Universiteit Utrecht

Master of Science Thesis

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TIMER 2.0 and the price of oil:

Addressing the mismatch between TIMER oil simulations and historic world oil developments between 2007 and 2016.

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“The trouble with writing fiction is that it has to make sense, whereas real life doesn't.”

Iain M. Banks

Preface.

Dear reader,

Before you lies my master thesis, concluding the master of science programme Sustainable Development, with a specialisation within in Energy and Materials. This work wouldn't have been possible without the support of my family. I'd also like to thank my supervisor, Wina Crijns-Graus for her input and guidance during the development of the thesis. Furthermore, I offer my thanks to Bert de Vries, with whom I had several useful discussions concerning the thesis.

Johan Boterenbrood.

Abstract.

Since the 2000s oil prices have become increasingly volatile, with exceptionally large price movements since 2007. A high price period in between 2010 and 2014 fostered rapid growth of unconventional oil, in particular of tight oil in the USA. Since 2014 crude oil prices have dropped significantly again, and remained low up to at least 2016 (i.e. up to this report). The TIMER model developed by PBL does not reflect this volatility, instead it assumes continued low prices, just above marginal costs of production.

This report investigates the mismatch between historic oil price dynamics since 2007, which is the latest year up to which TIMER is calibrated and the TIMER model. Through a literature study and semi-structured interviews insight is sought into which factors within TIMER are missing or which ones could be improved. From this list a number of key factors are selected, from which a system dynamic model is built to assess their impact. The identified factors resulted in the development of a model that assesses the following two factors:

1. The effects of increasing costs of discoveries and production of conventional oil, and;
2. The effects of rapid growth of unconventional oil and decreased price elasticity of demand on the price of oil.

Depletion in discoveries are expressed as an effort per yield function, derived from historical data. This shows that over time marginal discoveries increase in cost exponentially. Likewise decline in existing field production requires a growing amount of capital stock to meet demanded supply quantities. Price elasticity of demand is observed to decline over time, which is expressed using exponential decay. The influx of multiple types of unconventional oil is entered exogenously in the model, as is oil demand. The cost of production and market price of oil are produced endogenously. The model is run from 1980 to 2020. Results from the model show that growing production and exploration costs form the main driver behind the high price of oil in the period between 2010 and 2014. The influx of unconventional oil coupled with reduced price elasticity of demand resulted in the subsequent price crash.

By using marginal costs of exploration and production as described in this thesis, TIMER is able to shift away from using long term cost-supply curves to determine future costs of oil production. Long term cost-supply curves contain significant uncertainties as they are sensitive to variations in estimated future reserve additions.

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1. Introduction.

Since the industrial revolution anthropogenic CO_2 emissions have increased relentlessly, affecting the global climate. The IPCC (2014) show that this trend will continue into the future. Such a prediction relies on underlying models that undergo continuous improvements. One of the Integrated Assessment Models used to predict future development of the environment is the IMAGE model.

As described by van Vuuren et al. (2015) the IMAGE (which stands for Integrated Model to Assess the Global Environment) modelling framework has been developed by PBL (the Netherlands Environmental Assessment Agency) and its predecessors since the 1980s. Originally it has been developed as a model that focussed on future climate change, but has since been expanded to include various subsystems, such as the human energy system. This has been done so that IMAGE may be used to assess development scenarios that holistically encompass the human and natural systems. The IMAGE model has been used as core input for assessments by the Intergovernmental Panel on Climate Change (IPCC), the Global Environment Outlooks (GEOs) by the United Nations Environment Programme (UNEP) and the OECD Environmental Outlooks as described by Stehfest et al. (2014). Development of IMAGE and its various subsystems continues to this day, with the first results from IMAGE 3.0 expected in October/November 2016.

As part of the IMAGE, the Targets IMage Energy Regional (henceforth TIMER) model is used to forecast long term global energy demand and supply. It does so by modelling in detail the demand for energy and supply of solid, gaseous and liquid fuels, as well as taking into account trade effects across the globe and energy conversion from primary to secondary energy (e.g. electric power stations and hydrogen production) as described by Stehfest et al. (2014). Substitution effects and more are also included. Modelling is done using System Dynamics theory. The TIMER model has been developed since at least 1995 as described by de Vries et al. (2001) and has been extended significantly since, with continuing development up to this day. Its goal is to offer policy makers insight into the energy demand and supply development up to year 2050 and 2100 under various policy scenarios.

TIMER 2.0 is calibrated using historical data up to year 2007 as described by Stehfest et al. (2014), which happens to be just before the global economic crash of 2008 and its effects on oil (both demand, supply and price). The IEA (2015a) shows that the years 2010 to 2014 oil supply and demand developed in close tandem, after which an oversupply of oil was developed, causing prices to drop rapidly. Up to 2016 prices have remained low due to maintained oversupply of oil, as shown in figure 1.

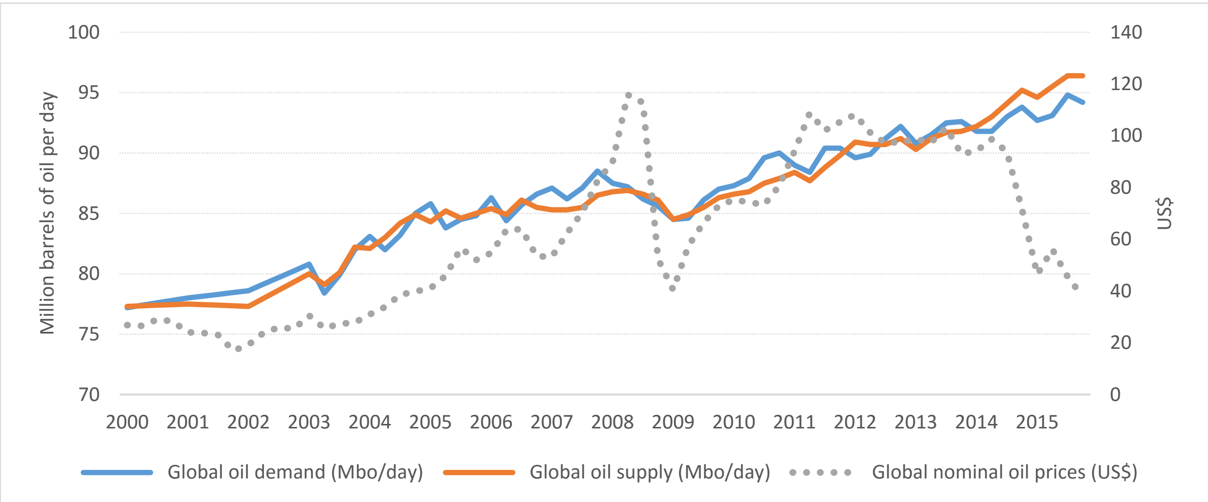

Figure 1: Historical data for oil demand, supply and prices, based on statistics from IEA (2015a) and EIA (2016e).

In this same time period non-conventional technologies such as tight oil in the USA managed to take-off, growing rapidly as shown by the EIA (2016b). For example, between 2010 and 2015 USA Tight oil supply grew 30% per year to 5Mboe/day. TIMER 2.0 does not predict this sustained oversupply of oil.

Figure 2 shows the global oil supply, demand and price resulting from the IMAGE 2.4 OECD Environmental outlook 2012 scenario used in the report written by the OECD (2012). The model makes use of calibration up to the 2008 crash, after which it shows a rapid increase in oil supply/demand as reality does, however, oil prices are highly stable. Other scenarios show similar pathways. It is not precisely known what the cause behind this mismatch between TIMER 2.0 results and observed historical behaviour is.

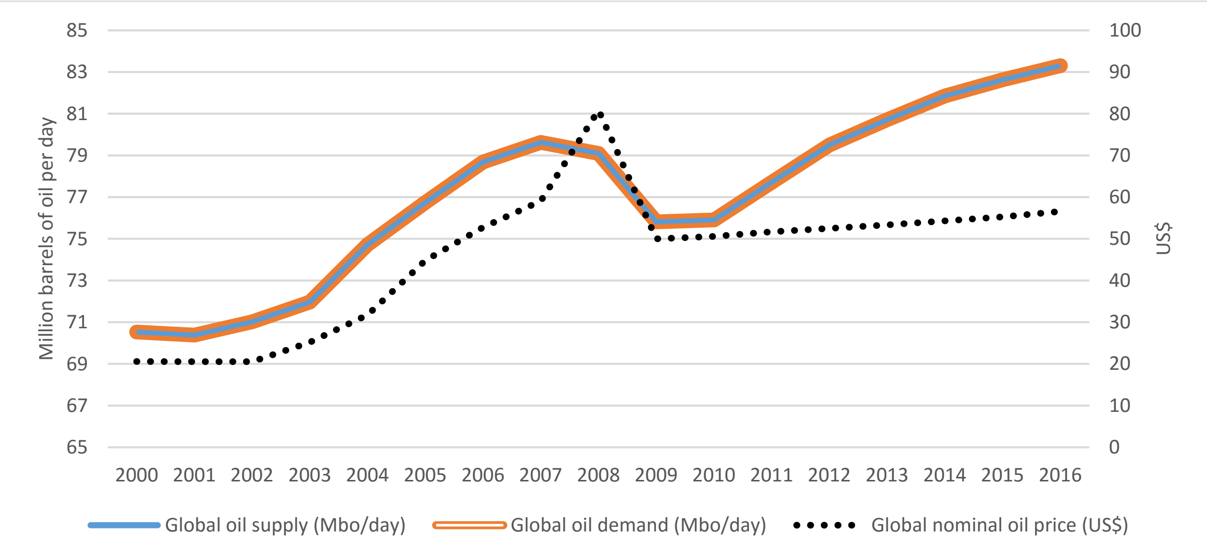

Figure 2: IMAGE 2.4 results for oil supply, demand and price for the OECD Environmental outlook 2012 scenario.

Given the fact that crude oil consumption constitutes roughly one third of global CO_2 emissions, as shown by the IEA (2015b), accurate modelling of future oil demand, supply and price is relevant for policy makers, as well as market parties.

TIMER 2.0 does not predict a multi-year oversupply of oil, instead Stehfest et al. (2014) show that it projects oil demand (i.e. liquid fuel) and supply to grow steadily, with producers producing slightly above their marginal costs and oil supply closely tied to demand. In fact, as shown in figure 2, crude oil supply and demand are equal at all times. This shows that certain economic demand and supply dynamics that are observed in the real-world are missing, or require adjustments within in the TIMER model. It is not yet known which factors are missing exactly, or require adjustments (and what adjustments precisely). This knowledge gap is addressed by this thesis project.

2. Research aim and relevance.

The value of this research is twofold. Firstly, its findings improve the modelling of oil dynamics in general, adding to the understanding of resultant behaviour of interacting factors not yet researched in this way (e.g. depletion effects forming a driver behind oil prices). Secondly, by making use of the TIMER model as a case study this project has both a concrete focus and recipient of results for which this project's results may lead to concrete improvements or extensions to the TIMER model. Improved simulations from the TIMER model will increase the legitimacy and value of TIMER and thus the IMAGE model, making it more valuable to be used by governments, organisations and corporations.

The results of this research may have the following effect within the TIMER model: Currently, the TIMER model is focused on long term behaviour, creating smooth supply-cost curves and quantities, which may give rise to a system that is too stable: historic data as shown in figure 1 shows that prices fluctuate strongly due to supply and demand mismatches. Such price volatility may cause quite a different long term behaviour from the smooth paths that TIMER suggests, as investments into capital stock is determined by crude oil demand, which affects crude oil prices. Furthermore, as shown by Perman et al. (2011) investors are risk averse, thus in a system in which high price volatility exists they would use higher discount rates than in a low volatility system. This would cause oil price peaks to rise, as higher prices are required before investments to increase capital stock become sufficiently Net Present Value positive. At the same time higher oil prices and volatility would hasten substitution effects away from liquid fossil fuels, thus altering the overall long term model behaviour in TIMER 2.0. The example scenario written in this paragraph shows that the effects of increased crude oil price volatility may in itself already produce different long term behaviour than the current model does.

Additionally, despite the focus upon TIMER, it may be useful to deliver results that can be used by all interested parties, rather than the TIMER team alone. Therefore, building an isolated model that investigates a set of selected parameters will deliver more valuable results to the scientific community as a whole.

3. Research framework and research questions.

3.1. Research framework.

Figure 3 shows the research framework for this investigation, which consists of four parts: a, b, c, d.

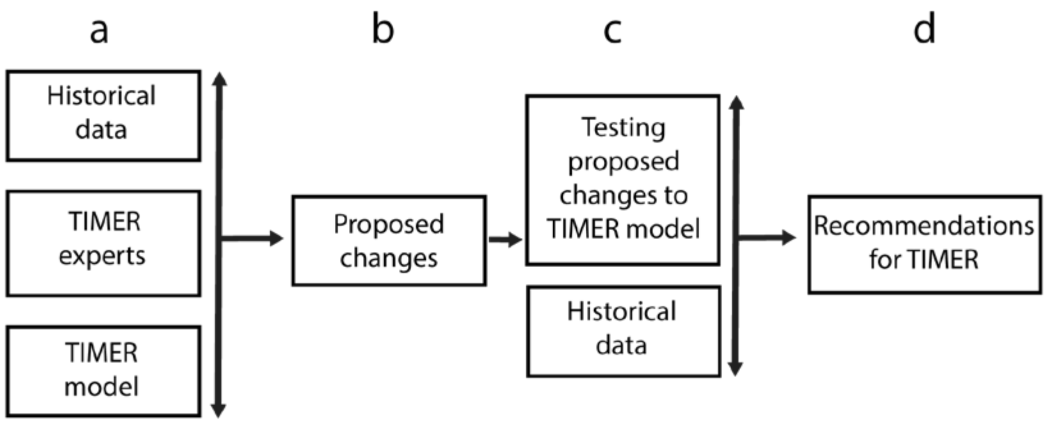

Figure 3: Research framework, following the method developed by Verschuren & Doorewaard (2015)

Part a forms the first step of the research project. A literature study on the historical data concerning the behaviour of crude oil's demand, supply and price is conducted to determine the main factors behind the increased price volatility. These factors are compared to the TIMER model as well as discussed with TIMER experts. These three parameters allow the identification of the factors that cause the TIMER model to diverge from observed historical data.

Part b builds upon the identified drivers from part a. This leads to a number of proposed changes within the TIMER model, which are likely to lead to more accurate TIMER behaviour. The proposals are discussed qualitatively.

Part c selects one or a small number of proposed changes from part b. These are tested to determine the resultant behaviour. Due to the complexity of the TIMER model, the proposed change is modelled separately from TIMER itself, in a simplified environment. Building an isolated model increases the model results' clarity, as it isn't influenced by various feedback loops produced by the TIMER model. Furthermore, it allows the outcomes to be used in projects other than TIMER itself.

Part d forms the conclusion of the thesis project. It leads to a number of recommendations for TIMER's liquid fuel subsystem.

3.2. Research questions.

From the research framework shown in figure 3 the main research question can be derived. Starting from the conclusion (part d) the main research question is defined:

Part d.

> **What changes in the liquid fuel subsystem of the TIMER model lead to improved emergent model behaviour of historically observed crude oil price, supply and demand development since 2007?**

The research framework allows the main research question to be answered methodologically, starting in part a, moving forward towards part c, the following questions are developed:

Part a.

1. What does the literature recognise as the main factors influencing the world's observed crude oil price, supply and demand behaviour since 2007?
2. What do TIMER experts recognise as relevant factors between observed historical data and the TIMER model's mismatch?
3. What differences exist between the TIMER model compared to the identified factors from research questions 1 and 2?
4. Which factors identified in question 3 are relevant to TIMER?

Part b.

5. Which factors are most relevant to model quantitatively, and how can they be modelled?

Part c.

6. Does the developed model show behaviour which explains the observed historical data on oil price, demand and supply?
7. What changes in TIMER would be needed to incorporate the model from question 6?

The answers to the research questions can be found in the following chapters:

- Chapter 5 answers questions 1 and 2. The specific answers are given in chapter 5.4.3.
- Chapter 6 answers questions 3 and 4. The specific answers are given in chapter 6.3.
- Chapter 7 answers questions 5, 6, and 7. The specific answers are given in chapter 7.6.4.
- Chapter 8 answers the main research question.

4. Methods.

Five steps are undertaken to answer the research questions and lead to recommendations for TIMER as shown in figure 4 below. It must be clarified that figure 4 is related to, but not similar to figure 3: figure 4 explains *how* the theoretical framework from figure 3 is executed. The arrows in figure 4 show chronological orders, and feedback loops (e.g. between step 2 and 1). Three main methods are applied, namely a literature review, semi-structured interviews, and system dynamics modelling.

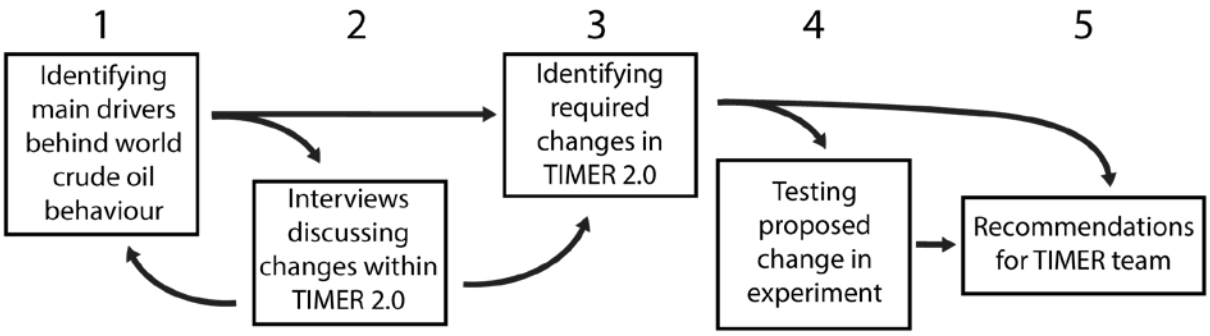

Figure 4: Methods

Each of the steps is described as follows:

1. A literature study is conducted to identify the main drivers behind historic behaviour of oil supply, demand and prices. The literature study was conducted in several steps. First reports from official institutions concerning oil development, such as the EAI, IEA, World Bank, OPEC, IMF and more are read (i.e. so called grey literature). These organisations publish reports regularly regarding many aspects of the global economy and oil supply, demand and changes therein. From these reports subjects of interests are identified and these are researched using sciencedirect.com, leading to a plethora of articles going in depth as to the causes and effects of the identified subjects. The findings of these articles are discussed and placed against one another to determine the strongest points made with the aim of finding the correct explanation for the observed phenomena. Also, factors identified by TIMER experts in step 2 are evaluated in a second phase of this step.

2. Findings from the literature study are discussed with five TIMER experts in individual semi-structured interviews. Besides discussing findings from literature, interviewees are encouraged to identify other drivers that may explain the differences between observed historical data and TIMER model behaviour. The interviews have three functions:
    a. The identified factors from the literature study are evaluated in respect to the TIMER model;
    b. Drivers not yet identified by the literature study but identified by the interviewee are discussed and fed back into step 1, effectively forming a single run feedback loop;
    c. Identifying which factors may be most important in the mismatch between observed historical behaviour and the TIMER model. This is to be used in step 3 and 4.

    Experts on the TIMER model are active within the Copernicus Institute in Utrecht as well as PBL Netherlands Environmental Assessment Agency in Bilthoven.

3. The results from step 1 and 2 allow a comparison between the TIMER 2.0 liquid fuel subsystem and the main factors behind observed global crude oil supply, demand and price behaviour. The comparison finds relevant parameters and/or interactions within TIMER 2.0's liquid fuel subsystem that need to be changed in order to allow the model to simulate historic data more accurately. The proposed changes are discussed qualitatively, and a selection is made within the factors that form the basis of the model in step 4.

4. An experiment is conducted using Vensim system dynamics software, developed by Venata Systems (2015). Vensim is chosen for this study for its accessibility to the thesis' author (i.e. it has good online documentation / tutorials) as well as having free academic licensing. Other system dynamics software packages are likely similar in their ability to deliver suitable results, therefore the precise software package used isn't crucial. Modelling a system dynamic model allows quantitative testing of the qualitative proposals from step 3. The model is built separately from TIMER, although some TIMER assumptions and data will be used as exogenous input values (e.g. initial crude oil production costs). Input data for the various factors within the model are from scientific sources, if data is missing explicit assumptions are made concerning relevant values.

5. Results from both step 3 and step 4 are brought together to identify which changes must be made in the liquid fuel subsystem of the TIMER software in order for it to simulate historic data more accurately. These changes would then lead to more accurate forecasting of TIMER and IMAGE scenarios.

5. Literature study and interviews on real world oil dynamics.

This chapter summarises and analyses the historical events that are relevant to the development of crude oil globally. Of particular interest is the period since 2007 up to 2016, as the TIMER 2.0 model has been calibrated using historical data up to that year as described by the PBL (2015).

The goal of this chapter is to answer the first two research question from part a, namely:

1. What does the literature recognise as the main factors influencing the world's observed crude oil price, supply and demand behaviour since 2007?
2. What do TIMER experts recognise as relevant factors between observed historical data and the TIMER model's mismatch?

The first question is addressed in chapter 5.1 through to 5.3. The chapter discussion in 5.4 combines the literature study with results from the interviews, and therefore addresses the second question.

5.1. Identified subjects for literature study.

The historic development of crude oil can be broadly categorised into its supply and demand, which are connected by the price of oil (e.g. high prices stimulate supply and depress demand). The price of oil forms a central role within the industry, determining investments, demand, supply quantities, etc. Using grey literature from the IEA (2013), IEA (2014b), IEA (2016), EIA (2015c), EIA (2016b), IMF (2011a), CIEP, (2015), OPEC (2015) as well as scientific literature such as written by Kesicki (2010), Tokic (2015) and Hamilton (2009) an overview of subjects within these broad categories is found, as their reports cover many areas of interest in this field. Added to these are the results from interviews with five TIMER experts, whose knowledge broadens the range of identified subjects. On the identified subjects the relevant scientific literature is assessed and discussed.

It must be noted that many of the identified points show close interconnectedness to one another, making clear disaggregation difficult. Therefore, it's not always possible to discuss one subject without detailing influencing factors to and from another. The main reason for the interconnectedness of the subjects is that they underlie the crude oil system and as such must be influenced and connected to one another. Subjects such as price elasticity of demand and price shocks could even be said to be two sides of the same coin. Likewise, a clear distinction between pre-2007 and post-2007 behaviour influences is not always useful to make. If need be, longer trends are analysed in order to understand post-2007 crude oil behaviour.

The following factors are discussed, ordered in supply and demand. The focus of these factors is their effect on the price of crude oil. Several factors affect both supply and demand, thus are addressed for both influences.

- Crude oil supply: Depletion effects, cycles of investment into capital stock, technological innovation, monetary policy, geopolitics, price volatility & -shocks.
- Crude oil demand: Emerging economies, price elasticity, monetary policy, price volatility & -shocks, speculation.

5.2. Crude oil supply.

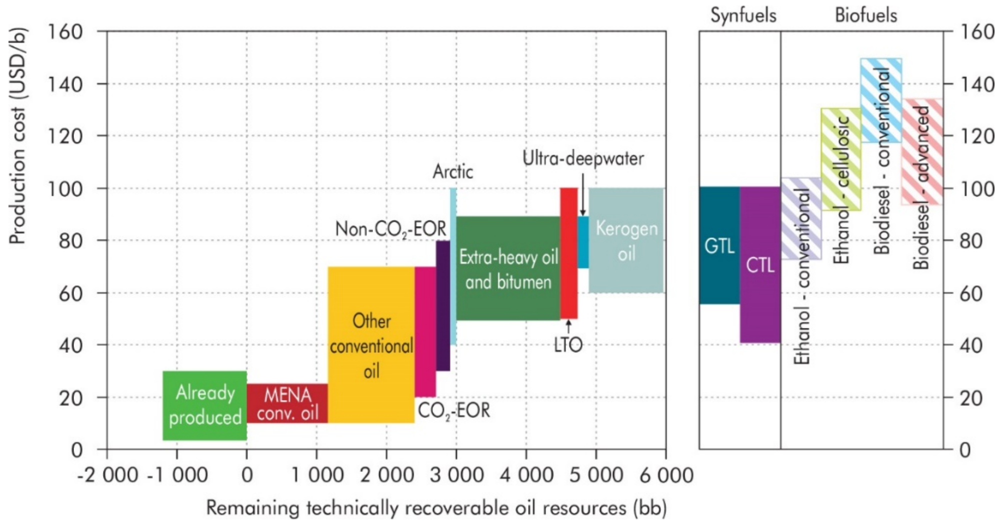

Figure 5: Marginal costs of oil, per type of production, source: IEA (2013).

Figure 5 shows the cost supply curve of the estimated remaining resources of oil as determined by the IEA (2013), subdivided into types and order by cost. Given the large amount still remaining compared to the 'Already produced' box, it seems unlikely that oil shortage is imminent. Nevertheless, production struggled to keep pace with demand growth, as shown in Figure 1. Only since 2014 supply exceeded demand, with a few small periods of oversupply in between. Several geological and technological reasons play important roles in figures 1 and 2, the interaction of which results in a major part of the supply of crude oil globally.

One geological reason as to why supply is struggling to maintain equilibrium with demand may be depletion effects within oil fields.

5.2.1. Depletion effects.

The scientific literature contains a lot of discussion on the point of oil field depletion, in particular the concept of peak oil is subject of debate, which is often stated in papers concerning this subject. For example, Illum (2004) writes the following:

> *"The oil industry's analysts point to ever greater costs of matching growing demand with supply from an aging resource base. Depending mainly on developments in the Middle East and the development of the world economy in the coming years, production may peak within one or two decades. It is a question of geology, technology, economy, and the policies conducted by various nations."*
>
> From: Illum (2004): Oil-based Technology and Economy - Prospects for the Future.

A concrete example of the conclusion of Illum (2004) is the restricted supply leading to the oil price spike in 2007/2008. Supply appeared unable to expand sufficiently to meet demand in that period.

If decline of production is happening there may be multiple reasons for that occurrence. Höök (2009) offers several reasons for decline of production of a field or region. Decline may be caused either by man made forces (e.g. economic recession, war, a lack of timely investments, etc.) or natural forces (reduced reservoir pressure caused by sufficient oil extraction). Man-made forces usually disappear after a certain time, after which production increases again (e.g. the 1970s oil crises). Physical decline is much harder to reverse, given the technical challenges of doing so.

The scientific literature offers evidence for physical decline in production. Höök et al. (2009) show that for non-OPEC giant oil fields 84% are in the decline phase by 2009, and almost 50% of the OPEC giant oil fields are in decline. However, Höök et al. (2009) warn that prolonged plateaus tend to result in higher decline rates. Furthermore, it is found that small fields have higher decline rates and depletion rates than large fields, meaning that large fields decline earlier but slower than small fields. Such dynamics could concentrate production towards regions with giant oilfields (e.g. Saudi Arabia).

The decline of oil production was already predicted in 1956 by M. King Hubbert in his 1956's paper named 'Nuclear Energy and the Fossil Fuels'. Hubbert (1956) laid the foundation for what is currently known as 'peak oil', forming a bell curved production curve (i.e. the Hubbert curve) for oil production. Hubbert's (1956) peak theory as used by Bentley & Bentley (2015) and Hallock et al. (2014) is strengthened by Höök et al. (2009), who write that in every observed situation decline has occurred before 50% of Ultimately Recoverable Resource (URR) depletion has been reached. In a later study, Höök (2014) states that IEA estimates of future production in 2008 require depletion rates three times higher than the most extreme historical example and are thus unlikely to be correct. Results from the study conducted by Sorrell et al. (2012) agree with this assessment: they warn against the use of projections that use depletion rates of higher than half the recoverable resource as this is inconsistent with empirical evidence. Chapman (2014) agrees with this assessment, and adds to that that large organizations (e.g. Shell, IEA, etc.) assume peak oil periods roughly a decade later than individual researchers. Only one study from Shell (2008) assumes an early global peak-oil in 2015, and BP assumes no peaking at all. One reason may be the omission or misuse of the Hubbert's peak theory, whilst favouring Hotelling's rule[1].

Okullo et al. (2015) investigated geological depletion effects by developing an oil model that compares two runs, one without physical depletion effects (a simulation based primarily on Hotelling's rule) and one that does include Hubbert's peak theory (geological constraints such as appropriate depletion rate and decline rates). Their findings are that when depletion effects are included considerably higher oil prices and lower production volumes are produced than in the Hotelling simulation. Reynolds & Baek (2012) also compared the Hotelling rule to Hubbert's curve and found that the Hotelling discount rate has little effect on oil prices, but that Hubbert's curve does have a large effect on oil prices, due to difficulties in maintaining sufficient supply.

The study conducted by Aleklett et al. (2010) applied Hubbert's curve to predictions made by the IEA WEO 2008. It results in a world conventional oil supply around 1/3 lower than that predicted by the IEA. In fact, the IEA (2008) prediction of OPEC production in 2015 turned out to be an overestimation of 25%, as shown by OPEC (2015). Furthermore, Aleklett et al. (2010) estimate that unconventional oil will likely have a larger share in the global production by 2030 than the IEA study. These studies strengthen the positions held by Illum (2004) and Chapman (2014) concerning the dichotomy in production estimates between institutions and individual researchers.

Given the large scale and heterogeneity of global oil production it is unlikely to be a precise year in which decline of conventional oil production begins, but rather a period of time in which the production fails to increase, after which decline sets in. A 'bumpy plateau' may be evidence of global

[1] Hotelling's rule states that the cost of exhaustible resource such as fossil fuels rises at a minimum rate of equal to the capital market's interest rate. Hotelling (1931) basically states that an owner of a exhaustible resource has to make the decision to exploit the resource now and use the revenues to invest in the capital markets, or to exploit the resource later when it might be more profitable than the accumulated wealth from the markets.

peak oil, with costs rising faster than production. However, due to the nature of such a bumpy plateau the exact period of peak production is hard to determine. Warrilow (2015) investigated exactly that problem by analysing 24 countries where oil production is in decline. His findings are that peak production is usually 'bumpy' but that in a global system this may be smoothed out. However, Warrilow (2015) states that, as global peak approaches, fewer countries are on the upslope of production, leading to increased price volatility due to reduced spare capacity. Hamilton (2009) and the IMF (2011) agree with this assessment.

Difiglio (2014) notes that in the period between 2000 and 2013 OPEC oil production capacity only increased with 1 Mboe/day, whilst global crude oil consumption increased by 15 Mboe/day in that same period. Clearly most supply increase happened outside of OPEC and since 2010 the global supply originated mainly from Canadian tar sands and USA tight oil production: unconventionals. Without the large growth in unconventional oil, Difiglio (2014) writes that non-OPEC production would have been in decline by 2014.

5.2.2. Cycles of investment into capital stock.

Upstream capital investments are investments made into the exploration and development of oil fields. These determine future production quantities and may indicate long term production cycles due to depreciation. High oil prices stimulate investments into upstream capital, as it indicates increased demand (or lacking supply), making increased production profitable. Work done by Naccache (2011) shows that investment cycles of 20 to 40 years are correspond to the oil price variations seen historically, lending strength to the idea of long term investment cycles dominated by depreciation and reinvestment of capital stock. These cycles are confirmed by the EIA (2015a), showing a strong correlation between high oil prices and levels of investments into upstream capital.

Figure 6 shows the oil production of Saudi Arabia between 1971 and 2015. Despite high prices during 2007-2008 and 2011-2014 capacity was only marginally increased since, although this might be due to delay effects between investments and production. However, capacity declined in the 2005-2010 period, demonstrating a lack of spare capacity as oil prices were sufficiently high to stimulate supply increase. Only since 2010 production increased again. Given the large resources of Saudi Arabian oil, either large scale replacement of capital stock is occurring, or production is reaching the end of its plateau phase and starts declining soon (or both).

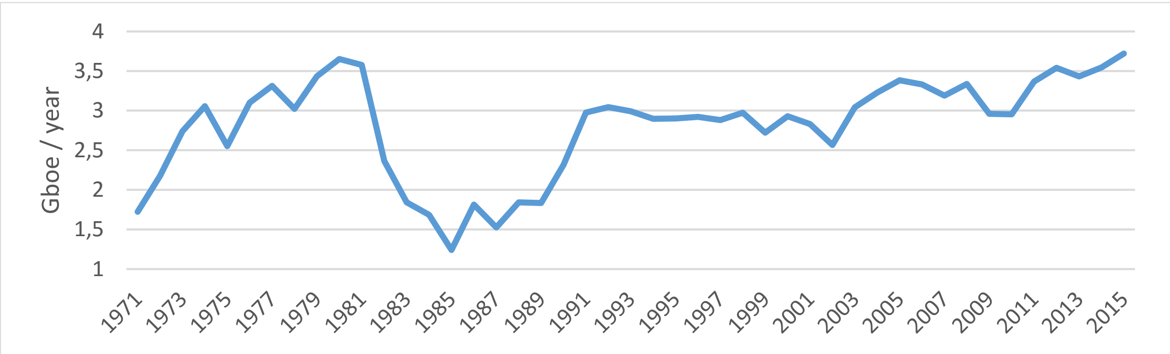

Figure 6: Historical production of Saudi Arabia since 1971, data from: EIA (2016e)

Babadagli (2007) finds that mature fields require increasingly costly investment in capital (e.g. additional wells, as well as enhanced recovery techniques) simply to maintain production. The IEA (2014a) shows that between 2000 and 2013 investments into upstream capital has grown from around 275 billion US$ to around 750 billion US$, a growth of a factor 2.7. Remarkably, production growth has grown by only a factor 1.6. This confirms Babadagli (2007) findings, but also suggests a shift of production towards higher marginal costs fields.

Upstream investments increase reserves due to additional exploration of oil fields. Bentley & Bentley (2015) show that discoveries peaked in the 1960s. After which discoveries of new oilfields dropped off. This makes sense, as the information effect causes discoveries to be rapid at first, and then to drop off, as discoveries in one region (information) stimulate more exploration in that area, as written by Jakobsson et al. (2012). The consequence of this is that regions containing large oilfields tend to be explored better than regions without, which leads to the risk of overestimating future discoveries. The analysis of Bentley & Bentley (2015) show that conventional oil production reached parity with discoveries in the 1980s. However, Wheeler et al. (2015) show that reserve growth outpaced demand growth since 2006, an indicator of extensive field exploration and a direct result of the high levels of upstream investment costs since then.

5.2.3. Technological innovation.

Despite the apparent imminence of global oil production decline, production went up, as shown in figure 1. In fact, since 2014 production exceeded demand consistently. One reason for this is the rapid growth of unconventional oil sources, such as USA Tight oil. In the period between 2010 and 2014 its production grew by 30% annually as shown in figure 7. Subtracting this supply from global crude oil supply completely removes the oil oversupply. In fact, a shortage between 3 and 4 Mboe/day would occur from 2013 onward. This is a shortage larger than during the three years before the 2008 crisis and the 2010 price rise.

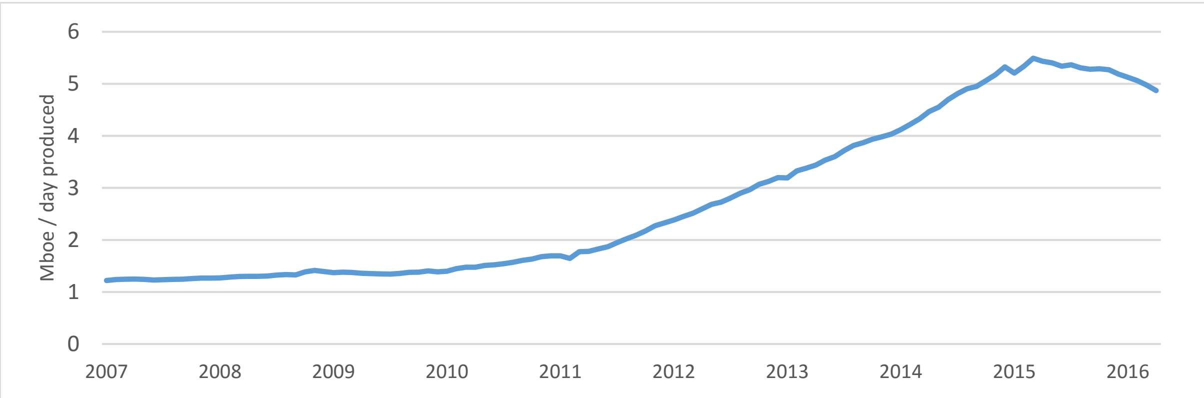

Figure 7: USA Tight oil production between 2007 and 2016, data from: EIA (2016b)

In his report 'Drill baby drill' Hughes (2013) finds that over 80% of USA tight oil production is from the Bakken and Eagle Ford plays, \$14 billion annual upstream investments is required to offset decline in these two plays alone. Hughes (2013) warns that tight oil production in these two plays may be a bubble that will collapse within 10 years time at around 2025, dropping back to 2012 levels of production as all drilling locations will be used up by then. Continued exploration and expansion to other plays is required to negate such a scenario.

The shale gas and tight oil production for the Bakken and Eagle Ford plays increased to sufficient proportions that they can easily be see from space, as shown in figure 8.

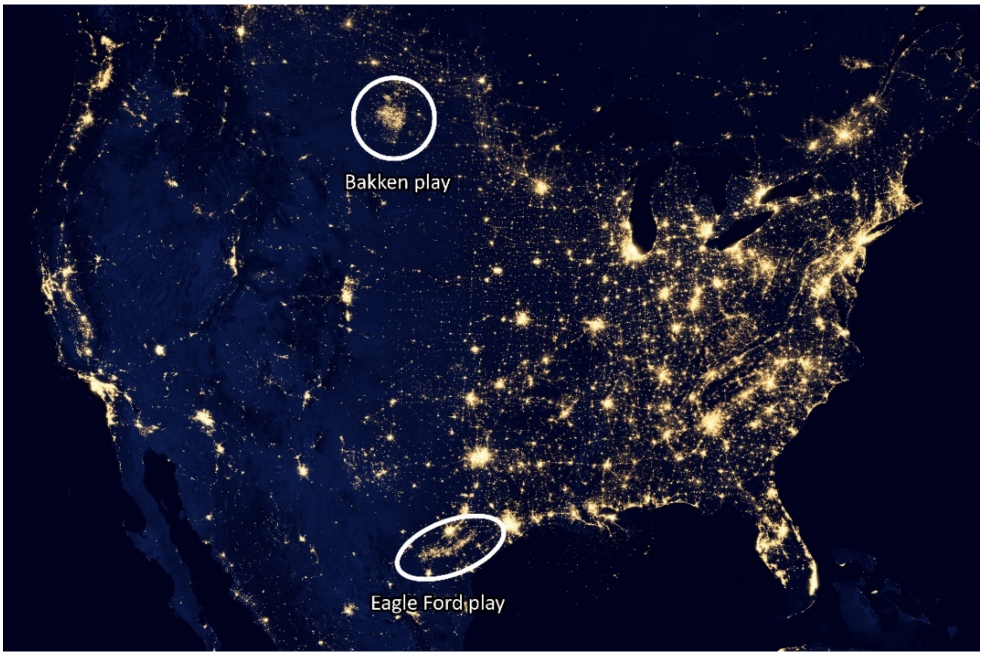

Figure 8: Bakken and Eagle Ford plays as seen from space. Source: NASA (2012)

Alquist & Guénette (2014) describe that the high prices found during 2010 to 2014 facilitated rapid growth in the tight oil sector. Technological innovation during this high price period allowed the technology to develop and become cheaper over time due to learning effects. The theory described by Brian (1989) concerning 'windows of opportunity' can be applied to the high price period that existed for tight oil to become competitive with conventional oil supply: the inability for the conventional oil supply to maintain low prices allowed unconventional oil supply to disrupt the status quo.

Nülle (2015) investigated how tight oil behaved since the 2014 price crash. His findings show that a combination of cost reduction of up to 30%, as confirmed by the EIA (2016a) and Difiglio (2014), and by focussing on the lowest marginal cost wells a significant fraction of tight oil production is able to continue at oil prices lower than what was previously profitable. However, given the short production time of tight oil wells it remains to be seen how long this tactic can hold out against a prolonged period of low oil prices. Difiglio (2014) emphasizes the risk of rapid depletion effects affecting tight oil production, as decline rates are considerably higher than in conventional oil production (due to limited underground oil mobility). Gevorkyan & Semmler (2016) write that as of 2016 a significant shake-out is occurring within the USA shale industry, meaning that only the most competitive companies manage to survive under oil price levels below 60 dollars.

Besides the development of USA tight oil production, Canadian tar sands increased by 10% year over year between 2007 and 2015 as shown by CAPP (2015a). However, since 2015 it has struggled to cope with lower oil prices. Findlay (2016) writes that investors 'flee in droves' from investing in tar sands operations. Compared to USA tight oil production, Findlay (2016) writes the followings:

> *"When compared with nimble LTO projects, oil sands investment decisions are slow, have historically been of much greater magnitude, and require large, well-funded balance sheets managed with longer-term foresight. Scale continues to be a*

formidable barrier to entry, essentially blocking out the type of enterprising smaller operators that made LTO so successful."

In a period of high price volatility it may be harder for tar sands production to adapt than for USA tight oil production.

USA tight oil production appears to be a unique phenomenon. Despite sufficient global tight oil reserves, Difiglio (2014) shows that other regions (e.g. Venezuela, Russia) have considerable difficulties developing those resources quickly. Reasons for the USA's rapid growth are beneficial infrastructure, free market initiatives, competition, and the easy availability of low interest liquidity.

5.2.4. Monetary policy

As written by Alquist & Guénette (2014), favourable above-ground circumstances such as existing oil infrastructure, open spaces owned by private actors and entrepreneurial spirit were not the only reasons why tight oil production flourished in the USA particularly well. Easy access to cheap credit due to the Federal Reserve's quantitative easing policies accelerated production of (at first) high cost, marginal technologies as described by Askari & Krichene (2010) and the CIEP (2015). As of 2015 the quantitative easing policies have ended, making access to capital more challenging for USA tight oil production. In contrast to USA tight oil production, Canadian tar sands developers have significantly more difficulty attracting sufficient investors, as shown by Findlay (2016). Due to the high costs involved with tar sands oil production, they require long term contracts, which favour low price volatility and sustained high prices (e.g. the 2010-2014 situation).

The research conducted by Mitchell & Mitchell (2014) shows that USA tight oil production is barely government controlled as far as volumes are concerned. One reason is that underground resources belong to the surface land owner: often private actors. Through a share in revenues it becomes attractive for land owners to allow access to their land for exploration and development of oil production capacity. The macro-economic effect of this is that instead of an optimal extraction curve, a rush to develop arises (a version of the boom and bust cycle). In most other countries around the world governments own underground resources, leading to different exploitation behaviour.

As written by Aguilera & Radetzki (2016), countries that have oil income tend to increase their fiscal extraction of that resource's production during periods of high crude oil prices. The UK increased its supplementary charge[2] from 10% in 2001 to 28% in 2008. However, this was reduced to 10% again in 2016, following the reduced oil prices as shown by HM Revenue & Customs (2016). Aguilera & Radetzki (2016) show that in 2010 Russia maintained a \$16 mineral tax and a \$40 export tax on its oil, cutting profits by \$56 dollars regardless of total cost. Such large taxation tariffs cut into the profit margins of oil companies, leading to reduced investments for exploration and production capital, leading to delayed production fall-back.

Besides governments increasing their share from corporate profits of oil, nationalisation of corporations caused most of the low-cost production capital to be government controlled. Described by Aguilera & Radetzki (2016), state ownership since the nationalisation waves of the 1960s and 1970s lead to significantly reduced efficiency of production. Due to inexperience in the production of oil, nationalised companies usually didn't manage to maintain the original production capacity in the years following their nationalisation. However, this effect is reduced over time. More relevantly, nationalised companies are subject to political influences, forcing behaviour that isn't focused on maximum efficiency / profitability (e.g. providing social employment). Besides additional costs, Aguilera &

[2] The supplementary charge is a UK tax targeted at oil producers. It's a kind of corporate tax, but is added upon the corporate tax.

Radetzki (2016) write that the effects of political interests cause increased bureaucratic overburden, leading to indecisiveness and thus larger delays when investments are needed. Furthermore, government owned companies tend to be overtaxed, meaning that their profits cannot be used to invest into capital stock and exploration as the company desires. Instead, those companies become dependent upon government budgeting, as shown by the IEA (2006).

5.2.5. Geopolitics, price volatility & shocks

Since 2007 there have been a number of relevant geopolitical events, both new and ongoing. Most notable were the Arab spring, civil war in Syria, the Russian-Ukrainian conflicts and the decade long oil sanctions on Iran's crude oil export which were lifted in January 2016. These geopolitical events mostly caused supply shocks. Given the difficulty to model such shocks into TIMER's future projections (i.e. who knows what geopolitical events will happen in year 2020, or 2050?) the relative impact of geopolitical events on the global crude oil system must be assessed. If these turn out highly significant and irreversible in nature it will result in increased uncertainty of future projections. However, if geopolitical events turn out to have only a minimal effect on the global crude oil system, and/or if the effects are reversed naturally over time (e.g. a temporary, self-correcting supply shock) the uncertainty of future projections in TIMER is not increased too much.

Chen et al. (2016) have investigated the effects of political risk shocks within the OPEC countries on world crude oil prices. Political risk shocks are perceived threats within a country that may adversely affect future oil supply from that country. Examples are (inter)national conflict, corruption, ethnic tensions, etc. The average price increase due to perceived risk is found to be roughly one fifth to the crude oil price, and appears roughly one and a half year after the perceived risk's appearance. This effect occurs mostly because with perceived risk investors expect higher future oil prices, thus invest in oil assets, raising demand and therefore the price (a self-fulfilling prophecy). Two and a half year after the initial risk perception most of the effect is gone. These results show that political risk shocks have a significant short term positive effect on global crude oil prices, but are reversed naturally.

The outcomes from research done by Kilian & Lee (2014) agree with what Chen et al. (2016) have written, although the effects of speculation are considered smaller. Both find demand shocks considerably stronger and supply shocks considerably weaker than political risk shocks, this suggests that stability of supply is actually a smaller factor on global crude oil prices than perceived political stability.

Despite the growth of USA tight oil supply, Belu Manescu & Nuno (2015) write that the unanticipated drop in oil price is not due to increased supply from the USA, but other unexpected increases in supply. These unexpected supply increases were mostly due to geopolitical events, such as lifted sanctions from rebel groups in Libya, etc. However, a relevant shortcoming in the analysis conducted by Belu Manescu & Nuno (2015) was that they expected Saudi Arabia to contract production to counter the tight oil supply: this has not occurred. Instead, Saudi Arabia has increased production, possibly attempting to maintain market share. Mitchell & Mitchell (2014) write that non-OPEC production is mostly responsible for the reduced oil prices. Also, Coleman (2012) found that oil prices are strongly influenced by the export quantities from OPEC nations towards OECD countries (i.e. OECD demand). When those exports drop, crude oil prices drop, making a strong case that tight oil production in the USA is a relevant factor in the recent price reduction of crude oil.

Economies that rely on high oil revenues to balance their budgets and lack sufficient financial buffers require significant budget cuts to balance the books. In fact, Belu Manescu & Nuno (2015) find that a 50% crude oil price reduction leads up to a 25% GDP in countries such as Venezuela, Angola and Kuwait. Saudi Arabia has sufficient financial buffers to sustain itself during this period of reduced prices for some time. However, internal tension within OPEC increases due to the varying urgency between member states to increase crude oil revenues. Van de Graaf & Verbruggen (2015) analysed the behaviour of nations whose oil revenues constitute more than 10% of GDP under reduced demand scenarios. They proposed five scenarios that could resolve the situation: quota agreements, efficiency improvements, compensation, diversification and price wars. Of these five scenario's there has only been clear evidence of a price war, as confirmed by the CIEP (2015). Nevertheless, doubts are expressed about the sense of the price war, as no benefits are gained.

Another reason OPEC refused to reduce their oil supply may have been the fact that countries with a high share of their GDP from oil revenues are vulnerable to reduced oil prices. They might attempt to make up this reduction of income by increased their supplied amount, attempting to maintain income. As written by Monaldi (2015), Venezuela had become highly dependent on oil revenues, which crashed since 2014, leading to increasing political difficulties, and attempts to boost income (e.g. via attracting foreign investments and increasing supply). Nevertheless, above ground difficulties make it hard to achieve these targets.

5.3. Crude oil demand.

Besides developments in the supply of oil, demand also showed developments in the years since 2007 to 2016. In particular growing demand from emerging economies (in particular China and India) continues to progress.

5.3.1. Emerging economies.

Globally the 2008 economic crisis was only short lived, resuming 4% growth in 2010 as shown by the World Bank Group (2016a). Although having multiyear repercussions in the EU and USA, economies such as China and India resumed GDP growth rapidly. Globally emerging economies (e.g. China, India) grew much faster than mature economies (e.g. USA, EU).

Van de Graaf & Verbruggen (2015) show that non-OECD crude oil demand overtook OECD oil demand since 2012. In fact, crude oil demand from the USA, Western Europe and Japan has dropped since early 2008 and remand stable since, with the rest of the world demand growing relentlessly. Continued strong growth in the large emerging countries was bound to overtake demand from the developed nations, and this was not in any way an unexpected development. Li & Xiaowen Lin (2011) find that the increasing demand from China and India (and other developing countries) may have been a driver behind the 2007-2008 and 2010-2014 high oil prices. This might've been true, but only in the sense that their demand would've grown faster than supply could anticipate upon, which seems improbable.

An often cited reason for the low crude oil prices is the slowdown of the Chinese economy since 2014. The World Bank Group (2016b) writes that in 2015 China showed slightly reduced growth, mostly due to internal corrections in the property sector, weakness in industrial productivity (i.e. overcapacity of housing and industry) and slower growth of credit. Consumer spending is expanding rapidly as well as a growing service sector. Reduced manufacturing and construction reduced import demands: China appears to be undergoing a slight shift from manufacturing to services. The IEA (2016) confirms this shift, but foresees increasing demand in 2016 onwards. Since 2014 crude oil demand from China has grown roughly half of its GDP growth.

As China moves ever closer towards a developed economy its reduced dependence on crude oil for GDP growth may continue. Li et al. (2016) find evidence for the existence of the Environmental Kuznets Curve[3] to be strong in the case of China. Additionally Li et al. (2016) emphasize that the China-US

[3] The Environmental Kuznets Curve is a curve that shows pollution emissions (i.e. fossil fuel consumption, among others) per unit of GDP per capita. Its hypothesis is that as nations develop their curve rises first (this increasing

climate accord suggest a break from previous emissions, with China aiming a peak in emissions in 2030 or earlier. Kang et al. (2016) have different findings. Their work finds that China exhibits an N-shaped Kuznets curve for CO_2 emissions. However, this N-shape is mostly caused by electricity consumption, which is largely produced by coal-fired power stations. Excluding the effect of coal, the Kuznets curve appears to hold true for the consumption of oil in China. Overall, it is likely that the lowering demand compared to GDP growth is likely to continue in the case of China.

Jebli, et al. (2016) tested the environmental Kuznets curve for 25 OECD countries and found that international trade was a beneficial factor in reducing polluting emissions. Given the large role of coal in China's electricity production increased international trade may reduce its CO_2 emissions, by increasing the share of Russian and USA gas in its electricity generation. Tiwari et al. (2013) found India to follow the environmental Kuznets curve as well. Given that China's GDP per capita is roughly 5 times that of India in 2015 as shown by the World Bank Group (2016b) India is likely to exhibit a strong increase of polluting emissions per unit of added GDP per capita for the years to come. For Latin American and Caribbean countries the environmental Kuznets curve was also investigated, but Pablo-Romero & De Jesús (2016) found no evidence for the Kuznets curve being valid in this region. It must be said, however, that their method measured only energy consumption, which is somewhat limited due to the lack of source and emission data (e.g. coal vs gas use, or the extensive use of biofuels in Brazil). Overall, GDP growth is the main driver behind crude oil demand growth, but its coupling reduces at higher levels of GDP.

5.3.2. Price elasticity.

One of the key factors Hamilton (2009) identified for the 2008 oil price crisis is the reduced price elasticity of demand compared to previous decades. Hamilton (2009) writes that (at least in the OECD) people were richer and energy use has a lower share in total expenditure than the decades before. Therefore, a rise in oil prices would have a reduced impact on oil consumption. The IMF (2011) confirms a reduction in price elasticity over the last decades, although there are differences in the exact values of the elasticity. Hamilton (2009) suggests a value between 0.5 and 0.7 with the elasticity around 0.6 in the first half of 2008. The IMF (2011) uses 0.68, which concurs with Hamilton's assessment.

Developing countries were found to have significantly higher price elasticities of demand for oil than developed countries. One result from this is that crude oil exports shift from developing towards developed countries in the case of increased prices. Therefore, differences in price elasticity of demand per region forms an indicator of changes in international trade flows, with regions containing the highest elasticities showing the largest responses..

Regardless of the exact value for the elasticity of demand, the main findings are that price elasticity of demand has reduced significantly in the last several decades, meaning they cannot be implemented as a constant value in modelling, but rather as a declining value as GDP per capita increases. The importance to eschew constant parameters such as price elasticity is underwritten by Bataa et al. (2016).

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polluting emissions per unit of GDP per capita) and then falls down again as people get richer. The idea behind this hypothesis is that a country first invests in industries and infrastructure, causing high levels of polluting emissions, after which is shifts towards a more service oriented economy.

5.3.3. Price volatility and shocks.

Price volatility is the flip-side of reduced price elasticity of demand, as prices need to shift more to achieve the desired response in demand, and increased price volatility increases the chance and severity of oil price shocks.

A Price shock is the sudden and unexpected change in the price of a commodity, either positive or negative. It can happen in either demand (e.g. the economic crisis of 2008) or supply (e.g. the supply disruptions in the 1970s). Rafiq et al. (2016) investigate the macro-economic trade effects of oil price shocks. Their findings are that a rise in oil prices benefit the real revenue of exporters, however, due to increased revenues oil exporting economies import more goods and services, lowering internal economic diversity, thus decreasing the country's resilience against a negative oil price shock.

Positive demand price shocks due to global demand forms a net-positive effect for Asian economies, as global economic activity outweighs the price increase of crude oil as shown by Cunado et al. (2015). Rafiq et al. (2016) find that oil importers are increasingly resilient against positive oil shocks, however, they do not identify the reason behind this. The driver may be reduced oil price elasticity as found by Hamilton (2009), Difiglio (2014), the IMF (2011) and Hughes et al. (2006).

D'Ecclesia et al. (2014) write about how investors used oil to diversify their investments: thus pushing its price upwards during the period up to 2008. Their study finds that futures contracts forms a significant role in price volatility, as amplifying effects arise in the price of oil (i.e. price bubbles).

5.3.4. Monetary policy

Tokic (2015) has a fairly unique point of view with regards to the 2014 oil price drops. He argues that the dramatic fall in oil prices was not a matter of fundamentals (i.e. traditional supply / demand effects), but that the 2014 oil price drop was preceded by a sudden difference in economic outlook between the Euro area and the USA, as well as Euro/US dollar exchange rates. These sudden changes were shown by a sudden drop in LIBOR values[4], causing a strong reaction in the oil financial assets. Unfortunately, Tokic (2015) offers no extensive explanation as to what the underlying mechanism is between the LIBOR and oil prices, apart from speculative behaviour in the oil market.

The identified effect of the exchange rate is clear, as the Euro depreciated against the US dollar in 2014, it became more expensive for the Eurozone to purchase crude oil in US dollars per barrel. This likely reduced short term crude oil import demand somewhat. However, taking into account the low price elasticity of demand in developed nations, this effect cannot explain more than a fraction of the reduced oil price: as otherwise a catch-22 situation would arise in which more expensive oil prices are needed to achieve lower oil prices. Askari & Krichene (2010) recognize similar processes as Tokic (2015) taking place in the 2008 crisis, where supply was rigid and demand was heavily influenced by low US interest rates and the US dollar exchange rate, amplifying the oil price. The cheap credit pushed by central banks that allowed the development of tight oil production to grow beyond a niche relatively quickly in the USA, also boosted global demand for oil, pushing up prices due to speculative behaviour. A depreciation of the US dollar leads to increased oil demand, as foreign money is able to buy more oil for the same local price.

[4] LIBOR (which stands for London Interbank Offered Rate) is the lowest daily interest rate banks and large financial institutions borrow each other money for. Bajpai (2015) writes that all over the world banks use the LIBOR to set their own interest rates. The LIBOR is also used for international exchange rates, setting futures contracts and allows central banks and other actors insight into the expectations of interest rates. Globally Bajpai (2015) estimates there are hundreds of trillions of US dollars tied to LIBOR, making it relevant in almost all economic activity.

5.3.5. Speculation.

D'Ecclesia et al. (2014) find that in the last 15 years a dramatic increase in the trading of crude oil futures is observed, growing nearly ten-fold. The strong increase in oil prices in between 2002 and 2008 corresponded with a period in which traders were particularly active in the commodities market. However, a dichotomy in researchers is identified as to what caused the 2008 price bubble: if it was mainly due to financialization (e.g. speculation) or fundamentals (e.g. a failure to increase supply). Gkanoutas-Leventis & Nesvetailova (2015) find that in late 2007 crises in many segments of the financial system pushed capital flow into financial crude oil, rapidly inflating crude oil prices whilst masking the systemic problems in the financial sector. Crude oil was treated as a hedge to offset risk elsewhere. History showed that this failed spectacularly. Gkanoutas-Leventis & Nesvetailova (2015) confirm the growth in financialization of the oil market.

The study conducted by Kilian & Lee (2014) sought to find the quantitative effects of speculation in the oil market. Their work suggests that the range of upward pressure due to speculation in oil prices is somewhere between 4% and 12% of real prices. Another finding is that speculation occurs mostly during periods of concerns about Middle Eastern stability affecting supply (i.e. the political stability factor as described in 5.2.5.). Downward pressure was also found, exacerbating lowering prices. The work done by Coleman (2012) finds that the effects of speculation is much more substantial. Having grown from 0.2 times the physical market in 1980 to over 20 times the physical market in 2007 Coleman (2012) finds that the futures market pushed nominal crude oil prices by up to 45 US dollars per barrel. It must be said that his argumentation for the 45 US dollars is not entirely clear and appears to be based on assuming similar growth in speculative value as the growth of futures market (i.e. a factor 100). Although consensus on the exact amount is lacking, speculation appears to be a relevant factor in the 2007-2008 oil price spike.

The link between geopolitical uncertainty (e.g. Libyan unrest, deployment of USA troops, etc.) and price volatility is recognized by Sornette et al. (2009) as well. They write that, although the magnitude is likely to be minor and hard to quantify, the increased uncertainty caused by geopolitical uncertainty likely increased speculative behaviour. Future price uncertainty appears to be the main driver behind speculation.

One factor that might dampen crude oil price volatility is inventories. Dvir & Rogoff (2014) found that the long term correlation between oil prices and inventories of oil formed a negative relationship before 1973, when supply was unrestricted. During those years inventories tended to increase during low oil prices and decrease when prices were higher. After 1973 supply became restricted the relationship inversed, and inventories grew with increasing oil prices. This may be caused by a fear of short-term oil shortages. Given that the study conduction by Dvir & Rogoff (2014) was conducted just prior to the drop in crude oil prices they wonder if this relationship reverses anew when supply exceeds demand. In fact, the EIA (2016c) shows that oil inventories have increased significantly since 2014, suggesting that this relationship has indeed reversed again. The reversal is likely due to oversupply of oil, making oil an attractive commodity for future sale when prices rise again, thus different forces operate on inventories' growth during high and low oil prices. This hypothesis is confirmed by Kolodziej et al. (2014).

The shift in behaviour of inventories forms a proxy on the kind of behaviour speculation has on the global oil markets. Since 2014 inventories have grown with depressed oil prices, which signifies a contango situation. During the inflated oil prices leading up to the 2008 crises speculators expected oil prices to remain high, thus using oil as a safe hedge, which didn't work in the end. This shows that when inventories increase during periods of rising oil prices a price bubble may be forming, leading to a crash.

5.4. Chapter discussion and conclusions.

The literature study conducted in this chapter has found a good number of aspects that affect the crude oil system. Many of these exhibit strong interrelationships with other factors. The factors identified in the literature study were discussed with TIMER experts in semi-structured interviews, the findings of which are included in the following discussion.

5.4.1. Supply

Firstly, it is found that the reasoning behind the geological constraints on oil production is based on considerable research, both theoretical and empirical. The reasons behind the dichotomy in peak production estimates between large institutions and individual researchers is not entirely clear from the literature. However, a potential reason may be that large organizations contain a large amount of inertia in their operation that new methods and insights may not always be picked up quickly. Compatibility with existing statistics may also hamper the adoption of new methodologies, effectively locking in a certain approach. Most uncertainty within this field is based upon factors such as the Ultimate Recoverable Resource which is used in determining the point at which decline is likely to start. Due to expanding reserves this point may be pushed back repeatedly. Also, during the interviews the point was made that when reserves are misrepresented, estimating depletion rates becomes pointless for those actors / fields, as depletion might not set in for considerable time. An example of unreliable data is the way OPEC's member states behave. They are allowed to produce a certain quantity of their reserves annually, thus boosting reserve estimates. Furthermore, non-sequential discoveries of new fields may push supply, whilst depressing oil prices. Essentially stochastic behaviour in field discoveries would form an adjustment or re-arrangement of the existing long-term cost-supply curve.

Nevertheless, global oil supply constraints appear to be one of the major reasons for the high crude oil price periods since 2000, and these periods of high revenue nurtured the development of new technologies, such as horizontal drilling and hydraulic fracturing, which lead to tight oil production taking off. Without depletion effects and production constraints market effects dictate that supply from conventional oil would increase until crude oil prices reached the marginal cost of production, thus taking away the window of opportunity for tight oil development. Results from the interviews confirm the effects of depletion to some extent: depletion occurs, but only at a certain price level (e.g. many fields with low marginal costs have entered decline, such as North Sea oil). Crude oil production with higher marginal costs increase supply, alleviating the restricted production. These dynamics form important cycles in which innovation grows and technology matures. The high rate of learning found in tight oil technologies allow the technology to move from a niche that can only survive during high crude oil prices towards open competition with conventional oil production.

Could long term capital stock replacement cycles have affected supply? Evidence suggest that during the 1970s oil price spikes large upstream investments into capital stock were made, which may have depreciated during the early 2000s, requiring replacement to maintain production. This may have taken up capital investment capacity, limiting sufficient growth in the time needed to meet demand. The interviews suggest this effect may have been minimal though, as oil producing technologies are easy to retrofit and upgrade throughout their lifetime. It seems unlikely then that this was a relevant factor in the oil price volatility seen since the 2000s.

The scientific literature offers several effects of monetary policy on the behaviour of oil prices, some of which were of such economic complexity that they were beyond my ability to assess in depth. Effects such as interest rates, and exchange rates, as well as effects on GDP due to crude oil price changes appear straightforward but may have quite complex reasons and results. Results from the interviews show that changes in the interest rate used in TIMER may have a visible effects on investment behaviour, not only for crude oil supply, but also beyond that sector. The financing of substitution technologies may be affected, or upstream investment in capital stock for crude oil production may be cheaper to make, stimulating the exploitation of high marginal cost fields. This effect was seen in the USA, where cheap credit stimulated the development of the tight oil sector, boosting its production and thus accelerating its learning over time. A feedback effect behind economic performance and interest rates (i.e. economic stimulus packages) is not included into the TIMER model, and may yield interesting developments.

Governments attempting to maximise their fiscal extraction from oil exports run into the problem that the companies who are placed into that regime risk making sufficient profits to invest into exploration and capital stock, thus leading to a delayed reduction of supply. This effect is stronger in government owned companies, which are sometimes seen as cash-cows whose purpose is to fatten the government's wallets. Publicly owned companies run into the problems that they have to apply for government money to explore and develop fields rather than use their profits for this purpose. Historical data shows that these government actors tend to show poor performance in expanding their oil production capacity compared to private actors.

Remarkably, the price of oil seems fairly resistant to supply shocks, as real world geopolitical disruptions in supply (e.g. USA invasion of Iraq in March 2003) led to small changes in oil price. Perceived future events have significantly stronger effects on the price of oil due to market speculation. For countries relying strongly on oil for their state revenues (i.e. countries with a high share of oil revenues in GDP) are vulnerable to negative oil price shocks. This effect may cause significant political unrest in such countries, having to cut back significant amounts of state expenditure, as shown by Monaldi (2015). The effect of the resource curse may have caused countries with high levels of GDP revenue shares from oil exports to become addicted to that income. This would lead such countries into crisis during reduced oil prices as governments have to cut spending significantly. Results from the interviews confirm this, and suggest that such countries might attempt to increase production to offset the effect of lower per-unit prices, leading to a vicious cycle and a form of the prisoner's dilemma.

The position of OPEC appears to have been substantially weakened by the influx of unconventional oil. By cutting supply OPEC would be raising global crude oil prices again, however, this would immediately foster significant capacity expansion of USA tight oil production (and perhaps other unconventional types of oil production which are not yet competitive). The alternative, undercutting USA tight oil production appears to reduce USA tight oil production, however, this is done at great financial cost to OPEC's own national budgets. Nevertheless, OPEC pushing down USA tight oil production sufficiently for global crude oil prices to rise again would simply lead to USA tight oil production to grow to its former capacity. Clearly, global oil prices are now determined by USA tight oil marginal costs of production. This means the global oil marketplace starts to behave more like a free market.

Of course, such a situation will only last as long as tight oil reserves remain out of decline, of which a crude estimate can be made by applying the 50% reserves depletion rate rule-of-thumb to the most recent proved USA tight oil reserves of roughly 20 billion barrels, as shown by the EIA, (2015b). At sustained production of 5 Mboe / day USA tight oil production decline would set in roughly five years from now (i.e. the early 2020s). Of course this estimate contains several caveats: production volumes may differ significantly (they will most likely remain below 5 Mboe /day in the coming years, given late 2015 decline and global crude oil oversupply) and proved tight oil reserves are likely to increase further (having shown growth figures of between three and four billion barrels per year since 2008). Given the high decline rates of tight oil wells it may be that once USA tight oil production decline sets in the USA's newfound position within international crude oil supply may disappear as quickly as it arrived.

5.4.2. Demand.

The structural change observed within China is interesting, although a predicted outcome by application of the environmental Kuznets curve. China (and India, etc.) are most likely developing close to expected patterns already implemented within the TIMER 2.0 model. Eventually emerging economies catch up with developed economies, during which economic growth gradually slows down and the internal structure is changed accordingly. Regardless of the slowdown of China's demand growth, it has still grown significantly since the early 2000s, causing tightness in supply.

Changes within the price elasticity of demand may explain a great deal of the increased price volatility of crude oil. Not only do the literature and interviews find that the share of income spent on crude oil products dropped over the last decades (i.e. people became richer faster than oil became more expensive), but due to increased government measures to reduce oil consumption elasticity of demand has been further decreased (e.g. taxations on fuels, energy efficiency rules, etc.). The various oil price shocks discussed are likely connected to the observed decrease in price elasticity of demand. As people respond less to price shocks than they did in the past, the shocks must expand to attain the desired response in behaviour. A negative effect may be that price induced efficiency improvement responses will decrease. Effectively, people can afford less efficient behaviour than they could in the past. An interesting finding from the interviews might be that high price volatility may lead to sustained increases in substitution and efficiency improvements effects.

Monetary policy affecting demand of crude oil is usually a tax, raising the cost of consumption, thus lowering demand. However, policies aimed at stimulating the economy that affect the exchange rates of money affects the price of oil as well. For example, devaluating the Euro vs the US dollar raising the cost of oil for European consumers. The reverse may also hold, as the Dollar may be depreciated due to monetary stimulus packages oil consumption becomes cheaper for all consumers not using the US dollar as currency. This shows how local actor policies may affect oil demand globally. The interviews show that environmental concerns are only really relevant to governments as long as their economies run well. Once economies require 'a boost', policies stimulating economic development tend to overrule environmental concerns. Therefore, it may be that actors (i.e. governments) increase oil demanding policies during low GDP growth, and oil reducing policies during high GDP growth.

As with the supply of oil, the effects of geopolitical events on crude oil appears rather limited. In fact, due to increasing speculation, political risk shocks, which are based on potential future changes in supply or demand have more effect on the price of oil than an actual invasion, or other significant geopolitical events. In other words, ideas about potential future events which may not even come to pass drive oil speculation stronger than events that actually happen. A proxy to determine future frequency of political risk shocks per region may be a combination of climate change data, population density and GDP per capita, all projected into the future. Climate change affects the 'liveability' of a region compared to the early 2000s, population density determines the size of potential political risk shocks (i.e. high population densities suggest large cities which depend on surrounding land for ecological support). The GDP per capita may suggest the adaptability of the population to deteriorating environmental conditions (i.e. poor groups, or regions with high income inequality may be affected stronger than rich and more homogenous groups). The product of this would result in a 'political risk shock' frequency factor placed unto current values to determine future political risk shock for year X. Evidence for climate change adversely affecting political stability is widespread in the literature, such as the reports written by Salehyan & Hendrix (2014), Barnett & Adger (2007) and Papaioannou (2016).

Vast increase in financialization of the crude oil system along with growing speculative behaviour are likely to boost price volatility. Although the literature is highly divided on the exact magnitude of these factors within the oil system, the fact that they increase is affirmed unanimously. Regardless of the desirability of these trends within the oil system, the lack of agreement between researchers, the plethora of sound arguments and analyses with various outcomes concerning the effects of speculation demonstrates that there is still a substantial knowledge gap in this field.

The behaviour of inventories forms a proxy for speculative behaviour: growing inventories during high or rising oil prices suggest an anticipation of even higher prices, increasing the risk of a bubble to form. Increasing inventories during low oil prices are more traditional speculative behaviour, as the oil market is in contango based upon reasonable assumptions concerning oil price behaviour. This effect is interesting for historical analysis, but not useful for modelling future scenarios: the fundamental reasons behind the observed behaviour has to be known for that to be modelled successfully. Given the difficulties of determining speculative / strategic behaviour this would require significant efforts. The interviews suggest that inventories have limited effect on oil prices, having been used only a few times in the past (e.g. the days after 9/11). Oil inventories may form a small stock, large flow field, alleviating large supply shocks.

5.4.3. Chapter conclusions.

The first research question addressed by this chapter:

1. What does the literature recognise as the main factors influencing the world's observed crude oil price, supply and demand behaviour since 2007?

The following main factors are identified:

- An increase of speculative behaviour over the last decades has occurred, increasing price volatility;
- Decreased price elasticity of demand, increasing price volatility, mainly due to increased per capita GDP, reducing expenditure costs on oil, thus allowing larger absolute fluctuations of prices without affecting relative costs too marge;
- Depletion effects and production constraints limit supply growth, despite significant reserves. Although depletion of global oil reserves is not imminent, many low marginal cost fields are in decline, meaning that future supply will increasingly consist of a small number of giant oil fields (e.g. Saudi Arabian fields) and unconventional oil suppliers making use of higher marginal cost fields;
- Sustained high crude oil prices due to supply stagnation fostered growth and increased the competitiveness of light tight oil production in the USA;
- National oil companies have a high risk of insufficient funding, leading to stagnant or declining production in the future;
- Governments tend to increase the tax burden on oil producers during high oil prices and lower these during lower oil prices after a certain delay, causing supply volatility;
- The USA contained specific social, financial and economic conditions which allowed tight oil production to grow rapidly;
- OPECs price setting ability is reduced due to the disruptive behaviour of USA tight oil production to the global demand / supply balance, although this may only be a temporary effect, as long term (i.e. >10 years) significant supply from USA tight oil is unlikely to remain at high enough capacity to disrupt global supply mechanisms;
- Demand from emerging economies kept rising roughly as they have in the past, with evidence of China shifting along the environmental Kuznets curve towards reduced oil consumption per unit of GDP growth.

The second research question addressed by this chapter:

2. What do TIMER experts recognise as relevant factors between observed historical data and the TIMER model's mismatch?

The following main factors are identified:

- Limited supply growth (scarcity of investment capital) and large Asian growth caused market tightness, pushing up oil prices until USA shale oil alleviated the situation;
- There may be a steep price increase when supply fails to meet demand by being unable to increase capacity in time;
- TIMER uses smooth GDP paths, causing demand to supply to meet expected demand predictably, this alleviates volatile behaviour. GDP growth is an exogenous factor;
- Unrest in the Middle East may have put off investors, limiting supply growth;
- Failed OPEC coordination may have increased price volatility;
- Prices are determined a lot simply by politics rather than supply and demand, which isn't captured in TIMER;
- The demand for oil may change too. Substitution effects within transport is occurring slowly but surely (i.e. electrifying transport). This is seen in rich western countries at least. Developing countries are unlikely to show this behaviour yet.
- Climate agreements may cause a flood of oil due to producers dumping their assets before they become stranded.

Given the various interactions within oil supply, demand and price dynamics a causal loop diagram is shown in figure 9 below. The various effects of supply and demand in relation to price is shown (e.g. an increase in crude oil price leads to increased exploration). The exact magnitude or possible delays are not shown in the diagram. A + sign in the arrow between 'A' and 'B' shows that when 'A' increases, 'B' increases. A – sign has the opposite effect (the OPEC coordination and control factor is an exception: it can both lead to an increased and decrease crude oil price, depending on their intentions).

Grey arrows indicate price volatility effects, which influence the price of oil differently than the regular connections. Their values are 'ipv': increased price volatility, and 'dpv': decreased price volatility.

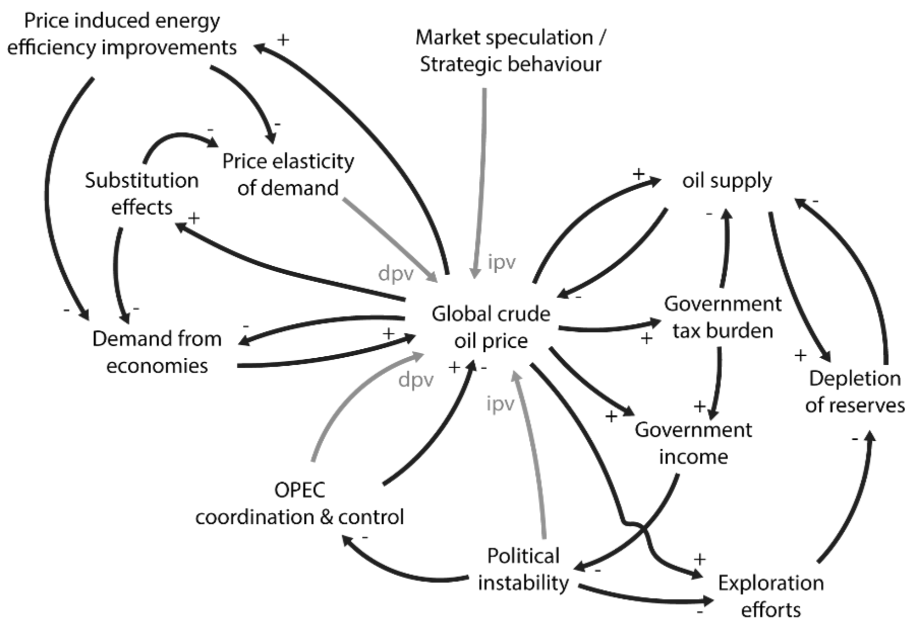

Figure 9: Causal loops derived from identified factors concerning oil price, supply and demand.

6. Identifying areas of improvement in the TIMER model.

This chapter answers research questions 3 and 4:

3. What differences exist between the TIMER model compared to the identified factors from research questions 1 and 2?
4. Which factors identified in question 3 are relevant to TIMER?

Research question 3 refers back to questions 1 and 2, which are:

1. What does the literature recognise as the main factors influencing the world's observed crude oil price, supply and demand behaviour since 2007?
2. What do TIMER experts recognise as relevant factors between observed historical data and the TIMER model's mismatch?

These are concluded in chapter 5.4.3. In order to answer questions 3 and 4, the TIMER model is investigated, which is described by several sources. These are: PBL (2014a, 2014b, 2014c); Stehfest et al. (2014); van der Sluijs et al. (2002); van Ruijven et al. (2010); van Ruijven & van Vuuren (2009); de Vries et al. (2001); van Vuuren et al. (2015). Furthermore, interviews with TIMER experts and the TIMER User Support System (i.e. TIMER interface software) supplied by the TIMER team are used to evaluate the TIMER model.

The TIMER model is compared to the identified factors from chapter 5, divided into supply and demand. The lists of results from chapter 5.4.3 are aggregated into the following lists:

- Supply:
  - Depletion effects and reserves;
  - Technological innovation;
  - Price volatility;
  - Monetary policy and geopolitics.
- Demand:
  - Emerging economies;
  - Price elasticity;
  - Price volatility;
  - Price shocks and speculation;
  - Monetary policy and geopolitics.

From the comparison between the discussed factors and TIMER, the factors are identified which are relevant to examine further in chapter 7.

Figure 10 on the following page shows the complete TIMER energy module, which factors are relevant and which connections exists. This gives an overview of the TIMER's workings, forming a starting point in the comparison between TIMER, the literature study and the interview results. The TIMER model is almost purely a techno-economic model. Geopolitical aspects are mostly excluded. Figure 10 shows that TIMER consists of a large set of input factors, many of which depend on exogenous datasets or projections (e.g. population size). As with the literature study the comparison is focused on the supply and demand of the liquid fuel sub-model of TIMER (i.e. oil).

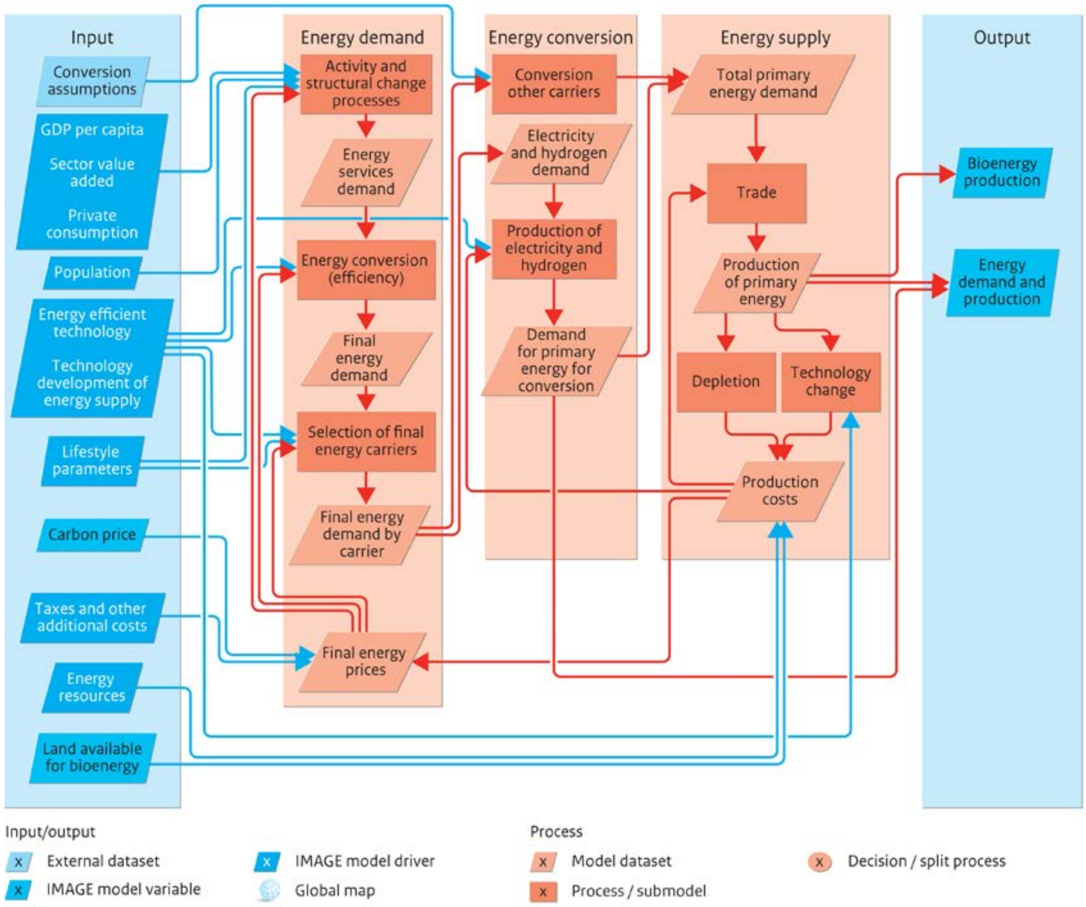

Figure 10: flowchart of the TIMER energy model in IMAGE 3.0, source: PBL (2014c).

From the overall model of TIMER we focus upon the liquid fuels sub system's supply and demand, which is shown in figure 11:

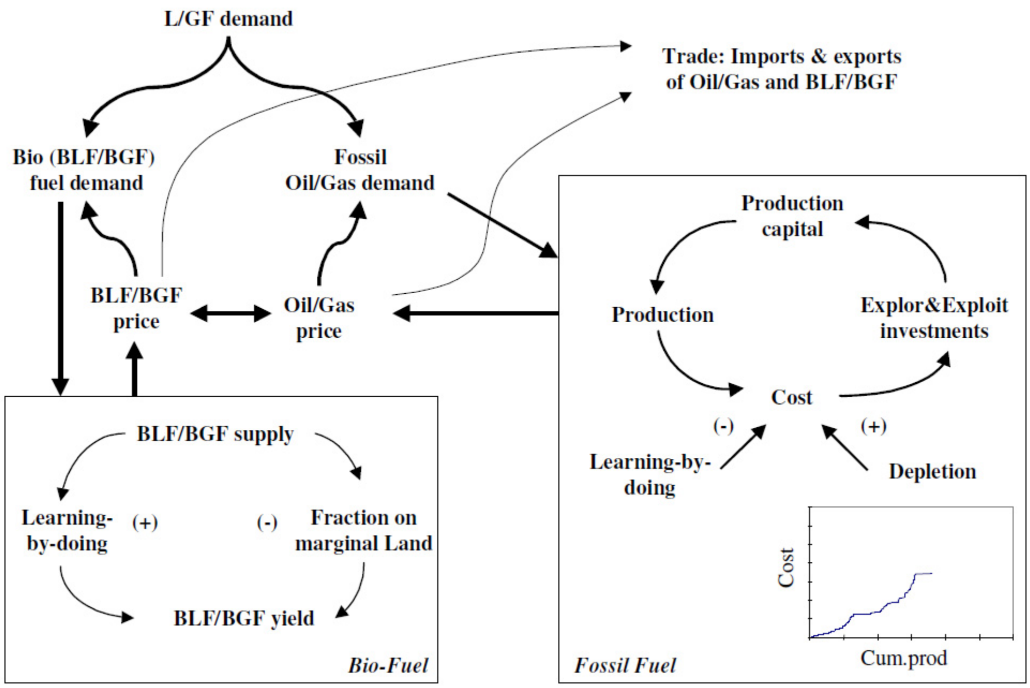

Figure 11: TIMER liquid fuel supply model, source: de Vries et al. (2001)

Figure 11 shows a general overview of the factors in supply and demand of the liquid fuel model within TIMER. BLF/BGF are Bio Liquid Fuels and Bio Gaseous Fuels. Based upon the figures in this chapter as well as the relevant literature described in the chapter introduction we can compare the supply and demand of oil within TIMER to the factors found in chapter 5, starting with supply.

6.1. Supply.

Figure 12 shows the supply submodule used in TIMER. TIMER's implementation of the following factors identified in chapter 5 are assessed: depletion effects, reserves, technological innovation, price volatility, monetary policy and geopolitics.

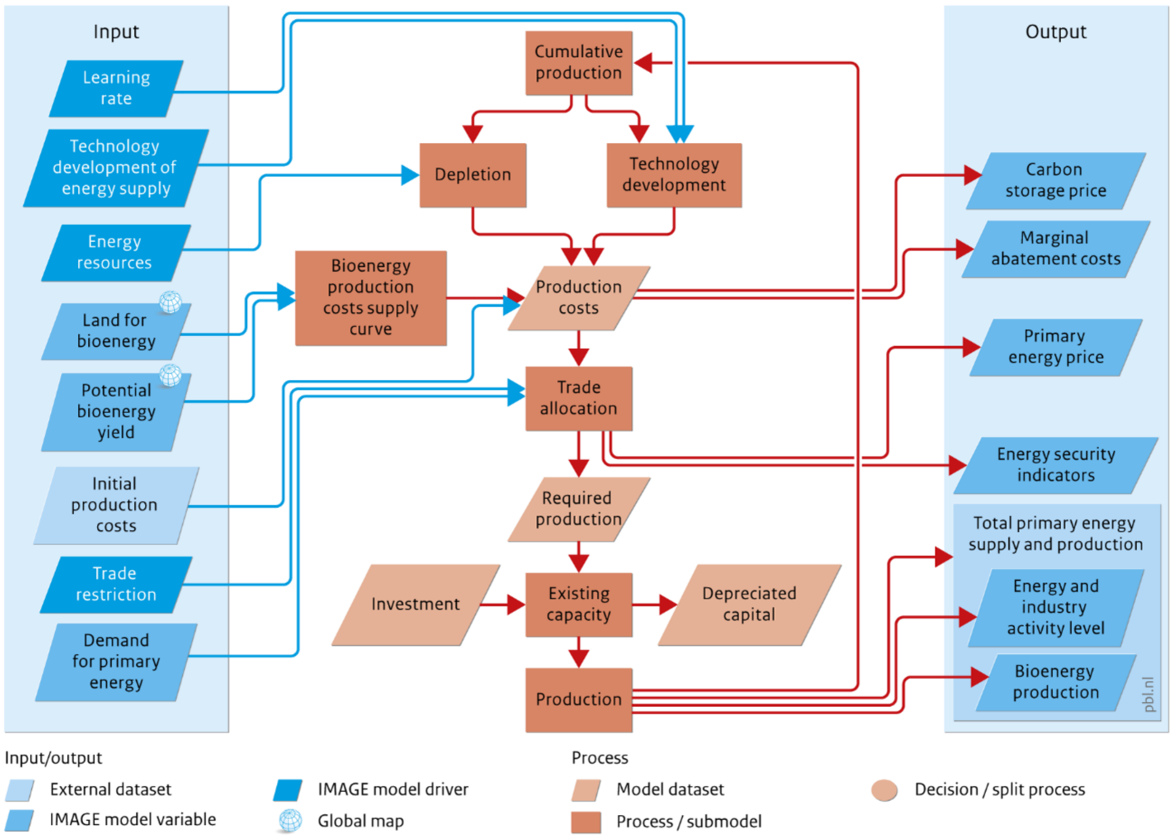

Figure 12: TIMER energy supply module, source: PBL (2014b)

Depletion effects and reserves.

TIMER's resources are aggregated into regions, carrier, as well as supply cost class, and these are represented by the boxes 'Energy Resources' as well as 'Depletion'. Energy resources are based upon external datasets, determining the initial cost as well as volumes of reserves. As written by Stehfest et al. (2014) TIMER assumes a long term depletion curve along which the price of resource increase according to depletion. A distinction between conventional and unconventional is made, and costs are determined by a combination of learning-by-doing and depletion. However, a Hubbert's curve type of depletion dynamic is not included, which may significantly impact oil supply per region / type. Total reserve sizes (i.e. Ultimately Recoverable Resources) are entered exogenously, depending on scenarios. Adding a Hubbert's curve to the reserves may limit capacity growth, thus raising prices as well as boosting development of unconventional oil (e.g. USA tight oil, and Canadian tar sands).

Technological innovation.

TIMER makes use of learning-by-doing effects, determined by the learning-rate of technologies. Based upon empirical data TIMER incorporates the fact that new technologies tend to have higher learning-rates than mature technologies, thus become cheaper faster. This means that over time new technologies may become cheaper than mature technologies, displacing them. The box 'Technology development of energy supply' includes both learning curves and exogenous learning of technology. This is important to determine likely future technological development in the energy supply sector. Technological competition between oil producing technologies is based upon cost of production. However, the way TIMER models supply growth, supply from unconventional sources only occurs once conventional sources become increasingly scarce. Using multinomial logit functions TIMER simulates that technologies that aren't the cheapest still get a certain amount of market share, allowing growth of the respective technologies before they become directly competitive.

Price volatility.

Due to the operation of TIMER's supply growth price volatility is automatically negated (i.e. supply meets demand perfectly). This is also due to the fact that TIMER focuses on the long term development in which price volatility may be averaged out. Nevertheless, high price volatility may lead to different development paths within TIMER, as results from the interviews suggest (e.g. the high price period between 2010 and 2014 allowed high marginal cost technologies to become competitive at lower price points later on). TIMER determines the price of oil via production costs and a profit margin rather than via supply and demand mechanics.

Monetary policy and geopolitics.

Above-ground policies and factors such as interest rates are fixed within TIMER. This was a conscious choice, as TIMER is purely a techno-economic model. Nevertheless, access to cheap credit since the 2008 crisis formed one of the drivers behind the success of USA tight oil supply. TIMER includes a form of geopolitical behaviour, such as oil-exporting regions attempting to maintain oil prices just under the marginal cost price of production within oil-importing countries. Even so, TIMER oil price behaviour does not reflect the behaviour seen in historic data.

Government taxation dynamics with regards to oil production are not included in TIMER as endogenous factors: they can be added exogenously in scenarios. The dynamic behaviour observed in which governments add taxes during high prices (thus boosting prices further) and lowering them after dropped prices is not included. The inefficient behaviour of nationalised corporations, in which governments extract more money than is useful for the oil producing corporation is not included in TIMER. These government control effects can lead to significant delays in supply increase, and costs higher than the marginal cost of production that the fields would suggest.

6.2. Demand.

Figure 13 and 14 show the demand submodule used in TIMER. Figure 13 shows what factors are involved, whilst figure 14 shows a causal loop diagram for determining final energy demand. TIMER's implementation of the following factors identified in chapter 5 are assessed: emerging economies, price elasticity, monetary policy and geopolitics, price volatility & price shocks, and speculation.

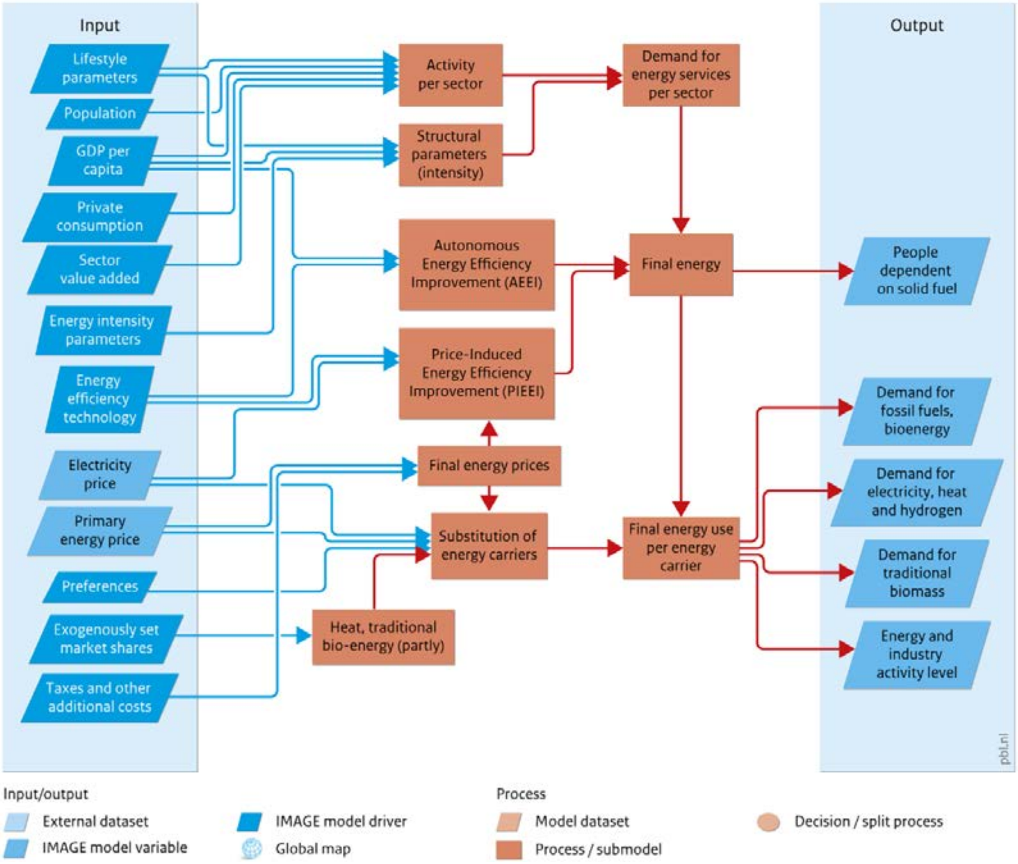

Figure 13: TIMER energy demand module, source: PBL (2014a)

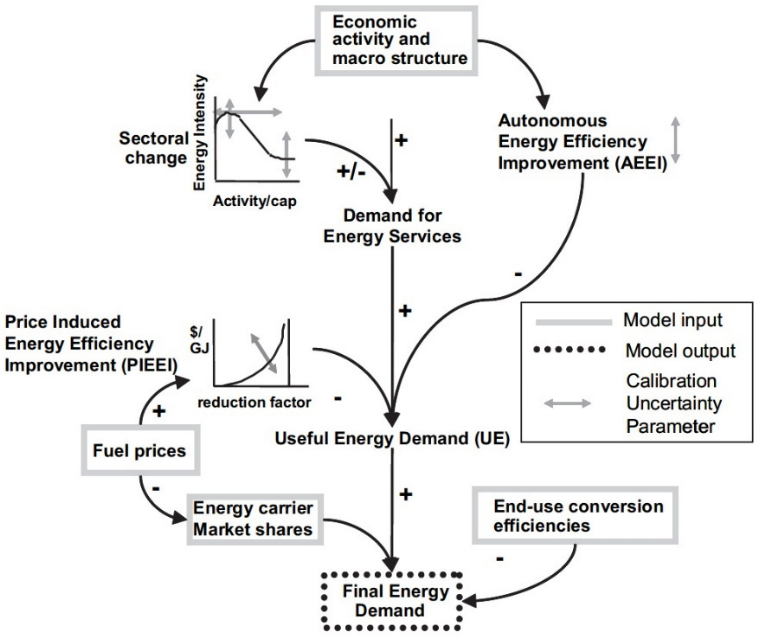

Figure 14: Timer energy demand model causal loop diagram, source: van Ruijven et al. (2010)

Emerging economies.

Demand from (emerging) economies is a driver within TIMER's oil demand, based upon (among others) population size, GDP growth, and economic structure. Given the strong impact of exogenous assumptions influencing demand (e.g. future GDP growth rates, population growth), oil demand can be seen as a semi-endogenous driver. The modelled development economic structure within TIMER is related to the Environmental Kuznets curve, in which the energy intensity of an economy becomes higher as it grows in GDP and then declines again. In this way TIMER agrees with observed structural change regarding emerging economies such as China. Rapid growth in demand from emerging economies is anticipated and modelled.

Price elasticity.

The observed reduction in price elasticity of demand is not modelled as a specific value in TIMER. However, its effect is present through the effects of structural change within demand as shown in figure 14. Price Induced Energy Efficiency Improvements as well as Autonomous Energy Efficiency Improvements and substitution effects cause energy intensity to lower over time. In this way the share of energy costs of GDP are reduced, leading to reduced sensitivity and therefore lower price elasticity of demand. In this way TIMER agrees with observed historical data concerning the reduction of price elasticity over time.

Price volatility.

Price volatility is influenced strongly by a reduced price elasticity, caused by a lower share of energy in expenditure. This can be achieved by energy efficiency improvements. Currently TIMER assumes that the Price Induced Energy Efficiency Improvements during high energy prices fall back by 50% once energy prices drop to previous prices again. This is an assumption for which no clear evidence is given. TIMER shows very low price volatility, the effects of price induced energy efficiency improvements is not highly relevant. In the case of high price volatility this effect will become relevant as such a model will lead to faster sustained demand reduction as price shocks boost energy efficiency improvements.

Price shocks and speculation.

TIMER endogenously produces a stable price situation because it determines the price of oil by supply costs plus profit margin, the totality of which increases slowly due to depletion effects. Price shocks are foreign to this model. Given the stochastic nature of economic crises their influence on demand is difficult to forecast. Nevertheless, speculative behaviour in demand may be added as temporary random events throughout the model causing short lived oil price bubbles of several dollars per barrel. The result of this would lead to increased energy efficiency improvements and quicker adaptation of higher marginal cost energy sources as they become more competitive during high prices. A downside would be increased model uncertainty due to additional 'noise' in the price of oil.

Monetary policy and geopolitics.

Monetary policy within TIMER is highly dependent on scenarios and consists mostly of taxes such as carbon pricing affecting final energy prices. Also, within TIMER various adjustments can be made in discount rates for investments, and efficiency standards, affecting end user behaviour. However, these are all exogenous values, chosen by the scenario developer. TIMER does not offer an endogenous way of monetary policy (e.g. economic stimulus packages during low economic growth). TIMER only makes use of the US dollar, thus effects such as changing exchange rates between regional currencies aren't modelled. Then again, exchange rates effects are of a sufficiently stochastic nature that their inclusion might only increase random price fluctuations, adding unnecessary uncertainty. As with supply, geopolitical aspects are kept out of demand for the most part, although certain aspects such as oil export / import barriers are included. These may alter local oil prices, and therefore encourage certain demand behaviour. The values used are based upon historical calibration by the TIMER team.

6.3. Chapter discussion and conclusions.

This chapter answers research questions 3 and 4:

3. What differences exist between the TIMER model compared to the identified factors from research questions 1 and 2?
4. Which factors identified in question 3 are relevant to TIMER?

To answer question 4: The most relevant differences between the TIMER model and observed historic behaviour are mostly related to depletion and decline effects in oil fields limiting production quantities, (geo)political behaviour of global actors which influence supply behaviour, speculative behaviour which may increase price volatility, or price in general.

To answer question 3: The most notable differences are discovered to be those identified for question 4. The demand and supply within TIMER are highly stable: expected increases in demand are easily met as oil demand from growing global GDP is predictable. However, if supply limits are introduced via a form of Hubbert's curve suppliers would face exponentially risings costs to maintain production far earlier than the region's oil reserves would suggest. This could lead to oil production costs rising significantly faster than the TIMER model currently suggests. High oil production costs from mature technologies coupled to technological development of new technologies and their learning effects would allow high cost technologies to become profitable faster (e.g. USA tight oil, biofuels, etc.) and gain larger market share within TIMER than they do now. This could lead to significantly different pathways of development, especially in the long term.

The lack of price volatility produced by TIMER is partly a consequence of the choice to exclude most effects of geopolitics, another reason is that the oil price is determined mostly by the cost of production. However, in the real world geopolitics influences the price of oil considerably, with actors behaving in various ways (e.g. failed OPEC coordination since 2014). Also, local effects such as favourable above ground settings found in the USA boosted local production of tight oil supply. These are not included in TIMER. Effects from the increased financialization of oil lead to additional observed price volatility. The choice to determine the price of oil mostly by the cost of production leads to inaccurate short term prices, but may be valid for the long term, given that suppliers simply cannot produce below the cost of production for very long periods of time. However, supply tightness may lead to inflated oil prices, which isn't expressed by TIMER. A combination of supply restrictions coupled to supply and demand interactions may lead to rapidly rising oil prices.

TIMER does not include speculative effects, reducing price volatility. Furthermore, the different behaviour between private and publicly owned companies is not modelled within TIMER. Regions which maintain publicly owned companies risk difficulties to maintain or expand supply due to excessive government control and underfunding. Regions in which private companies operate export tariffs and additional production taxes during high global oil prices (i.e. high private profits) drive prices upwards and undermine profitability during reduced oil prices. This would lead to regional differences in profitability, and thus changes in development of the trade flows within TIMER.

7. Thesis model.

This chapter addresses the following research questions:

5. Which factors are most relevant to model quantitatively, and how can they be modelled?
6. Does the developed model show behaviour which explains the observed historical data on oil price, demand and supply?
7. What changes in TIMER would be needed to incorporate the model from question 6?

Question 5 can be answered from the findings of chapter 6. It is found that a model including the following three factors, ordered in relevance, may deliver valuable insight into global oil price behaviour that the TIMER model currently doesn't include:

1. Depletion and decline effects in oil fields limiting production quantities;
2. (geo)political behaviour of global actors which influence supply;
3. Speculative behaviour which may increase price volatility, or price in general.

The first factor is closest to TIMER's current philosophy of techno-economic modelling. Therefore its results will be easiest to interpret and apply to TIMER. The second and third factors are likely to require significantly more fundamental change within TIMER, of which the second factor is most significant as it introduces (geo)political goals into the system. Speculative behaviour is fairly isolated (i.e. it has a small number of connections throughout the rest of the model, given that it focusses purely on price) and may be easier to introduce for that reason. Given the empirical data supporting depletion effects, as described in the literature study, their effects are likely to contain the least amount of uncertainty. (Geo)politics contain more uncertainty as it involves human society's behaviour, and speculative behaviour contains more uncertainty still as it regards individual human behaviour. The literature study confirms this, given the lack of agreement within the scientific community on (in particular) the speculative effects on the price of oil. Therefore, option 1: Depletion and decline effects limiting production quantities is chosen to model. Added to this model is the declining price elasticity of demand, allowing the price of oil to be modelled according to the model's supply and demand output.

The second part of question 5 is answered as follows: The methodology to build the model is as follows: First the main focus, assumptions and model limitations (boundaries) are set. Then a conceptual description is made that allows a grasp or 'feel' of the model without going into technical details yet. From these two steps a causal loop diagram is built, which allows the identification of each parameter and their interconnectedness. Each parameter is then quantified so that it can be used within the final model. Using Vensim 6.4a (academic license) system dynamics software developed by Venata Systems (2015) a model is built that attempts to answer the research questions.

Finally the model and its results are discussed, recommendations are made and the research questions are answered.

7.1. Focus, assumptions and limitations.

The goal of this model is to understand in what way depletion effects impact the costs involved in producing oil, as well as the effects an influx of unconventional oil has on the price of oil. In particular the period between 2000 and 2016 is of interest as that is the time in which historic oil prices started in a way that is not explained by the TIMER model. Modelling future behaviour, although interesting, is not the goal or ability of this model, as it lacks essential mechanisms to determine future behaviour (e.g. feedback between oil price and demand). A 40 year period between 1980[5] and 2020 is chosen for the model, with the model responding to exogenous demand.

The model developed in this thesis models the production of conventional oil endogenously. The reason conventional oil is chosen is because – in contrast to production technologies such as tight oil or tar sands – it is clearly in a mature state of development. Therefore, decline in new discoveries and field production may increasingly limit conventional oil supply. In order to determine the demand for conventional oil its demand must be isolated from the overall demand for crude oil. This is done by removing the supply of unconventional oil from overall demand, leading to an adjusted demand curve that represents demand for conventional oil. Applying price elasticity of demand to the supply of oil as well as demand and supply of conventional oil, price formation is possible. Note that price elasticity only affects supply quantities and the price of oil in this model: demand is exogenous and doesn't respond to the price of oil.

The model aggregates conventional oil to a global level. This means there are no regional differences present (they are averaged out), simplifying the modelling process. One must understand that the model (any model) is not a representation of reality, but a representation of simplified reality (i.e. *'the map is not the territory'*). The following analogy allows a conceptual understanding of the model's general setup and assumptions without delving into the technicalities.

7.1.1. Conceptual description.

The modelled world only contains a few types of energy resources. Namely conventional oil, tar sands, tight oil and biofuels. The conventional oil resource is exploited by a number of suppliers, aggregated into one supply actor, attempting to supply oil equal to the demand. However, they notice that over time existing reserves gradually deplete, requiring additional investments into existing fields to maintain supply, and even more to meet growing demand. Likewise, cheap resources were found initially, but additional reserves to maintain reserves to production ratios at the desired level are increasingly expensive (i.e. difficult) to find. This may be due to distances involved, harsh environments, deeper fields etc. These two effects drive production costs upwards The total amount of undiscovered oil reserves is not known, but the increasing cost of additional discoveries is a known process. Regardless, the actor proceeds to add discoveries, as long term demand maintains growth.

Given the time taken to construct oil production capacity, the supplier looks forward in time to determine future demand. According to that expectation, investments into capital stock are made, also taking into account the growing depletion effects operating on the resource base. Spare capacity allows short term production adjustments up to 110% capital stock capacity to meet demand in the case of insufficient capital stock. Increased capital stock additions are produced to compensate, but that takes a number of years.

[5] One reason for using 1980 as a starting year for the model guarantees a long enough 'run-up' to year 2000 and beyond, given that initial investment behaviour may impact the model's behaviour for a number of years. Another reason is that it allows sufficient comparison to historic behaviour and trends, offering possibilities for model calibration.

Oil consumers are not interested in the exact price of oil: their elasticity of demand is effectively zero, meaning that demand retains its growth regardless of price[6]. Nevertheless, the supplier attempts to maintain a modest profit level above costs of production, although it reduces supply if supply/demand effects cause a price that is too low. Therefore, oil production cots + desired profit determines the price of oil. A supply shortage drives price, whilst supply excess suppresses price.

Due to historical output of unconventional oil, a sudden increase thereof is observed in the early 21st century. Although tar sands grew smoothly since the 1980s, biofuels and tight oil supply in particular grew strongly in the years following 2000. The sudden influx of unconventional oil in that period suppressed demand for conventional oil: growth was nearly zero during 2010 to 2014, although it resumed thereafter, as demand exceeds unconventional oil supply. The way suppliers respond to that change in demand determines the fluctuations in oil price.

7.1.2. Modelling considerations from the conceptual description.

What the conceptual description tells us is that a model needs to be derived that forecasts future demand (i.e. expected demand), upon which it invests capital stock to meet long term demand growth. This forms a long term supply cycle. A short term supply cycle also exists, in which supply adjusts to short term demand fluctuations. This is needed as long term investment behaviour cannot adapt quickly enough to short term changes. Furthermore, the fields that are exploited need a function to indicate their depletion level, which raises demand for capital stock to maintain supply. Furthermore, via exploration additions are made to proven reserves, securing future supply of oil. A function to indicate increasing difficulty of finding new reserves is added, raising marginal costs of discoveries. Finally, decreasing price elasticity as well as an influx of unconventional oil is added which impact the demand for conventional oil as well as the price formation of oil.

7.2. The model's setup.

From the conceptual description a more concrete model is built. This is done by starting with a causal loop diagram, identifying relevant parameters of the model that are needed to produce the desired results. Building upon the causal loop diagram a table is made that summarises all parameters, and connects them to the relevant parts in chapter 7.3 that explains their specific operation.

7.2.1. Causal loop diagram.

From the model's purpose and operation, as described in 7.1, the causal loop diagram shown in figure 15 is constructed. A causal loop diagram explains each parameter's causal effect on the one it's connected to (indicated by an arrow). A plus sign indicates that if parameter A increases, parameter B does so too, a minus indicates that an increase in A leads to a decrease in B. A line with two lines across it indicate a delay in the system, such as construction time required for capital stock to be created.

[6] The model has exogenous historic global oil demand as input, and does not contain a feedback on demand via the price of oil, only towards supply. One must consider that price elasticity is already a part of expressed demand, as historic oil prices helped shape the actual demand quantity.

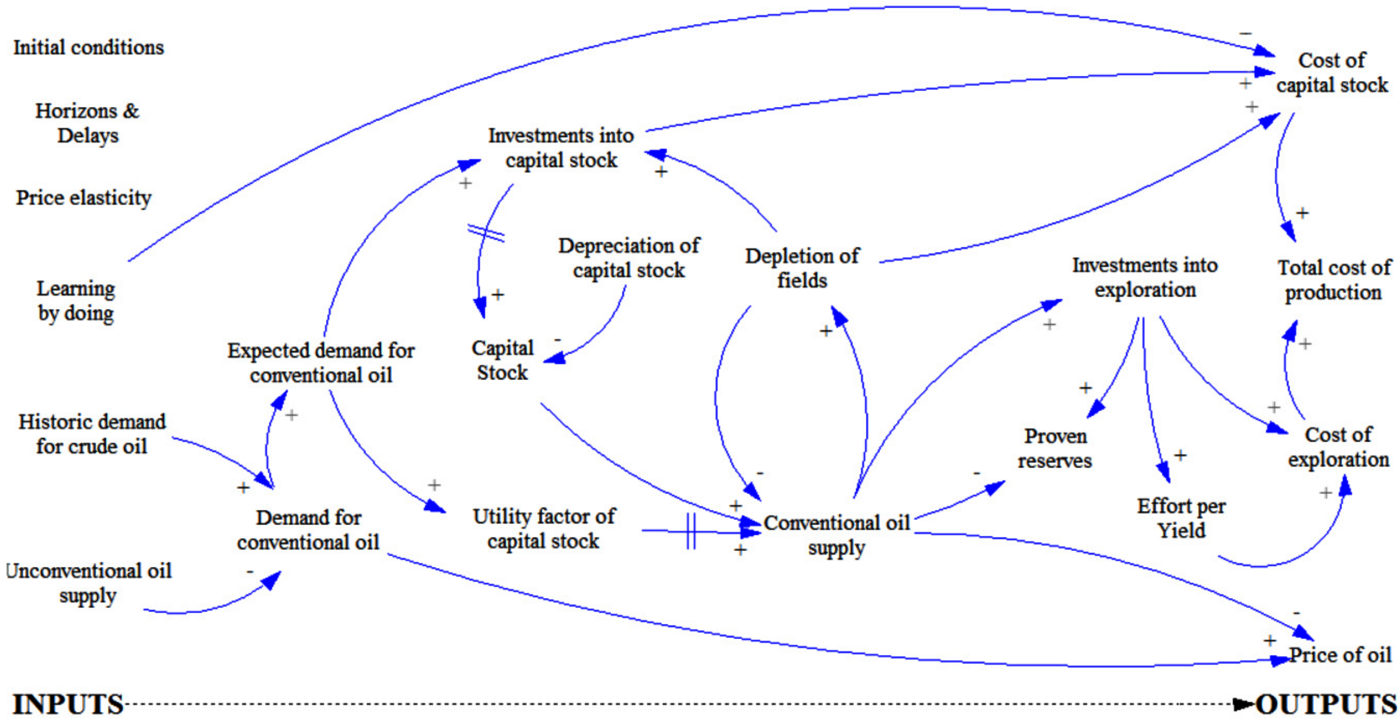

Figure 15: Causal loop diagram of thesis model.

The causal loop diagram can be read from left to right, starting with input variables and ending with its output. In the top left of the diagram several parameters are unconnected, which is because they are input variables but not directly causative in a positive or negative way. The parameters are:

1. Initial conditions. These determine the starting point of the model. For example, initial costs of exploration.
2. Horizons & Delays. These impact the way the model behaves over time. A longer or shorter delay in production time has effects within the rest of the model, as do investments horizons used in determining expected demand (e.g. too much capital stock coming online if demand is less than expected).
3. Price elasticity. This plays an important role in the price formation of oil. The price elasticity effectively impacts the volatility of oil prices.

7.2.2. Model summary.

The causal loop diagram shows the relevant model parameters. These are emplaced in table 1, below. Each parameter has a short description, and the chapter than addresses the parameter in detail is attached. Furthermore, the relevant sources for each parameter are added. Some parameters play a role in multiple parameters, as shown in the causal loop diagram. Therefore, they may be present in multiple chapters.

Table 1: Thesis model parameter summary.

Parameter		
Historic demand for crude oil	Description	Exogenous input that determines the amount of oil that needs to be produced. This can be altered to determine actual demand for conventional oil in the model.
	Relevant sources	BP (2016)
	Units	Million barrels per month
	Chapter	7.3.7.
Expected demand	Description	Expected demand at different time-points in the future. The model uses this to determine capacity expansion.
	Relevant sources	EIA (2016b)
	Units	Million barrels per month
	Chapter	7.3.2., 7.3.4., 7.3.8.
Demand for conventional oil	Description	The actual demand for conventional crude oil, as used in the model. This determines how much conventional oil must be supplied.
	Relevant sources	BP (2016), CAPP (2015b), IEA (2007), IEA (2011), IEA (2013), EIA, (2016b), EIA (2016c)
	Units	Million barrels per month
	Chapter	7.3.7.
Horizons	Description	Horizons determine the length of time into the future for which predictions for expected demand are made.
	Relevant sources	Morecroft (2015)
	Units	Months
	Chapter	7.3.2., 7.3.4., 7.3.7., 7.3.8.
Unconventional oil	Description	Oil from unconventional sources. These are Canadian tar sands, USA tight oil and global biodiesel & bio-ethanol.
	Relevant sources	CAPP (2015b), IEA (2007), IEA (2011), IEA (2013), EIA, (2016b), EIA (2016c)
	Units	Million barrels per month
	Chapter	7.3.7.
Conventional oil supply	Description	The amount of oil that is supplied to the market to meet conventional oil demand.
	Relevant sources	BP (2016)
	Units	Millions of barrels per month
	Chapter	7.3.4., 7.3.8.
Capital stock	Description	The amount of production capacity that is active.
	Relevant sources	de Vries, et al. (2001), BP (2016)
	Units	Millions of dollars
	Chapter	7.3.3, 7.3.4.
Utility factor for capital stock	Description	The share of existing capital stock that is being used to meet actual supply.
	Relevant sources	EIA (2016b)
	Units	Millions of barrels per month
	Chapter	7.3.4., 7.3.8.
Investments into capital stock	Description	The amounts of capital stock additions added to future production capacity.
	Relevant sources	Morecroft (2015), Bentley (2002)
	Units	Millions of dollars
	Chapter	7.3.4.
Depreciation of capital stock	Description	The amount of capital stock that is taken out of production due to depreciation.
	Relevant sources	de Vries et al. (2001)
	Units	Millions of dollars

	Chapter	7.3.4.
Delays	Description	Delays are present in the construction of capital stock, as well as exploration and short term supply adjustments.
	Relevant sources	de Vries et al. (2001)
	Units	Months
	Chapter	7.3.2., 7.3.3., 7.4.4.
Depletion of fields	Description	The decline in field production caused by a depletion of the existing fields in operation.
	Relevant sources	Höök (2014), Höök et al. (2014), Bentley (2002)
	Units	Dimensionless
	Chapter	7.3.3.
Proven reserves	Description	The amount of reserve that can be used for oil production.
	Relevant sources	Owen, et al. (2010)
	Units	Millions of barrels of oil
	Chapter	7.3.5.
Investments into exploration	Description	The amount of additional reserves found due to investments into exploration
	Relevant sources	Owen, et al. (2010)
	Units	Millions of barrels of oil
	Chapter	7.3.2., 7.3.5.
Effort per Yield	Description	The effort it takes to find new reserves. This increases over cumulative reserves.
	Relevant sources	Hubbert (1980)
	Units	Dollars per barrel
	Chapter	7.3.2.
Cost of exploration	Description	The cost associated with the required investments into exploration and the effort per yield.
	Relevant sources	IEA (2008), IEA (2014a), Katakey (2016), Bret-Rouzaut & Favenne (2011)
	Units	Dollars per barrel
	Chapter	7.3.2., 7.3.5.
Cost of capital stock	Description	The costs associated with the amount of capital stock needed to produce to the demanded quantity of oil
	Relevant sources	de Vries et al. (2001)
	Units	Dollars per barrel
	Chapter	7.3.6.
Total cost of production	Description	The total cost made to produce a barrel of oil as well as making the required expansion of reserves to maintain sufficient reserves for future production.
	Relevant sources	de Vries et al. (2001), Hubbert (1980)
	Units	Dollars per barrel
	Chapter	7.3.2., 7.3.5., 7.3.6.
Price Elasticity	Description	Determines the volatility of price movement during mismatches between supply and demand
	Relevant sources	Hamilton (2009), IMF (2011)
	Units	Dimensionless
	Chapter	7.3.8.
Price of oil	Description	The price of oil determined by market mechanisms of supply and demand.
	Relevant sources	Hamilton (2009), IMF (2011)
	Units	Dollars per barrel
	Chapter	7.3.8.

7.3. Model parameters.

In chapter 7.2 the relevant model parameters are identified. Each of these parameters are described and developed into useful information that can be used within the final model, which is constructed after this step. All costs are in year 2000 US dollars, the model operates on a per-month time step and oil volumes are in barrels of oil. The starting year is 1980, end year 2020.

7.3.1. Depletion.

Given the focus of the model upon depletion, these are quantified first.

Two types of depletion can be distinguished , namely:

1. Depletion caused by increased difficulty in discovering new oil fields, and;
2. Depletion caused by extraction from proven reserves.

7.3.2. Declining oil field discoveries.

Discoveries tend to find huge fields at first, followed by fields of decreasing size, quality, increasing depth, etc. Figure 16 by Sorrell et al. (2010) shows the historic 2p (proven and probable) discoveries and cumulative discoveries of (off-shore) conventional oil. The observed cumulative discoveries follow a logistics growth curve, which leads to the hypothesis that continued discoveries along this pathway will result in a ceiling of total discoveries somewhere between 2500 and 3000 billion barrels of oil.

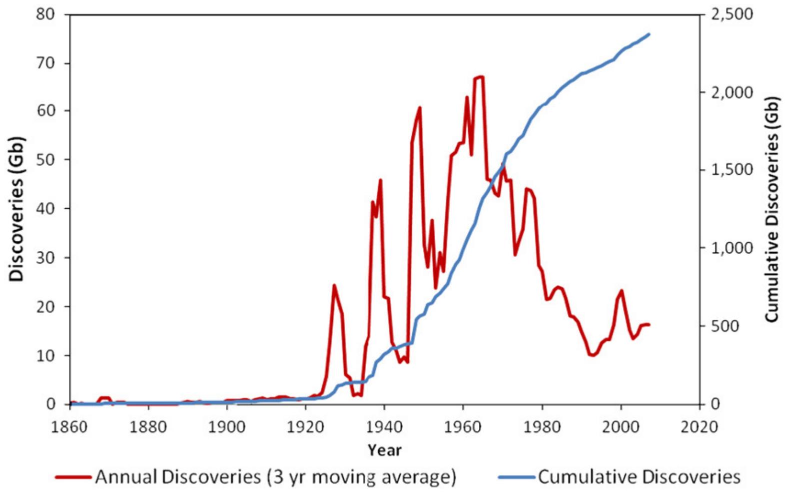

Figure 16: oil discoveries over time, source: Sorrell et al. (2010).

In order to model the phenomenon of declining growth in discoveries, discoveries must be expressed as a function of costs, allowing more fields to be discovered when more investments into discoveries are made. Hubbert (1980) has applied this to USA oil discoveries. His work developed the concept of barrels of oil yielded per foot drilled, which not only predicted the effort required for future discoveries, but also predicted total final USA reserves quite accurately. Over time the barrels of oil per foot drilled declines, signifying increasing scarcity of fields and requiring increasing effort to discover oil at a constant rate. Hubbert's (1980) yield per foot drilled can also be expressed in yield per dollars invested.

A model similar to Hubbert's (1980) model is built for global oil exploration and discoveries. Using data from the IEA (2014a), the IEA (2008), Katakey (2016) and Bret-Rouzaut & Favenne (2011) the historical upstream investments and corresponding discoveries between 1980 and 2013 are found. Global upstream investment costs are used and fields discovered are divided by those investments. This leads to barrels of oil per US dollar investments into exploration. It must be noted that upstream investments are an aggregate of exploration and (initial) production investments, making it hard to isolate pure exploration costs. However, the trends observed within the data are still likely to be correct.

The YPE over time is shown in figure 17. This shows a clear decline in yields, drawing a bleak picture for future discoveries of conventional oil. However, in contrast to annual Yields per Effort, oil explorers wish to know the effort required to discover a certain amount of oil, therefore an Effort per Yield (EPY) value is required, which is obtained by dividing costs of exploration by discoveries. Figure 186 shows the EPY over cumulative discoveries. This way we know the cost associated with a certain amount of marginal exploration, which is needed for the model.

Notice how figure 18 shows the decades increase in horizontal distance: this demonstrates that in the 2000s more reserves were added than in the 1990s, although at considerably higher cost. A clear sign of increasing reserve scarcity, it is remarkable to note the doubling in exploration cost per barrel between 2000 and 2010.

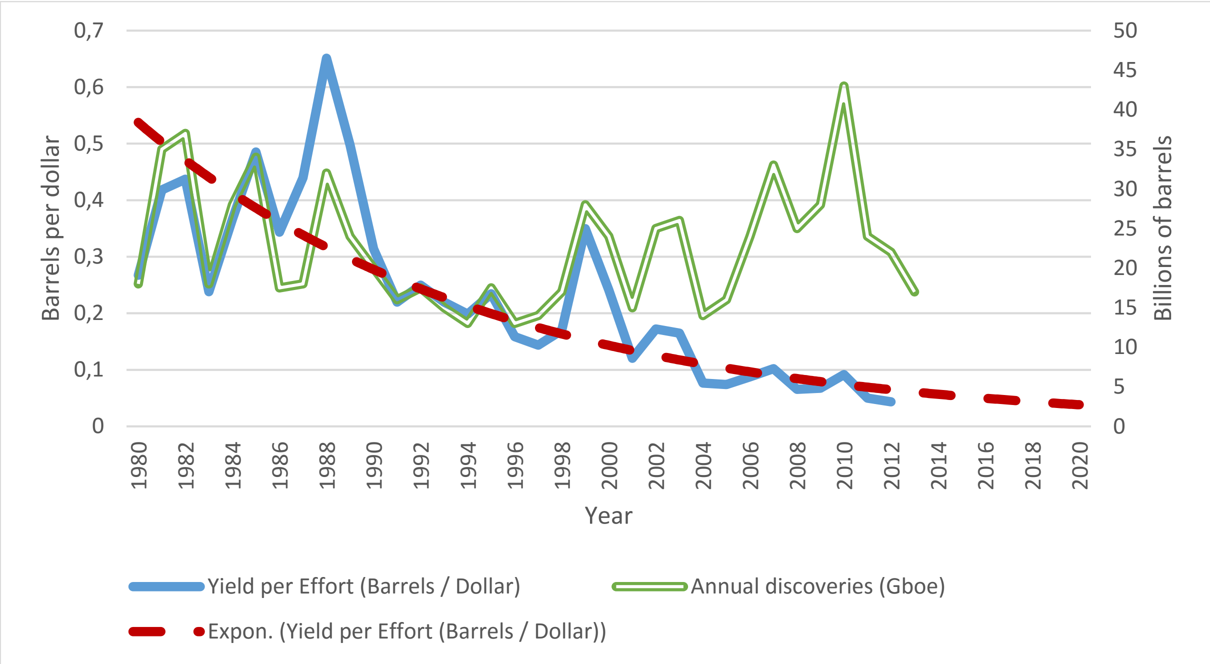

Figure 17: Yield per Effort over time, derived from: Hubbert (1980), IEA (2008), IEA (2014a), Katakey (2016), Bret-Rouzaut & Favenne (2011), BP (2016).

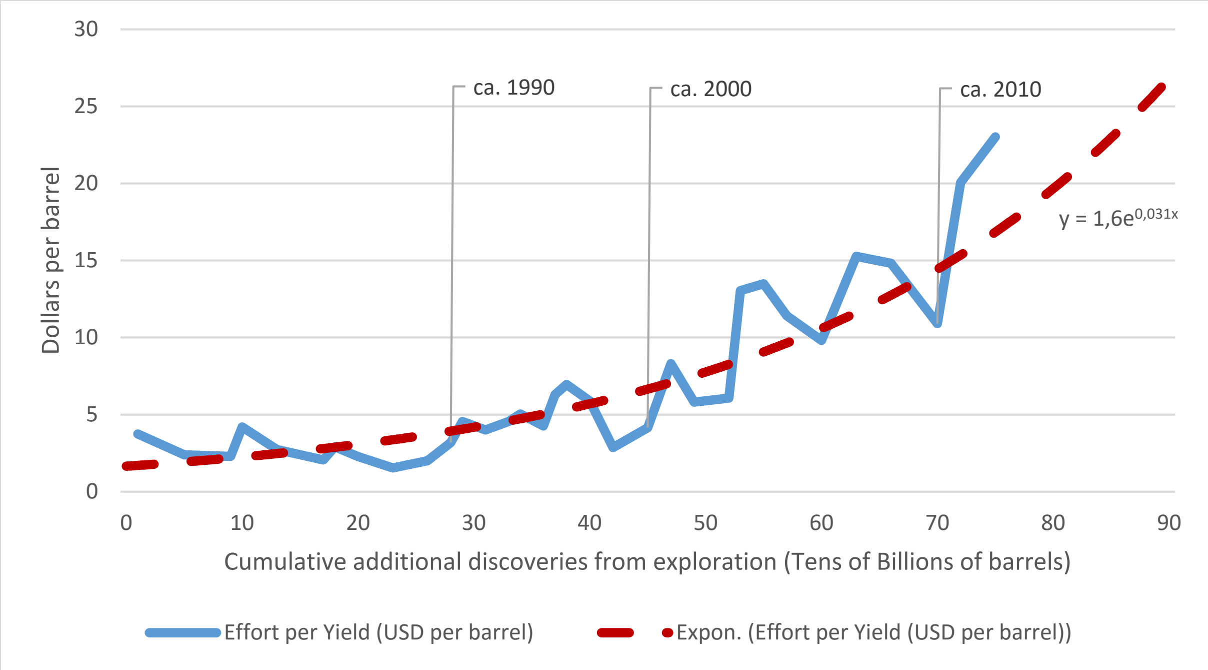

Figure 18: Effort per Yield over cumulative discoveries, derived from: Hubbert (1980), IEA (2008), IEA (2014a), Katakey (2016), Bret-Rouzaut & Favenne (2011).

The effort required for new discoveries (EPY) after cumulative investments (starting in 1980) is given by the formula, which is derived from the exponential trend-line as shown in figure 18 and the work done by Hubbert (1980):

Formula 1: $EPY_x = EPY_0 * e^x$

In which:

EPY_x The Effort per Yield at cumulative discoveries x, in dollars needed per barrel of oil;

EPY_0 The Effort per Yield at the cumulative additional discoveries 1980, in dollars needed per barrel of oil;

e^x Exponential growth rate of EPY at cumulative discoveries x.

Using the values derived from figure 18, we find the following formula for global conventional oil since 1980: $EPY_x = 1{,}6e^{0{,}031x}$.

By making use of the EPY graph the ultimately recoverable resources (URR) needn't be known. This fact is quite important, as the URR values are subject to considerable of uncertainty due to constant expansion through discoveries. Using the method derived in this thesis, one can assume the exponential rise of costs to continue indefinitely, although at some point in time costs for additional discoveries will become sufficiently high to stop further exploration.

The values given in figures 17 and 18 are for conventional (off-shore) oil at a global level. Unconventional oils such as tar-sands and shale oil and various regions are likely to have similar curves, but are at different points of their respective EPY curves.

7.3.3. Reserve depletion and decline.

As described in the literature study, a well-known fact of oil production is decline of field supply. A developed field grows in supply at first, reaches a short peak or plateau phase and then enters decline. Höök (2014) has developed a mathematical framework for aggregated fields decline rates (i.e. regions).

When observing a well (or region) which is exploited at a constant rate, and upon which no additional reserves are added, the depletion occurs as a simple natural decline rate. This is due to the underground physics of the well: At first, noticeable decline does not occur: underground pressure is maintained due to various effects, such as subsidence of sediment, rising water-levels or gas expansion. These effects cause decline to become noticeable after 10 to 15 percent of the fields' resources have been extracted as shown by Höök et al. (2014).

Given the global aggregation of fields in this thesis' model, decline is assumed to be occurring from the starting year (1980). This makes sense given the maturity of global reserves, as well as the decline in field additions as shown in figure 17. The decline rate is found to range between 4 and 8 percent annually, as shown by Höök (2014). A global oil field decline rate of 6% is assumed in the model.

It is important to understand conceptually that it is not the field that produces oil, but rather the capital stock placed upon it. This means that reserve additions do not increase supply, but capital stock expansion does. Furthermore, existing capital stock's output may be enhanced through Enhanced Oil Recovery (EOR) techniques. These techniques consist of injecting water or CO_2 into the field, raising underground pressure. Another EOR technique is horizontal drilling and the fracking of existing fields. Due to the extra effort required, EOR techniques add costs to production, thus resulting in extra costs of capital stock per unit produced. The thesis' model expresses field decline and EOR techniques through higher cost per barrel of oil produced over time, driven by depletion of existing fields.

Increasing output (i.e. adding more capital stock) leads to higher decay later on, of which the result is that the decline rate steepens. This effect has been shown by Bentley (2002), in figure 19. In the end, decline becomes sufficiently steep to overcome additions from expanded capital stock in new fields.

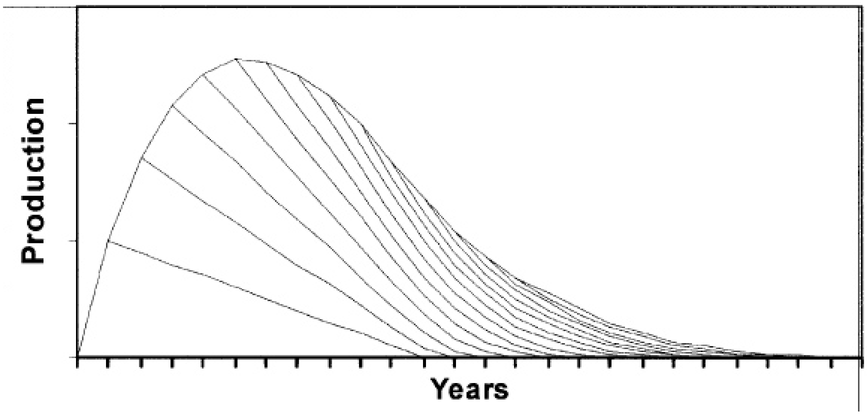

Figure 19: Decline of production over time including field additions (larger fields first, 1 year delay between additions), source: Bentley (2002)

Formula 2, derived from Bentley's (2002) work shows how the capital stock output (i.e. supply of conventional oil) develops over time, including depletion. It calculates current supply by multiplying the previous month's supply with the decline rate and the relative change in capital stock. This shows that continued additions in capital stock are needed to maintain supply, without which exponential decline reduces supply. Figure 20 shows capital stock output from formula 2 expressed over time with a constant rate of capital stock additions and a 6% annual decline rate.

Formula 2: $$CSO_n = Decline\ Rate * CSO_{n-1} * \frac{CS_n}{CS_{n-1}}$$

In which:	CSO_n	Capital stock output at the current month, the output delivered to market, million barrels of oil per month;
	CSO_{n-1}	Capital stock output at the previous month, the output delivered to market, million barrels of oil per month;
	CS_n	Capital Stock at the current month, million barrels of oil per month;
	CS_{n-1}	Capital Stock at the previous month, million barrels of oil per month;
	Decline Rate	Factor derived from decline percentage per month[7]

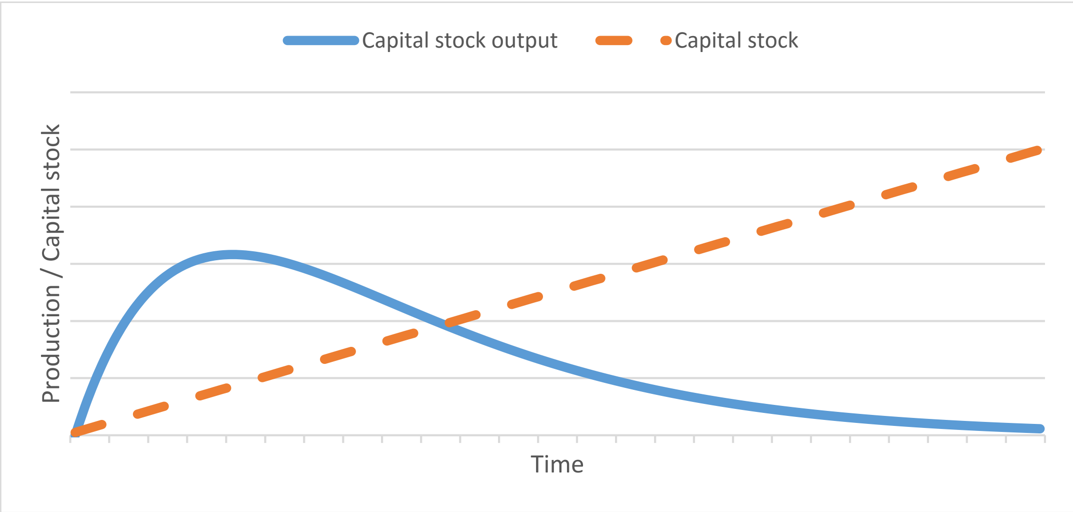

Figure 20: Capital stock output decline over time with constant capital stock additions and 6% annual decline.

An implication from formula 2 and figure 20 is that constant output levels require exponential growth in capital stock.

7.3.4. Capital stock and supply management.

The capital stock determines production of oil, and requires constant investments to be maintained, and even more investments to grow. It is important to have a firm understanding of costs of capital stock, as it's one of the main cost drivers within oil costs in this model.

The TIMER model developed by de Vries, et al. (2001), makes use of initial production costs in 1971 ranging between 0.5$/GJ (Middle East) and 3.4$/GJ (Japan). Using the total resource base as weighted average for each region, the average value is 1.5$/GJ, mainly due to huge reserves in low cost regions such as the Middle East. 1.5$/GJ equates to around $9/barrel of oil. The early 1980s are a period of high oil price, which collapsed back to 1970s price levels in the 1990s. Therefore, these cannot be used to estimate the cost of production in 1980. Instead, by placing a straight line between the 1970s and 1990s price levels it is estimated that the initial cost of production is around $10/barrel.

It is assumed that initial production capacity is equal to initial demand, which is set at 1700 million barrels per month in 1980, as shown by BP (2016). This leads to total initial production costs of 17 billion US dollars per month.

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[7] An annual decline rate has to be converted to a monthly decline rate, for example, a 6% annual decline rate (i.e. 0.94) equals a $0.94^{(1/12)}$=0.995 monthly decline rate.

Due to depreciation of capital stock continuous investments are needed in order to maintain supply. TIMER uses a 180 months (i.e. 15 years) technical lifetime of capital stock, which is maintained in this model. This means that without investments, capital stock no longer operates after 180 months: a complete turnover has happened. The model shows high resilience against change in this value: a halving or doubling of technical lifetime leads to insignificant change in output values. Therefore, the accuracy of the 180 months is not too important to the model's workings.

Investments into capital stock require the investor to know future demand, as building capital stock takes time. A forecast of current demand towards demand into the future is made. The period into the future to which the forecast is made (i.e. the horizon) is equal to the construction time of capital stock. This allows the investor to gauge demand for when his investments start producing, thus meeting demand at the appropriate time.

Short term demand can fluctuate, therefore the demand is smoothened over time. The model assumes 12 months time over which the expected demand is smoothed. The reason this is done is that investors wish to find the trend in future demand, and taking too short intervals leads to misjudgements in expected demand (e.g. a short peak would lead to wild overestimations of demand, if not enough time is taken into the trend). In the case of a smooth increase in supply the smoothing is hardly relevant, however, when a demand becomes volatile the smoothing becomes increasingly relevant with relation to demand volatility. Despite the need for smoothing erratic demand, it is hard to determine what time is used in practice. Therefore, the 12 months is an assumption, which can be adjusted in the model. The model has low sensitivity to this factor, as delays further in the model buffer volatile investment behaviour.

If long term expected demand exceeds expected supply, the difference between them is invested, multiplied by the capital stock investment factor. The capital stock investment factor consists of the total producing capital stock divided by their output[8]. The construction time of capital stock (production delay) is 60 months, which is a normal delay as described by Morecroft (2015). The horizon of expected demand is therefore also 60 months.

Given the heterogeneity of global conventional oil production (e.g. Saudi Arabia oil rigs in the desert to off-shore production facilities in the North Sea, etc.) not all capital stock takes equally long to construct. Therefore, rather than a fixed delay, a third order delay is used that 'smears' out produced capacity over a number of years via a lognormal distribution. The first piece of capital stock enters the market around month 20 (e.g. the simplest rigs in Saudi Arabia), most around month 60 and over 90% has been delivered by month 120 (e.g. the largest off-shore platforms in distant fields).

The investments into capital stock production capacity forms a long term trend to meet demand. However, demand might be erratic, therefore supply needs to be able to respond quicker than via production of capital stock.

In the short term, suppliers can reduce their capacity during oversupply and expand supply to maximum spare capacity utility during unanticipated high demand. In order to estimate how quickly suppliers respond to a change in oil price, the rig count of USA tight oil is placed against that of oil price. This is chosen as tight oil producers responded strong to a fall in oil prices. Using data from the EIA (2016b) we find that tight oil rigs reduced their numbers rapidly in the fall of 2014, roughly three to four months behind the crash in oil prices. This is a sensitive value in the model: longer delays in adjusting production leads to supply over- or undershooting demand, with price shocks as a

[8] The capital stock investment factor increases over time, as the amount produced per unit of capital stock declines due to reserve depletion, as can be seen in figure 18.

consequence. However, given the private enterprise nature of the USA's oil industry it's probable that their response is at the quick end of the spectrum. Therefore, a short term response delay time of 3 months is assumed, but this is adjusted for different scenario's.

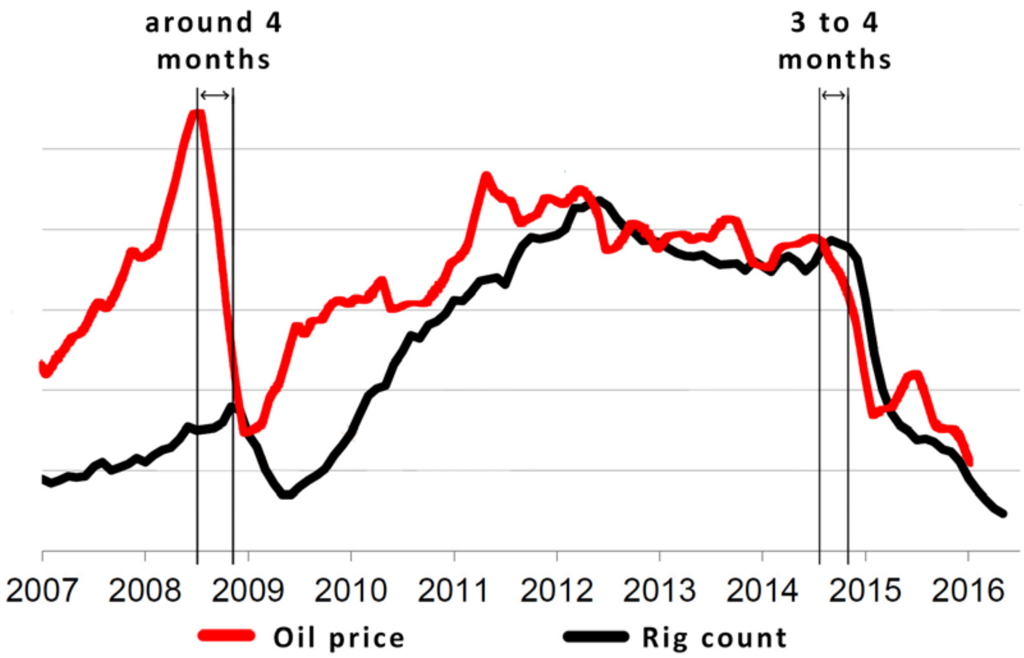


Figure 21: Historic oil price and Bakken play rig count, 2007-2016. Vertical axis not to scale. Data from: EIA (2016b).

What figure 21 also shows is that as price went up in the period of 2009-2012, oil rigs responded slower than during a decline in price. This is because most growth in that time exceeded the growth up to 2009, requiring additional capital stock investments, which have a larger delay.

Fattouh (2007) shows that most oil suppliers maintain a spare capacity of around 10% (it fluctuates between 5% and 20% over time) of their nominal capacity. Therefore, it is assumed that the model can extend supply capacity to 110% of capacity stock output. At the same time, excess demand signals the investors that additional investments are needed, eventually absorbing the demand and bringing the 110% utility factor down to 100%. Finally, supply of oil into the marketplace extracts resources from the reserves, signalling additional exploration

7.3.5. Oil reserves and expansion through exploration.

Total global proven and probable (2p) reserves were estimated around 650 billion barrels in 1980, as shown by Owen, et al. (2010), these are emplaced into the model as initial reserves. Since then global additions have fluctuated roughly between 15 and 35 billion barrels per year. Total additions to reserves are estimated to reach around 1000 billion between 1980 and 2020 as shown in figure 22.

The model explores by maintaining a desired Reserves to Production Ratio (RPR). Once extraction of resources drop below that value the model explores for new resource and adds it to the reserves by the required amount to reach the desired RPR. Calibrating the model to deliver annual reserve additions similar to historic leads to an RPR of 22. Likewise, the EPY costs as shown in figure 18 is also reproduced under that RPR. Therefore, a desired RPR of around 22 is assumed in the model.

As with capital stock investments, a delay is added between investments into exploration and additional reserves being found. The delay is set at 12 months, which might seem rather low, however, the model shows considerable insensitivity to this parameter (which makes sense, given the large buffer total reserves form). The delay is a 3rd order delay, as with capital stock production, as not all fields are discovered at the same time.

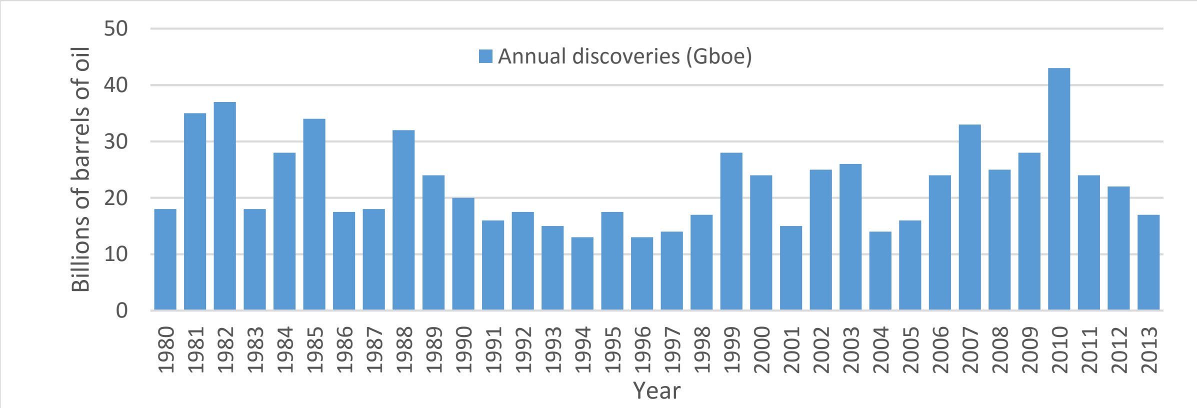


Figure 22: Annual oil discoveries, source: BP (2016)

7.3.6. Learning by doing.

Over time companies reduce costs due to learning by doing, indicated by a learning rate. The TIMER model includes learning by doing as an essential part of its model, as its effect may be considerable over a long time period. De Vries, et al. (2001) maintain a learning rate of between 0.75 and 0.95, depending on the region. The global average learning rate is around 0.90.

The increasing costs of exploration, as shown Figure 17, is derived from historic data, which means that this already includes learning effects in the final costs. Therefore, expanding exploration costs are not affected by learning effects in the model. This means that only investments into capital stock are affected by learning effects.

Formula 3, derived from Blok (2007), shows how the marginal costs of production declines over cumulative production.

Formula 3: $$CSO_n = CSO_i * \left(\frac{SOn}{SO_i}\right)^b$$

In which:
- CSO_n The cost to supply one barrel of oil at month n;
- CSO_i The initial cost to supply one barrel of oil, at January 1980;
- SO_n The cumulative supply of oil to market at month n;
- SO_i The initial cumulative supply of oil to market, at January 1980;
- b slope of the function, given by by the log of the learning rate/log2

Formula 3 tells us that the cost to supply one barrel of oil becomes cheaper over time, however, due to depletion effects, considerable more capital stock may be required. Therefore, to find the real cost of oil producing one barrel of oil, formula 4 is used which multiplies the marginal cost of production with the fraction amount of capital stock divided by the amount of oil supplied:

Formula 4: $$MPC_n = CS_n * \frac{CS_n}{OS_n}$$

In which:
- MPC_n The Marginal Production Cost of oil per barrel, at month n, in dollars per barrel;
- CS_n The cost to supply oil at month n, in dollars per barrel;

CS_n Capital Stock at month n, in dollars;

CSO_n Capital Stock Output, at month n, in barrels per month.

As explained in 7.3.3., the production of oil declines over time due to field depletion, requiring increasing capital stock to maintain supply. From those facts and the learning curve it shows that the factor CS_n/CSO_n grows over time, and MPC_n shrinks over time. The combined effect leads to marginal production costs declining at first due to learning effects, and rising thereafter due to depletion effects, as shown in figure 23.

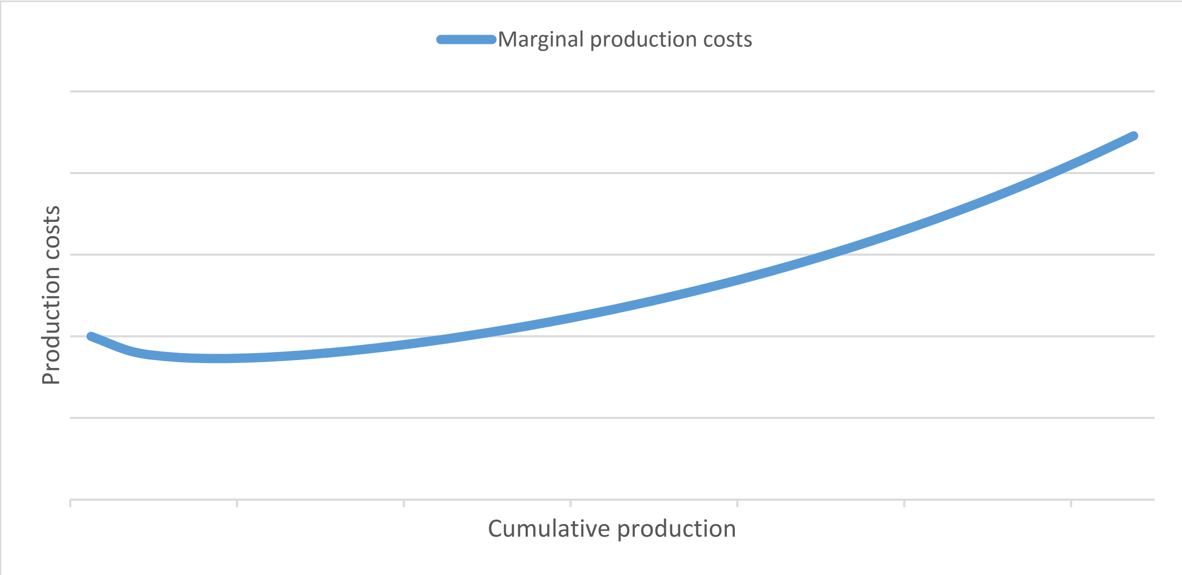


Figure 23: Marginal production costs over cumulative production according to formula 4.

7.3.7. Global demand and unconventional oil input.

The production quantities and associated costs have been defined for conventional oil. However, it has not yet been connected to demand. Demand is completely exogenous in this model: it is derived from historical data and extended up to 2020, as shown in figure 24. The growth is highly linear, of which the trend line is used in the thesis's model[9]. This starts at 1700 mboe/month and grows to 3000 mboe/month in 2020 (i.e. roughly 55 mboe/day to 10 0mboe/day, respectively).

As figure 24 shows, historic oil demand fluctuates around the trend line. This can be reflected in the model by adding a slight noise pattern to demand.

[9] This is done for two reasons: First, the historic demand data is not publicly available at a monthly resolution, Secondly, the Vensim software academic license prohibits exogenous data input via excel tables, requiring manual input.

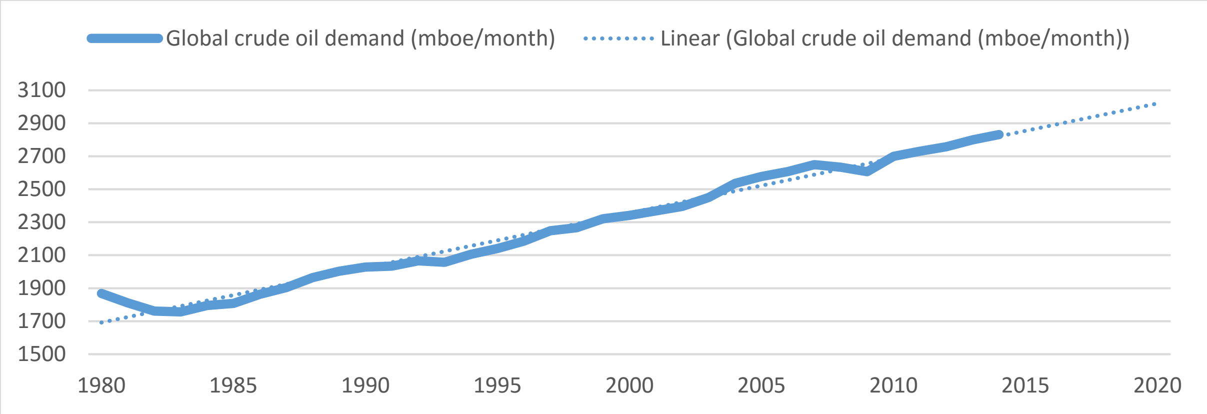


Figure 24: Historic globla oil demand extrapolated to 2020, source: BP, 2016

In order to determine share of demand for conventional oil in the global demand, the demand for unconventional oil has to be removed from global oil demand. It is assumed that global supply of unconventional oil is equal to their demand, which allows their supply to simply be subtracted from demand.

Three main unconventional sources of oil are included in the model:

- Tar Sands from Canada;
- Tight Oil form the USA;
- Global Biodiesel and Bioethanol.

Although Venezuela also produces oil from tar sands, gaining reliable information is considerably hard, and production quantities appear to be low. Venezuela is excluded from unconventional oil supply for those reasons. Canadian tar sands have grown from 3 mboe/month to 66 mboe/month in 2014 and is expected to keep growing to around 90 per month in 2020, as shown by CAPP (2015b) and IEA (2013).

Documentation on USA tight oil production, such as delivered by the EIA (2016b), shows that tight oil grew slowly from 0 to 10 mboe/month in 2010, and then accelerated rapidly to 170 mboe/month (around 5.5 mboe/day) in 2014, after which it declines somewhat. It is assumed that tight oil production declines slowly towards around 125 mboe/day in 2020, although scenarios can be made that show different future growth paths.

Biodiesel and bioethanol production grows from 3 mboe/month in 1980 to around 15 mboe/month in 2010, after which it accelerates to 93 mboe/month in 2020. This is derived from historical data and assumed projections made by the IEA (2011). Biodiesel and bioethanol aren't 100% clean from fossil fuel input, they require a certain percentage of crude oil input to produce output, depending on the type of biofuel and feedstocks. The IEA (2007) offers information to determine the net reduction in fossil fuel demand due to biodiesel and bioethanol production, which is around 25% on average. However, they replace fuels, not crude oil, therefore 1 barrel of bioethanol is not equal to 1 barrel of crude oil. The EIA (2016d) shows that from a barrel of oil roughly 80% ends up as fuels (diesel, jet fuel or gasoline). These two factors lead to a net crude oil reduction of 60% (i.e. 1 barrel of biodiesel or bioethanol leads to a reduction of 0.60 barrels of crude oil consumption).

Figure 25 shows their respective and combined input into the model, as well as the resultant global demand for conventional oil, as shown, the influx of unconventional oil causes demand to flatten for a number of years around 2010, after which it picks up again.

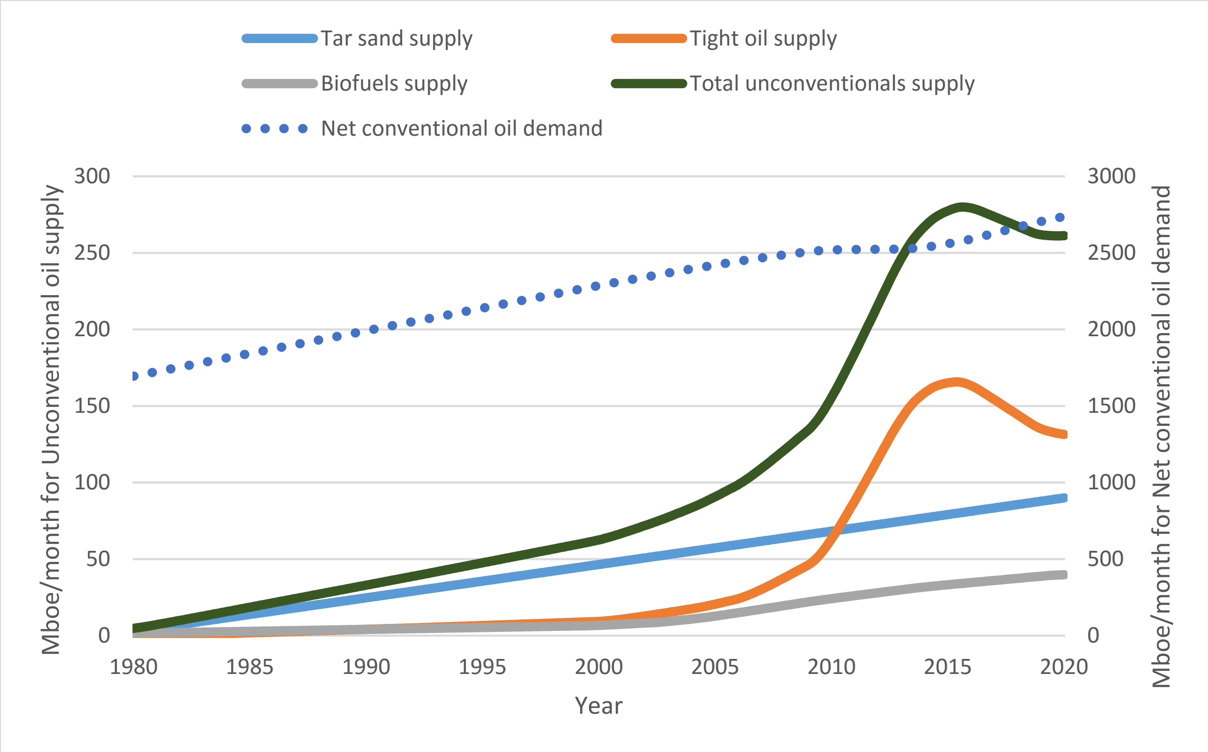


Figure 25: Supply from unconventional oil and net conventional oil demand.

7.3.8. Determining the price of oil.

The long term investment cycle is determined by long term expected demand. If long term demand falls away, so do investments. Costs are not a part of this cycle in the model. However, global supply cannot continue when it's running into a deficit: supply is reduced to reach a desirable price point above the cost of production. In reality the highest marginal cost producers are likely to cut supply first, as they run into deficit earliest when oil prices fall. The model incorporates this by assuming the following points for its supply:

- If the market price of oil is higher than the desirable level, no cut in supply is made.
- If the market price of oil is lower than the desirable level, future supply is cut sufficiently to raise the expected future price to desirable levels.

From these two axioms, formula 5 is used to determine future supply to raise the price of oil. This formula is based upon standard price setting formulas using price elasticity of demand. An example of calculating a product's price using price elasticity of demand in combination with changing demand is given by Moffatt, (2016). The thesis' model attempts to meet future demand for conventional oil, therefore future demand can be expressed as future supply, allowing the construction of formula 5:

Formula 5: $$S_{df} = \left(\frac{P_d}{P_c} - P_c\right) * PE + D_e$$

In which:

S_{df}	Desired Future supply, in barrels of oil per month;
P_d	Desired oil price, in dollars per barrel;
P_c	Current oil price, in dollars per barrel;
PE	Price Elasticity, dimensionless;
D_e	Expected demand, in barrels of oil per month.

Future supply requires a horizon to operate (i.e. how for does one look ahead to determine future supply to demand). The length of the horizon determines the distance the current trend is assumed to extend, and how strong the response will be. Therefore the horizon must be short enough to allow small changes in supply, otherwise suppliers risk losing income. A default value of a 2 month horizon is chosen, forming a compromise between rapid and slow forecasts[10]. This is a model assumption, as information on this data is next to impossible to find from reliable sources. Scenarios allow changes in these parameters, which gives insight into appropriate horizon values by comparing results with historic oil price developments.

The desirable price of oil is expressed using formula 6, which adds a minimal profit margin to the future total production costs of oil:

Formula 6: $P_d = PC_f + m$

In which: P_d Desirable oil price, in dollars per barrel;

PC_f Future Total Production Cost of oil, in dollars per barrel;

m Minimal profit margin above the production cost of oil, in dollars per barrel;

The minimal profit margin can be estimated by subtracting the initial production and exploration costs of oil from the price of oil. Initial production costs is $10, initial exploration cost is $1.6, initial price of oil is $25. The minimal profit margin is $13.4, which is rounded off to $13.

Using formula 7, the current price of oil can be determined, using general price formation formulas such as used in formula 5:

Formula 7: $P_c = P_{old} + \frac{\frac{S-D_{old}}{D_{old}}}{PE} * P_{old}$

In which: P_c The current price of oil, in dollars per barrel;

P_{old} The previous month's price of oil, in dollars per barrel;

S The current supply of oil, in barrels of oil;

D_{old} The previous month's demand of oil, in barrels of oil;

PE The price elasticity, entered exogenously.

Price elasticity is a highly sensitive value. As described in chapter 5.3.2., the price elasticity declined between 1990 and 2015 by a factor of 4 to 6. Hamilton (2009) and the IMF (2011) suggest a value between 0.5 and 0.7 in the late 2000s. Therefore it's likely to have been between 3 and 6 in the 1980s. However, elasticity decline is not likely to have been linear: otherwise it would reach 0 in a short few years. Rather, it is assumed that elasticity approaches a lower boundary via exponential decay, which is tested using historical data and formulas 6 and 7, as shown in figure 26.

Figure 26 shows the historic oil price (in 2016 US dollars) compared to the oil priced derived from historic supply and demand data, using an exponentially decaying elasticity factor. The starting price is derived from the historic price exponential trend line.

[10] A 1 month forecast may lead to suppressed expectations of demand changes, whilst a 4 months forecast could lead to exaggerated expectations of demand changes.

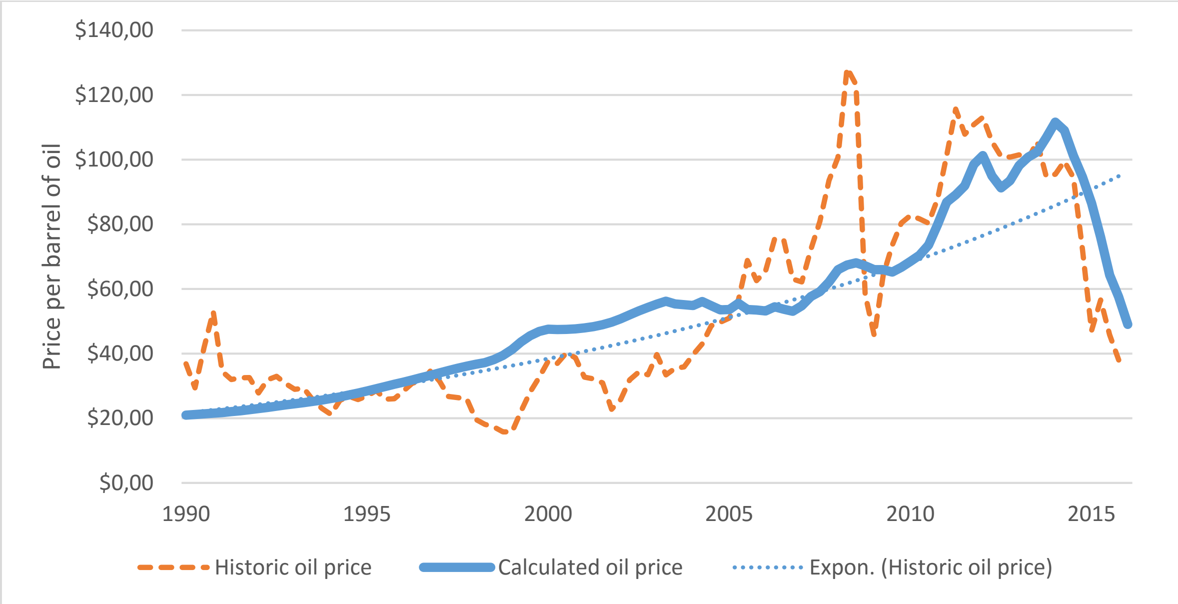


Figure 26: Historic and calculated oil prices from supply and demand, derived from: BP (2016), IEA (2015a) and EIA (2016e)

The decay in elasticity is described using formula 8, leading to an exponentially decaying line.

Formula 8 : $PE_0 * Decay^n$

In which: PE_0 This is the price elasticity at the start of simulating;

Decay The exponential decay of elasticity, per month;

n The month since the start of simulation.

The values used in figure 26 are $PE_0 = 2.5$ in 1990 and annual decay is 0.90 (i.e. 0.974 per month) results in a price elasticity value of 0.16 in 2016. The thesis' model is highly sensitive to the initial price elasticity and decay values (especially the decline rate). However, the sensitivity is only expressed in price height and price volatility, not in structural behaviour of the model (i.e. any price change that were to happen still happens, just in stronger or weaker fashion). A starting price elasticity in the model of 2.0 in 1980 and an annual decay of 0.92 leads to values similar in figure 26.

7.4. Model construction.

Using Vensim 6.4a (academic license) system dynamics software developed by Venata Systems (2015) a model is built. From this model various scenarios can be made to reflect the model response to input. The model is built up from seven sub-models / cycles that are connected to one-another through input output parameters (e.g. 'investments into capital stock' forms an output from the investment cycle and an input for the capital stock cycle). Figure 27 on the following page offers an overview of the entire model, with the seven sub-models separated. For a detailed view of each sub-module the reader is referred to the appendix.

Some comments must be made on the model: The capital stock and existing fields module contains several parameters that are not yet described in this chapter. The reason for this is that they are model-dependent, meaning that for the model to function properly they are required to be added. These are:

- The 'investments and depreciation from before model input' is added to compensate for the input delay of capital stock. Basically it assumes investments in the 1970s in order to allow the model to have a running start. Additionally, the model has a delay on the onset of decline in fields, which is needed to compensate for the input delay of capital stock. The problem is that without these two inputs existing fields enter decline before additional capital stock is added to their production, leading to a mismatch between 'real' output and capital stock investments.
- Exogenous demand contains a number of smoothing for the input of tight oil as well as biodiesel and bioethanol. This is done because their values are entered manually in a graph within the Vensim software, which causes hard 'turning points'. The smoothing (a few months) buffers these and cause their output into the demand module to become smooth graphs.

For a detailed presentation of all seven sub-modules as well as a complete list of every parameter equations the reader is referred to the relevant appendix. From that appendix the thesis' model can be reproduced accurately.

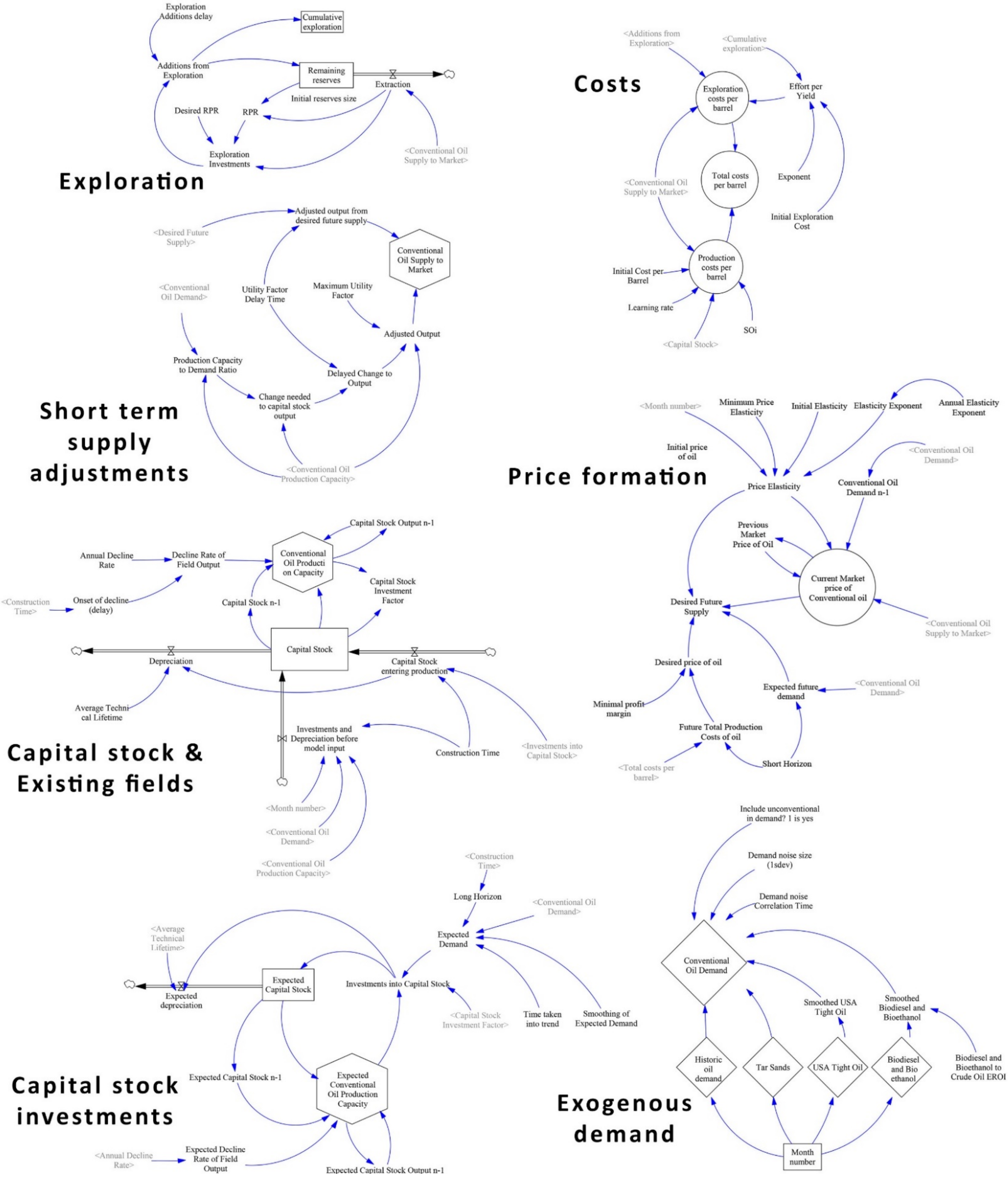


Figure 27: Thesis model overview

7.5. Model scenarios, results and discussion.

Four scenarios are run:

1. A standard run with default input and no unconventional oil inputs (i.e. historic demand for crude oil = conventional oil demand).

This scenario allows a default evaluation of the model and comparison of assumption made to real world input. In particular it allows the examination of the effects of depletion on the effect of costs and price. During model testing scenario 1 and scenario 2 were used for general calibration of the price elasticity variables. A 'small growth of future unconventionals scenario' isn't included, as the model will likely behave as if in between scenario 2 and 1 in that case.

2. A standard run with unconventional oil subtracted from conventional oil demand;

This scenario allows a clear understanding of the effect unconventional oil has on the model's price, costs, demand and supply development.

3. A run with future high tight oil supply growth;

In the case of high unconventional oil supply growth (i.e. tight oil supply resumes its 30% annual growth rate after 2015) its effect upon conventional oil is explored up to 2020. It must be noted that the thesis' model is not built to forecast future developments, however, this scenario might offer insight into price developments if unconventional growth is resumed (i.e. if it manages to keep prices suppressed).

4. A run with noise added to demand input which is curve fitted to historical data.

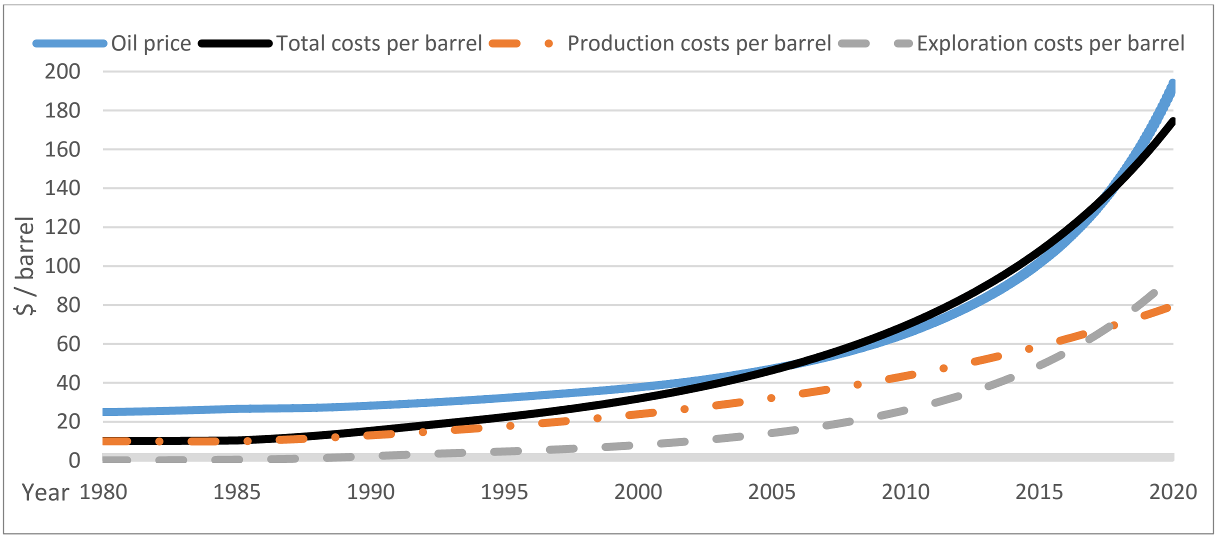
This scenario attempts to recreate historical developments on price development. Only noise values in demand, price elasticity developments and short term forecasting + responses of suppliers are adjusted from the default scenario. This scenario is made to evaluate the model's ability to reproduce historical data, and which parameter values are required to do so. If the parameter values are found to be consistent with literature or reasonable assumptions, the model gains additional validation.

Of each of the four scenarios the relevant input data are shown in the graph below. All other parameters are identical. The market price of oil, production costs, supply and demand quantities and demand quantities are given.

Parameter	**Scenario 1:** standard run	**Scenario 2:** historical unconventionals	**Scenario 3:** high unconventionals	**Scenario 4:** historical reproduction
Demand noise size (1s.dev. noise in mboe/month)	0	0	0	15
Subtraction of unconventionals from crude oil demand	No	Yes	Yes	Yes
Tight oil growth to 2020 (mboe/month)	Default	Default	300	Default
Short Horizon (months)	2	2	2	1
Utility Factor Delay Time (months)	3	3	3	3
Annual elasticity exponent	0.92	0.92	0.92	0.93
Initial Elasticity	2.00	2.00	2.00	2.00

Table 2: Model scenario parameters

7.5.1. Results from the standard run.



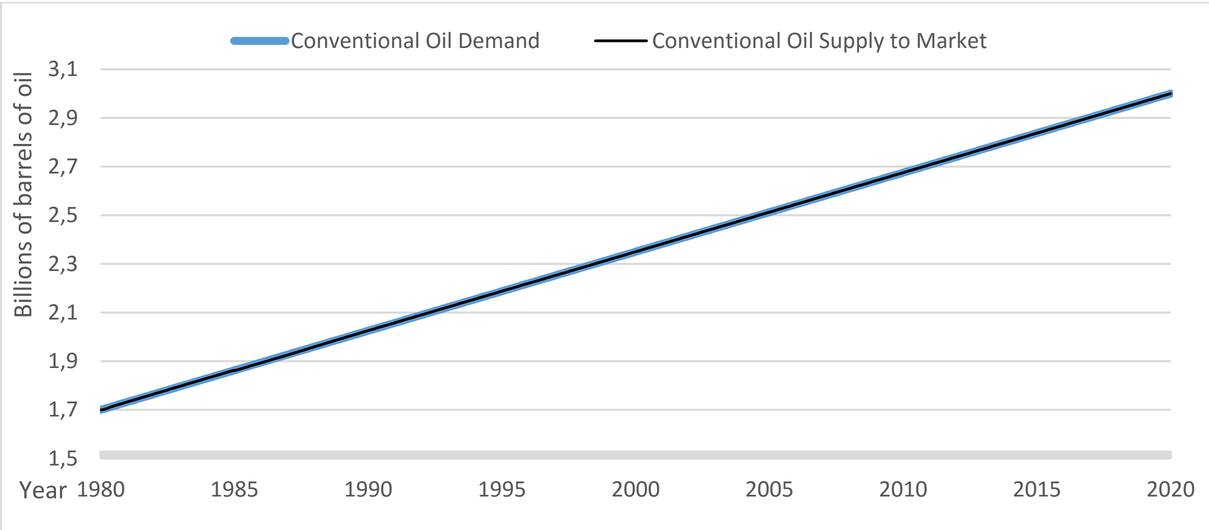
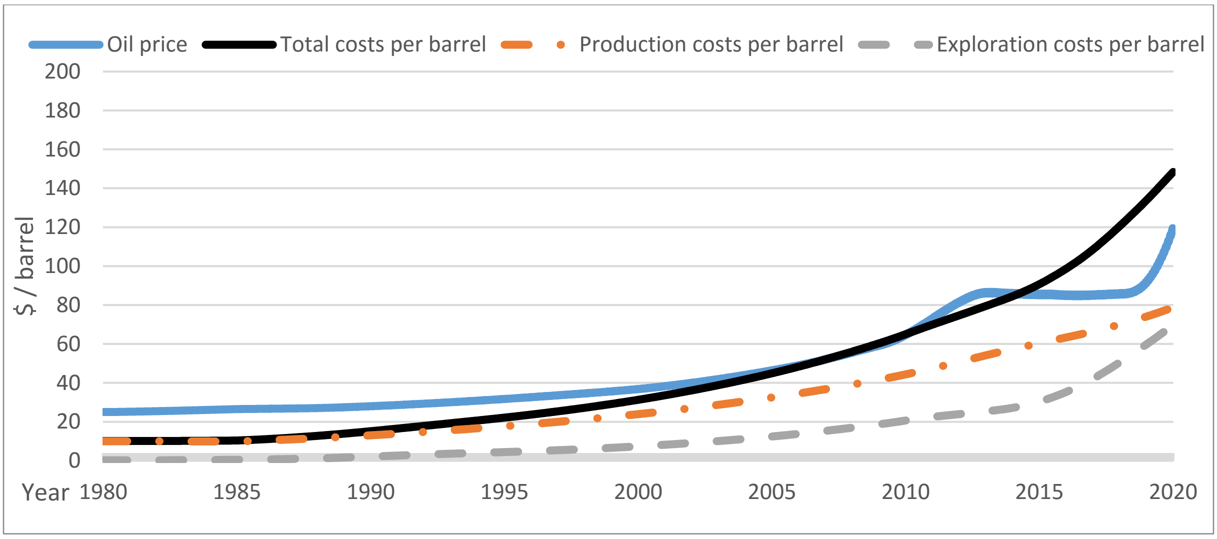


Figure 28: Results from scenario 1: the standard run.

In this scenario the model increases the price smoothly up to around 190 dollars per barrel around 2020. This would be ideal for oil producers, as they do not need to cut into their profits, and are able to explore sufficient resources to maintain supply for the foreseeable future. In the period between 2007 and 2017 oil prices are just below profitable, with demand growing somewhat faster than the short term adjustments manage. Nevertheless, this is compensated in the period after that time, as prices are driven upwards. Remarkable, it is observed that the model shows that cost to find additional reserves exceeds the production costs of existing reserves by 2017, thus the obvious way for producers to cut costs is to cut into exploration efforts (with the resulting decline in existing reserves). Obviously, real world demand would respond to excessively high prices of oil through demand reduction (i.e. the world economic growth would be slowed). Therefore, the real world oil price would likely be lower in 2020 in this scenario.

The main result of this scenario is that, even with linear, smooth growth of demand, the price of oil rises exponentially, driven by costs. The only ways this can be stopped is by a change in demand through price induced effects, which isn't included in the model, or a change in supply, which is included in the model, and results in scenario 2.

7.5.2. Results from the historical unconventionals run.



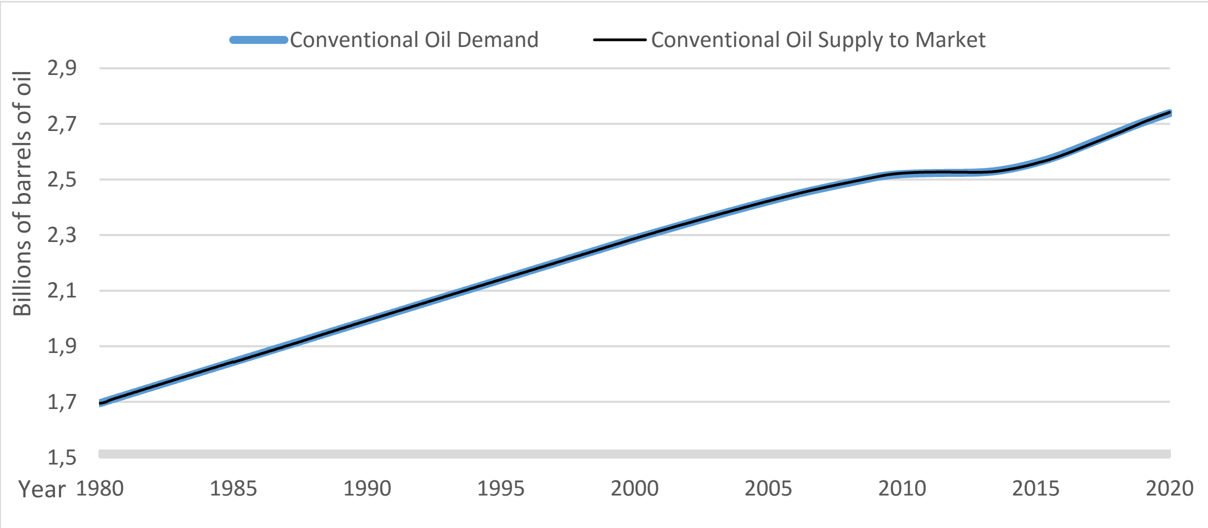
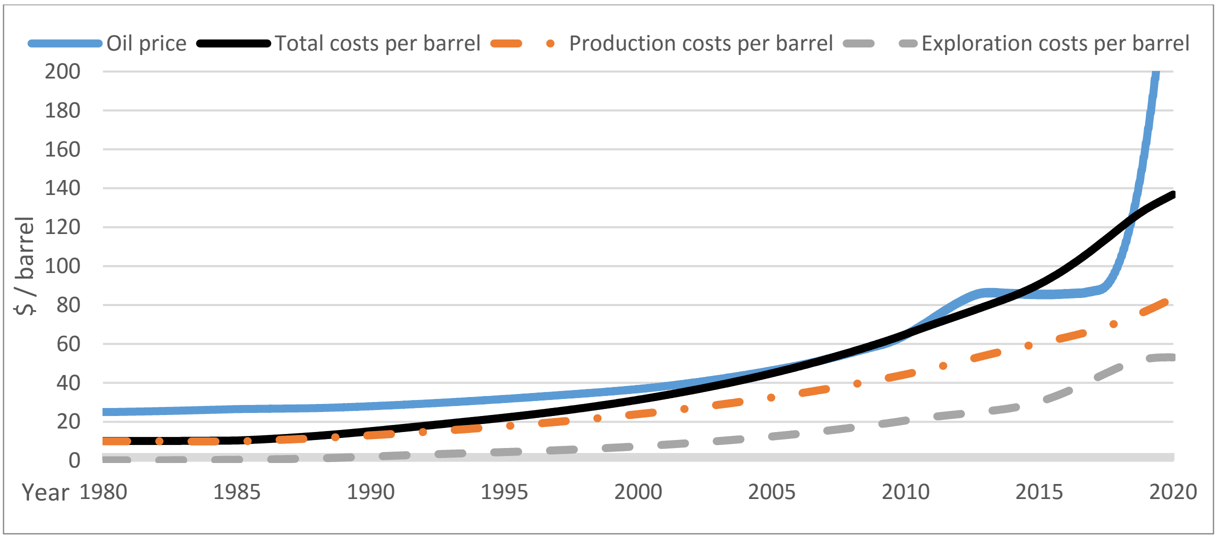


Figure 29: Results for scenario 2: historical unconventionals.

By subtracting unconventional oil supply from global crude oil demand we find that the price of oil grows up to around 90 dollars in 2012, after which it stagnates due to suppressed demand. The model manages to maintain the price of oil between 80 and 90 dollars up to around 2018, after which excess demand causes a rapid spike in prices. Peculiarly, the model doesn't raise prices quickly enough, running into a deficit. A reason for the price dipping below (global average) profitability beyond 2015 is the way short term forecasting works: During the period of suppressed demand it manages to maintain oil prices by cutting back on supply, however, once it sees oil demand rising again around 2015 it increases supply, but insufficiently to raise the price of oil at first. Later on the model does adjust sufficiently, leading to the subsequent price shock/adjustment.

The production costs show that long term investments into capital stock aren't affected strongly by the change in demand. Due to the flat supply in the 2010-2015 period, exploration efforts are cut back, as the RPR declines slower. This is seen by the suppressed costs of production in that period, after which it rapidly grows to find sufficient new reserves, almost breaking even with production costs in 2020. Demand and supply are maintained in near-perfect equilibrium due to good operation of the short term supply management.

7.5.3. Results from the high unconventionals run.



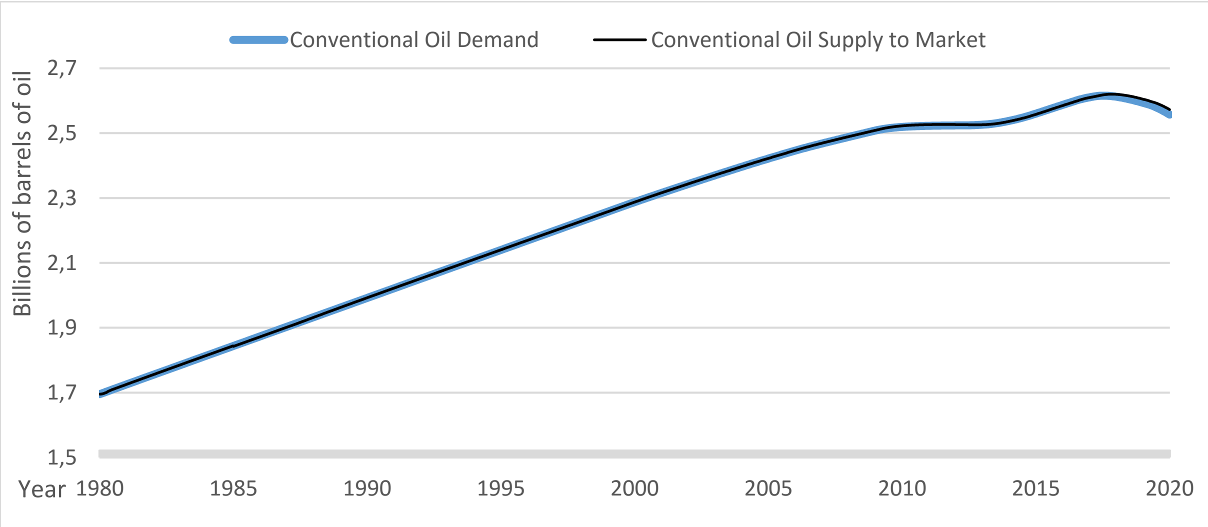


Figure 30: Results for scenario 3: High unconventionals run.

Remarkably, a doubling of USA tight oil between 2016 and 2020 leads to no significant change in model operation in that period. Demand and supply show that conventional oil demand actually declines from 2018 onwards, but the price of oil explodes in the same time period (it goes off the charts, nearly to 300 dollars per barrel). This price development is due to the same effect as in scenario 2, except in a more amplified way. It must be noted that the model is not developed to forecast future price developments, therefore, this price 'spike' must be taken with a grain of salt.

The cost of producing oil is about 10 dollars lower by 2020 than in scenario 1, which shows that even in a scenario that has unconventional oil flowing into the system at a rate that is at the high end of potential growth, the cost of producing oil keeps growing almost at the same pace. This is because of the small share of unconventionals in the total oil supply, requiring most supply to come from conventional oil production. Around 2018, when the demand for conventional oil drops (i.e. tight oil supply grows faster than global oil demand growth), exploration costs stop increasing. This buffers production costs for the years after, limiting the minimum price of oil producers need to break even. Regardless, even if tight oil (any other source of oil, in fact) grows to double or triple their current capacity, their effect on the price of oil is only temporary. Sustained demand growth forces additional costs to be made to produce conventional oil, leading to a higher price of oil sooner or later.

7.5.4. Results from the historical reproduction run.

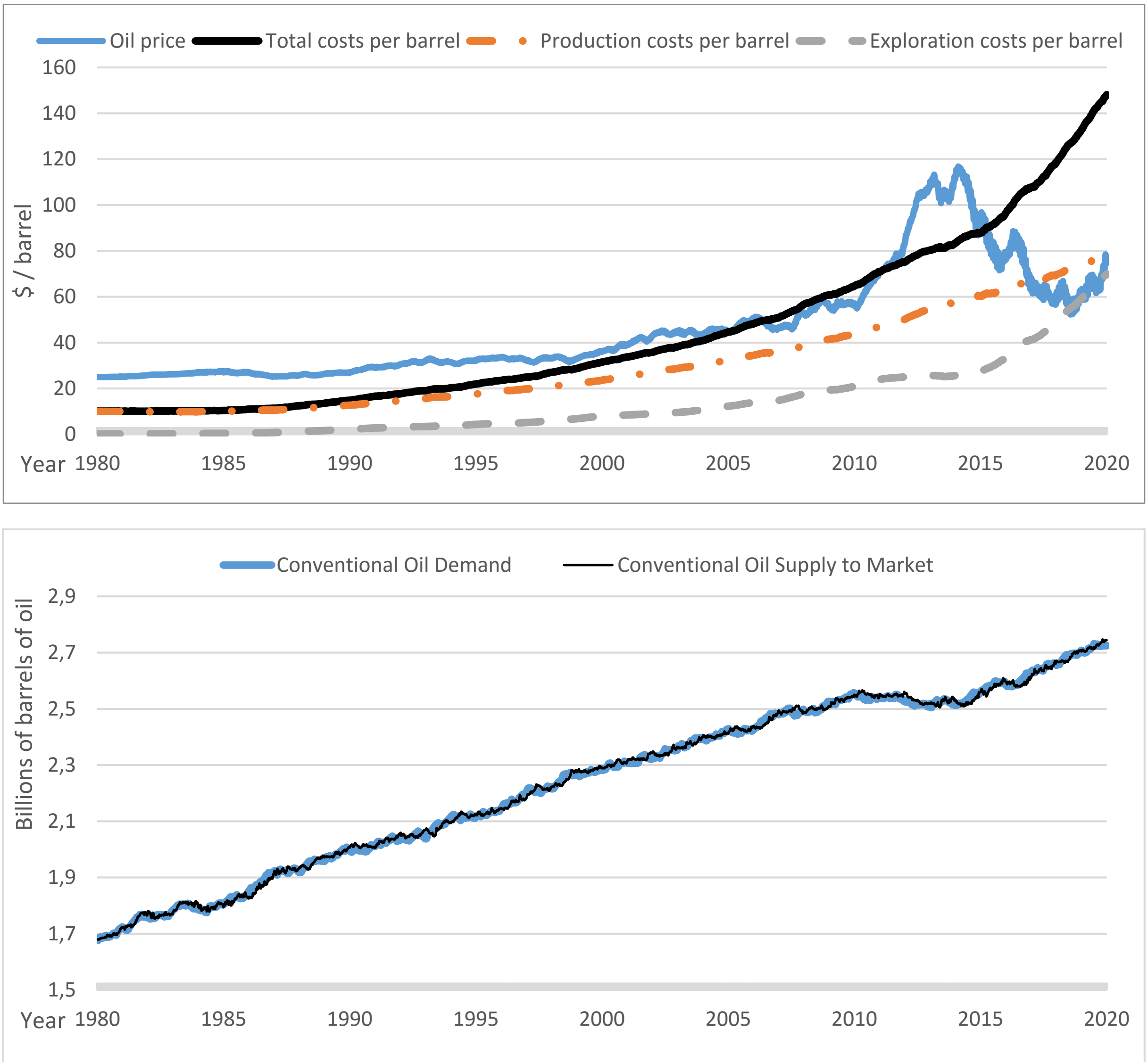


Figure 31: Results for scenario 4: Historic reproduction run.

By recreating a more realistic demand curve for conventional oil by adding noise levels similar to historically observed, as well as reducing the short term horizon for predicting future price of oil, and reducing the decline rate at which the price elasticity decays. The main result from this scenario is the need for slight noise in demand to ‘kick-start’ the volatile price development that has been observed historically since 2005.

Despite growing costs equal to scenario 2, the model is unable to maintain prices at a sufficiently high level. This is because the demand noise causes misjudgements in expected short term demand which leads to a failure to adjust supply appropriately to maintain a high market price. In effect, the supplier sees short term demand rising, thus doesn’t cut supply. However, demand one month later might actually have dropped somewhat, leading to an exaggerated misjudgement of expected demand, and subsequent supply adjustments into the wrong direction. This can be seen in the demand/supply graph within figure 31, as they aren’t perfectly aligned, but supply consistently ‘runs ahead’ of demand by a small margin, causing price volatility. As the overall demand trend rises again beyond 2015, the price initiates a recovery from 2017 onwards. Clearly, the model struggles dealing with adapting to structural changes in demand for conventional oil, which is also seen in the real world.

7.6. Chapter discussion and conclusions.

The four scenarios show price development of oil not too dissimilar from the real world up to 2010, driven by costs. From 2010 on they diverge, responding in different ways to input parameters. Figure 32 shows the price of oil between 2000 and 2015, in scenarios 1, 2 and 4, as well as the historic price of oil. Scenario 3 is excluded as it is nearly identical to scenario 2.

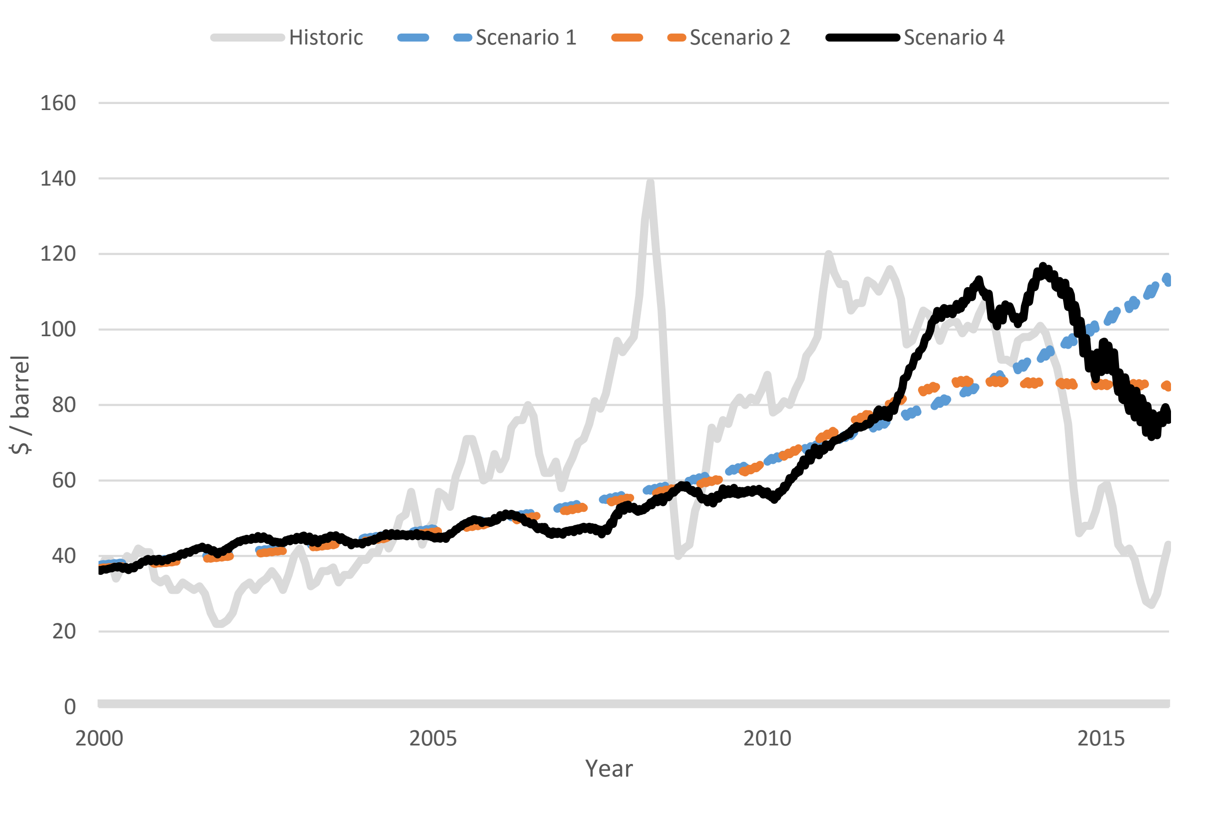


Figure 32: Oil price developments from model scenarios and historic price, source: IEA (2015a).

Figure 32 shows that all scenarios lead up to a price around 80-120 dollars around 2012, as well as having nearly identical prices in 2000. The price is produced endogenously from the model, therefore, it is remarkable how close it gets to historical reproduction. In particular scenario 4.

Interestingly, the price spike in 2007/2008 was not reproduced by the scenario, but neither was it developed by the calculated oil price in figure 26 (page 58). In fact, scenario 4 shows remarkable similarities to the price development in figure 26. This offers evidence for the notion that the price spike in 2007/2008 was not caused by fundamentals, but other market mechanisms such as speculation.

7.6.1. Model discussion and implications.

Despite the chosen scenario, the model leads to total costs of production exceeding $135 by 2020. This suggests that the low prices of oil seen as of 2016 cannot be maintained for more than a few years, with the exception that producers can cut investments into exploration to reduce costs. If exploration is removed, global production break-even costs end up at around $75 by 2020. In fact, cutting costs in exploration is exactly what is happening since the fall of oil prices in 2014, as shown by Bousso & Zhdanikov (2016), who write:

“The surprise departure of BP's exploration boss has turned the spotlight on an oil search strategy that, after years of spending cuts, is focusing mainly on expanding existing fields rather than venturing expensively into the unknown.

[…]

But Herbert, who worked with Dudley in Russia in the 2000s, had also seen his annual budget shrink from $3.5 billion in 2013 to $1 billion this year - not enough to drill even a dozen complex deep-water wells, and certainly not enough to throw at a frontier exploration with potential high gain, but also a high risk of coming out empty-handed. Royal Dutch/Shell sank $7 billion into an Alaskan exploration that it abandoned last year.

[…]

But another indicator, the reserves replacement ratio reveals a less rosy picture. BP's RRR fell last year to 61 percent, its lowest in many years, from 129 percent in 2013.The RRR reflects not only a failure to unlock new deposits - a problem for all the multinationals - but also a reluctance to commit investment as oil prices languish about 60 percent below mid-2014 levels.”

This quote clearly shows that exploration efforts are cut in an effort to reduce production costs. However, as with the scenario 2 and 4 results, exploration is likely to pick up rapidly to restore the RPR when demand grows and oil prices rise to sufficient levels to permit additional exploration. Effectively, oil producers are currently ‘eating’ into their reserves, waiting for better times.

Given the decline in existing field production, the model suggests that conventional oil supply simply cannot be maintained if the current price situation persists beyond 2020, forcing price upwards due to supply scarcity and a need for field additions. This begs the question of how big the impact of unconventional oil supply must be to maintain low prices. This question is partially answered by scenario 3, which shows that extreme growth in unconventional oil supply is needed, at least doubling current supply to offset further conventional oil demand growth, and even more to suppress it.

Given scenario 3’s results, oil production costs keep rising in the foreseeable future, as unconventional oil production simply isn’t big enough yet to substitute enough conventional oil in the market. Therefore, if the model’s results are indicative of what the future will bring, considerably strong upward shocks in the market price of oil can be expected somewhere around 2018 or 2020. High oil prices may then be sustained unless unconventional oil supply can grow fast and sustained enough to suppress further conventional oil demand. However, the dynamics of tight oil production in the USA show that such a scenario seem unlikely, as described in chapter 5.2.3. Half a decade or a full decade of high oil prices in the 2020s seems likely, until sufficient amounts of substitutes are developed for conventional oil, or demand has decreased sufficiently due to energy efficiency improvements and electrification of society (or of demand is reduced through a recession).

7.6.2. Model strengths, weaknesses and limitations.

It must be understood that the model developed for this thesis isn't perfect - no model is. As stated before, the model's goal is to explain historic behaviour, and it has succeeded well in explaining that between 2000 and 2016 at least. One of the main strengths of the model is that it does not make use of estimating how much remains to be discovered (i.e. the Ultimately Recoverable Resources), rather it merely describes how costs of additional discoveries increase over time. This reduces uncertainty regarding future oil price as the model relies on empirical data concerning marginal discovery costs. Furthermore, including limited / imperfect knowledge for suppliers about short term future demand in combination with a slight noise on demand leads to frequent misjudgements of expected demand. This mismatch causes volatile price movements, especially in the case of reduced price elasticity and a structural change in crude oil demand. Therefore, we can conclude that uncertainty within future demand forms a strong driver behind price volatility and price trends falling below cost-price.

The model does contain a number of relevant uncertainties however. The short term horizon on expected demand is one assumption which shows strong influence on model behaviour. Reducing the horizon leads to increased volatility, but the evidence for the exact value on this is lacking. It is not yet evaluated of this is the correct approach towards oil short term supply adjustments, however, the reasoning behind it seems reasonable. After all, one wishes to know the short term future demand so supply can be adjusted accordingly. The precise price elasticity development over time is also an uncertain value, but is supported by historical data.

Regarding the most fundamental drivers behind cost development in the model: exploration costs and production costs, these are grounded in historical data, and thus contain fairly low uncertainty. Of these two factors, exploration costs contain the most uncertainty, as upstream investments data may also contain more costs than just exploration. Nevertheless, cutting the initial costs of exploration in two halves the exploration costs throughout the model run. This seems like a large adjustment, but it isn't: Due to the nature of exponential growth it only delays excessively high costs by a few years. The exponent driving the growth rate of exploration costs is more strongly founded in historical data than the initial price, thus it contains lower uncertainty than the initial costs of exploration (although it may be improved by using a longer historical dataset to determine its value).

The rate at which costs increase due to declining field output is an assumption. Currently it is assumed that, as global field production halves due to depletion, the cost to maintain original supply is doubled (i.e. 2*0.5=1). The assumption is based upon the idea that – globally at least - a double amount of production capacity is installed, however, that assumption might not be correct. It could be that costs of production increases differently than assumed due to OER techniques, etc. Further research may be conducted to evaluate the precise cost increase over existing field depletion.

Given the explanatory focus of the model it isn't currently developed to be used as a predictive tool. This has several reasons: First of all, the model contains no feedback between price and demand, which is relevant during periods of high price (i.e. which the model suggests will be a likely future). Secondly, the model doesn't include proper modelling of unconventional oil supply, making any scenarios into the future flawed as it does not include dynamics between conventional and unconventional oil (i.e. supply of unconventional oil is completely exogenous or based upon assumptions, such as in scenario 3). It is easy to extend the model run-time to 2030 or beyond, but because of these factors it cannot lead to accurate forecasts beyond its standard run-time. Thirdly, regional differences in cost development aren't included in this model, although the results suggest sufficient accuracy at a global level regarding price development. By adding regional heterogeneity one can observe which regions suffer most/least from the 2014 price crash, adding information on future developments. Also, it may offer higher accuracy in exploration costs and desired RPR ratios, etc. than the model does currently.

7.6.3. Chapter conclusions.

This chapter addresses the following research questions:

5. Which factors are most relevant to model quantitatively?
6. Does the developed model show behaviour which explains the observed historical data on oil price, demand and supply?
7. What changes in TIMER would be needed to incorporate the model from question 6?

- Research question 5.

The most relevant factors (as described in the introduction of this chapter) are to model the depletion effects in relation with an influx of unconventional oil and decreasing price elasticity. This is done because it contains the lowest amount of uncertainty as well as that it remains within the techno-economic framework of the TIMER / IMAGE models.

- Research question 6.

The model developed for this thesis offers an explanation for the observed historical price, supply and demand developments. The model suggests that the inflation of oil prices in the time between 2000 and 2015 were caused primarily by escalating production and exploration costs. The subsequent fall in oil prices were caused by the influx on unconventional oil, coupled to inadequate response behaviour of conventional oil and low price elasticity. Imperfect information about short term future demand / expected oil prices form an underlying driver behind the inadequate response of conventional oil to the fall in oil prices.

- Research question 7.

Only a number of findings from this chapter make sense to apply within TIMER. The changing price elasticity and short-term uncertain supply prediction with the thesis' model's price setting mechanism aren't necessary for TIMER for the following reasons: TIMER models the price elasticity decline through a declining energy intensity (i.e. share of energy in the economy's GDP) and energy efficiency improvements. Therefore, change in this part of TIMER is unlikely to deliver improved results. The Uncertainty about short-term future demand / oil price may be added to TIMER, leading to different actor behaviour and therefore price developments that may seem irrational at first, as in scenario 4 of this thesis' model. However, given the focus of TIMER on long term developments, this might not deliver improved results over smooth demand lines in the long term.

Applying the results from the model developed for this thesis within TIMER requires the following three changes to be made in TIMER:

1. Initial exploration costs, and their associated exponent needs to be developed for each region in TIMER, for both conventional and unconventional oil;
2. The rising costs of production due to depletion of exploited fields needs to be developed for each region, for both conventional and unconventional oil. Especially different types of technologies are likely to have different decline rates (e.g. tight oil might have high decline rates, while tar sands has low decline rates);
3. TIMER needs to remove total remaining reserves for liquid fuels, and its associated long term supply-costs curve. The cost of production, as well as the additions to existing reserves are henceforth produced endogenously through points 1 and 2.

8. Thesis conclusions.

This thesis set out to answer the following research question:

> What changes in the liquid fuel subsystem of the TIMER model lead to improved emergent model behaviour of historically observed crude oil price, supply and demand development since 2007?

This has been built up by the following seven questions:

1. What does the literature recognise as the main factors influencing the world's observed crude oil price, supply and demand behaviour since 2007?
2. What do TIMER experts recognise as relevant factors between observed historical data and the TIMER model's mismatch?
3. What differences exist between the TIMER model compared to the identified factors from research questions 1 and 2?
4. Which factors identified in question 3 are relevant to TIMER?
5. Which factors are most relevant to model quantitatively?
6. Does the developed model show behaviour which explains the observed historical data on oil price, demand and supply?
7. What changes in TIMER would be needed to incorporate the model from question 6?

Chapter 5 answered questions 1 and 2. It was found that a large number of factors were recognised as influential in the behaviour of oil. However, significant factors were found to be:

a. Depletion of oil fields driving costs of production upwards;
b. Technological innovation within unconventional oil supply, increasing its competitiveness;
c. A decline in price elasticity of demand over the last several decades, increasing price volatility;
d. Governments extracting wealth from oil companies' profits, forcing higher oil prices for suppliers to remain profitable;
e. Speculative behaviour in the futures market of oil, increasing price volatility;
f. Political events within nations and government influence suppressing supply over time due to underfunding of upstream investments, leading to an inability to maintain supply;
g. Failed geopolitical coordination within OPEC to control supply, leading to an inadequate response to the influx of USA tight oil.

Chapter 6 answered questions 3 and 4. It was found that TIMER generates low price volatility due to its price formation being determined by supply costs plus a slight profit margin. Supply always manages to forecast future demand accurately as demand is derived from smooth GDP growth with several efficiency functions acting upon it. Furthermore, TIMER doesn't include the following factors:

a. Depletion and decline effects of oil fields limiting production quantities;
b. (geo)political behaviour of global actors which influence supply behaviour;
c. Speculative behaviour which may increase price volatility, or price in general.

Chapter 7 answered questions 5, 6 and 7. It was found that point a from question 4, along with a price setting mechanism based upon supply and demand and declining price elasticity would lead to a model that is closest to TIMER's current techno-economic focus. Also, those chosen factors contain the least uncertainty for modelling, as they are derived from historical, empirical data.

The results from the designed model shows that depletion effects from a strong driver behind the increasing oil price in the 2000s, as well as the peak in price around 2014. Scenario analysis shows that the influx of unconventional oil into the system results in a price decline consistent with historical data, depending on the scenario chosen. Due to the iterative nature of price setting from supply and demand, the model's supply side was unable to forecast the future price accurately (this was not an error). This results in misjudgements of expected demand, leading to a further price-fall, as was seen in the historic price development of oil, in which supply isn't cut back sufficiently[11]. Finally, due to the model's disaggregation of exploration and production costs, it was found that supply actors could make cuts in exploration efforts to maintain profitability during times of low oil prices. Evidence shows that this decision is also taken by real world actors, strengthening the model's results and interpretation.

Together with question 7 we can answer the main research question. Applying the results from the model developed for this thesis within TIMER requires the following three changes to be made in TIMER:

1. Initial exploration costs, and their associated exponent needs to be developed for each region in TIMER, for both conventional and unconventional oil;
2. The rising costs of production due to depletion of exploited fields needs to be developed for each region, for both conventional and unconventional oil. Especially different types of technologies are likely to have different decline rates (e.g. tight oil might have high decline rates, while tar sands has low decline rates);
3. TIMER needs to remove total remaining reserves for liquid fuels, and its associated long term supply-costs curve. The cost of production, as well as the additions to existing reserves are henceforth produced endogenously through points 1 and 2 as described in chapter 7 of this thesis.

By applying these three points TIMER will hopefully be able to result in cost, price, supply and demand behaviour that is more consistent with actual behaviour. It is hoped that the following result will be developed endogenously within timer: Costs driven upwards by depletion effects would allow unconventional oil types to develop faster, becoming competitive and suppressing demand for conventional oil to some extent, resulting in the 2016 situation without exogenous input of demand and supply.

[11] Although this was also due to geopolitical reasons, as shown in chapter 5.4.

9. Thesis discussion and recommendations for further research.

9.1. Discussion of thesis results.

The model developed in this thesis expands upon the Yield per Effort curve developed by Hubbert (1980). Although multiple variants of the Hubbert curve are used in a considerable amount of scientific literature, his YPE curve has not yet been applied in this way at a global level. By reformulating the Yield per Effort curve into an Effort per Yield curve it allows us to forecast future exploration costs, negating the need for Ultimately Recoverable Resource figures. This is a great improvement over the use of URR values as their values are often a source of uncertainty. Uncertainties exist within URR values because they are subject to field additions through more-than-expected discoveries, or use of different types of exploration data. For example, by using either proven (1p), proven and probable (2p), or proven, probable and possible (3p) field data, large differences in expected future discoveries are possible. An example is given by Miller (2011), who shows that there is hardly a consensus on expected future discoveries within the scientific community. The EPY curve does away with all that and bases itself merely on historic data on discoveries and its associated costs extrapolated into the future. In theory infinite reserves are possible, but at infinite costs.

Of course, if sudden discoveries of extremely cheap giant oilfields were made this would up-end the EPY curve to some extent. However, that giant oil field wouldn't be able to affect global supply / price for more than a couple of years, as global demand growth would quickly overrule its effect (similar to the influx of unconventional oil, as shown by the thesis' model). In fact, the thesis' model shows that due to additional depletion within remaining fields, discoveries of unexpected giant oil-fields might be needed to prevent oil prices from growing to harmful[12] levels.

The model shows that the recent price drop is not sign of a 'new era of cheap oil', but rather a misjudgement in supply which is unable to cope adequately to a positive supply shock from unconventional oil. The model suggests that the price of oil will grow rapidly again in the period around 2018-2020 or thereabouts. Although the model is not built to forecast future oil prices, the continued growth in total production costs will force oil prices to rise again, possibly to unprecedented levels. Only a sustained growth in cheap new discoveries, alternative fuel sources such as tight oil, tar sands and biofuels, or demand reduction can overcome this problem. However, the share of unconventionals is still small in the total mix of oil (under 7% by 2015 in the thesis' model) , meaning that global demand is not affected enough to sustain low prices. Furthermore, it seems likely that conventional oil supply will concentrate in regions with low marginal costs of production and high RP ratios, such as Middle Eastern countries.

One of the less obvious results from this research is that the thesis' model develops the price of oil consistent to when it is derived from historic supply and demand: the 2007/2008 price peak isn't developed in either model. This is important data as it shows that peak was caused by other factors than supply and demand fundamentals. The corollary is that the price developed by the thesis' model as well as historic values strengthen the correlation between them, and thus the argument for depletion-driven cost increase. Of course, it is unlikely that depletion has been the sole driver behind the high oil price between 2010-2014. The uncertainties within the thesis' model's cost development allow sufficient room for alternative explanations for that price period (e.g. lower initial costs of production and exploration, etc.). Nevertheless, taken over a longer period, the price of oil grew at a consistent rate since the early 2000s, which is explained well from the model's results. If future oil

[12] i.e. levels that harm economic development sufficiently to limit demand, which, due to regional differences in price elasticity of demand, will affect the poorest nations first, as shown in chapter 5.3.2. From that fact it is reasonable to expect increasing wealth inequality due to high oil prices, as the poor effectively 'pay the price'.

prices rebound to 2010-2014 levels or higher by the year 2000, it would deliver substantial validation of the model's projections concerning continued depletion and its subsequent drive behind oil production cost growth.

9.2. Reflections on the research method.

The methodology of this thesis delivered useful research. In particular the interviews with TIMER experts aided the search for possible improvements. The literature research was useful in forming a broad foundation of possible factors which were subsequently distilled down towards a small selection of important factors. These were tested and evaluated, leading to recommendations for the TIMER team. However, it may have been more useful to hold two rounds of interviews. One round at the start of the research that allows for a 'broad sweep' of information on possible factors, guiding the literature study. Then, the literature study could have been more focussed, leading to higher efficiency in research (although at the cost of possible serendipity). After the literature study a second round of interviews could be conducted to receive feedback on the identified factors, similar to the current research method. However, despite possible efficiency improvements in the methodology, the current methodology resulted in valuable results to the scientific community and the TIMER team in particular.

9.3. Directions for future research.

Before this model can be used within TIMER considerable additional research must be undertaken. For example, the use of 26 regions within TIMER as well as multiple types of oil production require each region and technology to have their respective EPY curves. That means that for each of those curve the correct values have to be determined. Also, for relatively new technology types such as USA tight oil, significant uncertainty will be present as fairly little historical data on costs of exploration and exploration quantities exist. However, they may be compared to conventional oil and a EPY curve may be derived from that. Furthermore, the appropriateness of an EPY curve has to be evaluated for technologies such as tar sand oil production, which is produced rather differently than oil from underground reservoirs.

Another area of research is the further validation of the appropriate EPY curve for conventional oil. In this study data from 1980 to 2013 was used to determine the EPY curve for conventional oil, but additional data will increase its accuracy. The exploration costs will also need to be disentangled from the costs of production, which are still intermixed in the model to some degree. Currently this forms a weakness in the thesis' model, which must be resolved to deliver more accurate historical results and useful projections into the 21st century (although, as stated in chapter 7.6.3., the exponential growth component is of greater influence in future costs).

The tested factors in chapter 7 weren't the only factors that were found to be relevant to the TIMER model: (geo)political behaviour of global actors which influence supply as well as speculative behaviour which may increase price volatility, or price in general. Given the financial focus of of both of these factors they may either be researched individually or in combination with each other. One could do this by using a financial framework for speculative behaviour and a geopolitical, actor-driven framework for the geopolitical aspects. The precise method is up to future researchers, however, research on their influence on the price of oil may offer additional insight in the way oil prices have developed, and the way in which they may develop in the future.

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Attachments.

Thesis model stock-flow diagrams and parameter values.

This attachment allows a faithful reproduction of the model used in this thesis. The model is built using Vensim PLE 6.4a academic license as developed by Venata Systems (2015). Of each sub-model the stock-flow diagram is shown as well as a table containing all parameters and their corresponding values for the scenario 2 run. An empty cell in the table indicates no input for that parameter (e.g. no initial value, or a dimensionless number).

Exogenous demand and supply module.

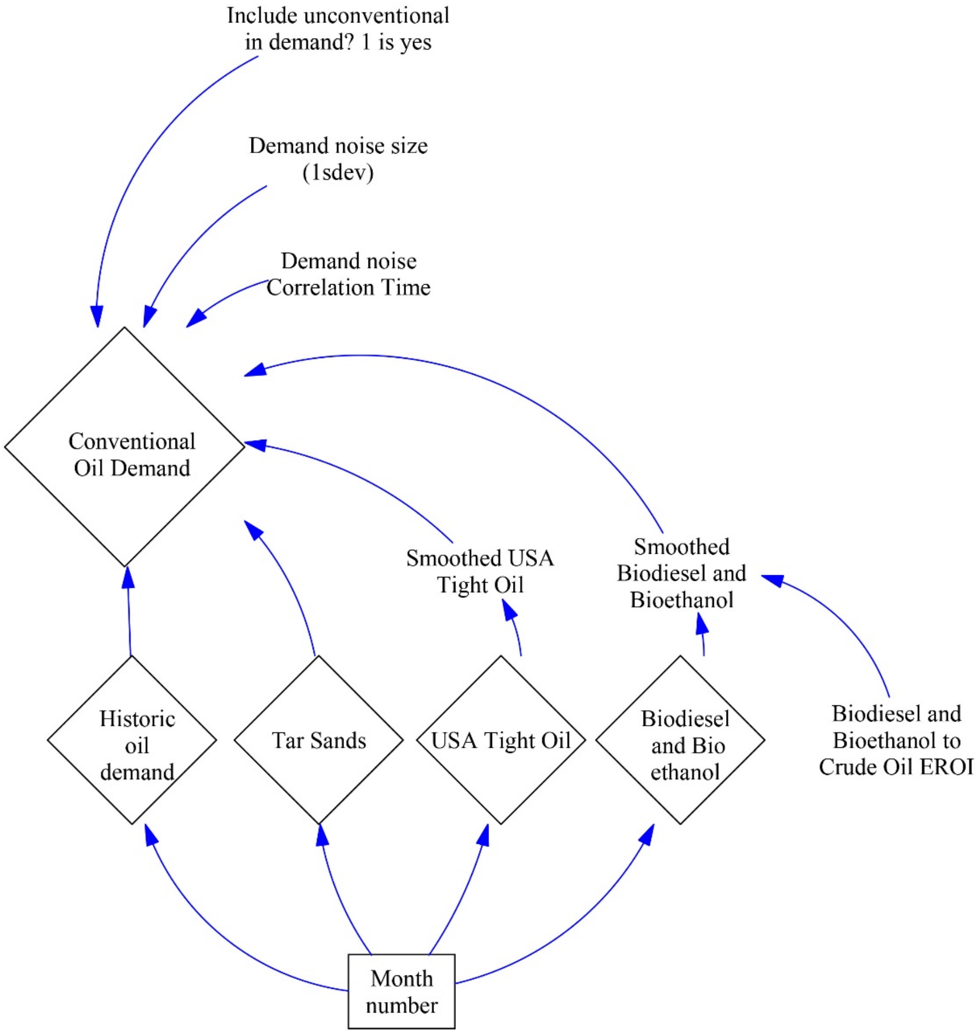

Figure 33:Thesis model sub-module: Exogenous demand and supply.

Table 3: Exogenous demand and supply module parameter values.

Name Include unconventional in demand? 1 is yes	**Type & Sub-type** Constant	**Units**	**Initial**
Equation 1			

Name	Type & Sub-type	Units	Initial
Demand noise size (1sdev)	Constant		
Equation 0			

Name	Type & Sub-type	Units	Initial
Demand noise Correlation Time	Constant		
Equation 12			

Name	Type & Sub-type	Units	Initial
Conventional Oil Demand	Normal	mboe/Month	
Equation IF THEN ELSE("Include unconventional in demand? 1 is yes"=1, RANDOM PINK NOISE(0, "Demand noise size (1sdev)", Demand noise Correlation Time, 1) + Historic oil demand-Smoothed Biodiesel and Bioethanol-Smoothed USA Tight Oil-Tar Sands, RANDOM PINK NOISE(0, "Demand noise size (1sdev)" , Demand noise Correlation Time, 2) +Historic oil demand)			

Name	Type & Sub-type	Units	Initial
Smoothed USA Tight Oil	Normal	mboe/Month	
Equation SMOOTH(USA Tight Oil, 10)			

Name	Type & Sub-type	Units	Initial
Smoothed Biodiesel and Bioethanol	Normal	mboe/Month	
Equation (SMOOTH(Biodiesel and Bioethanol, 10))*Biodiesel and Bioethanol to Crude Oil EROI			

Name	Type & Sub-type	Units	Initial
Historic oil demand	Auxiliary with lookup	mboe/Month	
Equation Month number			
Lookup ([(0,1000)-(600,3500)],(0,1700),(480,3000),(614.679,3390.35))			

Name	Type & Sub-type	Units	Initial
Tar Sands	Auxiliary with lookup	mboe/Month	
Equation Month number			
Lookup ([(0,0)-(480,90)], (0,3) ,(480,90))			

Name	Type & Sub-type	Units	Initial
USA Tight Oil	Auxiliary with lookup	mboe/Month	
Equation Month number			
Lookup ([(0,0)-(600,200)] , (0,0) , (139.2,5.26316), (238,9.64912) , (286.6,19.2982) , (309.4,26.3158) , (347.4,52.6316) , (388.5,149.123) , (397.6,163.158) , (409.7,168.421),(423.4,166.667),(437.1,151.754), (462.4,130.702),(600,122.807))			

Name	Type & Sub-type	Units	Initial
Biodiesel and Bioethanol	Auxiliary with lookup	mboe/Month	
Equation Month number			
Lookup ([(0,0)-(621,100)],(0,3),(230,11),(267.3,15.2632),(290,21),(344.7,38.9912),(399,53.4211),(470,67),(490,67),(621,93.4211))			

Name Month number	Type & Sub-type Level	Units Month	Initial 0
Equation 1			

Investment cycle module.

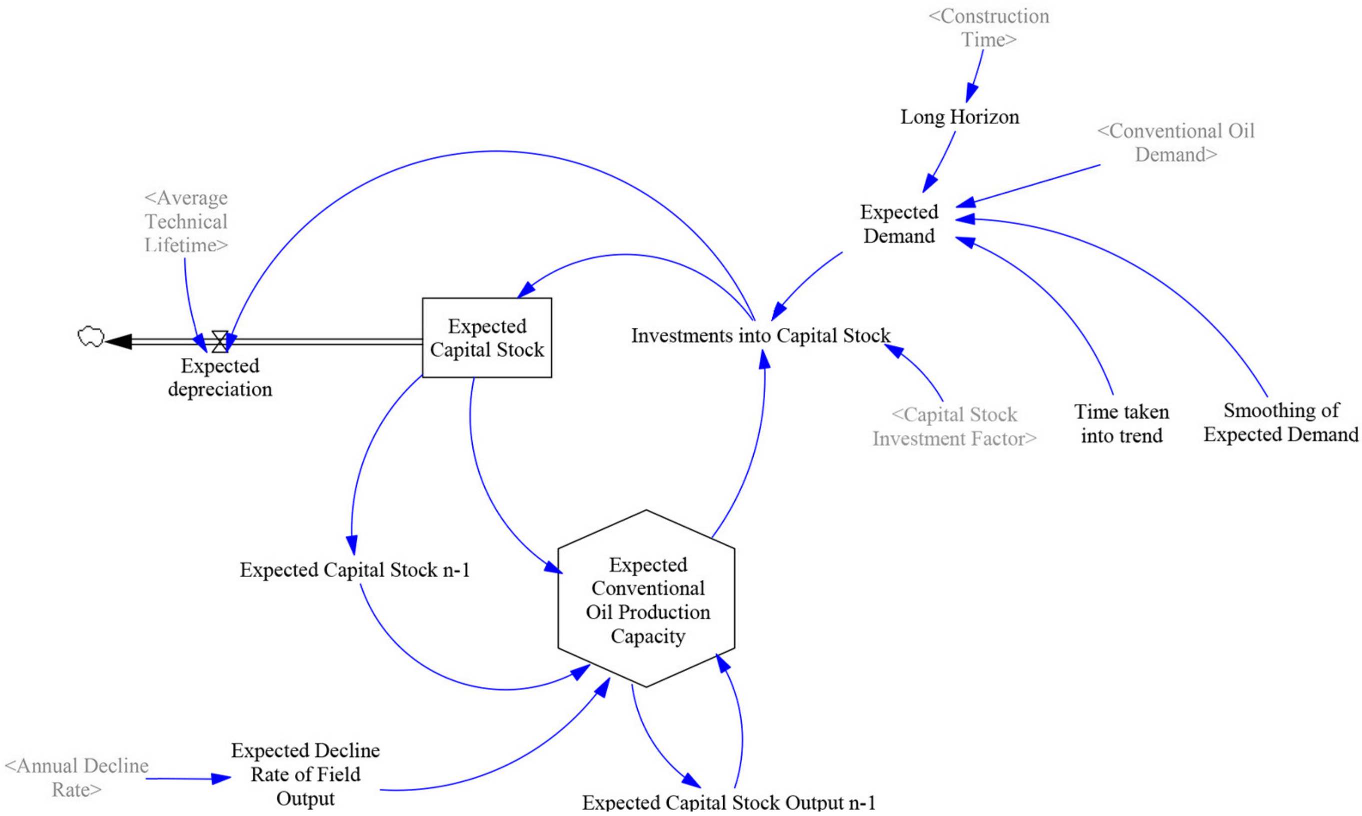

Figure 34: Thesis model sub-module: Capital stock investments.

Table 4: Investment cycle module parameters values.

Name	Type & Sub-type	Units	Initial
Smoothing of Expected Demand	Constant		
Equation 12			
Name Time taken into trend	**Type & Sub-type** Constant	**Units**	**Initial**
Equation 12			
Name Long Horizon	**Type & Sub-type** Auxiliary	**Units**	**Initial**
Equation Construction Time			
Name Expected Demand	**Type & Sub-type** Auxiliary	**Units** Mboe/Month	**Initial**
Equation SMOOTH(FORECAST(Conventional Oil Demand, Time taken into trend , Long Horizon), Smoothing of Expected Demand)			

Name	Type & Sub-type	Units	Initial
Investments into Capital Stock	Auxiliary	Million barrels original capacity	
Equation			
MAX((Expected Demand-Expected Conventional Oil Production Capacity)*Capital Stock Investment Factor, 0)			

Name	Type & Sub-type	Units	Initial
Smoothed Biodiesel and Bioethanol	Normal	mboe/Month	
Equation			
(SMOOTH(Biodiesel and Bioethanol, 10))*Biodiesel and Bioethanol to Crude Oil EROI			

Name	Type & Sub-type	Units	Initial
Expected Capital Stock	Level	Million barrels original capacity	Conventional Oil Demand
Equation			
-Expected depreciation+Investments into Capital Stock			

Name	Type & Sub-type	Units	Initial
Expected depreciation	Auxiliary	mboe/Month	
Equation			
DELAY FIXED(Investments into Capital Stock, Average Technical Lifetime , 0)			

Name	Type & Sub-type	Units	Initial
Expected Capital Stock n-1	Auxiliary	Million barrels original capacity	
Equation			
DELAY FIXED(Expected Capital Stock, 1 , 0)			

Name	Type & Sub-type	Units	Initial
Expected Decline Rate of Field Output	Auxiliary		
Equation			
Annual Decline Rate^(1/12)			

Name	Type & Sub-type	Units	Initial
Expected Conventional Oil Production Capacity	Auxiliary	mboe/Month	
Equation			
IF THEN ELSE("Expected Capital Stock n-1">0,Expected Decline Rate of Field Output*"Expected Capital Stock Output n-1"*(Expected Capital Stock/"Expected Capital Stock n-1") , Expected Capital Stock)			

Name	Type & Sub-type	Units	Initial
Expected Capital Stock Output n-1	Auxiliary	mboe/Month	
Equation			
DELAY FIXED(Expected Conventional Oil Production Capacity, 1 , 0)			

Capital stock & existing fields module.

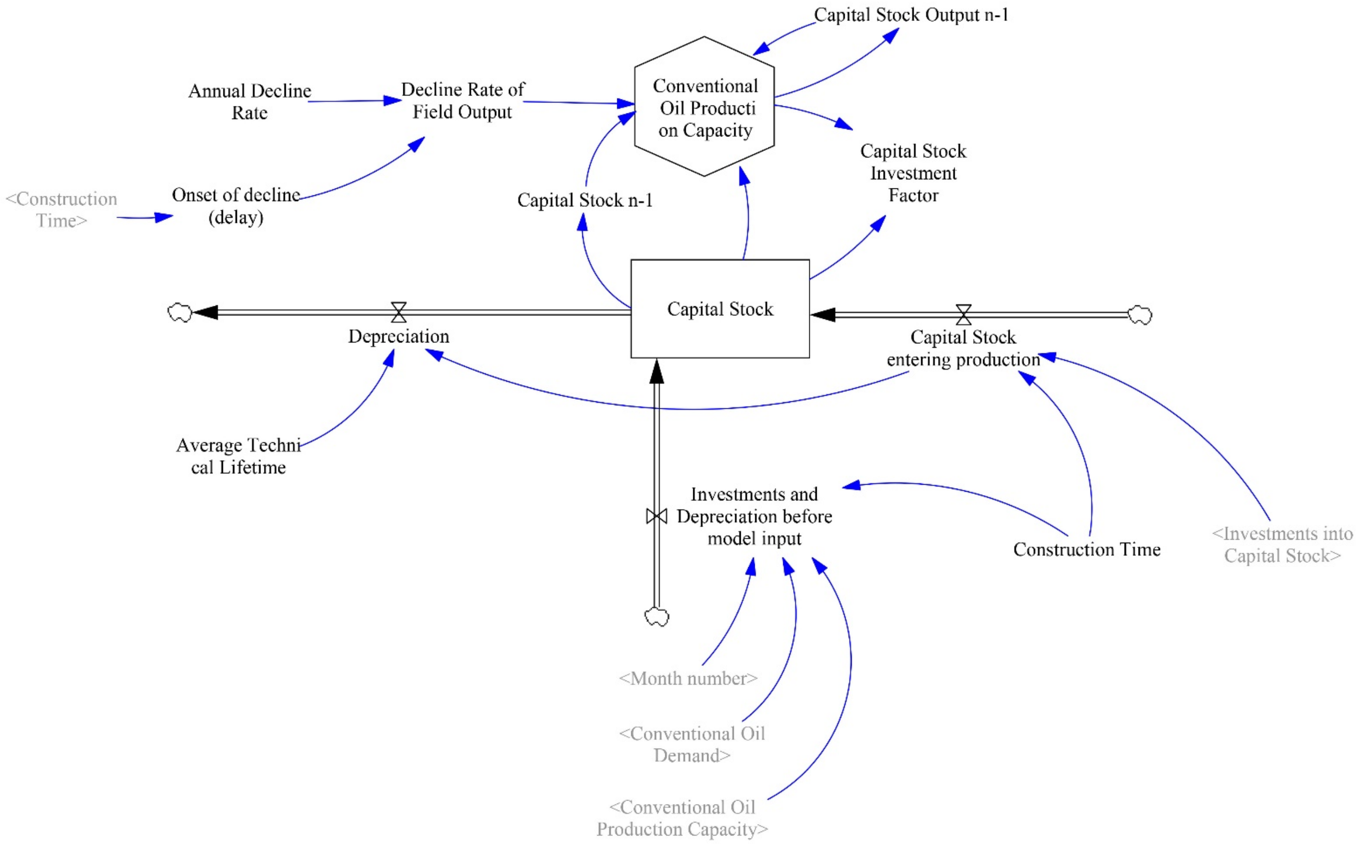

Figure 35: Thesis model sub-module: Capital stock & Existing fields.

Table 5: Capital stock & existing fields module parameter values.

Name	**Type & Sub-type**	**Units**	**Initial**
Investments and Depreciation before model input	Auxiliary	mboe/Month	
Equation IF THEN ELSE(Month number<Construction Time, Conventional Oil Demand-Conventional Oil Production Capacity , 0)			
Name	**Type & Sub-type**	**Units**	**Initial**
Construction Time	Constant	Months	
Equation 60			
Name	**Type & Sub-type**	**Units**	**Initial**
Capital Stock entering production	Auxiliary	mboe/Month	
Equation DELAY3(Investments into Capital Stock, Construction Time)			
Name	**Type & Sub-type**	**Units**	**Initial**
Capital Stock	level	Mboe/Month	Conventional Oil Demand
Equation Capital Stock entering production+Investments and Depreciation before model input-Depreciation			

Name	Type & Sub-type	Units	Initial
Depreciation	Auxiliary	Million barrels original capacity	
Equation DELAY FIXED(Capital Stock entering production, Average Technical Lifetime , 0)			

Name	Type & Sub-type	Units	Initial
Average Technical Lifetime	Constant	Months	
Equation 180			

Name	Type & Sub-type	Units	Initial
Onset of decline (delay)	Auxiliary	Months	
Equation Construction Time			

Name	Type & Sub-type	Units	Initial
Annual Decline Rate	Constant		
Equation 0.94			

Name	Type & Sub-type	Units	Initial
Decline Rate of Field Output	Auxiliary		
Equation DELAY FIXED(Annual Decline Rate^(1/12), "Onset of decline (delay)" , 1)			

Name	Type & Sub-type	Units	Initial
Capital Stock n-1	Auxiliary	mboe/Month	
Equation DELAY FIXED(Capital Stock, 1 , 0)			

Name	Type & Sub-type	Units	Initial
Conventional Oil Production Capacity	Auxiliary	mboe/Month	
Equation IF THEN ELSE("Capital Stock n-1">0, Decline Rate of Field Output*"Capital Stock Output n-1"*(Capital Stock/"Capital Stock n-1") , Capital Stock)			

Name	Type & Sub-type	Units	Initial
Capital Stock Investment Factor	Auxiliary		
Equation Capital Stock/Conventional Oil Production Capacity			

Name	Type & Sub-type	Units	Initial
Capital Stock Output n-1	Auxiliary	mboe/Month	
Equation DELAY FIXED(Conventional Oil Production Capacity, 1 , 0)			

Short term supply adjustments module.

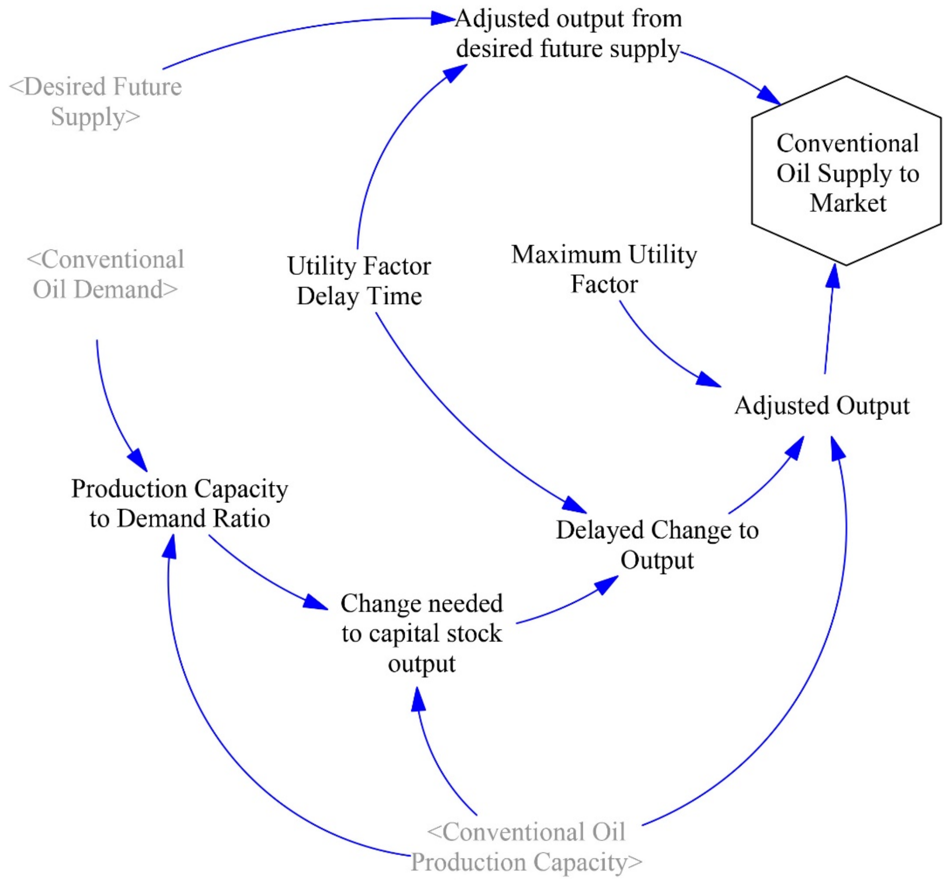

Figure 36: Thesis model sub-module: Short term supply adjustments.

Table 6: Short term supply adjustments module parameter values.

Name	**Type & Sub-type**	**Units**	**Initial**
Production Capacity to Demand Ratio	Auxiliary		
Equation			
Conventional Oil Production Capacity/Conventional Oil Demand			
Name	**Type & Sub-type**	**Units**	**Initial**
Change needed to capital stock output	Auxiliary	mboe/Month	
Equation			
(Conventional Oil Production Capacity/Production Capacity to Demand Ratio)-Conventional Oil Production Capacity			
Name	**Type & Sub-type**	**Units**	**Initial**
Utility Factor Delay Time	Constant	Months	
Equation			
3			
Name	**Type & Sub-type**	**Units**	**Initial**
Delayed Change to Output	Auxiliary	Mboe/Month	Conventional Oil Demand
Equation			
DELAY FIXED(Change needed to capital stock output, Utility Factor Delay Time , 0)			

Name	Type & Sub-type	Units	Initial
Maximum Utility Factor	Constant		
Equation 1.1			

Name	Type & Sub-type	Units	Initial
Adjusted Output	Auxiliary	mboe/Month	
Equation MIN(Delayed Change to Output+Conventional Oil Production Capacity, Conventional Oil Production Capacity *Maximum Utility Factor)			

Name	Type & Sub-type	Units	Initial
Adjusted output from desired future supply	Auxiliary	mboe/Month	
Equation DELAY FIXED(Desired Future Supply, Utility Factor Delay Time , Conventional Oil Demand)			

Name	Type & Sub-type	Units	Initial
Conventional Oil Supply to Market	Auxiliary	mboe/Month	
Equation IF THEN ELSE(Adjusted Output>Adjusted output from desired future supply, Adjusted Output , Adjusted output from desired future supply)			

Exploration module.

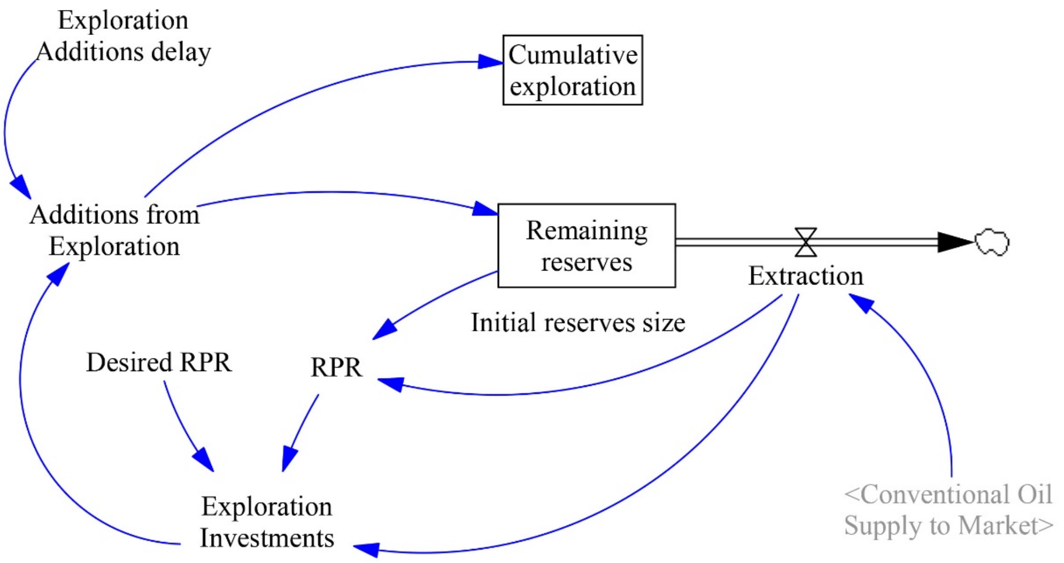

Figure 37: Thesis model sub-module: Exploration.

Table 7: Exploration module parameter values.

Name	Type & Sub-type	Units	Initial
Name Exploration Additions delay	**Type & Sub-type** Constant	**Units** Months	**Initial**
Equation 12			
Name Additions from Exploration	**Type & Sub-type** Auxiliary	**Units** Million barrels	**Initial**
Equation DELAY3(Exploration Investments, Exploration Additions delay)			
Name Cumulative exploration	**Type & Sub-type** Level	**Units** Million barrels	**Initial** 0
Equation Additions from Exploration			
Name Desired RPR	**Type & Sub-type** Constant	**Units**	**Initial**
Equation 22			
Name RPR	**Type & Sub-type** Auxiliary	**Units**	**Initial**
Equation (Remaining reserves/Extraction)/12			
Name Exploration Investments	**Type & Sub-type** Auxiliary	**Units** Millions of barrels	**Initial**
Equation Extraction^(Desired RPR/RPR)			
Name Extraction	**Type & Sub-type** Auxiliary	**Units** mboe/Month	**Initial**
Equation Conventional Oil Supply to Market			
Name Initial reserves size	**Type & Sub-type** Constant	**Units** Millions of barrels	**Initial**
Equation 650000			
Name Remaining reserves	**Type & Sub-type** Level	**Units** Millions of barrels	**Initial** Initial reserves size
Equation -Extraction+Additions from Exploration			

Costs module.

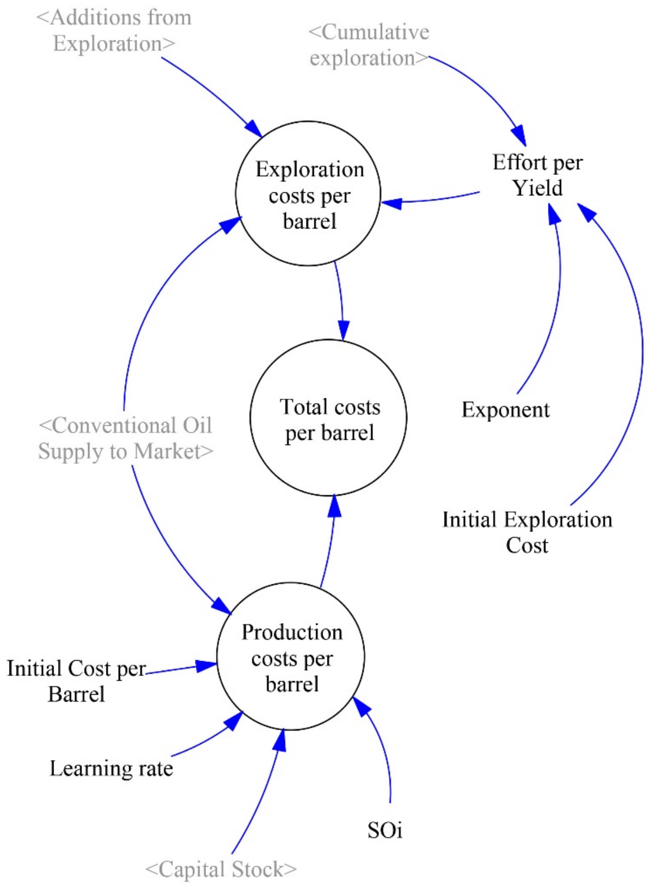

Figure 38: Thesis model sub-module: Costs.

Table 8: Costs module parameter values.

Name	**Type & Sub-type**	**Units**	**Initial**
Exploration costs per barrel	Auxiliary	$/Barrel	
Equation (Additions from Exploration*Effort per Yield)/Conventional Oil Supply to Market			
Name Effort per Yield	**Type & Sub-type** Auxiliary	**Units** $/Barrel	**Initial**
Equation Initial Exploration Cost*EXP(Exponent*(Cumulative exploration/10000))			
Name Exponent	**Type & Sub-type** Constant	**Units**	**Initial**
Equation 0.031			
Name Total costs per barrel	**Type & Sub-type** Auxiliary	**Units** $/Barrel	**Initial**
Equation Exploration costs per barrel+Production costs per barrel			

Name Production costs per barrel	**Type & Sub-type** Auxiliary	**Units** $/Barrel	**Initial**
Equation (Initial Cost per Barrel*(Conventional Oil Supply to Market/SOi)^(LN(Learning rate)/LN(2)))*(Capital Stock/Conventional Oil Supply to Market)			
Name Initial Cost per Barrel	**Type & Sub-type** Auxiliary	**Units** $/Barrel	**Initial**
Equation 10			
Name SOi	**Type & Sub-type** Initial	**Units** Million barrels original capacity	**Initial**
Equation Capital Stock			

Price formation module.

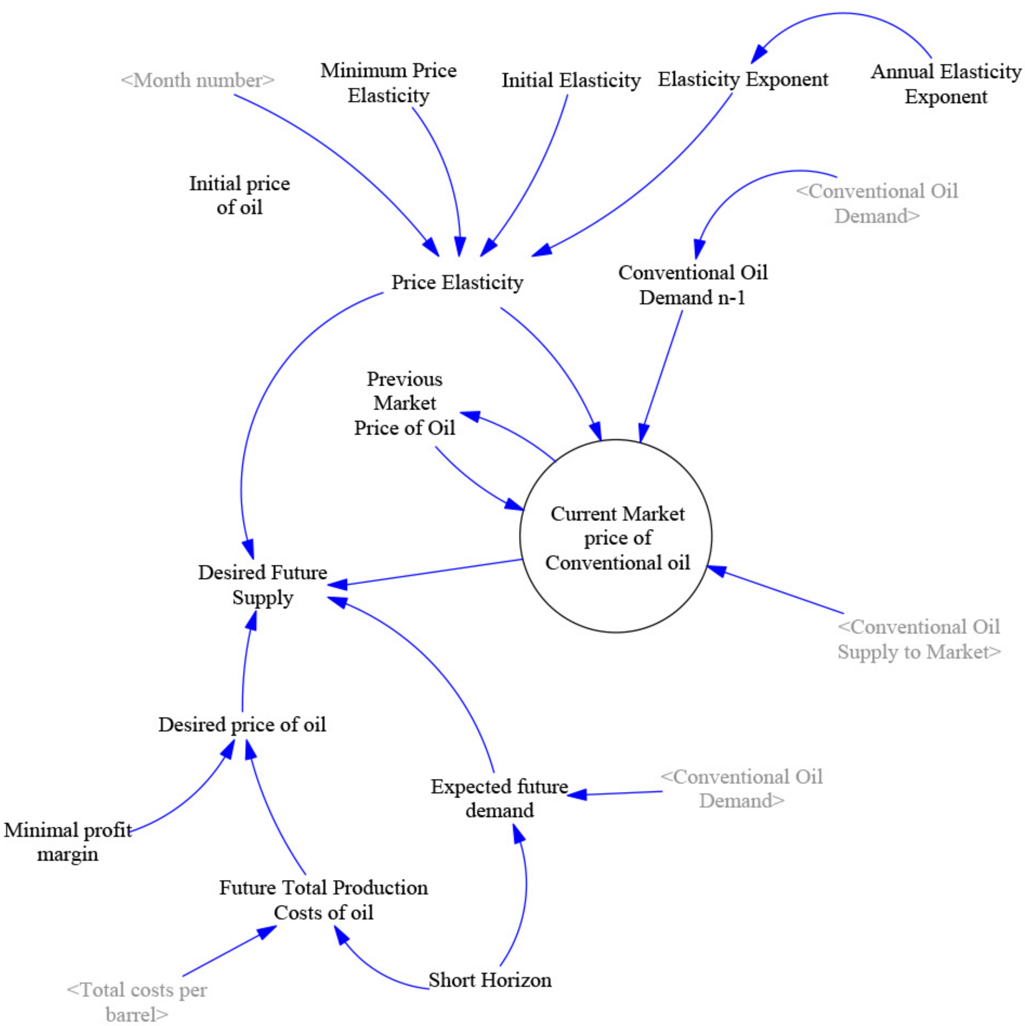

Figure 39: Thesis model sub-module: Price formation.

Table 9: Price formation module parameter values.

Name Annual Elasticity Exponent	**Type & Sub-type** Constant	**Units**	**Initial**
Equation 0.92			
Name Elasticity Exponent	**Type & Sub-type** Auxiliary	**Units**	**Initial**
Equation Annual Elasticity Exponent^(1/12)			
Name Initial Elasticity	**Type & Sub-type** Constant	**Units**	**Initial**
Equation 2			
Name Minimum Price Elasticity	**Type & Sub-type** Constant	**Units**	**Initial**
Equation 0			
Name Production costs per barrel	**Type & Sub-type** Auxiliary	**Units** $/Barrel	**Initial**
Equation (Initial Cost per Barrel*(Conventional Oil Supply to Market/SOi)^(LN(Learning rate)/LN(2)))*(Capital Stock/Conventional Oil Supply to Market)			
Name Initial Cost per Barrel	**Type & Sub-type** Auxiliary	**Units** $/Barrel	**Initial**
Equation 10			
Name Initial price of oil	**Type & Sub-type** Constant	**Units** $/Barrel	**Initial**
Equation 25			
Name Price Elasticity	**Type & Sub-type** Auxiliary	**Units**	**Initial**
Equation MAX(Initial Elasticity*(Elasticity Exponent^Month number), Minimum Price Elasticity)			
Name Conventional Oil Demand n-1	**Type & Sub-type** Auxiliary	**Units** mboe/Month	**Initial**
Equation DELAY FIXED(Conventional Oil Demand , 1 , Conventional Oil Demand)			
Name Previous Market Price of Oil	**Type & Sub-type** Auxiliary	**Units** $/Barrel	**Initial**
Equation DELAY FIXED(Current Market price of Conventional oil, 1 , Initial price of oil)			
Name Current Market price of Conventional oil	**Type & Sub-type** Auxiliary	**Units** $/Barrel	**Initial**
Equation			

Previous Market Price of Oil+(((Conventional Oil Supply to Market-"Conventional Oil Demand n-1")/"Conventional Oil Demand n-1")/Price Elasticity)*Previous Market Price of Oil			
Name Desired Future Supply	**Type & Sub-type** Auxiliary	**Units** mboe/Month	**Initial**
Equation ((Desired price of oil/Current Market price of Conventional oil)*Price Elasticity)+Expected future demand			
Name Desired price of oil	**Type & Sub-type** Auxiliary	**Units** $/Barrel	**Initial**
Equation Minimal profit margin+Future Total Production Costs of oil			
Name Minimal profit margin	**Type & Sub-type** Constant	**Units** $/Barrel	**Initial**
Equation 13			
Name Future Total Production Costs of oil	**Type & Sub-type** Auxiliary	**Units** $/Barrel	**Initial**
Equation FORECAST(Total costs per barrel, 4 , Short Horizon)			
Name Short Horizon	**Type & Sub-type** Constant	**Units** Months	**Initial**
Equation 2			
Name Expected future demand	**Type & Sub-type** Auxiliary	**Units** mboe/Month	**Initial**
Equation FORECAST(Conventional Oil Demand, 1 , Short Horizon)			