - \frac{Max\ (refining, production) - Min\ (refining, production)}{Max\ (refining, production)}\right) x\ 100\%$$

BIVI is similar to the SIVI model, measuring the balance between upstream and downstream operations, but allows for all petroleum companies in the database to be included because their BIVI values are bounded between 0 and 100. I use this model to analyze two data sets. The first data set being all petroleum companies and the second only the large integrated companies included in the SIVI data set. See Appendix A.

Figure 5.5 depicts graphically the bivariate relationship between firm-level adoption of horizontal drilling using tight-oil technologies and BIVI. As in the SIVI model, results reveal statistically significant negative effects of horizontal drilling on petroleum industry vertical integrations using all-company (Table 5.2) data and large integrated producer (Table 5.3) data,[92] consistent with PRT predictions.

Unlike the SIVI model, the independent variable for tight-oil technology stayed statistically significant in all trials for both data sets. The BIVI results support that tight-oil technology's introduction was a contributor in firm vertical disintegration during the

[92] Leading values (t-1, t-2) of company horizontal production volumes were also negatively correlated with BIVI, but to a lesser extent. U.S. horizontal percentage crude volume did not exhibit significant correlation.

sample period. This supports PRT predictions that increasing technological intensity is negatively correlated with vertical integration.

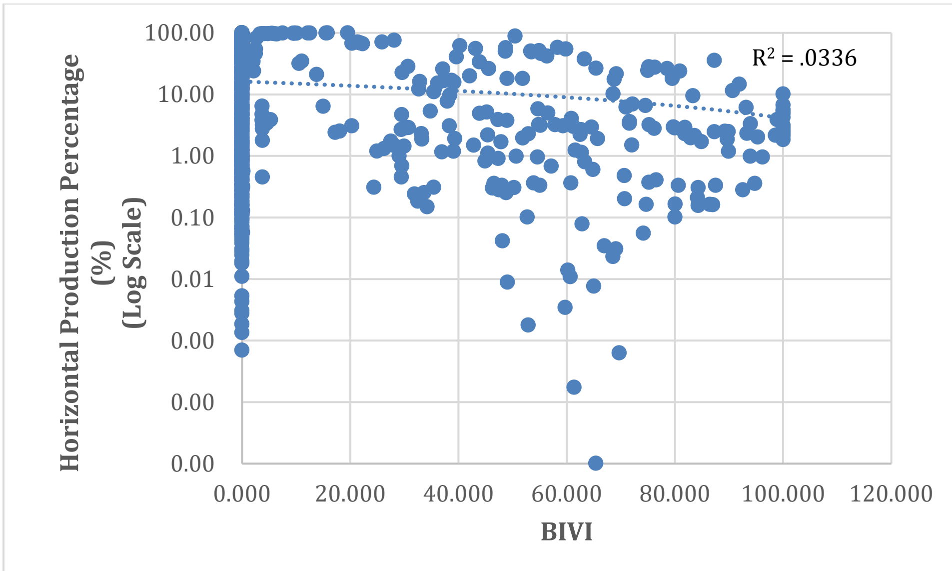

Figure 5.5: Natural Log of Individual Company Horizontal Production Percentage vs Balance Index (BIVI)

The full STATA results for trial 5 using the all U.S. petroleum company data set (MasterData.xlsx) can be found in Appendix C, and for large integrated companies in Appendix D.

Introduction of Tight-Oil Technology

Unlike the SIVI model, the independent variable for tight-oil technology stayed statistically significant in all trials for both data sets. The BIVI results agree with the SIVI model support that tight-oil technology's introduction was a contributor in firm vertical disintegration during the sample period. This supports PRT predictions that increasing technological intensity is negatively correlated with vertical integration.

The full STATA results for trial 5 using the all U.S. petroleum company data set (MasterData.xlsx) can be found in Appendix C, and for large integrated companies in Appendix D.

Downstream Technology

The BIVI model, using the data for the entire industry, shows no correlation between the downstream technology factors and vertical integration as measured by BIVI.

As stated, the results using only large integrated companies as a data set were very similar to the SIVI model. The BIVI and SIVI models treat large integrated firms similarly, so this may not be surprising. Refinery capacity is significantly negatively correlated as soon as it is introduced into the model and stays significant as other covariates are introduced. Refinery complexity emerges as negatively significant once all covariates are considered in the model. These results do not support predictions of PRT and TCE theories.

Table 5.2: BIVI Model Trials – All U.S. Petroleum Companies

Dependent Variable **BIVI** Master Data.xlsx

Green cells indicate significant effect in that trial.

t or z test value is in parenthesis.

		1	2	3	4	5
	Trial	1	2	3	4	5
	Best Estimator	FE**	FE**	FE**	FE**	FE**
	Observations	1,570	233	233	233	233
	R-sq	0.0336 overall	0.0448 overall	0.0775 overall	0.0179 overall	0.3772 overall
	Prob > F	0.0000	0.0000	0.0000	0.0000	0.0000
	Constant	9.089 (16.89)	96.887 (1.19)	86.749 (1.18)	103.136 (0.81)	-30.469 (-0.23)
Upstream Introduction of Tight Oil Technology	**Natural Log Company Horizontal Production Percentage**	-0.662 (-2.33)	-3.404 (-4.11)	-2.375 (-2.20)	-2.272 (-2.43)	-2.265 (-2.49)
Downstream Technology	Refinery Complexity		0.342 (0.57)	0.699 (0.93)	0.605 (0.86)	0.589 (0.88)
	Refinery Capacity		-0.009 (-0.75)	-0.019 (-0.60)	-0.015 (-0.48)	-0.014 (-0.45)
	Refinery Energy Efficiency		-0.034 (-0.58)	0.000 (0.01)	0.013 (0.34)	0.012 (0.30)
Firm Demographics	Size			0.009 (0.47)	0.008 (0.39)	0.007 (0.37)
	Age			-0.504 (-1.15)	-0.330 (-0.48)	0.686 (0.95)
Market Factors	**Refinery Concentration**				-0.574 (-1.87)	-0.680 (-2.02)
	Production Concentration				-0.531 (-0.74)	0.208 (0.25)
	WTI Price				-0.084 (-1.54)	-0.061 (-1.12)
	Crude Price / Product Price				0.301 (1.57)	0.282 (1.53)
	Oilfield Service Capitalization				-0.281 (-0.91)	-0.279 (-0.93)
Macroeconomic Factors	**Treasury Rate**					2.869 (1.72)
	GDP Growth					0.122 (0.46)
	Inflation					0.381 (0.69)

* Random Effects estimator with cluster robust standard error Hausman Test >.05

** Fixed Effects estimator with cluster robust standard error Hausman Test <.05

*** OLS Linear Regression, Breusch-Pagan LM test for random effects versus OLS: Prob > chibar2 = 1.0000

Grey cells are industry or nationla level variables.

Table 5.3: Balance Index Model Trials – Large Integrated U.S. Petroleum Companies

Dependent Variable **BIVI** Master Data-Majors.xlsx

Green cells indicate significant effect in that trial.

t or z test value is in parenthesis.

	Trial	1	2	3	4	5
	Best Estimator	RE*	FE**	RE*	FE**	OLS***
	Observations	211	192	192	192	192
	R-sq	0.1185 overall	0.0011 overall	0.7345 overall	0.6160 overall	0.7927
	Prob > F	0.0000	0.0021	0.0000	0.0000	0.0000
	Constant	49.171 (6.83)	85.996 (1.15)	54.773 (1.20)	84.493 (1.13)	55.893 (0.59)
Upstream Introduction of Tight Oil Technology	**Natural Log Company Horizontal Production Percentage**	-2.928 (-4.49)	-2.675 (-4.13)	-2.072 (-2.05)	-2.182 (-2.15)	-1.469 (-3.16)
Downstream Technology	Refinery Complexity		-0.093 (-0.39)	-0.489 (-1.92)	-0.558 (-1.42)	-0.711 (-5.05)
	Refinery Capacity		-0.021 (-2.10)	-0.094 (-10.29)	-0.092 (-8.78)	-0.124 (-18.33)
	Refinery Energy Efficiency		-0.011 (-0.20)	-0.022 (-0.84)	0.021 (0.75)	0.012 (0.20)
Firm Demographics	Size			0.058 (8.30)	0.057 (6.51)	0.086 (20.27)
	Age			0.359 (1.67)	0.042 (0.09)	0.175 (3.41)
Market Factors	**Refinery Concentration**				-0.486 (-2.44)	-0.326 (-0.67)
	Production Concentration				-0.937 (-1.90)	-1.088 (-1.67)
	WTI Price				-0.005 (-0.16)	-0.059 (-0.58)
	Crude Price / Product Price				0.284 (2.11)	0.352 (0.96)
	Oilfield Service Capitalization				0.041 (0.14)	0.177 (0.25)
Macroeconomic Factors	**Treasury Rate**					1.143 (0.58)
	GDP Growth					0.577 (0.65)
	Inflation					-0.123 (-0.07)

* Random Effects GLS estimator with cluster robust standard error
Hausman Test >.05

** Fixed Effects estimator with cluster robust standard error
Hausman Test <.05

*** OLS Linear Regression, Breusch-Pagan LM test for random effects versus OLS: Prob > chibar2 = 1.0000

Grey cells are industry or nationla level variables.

Firm Demographics

The BIVI model using the all petroleum company database shows no correlations between firm size and age and vertical integration.

When using the large petroleum company database, the BIVI model behaves similarly to the SIVI model. The model shows that size and age are positively correlated with a firm's vertical integration structure. Older and larger firms tend to be more vertically integrated.

Market Factors

The model using all U.S. petroleum companies demonstrates a negative correlation between refinery industry concentration and vertical integration as measured by BIVI. Figure 4.8 shows that refinery concentration increased over the sample period, demonstrating that increasing refinery concentration encourages increased vertical integration among firms. Neo-classic theory predicts that fewer refiners in relation to producers would reduce the need for refiners to vertically integrate backwards, but may increase the incentive for producers to forward integrate.

When using the large integrated company database, refinery concentration and crude/product price ratio are statistically significant when first introduced into the model, but become insignificant when macroeconomic factors are considered.

Macroeconomic Factors

The macroeconomic factors are not significant in this model and do not appear to affect other factors when introduced. Again, this may be due to the granularity issue between the firm level and U.S. industry level variables.

5.3 Probit Integration Index (VIL)

A Probit model is also analyzed to verify the robustness of the other model results. The model compares each firm's refining and crude production volumes. If the smaller is at least 50% of the larger, it is defined to have significant production and refining capabilities and to be vertically integrated. Independent variables are introduced into the model in the same manner as the other models. The VIL model is a firm level dependent variable, as are SIVI and BIVI.

The Probit model demonstrates that a number of the expected determinants of vertical integration are correlated with the dependent variable, as shown in Table 5.4. The full STATA results for Trial 5 can be found in Appendix E.

As described in Chapter 4, the dependent variable is a dummy variable, VIL_{it}, for whether a firm *(i= 1,2,3… j)* has significant upstream and downstream operations at time *t*.

$$VIL_{it} = \begin{cases} 1 & \textit{if firm i owns both significant production and refining capabilities} \\ 0 & \textit{otherwise.} \end{cases}$$

Figure 5.6 shows the average VIL value over time. It can be seen that firms' organizations were undergoing a general vertical disintegration during the sample period.

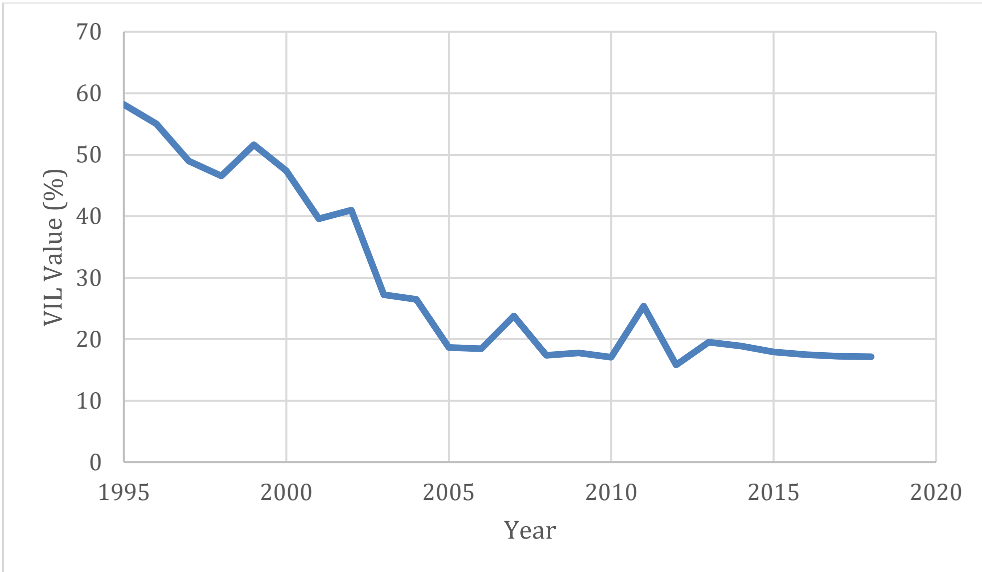

Figure 5.6: Weighted Average VIL Among Petroleum Companies

Table 5.4: VIL Model Trials

Probit Model (Panel data) Master Data.xlsx

Dependent Variable **VIL**

Green cells indicate significant effect in that trial.

z-test value is in parenthesis

		1	2	3	4	5
	Trial	1	2	3	4	5
	Observations	1,570	233	233	233	233
	Prob > chi2	0.0030	.	0.0000	0.0000	0.0000
	Constant	-7.2152 (-0.91)	7.6535 .	7.8313 (0.92)	39.6607 (1.60)	75.2669 (2.13)
Upstream Introduction of Tight Oil Technology	**Natural Log Company Horizontal Production Percentage**	-0.332 (-2.97)	-0.493 (-0.13)	-0.755 (-2.19)	-0.849 (-1.73)	-1.016 (-1.97)
Downstream Technology	Refinery Complexity		0.097 .	0.125 (1.30)	0.106 (1.35)	0.167 (1.58)
	Refinery Capacity		-0.002 (-0.03)	-0.010 (-5.38)	-0.010 (-5.13)	-0.016 (-4.32)
	Refinery Energy Efficiency		-0.006 .	-0.009 (-1.18)	-0.022 (-1.72)	-0.038 (-2.01)
Firm Demographics	**Size**			0.007 (5.09)	0.008 (5.25)	0.012 (4.17)
	Age			0.020 (0.56)	0.011 (0.42)	0.017 (0.36)
Market Factors	Refinery Concentration				-0.023 (-0.45)	-0.009 (-0.12)
	Production Concentration				-0.172 (-0.88)	-0.439 (-1.91)
	WTI Price				-0.021 (-3.63)	-0.009 (-0.72)
	Crude Price / Product Price				-0.001 (-0.02)	-0.103 (-1.20)
	Oilfield Service Capitalization				-0.170 (-1.87)	-0.448 (-3.02)
Macroeconomic Factors	**Treasury Rate**					1.466 (3.68)
	GDP Growth					0.425 (1.23)
	Inflation					-0.614 (-2.93)

Grey cells are industry or national level variables.

Introduction of Tight-Oil Technology

The model also demonstrates a significant negative correlation between individual company horizontal crude production percentage and VIL.[93] Tight-oil technology, when regressed individually, is statistically negatively correlated with VIL. Curiously, it alternates between insignificance and significance as additional covariates are added. It emerges as statistically negatively correlated when all covariates are considered. Since average VIL declined over the sample period, tight-oil technology's negative correlation supports the hypothesis that it was a contributor to the disintegration of the petroleum industry's vertical organization. This negative correlation supports prediction of PRT.

Downstream Technology

The model also demonstrates a negative correlation with the downstream technology metrics of refinery capacity and refinery energy efficiency. Capacity is not statistically significant when first introduced, but becomes significant when firm demographic factors are added to the model. It remains negatively significant when all covariates are considered. This result is consistent with the SIVI and BIVI models. Refinery energy efficiency is marginally negatively correlated only when all covariates are considered, in contrast with the CVIR and RVIC model's positive correlations. Again, these results are contrary to PRT and TCE predictions.

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[93] No correlation was found between U.S. horizontal crude production percentages and VIL.

Firm Demographics

The model finds a small but significant positive correlation between firm size and the extent of vertically integrated organizational structure.

Market Factors

The model shows a negative correlation between crude production market concentration and VIL that emerges when all covariates are considered. This is consistent with the SIVI model, but inconsistent with RVIC and CVIR. Additionally, the model finds a negative correlation between oilfield service company inroads into the industry and vertical integration, which is consistent with neo-classical microeconomic theory. Oilfield services is negatively significant when it is first reduced and stays significant when all covariates are considered contrary to expectations.

Refinery market concentration and WTI crude price are statistically significant when first introduced into the model, but become subsequently insignificant when other covariates are added to the model.

Macroeconomic Factors

The VIL model finds a positive correlation with treasury rate and vertical integration, consistent with neoclassical theory, which states that uncertainty rises with interest rates motivating firms to vertically integrate. The model also finds a negative correlation with inflation, which is inconsistent with expectations.

5.4 Forward Integration Index (CVIR)

The SIVI, BIVI, and VIL dependent variables are firm specific for each time period. In contrast, the CVIR and RVIC models use dependent variables that are at the U.S. industry level. The CVIR and RVIC dependent variables are measures of vertical integration over the entire industry for each time period. CVIR is a measure of the crude producers' tendency to forward integrate downstream into refining, while RVIC attempts to measure refiners' tendency to backward integrate into crude production.

CVIR is calculated by dividing the maximum amount of crude oil that could theoretically be produced and refined in-house industrywide with the total U.S. crude equivalent production. As described earlier, the formula is:

$$CVIC = \frac{\sum RC_{it} + \sum CP_{jt}}{Total\ Crude\ Production}$$

RC: *Refinery capacity.*

CP: *Crude production.*

i: *Firms where refinery capacity is less than crude production*

j: *Firms where refinery capacity is greater than crude production*

t: *Year*

Covariates are introduced in a stepped manner as in the other models. The CVIC model shows correlations with many of the expected determinants of vertical integration as shown in Table 5.5.

Table 5.5: CVIR Model Trials

Dependent Variable: CVIR Master Data.xlsx

Green cells indicate significant effect in that trial.

t or z test value is in parenthesis.

	Trial	1	2	3	4	5
	Best Estimator	FE**	FE*	FE*	RE***	RE***
	Observations	3,176	1,537	1,537	1,537	1,537
	R-sq	0.8775 overall	0.8857 overall	0.8855 overall	0.9699 overall	0.9745 overall
	Prob > 0 or Prob> chi2	0.0000	0.0000	0.0000	0.0000	0.0000
	Constant	43.743 (683.12)	85.460 (37.13)	66.611 (24.68)	-60.369 (-21.52)	-71.397 (-16.72)
Upstream Introduction of Tight Oil Technology	**ln U.S. Horizontal Production Percentage**	-6.954 (-224.69)	-6.525 (-80.64)	-2.572 (-7.52)	-1.807 (-46.01)	-1.928 (-19.64)
Downstream Technology	Refinery Complexity		-0.057 (-1.976)	-0.036 (-1.929)	-0.006 (-1.57)	-0.006 (-1.78)
	Refinery Capacity		-0.002 (-6.398)	-0.004 (-2.053)	0.000 (-0.44)	0.000 (-0.95)
	Refinery Energy Efficiency		-0.029 (-19.1)	0.011 (3.21)	0.014 (13.22)	0.019 (8.29)
Firm Demographics	Size			0.003 (-1.59)	0.000 (0.49)	0.000 (1.03)
	Age			-0.824 (-13.20)	0.000 (-0.39)	-0.001 (-0.84)
Market Factors	**Refinery Concentration**				0.050 (2.72)	0.055 (3.23)
	Production Concentration				1.285 (68.33)	1.450 (53.32)
	WTI Price				-0.043 (-17.51)	-0.048 (-11.64)
	Crude Price / Product Price				0.116 (27.83)	0.101 (19.73)
	Oilfield Service Capitalization				0.519 (27.82)	0.665 (61.37)
Macroeconomic Factors	**Treasury Rate**					-0.568 (-7.78)
	GDP Growth					-0.355 (-16.42)
	Inflation					0.203 (5.12)

* Random Effects GLS regression with cluster robust standard error
Hausman Test >.05

** Fixed Effects estimator with cluster robust standard error
Hausman Test <.05

*** BP Test recommends OLS estimator. Stata converts OLS to RE GLS regression

Grey cells are industry or nationla level variables.

Figure 5.7 shows a high correlation between U.S. horizontal crude production percentage and vertical integration as measured by CVIR over the sample period, when no other covariates are included in the model. Individual company crude production percentage also has a high correlation with CVIR, with an R^2 value of .4070, when other covariates are not considered. See Appendix F.

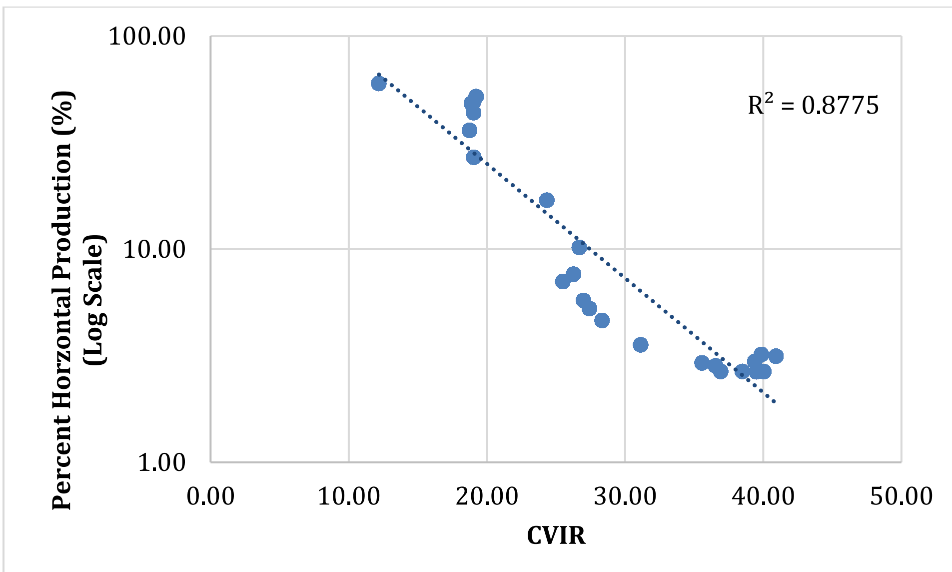

Figure 5.7: Natural Log of U.S. Horizontal Production Percentage vs Forward Integration Index (CVIR)

Table 5.5 shows that CVIR remains significantly negatively correlated with U.S. horizontal crude production percentage, with a strong negative regression coefficient β, as the covariates are added into the model.[94] This supports PRT predictions that upstream technology is negatively correlated with vertical integration. The full STATA results for Trial 5 can be found in Appendix G.

Downstream Technology

CVIR is positively correlated with refinery energy efficiency,[95] consistent with neo-classical microeconomic theory, TCE and PRT. As downstream technology improves and that stage becomes more efficient, motivation to integrate increases.

Refinery capacity is significant when first introduced but with a very small coefficient. This significance is lost as other covariates are added to the model. Refinery complexity is not statistically significant in the CVIR model. This may be due to the differences in granularity between the dependent (industry level) and refinery capacity and complexity (firm level), which most likely increases the noise in the sample, increasing the difficulty in obtaining significant results.

Market Factors

The model exhibited positive correlations with both of the market concentration

[94] CVIR was also negatively correlated with leading values (t-1, t-2) of these U.S. Horizontal crude production percentage variables, but not as highly as same year. CVIR was not significantly correlated with individual company horizontal crude production percentage when all covariates were considered. See Appendix F.

[95] Both CVIR and refinery energy efficiency are pooled values for the industry, as a whole, for each time period. The other two refinery metrics are company specific.

independent variables as predicted by neo-classical theory. The model indicates that crude producers would be more encouraged to forward integrate as the upstream and downstream markets become more concentrated. Figure 5.8 shows crude production industry concentration declining over the sample period. Combined with a positive regression coefficient, the model indicates this trend contributed to vertical disintegration during the sample period.

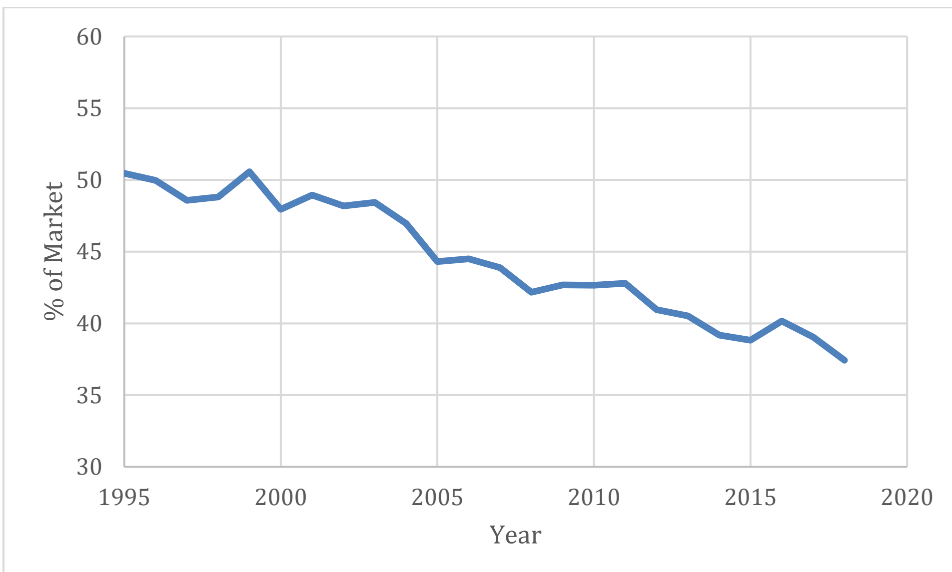

Figure 5.8: Market Concentration of Crude Production, Percentage Controlled by 15 Largest Producers

The CVIR model also indicates a positive correlation between refinery market concentration and vertical integration, consistent with neo-classical microeconomic theory. As downstream markets become more concentrated, there is a motivation for upstream suppliers to forward integrate to ensure market share. Refining market concentration increased, as shown in Figure 5.9, indicting this trend encouraged higher levels of vertical integration.

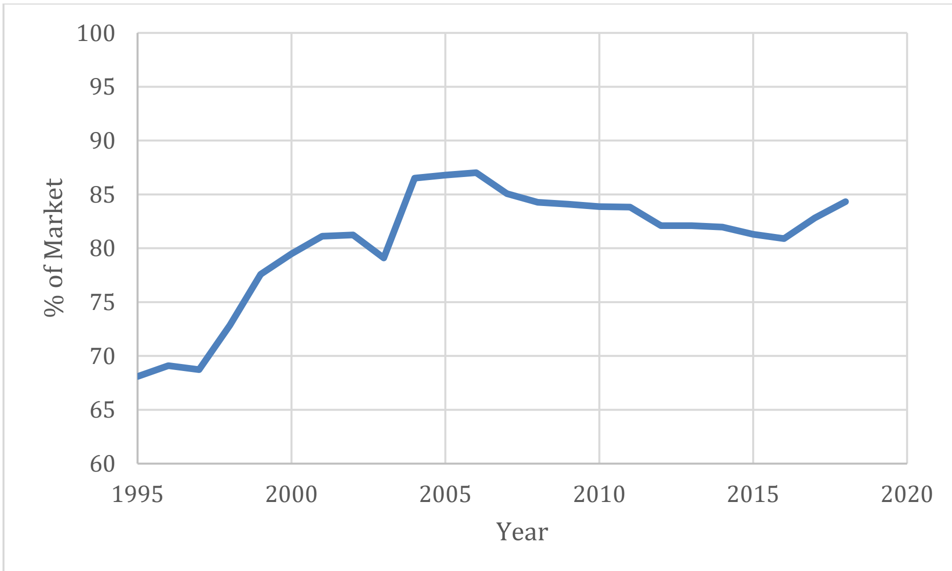

Figure 5.9: Market Concentration of Refinery Industry, Percentage Controlled by 15 Largest Refiners

The CVIR model predicts that the importance of crude price as a percentage of refined product prices is positively correlated with vertical integration. This is consistent with neo-classical microeconomics, and TCE theory, principally saying as feedstock becomes more important, disruptions in supply become more costly, which downstream refiners will increasingly want to mitigate, possibly through vertical integration. The model demonstrated that absolute crude pricing was negatively correlated with vertical integration.

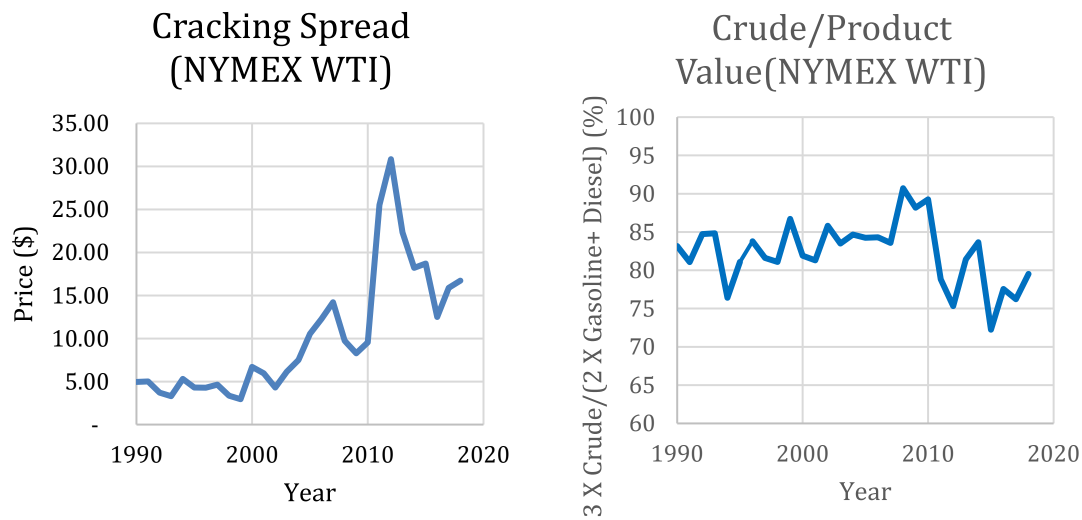

Figure 5.10: NYMEX Refinery Pricing Spreads (WTI)[96]

Interestingly, the size of the oilfield service industry in comparison to the petroleum operating industry[97] is positively correlated with vertical integration. This is in contrast to expectations since expanded oilfield services should allow for smaller companies to also obtain technologies and services that would be otherwise only available to larger companies, increasing small company competitiveness.

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[96] Both chart values are calculated by the same information. The crack spread is the common form used by the petroleum industry. The "cracking spread" is obtained from the formula:

$$Crack\ Spread = {}^{1}/_{3}\ (2\ x\ Gasoline\ Price + Diesel\ Price - 3\ x\ Crude\ Price)$$

The crude/product ratio is calculated by:

$$C\ /\ P = (3\ x\ Crude\ Price)\ /\ (2\ x\ Gasoline\ Price + Diesel\ Price)$$

The crude/product variable is used in this research because it removes an inflationary bias.

[97] These were compared by market capitalization on a global scale.

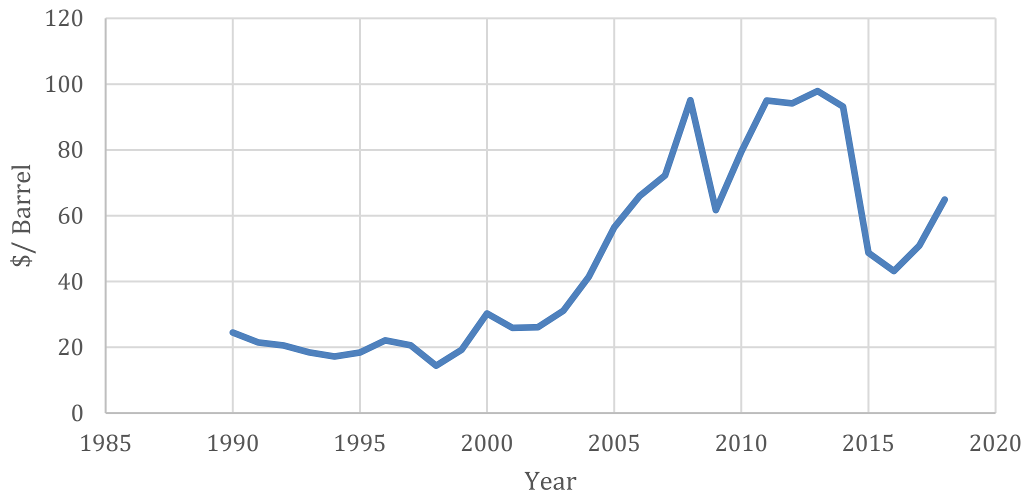

Figure 5.11: WTI Annual Average Price (NYMEX, Cushing)

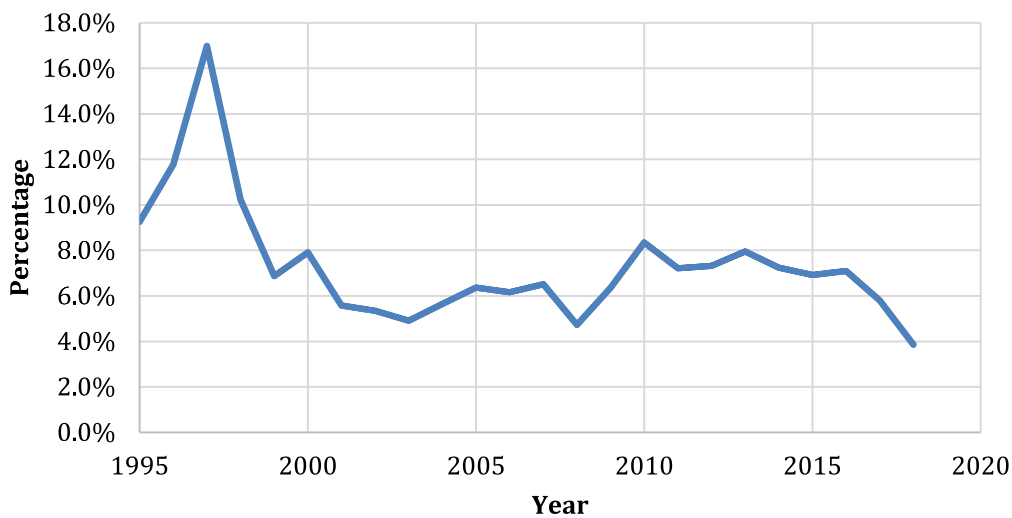

Figure 5.12: Oilfield Service Company / Oil Operations Company Market Capitalization [98]

[98] Bloomberg Professional Services. Data included market cap of global operations for oilfield service and operating companies.

Macroeconomics Factors

Treasury rates were negatively correlated with forward vertical integration. As interest rates increase, upstream producers are possibly less inclined to invest in forward integration. Figure 5.13 shows that interest rates generally declined over the sample period.

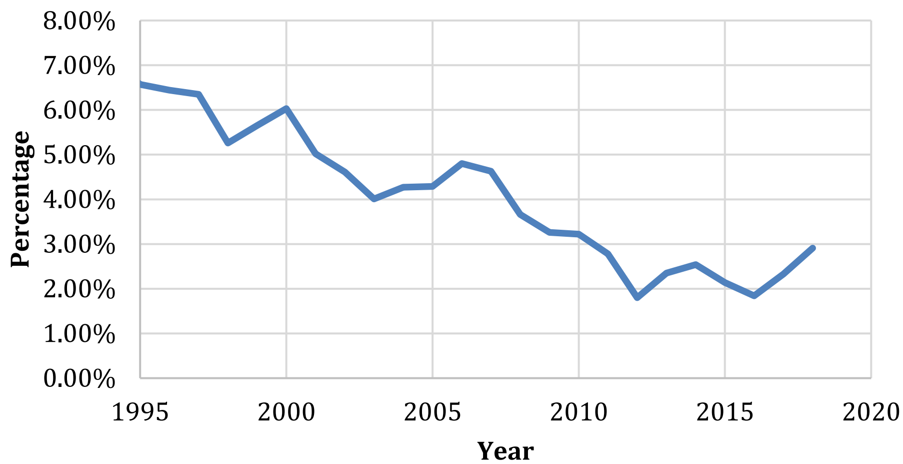

Figure 5.13: Annual Average 10-Year Treasury Rate [99]

GDP growth was also negatively correlated with vertical integration, as predicted by neo-classical microeconomic theory. As the economy improves, risks are reduced, decreasing the need for risk reduction by actions, such as vertical integration. Figure 5.14 shows a small decline in annual growth rate over the sample period. This combined with a negative

[99] Bloomberg Professional Services.

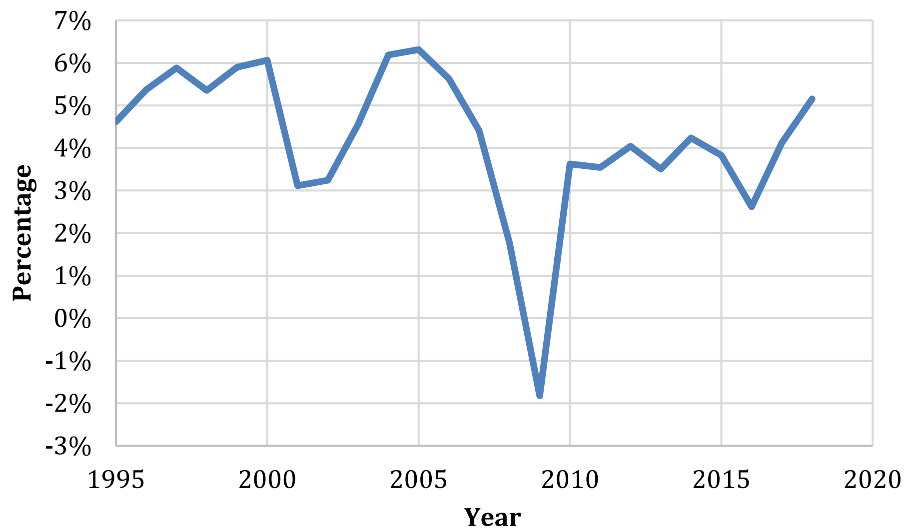

Figure 5.14: U.S. Annual GDP Growth Rate[100]

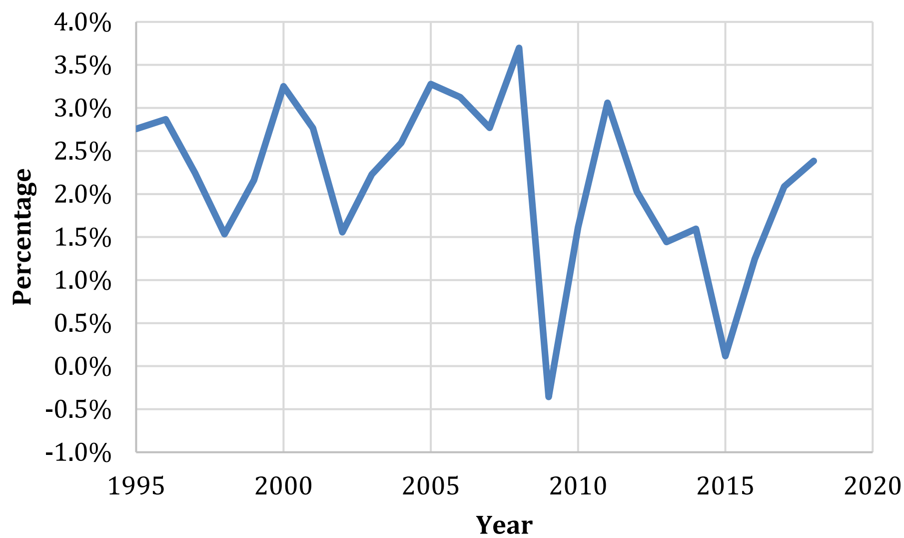

Figure 5.15: Annual C.P.I. Inflation [101]

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[100] U.S. Bureau of Economic Analysis.

[101] U.S. Bureau of Labor Statistics.

coefficient has an increased firms' motivation to vertically integrate. Inflation is positively correlated so as inflation increases, uncertainty and risk rise, increasing the motivation to vertically integrate. Figure 5.15 shows the inflation rate over the sample period has decreased, so decreasing the motivation to vertically integrate.

5.5 Backward Integration Index (RVIC)

RVIC is similar to CVIR but attempts to measure the tendency for backward integration by refiners. RVIC is calculated by dividing the maximum amount of crude oil that could theoretically be produced and refined in-house, industrywide, with the total U.S. industry refinery capacity. As described earlier, the formula is:

$$RVIC = \frac{\sum RC_{it} + \sum CP_{jt}}{Total\ Refinery\ Capacity}$$

RC: *Refinery capacity.*

CP: *Crude production.*

i: *Firms where refinery capacity is less than crude production*

j: *Firms where refinery capacity is greater than crude production*

t: *Year*

Similar to CVIR, the RVIC model demonstrates a number of the expected determinants for vertical integration to be correlated with the dependent variable. The full STATA results for Trial 5 can be found in Appendix I.

Table 5.6: RVIC Model Trials

Dependent Variable: RVIC Master Data.xlsx

Green cells indicate significant effect in that trial.

t or z test value is in parenthesis.

	Trial	1	2	3	4	5
	Best Estimator	FE**	FE**	FE**	RE***	RE***
	Observations	3,018	1,444	1,444	1,444	1,444
	R-sq	0.7293 overall	0.7759 overall	0.0087 overall	0.9811 overall	0.9870 overall
	Prob > 0 or Prob> chi2	0.0000	0.0000	0.0000	0.0000	0.0000
	Constant	39.781 (467.93)	114.756 (19.37)	93.881 (31.05)	32.081 (18.51)	3.725 (1.22)
Upstream Introduction of Tight Oil Technology	**ln US Horizontal Production Percentage (1 Year Lead)**	-5.741 (-134.81)	-5.031 (-47.84)	1.717 (5.06)	-2.418 (-40.4)	-1.197 (-18.61)
Downstream Technology	Refinery Complexity		-0.049 (-1.03)	0.007 (0.56)	0.001 (0.42)	0.000 (0.20)
	Refinery Capacity		-0.003 (-4.59)	-0.001 (-0.64)	0.000 (-0.23)	0.000 (0.29)
	Refinery Energy Efficiency		-0.052 (-13.07)	0.008 (2.58)	0.003 (1.51)	0.014 (11.00)
Firm Demographics	Size			0.000 (0.36)	0.000 (0.16)	0.000 (-0.47)
	Age			-1.388 (-25.11)	0.001 (1.88)	0.001 (2.74)
Market Factors	**Refinery Concentration**				-0.462 (-26.65)	-0.449 (-44.13)
	Production Concentration				0.475 (24.38)	0.627 (25.26)
	WTI Price				-0.059 (-48.16)	-0.033 (-22.96)
	Crude Price / Product Price				0.187 (43.02)	0.137 (54.25)
	Oilfield Service Capitalization				0.157 (12.15)	0.109 (6.41)
Macroeconomic Factors	**Treasury Rate**					1.253 (29.85)
	GDP Growth					-0.180 (-14.51)
	Inflation					0.108 (6.74)

* Random Effects GLS regression with cluster robust standard error Hausman Test >.05

** Fixed Effects estimator with cluster robust standard error Hausman Test <.05

*** BP Test recommends OLS estimator. Stata converts OLS to RE GLS regression

Grey cells are industry or national level variables.

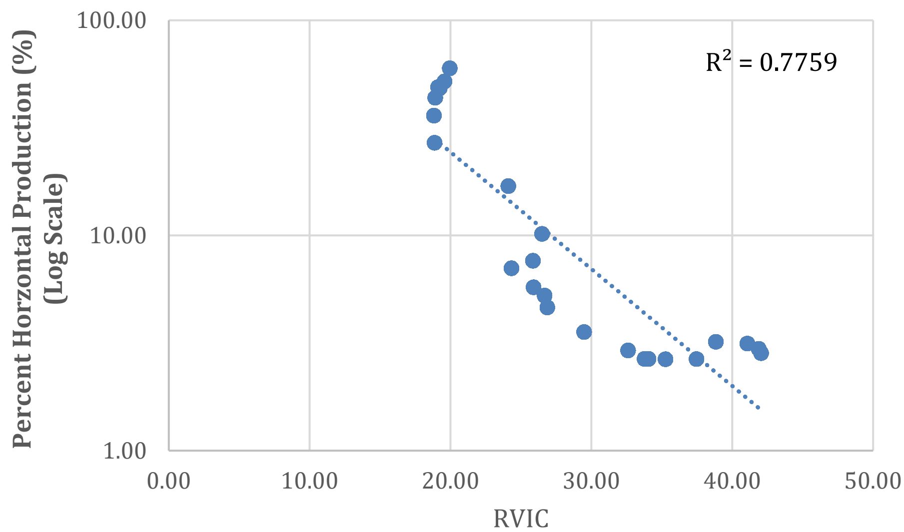

Figure 5.16: Natural Log of U.S. Horizontal Crude Production Percentage vs. Backward Integration Index (RVIC) (1-Year Lead)[102]

Introduction of Tight-Oil Technology

This model exhibits a negative correlation between RVIC and U.S. crude volume percentages from horizontal wells, as shown in Table 5.6.[103] Figure 5.16 shows this negative correlation in a simple two variable scatter diagram between RVIC and U.S. horizontal crude production volume percentage, when no other covariates are considered.

As other covariates are added to the model, upstream tight-oil technology remains negatively correlated to RVIC supporting PRT predictions that increasing upstream

[102] The model also showed negative correlations with same year and two-year lead data. Data utilizing one-year lead had the highest correlation with RVIC.

[103] Individual company horizontal crude production percentages were not statistically significant to RVIC. See Appendix H.

technology intensity is a causation of vertical disintegration. This result is consistent in all earlier models in this research.

Downstream Technology

Similarly to the CVIR model, refinery energy efficiency was positively correlated with RVIC, in agreement with neoclassical microeconomic theory, TCE, and PRT. Refinery capacity and complexity were not statistically significant.

Firm Demographics

Age has a small but statistically significant positive correlation with vertical integration as measured by RVIC. It is unlikely that this drove vertical integration decision making directly among firm management. Firm size is found to be insignificant in this model.

Market Factors

Refinery industry concentration is negatively correlated with RVIC while crude production concentration is positively correlated. This supports both neo-classical microeconomics, TCE, and PRT theories in regards to backward integration, where higher crude production concentration increases refiner risk and motivates them to backward integrate to ensure supply. Higher refinery concentration in relation to crude production would tend to reduce crude supply risk and reduce the need to backward integrate.

Consistent with the CVIR results, crude oil importance, as compared to final product price, is positively correlated with RVIC in support of neo-classical microeconomic theory.

Absolute crude price was negatively correlated with RVIC.

The importance of the oilfield service industry is positively correlated with RVIC, similar to CVIR, contrary to expectations.

Macroeconomics Factors

The macroeconomic covariates affect RVIC, as forecast by neo-classical microeconomics. Treasury rates and inflation are positively correlated with vertical integration, as measured by RVIC. Rising uncertainty, such as increasing interest rates and inflation, motivates companies to vertically integrate to reduce risk. GDP Growth is negatively correlated indicating that companies are less inclined to reduce risk by vertically integrating in a rising economy.

CHAPTER 6

CONCLUSIONS AND IMPLICATIONS

This research has gathered petroleum industry data of various factors that have been identified in earlier research as significant in determining an industry's tendency to vertically integrate its organizational structure. The findings are consistent with earlier research which concluded that there are a number of competing factors that firms' managers must weigh in their decisions to integrate or disintegrate their firms' vertical structures. These competing factors are possibly the reason that there are also competing, or perhaps complimentary, economic theories. Most likely there will never be one theory that can easily encompass such a complicated decision. Managers must consider market power, risk and uncertainty, transactions costs, optimum business investments, and capital costs. Earlier decisions may also need modification or change in the future as conditions evolve, as the petroleum companies did in the face of changes in the political, market, and technological environments.

Table 6.1 provides a summary of the five models, including the regression correlation values and the direction of influence to vertical integration. The orange down arrows indicate influences toward disintegration, and the blue up arrows are influences toward increased integration.

Table 6.1: Summary Results

Category	General Trend During Period	Fim Level Dependent Variables						U.S. Industry Level Dependent Variables			
		Self Sufficiency		Balance		Probit		Forward Integration		Backward Integration	
		Coeff.	Effect	Coeff.	Effect	Coeff.	Effect	Coeff.	Effect	Coeff.	Effect
Tight Oil Technology	↑	-1.16	↓	-1.47	↓	-1.02	↓	-1.93	↓	-1.20	↓
Down Stream Technology											
Refinery Complexity	↑	-0.80	↓	-0.71	↓						
Refinery Capacity	↑	-0.14	↓	-0.12	↓	-0.02	↓				
Refinery Energy Efficiency	↑					-0.04	↓	0.02	↑	0.01	↑
Firm Demographics											
Size	↑	0.10	↑	0.09	↑	0.01	↑				
Age	↑	0.16	↑	0.17	↑					0.00	↑
Market Factors											
Refinery Concentration	↑			-0.68	↑			0.06	↑	-0.45	↓
Production Concentration	↓					-0.44	↑	1.45	↓	0.63	↓
Crude Oil Pricing	↑							-0.05	↓	-0.03	↓
Crude Oil / Product Price	↓							0.10	↓	0.14	↓
Oilfield Services	↓					-0.45	↑	0.67	↓	0.11	↓
Macroeconomics Factors											
Treasury Rate	↓					1.47	↓	-0.57	↑	1.25	↓
GDP Growth	↓							-0.35	↑	-0.18	↑
Inflation	↓					-0.61	↑	0.20	↓	0.11	↓

To assist in the reading of Table 6.1, the arrows in the column marked "General Trend During Period" gives the general trend direction of each of the independent variables over the sample period, 1995-2018. For example, tight-oil technology went up during the period, resulting in an up arrow, while treasury interest rates declined, giving a down arrow. The values in the blue and orange boxes are the significant regression coefficients, with positive coefficients in blue and negative in orange. The orange and blue arrows are the resulting effects that the various models predicted that the independent variable influenced vertical integration as measured by the models. A negative trend in an independent variable multiplied by a negative regression coefficient results in a positive influence on vertical integration.

6.1 Introduction of Tight-Oil Technologies

All five models consistently supported the hypothesis that the introduction of tight-oil technologies had a significant influence on company and industry vertical disintegration, as predicted by PRT theory. Taking into account the large increase in crude oil volume from horizontal U.S. wells, the introduction of tight-oil technology into upstream crude production has been a major factor in the general disintegration trend experienced by U.S. petroleum industry's organizational structure.

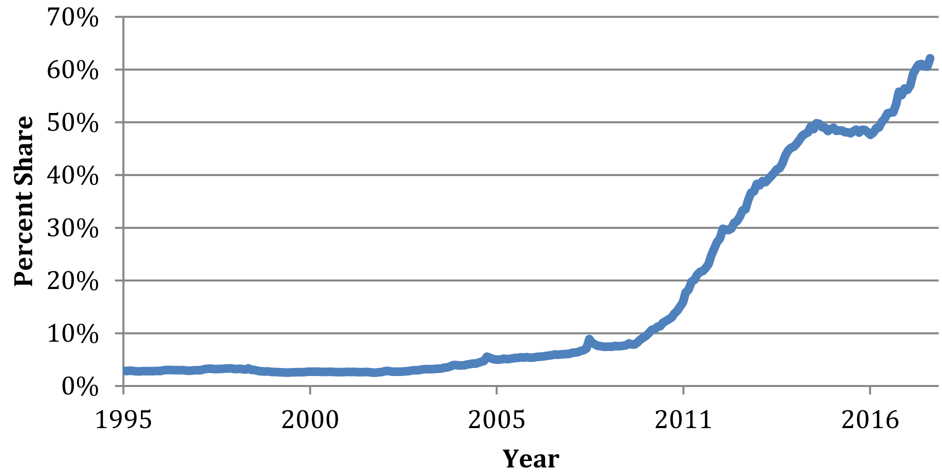

Figure 6.1: Percent of U.S. Crude Oil Production Utilizing Horizontal Production Technology[104]

The SIVI, BIVI, and VIL model's dependent variables were firm specific, and all demonstrated a negative correlation with individual companies' horizontal crude production percentage. None of them demonstrated a statistically significant correlation with overall U.S. horizontal crude production percentage. The CVIR and RVIC model's dependent variables were industry wide and both demonstrated a negative correlation with U.S. horizontal crude production percentage and no statistically significant correlation with individual companies' horizontal crude production percentage. Most likely, this was due to the noise created when comparing data of different granularities.

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104 Enverus – Drillinginfo.

6.2 Downstream Technologies

Neo-classical microeconomics, PRT, and TCE all predict that downstream technological intensity would encourage downstream refiners to backward integrate, meaning a positive correlation. The results from this research demonstrated a more complex outcome. The SIVI, BIVI, and VIL models show a negative correlation between refinery complexity and capacity and vertical integration. Table 6.2 possibly demonstrates why reality did not comply with theory in this case. The table shows that, in 1995, the largest refinery companies were all integrated companies. These companies also owned the most complex refineries by the NCI measurement. By 2018, this had changed dramatically where the list of largest capacity refiners was now dominated by non-integrated companies, with these same refiners also generally owning the most complex refineries.

This transition would indicate a negative correlation between refinery capacity and complexity and vertical integration. This trend may be influenced by the reduction in the total number of refineries in the U.S. while overall capacity was increasing.[105] Generally, many smaller refiners were closing while large complex refineries were being expanded during the sample period. Though data is not available to confirm this, the result may have been that though actual total downstream assets had decreased, they were significantly more productive. This may also be an example of the simultaneity problem discussed in

[105] Many small uneconomical refineries were being closed, while larger refineries were being expanded during the sample period.

Chapter 2. The strong trend for the ownership of the largest refiners from integrated to non-integrated companies may have biased the results in the negative direction.

Table 6.2: Largest U.S. Refining Companies

1995			2018		
	Capacity (MBOE/D)	SIVI (%)		Capacity (MBOE/D)	SIVI (%)
Chevron	1060.9	63.4	Marathon Petroleum	2881.5	0.0
Amoco	1008.7	71.2	Valero	2177.0	0.0
Exxon	992.0	96.2	Phillips	1826.2	0.0
Mobil	970.6	54.6	ExxonMobil	1706.0	58.3
Shell	910.2	74.2	Shell	1034.0	37.1
Citgo*	749.7	*	Chevron	906.0	87.3
BP	693.5	84.0	PBF Holdings	878.5	0.0
Sunoco/Sun	692.0	0.0	Citgo*	763.8	*
Texaco	687.5	94.6	BP	719.9	107.3
Marathon	531.0	45.4	Motiva*	600.0	*
Koch	525.0	0.2	Koch	582.4	0.0
Tosco	476.5	0.0	HollyFrontier	441.0	0.0

* Foreign Owned Company with Crude Production Capacity Outside U.S.

The RVIC and CVIR models supported the hypothesis that there is a small but consistent positive effect of improving refinery energy efficiency and increased vertical integration. They both showed no correlation with refinery capacity or complexity, again possibly due to data granularity. Energy usage is a major cost function in U.S. refining, in addition to labor and crude oil costs. U.S. refining has seen a steady increase in technological advancement, including both in process technologies and in controls and automation. These technological innovations should lead to the increased energy efficiency that the industry has experienced. Energy efficiency data was only pooled across all refineries for each annual period. More granulated information showing energy efficiency at the individual refinery level may provide more conclusive results in the other models.

6.3 Firm Demographics

It would be expected that older and larger companies would tend to be more vertically integrated. The SIVI, BIVI, and VIL models show a small, but statistically significant, correlation between size, age, and vertical integration as measured by those models. These factors are most likely not influential in integration decisions by companies.

6.4 Market Factors

6.4.1 Market Concentration

Neo-classical microeconomic theory predicts that increased horizontal integration leads to increased uncertainty among agents, which leads to increased vertical integration. The models did not provide consistent results on this issue. The VIL models resulted in a negative correlation between crude production market concentration and vertical integration. Since crude oil producer market concentration steadily decreased over the sample period (Figure 5.8), this would indicate a trend supporting more vertical integration. Both the CVIR and RVIC model demonstrate a positive correlation between crude production concentration and vertical integration.

Refining concentrated during the late 1990's and early 2000's (Figure 5.9), when a number of the majors merged with each other. After that period, the market concentration was fairly steady. The BIVI and RVIC results demonstrate a negative correlation between refinery market concentration and vertical integration. The CVIR model demonstrated a positive correlation, providing conflicting results.

Data for market factors granularity was at a national level, while actual firm managerial decisions in regards to market concentration commonly are related to local situations and vary even within companies with wide geographic operations. A finer granularity in the data would possibly have better results in the SIVI, BIVI, and VIL models.

6.4.2 Pricing

The CVIR and RVIC models were the only two containing results of statistically significant effects from pricing. As predicted by neo-classical theory, the crude/product ratio had a positive correlation with vertical integration. Since the crude/product ratio stayed in a relatively small band during the sample period, in actuality, it most likely had only a small effect. Both models also indicated a small negative correlation with absolute crude pricing. Since absolute crude price has generally increased since the 1990's (See Figure 5.11), this would have contributed to vertical disintegration.[106]

6.4.3 Oilfield Service Companies

The CVIR and RVIC models resulted in positive correlations between the ratio of market

[106] This metric used nominal pricing. Real pricing, using CPI inflation, would have resulted in a flatter curve. CPI data excludes energy costs.

caps for oilfield service companies and operation companies. The VIL model resulted in a negative correlation. The increasing penetration by oilfield service companies into the operations of production and refining companies would be expected to allow access to technology and services to smaller companies that would otherwise only be available to larger, more technologically sophisticated, companies. This would allow easier access into the market, reducing vertical integration. Only the VIL model was consistent with this logic.

The market cap ratio between oilfield service companies and operating companies fell dramatically from a peak in the 1990's and has remained in a fairly small range since. See Figure 5.12. Because of this, it is likely that oilfield service company market penetration did not greatly influence petroleum company vertical integration during most of the sample period.

6.5 Macroeconomic Factors

6.5.1 Interest Rates

Treasury rate information resulted in significant results in the industry level CVIR and RVIC models. More granular information for the available weighted cost of capital (WACC) for individual companies in the sample would most likely have resulted in more significant results in the SIVI and BIVI models. The CVIR model indicated a negative correlation, while the RVIC model indicated a positive correlation between treasury rates and vertical integration as measured by those models. The VIL model indicated a positive correlation.

TCE predicts a positive correlation as interest rates increase the costs of market transactions. Figure 5.13 shows a general rate decline from above 6% to between 2-3% during the sample period. The regression coefficients β in the model indicate that rates had only a small effect on petroleum company vertical integration.

6.5.2 Economic Growth

Both the CVIC and RVIC models indicate a positive correlation between GDP growth rate and vertical integration, as predicted by neo-classical theory. High growth would reduce uncertainty and the need to mitigate risk, potentially reducing the need to vertically integrate. Since growth rate mostly stayed within a steady band in the U.S. (Figure 5.14), the factor most likely had little actual effect on the change in the petroleum industry's industrial organization.

As for other covariates, more granular data on growth for individual companies, using revenue or gross margin changes, may have resulted in better results for the individual firm dependent variable models. This type of information was not available for all companies in the sample.

6.5.3 Inflation

The CVIR and RVIC models resulted in a positive correlation between inflation and vertical integration as measured in those two models, consistent with neo-classical theory. Higher inflation induces more uncertainty, possibly causing companies to vertically integrate to reduce risk.

The VIL model indicated a negative correlation between inflation and vertical integration, in contrast to theory. This result may be influenced by the lack of specific inflation pressure data at the individual firm level. Inflation varied in a narrow band during the sample period (Figure 5.15) so it most likely had little effect on vertical integration.

Due to the excellent available data on horizontal crude production, it is likely that the results of its relation to vertical integration is of high quality, supporting the primary goal of this research to determine this relationship. The quality of the available data for the other covariates is more mixed, with resulting mixed results.

6.6 Discussion

The Nature of Technological Innovation and Its Economic Effects on Industrial Organization

Technology and innovation are factors that can affect an organization at varying rates and in different manners, depending on the nature of the technology. This research observed at least two different technologies being applied to the petroleum supply chain. The first being the well-defined innovation of tight-oil technology. This had the general effects of increasing a commodity supply in an upstream stage of the supply chain, increasing individual well costs and, at the same time, reducing the risk of unsuccessful wells. This innovation was strictly limited to an upstream stage with no real technical effects in other parts of the supply chain. All five models' measurement methods show a general trend toward vertical disintegration of the U.S. petroleum's organizational structure over the sample period of 1995 – 2018 as tight-oil technology was being introduced. See Figures 4.1, 4.4, 4.5, and 5.8. The research results conclusively show the technology's introduction is a major influence in the disintegration trend of U.S. petroleum companies' vertical organization. This is consistent with the Property Rights Theory (PRT), which says that this innovation would increase the motivation for upstream suppliers to retain their residual rights over their upstream assets and provide increased motivation to vertical disintegration.

Transportation cost data was not available, but most likely increased due to the disruption in the transportation system as new supported production fields appeared. This would have increased transaction costs between producers and refiners, which TCE predicts would be a factor that would have encouraged higher vertical integration.

The introduction of new technologies in the downstream refining stage was also measured. U.S. refining had experienced a general modernization during the sample period, where uneconomic refineries were closed and others were expanded and modernized. The modernizations were a collection of different technologies, including new chemical process technologies, advanced automation, and computer technologies, among others. Refineries had an aggregate trend of increasing energy efficiency of their process, while also becoming generally larger and more complex. In aggregate, these changes decreased processing costs while increasing throughput. The improvement in energy efficiency was correlated with increases in the petroleum industry's vertical integration, consistent with TCE (as the additional investments would increase asset specificity and motivate refiners to backward integrate), and neo-classical theory. Contrarily, increases in refinery size and complexity were correlated with organizational disintegration, which did not support TCE. As discussed earlier, these results may be biased due to granularity issues and simultaneous effects. The observation in regards to technological innovation is that the nature of innovations can affect the supply chain in different manners. These two different suites of technologies were introduced in approximately the same time frames but were different in nature and in different stages of the supply chain, consequently causing different effects on the U.S. petroleum industry's organizational structure.

How This Research Supports the Literature

This research exploited the unexpected and measurable introduction of a new technology into the upstream production stage of a mature industry. It correlated whether this new technology regime might be playing a role in reducing the industry's high degree of vertical integration. This empirical case is an addition to the academic literature on the relationship between technological innovation and industrial organization. Earlier studies typically used proxies in measuring innovation, while this study used a measurable metric of the actual introduction of innovative technologies into a mature industry's supply chain. Tight-oil technology was largely developed by small companies and was largely an unexpected development in the industry, minimizing any biases caused by the simultaneous effects between innovation and industrial organization.

Suggested Future Research

Better metrics used to measure refinery technological innovations are available, but not public, beyond that used in this research. More granular data, including individual refinery energy costs, labor costs, and operating costs, if they do become available, could be used to better identify the industrial organizational effects of the introduction of Digital Oil Oilfield technology and advanced refinery processes. This research would also then be able to directly measure the deployment of the technologies into the supply chain. Other data, not publicly available, would include historical pipeline and other shipping tariff costs which could then be related to transaction costs and industrial organization.

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BIOGRAPHICAL SKETCH

William Dalton Jackson was born in Fort Campbell, Kentucky into a military family. He attended high school in Mannheim, West Germany. He received a Bachelor of Science in Mechanical Engineering, Energy Sequence from the University of Notre Dame in 1981. Later, he received a Master of Business Administration from Rutgers University-Camden in 1991. After his undergraduate studies, he graduated from the U.S. Navy's Nuclear Power Program and served as a junior officer aboard a nuclear submarine. Upon leaving the Navy, he worked in engineering and management positions in the energy industry for companies such as Mobil Oil, Air Products, and Chemicals and CB&I. He currently is a senior consultant at Baker & O'Brien Inc. In 2013, he entered the Doctor of Philosophy in Economics program at The University of Texas at Dallas.

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Following graduation with a Bachelor of Science degree in Mechanical Engineering in 1981, Bill served in the United States (U.S.) Navy, gaining the rank of Lieutenant. He completed the Navy's Nuclear Power Program and then served aboard the nuclear submarine U.S.S. Plunger (SSN 595), home ported in San Diego, California. Bill earned his "Dolphins" as a qualified submariner and held a Top Secret SCI security clearance. He served as the ship's Electrical Officer, First Lieutenant, and Sonar Officer.

In 1985, Bill joined BOC/Airco as a Plant Engineer at their North American headquarters in Murray Hill, New Jersey, in their specialty gases division. In addition, Bill served as the Maintenance Engineer at BOC's Riverton, New Jersey, facility.

Bill joined Sartomer Company, Inc. as a Project Engineer in 1988 in West Chester, Pennsylvania. During this time, he managed and executed a number of engineering and construction projects at this specialty chemicals manufacturer.

In 1989, Bill joined Mobil Oil Corporation (Mobil) and became a Project Engineer at their Paulsboro, New Jersey, refinery. Bill managed a wide variety of refinery projects for the processing units at that location. Upon completion of his M.B.A., he assumed the duties of Planning Engineer, responsible for long-range strategic planning coordination and analysis of the refinery's capital expenditures and capital appropriations.

In 1993, Bill transferred to Mobil's Chalmette, Louisiana, location as a Senior Project Engineer. He managed and executed a variety of refinery projects, including major unit upgrades and an H_2 pipeline project with Air Products. Bill also served as the area

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In 1996, Bill joined Air Products & Chemicals' (Air Products) Hydrocarbon Group as a Lead Project Engineer at their headquarters in Allentown, Pennsylvania. He managed and executed engineering, procurement, and construction (EPC) projects for the chemical, natural gas, and oil industry companies utilizing Air Products' hydrocarbon separation technologies.

In 2002, Bill joined CBI/Howe Baker (CBI) as a Project Manager at their offices in Dallas, Texas, and Tyler, Texas (Howe Baker). He managed engineering, fabrication, and construction projects of refinery processing units for major and independent petroleum companies.

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