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Strategic Investment Decisions in Crude Oil Production Capacity and the Impact on Future Supply Bottlenecks

Combining a Nash Investment Game and a Complementarity Model

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Abstract

This work investigates the incentives of the two most important crude oil suppliers, Saudi Arabia and Russia, to invest in additional production capacity in the current economic and political environment. Future demand for crude oil is highly uncertain for mainly two reasons: on the one hand, it depends acutely on the speed and sustainability of economic recovery after the current global economic crisis. On the other hand, a breakthrough in international negotiations to mitigate global warming and reduce greenhouse gas emissions could lead to a drastically reduced demand for fossil fuels. Hence, the profitability of any investment in crude oil production capacity is contingent on these two aspects.

A general difficulty in investment analysis lies in the sequentiality of strategic non-cooperative behaviour: investment decisions today affect production decisions tomorrow. For the sake of tractability, any analysis of multi-level games must accept simplifications either in the complexity of the game structure or in the size of the problem investigated, such as reducing the number of agents included, functional form, or the model time horizon.

This work focuses on the strategic investment incentives under the current economic uncertainty; hence, it simplifies with regard to future strategic interaction for the sake of a detailed analysis of the global crude oil market. The core of this work is a market equilibrium model with both Cournot and perfectly competitive suppliers and endogenous investment. The model specifically accounts for the existence of arbitragers, liquid spot markets and price indices, which lead to price convergence across demand regions.

The model is numerically solved for four scenarios of demand development for the time period of 2012–2030, both with and without initial investment by Saudi Arabia and Russia respectively. The scenarios consist of the following: a quick global economic upturn (*Speedy Recovery*); the implementation of an international agreement to curb global warming and reduce greenhouse gas emissions (*Green Rebound*); a prolonged recession (*Long Slump*); and a combination of continued weak growth in OECD countries and a rapid recovery for the rest of the world (*Tiger & Dragon*). The discounted profits in each scenario of the suppliers under investigation are then used as the basis of a Nash investment game.

The (unique) Nash equilibrium of this game is the following: investment by Saudi Arabia, but none by Russia. This is in line with the investment schemes published by Saudi Aramco, the national oil company, as well as the low level of investment in Russia due to increased political risk in recent years. The results indicate that the low investment activity carries no great financial loss for the Russian state. It is worth pointing out that this Nash equilibrium is identical in all demand scenarios, even though the actual level of earned profits varies considerably between them.

In addition to the investment incentives, the simulation results allow a detailed analysis of the crude oil market over the next decades, considering aspects such as security of supply and remaining reserves. The crude oil price – in the scenario of a quick economic recovery – will be around 200 US $ per barrel in the year 2030, with a daily consumption in excess of 100 million barrels. In contrast, assuming a global agreement to curb greenhouse gas emissions only yields a crude oil price of approximately 105 US $ per barrel, and a global consumption of 80 million barrels per day. The importance of the Persian Gulf region as a key supplier will not diminish over the next decades.

The ratio of remaining global reserves to actual production in the year 2030 will be around 40 years, depending on the scenario. The remaining reserves, however, will be even more concentrated in the Middle East; Canada will be the only OECD country with substantial remaining reserves. In spite of the reserve growth assumed in the model, Russia will almost deplete its reserves in the next three decades. As a consequence of the increased concentration of crude oil reserves in only few regions, the risk of significant crude oil price spikes due to geopolitical issues may increase further.

The results of this work indicate that the strategies currently pursued by Saudi Arabia and Russia are valid from their respective strategic point of view: Saudi Arabia invests in additional production capacity to profit from the – in all likelihood – increasing crude oil demand in the coming years; Russia has a rather moderate interest in additional investment and, instead, seems to arm-twist existing crude oil production capacity into the realm of enterprises close to the Kremlin, in order to gain a higher share of the revenues from already developed fields.

Zusammenfassung

Diese Arbeit untersucht die ökonomischen Anreize der beiden bedeutendsten Erdölproduzenten, Saudi Arabien und Russland, unter den derzeitigen wirtschaftlichen und politischen Umständen in zusätzliche Förderkapazitäten zu investieren. Die Prognose der zukünftigen Rohölnachfrage ist aus zwei Gründen sehr schwierig: auf der einen Seite hängt die Nachfrageentwicklung von Geschwindigkeit und Nachhaltigkeit des wirtschaftlichen Aufschwungs nach der weltweiten Wirtschaftskrise ab. Auf der anderen Seite könnte ein Durchbruch in den internationalen Verhandlungen zur Reduktion von Treibhausgasemissionen die Nachfrage nach fossilen Energieträgern drastisch reduzieren. Die Profitabilität von Investitionen in zusätzliche Förderkapazitäten hängen also direkt von diesen beiden Entwicklungen ab.

Eine prinzipielle Problematik bei der Investitionsanalyse liegt in der Mehrstufigkeit von strategischem Verhalten: Investitionsentscheidungen heute beeinflussen Produktionsentscheidungen morgen. Im Allgemeinen müssen bei der Analyse von mehrstufigen Spielen entweder bei der mathematischen Komplexität des Ansatzes oder bei der Größe des Modells Abstriche gemacht werden, etwa bei der Zahl der Agenten, der funktionalen Form der Gleichungen oder dem Modellhorizont.

Diese Arbeit konzentriert sich auf die strategischen Investitionsanreize unter der derzeitigen Unsicherheit der Nachfrageentwicklung und vereinfacht daher in Bezug auf zukünftige strategische Entscheidungen zugunsten einer möglichst umfassenden Abbildung des international Rohölmarktes. Kern dieser Arbeit ist ein partielles Gleichgewichtsmodell mit Produzenten, die entweder Cournot-Marktmacht ausüben oder wettbewerblich agieren, sowie endogenen Investitionsentscheidungen. Das Modell berücksichtigt im Speziellen die Präsenz von Arbitrageuren und Preisindizes im Erdölmarkt und die damit einhergehende Konvergenz der Preise zwischen verschiedenen Regionen.

Das Gleichgewichtsmodell wird für vier Szenarien der Nachfrageentwicklung für den Zeitraum 2012–2030 numerisch gelöst, und zwar jeweils mit und ohne heutigen Investitionen von Saudi Arabien und Russland. Die Szenarien umfassen einen raschen Wirtschaftsaufschwung (*Speedy Recovery*); die Implementierung von internationalen Maßnahmen zur Reduktion von Treibhausgasemissionen (*Green Rebound*); eine lange Periode der Stagnation (*Long Slump*); und eine Kombination aus schwachem Wirtschaftswachstum in den OECD-Ländern und einem raschen Aufschwung im Rest der Welt (*Tiger & Dragon*). Die diskontierten Profite von Saudi Arabien und Russland dienen dann als Grundlage eines Nash-Investitionsspiels zwischen den beiden Produzenten.

Das (einzige) Nash-Gleichgewicht dieses Spiels im Hinblick auf Investitionen in zusätz-

liche Förderkapazitäten ist folgendes: Saudi Arabien investiert, aber Russland nicht. Dies deckt sich mit den Investitionsplänen von Saudi Aramco, dem nationalen Ölkonzern, wohingegen Investitionen in Russland aufgrund des politischen Risikos nur schleppend vorankommen. Das Ergebnis dieser Arbeit deutet darauf hin, daß die geringe Investitionstätigkeit in Russland zumindest keinen großen finanziellen Verlust für den russischen Staat darstellt. Es ist weiters interessant, daß dieses Nash-Gleichgewicht in allen Nachfrageszenarien gleich ist, obwohl das Niveau der lukrierten Profite zwischen den Szenarien beträchtlich variiert.

Die Simulationsergebnisse erlauben außerdem eine Analyse der Ölmarktentwicklung in den nächsten Jahrzehnten, im speziellen Versorgungssicherheit und verbleibenden Erdölreserven. Der Ölpreis wird im Szenario eines raschen Wirtschaftsaufschwunges im Jahr 2030 um die 200 US $ je Fass Rohöl liegen, bei einem täglichen Verbrauch von über 100 Millionen Fass; im Falle einer raschen Umsetzung wirkungsvoller Maßnahmen zur Reduktion von Treibhausgasemissionen und Abschwächung des Klimawandels wird der Ölpreis bis zum Jahr 2030 nur auf etwa 105 US $ je Fass steigen, bei einem Verbrauch von etwa 80 Millionen Fass täglich. Die Bedeutung des persischen Golfs als Erdöllieferant wird an Bedeutung noch weiter zunehmen.

Das Verhältnis von weltweit verbleibenden Reserven zu Produktion im Jahr 2030 liegt im Bereich um die 40 Jahre, je nach Szenario. Die Reserven sind aber noch stärker als heute im Mittleren Osten konzentriert; Kanada ist dann das einzige OECD-Land mit nennenswerten Erdölvorräten. Russland wird – trotz der angenommenen Reservenzuwächse über die nächsten beiden Jahrzehnte – bis zum Jahr 2030 seine Reserven weitestgehend erschöpfen. Als Folge der noch stärkeren Konzentration von Erdölvorräten in wenigen Regionen steigt das Risiko, daß geopolitische Krisen zu starken Schwankungen des Erdölpreises führen.

Die Ergebnisse dieser Arbeit deuten darauf hin, daß die von Saudi Arabien und Russland verfolgten Strategien aus strategischem Blickwinkel durchaus Sinn machen: Saudi Arabien investiert, um von der mittelfristig wahrscheinlich steigenden Erdölnachfrage zu profitieren. Russland hat weniger Interesse an zusätzlichen Investitionen und versucht stattdessen, bestehende Kapazitäten in den Einflußbereich staatsnaher Unternehmen zu manövrieren, um einen höheren Anteil an den daraus zu erzielenden Gewinnen zu lukrieren.

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Contents

1. Introduction

Ever since the first oil crisis and the emergence of the Organisation of Petroleum Exporting Countries (OPEC) as a key player, economists have tried to grasp and categorise the crude oil market. Many theories have been proposed, discussed, dismissed and rehashed to explain the fundamentals of the oil price level and the behaviour of market participants.

Crude oil accounted for approximately 35 % of global primary energy demand in 2008 (BP, 2009), making it the most important fuel in the global energy mix. The influence of crude oil is even more pronounced than its share in the global energy mix suggests: the price of the second most important fuel, natural gas accounting for 25 % of primary energy demand (ibid.), is in effect linked to the crude oil price in many countries (Brown and Yücel, 2008). Transport is the single most important final demand sector, and its energy consumption is covered to a large extent by oil products. As this sector is also the one area of energy demand expected to see the biggest increase over the next decades, the dependence of the global economy on crude oil is unlikely to change anytime soon (IEA, 2009a).

1.1. Fossil resources & climate change

For many years, exhaustibility of crude oil reserves dominated the scientific debate regarding the long-term prospects of this industry. The scientific and political upheaval about the effects of climate change and global warming changed that; concerns about emissions of CO_2 and other greenhouse gases (GHG) from burning fossil fuels relegated the fear of reserve depletion to second place. Consequently, no long-term analysis of any fossil resource can be undertaken without first taking a glance at the debate on climate change.

For any economist, the politics on how to combat climate change is a bonanza: *"it is a prisoner's dilemma, a free-rider problem and the tragedy of the commons all rolled into one"* (The Economist, 2009a, p. 4). The most important player in the field between policy makers and the scientific community is the Intergovernmental Panel on Climate Change (IPCC). It was established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO). Its publications are closest to what can be described as the scientific consensus on climate change. In its latest publication, it recommends a long-term stabilisation of GHG gases in the atmosphere of 450 parts per million (ppm) CO_2-equivalents (CO_2-eq)[1] to keep the probability of drastic long-term damage sufficiently low (IPCC, 2007).

A brief history of the political narrative to curb emissions: the United Nations Framework Convention on Climate Change (UNFCCC) went into effect on March 21, 1994. The convention aims for a "stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system"(UNFCCC, 1992, Article 2). Its main decision-making body is the Conference of the Parties (COP). The first international treaty implementing legally binding GHG emissions reduction targets was signed in Kyoto, Japan, on December 11, 1997; hence it is referred to as the *Kyoto Protocol*. It entered into force on February 16, 2005.

Within the treaty, developed countries (referred to as Annex 1-countries)[2] are obliged to reduce their GHG emissions by a certain percentage relative to the emission levels in 1990 until 2012; other countries are, through the Clean Development Mechanism (CDM), given the opportunity to trade emission-reducing investments with Annex 1-countries that fail to achieve sufficient reductions at home.

Even if the Kyoto Protocol was an important step to curbing GHG emissions, the EU Emission Trading System (ETS) remains the only comprehensive framework to curb emissions in a supra-national framework using a joint tool and a common price for carbon emissions to date. In the United States of America (USA), the political rhetoric has certainly intensified since the election of Barack Obama as President of the United States. The passage of the bill *H.R. 2454: American Clean Energy and Security Act of 2009* by the US House of Representatives (referred to as *"Waxman-Markey-Bill"* after the main sponsors) raised hopes of a serious commitment to tackle emissions in North America. This momentum was subsequently lost in partisan politics in Washington, D.C; however, the sinking of the *Deepwater Horizon* oil rig in the Gulf of Mexico in the spring of 2010 has brought energy and the environment back on the US domestic agenda. The ensuing massive oil spill is believed to be the greatest man-made environmental catastrophe on US territory. A moratorium on offshore drilling was subsequently revoked, but more regulation on fossil resource extraction is to be expected.

The United Nations Climate Change Conference taking place in Copenhagen in December 2009 (commonly known as the "Copenhagen Summit") aimed to initiate a political follow-up agreement to the Kyoto Protocol. The conference included the 15^{th} Conference of the Parties (COP 15) to the UNFCCC. While there was no shortage of long-term commitments by politicians attending the conference, any legally binding short-term reductions were not included in the final document.

[1] Emissions of different GHG are converted to CO_2-equivalents using the measure of *radiative forcing*, introduced by the IPCC.

[2] The President of the USA signed the Kyoto Protocol but Congress refused its ratification.

1.2. An outlook on world energy

The International Energy Agency (IEA) published its “World Energy Outlook 2009” (WEO 2009) shortly before the COP 15.[3](IEA, 2009a) In this document, the IEA pointed out both the opportunity offered and the threat posed to future energy supplies by the current economic crisis. On a positive note, the downturn caused – for the first time in decades – a reduction of GHG emissions due to lower consumption.

Several effects have contributed to a serious reduction in energy investments in the immediate wake of the crisis. These are tighter credit conditions and a more difficult funding situation for energy companies, lower profitability due to the fuel price collapse in the second half of the year 2008, and less immediate need for additional capacity due to lower demand. It must be noted that a large proportion of national economic stimuli to ward off the recession were dedicated to measures which improve energy efficiency and support investment in renewable energy sources. Consequently, while investment in renewable and clean energy projects did fall in recent months, the drop was far less pronounced due to these stimuli. Consequently, the crisis offers a *window of opportunity*, where the global energy mix can be tilted to a more sustainable footing at relatively low extra cost. As energy investments are generally long-term, a fall in (non-renewable energy) investments reduces the lock-in effect in carbon-intensive technologies in the coming decades.

On the other hand, the drop in investment poses the threat of a medium-term supply bottleneck, if the global economy – and hence energy demand – recovers quickly. This problem is particularly acute for the crude oil market, where many projects have been shelved in recent months (Wurzel et al., 2009). If a quick rebound indeed occurs, the crude oil price spike in 2008 could look small in comparison. In turn, a rapid price increase could dampen the economic recovery, counteracting the national economic stimuli and leading to a prolonged recession.

Two scenarios are compared in the WEO 2009: in the *Reference Scenario*, no further actions to mitigate climate change are taken by the international polity other than measures already implemented or legally pledged. It serves as a baseline for future energy demand in the absence of serious political commitments to curb global warming. Primary energy demand increases by 40 % until 2030 compared to 2008; demand for crude oil rises by around 25 %. The increase in crude oil demand is mostly driven by the transport sector. As natural gas is the most environmentally friendly (or rather least harmful) fossil fuel, demand for it increases by more than 40 %; about half of this increase is attributed to new power plants. Energy-related GHG emissions rise to about 55 Gt CO_2-eq, which implies a concentration of GHG in the atmosphere of around 1,000 ppm by the end of the century. According to the IPCC (2007), this puts

[3]The IEA specifically intended to provide international negotiators with the hard facts needed to reach a global agreement on curbing climate change, as pointed out by Nobuo Tanaka, Executive Director of the IEA, in the foreword to the document. Alas, the international community did not reach such a global agreement, as we now know.

us in the range of a temperature increase of 6 °C.

In addition to the Reference Scenario, a *450 Scenario* is presented in the WEO 2009. By assumption, sufficient measures are taken by the international community and national governments to ensure that the concentration of GHG in the atmosphere stabilises at 450 ppm CO_2-eq, implying a temperature rise of approximately 2 °C. Demand for all primary energy sources apart from coal would still increase considerably, though at a much slower pace than in the Reference Scenario. Demand for coal, being the dirtiest fossil fuel unless Carbon Capture and Storage (CCS) is proven to work, is assumed to peak in 2015 and then go into steady decline. China accounts for the lion's share of this reduction.

In order to achieve the emission trajectory in the 450 Scenario, investments by national governments, consumers and companies in renewable energy sources have to be substantially larger than what is currently pledged (i.e., the level assumed in the Reference Scenario). The most important factor in reducing demand is a global carbon price of around 30 US $ per ton of CO_2 in 2020; in addition, a redesign of the CDM or a similar structure is needed to transfer funds from the developed to the developing world and ensure their most efficient and effective use in CO_2 abatement. The WEO 2009 goes to great length not to recommend any particular allocation of burdens, as this is an inherently political decision. However, it attaches a price tag to the incremental investment to move from the Reference Scenario to the 450 Scenario – namely a fourfold increase compared to the investments in the Reverence Scenario. It has to be noted, though, that a large part of this investment has to occur on the household level, such as increased energy efficiency and a change of the automobile fleet to hybrid and electric vehicles. Most of these investments are expected to be amortised fairly quickly, so the WEO 2009 identifies funding as the bottleneck, and not so much the actual level of the investment needs.[4]

The two scenarios of the WEO 2009 will be used in this work to gauge potential future crude oil demand; these aspects are presented in more detail in Sections 5.1.1 and 5.1.2, respectively.

1.3. Investment and uncertainty

The WEO 2009 draws much attention to the high uncertainty regarding the long-term economic impact of the current crisis. As demand for energy services is directly related to economic activity, future energy demand is linked to how quickly the global economy leaves the current trough. The economic uncertainty is exacerbated by the political ambiguity regarding a political commitment to curb climate change. Any serious political accord to change the global energy mix will reduce demand for fossil resources, either through outright regulation or a market-based mechanism such as a cap-and-trade sys-

[4] As the benefit for human welfare of living on an inhabitable planet is as yet unpriced, this is not specifically considered in the WEO 2009.

tem. While the Copenhagen Summit was a disappointment for anyone who expected a follow-up agreement to the Kyoto Protocol, a consensus is still within reach in the coming years. The environmental catastrophe in the Gulf of Mexico following the explosion of the "Deepwater Horizon" oil rig could strengthen the political support for a political paradigm shift regarding energy and the environment.

In any case, the dependence on crude oil is not going to disappear in the coming years, so the crude oil price and economic recovery will remain closely related. Too high an oil price has the potential to choke off any upswing in economic sentiment. One area of concern, consequently, is the low level of investment on the part of crude oil suppliers, as this could lead to supply bottlenecks. On the other hand, not only is the funding environment rather hostile for energy companies, but the profitability of any investment is uncertain.

This diploma thesis, therefore, investigates the profitability of investments for certain important crude oil suppliers under both economic and political uncertainty. The incentives to add production capacity are examined in the following way: the first level is a Nash game to add production capacity at present, under uncertainty regarding future demand levels. The latter level is a partial equilibrium market model, numerically solved for a number of demand development scenarios and initial investment decisions. This model is formulated as a Complementarity Problem (CP). The results from the market equilibrium model serve as inputs to the investment analysis. Different from other works in this field, this approach allows to specifically account for strategic behaviour in the crude oil market by key suppliers through combining investment analysis and a market equilibrium model.

1.4. Countries under Investigation

This work focuses on the two most important suppliers: Saudi Arabia and Russia, together accounting for a quarter of global production in the base year (IEA, 2009b), and more than a quarter of global proved reserves BP (2009), excluding Canadian oil sands.

According to The Economist (2009b), Saudi Aramco recently completed a five-year, 70 billion US $ investment scheme to add 2.5 million barrels of daily production capacity; in addition, it set aside another 60 billion US $ for further expansions. Hence, an investigation of whether a further expansion makes sense from a strategic point of view is worthwhile, especially given the Saudi claim that it sits on 4.5 MMbbl/d of unused capacity.[5]

Russia is a more complex case: its political situation is certainly different from the monolithic Saudi kingdom. Over the past decade, the Kremlin has used soft and not so soft pressure to coerce independent Russian and Western firms into relinquishing assets and operations to oil companies close to the Russian state. The expropriation of the

[5] The actual size of its unused capacity is debated, as discussed by (Salameh, 2009).

oil company *Yukos* and the conviction of Michail Chodorkowski are the – unfavourable – highlight in this story. At the same time, it is common wisdom that Russia cannot expand its production significantly without foreign expertise and financing. Hence, the investment analysis in this work allows to estimate the “price tag” that political interference and the resulting reluctance by foreign oil companies to invest carries to the Russian government.

1.5. Structure of this Work

The structure of this diploma thesis is as follows: Chapter 2 provides an introduction to the literature concerning crude oil; as the number of publications is vast and the topic was approached from many different angles, I will only focus on some aspects and derive several assumptions relevant for this work. This chapter also discusses an alternative approach to investment analysis, namely Real Options (RO), and their application to the crude oil industry. Chapter 3 presents a brief introduction into Variational Inequalities (VI) and Complementarity Problems (CP), as well as a description of the two-level game and the solution approach. The market equilibrium model, formulated as a CP, is introduced in Chapter 4. The different demand scenarios are specified in Chapter 5, as are the sources, from which the input data is derived. Here, an investigation of different market power setups and the calibration are covered as well. The numerical results are presented in Chapter 6; this section also discusses potential “security of supply” issues. Chapter 7 concludes.

2. A Primer on Crude Oil Literature

Given the importance of crude oil, the scope of economic research on this topic is enormous. And as an issue discussed for the better part of a century, the crude oil literature provides an insight into both the political and societal worries of the day, as well as the economic techniques and methods applied to shed light on them. Hotelling (1931) and Hubbert (1962) used analytic models to gauge the question of how long resources would be available and how to price them; dynamic programming was applied to determine market equilibria and price paths; the oil crisis turned the spotlight on OPEC; the ambiguity of OPEC behaviour called for game theory to investigate cartel stability and national incentives; econometrics were applied to determine the stochastic process underlying the crude oil price.

There are several characteristics of the crude oil market which - in their combination - distinguish it from any other resource and make every attempt to solve the Gordian knot a Sisyphean challenge. These characteristics include the following: the crude oil market is global and integrated - so much so that Adelmann coined the phrase that the "world oil market, like the world ocean, is *one great pool*" (Adelmann, 1984, p. 531). A cartel is active in the market, namely the Organisation of Petroleum Exporting Countries (OPEC) - but maybe this is not actually a cartel? The lion's share of production is located in countries which do not adhere to any notion of transparency or accountability, so any work on crude oil is complicated by patchy data.

In no other field is there such an extensive debate about whether supply and demand drive prices - or maybe it is the other way round? The emergence of futures and other financial instruments have only added oil to the fire. Lastly, as the events surrounding the price spike of 2008 demonstrated vividly, there is a political aspect to crude oil, ranging from issues of supply security for Western markets to fuel-subsidy programs in many developing countries.

As the literature is vast, I will not attempt to cover it thoroughly. Instead, I will elaborate along the lines laid out in the previous paragraphs; the aim is to introduce some concepts and ideas, and to justify several assumptions and simplifications necessary in my approach and the partial equilibrium model presented in the subsequent chapters.

In addition, this chapter also introduces Real Options, an investment analysis framework, and its application to the crude oil market.

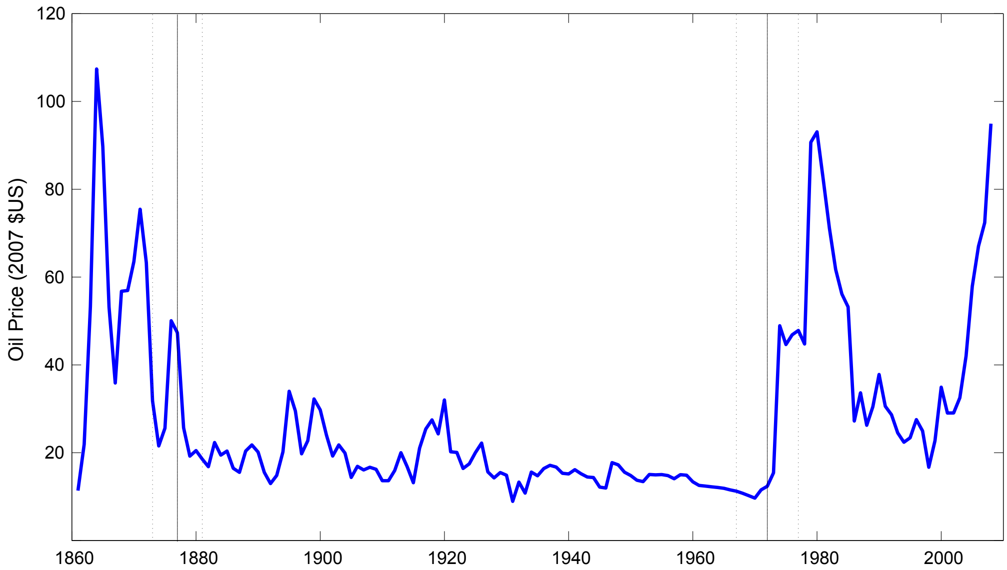

Figure 2.1.: Real Oil Price from 1861-2006, adapted from Dvir and Rogoff (2009)

2.1. Exhaustibility of crude oil

Any comprehensive discussion of the crude oil price literature necessarily includes the seminal article by Hotelling (1931), and his assertion that, for any non-renewable resource, the marginal value of the stock must increase at the rate of interest. This is known in economics as the *Hotelling rule*. A reformulation of this concept was proposed by Solow and Wan (1976), specifically allowing for heterogeneous extraction costs of various deposits and focusing on the optimal consumption trajectory.

An extension of the Hotelling model along a different rationale was proposed by Salant (1976), namely to include market power. He assumes a number of identical and independent "extraction units" (i.e. firms with identical cost structure and reserve size). A cartel would be formed by the unification of several of these units, exerting market power by withholding supplies from the market to push prices up. All other firms then form a *competitive fringe*, i.e. their marginal costs equal the price in equilibrium. Salant shows that the competitive fringe exhausts its reserves before the cartel, from which time the cartel is the sole supplier. An interesting observation is that the competitive suppliers see their revenue increase by a relatively higher ratio than the cartel after the formation of the cartel; this is explained by the fact that the formation of the cartel raises the oil price – and hence profits – for all producers, but the cartel must hold back some of its production until after the termination point, when competitors' reserves are depleted.

However, while convincing in theory, there is a conundrum about the Hotelling rule: any long-term investigation of crude oil prices fails to confirm an exponential increase of the price over time. For a graphical illustration of this point, take a glance at the real oil price over the last 130 years (Figure 2.1). Krautkraemer (1998) attributes this to the many uncertainties and dynamics related to the crude oil stock: exploration stochastically expands the resource stock; extraction costs may vary considerably and are difficult to predict; and technological progress makes deposits accessible that were previously beyond the reach of geologists and engineers. All these factors dilute the theoretical purity of the exponential price increase. This idea was formulated even more drastically by Adelman (1995). He compares exploration and development of oil fields to efforts of research and development (R&D), with uncertain profits, rather than the extraction of a certain part from a known total.

Hubbert (1962) first drew attention to the bell-shaped production curve of any specific well or oil field; this is now referred to as *Hubbert production curve*. A characteristic point on the Hubbert production curve is the Mid-Depletion Point (MDP), at which half of the reserve is exploited. The possibility that most super-giant oil fields are nearing the MDP (or may have already passed it) led Kjärstad and Johnsson (2009) to revisit the issue of resources and future supplies. They find that the resource base is unlikely to be the limiting factor of crude oil supply in the next decades. Instead, above-ground factors will play a more important role: these include geopolitical issues; the maturity of super-giant fields, whose capacities will decline in the next years and which are difficult to replace by small fields; limited access to reserves, as nation-states seek to gain influence on or control of the exploitation of reserves; and, of course, investment constraints, as already discussed in Chapter 1.3.

So one may draw the conclusion that short-term considerations have a higher influence than Hotelling inter-temporal optimisation.

2.2. Supply and demand

Any economist would argue that, in an efficient market, the price is determined by supply and demand. Dvir and Rogoff (2009) offer a historical narrative of supply and demand and its influence on the crude oil price from 1861 until 2008. They identify three structural shifts in price persistence and price volatility: before 1878, oil prices were highly volatile and persistent; until 1934, both volatility and persistence were lower; until 1972, volatility was even lower, while persistence remained roughly at the same level; and after 1972, both persistence and volatility returned to high levels. Linking these epochs of crude oil price behaviour to the historical circumstances, the first and the third breaking point can be attributed to technological and geographical factors leading to changes in the market structure. These are namely the construction of the first long-distance pipeline, *Tidewater*, in 1878, which put an end to the monopoly of railroads over crude oil transportation; and the peak of the East Texas Oil Field in 1970, signalling the end of U.S. control over crude oil production and the rise of OPEC. The discovery of this very oil field can explain the shift of market structure observed around 1934.

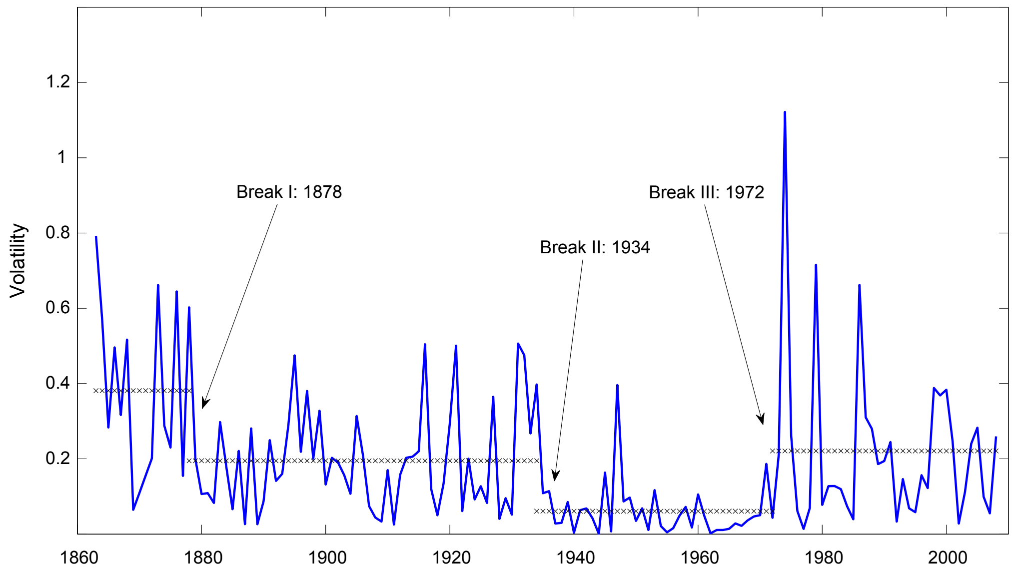

Figure 2.2.: Oil Price Volatility from 1861–2006, from Dvir and Rogoff (2009)

Dvir and Rogoff draw the conclusion that high volatility and high persistence of crude oil prices occur whenever an oligopolistic market structure coincides with rapidly growing demand. In the middle of the 19th century, railroad transport capacity was the limiting factor of crude oil supply in the United States of America (USA). A highly competitive production and refinery market was linked by an oligopoly of railroad companies. At the same time, the USA were industrialising fast. Rockefeller's *Standard Oil* aimed at gathering enough bargaining power with the railroad companies to push prices down, but the real breakthrough came with the installation of long-distance pipelines. These offered high capacity at low cost, so increasing market share aggressively became the strategy of choice for the oil companies.

Between 1887 and 1972, demand increased considerably during the two world wars, and a number of supply crises occurred in the Middle East (Iran 1953, Suez 1956, Six-Day-War 1967). However, since at no point in time did supply and demand shocks coincide, the effect on prices was marginal and short-lived compared to the spikes before and after this period. The Yom Kippur War in 1973 can be identified as the turning point to the next era of high volatility and high persistence: the simultaneous peaking of the East Texas Oil Field marked the end of US influence over global crude oil production. After that point in time, only the Middle East had significant spare capacity. This effect was aggravated by the subsequent nationalisation of crude oil production in the OPEC countries. At around the same time, East Asia started its ascent, first Japan and then China, adding a demand shock to the newly oligopolistic supply market. The confluence of rapidly growing demand and limited, non-competitive supply continued mostly unabated until very recently.

But while this narrative explains what happens if rigid demand and market power on the supply side coincide, it does not tell us where the market power originates from. So let's turn to what is by many referred to as the cartel in the crude oil market.[1]

2.3. Crude Oil & the OPEC "Cartel"

OPEC is a cartel - at least in theory; Article 2 of its statute reads as follows (OPEC, 1961):

> A. The principal aim of the Organization shall be the coordination and unification of the petroleum policies of Member Countries and the determination of the best means for safeguarding their interests, individually and collectively.
>
> B. The Organization shall devise ways and means of ensuring the stabilization of prices in international oil markets with a view to eliminating harmful and unnecessary fluctuations.
>
> C. Due regard shall be given at all times to the interests of the producing nations and to the necessity of securing a steady income to the producing countries; an efficient, economic and regular supply of petroleum to consuming nations; and a fair return on their capital to those investing in the petroleum industry.

This text is a rather crude venture at collusion, as defined in any economics textbook. However, until the first oil crisis in 1973, OPEC led a rather obscure existence. The "Energy Crisis" of the 70's pushed OPEC into the spotlight of economists. Griffin (1985) was one of the first to compare the descriptive power of different theories *en vogue* at the time: the cartel, the competitive model, the target revenue approach (which will be elaborated later) and the property rights theory. He finds evidence for market-sharing among OPEC suppliers and a competitive fringe, i.e. perfectly competitive non-OPEC suppliers.

Rauscher (1988) claims that, prior to the first oil crisis, OPEC had little knowledge of demand elasticity and backstop prices. It was actually taken by surprise about the size of its market power, as demand was more rigid than expected and assumed backstop prices unrealistically low. This insight subsequently allowed it to raise prices again in 1979–80. However, the second price increase was met by far more elastic consumer demand than the first increase, probably due to changed consumer expectations about the longevity of the price increase. Rauscher concludes that this forced OPEC to reduce prices again in 1986, since demand for OPEC oil had sunk too low for its liking.

The mechanism behind the cartel is the allocation of production quota to each member state according to the size of its reserves. Consequently, each country has an incentive

[1] As the term *dominant firm* is used alternatively for either OPEC or Saudi Arabia by various authors, I avoid this notion in this work.

to exaggerate its figures in order to obtain a bigger *slice of the cake*. And as each member is independently in charge of determining its reserve base, they all have ample opportunity to do so. This is demonstrated in detail for Saudi Arabia (Salameh, 2009). But not only the allocation of quota as such is subject to scepticism: the assigned quota themselves are seen by the members more as recommendations and "guidelines" rather than concrete upper bounds. As pointed out by Adelman (1995), the marginal producer always has an incentive to cheat.

Hence, a different storyline is proffered by Griffin and Neilson (1994) for the 1986 price collapse: they conclude that Saudi Arabia acted as *swing producer* after the introduction of the OPEC quota in 1983. However, when cheating became too widespread among other OPEC members, Saudi Arabia drastically increased its production to regain lost market share and punish other OPEC producers. This forceful action caused crude oil prices to drop from 28 to 8 US $ per barrel. After Saudi Arabia's drastic presentation of power, other OPEC producers were willing to abide by the newly assigned quota. Griffin and Neilson postulate that Saudi Arabia afterwards threatened a *tit-for-tat strategy* to prevent other OPEC members from again over-producing their quota excessively; they note, however, that small instances of cheating are usually tolerated.

On a more recent note, Kaufmann et al. (2008) test for a production-sharing agreement between OPEC suppliers; they do not find any evidence for a tit-for-tat behaviour by Saudi Arabia. As they admit, this does not necessarily mean that Saudi retaliation is ineffective; instead, the threat might suffice to deter any significant over-production by other OPEC members. Another detailed analysis of cheating within OPEC is carried out by Dibooglu and AlGudhea (2007). In contrast to Kaufmann et al., they conclude that the quota system is not effective. OPEC members generally over-produce their quotas, but conform to a *public finance* argument for large real oil price shocks. According to this rationale, a country aims to generate a certain amount of income rather than maximising profits. Higher oil prices thus lead to lower production, contrary to classic production theory. This is motivated by the observation that – especially small or less developed – countries can only reasonable re-invest a certain amount of income. Graphically, this leads to a *backward-bending supply curve* for that particular country. This policy is also known as *target revenue* behaviour (Alhajji and Huettner, 2000).

In this context, it is sometimes suggested that Saudi Arabia acts as a *Stackelberg leader* in the crude oil market (Adelman, 1995; Rauscher, 1988). In such a market, one player has an informational advantage over the other players: he is able to anticipate their reaction to his action, and can include this reaction in his decision (von Stackelberg, 1934).

So if OPEC is not a classic textbook cartel aiming to maximise joint profits, but rather an accumulation of individual national interests, we need to focus on the national level.

2.4. National Oil Companies

More than a century ago, *Standard Oil* of John D. Rockefeller controlled US oil market (Yergin, 1991). A breakup of Standard Oil by the US Supreme Court and many a nationalisation all over the world later, the picture today is rather different: more than 60 % of crude oil production originate from National Oil Companies (NOC); about 90 % of global proven reserves lie in fields controlled by NOCs (Wolf, 2009).

Given the dominance of NOCs within the crude oil market, Hartley and Medlock (2008) compare their characteristics to those of privately owned companies. The latter can generally be assumed to maximise profits, act risk-neutrally and apply a market-based discount rate when valuing investments. The former, on the other hand, have a wide array of objectives to fulfil.[2] These include a preference for current profits, as these directly feed into the treasury and can be doled out to favoured constituencies – hence a higher discount rate applies to future profits. Secondly, a publicly-owned company internalizes social benefits, such as wages to employers; this encourages a greater number of staff than a comparable privately owned oil company. On a similar note, a subsidised fuel prize may be seen as an efficient way of sharing the resource rent with the population (i.e., the electorate). A third observation is a usually asymmetric reward system in the public sector, which leads managers to act more risk-averse than their peers accountable to shareholders. Hartley and Medlock develop a structural model to gauge the influence of these factors; they find that all of them tend to contribute to pushing production from the future to the present, below the socially efficient optimum.

Approaching this issue form a purely financial perspective, Wolf (2009) compares profitability, efficiency and other indicators of NOCs and international (private) oil companies. The dataset covers over 130 firms in the time period of 1987–2006. The findings indicate that NOCs under-perform their peers by about 20–30 %. Nevertheless, as the article points out, the preference for governmental control of resources continues unabated, and – usually Western – international oil companies may face difficulties to secure the rights to develop and exploit fields in many parts of the world in the coming decades.

Disaggregating the crude oil market down to a national level may explain a number of phenomena; still, it is also not quite satisfactory, as the insights gained can not easily be used to predict the future development of the crude oil price. Hence, many economists have turned directly to the study of the crude oil price.

2.5. Crude Oil Prices

A model explicitly formulated to rationalise crude oil volatility is presented by Rauscher (1988): many models and approaches rely on the assumption of perfect information to derive smooth price trajectories derived from Hotelling or monopoly rent theory,

[2]These objectives tend to be handed down from national politicians and are sometimes designed to maximise re-election probability rather than public welfare.

but this is actually implausible in reality. In a world of imperfect information, small perturbations are exacerbated by overshooting reactions of the economic agents. If the planner, whether a social welfare optimiser or a cartel, does not have access to correct information, this may lead to suboptimal decisions. The revisions can then cause price shocks. On a similar train of thought, Morrison (1987) identifies the cartel and the Cournot market as upper and lower bounds of the crude oil price, and then develops the following metaphor:

> These upper and lower bounds of oil prices might be viewed as the banks of a river. It is the objective of 'the good ship' OPEC to steer an optimal course between the banks. To stretch the metaphor a little further, we might envisage that the river is covered with a layer of mist which does not allow the captain of the ship to see either of the banks from mid-stream. He is therefore unable to steer an optimal course and hence uses a simple rule-of-thumb to set his course – if he steers too close to one of the banks then he has to change course in order to avoid hitting it. Hence the course tends to be rather erratic. (Morrison, 1987, p. 401)

On a similar note, Zaklan et al. (2010) investigate the effect of oil price changes on production, but they specifically account for the lags with which production can be adjusted or new production capacity can come online. They find that OPEC acts pro-cyclically in the short term, but counter-cyclically in the longer term; this supports both a market power hypothesis and the target revenue approach presented above. The picture is rather mixed with regard to non-OPEC countries, but competitive behaviour prevails.

In contrast to the structural approaches presented above, many economists approach the problem from a purely econometric perspective. Pindyck (1999), for instance, argues that non-structural models should incorporate mean reversion, even though the trend line may fluctuate stochastically. A more elaborate model is developed by Bernabe et al. (2004), where they construct two stable mean-reversion price processes, one a high-price regime, the other at a low-price; a jump strategy moves the price from one regime to the other. Abid and Kaffel (2009) show that Geometric Brownian motion (GBM) with jumps best describes the crude oil price process. Hamilton (2009), on the other hand, cites a number of findings supporting the proposition that the crude oil price follows a random walk without drift (or jumps). Let this brief overview suffice to show that there is no agreement on the nature of a stochastic process underlying the crude oil price.

Focusing on the demand side, Wirl (2008) revisits several theories regarding oil price volatility: *homo oeconomicus*; price reaction functions contingent on capacity utilisation or cartelisation; econometric approaches; political models; and demand uncertainty. He attributes the recent price spikes to demand uncertainty and sluggish investment, while political factors contributed little to the price increase.

2.6. Crude Oil & Price Indices

Kaufmann and Ullman (2009) also investigate the recent price spike, but approach the topic by comparing the causality between different oil price indices. They conclude that market fundamentals were driving the long-term price increase, but that speculation added to the effect. As the term speculation is politically connotated, one could consider to call it *"inter-temporal arbitrage by the stock market with rational expectations"* instead.[3] On a more theoretical note, Alquist and Kilian (2010) examine the relation between spot prices and futures, as well as the validity of using crude oil futures as predictors of future oil prices. Both articles support the notion that speculation or precautionary demand – which can be argued to be two sides of the same coin – are able to increase spot prices.[4]

Bentzen (2007), in comparison, only considers the three most important crude oil indices, and the direction of causality between them: *West Texas Intermediate* (WTI) in Cushing, OK, USA, and Brent (Northwest Europe) on the one hand and the OPEC price basket on the other. He finds a bi-directional causality between the indices, and refutes the notion of regionalisation in crude oil markets.

2.7. Crude Oil & Investment Analysis

Several authors have focused on investment incentives in the crude oil industry. The following section briefly introduces Real Options (RO), an investment analysis framework, and some applications to the crude oil market. The aim is to highlight the differences to the approach pursued in this work. For a detailed treatise of RO, one may refer to Dixit and Pindyck (1994) and Shreve (2004).

When valuing an investment opportunity, business and economics students are commonly taught to look at the Net Present Value (NPV) of discounted (expected) future cash-flows net of investment costs. If the NPV is positive, the investment is to be undertaken. In this context, the investment is considered from a "now or never" perspective. However, in most real world situations, the actual choice should be phrased as "now or later" instead, where "later" means waiting for some of the uncertainty regarding the investment to resolve. For instance, the profitability of exploiting oil sands is depending acutely on the (future) level of oil prices due to high investment and production costs. An oil company might find it preferable to postpone the decision on such an investment until the trend of future crude oil prices can be estimated with greater certainty.[5]

[3]Unfortunately, a discussion whether the stock market is based on rational expectations is beyond the scope of this diploma thesis.

[4]The difference between speculation and precautionary demand is the agent: a *speculator* expects to make a profit from other agents' future demand; a *risk-averse consumer* buys for his own future consumption.

[5]Please accept my apologies that, from a mathematical perspective, the term "greater certainty" is rather badly chosen; however, I believe that it underscores the point made in this section better than any mathematically consistent formulation.

There are two important features, which must be satisfied in order to consider an investment a real option: first, it must be (at least partly) irreversible (i.e., investment costs are *sunk*). Second, there must exist a possibility to delay the investment, in order to gather additional information about the development of an underlying feature, such as the pay-off or the cost structure of the investment. Both of these conditions – in general – apply for investment in crude oil production capacity.

An early contribution to the real option literature is the article by Paddock et al. (1988). He examines the valuation of offshore oil field leases; a characteristic of such leases (at least in the USA) is that they expire if the firm does not start development within a certain time period (usually several years). Another speciality of such leases is the sequentiality of exploration, development and extraction. The standard NPV dictates that a number of expectations are formed over the total development cycle before any exploration takes place (i.e., at the time of bidding for the lease); these include the actual timing of development and detailed assumptions on reservoir size, quality and extraction costs. However, these estimates are bound to be erroneous. A better valuation technique would be to first explore the field, and only develop it if size, quality and cost are deemed appropriate; then, once the field is developed, crude oil would only be extracted if the market price is sufficiently high. A petroleum reserve market equilibrium based on a Wiener Process is used to close the model. The authors develop a methodology to derive a lease valuation from such a two-stage option approach.

Paddock et al. then compute valuations of offshore oil field leases auctioned on November 18, 1980, in federal lease No. 62.[6] They compare the computed valuations to both the U.S. Geological Survey (USGS) estimates based on the classical NPV approach and to actual industry bids. The results indicate that the RO approach has a higher correlation to industry bids than the USGS valuations; the authors take this as an indication that their approach is indeed more in line with industry expertise, which often includes rules-of-thumb and experience, rather than the traditional NPV method.

Smith (2005) examines the chain of decisions regarding trial wells (or *wildcatter* in the industry terminology) when exploring a prospective oil field. The author compares two approaches usually used in the industry to valuing a trial well – and the option to drill another well in the same area, if the first attempt is not successful. Emphasis is drawn on the importance of the initial probability to strike oil and the dependance between the first and later trials (i.e., the probability to strike oil in the second attempt is certainly not greater than the probability of success in the first trial, but rather smaller). The actual values of initial probability and dependance can lead to divergence between the two approaches commonly used for valuation of a trial well. Smith then proposes a corrected valuation formulation taking into account these two parameters, and finds that higher dependance between subsequent drilling success probabilities reduces the option value of the whole venture.

[6]The authors use only 21 out of 67 tracts in the Gulf of Mexico awarded in that lease for data consistency and methodology reasons

A different application of real options is developed by Conrad and Kotani (2005): they ask which oil price level would justify drilling for oil in the Arctic National Wildlife Refuge (ANWR). The irreversibility, in this work, refers to the damage done to the environment and the ecological system in the arctic if the ban on drilling is lifted by the U.S. Congress. A stochastic oil price is assumed, determined either by geometric Brownian motion (GBM) or a mean-reverting (M-R) process. The – rather arbitrarily chosen – amenity value of preserving ANWR in its current state ranges from 200–300 million US $ per year. The authors then determine trigger prices in both price regimes (GBM and M-R) and amenity values, at which drilling should be allowed; these trigger prices are in the region of 20–30 US $ per barrel.[7]

A very recent contribution to the RO literature comes from Abid and Kaffel (2009); they develop a methodology to value an oilfield development contingent on three risk factors: crude oil price, convenience yield and risk-free interest rate. Each of these factors follows, according to their analysis, independent stochastic processes. They compare a model including only one factor at a time to a simultaneous inclusion of two and three factors, respectively. Using Monte-Carlo-simulation, they apply their approach to a real-world problem, namely a Tunisian oil field development in the early 1990s. Their results are ambiguous depending on the number of factors included in the analysis.

A caveat of RO theory is not the framework itself, but its origin: it is derived from financial markets, where the *efficient market hypothesis* looms large. Consequently, concepts such as the *Markov Property* (assumption of no or limited memory of stochastic processes) are predominant, as is the notion that the action of any one agent cannot have any influence on the underlying process. As shown in the previous paragraphs, all applications of RO theory to questions related to crude oil assume a stochastic process to underlie the crude oil price. More importantly, the process is exogenous to and independent of the investment decision. This is not unrealistic regarding the valuation of one specific field or tract; however, it certainly ignores the strategic aspect of development. It would be highly implausible to assume that the decision of Saudi Arabia or Russia on whether or not to increase their production capacity by 10 % or more does not seriously affect the crude oil price, both in the short and the long term. The approach developed in this work allows to account for this strategic aspect of investment under uncertainty.[8]

[7]The discussion concerning the lift of the ban is ongoing at the time of writing, even though the trigger price has long since been surpassed; this suggests that either the members of Congress value the ANWR higher than the authors, or that the debate is determined by political considerations rather than economic rationale.

[8]Obviously, the approach in this work neglects some other important features.

2.8. Assumptions for this work

From the literature presented above, I derive the following assumptions for this work:

- The reserve constraint and inter-temporal optimisation as stipulated by the Hotelling rule are of secondary importance compared to marginal cost curves and market power of the individual suppliers; this is both a simplification grounded in the literature (as elaborated earlier, there are doubts about the applicability of Hotelling to the crude oil market), and a practical one: the focus of this work is put squarely on the next two decades, so exhaustibility of reserves would not be a major issue for most suppliers; besides, deriving a credible estimate on a backstop technology half a decade from now - which is necessary for tractability of a dynamic programming Hotelling model - is a futile exercise.
- The price of crude oil is formed by the equilibrium of supply and demand.[9] I ignore the short-term fluctuations of the crude oil price and use yearly average prices.
- Deriving a plausible market power setup from the literature seems difficult due to the many contradicting opinions and findings. Hence, as part of the calibration, the model is run for a number of market power settings, and the one yielding the best fit is used for the subsequent simulations.
- Price indices formed in liquid spot markets and the existence of arbitragers exert an influence on the refinery gate prices of crude oil, leading to a convergence of crude oil prices globally; i.e. spatial price discrimination is virtually non-existent. This is accounted for in the partial equilibrium model by explicitly including arbitragers that act from several pool hubs.

[9] This statement would be seen as a truism in any other area of economics; in the crude oil research, it is not, as made evident by the extensive literature on what drives crude oil prices (e.g., Wirl, 2008; Kaufmann and Ullman, 2009).

3. Methodology

The topic under investigation in this work are the strategic incentives of important crude oil suppliers to invest in additional production capacity. As elaborated in Chapter 1, the economic viability of the investment depends on the future global demand for crude oil; this is highly uncertain, due to ambiguous political signals regarding the combat of climate change and the precarious economic situation. A market equilibrium model is developed and numerically solved for several scenarios of crude oil demand trajectories; the results serve as inputs for the investment analysis. The market model is formulated as a complementarity model; hence, this chapter offers a brief introduction to the wide field of variational inequalities and complementarity problems. A description of how the investment analysis is carried out based on the numerical results from the complementarity market equilibrium model is given at the end of this chapter. The actual formulation of the market equilibrium model is provided in Chapter 4.

3.1. Variational Inequality & Complementarity Problem

The field of variational inequalities (VI) and complementarity problems (CP) is used in a number of distinct fields: examples of applications range from engineering problems (frictional contact problems) to Operations Research (OR, traffic equilibrium problems) to actuarial mathematics (option pricing) to economics (Walrasian general equilibrium problem). One application of this field frequently used in economics are the Karush-Kuhn-Tucker conditions, which are discussed in more detail below. First, some general notation is introduced.

Facchinei and Pang (2003) provide a comprehensive discussion of finite-dimensional CP, its generalisation, namely VI, the interconnection between the two, and the relation of both to standard nonlinear programs. Most of the following definitions and the notation follow Facchinei and Pang; Definitions 1, 2, 3, and 5 are literal quotes.

Definition 1 (Variational Inequality)**.** Given a subset K of the Euclidian n-dimensional space $\mathbb{R}^n$ and a mapping $F : K \to \mathbb{R}^n$, the *variational inequality*, denoted VI(F, K), is to find a vector $x \in K$ such that

$$(y - x)^T F(x) \geq 0, \qquad \forall\ y \in K. \tag{3.1}$$

The set of solutions to this problem is denoted SOL(K, F).

Definition 2 (Complementarity Problem)**.** Given a cone K and a mapping $F : K \to \mathbb{R}^n$, the *complementarity problem*, denoted $\mathrm{CP}(K, F)$, is to find a vector $x \in \mathbb{R}^n$ satisfying the following conditions:

$$K \ni x \quad \perp \quad F(x) \in K^*,$$

where the notation $\perp$ means "perpendicular" and K^* is the *dual cone* of K defined as:

$$K^* \equiv \{d \in \mathbb{R}^n : v^T d \geq 0 \quad \forall\ v \in K\};$$

that is, K^* consists of all vectors that make a non-obtuse angle with every vector in K.

Any vector $x \in \mathbb{R}^n$ is said to be *feasible* to $\mathrm{CP}(K, F)$ iff $x \in K$ and $F(x) \in K^*$[1]; the feasible region is denoted as $\mathrm{FEA}(K, F)$. The perpendicular operator ($\perp$) indicates that $F(x)$ and the variable x are complementary, i.e. that for all $x \in \mathrm{SOL}(K, F)$, $x^T F(x) = 0$. It is straightforward to show that $\mathrm{SOL}(K, F)$ is a subset of $\mathrm{FEA}(K, F)$.

In the general case of the VI, the set K is closed and the function F continuous (and differentiable, where appropriate). In a CP, the set K is a closed convex cone. Setting K equal to the non-negative orthant ($\mathbb{R}^n_+$) leads to a nonlinear complementarity problem (NCP), denoted $\mathrm{NCP}(F)$.

A combination of a CP and a NCP yields a mixed complementarity problem (MCP).[2] If the cone K is of the form $K = \mathbb{R}^{n_1} \times \mathbb{R}^{n_2}_+$, with $n_1 + n_2 = n$, the vector x and the function $F(x)$ can be partitioned into two vectors u and v; and two functions G and H respectively. This leads to the following definition:

Definition 3 (Mixed Complementarity Problem)**.** Let G and H be two mappings from $\mathbb{R}^{n_1} \times \mathbb{R}^{n_2}_+$ into $\mathbb{R}^{n_1}$ and $\mathbb{R}^{n_2}$, respectively. The $\mathrm{MCP}(G, H)$ is to find a pair of vectors (u, v) belonging to $\mathbb{R}^{n_1} \times \mathbb{R}^{n_2}$ such that

$$\begin{aligned} G(u, v) = 0 \quad &, \quad u \text{ free} \\ 0 \leq v \quad &\perp \quad H(u, v) \geq 0. \end{aligned}$$

3.1.1. The Karush-Kuhn-Tucker conditions

An application of a MCP are the Karush-Kuhn-Tucker (KKT) optimality conditions, which are a standard tool in economics. The problem is, from an economist's perspective, derived from constrained optimisation problems, such as profit maximisation of

[1] For non-mathematicians: "iff" is short-hand notation for "if and only if".

[2] Mixed Complementarity Problems are abbreviated as MiCP by Facchinei and Pang (2003); in this work, I follow the notation more commonly encountered in the literature.

economic agents under operational constraints.

Definition 4 (Karush-Kuhn-Tucker conditions)**.** Assume a constrained optimisation problem as follows:

$$\begin{aligned} \max F(x,y) \\ \text{s.t. } K_1(x,y) = 0 \\ K_2(x,y) \leq 0 \\ x \geq 0 \end{aligned}$$

then the first order (KKT) conditions of this problem are:

$$\begin{aligned} \frac{\partial F}{\partial x} - \lambda \frac{\partial K_1}{\partial x} - \mu \frac{\partial K_2}{\partial x} \leq 0 \quad &\perp \quad x \geq 0 \\ \frac{\partial F}{\partial y} - \lambda \frac{\partial K_1}{\partial y} - \mu \frac{\partial K_2}{\partial y} = 0 \quad &, \quad y \text{ free} \\ K_1(x,y) = 0 \quad &, \quad \lambda \text{ free} \\ K_2(x,y) \leq 0 \quad &\perp \quad \mu \geq 0 \end{aligned}$$

In this formulation, λ and μ are the dual variables (or Lagrange multipliers) of the constraints $K_1(x,y)$ and $K_2(x,y)$. As above, the perpendicular operator ($\perp$) indicates that the equation $K_2(x,y) \leq 0$ is complementary to the variable μ, meaning that $K_2(\bar{x},\bar{y}) \cdot \bar{\mu} = 0$ must hold in the optimum $(\bar{x},\bar{y},\bar{\mu},\bar{\lambda})$. Assuming convexity of $K_1(x,y)$ and $K_2(x,y)$ and strict quasiconcavity of $F(x,y)$, we know that the problem is tractable and that there exists a unique solution.

The KKT system can be interpreted as a special case of a variational inequality, namely VI$(K,\nabla F)$, where K is the set of all vectors (x,y) satisfying $K_1(x,y) = 0$ and $K_2(x,y) \leq 0$.

3.1.2. Complementarity models in energy markets

An early equilibrium model for energy studies was the Project Independent Evaluation System (PIES) employed by the U.S. Department of Energy (Hogan, 1975, 1977). Facchinei and Pang (2003) explain how important the PIES solution algorithm was in advancing the development of the VI/CP field. The PIES model has since become the National Energy Modeling System (NEMS)(Gabriel et al., 2001) employed by the EIA (Energy Information Administration).

At the time of the the two oil price shocks, a lot of attention was devoted to understanding the crude oil market and the influence of OPEC. However, applications of partial equilibrium models faced several serious caveats: to be solved analytically, one needed assumptions such as identical cost structures for all producers or uniform distribution of resources amongst producers. A typical example of this is Salant (1976).

As for numerical computation, solution methods were restricted to linear programs or heuristic solution algorithms (Salant, 1982). A detailed review of models on the crude oil market is given in Al-Qahtani et al. (2008a).

Research on the crude oil markets subsequently moved away from the investigation of equilibrium of supply and demand. Instead, economists focused on questions such as cartel stability, whether OPEC members were pursuing strategies so as to maximise profits or rather aimed to reach a certain level of income (i.e., target revenue), and econometric investigations of the crude oil price trajectory, to name but a few.

Due to the development of numerical solvers for large-scale non-linear equilibrium problems, market equilibrium models have come into fashion again in modelling resource and energy markets in recent years. These new computational methods allowed for some of the rather unrealistic assumptions to be dropped, and equilibrium models were developed to describe the markets for natural gas: these include the *GASTALE* model (Lise et al., 2008); the *World Gas Model* (WGM, Egging et al., 2008, 2009); and *GasMod* (Holz et al., 2008). Besides, there are models on steam coal (Haftendorn and Holz, 2010) and electricity markets (Hobbs, 2001; Ehrenmann and Neuhoff, 2009).

A central feature of all these models is that they are simultaneous-move games, either in Nash-Cournot or perfectly competitive market environments settings (or a combination of these). However, when looking at the crude oil market, one cannot fail to notice the important position of Saudi Arabia. The notion of a two-level game quickly comes to mind, or – in economists' language – a Stackelberg leader-follower market. Such a market can be modelled by extending the VI/CP framework.

3.1.3. Mathematical Programs under Equilibrium Constraints

This extension of the VI/CP framework introduced so far are *parametric VIs*, where the set K and the function F depend on a parameter $\mathbf{p} \in \mathcal{P}$. This leads to a family of VIs, namely $\{\text{VI}(K(\mathbf{p}), F(\cdot, \mathbf{p})) : \mathbf{p} \in \mathcal{P}\}$. The class of Mathematical Programs under Equilibrium Constraints (MPEC) is one important application of parametric VIs.

Definition 5 (Mathematical Programs under Equilibrium Constraints)**.** Consider a constrained optimisation problem:

$$\begin{aligned} \max\ & \theta(x, y) \\ \text{s.t.}\ & (x, y) \in Z \\ & y \in \text{SOL}(K(x), F(\cdot, x)) \end{aligned}$$

Here, θ is a function $\mathbb{R}^{n+m} \to \mathbb{R}$ and Z is a given subset in $\mathbb{R}^{n+m}$. The variable (or vector) x is called the *design variable*, while y is the *state variable*. In addition to being an element of Z, the variable (or vector) y must be a solution to the parametric $\text{VI}(K(x), F(\cdot, x))$.

As mentioned before, MPECs can be used to model a Stackelberg leader-follower market. The leader chooses the design variable x under the condition of an equilibrium in the second-level game; the state variable y can be interpreted - in game-theoretic terms - as the optimal response of the follower(s) to the leader's decision.

3.1.4. Open vs. Closed Loop and the issue of Time Consistency

When modelling multiple-period games, there are two general approaches to formulating a model and finding a solution: if all decisions are taken simultaneously by all agents over the total game horizon, this is referred to as an *open-loop* model. If, on the other hand, the players are aware of the actual actions in period t before deciding on their actions in period $t+1$, this is referred to a *closed-loop* solution. In game-theoretic terms, the difference between the two approaches lies in the set of information on which the decision of an agent is based.

If each agent were able to contractually bind itself to its strategy announced at the start of the first period, the difference between the two approaches would be negligible; however, that is implausible in most real-world scenarios. In general, an agent may have an incentive to announce one strategy, but then deviate from it at a later stage. Such a situation is referred to as a *time-inconsistent strategy*. For a thorough reading on the game-theoretic concepts, refer to Fudenberg and Tirole (1991).

Kydland and Prescott (1977) investigate this problem in a general social-policy context, while Newbery (1981) examines the difficulty of finding time-consistent price paths with specific regard to the crude oil market and OPEC. He finds that a Stackelberg-approach yields time-consistent results only under certain conditions, and that under realistic assumptions, a cartel would have an incentive to deviate from the initial plan. He concludes that a Cournot-strategy vis-à-vis a perfectly competitive fringe is the best approximation to a rational-expectations Stackelberg equilibrium.

Murphy and Smeers (2005) compare theoretical and numerical results for an open-loop, a closed-loop and a feedback model for investment in electricity generation capacity. They assume two suppliers: one for base-load and one for peak-load. Investment decisions are taken by two suppliers in the first stage, while actual generation (i.e., production of electricity) is carried out in the second stage of the game. The open-loop model (with simultaneous decisions on investment in the first period and generation in the second period) corresponds to a long-term-contract market; the closed-loop model (where generation in the second period takes into account the actual investment by the rival firm in the first period) describes a spot market.

Considering strategic behaviour in such a situation, the base-load supplier may deter the rival from entering the market by "over-investing", thereby threatening to drive down prices to such a level that the peak-load generator cannot be profitable; in the second stage of the game, the base-load supplier is then a monopolist and can drive up prices in the spot market by withholding generation capacity. Indeed, this is the result observed in a simple numerical example. In order to achieve tractability of the closed-loop model, Murphy and Smeers assume a very simplistic market, without considering network constraints or more than two suppliers. They conjecture that their results could be extended to a more general model, but are wary of the computational difficulties.

Closed-loop solutions often pose serious challenges due to non-convexities and highly non-linear problems (Kydland, 1977).[3] However, the problem can be neglected in a hybrid Nash-Cournot/perfect competition market; in such a market, the open-loop solution can be shown to be time-consistent. A perfectly competitive agent follows a simplistic price rule[4], namely price equal to marginal cost; such a behaviour can be anticipated by other agents, and - by assumption - the agent does not have an incentive to deviate from that strategy. Along a similar rationale, an agent exerting Cournot market power does not have any incentive to deviate from its chosen strategy, given that no other agent deviates; this is true whether or not the strategy comprises one or several periods. Hence, a Nash-Cournot strategy is time-consistent; Newbery (1981) elaborates more on that issue.

3.1.5. Advantages & Caveats of equilibrium models

The advantage of formulating equilibrium models as MCP is the possibility to describe Nash-Cournot market behaviour. In such a market, producers strategically withhold supply and thereby push prices higher in order to maximise revenue. Looking at the OPEC "cartel" and the – by now almost periodical – natural gas disputes between Russia and Ukraine, strategic behaviour of suppliers cannot be ignored in energy markets. As mentioned earlier, several models describe the natural gas markets in such a way.

There are two caveats regarding multi-period Nash-Cournot models formulated as MCP: the first constraint is their implicit assumption of perfect foresight, since all decisions are taken simultaneously (i.e., all production decisions in all periods); this is implausible in any resource market, but especially so in the crude oil market with highly volatile prices. While it is possible to formulate stochastic MCP models, they tend to grow rather quickly in size and run-time, which limits the possibility of their application in large real-world problems. Research is under way to reduce the size of stochastic MCP formulations (e.g., Gabriel et al., 2009).

The second unrealistic limitation in models with endogenous investment is the continuous nature of variables. When considering investment decisions such as exploration and exploitation of an oil field, one does not usually consider incremental additions to capacity, but certain specific values. These could be, for example, the number of wells drilled or oil rigs of certain capacities put in place. This problem could be solved by applying Mixed Integer Problems (MIP); but this approach, again, might raise issues of tractability and run time, and I therefore opted against it here.

[3] Finding a solution is usually not the difficult part; rather, determining the solution found to be unique and time-consistent is.

[4] The term *price rule* is frequently used in the crude oil research: it is a function relating the output decision of a supplier to the prevailing price.

As stated previously, a closed-loop time-consistent Stackelberg market model is not easily tractable and beyond the scope of this work; hence, this work assumes an open-loop hybrid Cournot/perfect competition market setup. This is clearly only a second-best solution. In order to limit the caveat of perfect foresight and continuous investment, this work follows a different approach: remove the first period (i.e., the current period) of investment from the MCP model and treat it as a Nash game.

The MCP model computes the valuation of an investment in a number of scenarios; these are used as inputs to this investment game, as laid out in the following section. Using such an approach allows keeping the numerical work sufficiently small to investigate a larger number of countries and scenarios, while at the same time not entirely neglecting the strategic aspect.

3.2. The investment analysis

Given the high uncertainty of future demand levels, the current situation in the crude oil market can be described as a *two-level game*: in the first round of the game, each supplier decides whether or not to invest in additional production capacity in the initial period (period 0). The latter level is a hybrid Cournot/perfect competition market in the subsequent periods (periods $1--T$), which is formulated as a multi-period open-loop MCP model.

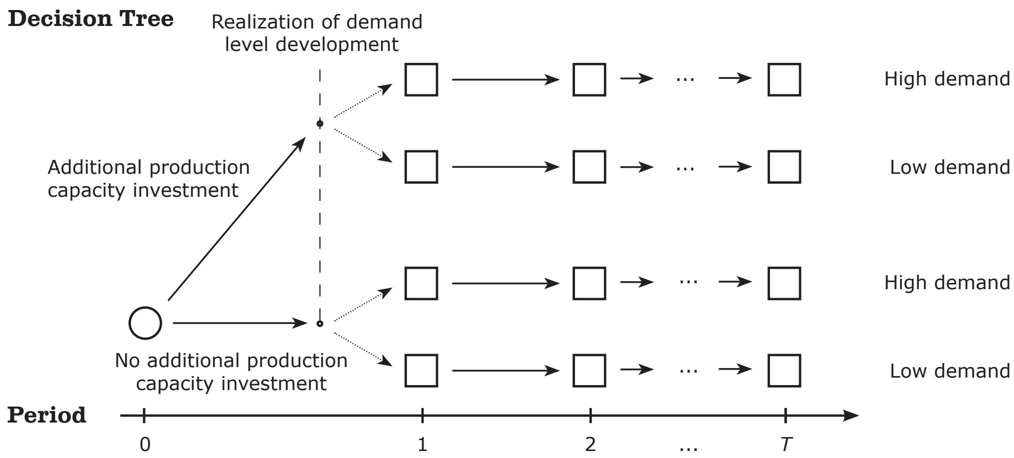

Figure 3.1.: Game structure in the crude oil market from the point of view of one crude oil supplier (○ - decision on initial production capacity investment; □ - hybrid (Cournot/perfect competition market) production/supply game & decision on additional production capacity investment)

In the market model, each supplier decides on the quantity of crude oil produced and supplied to the market in each period, and on its investment level in additional production capacity. They may either act according to Nash-Cournot market power (marginal cost equals marginal revenue) or perfectly competitive (marginal cost equals price). The structure of this game from the point of view of one crude oil supplier is depicted in Figure 3.1.[5].

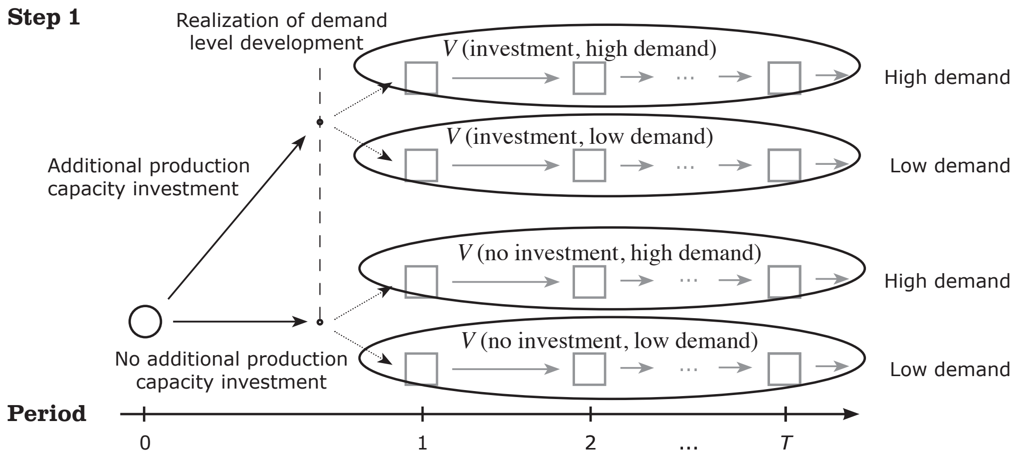

Figure 3.2.: Solution concept, step 1: For each demand development scenario and investment option, a multi-period hybrid market-game is solved numerically. This yields a (deterministic) profit $V(\cdot)$ for each path of the scenario tree.

As usual in dynamic programming, the problem is solved by applying backward induction: in the market model, each supplier solves a profit maximisation problem, which is specified in the following chapter. The KKT conditions of the suppliers are combined with the market clearing constraints to form a MCP market equilibrium model as specified in Definition 3. The total profits $V(\cdot)$ of each supplier are thus computed for each demand level scenario and both "investment" and "no investment" decision from the model solution, as depicted in Figure 3.2. The uncertainty is already resolved at this stage, so each of these games is a deterministic open-loop partial-equilibrium model.

As a second step, depicted in Figure 3.3, the expected profit $\mathbb{E}\ V(\cdot)$ is calculated for both investment options and analysed for each supplier. These values are then put into an appropriate pay-off matrix to determine any possible Nash equilibria between the different suppliers under investigation in this work.[6]

There are two crucial differences between the initial production capacity investment decision (period 0) and subsequent expansions (periods $1 - -T$): the initial decision is binary and strategic. This means that the supplier can either choose to build a certain (strictly positive) production capacity expansion, or not to invest at all in this period. All investment decisions in later periods are continuous, i.e. any value between zero and an upper bound is feasible. In addition, these investment decisions are non-strategic;

[5] The structure presented here is a simplified version; in the actual numerical simulation in this work, more than two demand development scenarios are considered

[6] A Nash equilibrium is a solution where no agent has an incentive to deviate from its chosen strategy given that no other agent changes its strategy.

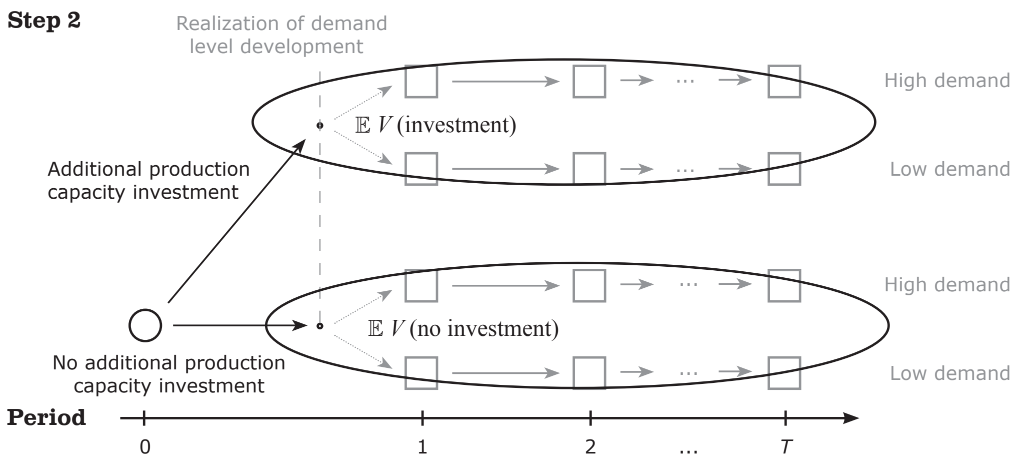

Figure 3.3.: Solution concept, step 2: For both the investment and the no-investment option, the expected profit $\mathbb{E}V(\cdot)$ (with uncertain demand level) is computed and compared

i.e., the supplier invests up to the point where marginal investment cost is equal to the shadow value of constrained capacity in future periods.

These two limitations are owed to the shortcomings of equilibrium models and the difficulty of formulating multi-level strategic games mentioned earlier. This leaves this work partly open to the two main criticisms regarding equilibrium models, namely the continuous and non-strategic nature of investment decisions and the assumption of perfect foresight. However, the main focus is to shed light on the investment incentives under the current economic environment; the approach applied in this work allows to compute reasonable estimates on the profitability of strategic investments today. At the very least, this approach avoids the shortcomings in the period which is of highest interest to this work (i.e., today).[7]

To emphasise the necessity of simplification, let me briefly mention the work by Yegorov and Wirl (2010): they develop a complex game between suppliers and transit countries in the natural gas market, specifically considering geopolitical power vs. production capacity expansions and pipeline investments.[8] However, even for only two asymmetric agents, the model exhibits multiple equilibria (or none at all) in several instances; extending this model to a longer time horizon and more players would – in all likelihood – mean to forgo any hope of a numerical simulation. Hence, I choose a less mathematically challenging approach in this work, for the sake of tractability and a comprehensive data set.

[7] Given the computational obstacles to implementing a closed-loop multi-period Stackelberg model with strategic investment, the approach chosen here is probably the best shot at investigating strategic investment incentives in a reasonably realistic data set.

[8] Their work is motivated by the competition between the natural gas pipelines *Nabucco* and *South Stream* in South East Europe.

The following chapter proposes the equilibrium model used to calculate the NPV in the different demand scenarios and investment cases.

4. A Crude Oil Market Model

Before venturing into introducing the model used in this work, there are two (numerical) crude oil market models that should be presented, in order to highlight the differences between earlier approaches and the one pursued in this work.

4.1. Comparison to other Crude Oil Models

The model proposed by Salant (1976) presented in Chapter 2.1 was subsequently solved numerically (Salant, 1982). It is a Hotelling-type model, but flexible in so far as that not only one cartel may own several extraction units, but a number of players may own more than one extraction unit. In addition, the model allows to model Nash-Cournot market power for certain suppliers; in the numerical example presented in this article, both Mexico and OPEC are Nash-Cournot players, while all other suppliers form a competitive fringe. The model matches the supply of the producers to an aggregated (global) demand curve. A restriction of this model (and indeed of any Hotelling-type model) is the need for assumptions on reserve stocks and a backstop technology[1] in order to solve it numerically.[2]

A more recent model to describe the crude oil market was proposed by Al-Qahtani et al. (2008b); however, they focus purely on the optimal strategy of Saudi Arabia regarding the production levels of different crude oil types. They use an extensive data base and differentiate between different types of crude oil. However, their model is formulated as an optimisation problem; they assume certain profitability margins for other OPEC suppliers, while all other suppliers form a competitive fringe. They formulate a benchmark model as a MCP where all suppliers act perfectly competitive; alas, they do not consider a Nash-Cournot market or non-cooperative game theory regarding other suppliers apart from Saudi Arabia.

The model used in this work, in comparison to the work by Salant, is not a Hotelling-type model; only the suppliers exhausting their stocks over the model horizon consider inter-temporal optimisation. All other suppliers only consider the prevailing price and their marginal costs. As stated in Chapter 2, the focus in this work is put on the next two decades, where total exhaustion of reserves is not a major concern. This also allows

[1] The backstop price was assumed to be 30 $/barrel, "regarded as the conventional wisdom of oil market 'experts' " (Salant, 1982, p. 268) before the Iranian revolution. One may take note that until well after the turn of the century, OPEC aimed for a crude oil benchmark price of 28 $/barrel.

[2] Salant uses a heuristic approach to determine a solution, and not the approach used in complementarity modelling, even though these techniques were already developed at that time (e.g., Hogan, 1975).

to avoid the necessity of making assumptions on a backstop technology; demand growth and expectations about future prices are implicitly included in the inverse demand functions of the consumers.

By formulating the model as a Complementarity Problem (CP), I can avoid the aggregation necessary in the model of Salant, where supply matches one global demand curve. Instead, this model retains a spatial dimension to crude oil trade, which is of interest when investigating the question of "security of supply" in coming decades. At the same time, by introducing arbitragers, the model ensures the convergence of prices observed in the real world. In addition, and in contrast to Al-Qahtani et al., the VI/CP framework allows to include non-cooperative game theory. The model in this work does not distinguish between different types and qualities of crude oil.

4.2. A Complementarity Model for the Crude Oil Market

The model presented here differs from my previous work (Huppmann and Holz, 2009): that approach adapted a model formulated to describe *POOLCO*[3] electricity markets, proposed by Metzler et al. (2003). In this POOLCO model, prices in a demand node must equal – by definition – the pool price plus transport costs between the pool hub and the demand node. This necessarily leads to some counter-intuitive results: for instance, simulation results indicate that prices in Russia, being a large producer, are higher than prices in Central Europe, because these nodes are closer to the pool hub. The model used in this work is more flexible in this regard: arbitragers lead to price convergence, but prices usually are in a range around the pool price, rather than exactly pool price plus transport costs. In general, the results yield a better and more realistic fit to observed values than the POOLCO approach applied earlier.

There are three types of agents included in the model: suppliers, arbitragers located in pool hubs and final demand. Let $y \in Y$ denote years and $n \in N$ the nodes in the model.[4]

4.2.1. The Supplier

The supplier $s \in S$ extracts crude oil at its production nodes n and sells it to final demand, either directly or via the arbitragers. At each production node where it is active, the supplier faces a total reserve of crude oil in place, $\overline{Res^S_{s,n}}$. This amount cannot, in this model, be changed by the supplier through exploration. Since this work focuses on strategic behaviour of oil producing countries, the stochastic nature of exploration and exploiting new reserves is neglected. While this is difficult to reconcile with reality on the level of an individual well, it is not implausible on a national level. While the actual location, size, or quality of reserves may be unknown, it is possible

[3]In a *POOLCO* market, all suppliers sell their output in a central auction, usually at a pool hub.
[4]A comment on notation: the superscript of each variable and parameter refers to the agent(s) to which it is related; subscripts refer to the index set(s).

with today's techniques to obtain reasonable estimates on the total amount of crude oil in the ground in a certain area. The same holds true for the costs associated with exploiting these reserves.

The initial production capacity restriction is denoted $\overline{Cap_n^S}$. The supplier can add additional production capacity $Add_{y,s,n}^S$ at a cost $C_{y,n}^{Inv}(\cdot)$ if this is economically viable. The capacity investment is assumed to exhibit constant unit costs denoted $inv_{y,n}^S$, i.e. a linear cost function. The investment per period may not exceed a maximum investment level $\overline{Add_{y,s,n}^S}$. Actual production is denoted by $Prod_{y,s,n}^S$.

Let $Cap_{y,s,n}^S = \overline{Cap_{s,n}^S} + \sum_{y'<y} Add_{y',s,n}^P$ denote total available capacity in year y, initial capacity plus investment in previous periods. The cost function of the producer follows the function proposed by Golombek et al. (1995). Production costs depend not only on total production in the respective period, but also on the ratio of capacity utilisation in that period, i.e. production costs increase sharply when producing close to full capacity. Any investment will therefore reduce production costs for the same amount of crude oil in future periods (ceteris paribus), as well as allow greater amounts to be produced.

$$\begin{aligned} C_{y,n}^{Prod}(\cdot) &= (lin_{y,n}^S + gol_{y,n}^S) \cdot Prod_{y,s,n}^S + qud_{y,n}^S \cdot \left(Prod_{y,s,n}^S\right)^2 \\ &\quad + gol_{y,n}^S \cdot (Cap_{y,s,n}^S - Prod_{y,s,n}^S) \cdot \ln\left(\frac{Prod_{y,s,n}^S}{Cap_{y,s,n}^S}\right) \end{aligned} \tag{4.1}$$

The cost function consists of a linear, a quadratic and a logarithmic term; lin^S, qud^S, and gol^S are the parameters associated with these terms, respectively.

The supplier decides on transportation via the pipeline network ($Flow_{y,s,n,m}^S$), exports by tanker ship ($Ship_{y,s,n,k}^S$), direct sales to final demand ($Sale_{y,s,n}^{S\to R}$) and sales to the arbitrager at the pool hub $i \in I$ ($Sale_{y,s,n,i}^{S\to A}$) in each period.[5] $A_{n,m}^{Ship} \subseteq (N \times N)$ is the set of all shipping routes (from node n to node m); $A_{n,m}^{Pipe} \subseteq (N \times N)$ is the set of all pipelines. The costs for transporting crude oil from node n to node m is denoted by $tc_{y,n,m}^{Ship}$ and $tc_{y,n,m}^{Pipe}$ for maritime shipping and pipeline, respectively. The supplier applies a discount rate ρ_s^S on profits in future periods.

There are two types of suppliers: those acting competitive (i.e., marginal cost equals price), denoted by the set $F \subseteq S$, and those exerting Cournot market power (i.e., marginal cost equals marginal revenue), $C \subseteq S$. The combination of Cournot and perfectly competitive players is discussed by (Salant, 1982, p. 257).

The suppliers face different profit maximisation problems. Let's first focus on the problem of the perfectly competitive supplier, $s \in F$:

$$\begin{aligned} \max \sum_{y \in Y, n \in N} \left(\frac{1}{\rho_s^S}\right)^{|y|} \cdot \Bigg[& Sale_{y,s,n}^{S\to R} \cdot \pi_{y,n}^R + \sum_{i \in I} Sale_{y,s,n,i}^{S\to A} \cdot (\pi_{y,i}^{Pool} - tc_{y,i,n}^{Pool}) \\ & - C_{y,n}^{Prod}(\cdot) - C_{y,n}^{Inv}(\cdot) - \sum_{l \in A_{n,l}^{Pipe}} Flow_{y,s,n,l}^S \cdot tc_{y,n,l}^{Pipe} - \sum_{k \in A_{n,k}^{Ship}} Ship_{y,s,n,k}^S \cdot tc_{y,n,k}^{Ship} \Bigg] \end{aligned} \tag{4.2}$$

[5]The subscript n of $Sale_{y,s,n,i}^{S\to A}$ refers to the node from which crude is sold to the arbitrager.

$$\text{s.t.} \quad Prod^S_{y,s,n} \leq \overline{Cap^S_{s,n}} + \sum_{y'<y} Add^S_{y',s,n}, \quad \alpha^{Cap}_{y,s,n} \geq 0 \quad \forall\ y \in Y,\ n \in N$$

$$\sum_{y \in Y} Prod^S_{y,s,n} \leq \overline{Res^S_{s,n}}, \quad \alpha^{Res}_{s,n} \geq 0 \quad \forall\ n \in N$$

$$Add^P_{y,s,n} \leq \overline{Add^P_{y,s,n}}, \quad \alpha^{Inv}_{y,n} \geq 0 \quad \forall\ y \in Y,\ n \in N$$

$$\begin{aligned} & Prod^S_{y,s,n} - Sale^{S\to R}_{y,t,n} - \sum_{i \in I} Sale^{S\to A}_{y,t,n,i} \\ & - \sum_{l \in A^{Pipe}_{n,l}} Flow^S_{y,s,n,l} - \sum_{k \in A^{Ship}_{n,k}} Ship^S_{y,s,n,k} \\ & + \sum_{m \in A^{Pipe}_{m,n}} Flow^S_{y,s,m,n} + \sum_{h \in A^{Ship}_{h,n}} Ship^S_{y,s,h,n} \leq 0, \quad \phi^S_{y,s,n} \geq 0 \quad \forall\ y \in Y,\ n \in N \end{aligned}$$

The supplier maximizes the profits from its sales net of production, investment and transport costs. The term $\pi^R_{y,n}$ represents the equilibrium market price at that demand node n; $\pi^{Pool}_{y,i}$ corresponds to the market price at the pool hub i, and $tc^{Pool}_{y,i,n}$ are the transport costs from production node n to the pool hub i. These will be introduced formally in the subsequent sections. The supplier is subject to a mass balance constraint at each node; the amount of crude oil it sells at and exports from any node must not exceed the amount it produces there or imports from other nodes.

Equation 4.3 is the maximisation problem of a supplier acting perfectly competitive. If, however, the supplier is aware of the inverse demand function at node n, it may be profitable to withhold supplies and thereby push up the price at that node. The supplier is then a Cournot player and able to consider the impact on the equilibrium price of its own sales, the sales of other suppliers and sales by arbitragers. This is commonly described as strategic behaviour on the part of the supplier. For simplicity, a Cournot trader is barred from selling to the arbitrager; a Cournot agent selling to the arbitrager would dilute its own market power at the demand nodes at which the arbitrager is present – selling crude oil to the arbitrager can therefore not be optimal for a Cournot supplier.

The profit maximisation problem of a Cournot supplier, $t \in C$, then looks as follows:

$$\begin{aligned} \max \sum_{y \in Y, n \in N} \left(\frac{1}{\rho^S_s}\right)^{|y|} \cdot \Bigg[& Sale^{S\to R}_{y,s,n} \cdot \Pi^R_{y,n}(\cdot) - C^{Prod}_{y,n}(\cdot) - C^{Inv}_{y,n}(\cdot) \\ & - \sum_{l \in A^{Pipe}_{n,l}} Flow^S_{y,s,n,l} \cdot tc^{Pipe}_{y,n,l} - \sum_{k \in A^{Ship}_{n,k}} Ship^S_{y,s,n,k} \cdot tc^{Ship}_{y,n,k} \Bigg] \end{aligned} \tag{4.3}$$

$$\text{s.t.} \quad Prod^S_{y,s,n} \le \overline{Cap^S_{s,n}} + \sum_{y'<y} Add^S_{y',s,n}, \quad \alpha^{Cap}_{y,s,n} \ge 0 \quad \forall\ y \in Y,\ n \in N$$

$$\sum_{y \in Y} Prod^S_{y,s,n} \le \overline{Res^S_{s,n}}, \quad \alpha^{Res}_{s,n} \ge 0 \quad \forall\ n \in N$$

$$Add^S_{y,s,n} \le \overline{Add^S_{y,s,n}}, \quad \alpha^{Inv}_{y,s,n} \ge 0 \quad \forall\ y \in Y,\ n \in N$$

$$-Sale^{S\to R}_{y,s,n} - \sum_{l \in A^{Pipe}_{n,l}} Flow^S_{y,s,n,l} - \sum_{k \in A^{Ship}_{n,k}} Ship^S_{y,s,n,k}$$
$$+ Prod^S_{y,s,n} + \sum_{m \in A^{Pipe}_{m,n}} Flow^S_{y,s,m,n} + \sum_{h \in A^{Ship}_{h,n}} Ship^S_{y,s,h,n} \le 0, \quad \phi^S_{y,s,n} \ge 0 \quad \forall\ y \in Y,\ n \in N$$

The term $\Pi^R_{y,n}(\cdot)$ represents the inverse demand function, which will be introduced in Equation 4.5.

4.2.2. The Arbitrager

The arbitragers act from one of several pool nodes $i \in I$ and aim to exploit price differentials between demand nodes that are not justified by transport costs. The decision variable is the amount sold to final demand nodes, $Sale^{A\to R}_{y,i,n}$. By assumption, each arbitrager acts perfectly competitive; hence, I assume one at each node. For simplicity, the index for the arbitrager and the pool hub at which it is located are identical.

Instead of formulating a profit-maximisation problem similar to that of the supplier, the formulation chosen for the arbitrager directly yields the no-profit KKT conditions.[6] The more concise notation is chosen for its run-time advantage in numerical computation. The problem of the arbitrager looks as follows:

$$\max \sum_{y \in Y, n \in N} \left(\frac{1}{\rho^A_i}\right)^{|y|} \cdot \left[Sale^{A\to R}_{y,i,n} \cdot (\pi^R_{y,n} - tc^{Pool}_{y,i,n}) \right] \tag{4.4}$$

$$\text{s.t.} \quad \sum_{n \in N} Sale^{A\to R}_{y,i,n} - \sum_{s \in F,\ n \in N} Sale^{S\to A}_{y,s,n,i} \le 0, \quad \pi^{Pool}_{y,i} \ge 0 \quad \forall\ y \in Y$$

4.2.3. Final Demand

Final demand at node n is represented by a linear inverse demand function, $\Pi^R_{y,n}(\cdot)$; this closes the model. As stated by (Metzler et al., 2003, p. 127), the use of affine demand functions is standard in this type of models.

[6] During parametrisation and calibration of the model, a more elaborate formulation was also determined for the arbitrager, with a distinct purchase price, market clearing between each supplier and the arbitrager, and a mass-balance constraint at the pool hub. The numerical results are identical.

$$int^R_{y,n} - slp^R_{y,n} \cdot \left[\sum_{s \in S} Sale^{S \to R}_{y,s,n} + \sum_{i \in I} Sale^{A \to R}_{y,i,n} \right] - \pi^R_{y,n} \leq 0, \qquad \pi^R_{y,n} \geq 0 \quad \forall \quad y \in Y, \; n \in N \tag{4.5}$$

4.3. Caveats of this model

There are several caveats with this model: as already mentioned earlier, this model does not explicitly consider the *heterogeneity of crude oil*. The model could be extended to include several types of crude, as well as different demand-side preferences for certain types - and hence a different willingness-to-pay for each; however, in the long term, refineries can be adapted to process different types of crude, and explicitly accounting for this adaption process is not trivial. In addition, obtaining reasonable estimates for adaption costs would be a challenge, as reliable data are hard to come by in the oil industry. Similarly, the parametrisation of different types would pose some difficulties on the production side. Nevertheless, some differences of crude oil quality are considered in the calibration of this model (this is discussed in Chapter 5.2).

Following a similar rationale, *production capacity depreciation* is not considered here – obtaining reliable estimates on the exhaustion of individual fields and the necessary investment to replace depreciated production capacity is virtually impossible for the level of disaggregation used in this model. By assumption, keeping the available production capacity constant is included in the daily production costs – in the terminology of this work, "investment" only refers to capacity expansions.

This model is not a Hotelling-model, so not all crude oil reserves are exploited within the model time horizon. This leaves open the question how to value remaining reserves in the model time horizon (commonly referred to as *scrap value* in Operations Research). In the approach pursued here, the scrap value is ignored completely: to determine the value of remaining reserves would require to make assumptions on future demand, interest rates and reserve growth for up to two centuries.

For the same reason, this approach does not take into account any *backstop technology*.[7] Explicitly including a backstop technology is possible (e.g., Huppmann et al., 2009); I have omitted it here for – again - the "no reliable estimate"-problem. Nevertheless, a backstop technology is implicitly included in the inverse demand function and the demand projections.

This model uses a *static inverse demand function*: the price of crude oil in one period does not have an influence on the demand in any other period.[8] As before, any substitution due to high oil prices is implicitly included in the parametrisation of the

[7] A *backstop technology* is a technique or resource which has the potential to replace the primary resource (i.e., bio fuel or coal liquefaction (Coal-to-Liquid, CTL to replace oil products) given a sufficiently high price level.

[8] In reality, a price spike might induce consumers to substitute crude oil or oil products with other energy sources in the long run.

inverse demand function. Explicitly including such a substitution, however, might lead to a non-convex problem and is therefore not pursued here.

Another shortcoming of this approach is the assumption of *profit maximisation*. As stated in Chapter 2.3, target revenue behaviour and production sharing agreements can be observed for some producers. One could consider using other functional forms for the optimisation problem of the supplier. However, parametrization of such a model would be highly ambiguous. Production costs and demand functions are the only data readily available, so any large-scale numerical exercise should mainly draw on these. On a similar note, any more elaborate or complex collusion mechanism among OPEC suppliers cannot be captured by a Cournot/competition model - this approach only allows to model a standard cartel or non-cooperative strategic behaviour.

Regarding *strategic behaviour*, this model allows for Cournot behaviour in the downstream market, but capacity expansions follow a competitive rule: if the marginal value of the capacity constraint plus the cost reductions in future periods due to the Golombek cost function exceed investment cost, the investment is undertaken. This neglects the strategic aspects of both under-investment to drive up prices in the future as well as over-investment to deter other suppliers. Unfortunately – and as discussed at length earlier – including this type of strategic behaviour in a partial equilibrium model would necessarily lead to multiple-level games, which are beyond the scope of this work. Obviously, this model also – unrealistically – assumes that the market power structure does not change over the model time horizon.

When analysing the results, there is one caveat with regard to the arbitragers and the pool market: it is not possible to determine the origin of the crude oil, which is sold by the arbitragers. One can only compare the relative amounts sold into the pool by different suppliers to the relative amounts sold on to final demand.

Last, but not least, it must be stated that any partial equilibrium model cannot easily consider (geo-)political factors: decisions why to import from or export to certain countries and not others, as well as special rebates offered to some consumers, are not usually driven by mathematically concise optimisation problems. It is for other fields of economics to study these aspects of the crude oil market.

4.4. Implementation

The profit maximisation problems and the operational constraints of the suppliers and the arbitragers presented in this chapter give rise to a MCP by deriving the KKT conditions, combined with the market-clearing conditions representing final demand. These are stated in Appendix A.

In the calibration presented in Chapter 5.2 and Appendix C, I compare the simultaneous-move game discussed so far to a Stackelberg market. As the calibration is only simulated for single periods, the problem of dynamic inconsistency does not arise in this case. The Stackelberg market is implemented as an MPEC by excluding one supplier from the

KKT derivation and using its profit maximisation problem as the upper-level problem (Definition 5). The KKTs of the other agents then form the lower-level problem.

The model is implemented in the General Algebraic Modeling System (GAMS) and solved as an MCP using the PATH solver (Ferris and Munson, 2000), while the NLPEC solver is applied to the MPEC.

The following chapter specifies demand scenario assumptions and input data for this work, as well as some notes on calibration and the market power setup.

5. Scenarios & Data

This chapter introduces the scenarios applied in this work, the suppliers under investigation, as well as presenting the data and an overview of the calibration.

The base year of the model data set is 2008. The model is computed for the time horizon 2012–2030 in three-year intervals. Two decades seem to be a sufficient period for amortisation of the initial investment. Simulating the model in three-year intervals is a trade-off between sufficient detail and acceptable computing time. Since this model is an open-loop model, the benefit of a higher time resolution would be small.

Every investment in production capacity is assumed to be available in the next period, i.e. after three years. This investment cycle is considerable shorter than suggested by other authors; for instance, Zaklan et al. (2010) consider an investment horizon of seven to ten years. By assumption, this work abstracts from exploration and development, assuming that reserve size and location are known (or rather, that development and exploration take place outside the model); this partly explains the shorter investment cycle. In addition, one may argue that many projects were shelved in recent months, as noted by Wurzel et al. (2009) – restarting them would generally be quicker than developing a new greenfield project. Depreciation of existing production capacity is neglected; its replacement is included in the regular production costs.

5.1. Demand Development Scenarios

5.1.1. Speedy Recovery

This scenario is based on the *Reference Scenario*, presented in the World Energy Outlook (WEO) 2009 (IEA, 2009a) introduced in Chapter 1.2. It simulates a quick global recovery from the current economic crisis. No additional political measures to mitigate climate change are taken, so demand increases significantly over the next decades. The consumption and price development is depicted in Figure 5.1: crude oil consumption surpasses 100 million barrel per day (MMbbl/day) in 2027, while the crude oil price reaches 200 US $ per barrel (bbl).

No or few political and regulatory restrictions are put on further exploration and development activities. In addition, a higher oil price makes developing new fields viable, which are currently beyond the engineers' reach. Hence, the reserve base is assumed to grow by 50 % over the time horizon compared to the base year.[1] Each production node

[1]Reserves are generally those quantities in place which can be recovered with reasonable likelihood

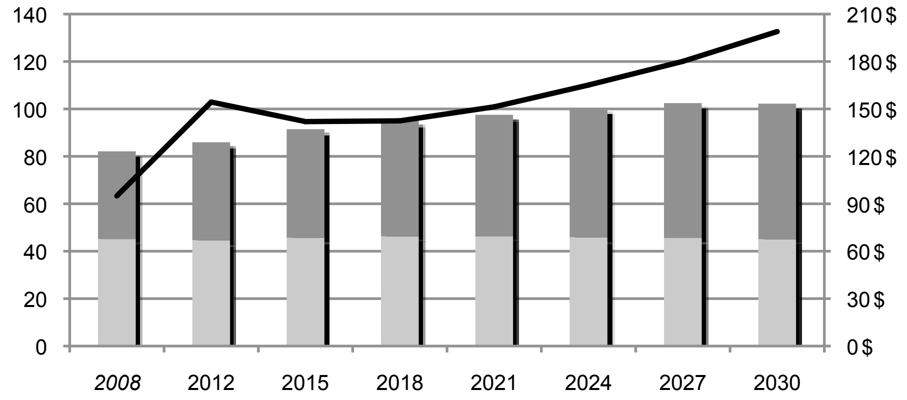

Figure 5.1.: Consumption (bar, left axis, in MMbbl/d) by ■ OECD and ■ Non-OECD; and price development (line, right axis, in US $/bbl) in Southern USA; "Speedy Recovery" scenario

is allowed to increase its production capacity by 8 % relative to the base year capacity, if this is economically viable.[2] Maritime transport costs are assumed to rise by 3 % per year due to increasing oil prices.[3]

In this scenario, the fear expressed in the WEO 2009 about a price spike in the next years becomes reality – sluggish current investment meets a strong demand increase, leading to a price spike.

5.1.2. Green Rebound

This scenario is based on *450 Scenario*, WEO 2009 (IEA, 2009a). It assumes that sufficient measures are taken to curb greenhouse gas (GHG) emissions and reduce global warming. As described in Knopf et al. (2010), the implementation of such an outcome depends squarely on a consensus within the international community.

This scenario assumes regulatory and political restrictions imposed on the oil industry as a result of GHG mitigation efforts, such as a ban on deep-water drilling or restricted access to sensitive natural habitats, as well as reduced global demand. Hence, the reserve base is assumed to only grow by 30 % compared to the base year, and capacity expansions are limited to 5 % relative to base year capacity. Maritime transport costs rise by 3 %, which is partly due to the increasing oil price, as well as the introduction of global carbon tax on fossil fuels or a similar measure.

In OECD countries, political measures to curb demand for fossil fuels quickly make

using today's methods. Since engineering and extraction methods are improving continuously, a growth in the reserve base accounts for this technical development.

[2] I must admit that this is an exogenously unrealistically large value; however, any lower value resulted in unrealistically high oil prices during calibration.

[3] Maritime shipping costs actually depend on the oil price; however, endogenizing transport costs would significantly complicate the model. Setting the cost increase exogenously is a second-best solution.

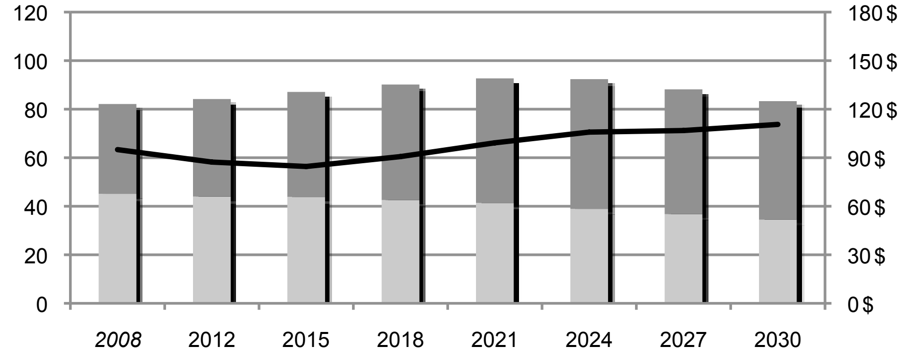

Figure 5.2.: Consumption (bar, left axis, in MMbbl/d) by ■ OECD and ■ Non-OECD; and price development (line, right axis, in US $/bbl) in Southern USA; "Green Rebound" scenario

an impact, while consumption in non-OECD countries continues to grow for another decade, albeit at a lower pace than in the "Speedy Recovery" scenario. After that, global consumption decreases, as depicted in Figure 5.2.

5.1.3. The Long Slump

This scenario presents the economic uncertainty regarding economic growth, compared to the "Speedy Recovery" scenario. Whether the reasons for sluggish growth are a sovereign default, a double-dip recession, or disruption of global travel due to volcanic activity, is of lesser relevance; the main assumption is that demand is reduced compared to the base year and growth is very slow, as depicted in Figure 5.3.

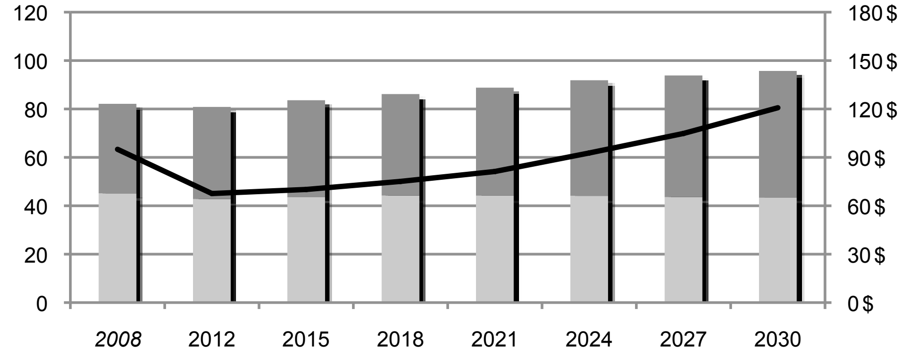

Figure 5.3.: Consumption (bar, left axis, in MMbbl/d) by ■ OECD and ■ Non-OECD; and price development (line, right axis, in US $/bbl) in Southern USA; "Long Slump" scenario

Due to the weak economic outlook in this scenario, further international GHG mitigation measures are stalled. Hence, both the reserve base growth and the maximum investment level are identical to the “Speedy Recovery” scenario. Due to the lower oil price, maritime transport costs only increase by 1 % per year.

5.1.4. Tiger & Dragon

This scenario is a combination between the “Speedy Recovery” and the “Long Slump” scenarios: while the economic recovery is slow in OECD countries, non-OECD countries quickly rebound from the current trough. The consumption and price development are shown in Figure 5.4.

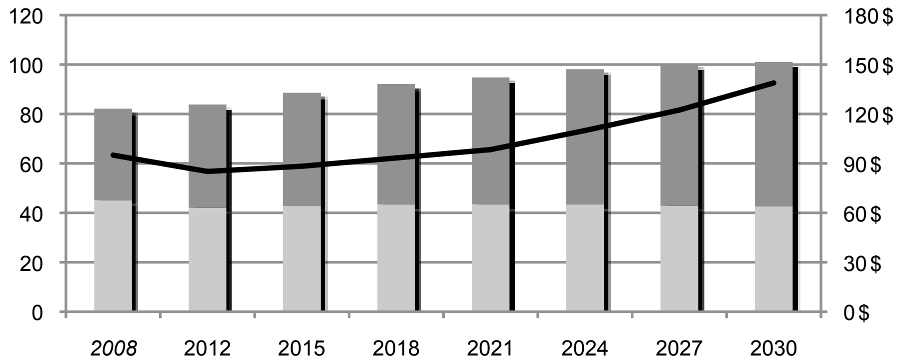

Figure 5.4.: Consumption (bar, left axis, in MMbbl/d) by ■ OECD and ■ Non-OECD; and price development (line, right axis, in US $/bbl) in Southern USA; “Tiger & Dragon” scenario

Again, without the initiative of OECD countries, no serious international measures against climate change are undertaken. The assumptions are as in the “Speedy Recovery” scenario, with maritime transport costs increasing by 2 % per year.

Table 5.1 summarises the different scenarios and the underlying assumptions.

Scenario	Reserve Base Growth (total)	Maximum Capacity Expansion (per period)	Maritime Shipping Cost Growth (p.a.)
Speedy Recovery	50 %	8 %	3 %
Green Rebound	30 %	5 %	3 %
Long Slump	50 %	8 %	1 %
Tiger & Dragon	50 %	8 %	2 %

Table 5.1.: Overview of scenario assumptions (compared to 2008 levels)

5.2. Data Sources & Model Assumptions

The base year of the model is 2008, as this is the most recent year for which reliable data was available at the outset of this work. For the calibration, data of the years 2005–2007 is also used. Reserve, production and consumption data in the base year are gathered from BP (2009) and IEA (2009b).[4] As the IEA usually includes natural gas liquids (NGL) in their crude oil data, I follow their methodology.[5] The data set comprises more than 93 % of global production and consumption in the base year.

For the US, consumption and production data are disaggregated along the four census regions (as published by the U.S. Census Bureau) and Alaska drawing on EIA data [6] ; for Canada, data from Statistics Canada is used for disaggregation. A map of countries and regions included in the numerical simulation is presented in Figure 5.5[7]; a full list is included in Appendix B.

Three pool hubs are assumed at which arbitrageurs are active: Southern USA (representing the *West Texas Intermediate* index, WTI); Great Britain (representing the *Brent* blend) and Indonesia (representing the *Tapis* and *Minas* benchmarks).[8] These nodes are chosen so as to be in line with the three main consumption regions.

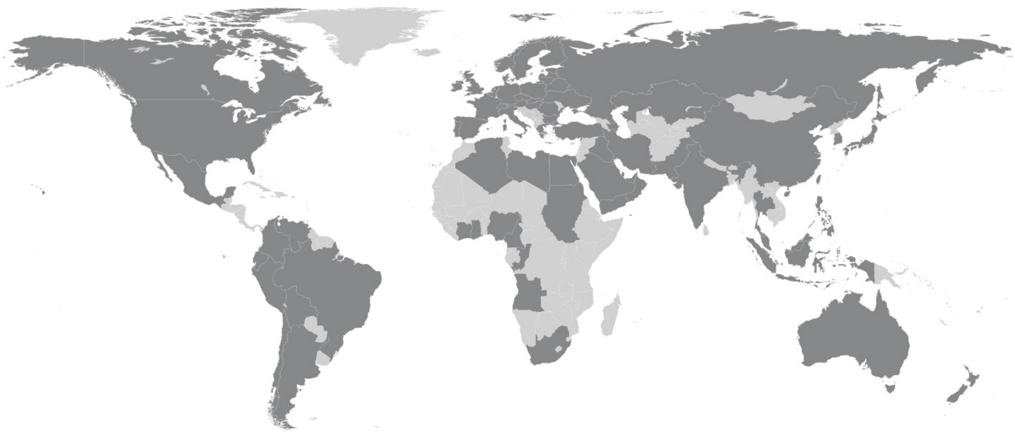

Figure 5.5.: Countries and regions included in the simulation

Pipeline distances are gathered from the country information provided by the EIA; distances between the main ports are taken from Petromedia Ltd. Transport costs are taken from data provided by the Oil & Gas Journal (OGJ). Pipeline routes are gathered

[4]Please note that there may be a considerable difference between BP versus IEA data; wherever possible, data from the IEA is used.

[5]Definition according to IEA (2009b): "NGL are liquid or liquefied hydrocarbons recovered from natural gas in separation facilities or gas processing plants".

[6]The census regions are similar to the "Petroleum Administration for Defense Districts" (PADD) used by the EIA; however, the differences are sufficient to cause a headache and frustration when compiling data from several sources.

[7]This graphic is based on `http://commons.wikimedia.org/wiki/File:BlankMap-World-v2.png`

[8]The Tapis index is actually located in Malaysia; however, Indonesia and Malaysia are aggregated and treated as one node in the model data set.

from the website of the Association of Oil Pipelines (AOPL) and the World Fact Book, a service hosted by Information Technology Associates.[9] Transport costs are derived from information on a website hosted by the American Petroleum Institute (API), which are based on OGJ databases. These data are complemented and compared with other sources, such as the EIA country information and the Joint Oil Data Initiative (JODI).

Production costs are derived from Aguilera et al. (2009), which provides average production costs for a large number of oil fields. Constructing a merit order of fields per country (or region, where no sufficient data is available) allows to derive a parametrisation of the national production cost functions as used in Equation 4.1. The model does not explicitly consider different types of crude oil; however, the aggregate API gravity of each country's crude oil was considered, with those countries producing "heavier" crude oil having a mark-up added to their production costs to reflect lower quality.[10]

Consumption trends in individual countries are deducted from the scenarios presented above. An overview of demand elasticities in a number of studies is given by Fattouh (2007); the values range from −0.11 to 0 in the short term and from −0.64 to +0.38 in the long run. In this work, I choose −0.10 to calculate the slope of the inverse demand function (Equation 4.5).

The interest rate by which suppliers discount future profits is assumed to be 5 % p.a. Investment costs in additional production capacity are derived from various OGJ and EIA articles as well as The Economist (2009b). Investments in refineries are not explicitly considered, as their capacities are pre-determined by the inverse demand functions.

5.3. Initial investment options

Regarding the initial investment options for Saudi Arabia and Russia, the following assumptions are used: for Saudi Arabia, it is assumed that an investment in the initial period (2008) would add 1 MMbbl/d in 2012 (equivalent to 10 % of actual production in 2008). This may seem a large increase in a short time-frame; however, this does not necessarily have to be new projects. Instead, this "investment" could (to some extent) be seen as a firm commitment by Saudi Aramco to bring online a certain part of its unused capacity.

For Russia, the investment option assumes an expansion of 0.5 MMbbl/d of production capacity (equivalent to 5 % of actual production in 2008), to be online in 2012. This may over-estimate the actual potential capacity expansions in the next years. However, I choose a relatively large value to make the difference in the NPV's more visible.

[9] See `http://www.theodora.com/pipelines/world_oil_gas_and_products_pipelines.html`

[10] *API gravity* is a measure of the relative density of crude oil to water, and it can be used as a – simplistic – proxy for the quality of crude oil. Besides the gravity, sulphur is a main indicator of crude oil quality.

5.4. Calibration and Market Power Setup

As stated in Chapter 2.8, determining market power in the crude oil industry is not quite straightforward. Consequently, as the first calibration step, the model is run as a one-period model for a number of market power setups. To reduce the bias of choosing one particular year as reference, each of the years 2005–2008 is used.

The data for the calibration runs follows the sources presented above; production costs are assumed to have increased by 2 % per year over the calibration time horizon; maritime shipping costs were adjusted according to OGJ data as well as the Baltic Dry Index (BDI)[11]

Since no reliable data is available regarding actual available capacity, a capacity utilisation rate is assumed for all suppliers and available capacity calculated from actual production levels. This capacity utilisation level is assumed to be 95 % for most OPEC suppliers, and in the range of 97–99 % for all others. Obviously, this is a rather crude attempt at estimating available capacity. However, as the focus of this work is strategic investment today and the outlook of crude oil, a more detailed study would lead too far off the topic. Whether one supplier restricts its output due to constrained capacity, strategic considerations or the OPEC quota is of lesser relevance in this modelling framework; the main aim is to decide which setup best describes observed values in the modelling framework used here. Aggregated calibration results are given in Appendix C.

As a first step, several market power scenarios are solved as simultaneous-move games (i.e., MCP):

- Nash-Cournot market *(Cournot)*[12]
- Perfectly competitive market *(Competition)*
- Non-cooperative OPEC oligopoly, i.e. OPEC suppliers are Cournot players, while non-OPEC suppliers form a competitive fringe *(Oligopoly)*
- OPEC Cartel, i.e. a joint OPEC supplier acts as a Cournot player, facing a competitive fringe of non-OPEC suppliers *(Cartel)*

Besides simultaneous-move games, the notion of sequential games is often raised in the crude oil literature. Hence, the following market power setups are computed as Stackelberg leader-follower markets (i.e., MPEC); because the Nash-Cournot market setup in the simultaneous-move games yields unrealistically high oil prices in all periods, all non-OPEC suppliers form a competitive fringe in these simulations:

- Saudi Arabia acts as Stackelberg leader; other OPEC suppliers are Cournot players *(Oligopoly MPEC)*

[11] The *Baltic Dry Index* is a daily index of maritime transport costs for several bulk cargo shipments on various transport routes. In this work, I use yearly average values as a proxy for the changes in shipping costs.

[12] As only competitive suppliers can sell to the arbitrageurs, these are not active in this setup; price convergence does not occur.

- The OPEC cartel acts as one supplier and is the Stackelberg leader, maximising joint profits *(Cartel MPEC)*

Choosing the best fit from the calibration results is not straightforward. Perfect competition, a Cournot market and the cartel setups (both simultaneous-move or Stackelberg leader) can be ruled out. Observed prices are usually between the results of the *Oligopoly* and the *Oligopoly MPEC* setups; however, Saudi Arabia significantly underproduces in the *Oligopoly* setup. Consequently, making Saudi Arabia a Cournot player is out of the question.

On the other hand, extending a Stackelberg model to multiple periods is not easily possible due to the problem of dynamic inconsistency, as elaborated earlier. Hence, I test another simultaneous-move setup: all OPEC suppliers except for Saudi Arabia act as Cournot players, while Saudi Arabia and all non-OPEC suppliers behave competitively *(Oligopoly 2)*. This choice of market power setup should not directly be seen as an assertion that Saudi Arabia does not exert market power; instead, this setup should be interpreted such that a hybrid Cournot/competition model cannot fully capture the complex interaction within OPEC and the non-economic incentives driving Saudi decisions.

This simulation yields results close to the setup where Saudi Arabia is the Stackelberg leader and OPEC is a non-cooperative oligopoly. Nevertheless, when examining the simulation results in more detail, one finds crude oil imports into OPEC countries; this is due to the under-supply of their domestic markets by OPEC suppliers, of which the arbitragers take advantage. To iron out this rather implausible result, all Cournot players are assumed to act competitively in their domestic market. In the model, this is achieved by replacing the KKT condition Equation A.11 by Equation A.8 for sales at the production node of the respective Cournot supplier. This setup is called *(Oligopoly 3)*. It delivers a reasonable fit to observed values in all calibration years, without any such implausible results.

Having obtained a market power setup that yields a reasonable fit to observed values, the data are then further calibrated; this is achieved by adjusting production costs and trade route costs. Once the fit is satisfactory, the production capacity and demand data for future periods are included for each scenario and investment option. The model is run as a multi-period model to obtain the scenario results, which are presented in the following chapter.

6. Results

6.1. Investment Game Nash Equilibrium

The interesting – and possibly counter-intuitive – result of this work is that the Nash equilibrium of the investment game does not depend on the demand development and the action of the other agent.[1]

Expanding capacity results in lower profits for Russia in some cases; accounting for investment costs, investment is never an optimal strategy. So even if there was no uncertainty regarding future demand for crude oil, Russia would be better off not investing today in any of the cases investigated in this work. This result occurs in spite of the high variation in the absolute level of profits between the different demand scenarios, as summarised in Table 6.1.

Of course, the actual profit levels depend on many assumptions underlying the numerical simulation. However, the fact that investment is not an optimal strategy for Russia in any demand scenario indicates that this result is fairly stable.[2]

Hence, one may conclude that the economic loss for Russia from its unstable political and economic environment – and the ensuing reluctance by foreign oil companies to invest in new infrastructure – is small. Given that many Russian oil fields are currently exploited by international oil companies, some arm-twisting by the Kremlin to bring more production under its influence – through either joint-ventures or outright nationalisation – may well be a better strategy than to increase production.[3]

The story is more straightforward for Saudi Arabia: in all scenarios, investment is the optimal strategy. Hence, the continued investment scheme by Saudi Aramco mentioned in Chapter 1.4 is a rational strategy. Of course, Saudi Arabia is in a different position than Russia: virtually all production is unified under one umbrella, Saudi Aramco; financing and expertise for further expansions are readily available; and last but not least, production and investment costs are much lower than for most other suppliers.

[1] If this had been obvious from the outset of this work, I would not have needed to go to all the lengths to develop this rather brainy and complicated Nash investment game combined with a market equilibrium model.

[2] If investment was an optimal strategy in one demand scenario and not in another, one would have to dedicate more analysis to the likelihood of each scenario, in order to arrive at a reasonable weighting of the scenario results. As the results are similar for all demand scenarios, a uniform probability distribution for the scenarios is assumed for simplicity.

[3] If the expropriation of an oligarch serves some domestic political aim at the same time, who were the Kremlin not to use the opportunity?

Expected pay-off (average of demand scenarios, uniform distribution)

		Russia: No Investment		Russia: Investment	
		Saudi Arabia	Russia	Saudi Arabia	Russia
Saudi Arabia	No Investment	5760	**3619**	5643	3535
	Investment	**5875**	**3339**	**5731**	3246

"Speedy Recovery" scenario

		Russia: No Investment		Russia: Investment	
		Saudi Arabia	Russia	Saudi Arabia	Russia
Saudi Arabia	No Investment	8444	**6319**	8182	6216
	Investment	**8499**	**5811**	**8210**	5680

"Green Rebound" scenario

		Russia: No Investment		Russia: Investment	
		Saudi Arabia	Russia	Saudi Arabia	Russia
Saudi Arabia	No Investment	4950	**2832**	4912	2745
	Investment	**5098**	**2603**	**4997**	2505

"Long Slump" scenario

		Russia: No Investment		Russia: Investment	
		Saudi Arabia	Russia	Saudi Arabia	Russia
Saudi Arabia	No Investment	4316	**2094**	4244	2039
	Investment	**4429**	**1973**	**4373**	1928

"Tiger & Dragon" scenario

		Russia: No Investment		Russia: Investment	
		Saudi Arabia	Russia	Saudi Arabia	Russia
Saudi Arabia	No Investment	5328	**3233**	5232	3141
	Investment	**5474**	**2971**	**5344**	2872

Table 6.1.: Nash-game: discounted supplier profits net of investment cost (2012-2032) by demand scenario and average, in billion US $; in each cell, the bottom left value is the discounted profit of Saudi Arabia, while the top right value is the discounted profit of Russia; dominant strategies are marked in bold

6.2. Demand Scenario Results

This section now takes a closer look on the individual scenario simulation results and the outlook on the crude oil market in the coming decades. Since the previous section established the Nash-equilibrium of the investment game to be "Saudi – investment, Russia – no investment", all results in this section are taken from that simulation run. Since the data set does not cover all production and consumption in the base year, the results presented below account for the non-model consumption and production trends. They are aggregated with non-OPEC, non-OECD countries, under the assumption that non-model trends follow these countries.

When looking at the results, it must be noted that Russia still expands production capacity in some scenarios, in spite of the result in the previous section. This is due to the limitation of the simulation model to allow only for non-strategic investment. Hence, even if the previous section established that investment is not an optimal strategy in a strategic game, Russia nevertheless expands capacity in the competitive setting of the equilibrium model in some demand scenarios. At the very least, one can gauge from these results the need for additional investment by other suppliers, in case Russia keeps up its strategic under-investment in the coming years. Saudi Arabia continues to invest in all periods of the equilibrium model.

For each of the four scenarios, three tables are provided on the following pages: production quantities, consumption trends and the crude oil price development. Refinery gate prices are provided as weighted averages for the three main demand regions: North America, Europe and the former Soviet Union, and Asia Pacific. Reference values for the base year are given in *italics*.[4]

[4]Please direct any complaints regarding the fact that 2008 reference production and consumption amounts do not match to: *BP p.l.c., 1 St James's Square, London SW1Y 4PD, United Kingdom.*

6.2.1. Speedy Recovery

In this scenario, demand grows quickly, with a price spike in the first model period (2012). This is due to demand exceeding available production capacity due to insufficient investment during the crisis and a quick upturn in demand – this is the risk pointed out by the WEO 2009 (as mentioned in Chapter 1.2). Investment catches up in the following periods, hence prices fall slightly at first, only to increase towards the end of the model time horizon, as more suppliers deplete their reserves. Higher oil prices lead to an increase in transport costs, so the prices diverge between the demand regions compared to the current situation; the Asia Pacific region experiences higher prices than North America or Europe.

	2008	2012	2015	2018	2021	2024	2027	2030
Saudi Arabia	*10.3*	11.4	12.2	13.1	13.9	14.7	15.5	16.4
Middle East OPEC	*13.4*	14.1	15.2	16.4	17.5	18.6	19.7	20.6
Other OPEC	*11.1*	11.6	12.5	13.4	14.4	15.3	16.1	16.3
OECD	*18.0*	18.5	19.1	18.4	17.0	15.7	14.0	12.3
Russia	*9.8*	10.0	10.8	11.6	12.4	13.2	14.0	14.0
Other	*19.2*	20.4	21.4	21.5	21.7	22.0	22.3	19.9
Total	***81.8***	**86.0**	**91.2**	**94.4**	**96.9**	**99.5**	**101.6**	**101.5**

Table 6.2.: Crude oil production in the “Speedy Recovery” scenario, in MMbbl/d

	2008	2012	2015	2018	2021	2024	2027	2030
North America	*23.8*	21.9	22.4	22.8	22.8	22.7	22.5	22.3
Eurasia	*20.2*	20.5	21.0	21.2	21.3	21.0	21.0	20.9
Asia Pacific	*25.3*	27.4	29.5	31.3	32.8	34.5	35.7	35.7
Middle East	*6.4*	7.2	8.2	8.7	9.2	10.2	10.6	10.5
South America	*5.9*	6.1	6.7	7.0	7.3	7.4	7.9	8.3
Africa	*2.9*	3.0	3.3	3.4	3.6	3.7	3.9	3.8
Total	***84.5***	**86.0**	**91.2**	**94.4**	**96.9**	**99.5**	**101.6**	**101.5**

Table 6.3.: Crude oil consumption in the “Speedy Recovery” scenario, in MMbbl/d

	2012	2015	2018	2021	2024	2027	2030
North America	142.94	130.64	126.04	134.10	146.62	160.70	177.64
Eurasia	141.92	132.22	133.35	141.24	154.19	168.60	186.62
Asia Pacific	144.28	134.42	135.49	143.25	156.01	170.18	188.05

Table 6.4.: Crude oil price (weighted average) in the “Speedy Recovery” scenario, in US $/bbl

6.2.2. Green Rebound

Climate change mitigation initiatives quickly lead to a reduction in demand in Europe and North America, while consumption in non-OECD countries continues to increase for approximately one decade. Prices are considerably lower than in the "Speedy Recovery" scenario; in addition, production in the OECD declines at a far quicker pace than in any other scenario due to the assumed restrictions on reserve growth and capacity expansions. Nevertheless, prices do not increase as steeply as in the other scenarios due to declining demand towards the end of the model time horizon.

	2008	2012	2015	2018	2021	2024	2027	2030
Saudi Arabia	*10.3*	11.4	12.2	13.0	13.8	14.6	15.4	16.2
Middle East OPEC	*13.4*	14.1	15.2	16.3	17.3	17.7	17.7	17.7
Other OPEC	*11.1*	11.4	11.7	12.2	12.5	12.6	12.5	12.5
OECD	*18.0*	17.4	17.0	16.6	16.3	15.0	11.6	8.0
Russia	*9.8*	9.8	10.4	10.5	10.5	10.5	10.4	10.4
Other	*19.2*	19.7	20.0	20.4	20.8	20.3	19.0	16.7
Total	***81.8***	**83.8**	**86.5**	**89.0**	**91.2**	**90.7**	**86.6**	**81.5**

Table 6.5.: Crude oil production in the "Green Rebound" scenario, in MMbbl/d

	2008	2012	2015	2018	2021	2024	2027	2030
North America	*23.8*	21.4	21.5	20.9	20.1	18.9	17.9	16.8
Eurasia	*20.2*	19.8	19.7	19.2	19.4	18.5	17.6	16.7
Asia Pacific	*25.3*	27.0	28.5	31.2	33.3	34.4	33.2	31.0
Middle East	*6.4*	6.6	7.0	7.5	8.0	8.5	8.0	7.6
South America	*5.9*	6.0	6.5	6.7	6.9	6.6	6.3	6.3
Africa	*2.9*	3.0	3.3	3.4	3.6	3.7	3.7	3.4
Total	***84.5***	**83.8**	**86.5**	**89.0**	**91.3**	**90.7**	**86.6**	**81.5**

Table 6.6.: Crude oil consumption in the "Green Rebound" scenario, in MMbbl/d

	2012	2015	2018	2021	2024	2027	2030
North America	82.04	78.50	85.31	93.38	99.43	100.02	102.59
Eurasia	81.83	80.35	87.43	95.77	102.07	102.66	106.01
Asia Pacific	82.85	81.93	89.52	97.75	103.85	104.14	107.36

Table 6.7.: Crude oil price (weighted average) in the "Green Rebound" scenario, in US $/bbl

6.2.3. Long Slump

Demand growth remains subdued for approximately one decade in this setting; afterwards, demand growth picks up speed. OECD countries and OPEC countries maintain a relatively stable production level across the entire model horizon. Prices drop considerably compared to 2008 levels, and then only slowly increase towards the end of the time frame under investigation.

	2008	2012	2015	2018	2021	2024	2027	2030
Saudi Arabia	*10.3*	11.4	12.2	13.1	13.9	14.7	15.5	16.4
Middle East OPEC	*13.4*	14.1	14.8	15.8	16.9	17.4	17.5	17.5
Other OPEC	*11.1*	10.5	11.0	11.6	12.2	12.5	12.6	12.7
OECD	*18.0*	16.0	16.2	15.7	15.3	15.8	16.1	16.6
Russia	*9.8*	9.4	9.3	9.4	9.4	9.6	9.7	9.8
Other	*19.2*	19.0	19.6	20.0	20.3	20.9	21.3	21.6
Total	***81.8***	**80.4**	**83.1**	**85.6**	**88.0**	**90.9**	**92.7**	**94.6**

Table 6.8.: Crude oil production in the “Long Slump” scenario, in MMbbl/d

	2008	2012	2015	2018	2021	2024	2027	2030
North America	*23.8*	20.7	21.1	21.5	21.5	21.5	21.3	21.1
Eurasia	*20.2*	19.2	19.5	19.9	20.0	20.3	20.2	20.2
Asia Pacific	*25.3*	25.2	26.6	28.0	29.5	31.0	32.1	33.0
Middle East	*6.4*	6.4	6.5	6.5	6.8	7.3	8.0	8.5
South America	*5.9*	6.0	6.2	6.5	6.8	7.3	7.5	7.9
Africa	*2.9*	2.9	3.1	3.2	3.3	3.6	3.7	3.9
Total	***84.5***	**80.4**	**83.1**	**85.6**	**88.0**	**90.9**	**92.7**	**94.6**

Table 6.9.: Crude oil consumption in the “Long Slump” scenario, in MMbbl/d

	2012	2015	2018	2021	2024	2027	2030
North America	64.00	64.71	69.64	76.13	87.15	99.02	114.51
Eurasia	63.79	66.74	71.62	78.03	89.21	101.16	116.58
Asia Pacific	64.68	67.65	72.61	78.92	90.39	102.39	117.86

Table 6.10.: Crude oil price (weighted average) in the “Long Slump” scenario, in US $/bbl

6.2.4. Tiger & Dragon

Non-OECD countries quickly expand consumption, benefiting from the depressed prices due to sluggish demand growth in Europe and North America. The final demand price divergence observed in the "Speedy Recovery" does not occur as strongly in this scenario.

	2008	2012	2015	2018	2021	2024	2027	2030
Saudi Arabia	*10.3*	11.4	12.2	13.1	13.9	14.7	15.5	16.4
Middle East OPEC	*13.4*	14.1	15.2	16.4	17.5	18.6	19.5	19.5
Other OPEC	*11.1*	11.3	12.1	12.8	13.5	14.0	14.2	14.2
OECD	*18.0*	17.0	17.2	16.6	15.7	15.7	15.4	15.3
Russia	*9.8*	9.8	10.5	11.3	11.4	11.5	11.6	11.6
Other	*19.2*	19.6	20.5	20.9	21.5	22.1	22.2	22.3
Total	***81.8***	**83.2**	**87.7**	**91.1**	**93.5**	**96.6**	**98.4**	**99.3**

Table 6.11.: Crude oil production in the "Tiger & Dragon" scenario, in MMbbl/d

	2008	2012	2015	2018	2021	2024	2027	2030
North America	*23.8*	20.4	20.8	21.1	21.2	21.2	20.9	20.8
Eurasia	*20.2*	19.3	19.7	20.1	20.0	20.1	19.8	19.8
Asia Pacific	*25.3*	27.3	29.0	30.7	32.3	34.0	35.2	36.1
Middle East	*6.4*	7.0	8.1	8.7	9.2	10.2	10.7	10.5
South America	*5.9*	6.2	6.7	7.0	7.2	7.4	7.9	8.3
Africa	*2.9*	3.0	3.3	3.4	3.6	3.7	3.9	3.8
Total	***84.5***	**83.2**	**87.7**	**91.1**	**93.5**	**96.6**	**98.4**	**99.3**

Table 6.12.: Crude oil consumption in the "Tiger & Dragon" scenario, in MMbbl/d

	2012	2015	2018	2021	2024	2027	2030
North America	80.00	80.92	85.03	91.52	102.64	115.04	130.89
Eurasia	79.75	83.21	88.25	94.62	105.82	118.49	134.52
Asia Pacific	81.46	85.35	90.53	96.62	107.87	120.44	136.40

Table 6.13.: Crude oil price (weighted average) in the "Tiger & Dragon" scenario, in US $/bbl

6.3. The Middle East and the "Security of Supply" issue

It is not surprising that the Middle East retains its dominant position in the crude oil market. As can be deducted from the previous section, Middle East suppliers account for at least 35 % of crude oil production in 2030 in all demand scenarios. Table 6.14 lists exports and domestic consumption by Middle East suppliers. An observation worth pointing out is that the Middle East has a higher (absolute) export level to the Pacific region in the *Green Rebound* scenario compared to *Speedy Recovery* scenario.

	Speedy Recovery	*Green Rebound*	*Long Slump*	*Tiger & Dragon*
Domestic	10.4	7.6	8.4	10.4
	27 %	*21 %*	*24 %*	*28 %*
Asia Pacific	17.1	18.5	17.8	18.5
	45 %	*52 %*	*50 %*	*50 %*
Europe	4.5	3.7	3.8	3.2
	12 %	*10 %*	*11 %*	*8 %*
North America	4.8	4.0	4.5	4.0
	13 %	*11 %*	*13 %*	*11 %*
Other	1.5	1.6	1.1	1.2
	4 %	*4 %*	*3 %*	*3 %*
Total	**38.3**	**35.3**	**35.5**	**37.3**

Table 6.14.: Domestic consumption and exports by Middle East suppliers, in MMbbl/d and relative to total production, in 2030 by scenario

	Speedy Recovery	*Green Rebound*	*Long Slump*	*Tiger & Dragon*
Middle East	4.8	4.0	4.5	4.0
	22 %	*24 %*	*21 %*	*19 %*
Russia	1.8	2.3	0.9	1.1
	8 %	*14 %*	*4 %*	*5 %*
Africa	3.3	2.4	2.4	2.5
	15 %	*14 %*	*11 %*	*12 %*
Other	1.4	1.0	0.8	1.0
	6 %	*6 %*	*4 %*	*5 %*
Domestic	10.9	7.1	12.6	12.2
	49 %	*42 %*	*60 %*	*59 %*
Total	**22.3**	**16.8**	**21.1**	**20.8**

Table 6.15.: Imports and domestic production for North America, in MMbbl/d and relative to total consumption, in 2030 by scenario

This effect is due mostly to the assumed climate change mitigation policy effects: on the one hand, a lower reserve growth means that smaller suppliers in the region exhaust their reserves sooner in this scenario; on the other hand, regulatory restrictions

	Speedy Recovery	*Green Rebound*	*Long Slump*	*Tiger & Dragon*
Middle East	4.8	4.0	4.5	4.0
	27 %	*28 %*	*23 %*	*20 %*
Russia	5.9	4.6	5.4	6.2
	35 %	*35 %*	*34 %*	*39 %*
Africa	4.0	3.0	3.1	3.3
	24 %	*23 %*	*19 %*	*21 %*
Other	2.1	1.7	1.8	1.7
	12 %	*13 %*	*11 %*	*10 %*
Domestic	0.3	0.0	2.2	1.5
	2 %	*0 %*	*13 %*	*10 %*
Total	**16.9**	**13.0**	**16.2**	**15.9**

Table 6.16.: Imports and domestic production for Europe, in MMbbl/d and relative to total consumption, in 2030 by scenario

on capacity expansions prevent other suppliers to expand their production capacity to make up for the shortfall. Combining these effects with the lower price due to reduced demand allows the Middle East suppliers to expand their market share in that region.

What is – perhaps – more surprising than the continued dominant situation of the Middle East is the observation gleaned from the import statistics of the main demand regions, presented in Tables 6.15–6.17: the share of imports in 2030 from the Middle East relative to total consumption is not lower in the *Green Rebound* scenario than in any other.

	Speedy Recovery	*Green Rebound*	*Long Slump*	*Tiger & Dragon*
Middle East	18.0	19.1	18.2	19.1
	50 %	*62 %*	*55 %*	*53 %*
Russia	2.8	0.2	0.0	0.9
	8 %	*1 %*	*0 %*	*3 %*
Africa	3.1	2.8	2.6	3.1
	9 %	*9 %*	*8 %*	*9 %*
Other	5.2	4.2	4.8	5.6
	15 %	*14 %*	*9 %*	*15 %*
Domestic	6.7	4.7	7.3	7.4
	19 %	*15 %*	*22 %*	*20 %*
Total	**35.7**	**31.0**	**33.0**	**36.1**

Table 6.17.: Imports and domestic production for Asia Pacific, in MMbbl/d and relative to total consumption, in 2030 by scenario

Western politicians often intertwine combating global warming with a higher security of supply in Sunday speeches, i.e. a reduced reliance on a few – possibly unstable – regions for a significant share of imports. The simulation results of this work suggest the opposite: North America sees its import dependence increase from 50 % to almost 60 % between the "Speedy Recovery" and the "Green Rebound" scenarios, with the share of Middle East crude increasing. For Asia Pacific, 60 % of crude oil consumption originates from the Middle East alone in the "Green Rebound" scenario, while import dependency increases from approximately 80 % to 85 %. Since Europe does not have any significant domestic production left in 2030 in any case, its import situation is similar in all scenarios.

Obviously, one may not directly draw conclusions about the impact of climate change mitigation policies on import dependency in general from these results. A more elaborate investigation would be necessary, including several fossil fuels and renewables and a more specific representation of mitigation policies. Nevertheless, this observation should give pause for thought to policy-makers trying to sell policy to their constituencies.[5]

6.4. Outlook on the Crude Oil Market

The results indicate that reserve depletion is not a major concern in the next two decades. However, the potential for future market dominance by OPEC remains large. Table 6.18 presents the share of proven reserves of different supplier groups by scenario. Proven reserves include the reserve growth assumed in the model in each scenario. At first glance, the high share of OECD reserves strikes as odd. However, when one examines the results in more detail, they reveal that the remaining OECD reserves are almost exclusively located in Canada. Most other OECD countries will have exhausted their reserves by 2030. Barring a far more radical discovery than assumed in this model or a leap in engineering and extraction methods, OECD countries except for Canada will cease crude oil production soon after 2030. This leaves the Middle East in an even more dominant position than it is today, accounting for more than 60 % of proven reserves.

Another interesting observation is the low level of remaining reserves in Russia in 2030. This may explain why Russia is keen on exploration and development in the Arctic; even if this work indicates that increasing production capacity is not an optimal strategy for Russia, it will need to replace exhausted fields in the medium future.

An important measure to examine the long-term outlook of the crude oil market is the *Reserve-to-Production ratio* (R/P ratio)[6], presented in Table 6.19. Again, the relatively large value for OECD countries is squarely due to the large reserves in Canada. The R/P ratio again indicates that Russia will not be able to keep up its production level after 2030 without a significant reserve growth.[7]

[5] Even if import dependence does not decrease in a "save the planet" scenario, I personally still prefer such a policy to "Drill, Baby, drill!".

[6] The *Reserve-to-production ratio* indicates the number of years a country could go on producing crude oil if extraction continues at the current rate.

[7] The results of this work with regard to Russia can also be interpreted in the following way: Russia is over-producing (i.e., exploiting too quickly) its crude oil reserves from a national-welfare perspective.

	Speedy Recovery	*Green Rebound*	*Long Slump*	*Tiger & Dragon*	2008
Remaing global reserves	1394	1180	1453	1417	1258
Saudi Arabia	20.7 %	20.1 %	19.9 %	20.4 %	21.0 %
Middle East OPEC	41.9 %	42.0 %	40.9 %	41.4 %	38.9 %
Other OPEC	15.0 %	15.4 %	15.6 %	15.3 %	15.1 %
OECD	16.3 %	16.5 %	15.9 %	16.2 %	7.1 %
Russia	1.8 %	2.0 %	3.1 %	2.4 %	6.3 %
Other	4.3 %	4.0 %	4.6 %	4.3 %	11.6 %

Table 6.18.: Remaining global reserves in thousand million barrels, and share by supplier group in 2030 by scenario

	Speedy Recovery	*Green Rebound*	*Long Slump*	*Tiger & Dragon*
Saudi Arabia	48.5	40.0	48.5	48.5
Middle East OPEC	77.7	76.8	92.9	82.5
Other OPEC	35.1	40.0	48.9	41.8
OECD	50.5	66.9	38.2	41.0
Russia	4.8	6.1	12.8	7.9
Other	9.8	10.3	11.1	9.8
Global	39.7	41.8	44.5	41.3

Table 6.19.: Reserve-to-production ratio in 2030 by scenario

6.5. Comparison between Initial Investment Cases

In Chapter 2.7, I argue that the assumption of an exogenous stochastic price process as applied in the standard real options approach ignores the impact of substantial strategic investments. This section presents evidence to that support that claim, by comparing price developments in two scenarios contingent on initial investment by Saudi Arabia and Russia.

Year	2012	2015	2018	2021	2024	2027	2030
No initial investment	154.35	141.99	142.47	151.33	165.13	180.09	198.94
Initial investment by							
Saudi Arabia	143.16	132.89	134.22	142.32	155.47	170.08	188.43
Russia	148.84	137.52	138.44	146.93	160.41	175.32	193.50
Saudi Arabia & Russia	137.76	128.57	130.09	137.88	150.57	164.74	182.69

Table 6.20.: Comparison of oil price development contingent on initial investment, "Speedy Recovery" scenario, US \$/bbl, Southern USA Refinery Gate Prices

In the "Speedy Recovery" scenario (Table 6.20), prices differ by more than 15 US \$/bbl in most years. In the "Green Rebound" scenario (Table 6.21), the difference in prices is in the range of 4-9 US \$/bbl. In the other scenarios, price differences are similar to the “Green Rebound” scenario.

A price difference of less than 10 US $/bbl may seem small given the large fluctuations in the crude oil price in recent years. However, considering that Saudi Arabia and Russia produce around 10 million barrels of crude oil per day, even such a small difference can mean a considerable difference to profits.[8]

Year	2012	2015	2018	2021	2024	2027	2030
No initial investment	87.31	84.58	90.70	99.21	105.83	106.80	110.58
Initial investment by							
Saudi Arabia	82.37	81.13	88.30	96.87	103.43	104.24	107.91
Russia	85.06	83.26	90.62	99.15	105.71	106.61	110.46
Saudi Arabia & Russia	79.86	79.53	86.64	95.26	101.77	102.43	105.80

Table 6.21.: Comparison of oil price development contingent on initial investment, “Green Rebound” scenario, US $/bbl, Southern USA Refinery Gate Prices

[8]There is a different reading to these results, from a political/consumer point-of view: if the impact of Saudi investment on crude oil prices is as small – and their financial incentives to invest as great – as these results suggest, why do the US bow so deeply before the Saudi kingdom?

7. Conclusion

This work investigates the strategic incentives of Saudi Arabia and Russia, the two most important crude oil suppliers, to invest in additional production capacity under demand uncertainty. This ambiguity stems from two effects: a demand-side risk, caused by the current economic crisis; and a political risk, from the possibility of an international climate change mitigation agreement, which in turn would have an impact on crude oil demand levels. The future development of these two issues will have a significant impact on crude oil demand, and consequently also on the profitability of any production capacity investment today.

Investment analysis leads to multi-level strategic games, which are not trivially tractable. Any research must either simplify with regard to the complexity of the game or the problem size. This work presents some contributions to the literature, which are quite complex mathematically, but – on the other hand – not easily tractable. Hence, the approach chosen in this work is a compromise between a sufficient presentation of the strategic game and a comprehensive and detailed data set.

The problem is posed as a Nash investment game between Saudi Arabia and Russia. Their profits, contingent on the demand development, are computed using an open-loop multi-period partial equilibrium model, formulated as a Complementarity Problem. Such models were extensively applied to the natural gas and electricity markets in recent years. The model proposed in this work differs from these other models, however, in so far as that it explicitly accounts for liquid spot markets and price indices; these make spatial price discrimination virtually non-existent in the crude oil market. At the same time, the model is more flexible than a POOLCO auction model, as is sometimes used to describe electricity markets. It combines Cournot and competitive suppliers, arbitragers aiming to exploit price differentials not warranted by transport costs, an extensive pipeline and shipping network and final demand represented by refineries. Investment in crude oil production capacity is endogenous. The data set covers more than 93 % of crude oil consumption and production in the base year (2008).

Since the debate of market power in the crude oil is not – yet – adequately settled, the model is first solved in a one-period setting for a number of plausible market power setups: a Nash-Cournot market; perfect competition; a (non-cooperative) OEPC oligopoly; a standard cartel. These are implemented both as simultaneous-move games and sequential Stackelberg leader-follower games. The best (albeit imperfect) fit is obtained from the market power setup in which Saudi Arabia acts as Stackelberg vis-à-vis an OPEC oligopoly and a competitive fringe. However, extending a Stackelberg market model to multiple periods is not easily tractable due to the problem of dynamically inconsistent strategies, so a second-best simultaneous-move solution is used instead: all OPEC suppliers exert Cournot market power, while Saudi Arabia and all other suppliers follow a competitive price rule. This should not be interpreted as an assertion that Saudi Arabia does not exert market power; rather, this setup is owed to the shortcomings of partial equilibrium models and the difficulty of including more complex game-theoretic concepts within a large-scale open-loop equilibrium model.

The model is numerically solved for the time horizon 2012–2030 for four demand scenarios: a quick global economic upturn (*Speedy Recovery*); the implementation of an international agreement to curb global warming and reduce greenhouse gas emissions (*Green Rebound*); a prolonged recession (*Long Slump*); and a combination of continued weak growth in OECD countries and a rapid recovery for the rest of the world (*Tiger & Dragon*). The discounted profits of Saudi Arabia and Russia are then used as an input to the Nash investment game.

The (unique) Nash equilibrium of this game is for Saudi Arabia to invest in additional production capacity, while Russia does not expand capacity. Even though the absolute level of profits earned in the different scenarios varies significantly, the equilibrium is the same in all scenarios and independent of the action of the other player.

The result can be interpreted in such a way that the investment schemes announced by Saudi Aramco are valid from its strategic points of view. At the same time, the results indicate that the "price tag" for the Kremlin of reduced investment by international oil companies due to the perceived political risk is rather small. Arm-twisting international oil companies to relinquish assets to companies close to the state – so that the Russian state can earn a higher share of the profits from existing capacity – seems to be a better strategy for Russia than to expand capacity.

However, there is a reservation to these results: due to a lack of reliable data, the approach pursued in this work neglects – amongst other issues – depreciation of existing production capacity and the exhaustion of developed fields; keeping production capacity constant is assumed to be included in daily production costs. However, Russia in particular is widely believed to require substantial investment in the coming years to maintain current production levels. Hence, this approach may under-estimate the reliance of Russia on foreign expertise and finance. Investigating these issues would require a more mathematically complex approach, possibly relinquishing tractability and a comprehensive model size.

Simulation results indicate that the reserve constraint is not a major concern over the next decades, assuming some reserve growth due to further exploration and technological advances; nevertheless, remaining reserves will be ever more concentrated in the Middle East. Canada will be the only OECD country in 2030 with considerable reserves. In the absence of major discoveries in the Arctic, Russia will deplete its reserves soon after 2030. Hence, the risk of oil price price oscillations due to geopolitical or other factors will rather grow in the future. The same holds true for the potential of suppliers exerting market power.

One noteworthy – and perhaps counter-intuitive – result concerns the issue of security of supply: it seems to be common knowledge among Western politicians that an effective policy to reduce greenhouse gas emissions and mitigate global warming leads to a more diversified energy mix and less reliance on a few – possibly politically unstable – regions to meet energy demands. This may be true in general; however, the results of this work indicate that the crude oil import dependency for both North America and the Asia Pacific region is considerably higher in the climate change mitigation scenario than in other scenarios. This is caused by the political and regulatory constraints imposed on future exploration and development, aiming to capture likely effects of climate change mitigation policies.

A. The Mathematical Formulation

A.1. The Karush-Kuhn-Tucker conditions

The equilibrium model is derived from the maximisation problems of the suppliers and the arbitrageurs specified in Chapter 4. They give rise to the following KKT conditions. Each equation listed below exists once in each node n where the supplier is present, and for each period y (apart from equation A.4). The inverse demand function at each node n closes the model.

For the sake of a concise notation, the simplification $Cap^P_{y,s,n} = \overline{Cap^P_{s,n}} + \sum_{y'<y} Add^P_{y',s,n}$ is used throughout this chapter. Bear in mind that $\frac{\partial Cap^P_{y,s,n}}{\partial Add^P_{y',s,n}} = 1$ for all $y' > y$.

A.1.1. The Supplier

$$\left(\frac{1}{\rho^S_s}\right)^{|y|} \cdot \left[\phi^S_{y,s,n} - lin^S_{y,n} - 2 \cdot qud^S_{y,n} \cdot Prod^S_{y,s,n} + gol^S_{y,n} \cdot \ln\left(1 - \frac{Prod^S_{y,s,n}}{Cap^S_{y,s,n}}\right)\right]$$
$$-\alpha^{Cap}_{y,s,n} - \alpha^{Res}_{s,n} \leq 0 \quad \perp \quad Prod^S_{y,s,n} \geq 0 \tag{A.1}$$

$$\left(\frac{1}{\rho^S_s}\right)^{|y|} \cdot \left[- inv^S_{y,n} - \sum_{y'>y} gol^P_{y',n} \cdot \left(\ln\left(1 - \frac{Prod^S_{y',s,n}}{Cap^S_{y',s,n}}\right) + \frac{Prod^S_{y',s,n}}{Cap^S_{y',s,n}} \right) \right]$$
$$+ \sum_{y'>y} \alpha^{Cap}_{y',s,n} - \alpha^{Inv}_{y,s,n} \leq 0 \quad \perp \quad Add^S_{y,s,n} \geq 0 \tag{A.2}$$

$$Prod^S_{y,s,n} - Cap^S_{y,s,n} \leq 0 \quad \perp \quad \alpha^{Cap}_{y,s,n} \geq 0 \tag{A.3}$$

$$\sum_{y \in Y} Prod^S_{y,s,n} - \overline{Res^S_{s,n}} \leq 0 \quad \perp \quad \alpha^{Res}_{s,n} \geq 0 \tag{A.4}$$

$$Add^S_{y,s,n} - \overline{Add^S_{y,s,n}} \leq 0 \quad \perp \quad \alpha^{Inv}_{y,s,n} \geq 0 \tag{A.5}$$

$$\phi^S_{y,s,n} - \left(\frac{1}{\rho^S_s}\right)^{|y|} \cdot tc^{Pipe}_{y,m,n} - \phi^S_{y,s,m} \leq 0 \quad \perp \quad Flow^S_{y,s,m,n} \geq 0 \tag{A.6}$$

$$\phi^S_{y,s,n} - \left(\frac{1}{\rho^S_s}\right)^{|y|} \cdot tc^{Ship}_{y,k,n} - \phi^S_{y,s,k} \leq 0 \quad \perp \quad Ship^S_{y,s,k,n} \geq 0 \tag{A.7}$$

For a perfectly competitive supplier, $s \in F$:

$$\left(\frac{1}{\rho_s^S}\right)^{|y|} \cdot \pi_{y,n}^R - \phi_{y,s,n}^S \leq 0 \quad \perp \quad Sale_{y,s,n}^{S \to R} \geq 0 \tag{A.8}$$

$$\left(\frac{1}{\rho_s^S}\right)^{|y|} \cdot \left(\pi_{y,i}^{Pool} - tc_{y,i,n}^{Pool}\right) - \phi_{y,s,n}^S \leq 0 \quad \perp \quad Sale_{y,s,n,i}^{S \to A} \geq 0 \tag{A.9}$$

$$\begin{aligned} Sale_{y,s,n}^{S \to R} + \sum_{i \in I} Sale_{y,s,n,i}^{S \to A} + \sum_{l \in A_{n,l}^{Pipe}} Flow_{y,s,n,l}^S + \sum_{k \in A_{n,k}^{Ship}} Ship_{y,s,n,k}^S \\ -Prod_{y,s,n}^S - \sum_{m \in A_{m,n}^{Pipe}} Flow_{y,s,m,n}^S - \sum_{h \in A_{h,n}^{Ship}} Ship_{y,s,h,n}^S \leq 0 \quad \perp \quad \phi_{y,s,n}^S \geq 0 \end{aligned} \tag{A.10}$$

For a Cournot supplier, $s \in C$:

$$\left(\frac{1}{\rho_s^S}\right)^{|y|} \cdot \left(\pi_{y,n}^S - slp_{y,n}^R \cdot Sale_{y,s,n}^{S \to R}\right) - \phi_{y,s,n}^S \leq 0 \quad \perp \quad Sale_{y,s,n}^{S \to R} \geq 0 \tag{A.11}$$

$$\begin{aligned} Sale_{y,s,n}^{S \to R} + \sum_{l \in A_{n,l}^{Pipe}} Flow_{y,s,n,l}^S + \sum_{k \in A_{n,k}^{Ship}} Ship_{y,s,n,k}^S \\ -Prod_{y,s,n}^S - \sum_{m \in A_{m,n}^{Pipe}} Flow_{y,s,m,n}^S - \sum_{h \in A_{h,n}^{Ship}} Ship_{y,s,h,n}^S \leq 0 \quad \perp \quad \phi_{y,s,n}^S \geq 0 \end{aligned} \tag{A.12}$$

A.1.2. The Arbitrageur

$$\left(\frac{1}{\rho_i^A}\right)^{|y|} \cdot \left(\pi_{y,n}^R - tc_{y,i,n}^{Pool}\right) - \pi_{y,i}^{Pool} \leq 0 \quad \perp \quad Sale_{y,i,n}^{A \to R} \geq 0 \tag{A.13}$$

$$-\sum_{s \in F, n \in N} Sale_{y,s,n,i}^{S \to A} + \sum_{n \in N} Sale_{y,i,n}^{A \to R} \leq 0 \quad \perp \quad \pi_{y,i}^{Pool} \geq 0 \tag{A.14}$$

A.1.3. Final demand

$$int_{y,n}^R - slp_{y,n}^R \cdot \left[\sum_{s \in S} Sale_{y,s,n}^{S \to R} + \sum_{i \in I} Sale_{y,i,n}^{A \to R}\right] - \pi_{y,n}^R \leq 0 \quad \perp \quad \pi_{y,n}^R \geq 0 \tag{A.15}$$

A.2. Convexity of the complementarity model

Let me point out that the cost function (Equation 4.1) is convex in all variables. All other terms in the objective functions and all constraints are linear. Uniqueness of any solution regarding trade flows cannot be guaranteed, though the level of profits earned by the suppliers are unique. Refer to Bazaraa et al. (2006) for solving non-linear optimisation problems.

A.3. Deriving the supplier's KKT conditions

For each Cournot supplier, $s \in C \subseteq S$; decision variables: $Prod^S,\ Add^S,\ Flow^S,\ Ship^S,\ Sale^{S\to R}$

$$\begin{aligned} L^C(\cdot) = \sum_{n\in N}\sum_{y\in Y}\left(\frac{1}{\rho_s^S}\right)^{|y|}\cdot\Bigg[& -Sale^{S\to R}_{y,s,n}\cdot\left(int^R_{y,n} - slp^R_{y,n}\cdot\left[\sum_{s\in S} Sale^{S\to R}_{y,s,n} + \sum_{i\in I} Sale^{A\to R}_{y,i,n}\right]\right) + \sum_{l\in A^{Pipe}_{n,l}} Flow^S_{y,s,n,l}\cdot tc^{Pipe}_{y,n,l} + \sum_{k\in A^{Ship}_{n,k}} Ship^S_{y,s,n,k}\cdot tc^{Ship}_{y,n,k} \\ & + (lin^S_{y,n} + gol^S_{y,n})\cdot Prod^S_{y,s,n} + qud^S_{y,n}\cdot\left(Prod^S_{y,s,n}\right)^2 + gol^S_{y,n}\cdot\left(Cap^S_{y,s,n} - Prod^S_{y,s,n}\right)\cdot\ln\left(\frac{Prod^S_{y,s,n}}{Cap^S_{y,s,n}}\right) + inv^S_{y,n}\cdot Add^S_{y,s,n}\Bigg] \\ & + \phi^S_{y,s,n}\cdot\left(-Sale^{S\to R}_{y,s,n} - \sum_{l\in A^{Pipe}_{n,l}} Flow^S_{y,s,n,l} - \sum_{k\in A^{Ship}_{n,k}} Ship^S_{y,s,n,k} + Prod^S_{y,s,n} + \sum_{m\in A^{Pipe}_{m,n}} Flow^S_{y,s,m,n} + \sum_{h\in A^{Ship}_{h,n}} Ship^S_{y,s,h,n}\right) \\ & + \alpha^{Cap}_{y,s,n}\cdot\left(Prod^S_{y,s,n} - Cap^S_{y,s,n}\right) + \alpha^{Inv}_{y,s,n}\cdot\left(Add^S_{y,s,n} - \overline{Add^S_{y,s,n}}\right) \\ & + \alpha^{Res}_{s,n}\cdot\left(\sum_{y\in Y} Prod^S_{y,s,n} - \overline{Res^S_{s,n}}\right) \end{aligned} \tag{A.16}$$

For each perfectly competitive supplier, $s \in F \subseteq S$; decision variables: $Prod^S,\ Add^S,\ Flow^S,\ Ship^S,\ Sale^{S\to R},\ Sale^{S\to A}$

$$\begin{aligned} L^F(\cdot) = \sum_{n\in N}\sum_{y\in Y}\left(\frac{1}{\rho_s^S}\right)^{|y|}\cdot\Bigg[& -Sale^{S\to R}_{y,s,n}\cdot\pi^R_{y,n} - \sum_{i\in I} Sale^{S\to A}_{y,s,n,i}\cdot(\pi^{Pool}_{y,i} - tc^{Pool}_{y,i,n}) + \sum_{l\in A^{Pipe}_{n,l}} Flow^S_{y,s,n,l}\cdot tc^{Pipe}_{y,n,l} + \sum_{k\in A^{Ship}_{n,k}} Ship^S_{y,s,n,k}\cdot tc^{Ship}_{y,n,k} \\ & + (lin^S_{y,n} + gol^S_{y,n})\cdot Prod^S_{y,s,n} + qud^S_{y,n}\cdot\left(Prod^S_{y,s,n}\right)^2 + gol^S_{y,n}\cdot\left(Cap^S_{y,s,n} - Prod^S_{y,s,n}\right)\cdot\ln\left(\frac{Prod^S_{y,s,n}}{Cap^P_{y,s,n}}\right) + inv^S_{y,n}\cdot Add^S_{y,s,n}\Bigg] \\ & + \phi^S_{y,s,n}\cdot\left(-Sale^{S\to R}_{y,s,n} - \sum_{i\in I} Sale^{S\to A}_{y,s,n,i} - \sum_{l\in A^{Pipe}_{n,l}} Flow^S_{y,s,n,l} - \sum_{k\in A^{Ship}_{n,k}} Ship^S_{y,s,n,k} + Prod^S_{y,s,n} + \sum_{m\in A^{Pipe}_{m,n}} Flow^S_{y,s,m,n} + \sum_{h\in A^{Ship}_{h,n}} Ship^S_{y,s,h,n}\right) \\ & + \alpha^{Cap}_{y,s,n}\cdot\left(Prod^S_{y,s,n} - Cap^S_{y,s,n}\right) + \alpha^{Inv}_{y,s,n}\cdot\left(Add^S_{y,s,n} - \overline{Add^S_{y,s,n}}\right) \\ & + \alpha^{Res}_{s,n}\cdot\left(\sum_{y\in Y} Prod^S_{y,s,n} - \overline{Res^S_{s,n}}\right) \end{aligned} \tag{A.17}$$

B. Regions and Countries

The following regions and countries are included in the model data set. Indented countries are aggregated with the previous country/region as one node. The abbreviations used in the model are given in brackets and follow the ISO 3166-1 alpha-3 codes, as published by the International Organization for Standardization (ISO).[1]

Africa	**(AFR)**	
Algeria	(DZA)	OPEC
Angola	(AGO)	OPEC
Egypt	(EGY)	
Gabon	(GAB)	OPEC
Libya	(LBY)	OPEC
Nigeria	(NGA)	OPEC
Sudan	(SDN)	
South Africa	(ZAF)	
Other West Africa	(WAF)	
Cameroon	(CMR)	
Congo	(COG)	
Côte d'Ivoire	(CIV)	
Ghana	(GHA)	

Caspian Region	**(CAS)**
Azerbaijan	(AZE)
Kazakhstan	(KAZ)

North America	**(NAM)**	
Canada	(CAN)	OECD
Canada East	(CA-E)	OECD
Canada West	(CA-W)	OECD
Mexico	(MEX)	OECD
USA	(USA)	OECD
Alaska	(US-A)	
Midwest	(US-M)	
Northeast	(US-N)	
South	(US-S)	
West (excl. Alaska)	(US-W)	

Europe	**(EUR)**	
Baltic Sea Region	(BAL)	
Belarus	(BLR)	
Denmark	(DNK)	OECD & EU
Finland	(FIN)	OECD & EU
Latvia	(LVA)	EU
Lithuania	(LTU)	EU
Sweden	(SWE)	OECD & EU
Central Europe	(CEU)	
Austria	(AUT)	OECD & EU
Czech Republic	(CZE)	OECD & EU
Hungary	(HUN)	OECD & EU
Slovakia	(SVK)	OECD & EU
Germany	(DEU)	OECD & EU
Poland	(POL)	OECD & EU
France	(FRA)	OECD & EU
Belgium	(BEL)	OECD & EU
Switzerland	(CHE)	OECD
Luxembourg	(LUX)	OECD & EU
Netherlands	(NLD)	OECD & EU
United Kingdom	(GBR)	OECD & EU
Ireland	(IRL)	OECD & EU
Spain	(ESP)	OECD & EU
Portugal	(PRT)	OECD & EU
Italy	(ITA)	OECD & EU
Norway	(NOR)	OECD
Ukraine	(UKR)	
Black Sea Region	(ASM)	
Bulgaria	(BGR)	EU
Greece	(GRC)	OECD & EU
Romania	(ROM)	EU
Turkey	(TUR)	OECD

[1] Due to their geographic size and significant production and consumption levels, both the USA and Canada are disaggregated into several nodes. For the USA, the disaggregation follows the U.S. Census Regions, with the exception of Alaska.

Russia	**(RUS)**	
Russia	(RUS)	

Middle East	**(MEA)**	
United Arab Emirates	(ARE)	OPEC
Iran	(IRN)	OPEC
Iraq	(IRQ)	OPEC
Kuwait	(KUW)	OPEC
Oman	(OMN)	
Yemen	(YEM)	
Qatar	(QAT)	OPEC
Saudi Arabia	(SAU)	OPEC
Other Middle East	(MEA)	
Israel	(ISR)	
Jordan	(JOR)	
Lebanon	(LBN)	
Syria	(SYR)	

Asia Pacific	**(ASP)**	
Australia	(AUS)	OECD
New Zealand	(NZL)	OECD
China	(CHN)	
Hong Kong	(HKG)	
India	(IND)	
Japan	(JPN)	OECD
Korea	(KOR)	OECD
Pakistan	(PAK)	
Thailand	(THA)	
Vietnam	(VNM)	
Chinese Taipei	TWN	
Indonesia	(IDN)	
Brunei Darussalam	(BRN)	
Malaysia	(MYS)	
Philippines	(PHL)	
Singapore	(SGP)	

South America	**(SAM)**	
Argentina	(ARG)	
Brazil	(BRA)	
Colombia	(COL)	
Ecuador	(ECU)	OPEC
Venezuela	(VEN)	OPEC
Peru	(PER)	
Bolivia	(BOL)	
Chile	(CHL)	

C. Calibration Results

This section presents the numerical calibration results discussed in Chapter 5.4.

Production level by supplier (in MMbbl/d)

	Cournot	Competition	Oligopoly	Oligopoly MPEC	Oligopoly 2	Oligopoly 3	Cartel	Cartel MPEC	*Observed values*
2005									
Saudi Arabia	9.5	10.5	6.3	10.5	10.5	10.5	5.6	6.4	10.4
Other OPEC	24.6	24.4	23.7	22.8	22.8	23.3	11.0	11.9	23.6
OECD	15.1	17.7	18.6	18.0	18.1	18.0	19.3	18.8	18.8
Russia	3.8	7.2	8.3	7.5	7.5	7.5	9.6	9.6	9.4
Other	10.7	13.8	14.7	14.1	14.1	14.1	15.7	15.6	15.1
Total	63.6	73.6	71.6	72.9	73.0	73.3	61.1	62.3	77.4
2006									
Saudi Arabia	9.5	10.3	6.2	10.3	10.3	10.3	5.6	6.2	10.2
Other OPEC	25.0	24.9	24.3	23.3	23.3	23.8	11.4	11.8	24.0
OECD	15.2	17.8	18.5	18.1	18.1	18.0	19.0	19.0	18.5
Russia	4.0	7.7	8.8	8.1	8.1	8.0	9.8	9.8	9.6
Other	11.1	14.5	15.4	14.8	14.8	14.7	16.1	16.1	15.5
Total	64.8	75.1	73.1	74.5	74.5	74.9	61.9	62.8	77.8
2007									
Saudi Arabia	9.5	9.9	6.2	9.9	9.9	9.9	5.4	6.3	9.8
Other OPEC	25.0	24.9	24.4	23.6	23.6	24.1	12.1	12.5	23.8
OECD	15.5	18.1	18.6	18.3	18.3	18.3	18.9	18.6	18.4
Russia	4.2	8.3	9.3	8.6	8.6	8.6	10.0	10.0	9.8
Other	11.5	15.1	15.8	15.3	15.4	15.3	16.3	16.3	15.8
Total	65.7	76.3	74.3	75.7	75.7	76.1	62.7	63.7	77.7
2008									
Saudi Arabia	9.7	10.4	6.2	10.4	10.4	10.4	5.8	6.5	10.3
Other OPEC	25.7	25.6	25.3	24.2	24.2	24.9	12.6	12.9	24.4
OECD	15.1	17.7	18.1	17.8	17.8	17.8	18.1	18.1	17.6
Russia	4.3	8.9	9.7	9.2	9.2	9.1	10.0	10.0	9.8
Other	11.9	15.5	16.1	15.7	15.7	15.6	16.2	16.2	15.7
Total	66.8	78.0	75.4	77.3	77.4	77.8	62.8	63.7	77.8

Consumption level by region (in MMbbl/d)
and weighted average price level for main consumption regions (in US $/bbl), in *italics*

	Cournot	Competition	Oligopoly	Oligopoly MPEC	Oligopoly 2	Oligopoly 3	Cartel	Cartel MPEC	*Observed values*
2005									
N. America	18.9	21.0	20.5	20.9	20.9	20.9	17.4	17.7	20.8
Eurasia	16.9	19.4	18.9	19.3	19.3	19.3	16.3	16.7	19.2
Asia Pacific	20.8	22.5	21.9	22.3	22.3	22.3	18.6	19.0	22.2
Middle East	2.4	4.7	4.5	4.6	4.6	4.8	3.8	3.9	4.6
S. America	3.3	4.1	4.0	4.0	4.0	4.1	3.3	3.4	4.0
Africa	1.4	1.9	1.9	1.9	1.9	1.9	1.6	1.6	1.9
Total	63.6	73.6	71.6	72.9	73.0	73.3	61.1	62.3	72.7
N. America	*89.37*	*46.26*	*60.06*	*50.23*	*50.27*	*49.57*	*137.06*	*129.44*	*52.77*
Eurasia	*94.47*	*46.02*	*58.39*	*49.56*	*49.79*	*49.40*	*126.68*	*115.56*	*52.33*
Asia Pacific	*85.72*	*46.36*	*61.15*	*51.32*	*50.99*	*50.00*	*138.12*	*130.26*	*53.06*
2006									
N. America	19.0	21.2	20.6	21.0	21.0	21.1	17.4	17.7	20.8
Eurasia	17.1	19.7	19.2	19.6	19.6	19.6	16.4	16.5	19.3
Asia Pacific	21.4	23.2	22.5	23.0	23.0	23.0	19.1	19.4	22.7
Middle East	2.5	5.0	4.8	4.9	4.9	5.1	4.0	4.1	4.9
S. America	3.4	4.2	4.1	4.2	4.2	4.3	3.5	3.5	4.2
Africa	1.4	1.9	1.8	1.9	1.9	1.9	1.5	1.6	1.9
Total	64.8	75.1	73.1	74.5	74.6	74.9	61.9	62.8	73.8
N. America	*103.29*	*51.26*	*68.16*	*55.99*	*55.98*	*54.87*	*165.53*	*155.54*	*62.39*
Eurasia	*110.69*	*51.07*	*66.49*	*55.40*	*55.71*	*54.98*	*155.42*	*155.92*	*63.27*
Asia Pacific	*100.16*	*51.40*	*69.19*	*56.97*	*56.70*	*55.47*	*166.55*	*156.56*	*64.32*
2007									
N. America	19.1	21.3	20.7	21.1	21.1	21.2	17.4	17.6	21.0
Eurasia	16.9	19.5	19.1	19.4	19.4	19.4	16.3	16.6	19.1
Asia Pacific	22.1	23.9	23.3	23.7	23.7	23.8	19.7	20.0	23.5
Middle East	2.6	5.1	4.9	5.0	5.1	5.2	4.1	4.2	5.0
S. America	3.6	4.5	4.4	4.5	4.5	4.5	3.7	3.7	4.4
Africa	1.4	2.0	1.9	1.9	1.9	2.0	1.6	1.6	1.9
Total	65.7	76.3	74.3	75.7	75.7	76.1	62.7	63.7	75.0
N. America	*117.97*	*58.69*	*76.52*	*63.32*	*63.26*	*62.29*	*187.66*	*178.94*	*69.44*
Europe	*126.14*	*58.05*	*74.08*	*62.29*	*62.28*	*61.69*	*174.84*	*160.46*	*71.32*
Asia Pacific	*114.54*	*58.72*	*78.69*	*64.75*	*64.81*	*63.15*	*189.36*	*181.02*	*72.53*
2008									
N. America	19.4	21.7	21.0	21.5	21.5	21.6	17.4	17.6	21.1
Eurasia	17.0	19.7	19.1	19.6	19.6	19.6	16.0	16.3	19.2
Asia Pacific	22.3	24.1	23.3	23.9	23.9	24.0	19.5	19.7	23.4
Middle East	2.8	5.7	5.4	5.6	5.6	5.8	4.5	4.5	5.5
S. America	3.9	4.8	4.6	4.7	4.7	4.8	3.8	3.9	4.6
Africa	1.5	2.1	2.0	2.0	2.0	2.1	1.6	1.7	2.0
Total	66.8	78.0	75.4	77.3	77.4	77.8	62.8	63.7	75.8
N. America	*156.87*	*69.95*	*102.67*	*77.65*	*77.87*	*75.39*	*268.85*	*256.72*	*97.33*
Europe	*166.74*	*69.45*	*99.17*	*76.10*	*76.30*	*74.56*	*251.13*	*239.53*	*94.05*
Asia Pacific	*150.56*	*69.96*	*104.60*	*79.56*	*79.32*	*76.09*	*270.41*	*258.85*	*100.37*

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General Notation

$y \in Y$ .... Years included in the model time horizon

$n \in N$ .... Nodes represented in the model

$s \in S$ .... Suppliers

$s \in C \subseteq S$ .... Cournot suppliers

$s \in F \subseteq S$ .... Competitive suppliers

$i \in I$ .... Pool hubs

$A^{Ship}_{n,m} \subseteq (N \times N)$ ..... Set of shipping routes (arc from node n to node m)

$A^{Pipe}_{n,m} \subseteq (N \times N)$ ..... Set of pipelines (arc from node n to node m)

The Supplier $s \in S$

There are two types of suppliers: Cournot players $s \in C \subseteq S$ and competitive players (i.e., the competitive fringe) $s \in F \subseteq S$. Their variables and parameters are identical.

$Prod^S_{y,s,n}$ .... *Amount of crude oil produced*

$Add^S_{y,s,n}$ .... *Investment in additional production capacity*

$\overline{Cap^S_{s,n}}$ .... Initial production capacity

$Cap^S_{y,s,n}$ .... Actual available production capacity in year y

$\overline{Res^S_{s,n}}$ .... Total reserve horizon

$\overline{Add^S_{y,s,n}}$ .... Maximum allowed investment in additional production capacity

$Ship^S_{y,s,n,m}$ .... *Amount transported by ship from node n to m*

$Flow^S_{y,s,n,m}$ .... *Amount transported by pipeline from node n to m*

$Sales^{S\rightarrow R}_{y,tsn}$ .... *Amount sold to final demand at node n*

$Sales^{S\rightarrow A}_{y,s,n,i}$ .... *Amount sold to arbitrageur at pool hub i from node n*[1]

ρ^S_s .... Discount rate applied to future profits

$\alpha^{Cap}_{y,s,n}$ .... Dual to the capacity constraint

$\alpha^{Res}_{s,n}$ .... Dual to the reserve constraint

$\alpha^{Inv}_{y,s,n}$ .... Dual to the maximum investment constraint

$\phi^S_{y,s,n}$ .... Dual to the mass balance constraint

[1]The option to sell to the arbitrageur is only available to competitive trading entities, $t \in F \subseteq T$.

The Arbitrageur at pool node $i \in I$

$Sales^{A \to R}_{y,i,n}$ .... *Amount sold by the arbitrageur form node i to demand node n*

$\pi^{Pool}_{y,i}$ .... Pool price

ρ^{A}_{i} .... Discount rate applied to future profits

Final demand at node $n \in R \subseteq N$

$\Pi^{R}_{y,n}(\cdot)$ .... Inverse demand function

$int^{R}_{y,n}$ .... Intercept of inverse demand function

$slp^{R}_{y,n}$ .... Slope of inverse demand function

$\pi^{R}_{y,n}$ .... Final demand price at node n

Cost Parameters

$C^{Prod}_{y,n}(\cdot)$ .... Production cost function at node n (as proposed by Golombek et al., 1995)

$lin^{S}_{y,n}$ .... Linear term of production cost function

$qud^{S}_{y,n}$ .... Quadratic term of production cost function

$gol^{S}_{y,n}$ .... Golombek (logarithmic) term of production cost function

$C^{Inv}_{y,n}(\cdot)$ .... Investment cost function at node n (additional production capacity)

$inv^{S}_{y,n}$ .... Unit cost of additional production capacity

$tc^{Ship}_{y,n,m}$ .... Transport cost by ship from node n to node m

$tc^{Pipe}_{y,n,m}$ .... Transport cost by pipeline from node n to node m

$tc^{Pool}_{y,i,n}$ .... Transport cost from pool hub i to node n

Internet Resources

American Petroleum Institute (API) http://www.pipeline101.com/

Association of Oil Pipelines (AOPL) .... http://www.aopl.org/

Energy Information Administration (EIA) .... http://www.eia.gov/

General Algebraic Modeling System (GAMS) .... http://gams.com

International Organization for Standardization (ISO) .... http://www.iso.org/

Joint Oil Data Initiative (JODI) .... http://www.jodidata.org/

Oil & Gas Journal (OGJ) .... http://www.ogj.com/

Petromedia Ltd. .... http://www.portworld.com/

Statistics Canada .... http://www.statcan.gc.ca/

List of Abbreviations

ANWR .... Arctic National Wildlife Refuge

AOPL .... Association of Oil Pipelines

API .... American Petroleum Institute

bbl .... Barrel

BDI .... Baltic Dry Index

CCS .... Carbon Capture and Storage

CDM .... Clean Development Mechanism

COP .... Conference of the Parties

COP (15) .... (15^{th}) Conference of the Parties to the UNFCCC

CP .... Complementarity Problem

CTL .... Coal-to-liquid

EIA .... Energy Information Administration

ETS .... EU Emission Trading System

GAMS .... General Algebraic Modeling System

GBM .... Geometric Brownian Motion (stochastic process)

GHG .... Greenhouse gas

IEA .... International Energy Agency

IPCC .... Intergovernmental Panel on Climate Change

ISO .... International Organization for Standardization

JODI .... Joint Oil Data Initiative

KKT .... Karush-Kuhn-Tucker (optimality condition)

M-R .... Mean-Reverting (stochastic process)

MCP .... Mixed Complementarity Problem

MDP .... Mid-Depletion Point

MIP .... Mixed Integer Problem

MMbbl/day .... million barrel per day

MPEC .... Mathematical Program under Equilibrium Constraints

NCP .... Nonlinear Complementarity Problem

NEMS .... National Energy Modeling System

NGL .... Natural Gas Liquids

NOC .... National Oil Company

NPV .... Net Present Value

OGJ .... Oil & Gas Journal

OPEC .... Organisation of Petroleum Exporting Countries

OPEC .... Organisation of Petroleum Exporting Countries

OR .... Operations Research

PADD .... Petroleum Administration for Defense Districts

PIES .... Project Independent Evaluation System

ppm .... parts per million

R/P .... Reserve-to-Production ratio

RO .... Real Options

UNEP .... United Nations Environment Programme

UNFCCC .... United Nations Framework Convention on Climate Change

USA .... United States of America

USGS .... U.S.Geological Survey

VI .... Variational Inequality

WEO .... World Energy Outlook, IEA

WGM .... World Gas Model

WMO .... World Meteorological Organization

WTI .... West Texas Intermediate, Crude Oil Price Index

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