MSc Program
Renewable Energy in Central & Eastern Europe

Peak Oil and Growth.

The challenges and opportunities posed by the finite character of the fossil fuels to the world economic order.

Master's Thesis submitted for the degree of
"Master of Science"

supervised by
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Affidavit

I, **Daniel Olev**, hereby declare

1. that I am the sole author of the present Master Thesis, "Peak Oil and Growth. The challenges and opportunities posed by the finite character of the fossil fuels to the world economic order.",
85 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master Thesis as an examination paper in any form in Austria or abroad.

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Date Signature

Abstract

Did you know that, if all oil, consumed in 2011, to put on one train,
its tail will encompass the earth equator almost 17 times,
making it 85 meters wide steel belt of 120 tone cistern cars.
Author, (BP, 2012)

In this work I have tried to demonstrate the fundamental difficulties our society faces as we are confronted by the imperative to transition our economy to low carbon future. I have specifically concentrated on the energy component of the economy as a creation source behind the production of goods and services. Oil in particular is on the top of the list in the table of primary energy providers as "enabling" and "connecting" fuel due to its universality in the use of the internal combustion engines designed to drive our machinery around the globe.

Given the finite nature of fossil deposits in the core of our planet and more or less accepted in scientific community fact that we have reached the maximum extraction rates of easy to find, produce and refine oil, as well as taking on board the fact that it is almost for certain that continuous usage of carbohydrates as a main source of energy can irrevocably destroy the fine natural balance of gases in our atmosphere I have tried to show the list of the open questions and the scope of the problems, faced by our civilization in efforts to address them.

Particular attention was paid to energy balance, also known as energy return on energy invested (EROEI or EROI), which determines net energy available for the society to use at its discretion. Albeit not a new idea – the concept does back 50 years and could be found in the works of economist Kenneth Boulding and ecologist Howard Odum, it was finally formulated in the works of economist Cutler J. Cleveland and professor Charles J Hall (Murphy & Hall, 2010). Although of a great importance in understanding and evaluating current and prospective technologies, very little data and scientific work exists up to now on correct accounting procedures for determining EROIE and its boundaries. This fact is changing now, in part thanks to realization from holistic school of economics that the travel down right side of the Hubbert curve will have to use different system of coordinates in comparison with left, ascending side.

Acknowledgments

I am sincerely grateful to the CEC team of the TU Wien for organising and letting me to take part in the “RECEE” MSc Program, as well as supporting me through the whole process of knowledge acquisition.

Special “thank you” goes to Professor Reinhard Haas for his courage, sincerity and guidance in helping me to choose, formulate and develop the subject of this work.

I am also in debt to Ms. Andrea Würz and Ms. Petra Aigner for offering me their help, when I most needed it.

I have to mention my wife, Jutta Olev, whose measured mix of carrots and sticks provided necessary encouragement for me to complete the whole project. It would not have been possible without you!
I am grateful to her for singlehandedly raising our two children during the last 40 or so weekends, it took me to finish this Thesis.

Thank you to all who encouraged me to start this education and to see it to the end!

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List of Acronyms

ASPO - The Association for the study of Peak Oil&Gas
BAU - Business as Usual (Refers to current state of affairs, status quo, without implementation of any structural changes)
BEV - Battery electric vehicles
BGR - Bundesanstalt für Geowissenschaften und Rohstoffe
BP - British Petroleum
CASSE - Centre for the Advancement of the Steady State Economy
CCS - carbon capture and storage
CGES - Centre for Global Energy Studies
CNG - compressed natural gas
CO2 - carbon dioxyde
CO2eq. - carbon dioxyde equivalent
CTL - coal-to-liquid synthetic fuel
DCL - direct coal liquefaction
DOE - Department of Energy of the United States Government
EIA - Energy Information Administration
ELM - Export Land Model
EOR - enhanced oil recovery
EROEI (also EROI) - Energy Return on Energy Investment
EU - European Union
FT - Fischer-Tropsch synthesis
GDP - Gross Domestic Product
GHG - Greenhouse Gas
GNE - Global Net Export
Gt - gigatonns (10^12 kg)
GTL - gas-to-liquid synthetic fuel
HEC - Hautes Etudes Commerciales
ICE - internal combustion engines
ICL - indirect coal liquefaction
IEA - International Energy Agency
IEO - International Energy Outlook
IGCC - Integrated Gasification Combine Cycle plant
IMF - International Monetary Fund
IPCC - Intergovernmental Panel on Climate Change
Jodi - Joint Organisations Data Initiative
kb/d - kilobarrels per day
LCA - Life Cycle Analysis
LNG - liquified natural gas
LPG - liquified petrolium gas
mb/d - million barrels per day
mtoe - million tones of oil equivalent
NEF - New Economic Foundation
NETL - National Energy Technology Laboratory
NGL - natural gas liquids

NOE -Net Oil Exports
NPC - National Petroleum Council
NPS - New Policies Scenario
ODAC - The Oil Depletion Analysis Centre
OECD - Organisation for Economic Co-operation and Development
ppm - parts per million
RECEE - MSc Course "Renewable Energy in Central and Eastern Europe" at TU Wien
SA - South Africa
TAG - triacylglycerol
toe - tones of oil equivalent
TTI - Transition Town Initiative
TU Wien - Technological University of Vienna
UCTE - Union for the Coordination of the Transmission of Electricity
UNECE - United Nations Economic Commission for Europe
USA - the United States of America
USGS - United States Geological Survey
WEO - World Energy Outlook
WTW - well-to-wheel
WW1 - The First World War
WW2 - The Second World War

1. Introduction

1.1 Motivation

Shortly before and during my studies in TU Wien I became first interested and then involved in Transition Town/Eco-village movement. This social phenomenon has in its roots permaculture design approach to life organization in response to three largest challenges modern civilization faces: growing consumption of finite resources and their possible peak - oil in particular, climate change and lately economic contraction/sovereign debt crisis. Permaculture Movement has itself started out as an alternative response to BAU during and after 70s oil crisis.
This interest has brought me to the RECEE course in TU of Vienna where I could learn more about alternative (to fossil fuel) energy carriers – so called “renewables” and where I was introduced to energy economics and EU Member States policies on that matter. Parallel I continued to investigate this topic, borrowing my knowledge heavily form Internet resources, such as oildrum.com, Post Carbon Institute (www.postcarbon.org), Energy Bulletin (www.energybulletin.net) as well as looking at alternative economic models proposed by Herman Daly and others through CASSE (www.steadystate.org), by contributors at gaianeconomics.org and by Richard Douthwaite from the Foundation for the Economics of Sustainability (www.feasta.org).
With the curiosity of uninformed child I tackled this wealth of information and through my unbiased analytical ability – I have no internal affiliation (at least before I started this process) with either the technocratic or with the holistic approach to the matter – I have managed to chisel out this core problem that is stated above in the headline.

1.2 Aim and objective

The main task of this work is to find out how the modern economy can manage the timely infrastructural and systemic transition from its build-in dependency on the finite resources for *transportation, heat and electricity* generation to provision of these vital utility services from alternative forms of energy, such as *wind, solar, geothermal, hydro and biomass*.
I am particularly interested to investigate how economic growth model upon which our world financial system is relied will be affected when world economic

development faces constrains caused by energy/price demands levied onto national economies by finite character of fossil fuels’ origin.

Finally, I want to address the limitations imposed on the process of transition by IPCC acknowledgment of imperative to stay below 450ppm in atmospheric concentration of $CO_{2\text{-eq.}}$ gases to avert dangerous consequences of climate change.

In conclusion I will try to assess if the top-down strategic actions of various governmental organizations can provide an adequate answer to transition imperative or if bottom-up local initiatives, such as TTI Movement, have more chances in building up local resilience and in preparing a flexible response to the near term problem of economic and cultural shift to green economy and sustainable future.

1.3 Citation of main literature

Databases, tables and graphs from research papers published by the following organisations:

IEA WEO Report Data, CGES, ASPO, DOE NETL Report 2007, ODAC, Jodi, BP Crude Oil Data 2010/2012, BP Statistical Review of World Energy 2010/2012, *Shell Oil Co. Reports, USGS.*

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Stern N.: *"Stern Review on the Economics of Climate Change*”, Executive Summary. Cambridge University Press, London, 2006

William R. Catton, *"Overshoot".* First Illinois, Chicago, 1982

Various **articles** from the following **scientific journals**:

Energy; Energy Policy; Energy Economics; Ecological Modelling and some other.

1.4 Structure of work

The opening part of the work will have a look at the share of oil in the total world primary energy mix and its important role in the global economy as enabler of most extraction and production processes. As the largest share of total oil consumption belongs to the transportation sector, this will be given a special attention.

Secondly, the oil trade market will be described and its plausible development during possible constrain in supply assessed. With the help of The Export Land Model (ELM) developed by Jeffrey J. Brown and Samuel Foucher, special accent will be given to the security of supply as the result of the dropping net exports.

The last part of this chapter will be answering the question “Will the peak in oil discoveries lead to peak oil in production?”, making a bridge to the following chapter, concerning the theory of peak oil and its various aspects, like timing and methodology.

Chapter six will then touch upon the connection between the energy, and oil in particular, and its ability to feed the economic growth. The correlation between low EROIE, high oil prices and economic dynamics is the focus of this part of the Thesis.

Chapter seven will introduce the second important core of this work by having a look at the existing substitutes for the oil technological function – both fossil and renewable – as well as different technologies available now and in the near future to help in compensating for the possible decline in supply. These technologies will be assessed from economic, environmental and most importantly – energetic points of view.

In chapter eight the above discussed information will be summarised and tied into the matrix of possible scenarios, one of which will be looked at in more detail. The dangers and opportunities will be listed and discussed with special attention given to EROIE and GHG emissions.

In conclusion possible adoption strategies will be listed and further discussion points highlighted.

2. Background

The history of human development is inextricably connected with common to all live beings strategy “of maximizing energy returns by minimizing inputs”. Humans did it by systematic technological adaptations passed through to the next generations via direct interactive communication. Ability to speak and later record speech, so unique in animal kingdom, gave us an advantage of building upon successful discoveries.

And so it ran: starting with taming the fire, inventing the wheel, through to Watt’s steam engine - thousands of years of human evolution landed us on the beach of The Industrial Revolution, some call it “Fossil Fuels Revolution” in 18th century. Using coal for heating the steam to drive these first industrial replacers of muscle power, human race began the era of industrialized fossil fuel extraction. The economic advantage of such production means over costly human/animal labour was very soon obvious with steam engines and then internal combustion engines (ICE) forcing a sharp decline in the use of the horses (**Fig 2.1.**) by the beginning of the 20th century.

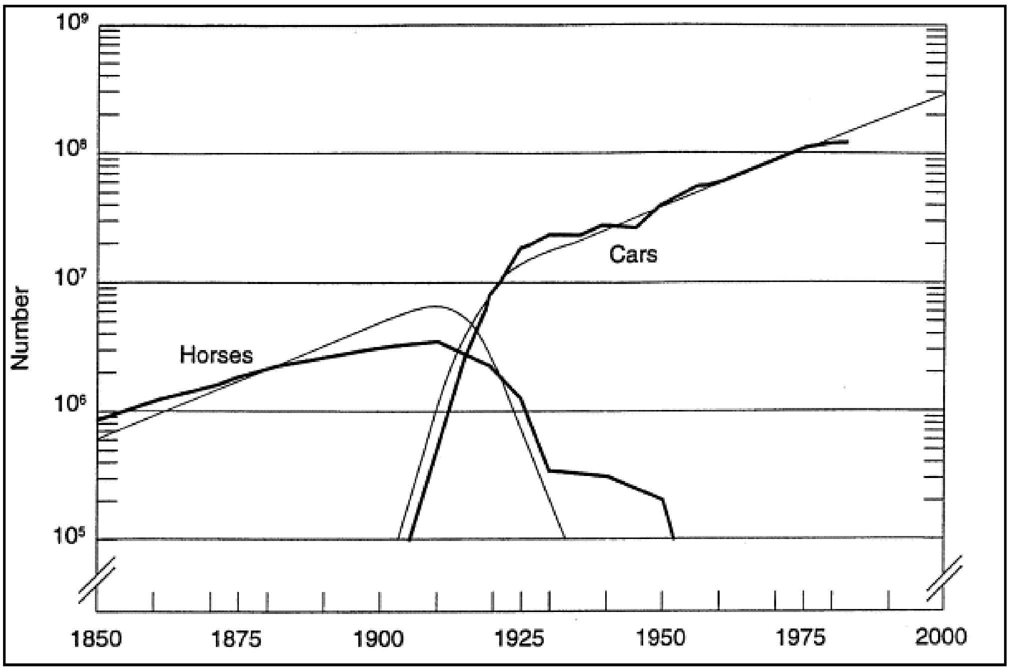

Figure 2.1.: Relative decline in the use of horses vs. cars in transportation. (Grübler A., 1999)

However any resource, when it is used above its naturally occurring replenishment rate, will soon be depleted as inhabitants of Easter Island infamously found out. As for coal, as well as oil and gas, their replenishment rate is very low, taking millions of years and requiring the right climatic and geological conditions. In this sense these fossil materials, plus all other metal and minerals, are considered to be finite resources and their extraction pattern always at the end can be described by a bell shaped curve at the top of which is the peak extraction/production point (**Fig. 2.2.).**

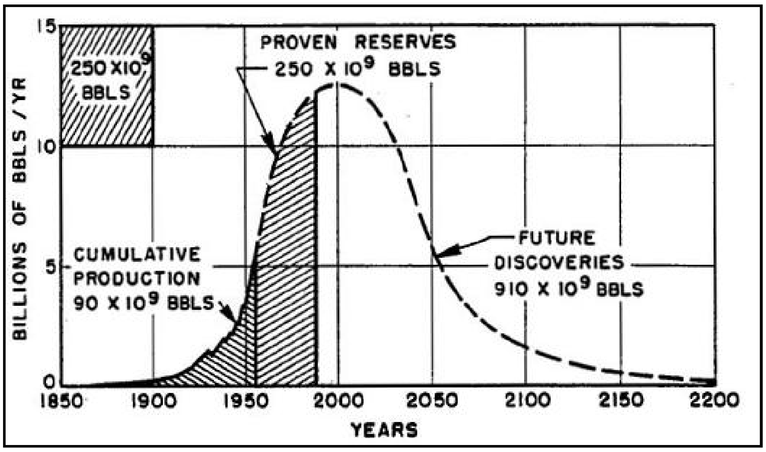

Figure 2.2.: Hubbert’s Peak. (Hubbert M. K., 1956)

England in turn discovered its coal peak in early 20th century, when coal production there hit the largest amount (1913) and begun its slow decline, owing to rising costs as the “low hanging fruit” had already been picked up or rather picked out (**Fig. 2.3.**)

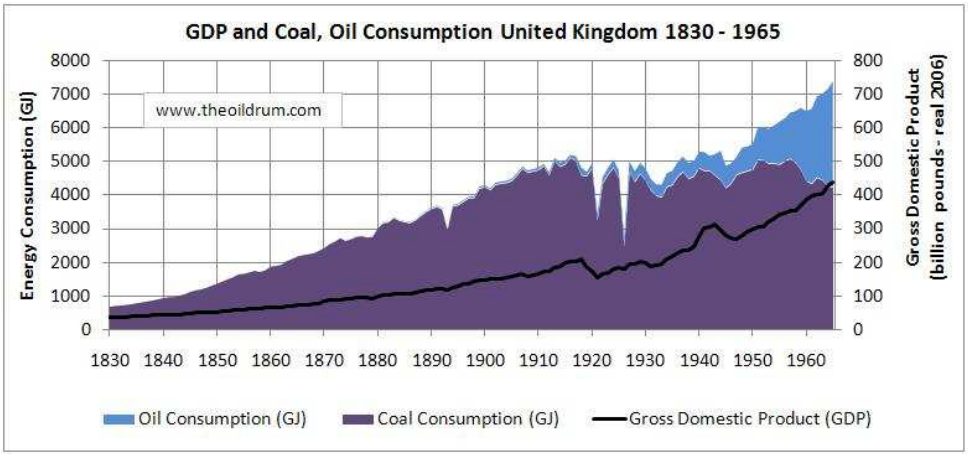

Figure 2.3.: British Coal and Oil Consumption and GDP 1830 - 1965. (Koppelaar, 2011)

There were other factors at play at that time, to be fair, such as economic depression between WW1 and WW2, oversupply and competition issues, efficiency of use, but the single and arguably the most important among them was the replacement of coal by oil as primary energy carrier, first adopted by Royal Navy after the WW1 and then by wider economy after the Second World War (see **Fig. 2.3.**) (Koppelaar, 2011).

The versatility of the oil as an energy carrier – energy density, ease of transportation at ambient temperatures, initially high Energy Return on Energy Investment (EROEI) at 100:1, meaning that in 1930-s, at the beginning of extraction boom in the USA the energy of one barrel of oil invested into production redeemed 100 barrels back - has soon became apparent and the world wide race in exploration and extraction began (**Fig. 2.4.**):

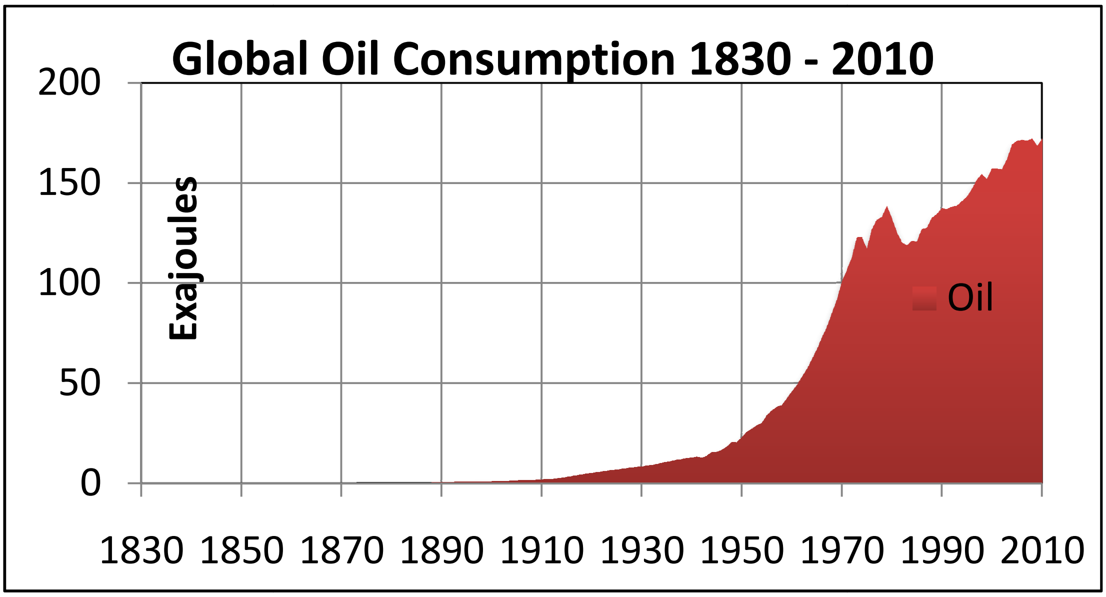

Figure 2.4.: Worldwide oil consumption. (Adopted from Smil, 2010)

The availability of such "rich" energy source, relative ease of its extraction fuelled post-war economic boom, giving birth to industrialized consumer societies in OECD countries, helping to create debt driven financial system and allowing people in these countries to pursue life style we - in Europe - enjoy today.

However, as mentioned before, oil is a finite resource and on planetary scale we are inevitably bound to repeat the same pattern of evens as England experienced with its coal in the first quarter of 20th century[1].

The strong believe in human ingenious and trust in science and technology that almost reached the religious status in modern society, both fuel the race that began the search for the viable alternative. This work is an attempt to have a look at fundamentals working at hand and to show the options human race has within the given period of time and economic, environmental and technological frames.

[1] IEA World Energy Outlook Report (2010) has all but in name admitted that conventional oil production had peaked in 2006, p. 101.

3. Method of approach

In approaching the main question the following logical method was applied:

- Discovery of reach energy sources matched with the technological advances fed the industrial revolution and gave birth to the industrialized society as we know it at least in the Northern Hemisphere.
- Abundance of easy to extract oil allowed this low entropy resource to provide necessary exergy to form a base for modern consumer-driven economy.
- Constant growth in high EROI energy use allowed almost permanent growth in economic output, which in turn induced the design of financial system underpinning this economic activity through fiat currencies and debt creation.
- If Hubbert got it right – and there few who argue with him on principle - at some point the energy demand driven by population growth, wealth creation and technology will come against the physical and economic/energetic constrains to the extraction of the necessary amounts of fossil primary energy carriers. This conflict will have serious consequences on the ability of the further economic growth, resulting in the inability of current financial system to function properly.
- Following financial contraction and, as the result of it, forced redesign of the economic model could and will lead to series of negative feedbacks, dismantling the first initial successes in building the renewable energy infrastructure. Without the willingness to pay for increasingly expensive – both in financial and energetic terms – oil, the shortage of the additionally necessary energy could make it impossible to achieve meaningful transition to stable “green economy” within given period of time.
- This could lead to short term solutions in search for substitutions within known resources: coal, gas, uranium. This path of actions when coupled with forced neglect to pay attention to climate change mitigation and multiplied by effects of stockpiling and resource nationalism, could very soon bring the undesirable results, fracturing the current world order.
- In order to avoid meeting these results in reality, human race has to come up with intelligent solution, accepted unanimously across the geographical, racial, ethnic, religious and class divides. This solution has to first and foremost accept the status quo as unsustainable and determine the future

path of human development within the ecological constrains of the earth ecosystem.

- The time available for the mindset change and the search for the global solution is under the circumstances described above is a critical factor. By using the available references in recent scientific publications to determine probable range of the peak oil date.
- Using the commonly used and accepted in scientific community databases to build plausible scenario(s) in oil production/consumption ratio.
- To determine the time frame and the options currently available within the proven technologies to mitigate the shortfall.
- Evaluate the results and discuss the possible outcomes.

4. Oil and World Economy

4.1. Oil is lifeblood of economic growth

The importance of oil as a single most valuable – in terms of trade[2] and technology enabler - component in literally fuelling last century economic development is difficult to overestimate (**Fig 4.1.**).

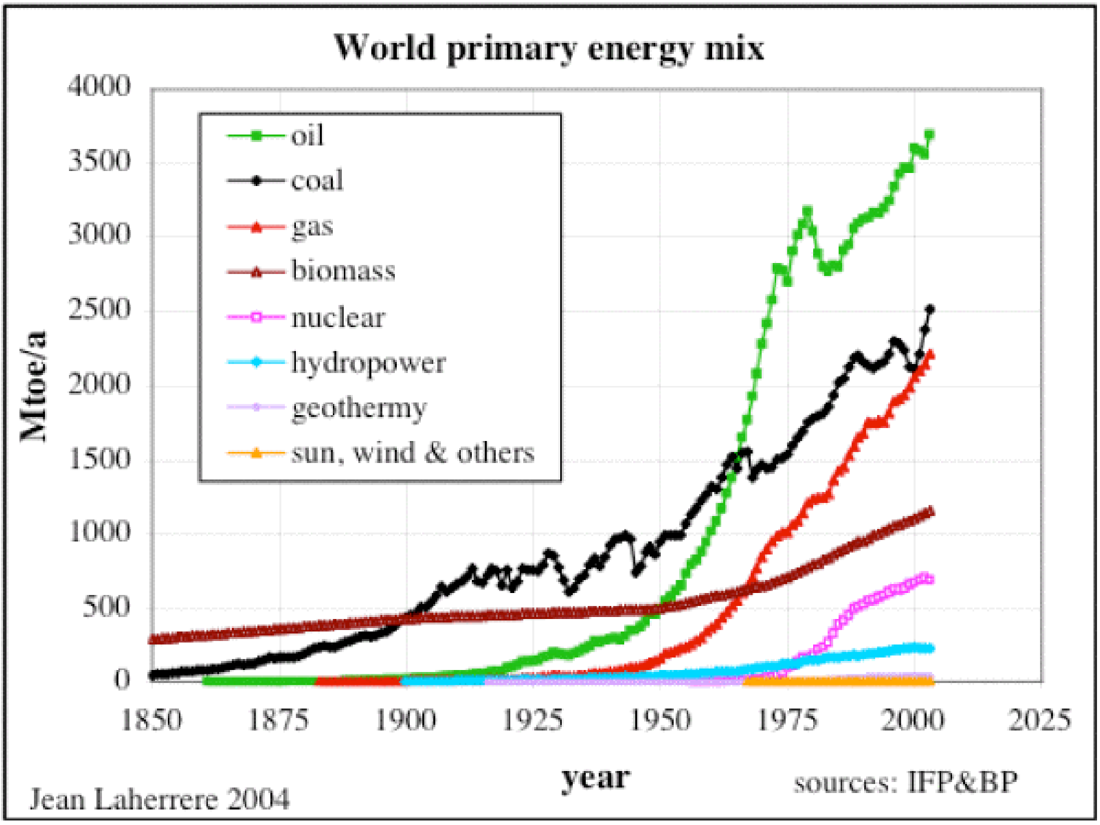

Figure 4.1. World primary energy mix. (Laherrere J. , 2004)

Results of its use penetrate all aspects of human economic life. It gave life to petro-chemical industry, which direct and indirect products envelope our existence from food and drugs to clothes and furniture production. It is still used to heat homes and businesses and to produce some electricity, although these two segments represent less than 10% of the total use and are showing continuous tendency to decrease[3].

[2] „Oil is the world's single largest traded commodity, accounting for over half the total value of all commodity transactions." (ODAC, 2011)

[3] Comparing IEA Reports "Key World Energy Statistics" for 2009 and 2011 shows currently 0.3% yearly drop in this sector and half of what it was in 1973. (IEA, 2011) (IEA, 2009)

Oil major use is attributed to transportation sector with over 53% worldwide (IEA, 2010) and nearly 70% for such heavy users as USA (**Fig. 4.2.**):

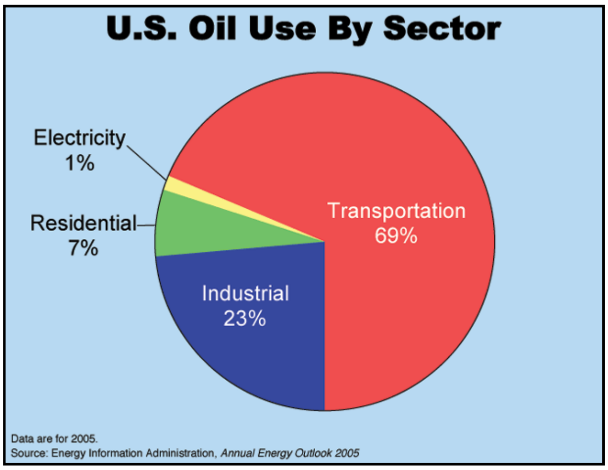

Figure 4.2. Oil use by sector. Source: (DOE/EIA, 2005)

Initial ease of extraction and wide availability of this unique in energy density fuel source[4] gave the world economy enough power to provide nearly constant growth for the last 50 years. It enabled mass mechanization of agricultural production, reducing human involvement from 40% of the total of population in the beginning of the century to less than 1% now in the USA (U.S. Environmental Protection Agency, 2012). It facilitated globalization of trade in goods and services, creating modern economy with complex networks of just-in-time delivery. At the end of the day it underpinned the growth that allowed the creation of the current international financial system.

4.2. Transport

In 1859 Edwin Drake’s opening of the production at his first oil well in Pennsylvania gave birth to the oil industry. J.D. Rockefeller’s Standard Oil, inventions of the internal combustion engines by Nikolaus August Otto in 1876 and Rudolph Diesel in 1893 and Henry Ford’s car manufacturing business shaped the world modern transportation system as we know it today. In 2010 there were over 2100 Mtoe refined and burned in combustion engines around the world, representing 53% of total oil consumption (IEA, 2010). With estimation of vehicle stock to more than double to over to 2 billion by 2030 (Dargay, Dermot, & Sommer, 2007) - developing

[4] To be precise, uranium atoms have much higher energy density per kg., but are not so easy to extract, enrich and transport.

countries driving demand[5] - IEA projects the additional growth in oil demand in its “New Policy Scenario” to over 15 mb/d by 2035 (**Fig 4.3.**). That is under assumption of 1.8% annual growth, whereas historically (1960-2002) the growth was 4.6% (Dargay, Dermot, & Sommer, 2007).

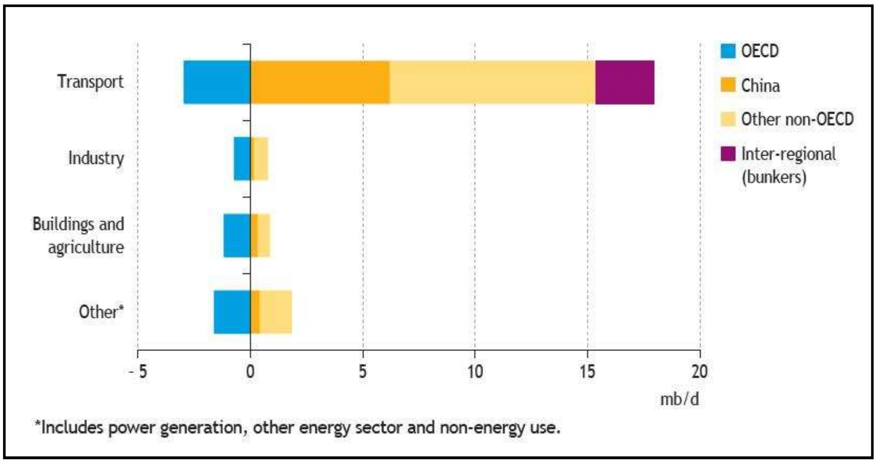

Figure 4.3.: Change in primary oil demand by sector and region in New Policies Scenario, 2009-2035[6]

Currently 23% demand of all oil-based fuels is taken up by heavy freight traffic, which is projected to go up another 5% by 2035 (**Fig. 4.4.**).

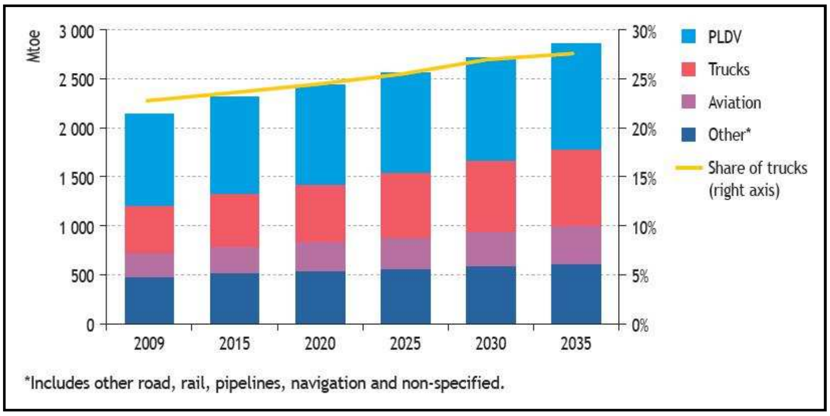

Figure 4.4.: Transport oil consumption by type in New Policies Scenario[7]

If all this increase can be converted to use of CNG this will help to save additional 0.6 mb/d.

The steady growth of 2.1% in aviation use will help to push its share in fuel demand from 12% in 2009 to 14% of total in 2035, driven mainly (**Fig. 4.5.**) by non-OECD countries.[8]

[5] According to IEA *World Energy Outlook 2010* China overtook USA in 2009 as the world largest car market with 13.9 million new car sales, (IEA, 2010) page 106.

[6] Ibid., p.106.

[7] Ibid., page 107.

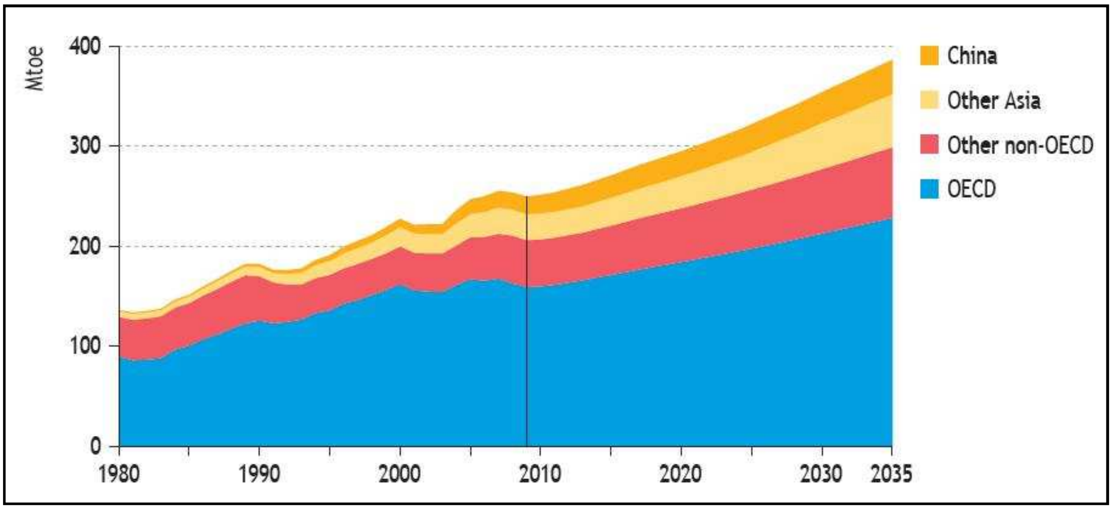

Figure 4.5.: Aviation oil consumption by region. (Source: IEA WEO 2010)

Although there are attempts in the aviation industry to experiment with biofuels (Oils & Fats International, 2012), this technology is not expected to break through the monopoly of kerosene as the main final energy source for jet engines in the foreseeable future to a significant extend.

4.3. Electricity

Using oil as a fuel for electricity generation has shown steady decline since First Oil shocks in 1970-s and this tendency is not expected to change as more and more efficient gas and coal power generators replace oil burners everywhere apart from Middle East. In US this is evident comparing the data from DOE, showing the drop in 0.11 mb/d or 25% for the last 10 years (**Fig. 4.6**. and **4.8**.):

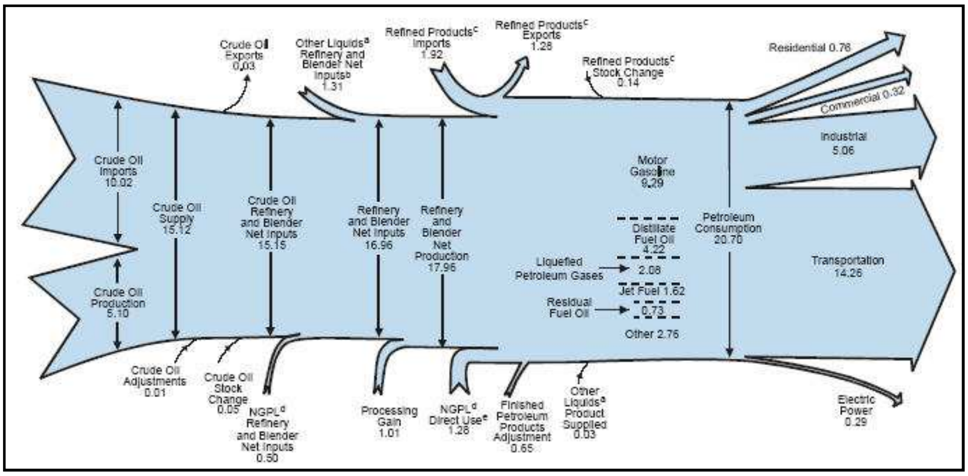

Figure 4.6.: Petroleum Flow in USA in 2009 (mb/d). Source: (DOE, 2011).

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[8] Ibid., page 113.

Accelerating decrease - due to rising costs - in the oil use for electricity production from current 5.1% (**Fig. 4.7.**) to less than 0.5% in 20 years time will help to reduce consumption, i.e. "save", over 3.5 m/d.

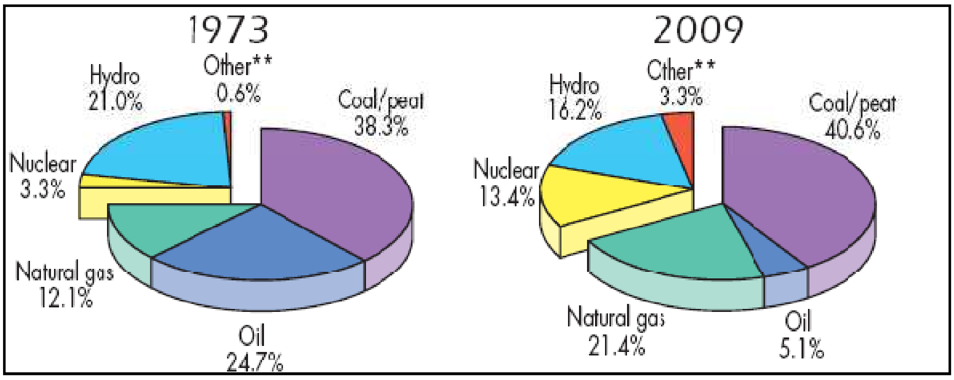

Figure 4.7. Electricity Generation by Fuel Share. (IEA, 2011)

4.4. Heat

The oil use for residential heating has also showed some reduction tendencies (Compare **Fig. 4.6. and 4.8.**) with residential use dropping 0.12 mb/d in the USA in the last decade.

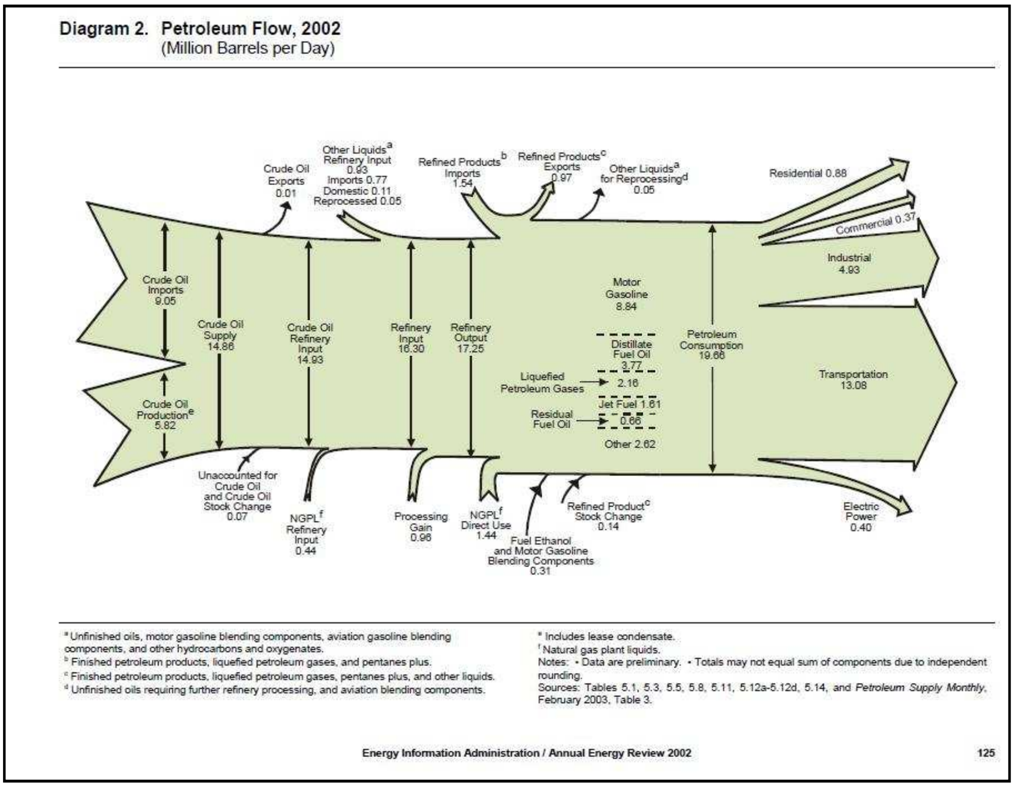

Figure 4.8. Petroleum Flow in USA in 2002 (Source: (DOE/EIA, 24/10/2003).

IEA is also not expecting much change on the global level in stationary (non-transport) oil demand with the efficiency improvements and switches to gas and renewable energy in residential and service sector in OECD countries "swallowing" any increases in petrochemical feedstock and in residential use in non-OECD countries.[9]

4.5. Agriculture/Food production

Since last century, when use of tractors and later chemicals as pesticides and fertilizers, became widespread and created the "green revolution" in 1960-s, food production, processing and distribution became industrialised on the global scale. Fossil fuel input in food production systems accounts for 17% of all fossil fuel use in the United States (Horrigan, 2005). Average American farm requires 3kcal fossil energy to produce 1kcal of grain. For industrial meat production this input is more than tenfold of that – 35 kcal. When one adds transporting, processing and packaging the average food calorie on your dinner table would have consumed 10 calories of fossil energy (Pfeiffer, 2006).
This explains sensitivity on the market prices of food to the rise in prices of crude oil, whose effect has trigged food shortages and riots in some third world countries in winter 2008 during the last oil shock (**Fig. 4.9.**):

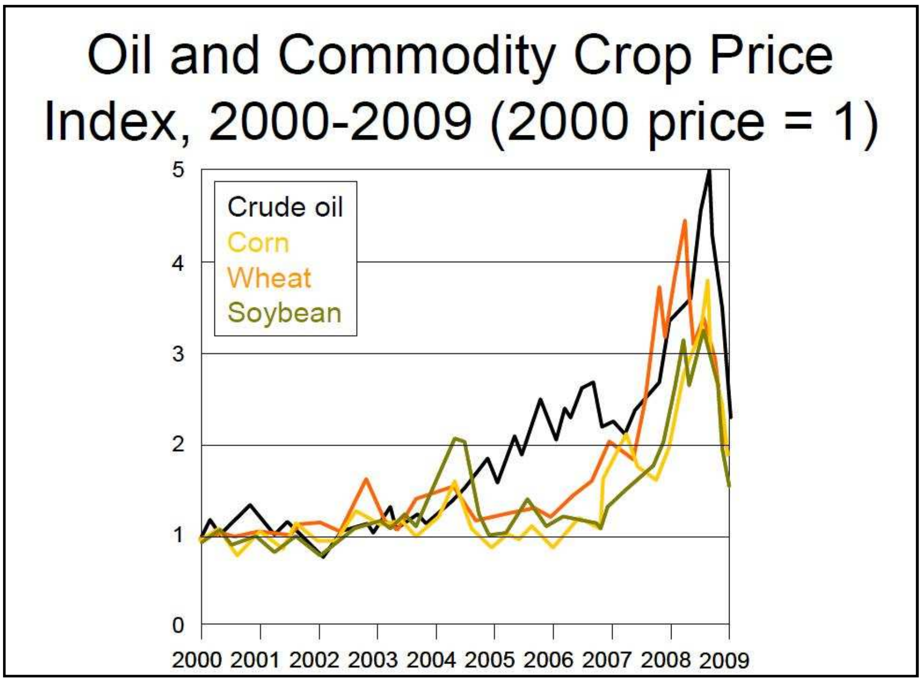

Figure 4.9.: Oil and Commodity Crop Price Index, 2000-09. (Bomford, 2008)

[9] (IEA, 2010), page 113

4.6. Industry.

The absolute amount of energy (toe) consumed by the industry remains remarkably stable since 1973 (Newbery, 2003).

The slight fall in use of oil in industrialized countries has been compensated by growth in industrial use in developing economies.

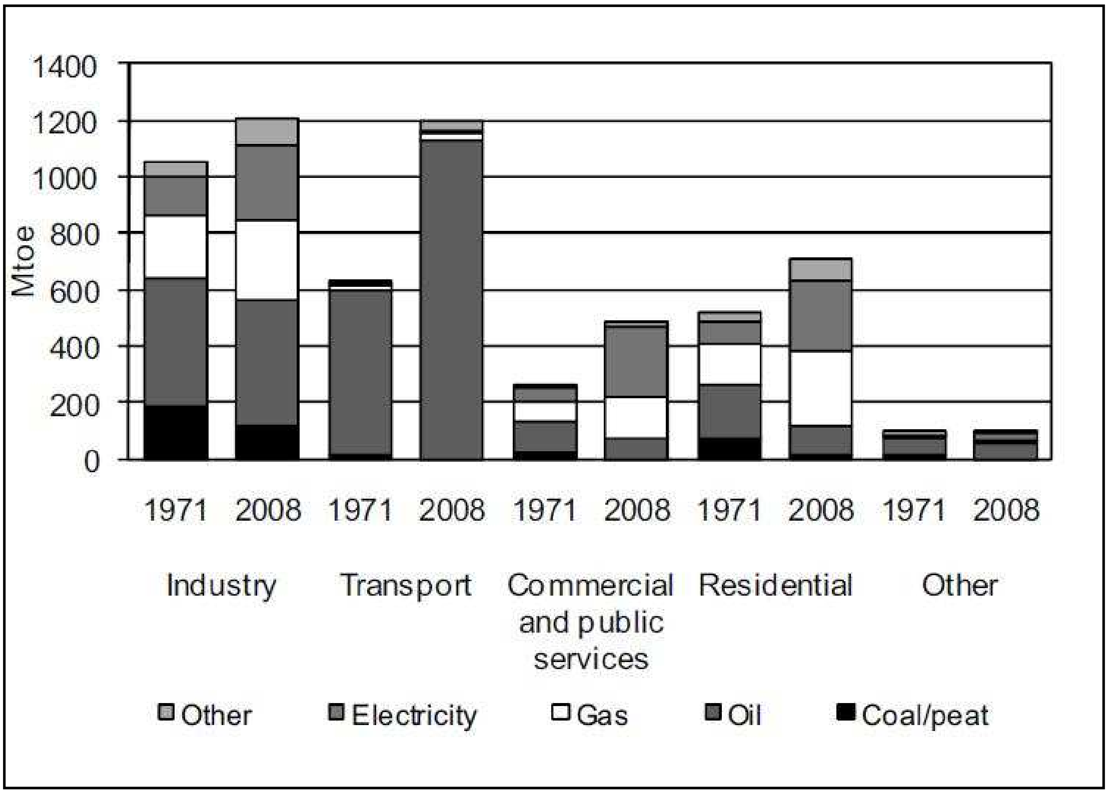

Figure 4.10.: TFC by fuel and by sector in the OECD. (Source: IEA 2010 Report *Energy Balances of OECD Countries*).

If one to speculate on complete removal of oil used for residential heating and in commercial and public services in all OECD countries by 2030, this will “free” additional 3.5 mb/d of consumable oil from the market.

4.7. Import/Export Market

4.7.1. Trade between producing/consuming countries

The distribution of the major oil deposits – as well as other natural resources – is subject to Pareto Principle. Due to geological nature of its creation most of the discovered oil deposits are occurring in the limited number of geographic spots on our planet. The main oil producing regions are “The Oil Triangle” of Saudi Arabia, Kuwait, Iran and Iraq; North America is the other, albeit diminishing producing region. Russia, Caspian Sea and the Atlantic continental margins of Africa and

South America are the other significant geographical locations for oil extraction. Global commodity market allows price regulated distribution of available for export oil deposits. These occur when the economy of the producing country consumes less oil than its oil industry can extract.[10](**Fig. 4.11.**):

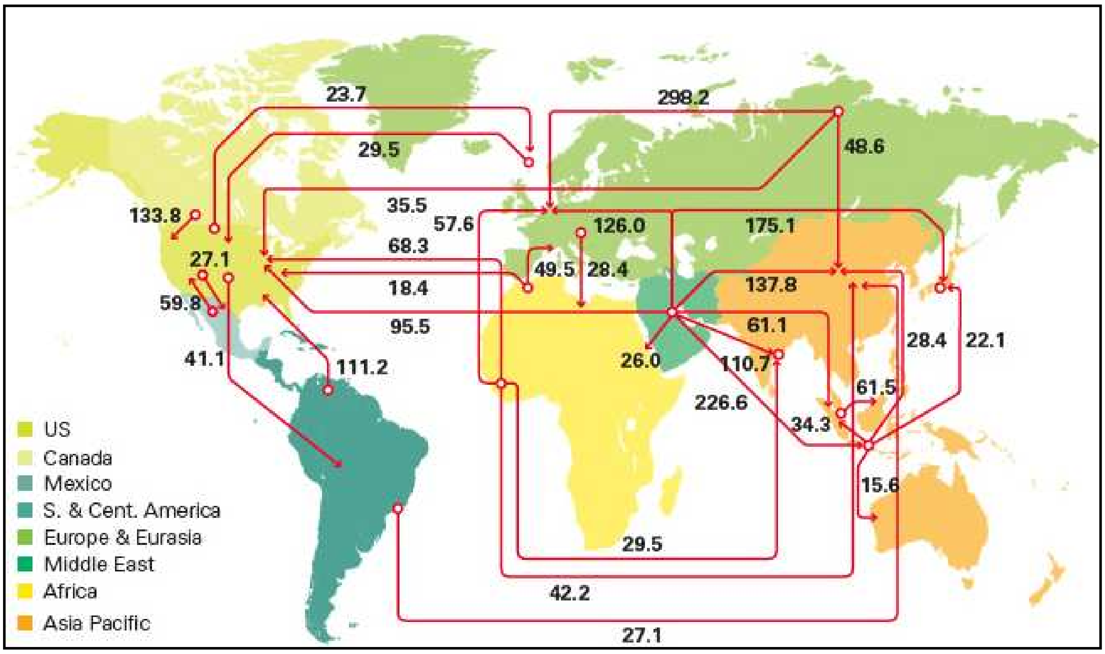

Figure 4.11.: Major trade flows of oil from producing to consuming countries. Source: (BP, 2012).

2125 million tonnes of crude oil and its products "changed hands" on the international market in 2009, making it the most tradable commodity in the world in terms of market capitalisation (IEA, 2011).[11] This amounted to over 50% of all extracted oil.

4.7.2. Security of supply

"Resource Nationalism" – priority in satisfaction of internal market before exporting the available surplus will play and does already (SPA, 2008), (Korsunskaya & Bachman, 2011) more important role in determining the volumes of internationally tradable stocks. With growing consumption rates in major oil producing countries

[10] When we talk about „oil producing state", it is important to mention that approximately 75% of the world oil is produced by national oil companies (NOCs) and the rest of the fields are developed by international oil corporations (IOC) most of the time in conjunction with national governments (through permits and licensing) and with their respective NOCs (through stakes and share swaps).

[11] Page 23.

and falling number of oil exporting nations (Appendix 1), Net Oil Exports (NOE) is the single most important factor determining the price between supply and demand curves in the world markets.
There are currently 43 oil exporting nations/regions. Top five of them - Saudi Arabia, Russia, Iran, Venezuela and Nigeria - are responsible for over 50% of all exported oil (IEA, 2011)[12]. 10 out the 43 – representing nearly 40% of all world extraction, are still growing (see Appendix 1.). The rest are at the peak or have already peaked in extracting oil.

The Export Land Model (ELM) developed by Jeffrey J. Brown and Samuel Foucher, PhD of ASPO-USA (Brown., 2007) (**Fig.4.12.**) studies the effect of dropping production and growing consumption rates on net exports:

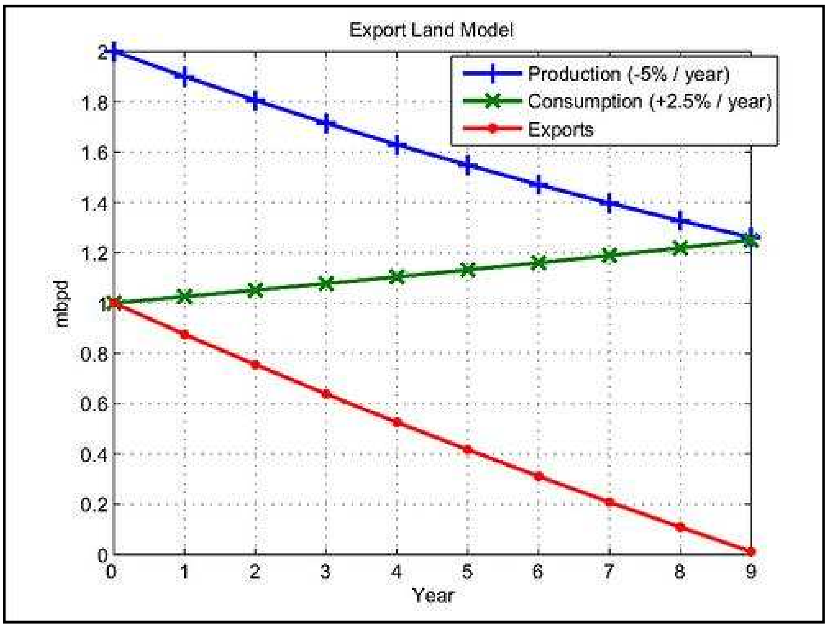

Figure 4.12.: Export Land Model (Source: Brown J.J., 2007).

As a result of this particular example, once exporting country hits its peak in extraction the decline in exports accelerates to zero in 9 years with the bulk of the decline happening in the first 3 years unless the consumption can be curbed or reversed (Brown, Foucher, & Silveus, 2010).

In reality it would mean that the regions with growing extraction have to “compensate” for the rapid decrease in available for export oil from the rest of the

[12] Ibid.

group just to keep things steady. In fact the drop in Global Net Export (GNE) has already started to show itself since its peak in 2005 (**Fig.4.13.**):

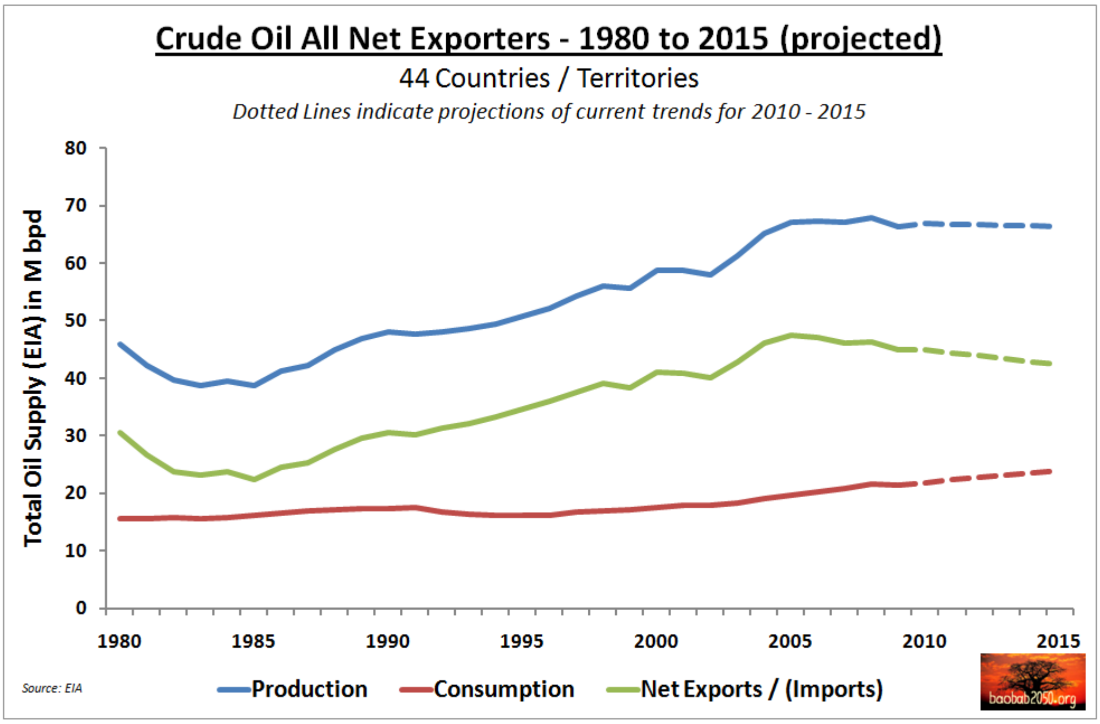

Figure 4.13.: Production, Consumption and Net Exports for all current net exporters 1980 - 2009, with projection for 2010 – 2015. Source: (Lordos, 2010)

4.7.3. Discovery rate

As oil is extracted and individual fields are reaching their respective peaks, to carry on producing the same amount of oil and/or increase this production requires the oil companies to use more sophisticated and hence expensive extraction technology, such as pumping in water or gas to increase the inner field pressure, or drill more wells and look for more new oil fields. Like any other type of business oil industry is subject to the law of diminishing marginal returns. The latter are inevitably falling as the "lower hanging fruits" – easier to discover and develop fields – are picked up first and experience and innovation increase efficiency at the beginning of the cycle.

In fact the humanity is living on a borrowed time because the extraction rates have been overtaking discovery rates for more than 30 years now (**Fig. 4.14.**):

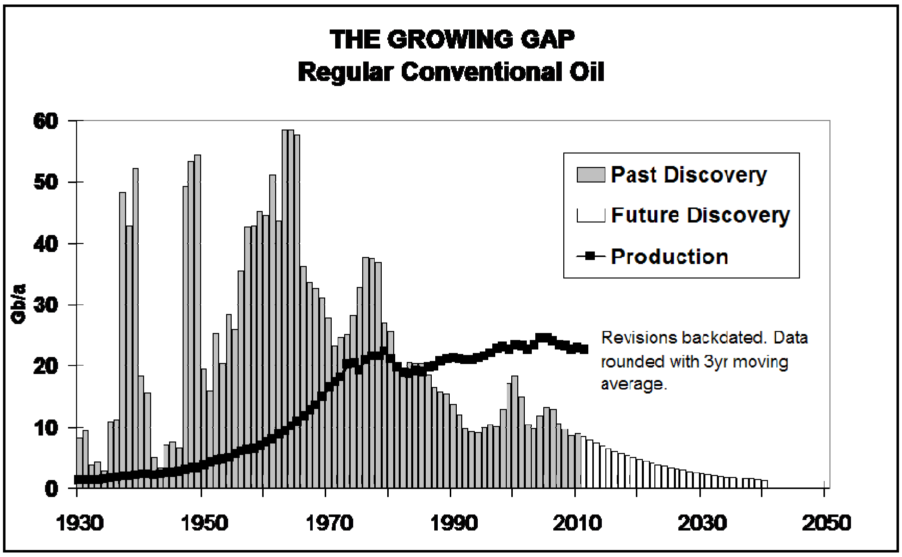

Figure 4.14.: The Growing Gap. Regular Conventional Oil: Discovery vs. Production. Source: (Campbell, 2012).

The discovery rate can be temporarily increased given the right economic incentives – price hikes – but this "blips" cannot reverse the historically proven data (**Fig. 4.15.**)

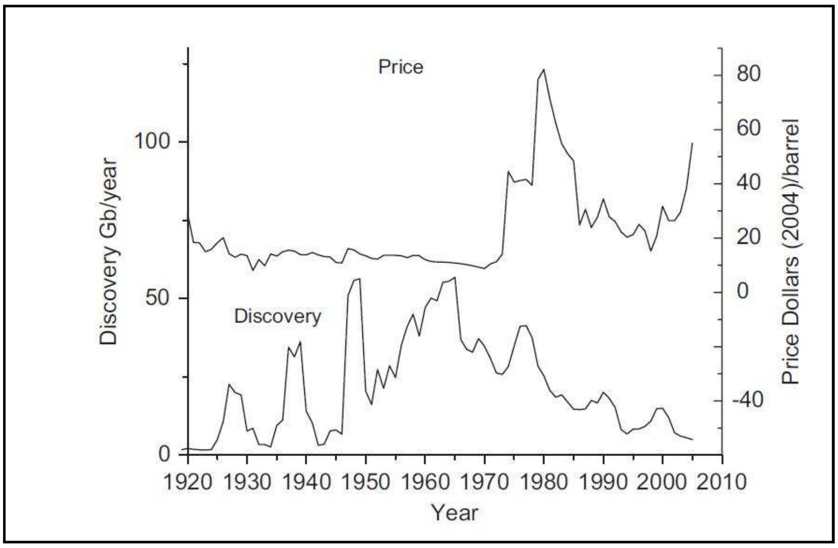

Figure 4.15.: Historical trends of world prices and discovery of crude oil. (Bardi U. , 2009)

Thus the oil we are extracting now has been long since discovered and for each new discovered barrel of oil world currently consumes 4 (ASPO, 2007). In this situation it is logical to expect the peak production to follow the peak of discovery. The only remaining question is "When?"

5. Peak Oil Theory

5.1. Hubbert’s Peak

The first person who successfully answered this question by using mathematical predictions techniques was American geologist M. King Hubbert.
Hubbert developed his theory by employing methodology used by population biologists to predict future growth, which he applied to available to him at a time data on production, cumulative production and past discovery trends (Deffeyes K. S., 2005).
In 1956 (Hubbert M. K., 1956) he presented his paper at meeting in American Petroleum Institute in St. Antonio correctly predicting the date of the USA peak extraction in 1970. He has later calculated that the world oil extraction peak will happen around 2000 (Hubbert M. , 1971) and, as IEA WEO 2010 confirmation of conventional peak oil proves (IEA, 2010), he was not far out on that estimate.
Hubbert has proposed that the production curve is “bell shaped” and it is symmetric, with “peak” occurring when the resource is about half way to be depleted (Bardi U. , 2009).

5.2. Timing and Methodology

Initially dismissed, Hubbert’s theory and the man himself became famous after USA “peaked” in 1970. Although the methodology he used was later successfully applied to describe the depletion curves of various natural recourses as well as population growth (Laherrère, 1997) the **exact date** of the peak is subject to wide-ranging disputes.

This is due on *supply side*, to extreme unreliability of data on reserve estimates – most of them in the “hands” of national oil companies or governments and are a highly guarded secret or unverifiable; on the rates of recovery and new oil discovery, unpredictability of weather or political disruptions of existing or planned production – Hurricane “Kathrina”, break-up of the USSR, Gulf Wars - and infrastructural constrains (Odland, 2006). The destruction of *demand* from the economical factors is another big variable.

All these factors influence the “spread” of estimates from 2005 (Simmons, June 5, 2006), (Deffeyes K. , 2006) to 2030 and beyond (IEA 2011, EIA 2009, USGS 2000). Some, like CERA while rejecting the peak oil theory, believe that production will follow an “undulating plateau” for one or more decades before eventually subsiding (**Fig.5.1.**):

Date of forecast	Source	PO date	Reference
2000	Bartlett	2004–2014	Bartlett (2000)
2000	EIA	2021–2112	Wood and Long (2000)
2000	IEA	Beyond 2020	IEA (2000)
2001	Deffeyes	2003–2008	Deffeyes (2001)
2002	Nemesis	2004–2011	Nemesis (2002)
2002	Smith	2011–2016	Smith (2002)
2003	Simmons	2007–2009	Simmons (2003)
2003	Deffeyes	Before 2009	Deffeyes (2003)
2003	Campbell	Around 2010	Campbell (2003)
2003	World Energy Council	After 2010	WEC (2003)
2003	Laherrere	2010–2020	Laherrere (2003a, b)
2003	Shell	2025 or later	Davis (2003)
2003	Lynch	No visible peak	Lynch (2003)
2004	EIA	2021–2112	Wood et al. (2004)
2004	Bakhtiari	2006–2007	Bakhtiari (2004)
2004	Skrebowski	After 2007	Skrebowski (2004)
2004	Goodstein	Before 2010	Goodstein (2004)
2004	CERA	After 2020	Jackson and Esser (2004)
2005	Koppelaar	After 2010	Koppelaar (2005)
2006	Skrebowski	After 2010	Skrebowski (2006)
2006	Smith	2011	Smith (2006)
2006	Koppelaar	After 2012	Koppelaar (2006)
2006	IEA	After 2030	IEA (2006)
2006	CERA	2035	Jackson (2006)
2007	Robelius	2008–2018	Robelius (2007)
2007	Koppelaar	2015	Koppelaar (2007)
2007	Laherrere	About 2015	Laherrere (2007)
2008	CERA	After 2017	CERA (2008)
2008	Shell	2020 or later	Shell (2008)

Figure 5.1.: Peak Oil Projections (de Almeida & Silva, 2009)

Methodology is also playing a factor here. From “business as usual” to “bell curve fitting” and “bottom-up analysis” they all include a number of educated guesses to fill in the void in various data parameters. The one of most important of these is the ultimate recoverable reserves (URR), since this figure ultimately determines the peak, being at a half way point of total extracted oil. As one can see from **Fig. 5.2.,** the estimate range of remaining conventional oil resources can dramatically vary depending on the data source:

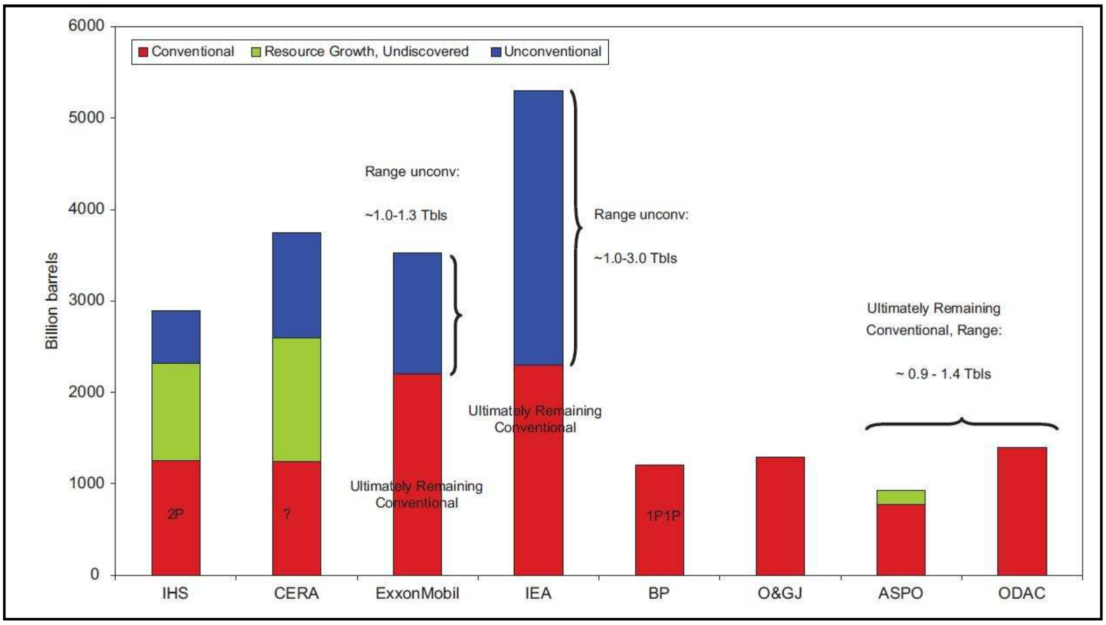

Figure 5.2.: Various estimates of proven reserves and remaining oil resources by the end of 2005 (IEA end of 2004, ASPO end of 2003). Remaining ''conventional'' resources refer to 1P reserves (BP and O&GJ), 2P reserves (IHS) and ultimate (ExxonMobil, IEA, ASPO/ODAC). However, both BP and O&GJ include some Canadian and Venezuelan unconventional oil. CERA's remaining conventional resources include arctic and deepwater. (Kja¨rstad & Johnsson, 2009).

This explains the spread of the peak oil estimates. However most of the researches not associated with oil industry converge on the date around 2010 or in the early half of the second decade of the 21 century (de Almeida & Silva, 2009). De Almeida and Silva (2009), who did this comparative study, estimate themselves the peak to occur before 2012, after which a resulting plateau will start a slow decline of 0.5%/year. On this decline rate I will base my calculations in below proposed scenarios.

However, let us first have a closer look at what kind of relationship exists between the economic growth and oil price and availability.

6. Oil & Economic Growth

6.1. Price Elasticity of Oil Demand

The argument between Cornucopian and Malthusian camps among geologists, i.e. between those, who believe that world has enough resources to continue with BAU, and those, who think that exponential growth on the finite planet would lead to a disaster, is weighted in by economists, who insist that in the free market - once the scarcity of the commodity drives up the price - the solution will be found through innovation, efficiency and substitution. Although this is generally true the ability of the world economy to whine itself off oil has been proven historically to be impossible so far.

The dependence of the GDP growth on availability of cheap energy and small price elasticity of the demand has been a subject of intensive research. In his latest publication, Hamilton J.D. (Hamilton, Oil Prices, Exhaustible Resources, and Economic Growth, 2011), after reviewing the recent works by economic scientists on this subject, describes the mechanics of the growth in extraction of oil after individual fields, regions and countries reached their respective peak and decline in production. Despite the technological advances in the last half a century and price jumps and increases in extraction rates, the most of the growth in supply of oil still comes in extensive fashion, i.e. through the development of more fields and drilling more wells. Moreover, despite the five-fold increase in price of oil between 2000 and now, the world demand for oil nevertheless shows exponential growth and is still projected to grow -albeit at slower rate - to 95 mb/d (International Energy Agency, 2011) by 2016. (**Fig. 6.1.**):

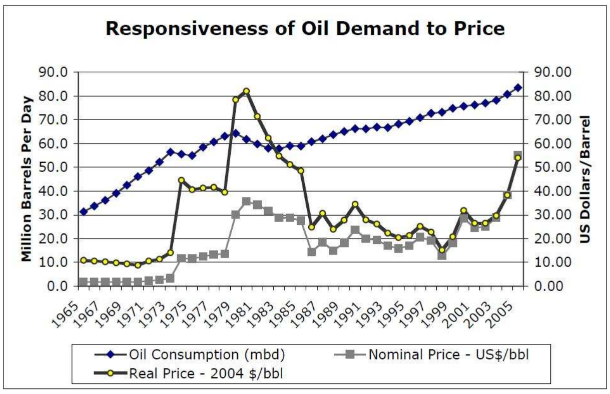

Figure 6.1.: Responsiveness of oil demand to price. Data from BP Statistical Review 2005 and EIA Short Term Energy Outlook , October 2005. (Odland, 2006)

6.2. GDP and oil

This inelastic behaviour of oil demand shows the important place oil supply occupies in the world economy. As an “enabler” of most economic processes, from mining and refining all other natural resources, to production and distribution of ready goods, oil has been so far indispensable component of human productive activity.
However oil’s abundant supply and relatively low cost of extraction until recently, allowed neoclassical economic models to disregard this important factor, as they described economic growth as a function of labour and capital productivity, enhanced by technological improvements and moderated by investment/savings and depreciation, all determined by the interest rate.

The defenders of these models, which became very influential fiscal policy tools, stipulated that infinite growth can exponentially continue as a logical result of the mathematical function with energy supply being only a fractional function of marginal cost, pricing and demand. Their opponents – biological economists, who studied how species behave within their environment, - insisted that the growth will be ultimately constrained by the limiting factors of the finite resources and carrying capacity of the ecosystem (Meadows, Randers, & Meadows, 2004). Their voices have been so far marginalized as our political and financial systems are so close intertwined with “the growth” meme.

This beginning to change however with multiple researches (see f.e. (Cleveland, Costanza, Hall, & Kaufman, 1984) and even some governmental reports (Hirsch, Bezdek, & Wendling, 2005), (BITRE, 2009), (Bundeswehr Transformation Centre, Future Analysis Branch, 2011) showing undisputable dependency of the economic stability and oil availability and price (**Table 6.1.**):

Table 6.1. Summary of significant post war events in correlation to oil shocks and business cycles. (Hamilton, Historical Oil Shocks, 2011)

Gasoline shortages	Price increase	Price controls	Key factors	Business cycle peak
Nov 47- Dec 47	Nov 47-Jan 48 (37%)	no (threatened)	strong demand, supply constraints	Nov 48
May 52	Jun 53 (10%)	yes	strike, controls lifted	Jul 53
Nov 56-Dec 56 (Europe)	Jan 57-Feb 57 (9%)	yes (Europe)	Suez Crisis	Aug 57
none	none	no	---	Apr 60
none	Feb 69 (7%) Nov 70 (8%)	no	strike, strong demand, supply constraints	Dec 69
Jun 73 Dec 73- Mar 74	Apr 73-Sep 73 (16%) Nov 73-Feb 74 (51%)	yes	strong demand, supply constraints, OAPEC embargo	Nov 73
May 79-Jul 79	May 79-Jan 80 (57%)	yes	Iranian revolution	Jan 80
none	Nov 80-Feb 81 (45%)	yes	Iran-Iraq War, controls lifted	Jul 81
none	Aug 90-Oct 90 (93%)	no	Gulf War I	Jul 90
none	Dec 99-Nov 00 (38%)	no	strong demand	Mar 01
none	Nov 02-Mar 03 (28%)	no	Venezuela unrest, Gulf War II	none
none	Feb 07-Jun 08 (145%)	no	strong demand, stagnant supply	Dec 07

Higher energy price tend to re-allocate expenditures from the areas that had previously added to GDP, mainly discretionary consumption, towards simply paying for more expensive energy, thus causing a recession. This happen in the USA case, when the petroleum expenditures as a percent of GDP climb above threshold of around 5.5% (Murphy D. H., 2011) (**Fig. 6.2.**):

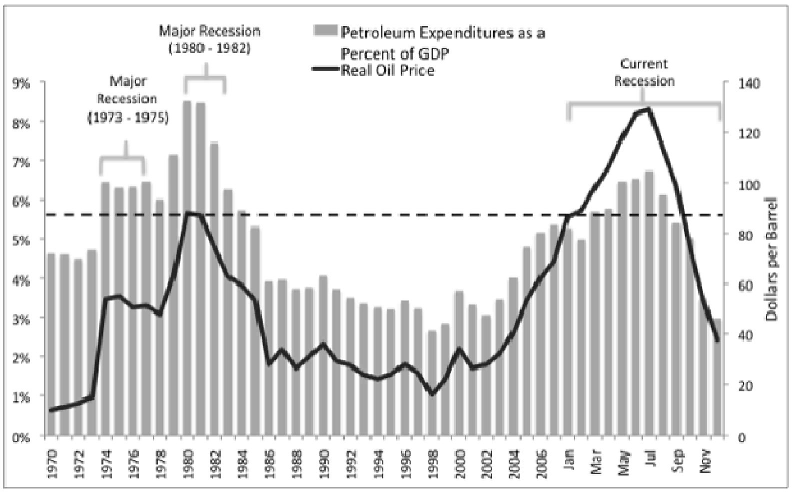

Figure 6.2.: Petroleum expenditures as a percent of GDP and real oil price. The dotted line represents the threshold above which economy moves towards recessions. Petroleum expenditures include distillate fuel oil, residential oil, motor gasoline, LPG and jet fuel. (Source: ibid.)

6.3. Return to Growth?

Once recession destroyed demand, the oil price falls making it affordable again for following expansion. All previous supply constrains with the rear exception (see **Table 6.1.**) were historically triggered by geopolitical events. The cardinal difference with the current situation is that the growing demand, especially from the developing countries, has hit the stagnant supply.

As mentioned in previous chapters, extraction companies are required to invest more money and energy to keep the existing fields producing oil. Ever increasing fraction of new oil is discovered in difficult to get to and develop places: deep water, arctic, tar sands, etc. (**Fig. 6.3.**):

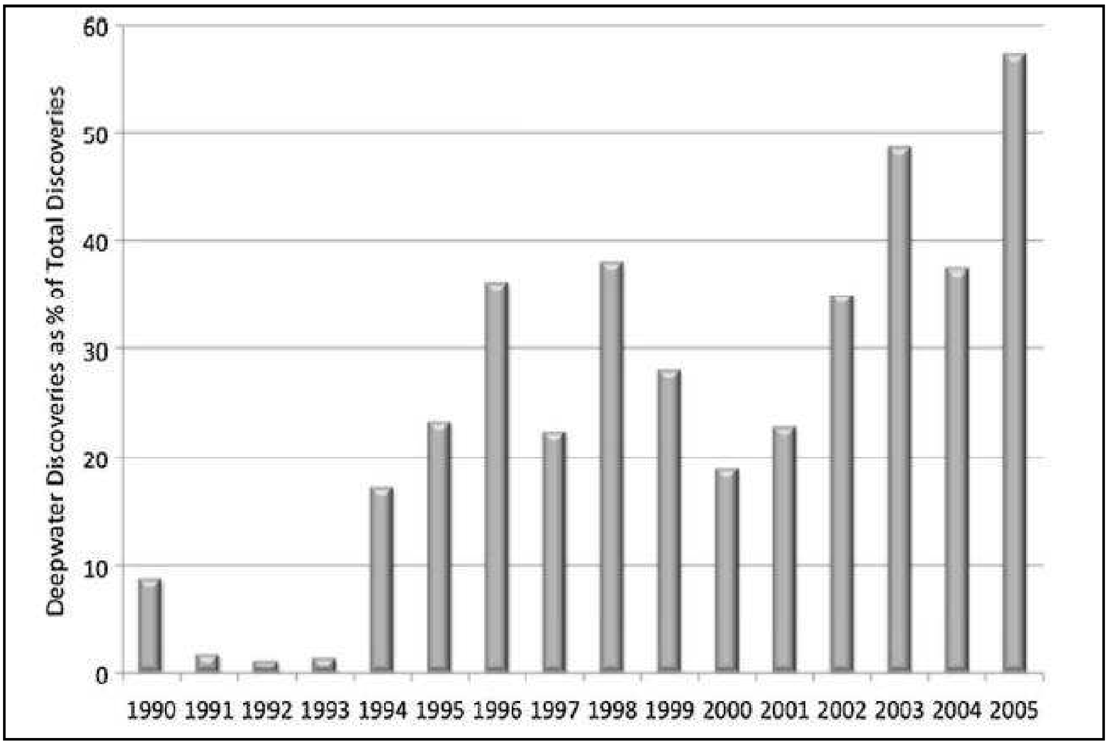

Figure 6.3.: Deep water discoveries as % total discoveries. Source (Murphy D. H., 2011)

This fact leads to substantial increases in discovery, development and extraction costs, as well as decreases energy return available for consumption by the society. The data indicates that there is inverse relation between EROI and price (**Fig.6.4.**):

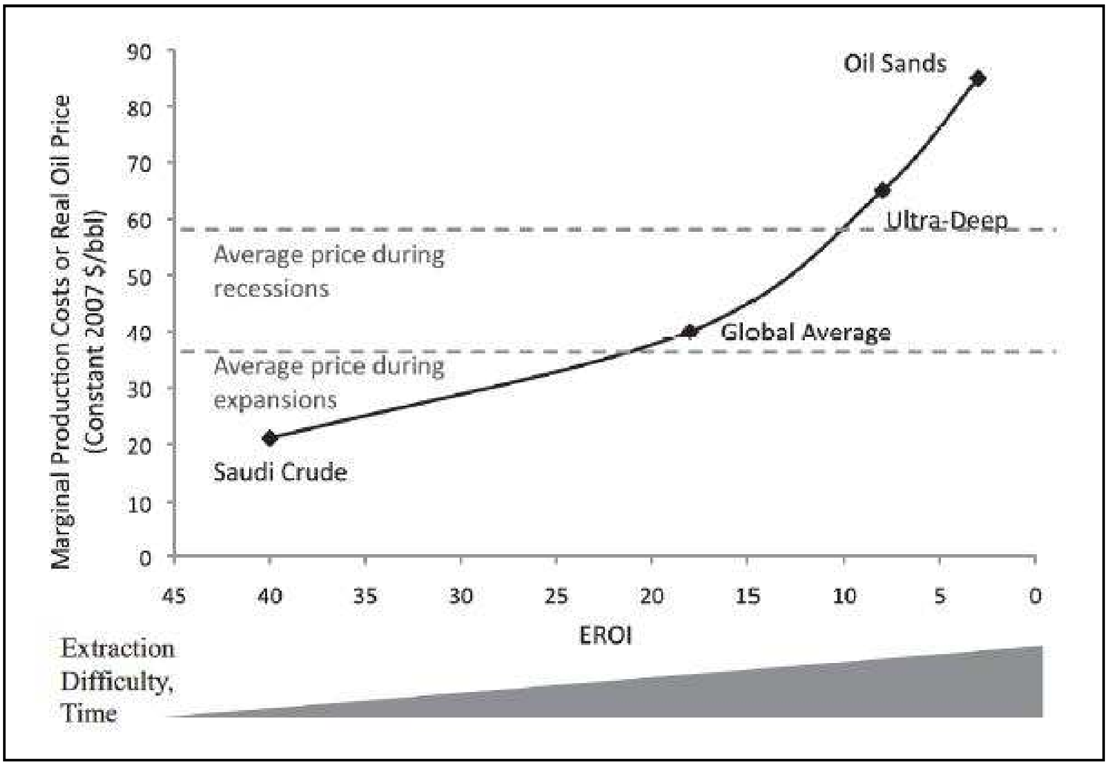

Figure 6.4.: Oil Production costs as a function of EROI. Source: (Murphy & Hall, 2011)

With growing share of the future world oil supplies coming from reserves, returning ever lower than currently EROI (Cleveland C. , 2005), the growing price of its extraction and delivery to the market will further dampen the demand. This increasing pressure on demand will inevitably translate into lower consumption and hence still slower economic growth. Slow growth – affecting how financial system operates - will make investments into production expansion problematic, putting more stress on supply, hence reinforcing this feedback loop of constant economic contraction.

6.4. Do we need Growth?

If oil is such an important factor, as the above mentioned researches suggest, in determining the behaviour of business cycles how will our economy and political systems be able “to handle” the inability of oil producers to increase supply, or even worse – its supply contraction?

The disparity in distribution of wealth between industrialized and developing countries is well documented (see f.e. (Bourguignon & Morrisson, 2002); (Milanovic, 2002) (**Fig.6.5.**):

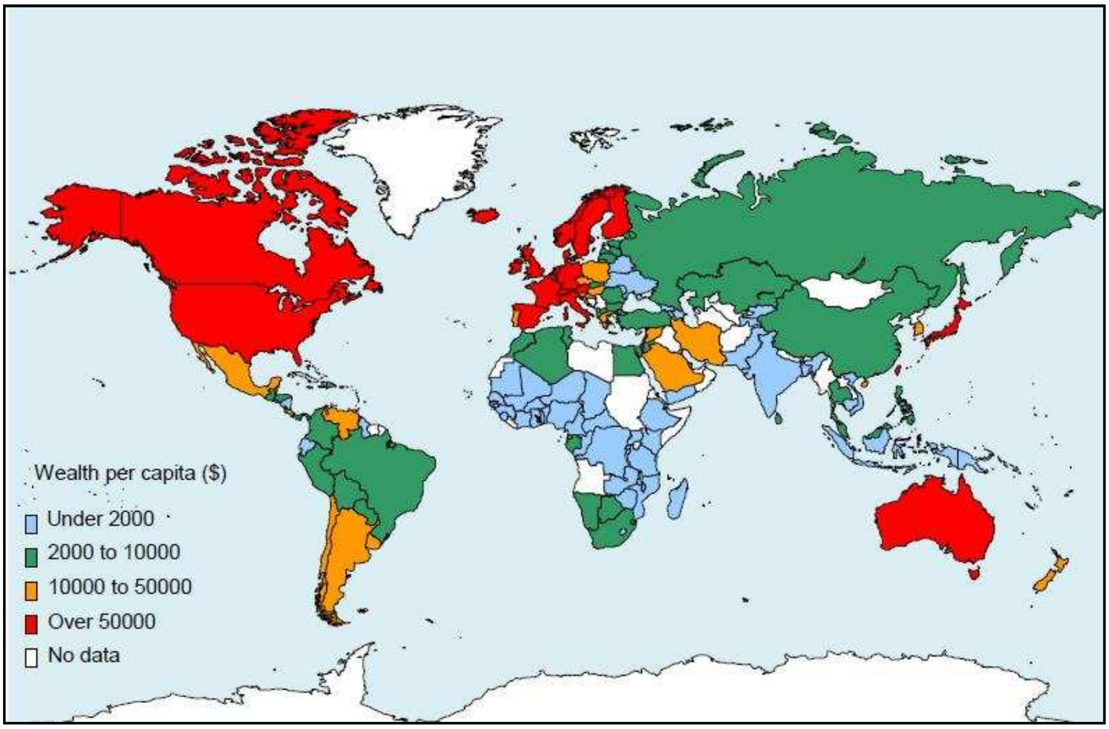

Figure 6.5.: World Wealth levels 2000. Source (Davies, Sandström, Shorrocks, & Wolff, 2008)

In addition there exists a huge disproportion of wealth allocation within every society (**Fig. 6.6.**):

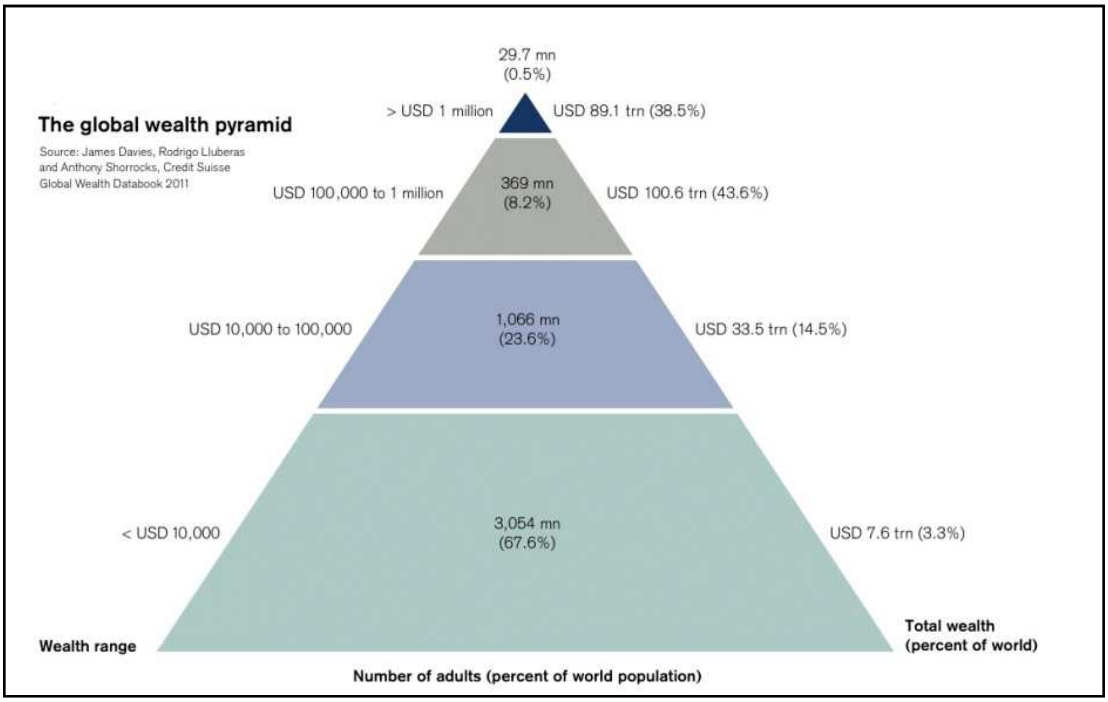

Figure 6.6.: The global wealth pyramid. Source: (Shorroks & Davies, 2010)

As long as the growth exists and trickles down the pyramid it is easier for the political powers to control resentment sentiment. When this "natural" distribution is slowed or stopped as economy contracts and incomes fall (**Fig. 6.7.**), it becomes more difficult to reinforce “social contract” resulting in political unrest, such as colour revolutions in Eastern Europe, Arab Spring uprisings and Occupation movements.

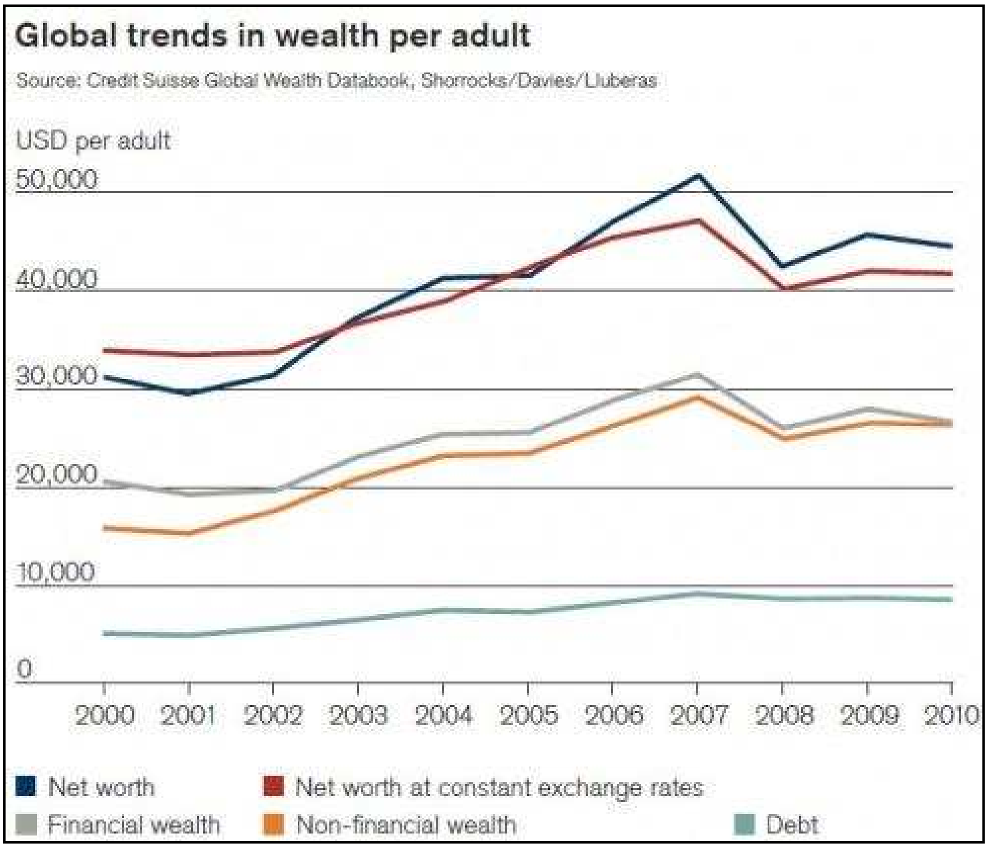

Figure 6.7.: Global Trends in wealth per adult. Source: Ibid.

The second, perhaps even a greater problem, that could be caused by slow or contracting economy is the ability of the household, business and more importantly governments to repay debt.

Last 30 years have seen an unprecedented growth in assets acquisition in western world driven mainly by debt creation fuelled by fractional reserve banking and fiat currencies. The structure of this financial schema resembles an inverted pyramid in which ever increasing amounts of money has to be “created” or loaned into existence in order to repay the principle and interest on debt. For this structure to be stable it requires constant expansion, either through increasing amount of actors – more people to loan money to, or through the newest investment avenues, like “dot.com boom”, financial engineering of 90s, lately - real estate bubble and currently – sovereign debt.

In the economy that is struggling to grow due to energetic constrains, it becomes increasingly more difficult to repay existing debts as well as take on new ones. The growing amount of defaults and write-offs, multiplied by securitization and hedging through complex financial instruments brought the world financial system to near collapse in 2008, which was only averted, some argue only delayed, by the governments stepping in and providing various financial measures to avoid the looming disaster. These forced measures had ballooned government debts to dangerously high levels (see **Fig. 6.8.**),

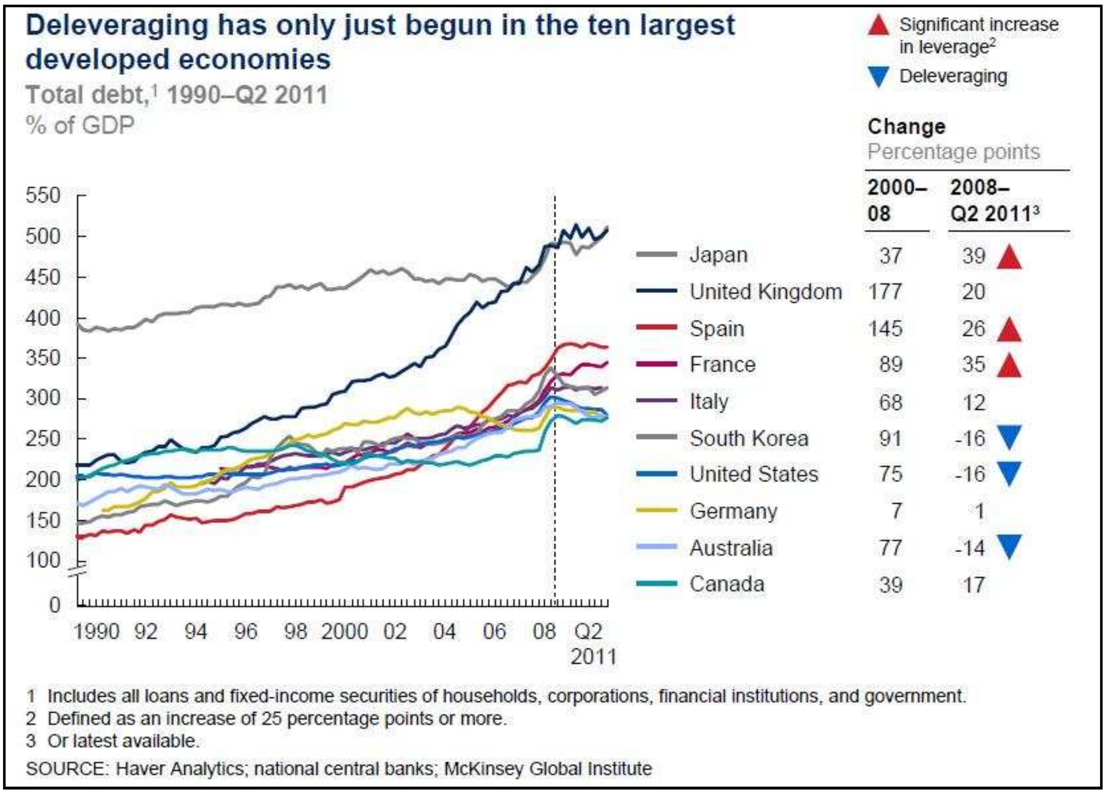

Figure 6.8.: Total Debt in ten largest developed economies. Source (Roxburgh, 2012)

where the interest payments alone swallow up to fifth of tax receipts income in US (**Fig. 6.9.**):

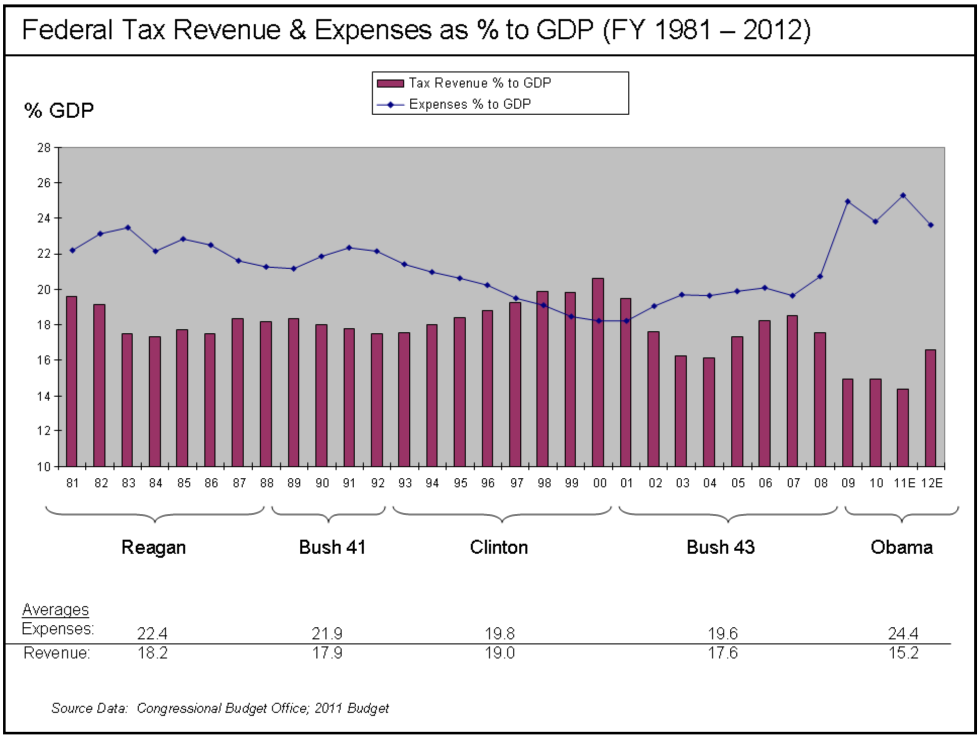

Figure 6.9.: USA Tax Revenue and Expenses as % of GDP. Source: (wikimedia, 2011)

There are of course practical limits on how much more debt can government accumulate before it is forced into default or has to inflate its currency, further destabilizing business atmosphere and creating downward spiral of economic contraction[13].

This matter deserves a special attention as we will be discussing below the necessary conditions of successful transition from fossil fuel economy to alternative energy sources. So far such transition for our species was ultimately way up the energy ladder: from lower density half-dried log wood to coal, and finally to high EROI liquid oil.

How the similar transformation can be done on the way down the energy hill, exacerbated by dropping margins on financial and energetic returns, absence of political will, lack of understanding of the scale of the transition from the populace, heavy brakes on any change, applied by vested interests from the established industries and looming on the background “elephant in the room” – the climate change - remains to be tested.

[13] More on this topic see (Heinberg, 2011)

7. Alternatives to Oil

There is ever more increasing amount of research, reports and investigations that came out in the last 5-7 years, strongly advocating that the peak oil presents a serious challenge to the existing order of things[14]. All of them came to the similar conclusions that politicians, military and business leaders have to pay immediate attention to the question of mitigation and intensify the search for alternative solutions. Most of the researches stress that irrespective of adopted variations, the transition strategy will require lengthy period of implementation time – up to 20 years (Hirsh et.al., 2005) and substantial coordinated efforts and financial investments to redesign the energy delivery system that fuels our global economy.

Although the debate on the seriousness of the situation, its urgency and possible strategies has intensified since the beginning of the 2008 economic crisis, it has yet to find its way into mainstream media and public policy domain. Every year of delay that leaves humanity less time to adapt to the new reality will lead to substantial increase in costs of transition and will cause more disruption to economy than we are experiencing right now.

Since the oil prerogative use is concentrated around transportation issue, this is the one area of economy which is the most vulnerable and where the most of replacement has to be concentrated.

7.1. Fossil alternatives and their EROEI

Some transition from conventional oil to various alternative solutions has already begun. These solutions can be divided in three groups: firstly, fossil based liquid hydrocarbons – either so called “unconventional” crude oils, such as deep water, tar sands, shale oil, etc. and synthetic liquid fuels (SLF). Secondly, biologically derived fuels, such as biodiesel and ethanol; thirdly, elimination of hydrocarbons altogether by replacement of the energy carrier with electricity or hydrogen (Farrell & Brandt, 2006).

[14] Apart from the ones mentioned above, see also (Sorrell, Speirs, Bentley, Brandt, & Miller, 2009), (Froggatt & Lahn, 2010), (Parthemore & Nagl, sept. 2010).

When considering different resources for the substitution of conventional oil or technologies applied to recover unconventional oil it is important to pay special attention to the problem of diminishing energy return on energy invested (EROEI) (more on that in chapter 8.4.4). This value becomes even more important, when it drops below threshold 8:1, representing so called "Net Energy Cliff" (**Fig. 7.1.**):

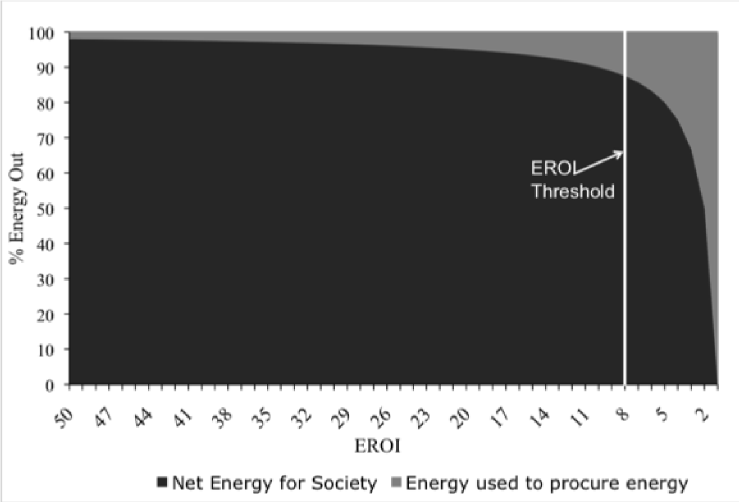

Figure 7.1.: Net Energy Cliff[15]

This is often overlooked, especially in economic analysis of peak oil mitigation. When considering different substitution technologies, detailed assessments of energy returns, together with Life Cycle Analysis (LCA) and climate impact costs are crucially important to help economy "to decide" which technological path to follow. Some of these substitutes can be temporary and costly solutions – both in financial and ecological terms, when all values are properly accounted for (**Fig. 7.2.**).

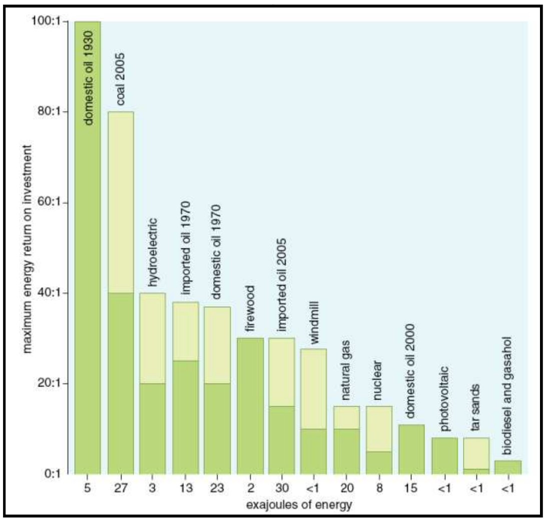

Figure 7.2.: EROI for different fuels. (Lighter colours indicate a range of possible EROI due to varying conditions and uncertain data.) Source: (Hall & Day, 2009).

[15] For detailed analysis of Net Energy Cliff see (Murphy D. , 2011)

To repeat once again, although most optimistic estimates of the conventional oil resources show that we have more than ¾ of the totally available fuel still to be recovered (**Fig. 7.3.**), the way the fields are spread, the fact that most giant fields are discovered long ago and many of them declining in production, the dropping rates of new discoveries coupled with increasing investment costs, the growing costs of extraction as a result of lowering rates of EROEI as well as the “above ground factors” which we had a look at only briefly, all that makes “peak oil” more of a “*when*” rather than “*if*” question.

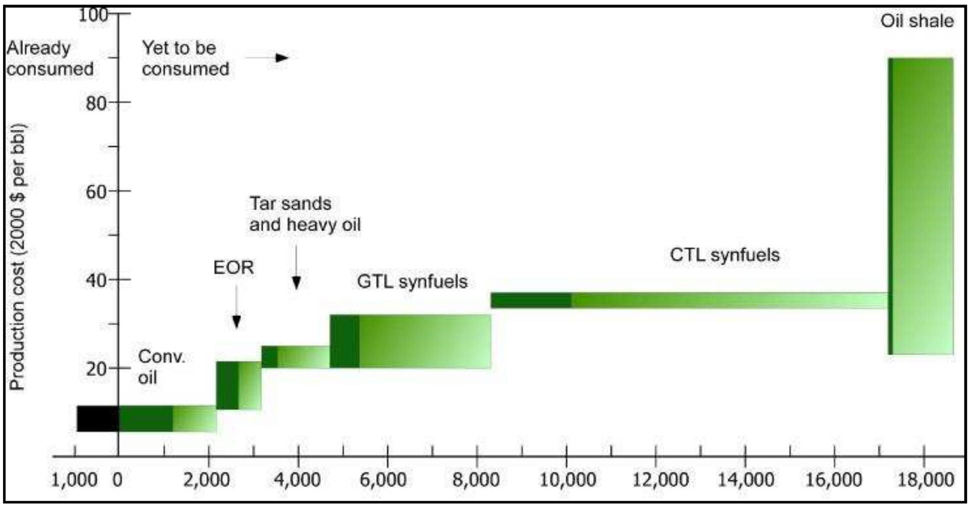

Figure 7.3.: Potential for hydrocarbon production. Source (Farrell & Brandt, 2006).[16]

Additionally currently observed corresponding rate of decline from all producing fields is at least 4% per year. That means that oil extraction has to grow yearly at current rates to additional 3 mb/d or equivalent to adding a new Saudi Arabia every 3 years just to keep up with the current rates of consumption (Sorrell, Speirs, Bentley, Brandt, & Miller, 2009).

The questions that I am trying to find an answer to here are: where all these additional oil will be coming from, could it be safely replaced, how much it would cost the economy, how much time we have to arrange the smooth transition away from oil dependency and how the results of this transition would look like.

[16] Global resources of fossil hydrocarbons that could be converted to liquid fuels. EOR is enhanced oil recovery, GTL and CTL are gas-and coal-derived synthetic liquid fuels. The CTL and GTL quantities are theoretical maxima because they assume all gas and coal are used as feedstock for liquid fuels and none for other purposes. The lightly shaded portions of the graph represent less certain resources. Results are based on conversion efficiencies of current technologies available in the open literature. Gas hydrates are ignored due to a lack of reliable data. Please note that the prices are of 2007 level.

7.1.1. Coal

Using coal as a feedstock for producing liquid hydrocarbon fuels (CTL) is a commercially proven technology based on three principal approaches: pyrolysis, direct coal liquefaction (DCL), and indirect coal liquefaction (ICL). These conversion techniques are assumed by many researches to play a significant role it mitigating future possible decline in liquid fuel production as a result of declining oil extraction.

The best known one of these three is Fischer-Tropsch (FT) synthesis, named after its German inventors in 1920 (Davis & Occelli, 2006).

The main candidates for future CTL technology considered to be DCL and ICL however. The latter successfully employed by the South African government owned “Sasol” in response to the oil embargo in 1950-s, and the former used in a brand new plant in China, developed by Shenhua Group Corporation.

While it is not easy to make direct comparisons in efficiency between these two technologies, as DCL produces synthetic crude which need to be refined further into usable fuel, whereas ICL can produce “designer” fuel, different studies estimate system efficiency for DCL between 60 and 70% and for ICL these are typically around 50% (Höök & Aleklett, 2009).

System costs estimate the cost of coal varying in the region of one to two tenth of the whole project costs with ICL planned plants in China costing estimated 5$US billion for 80 000 b/d facility (Sasol., 2006). The latest research into the subject shows the break-even price of 48-75 US$/barrel (Vallentin, 2008).

As far as emissions are concerned well-to-wheel analysis has shown that even with implementation of CCS, CTL production chain emissions are higher than that of petroleum derived fuels, mostly because of mining, and range from 30% to 90% for DCL and can reach even 110% higher for ICL products (Höök & Aleklett, 2009).

Another environmental concern is the high water consumption due process requirements reaching 1 m^3 for one barrel of DCL or ICL product and therefore putting logistical constrains on the location of the plant (National Energy Technology Laboratory, 2006).

The main difference between these two approaches to liquefaction of coal is that DCL is a relatively new process aimed at providing feedstock for the existing refinery infrastructure, whereas ICL is more proven and versatile technology, which could be useful in different scenarios of post peak-oil world from hydrogen production to combination within Integrated Gasification Combine Cycle (IGCC) plants.

Whether all or some of these technologies can be quickly scaled up is subject to considerable speculation. At the moment there are three ICL operational facilities in the world (SA) and one DCL in China with two more planned ICL facilities in China. There is a number of laboratory research and small scale plants around the globe, but nothing that could be seriously taken into account in the frame of “peak-oil mitigation” question.

Hirsch Report assumed 5 Mb/d CLT production achieved after 10 years of intensive building program with first plant coming on-line 4 years after “go-ahead” sign (Hirsch, Bezdek, & Wendling, 2005). The Report did however admit that it has no idea, how and where these plants – 5 per year with the capacity of 100 000 b/d – will or could be build.

Different literature estimates of coal consumption by CTL provide a range of figure between 1 and 2 barrels of syncrude per ton. Sasol empirical comparison gives a range of 1-1.4 barrels per ton of bituminous coal. (Höök & Aleklett, 2009). To reach the oil substitution production of 5 Mb/d according to Hirsch projections will thus require extraction of 130-183 Mton of bituminous coal annually, this figure is increasing if the coal quality is lower. This would represent around 2.4% annual increase in total coal production for 2011 (BP, 2012). This potential increase can only come from the top producing nations: USA, China Russia, India, Australia and South Africa, controlling 82% of the coal deposits and accounting for nearly 80% of the world’s coal production. The largest exporting nations outside this “Big Six” are Canada, Colombia, Indonesia, Poland, Vietnam and Kazakhstan, combined they account for almost 40% of the world coal exports (Höök, Zittel, Schindler, & Aleklett, 2010). They also account for 10% of total world coal extraction (**Fig. 7.4.**):

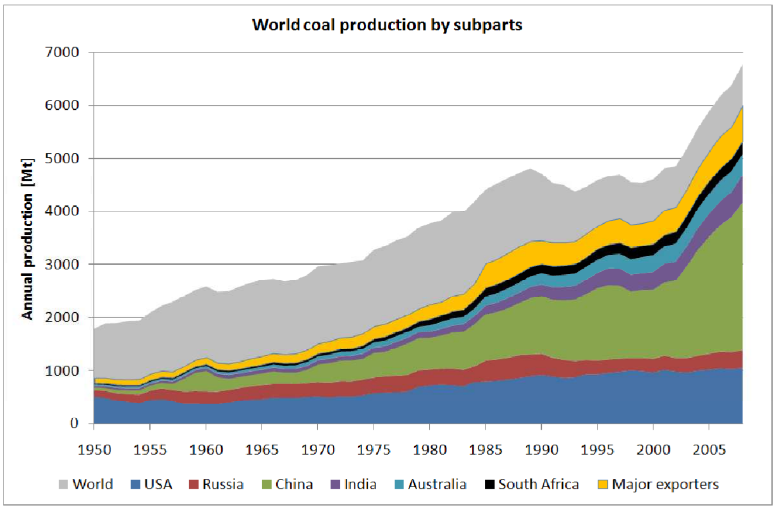

Figure 7.4.: Total world production 1950-2008 and the contribution from the members of the Big Six and the major exporters. Source: ibid.

Needless to say that even if it was technically and economically possible to implement this transition strategy of substitution one dwindling fossil fuel resource for another, it will do little to evaluate the concerns of the rest of the world about supply security. Moreover, the growing need for coal as a major source of fuel for electricity production in developing nations, notably India and China, will inevitably create the competition for the existing reserves, driving up the prices, making CTL processes less economical or further lowering P/R ratio, thus bringing the potential peak coal point closer to modernity on the historical time-scale.

The peak coal will in turn be determined by the production situation in China as the world top producer (49.5%) (BP, 2012). Most studies give 2025 (**Fig. 7.5.**) as the date for maximum production in China (Höök, Zittel, Schindler, & Aleklett, 2010), making coal – even disregarding environmental and social issues, a questionable candidate for production of the liquid fuel as oil substitutes.

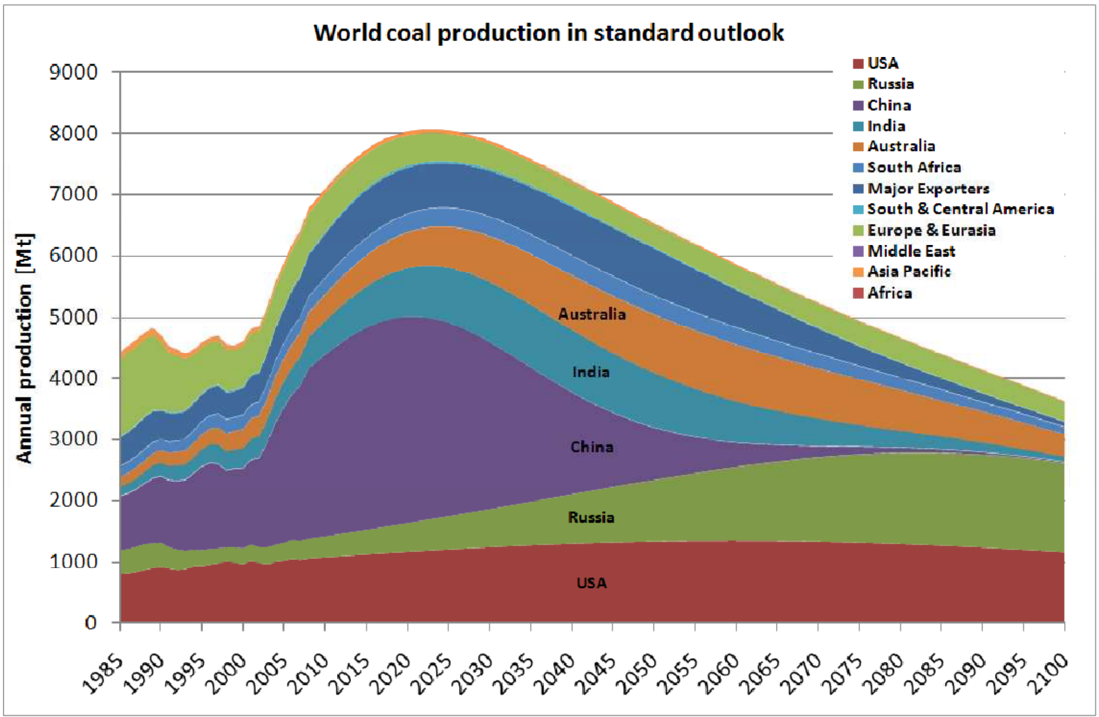

Figure 7.5.: Standard case outlook for future global coal production. Source: ibid.

If coal is to play a role in the process of peak oil mitigation it could only be on a local scale and in combination with other strategies.

7.1.2. Unconventional Oil Alternatives: Natural bitumen, Shale Oil, Heavy Oil, and Deepwater Oil

As conventional oil production nearing its peak, more and more attention is given to economic viability of extraction and processing of other types of liquid hydrocarbons such as unconventional and deepwater oil. Unconventional oil resources, such as tar sands (natural bitumen), heavy and extra heavy oil, shale oil and kerogen (oil shale) are increasingly becoming economic to exploit and considered by some researches and institutions to play an important part in mitigating decreasing light oil production.

Heavy crude oil is defined as high-viscosity crude oil with a density equal to or less than 20° API[17] (934 kilograms per cubic metre). Extra heavy oil is crude oil with a density equal to or less than 10°API (1,000 kilograms per cubic metre). Unlike tar sands, the viscosity of these hydrocarbons is below 10,000 millipoise. Heavy oil is formed by the degradation of conventional oil in shallow reservoirs (Rogner, et.al., 2004).

BGR (BGR (Bundesanstalt für Geowissenschaften und Rohstoffe [Federal Institute for Geosciences and Natural Resources]), 1995) estimates that around 315 gigatonnes are existing in earth crust with 33 considered to be reserves and 77 Gt – as resources. About half of heavy oil resources are in Venezuela; the former Soviet Union, Kuwait, Iraq, Mexico, and China account for most of the rest and these countries are responsible for all heavy oil production (Ibid.).

Tar sands (natural bitumen) – another perspective replacement of conventional oil - are sands or sandstones that contain a large portion of tarry hydrocarbons with a viscosity exceeding 10,000 millipoise. They are formed by thermal metamorphism and biodegradation of conventional oil deposits. The high viscosity of these hydrocarbons requires unconventional extraction methods such as mining with bucket-wheel excavators or in truck and shovel operations. Natural bitumen typically contains large portions of sulphur and trace elements, including vanadium and nickel (Rogner & et., 2004).

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[17] API gravity is a measure developed by American Petroleum Institute to characterize the crude oil according to mixture of compounds of carbon and hydrogen in its structure by using the following formula:

$$\boxed{API \quad gravity = \left[\frac{141.5}{specific \quad gravity}\right] - 131.5}$$

BGR (1998) estimate that 115 out of the 658 gigatonnes of tar sands qualify as possible reserves. Commercial production is only taking place in Alberta, Canada with the current volume estimated around 1.5 mb/d (EIA, 2011).

Oil shale is a sedimentary rock rich in organic matter containing more than 10 percent kerogen. It can be used directly as a fuel in power plants or processed to produce synthetic petroleum products. The kerogen content of oil shale varies widely. According to BGR (1995), only about 1 percent of world resources contains more than 100 litres of oil per cubic meter rock, while 85 percent have less than 40 litres per cubic meter (Rogner, et.al., 2004).

Although it is estimated (BGR, 1998) that there are substantial amounts of oil shale resources (482 Gt), because of high costs of mining and processing, reflecting the low - 3.5:1 EROI (Mut, 2005), production so far is limited to small quantities in China and Estonia. This is not going to change much in the future according to projections from EIA “International Energy Outlook 2011” Report (**Fig. 7.6.**):

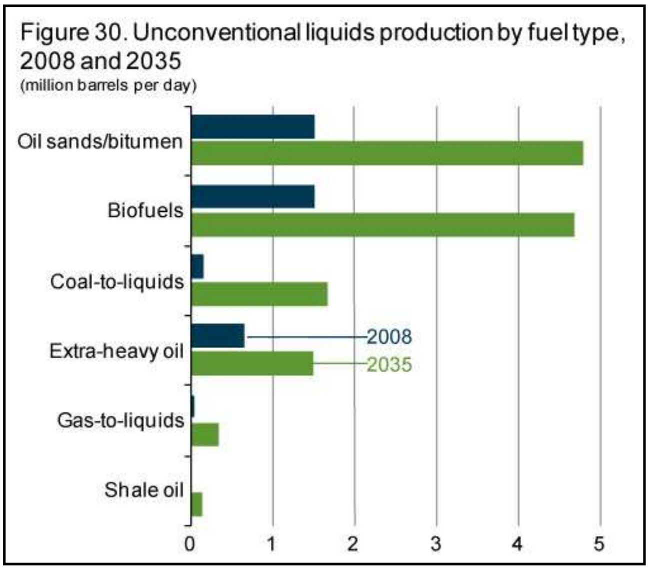

Figure 7.6.: Unconventional liquids production by type, 2008 and 2035. (EIA, 2011)

The other Agency (IEA) in its WEO 2010 Fact Sheet gives a prominent role to unconventional type of oil extraction in providing necessary replacement barrels to conventional oil in order to satisfy growing world demand. It projects the growth from current 2.3 mb/d (2009 figures) to 9.5 mb/d in 2035 with Canadian oil sands and Venezuela’s heavy oil dominating the mix at 4.8 and 1.5 mb/d respectively (IEA, 2010).

There are few problems however that needed to be overcome for these expectations to fulfil themselves.

Firstly, it’s the refinery capacity. Most of the refineries in the world are designed to handle light crude and new capacity has to be added to handle the projected increase. This is may be more of a logistical problem that economical, since once the demand keep on pushing the price up, the investment will be forthcoming. China, Japan and some other counties are currently investing heavily in Venezuelan refinery capacity (USGS, 2010).

Secondly, the heavy oil and bitumen from tar sands have to be extracted and prepared, before they can be transported to the refineries. This technology is energy and water intensive, lowering the EROEI from unconventional oil extraction to 3:1 even before refining (Simms, 2010). It means that we need to “invest” 7 times more energy in extracting one barrel of oil form unconventional sources in comparison with conventional oil (global average EROI for oil in the first half of the 2000s, was approximately 20:1) (Gagnon *et al.* (in preparation), cited in Hall, Balogh, & Murphy, 2009).

Thirdly, as a result of the above, the GHC emissions associated with extraction of the unconventional oil are on average three times higher than those incurred from the drilling for light crude (**Fig. 7.7.**).

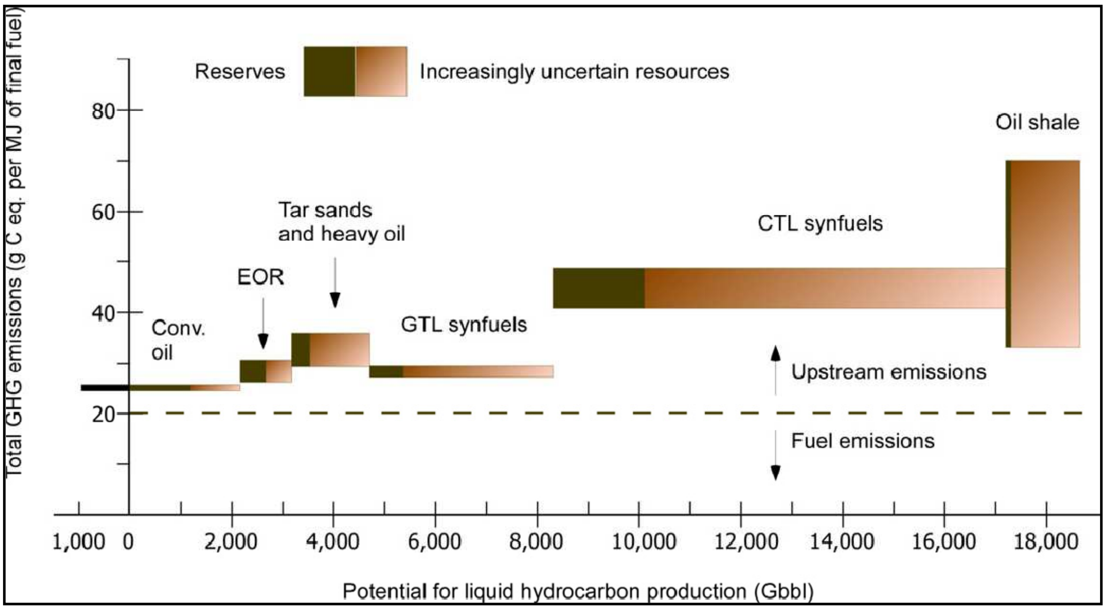

Figure 7.7.: Global supply of liquid hydrocarbons from all fossil resources and associated GHG emissions. Source: (Farrell & Brandt, 2006)

Nevertheless, if we are to disregard these objections, the technical potential of developing resources of unconventional oil alone can provide the world with additional reserves to smoothen the decent in Best Case Scenario, according to Steven Mohr model[18] (**Fig. 7.8.**):

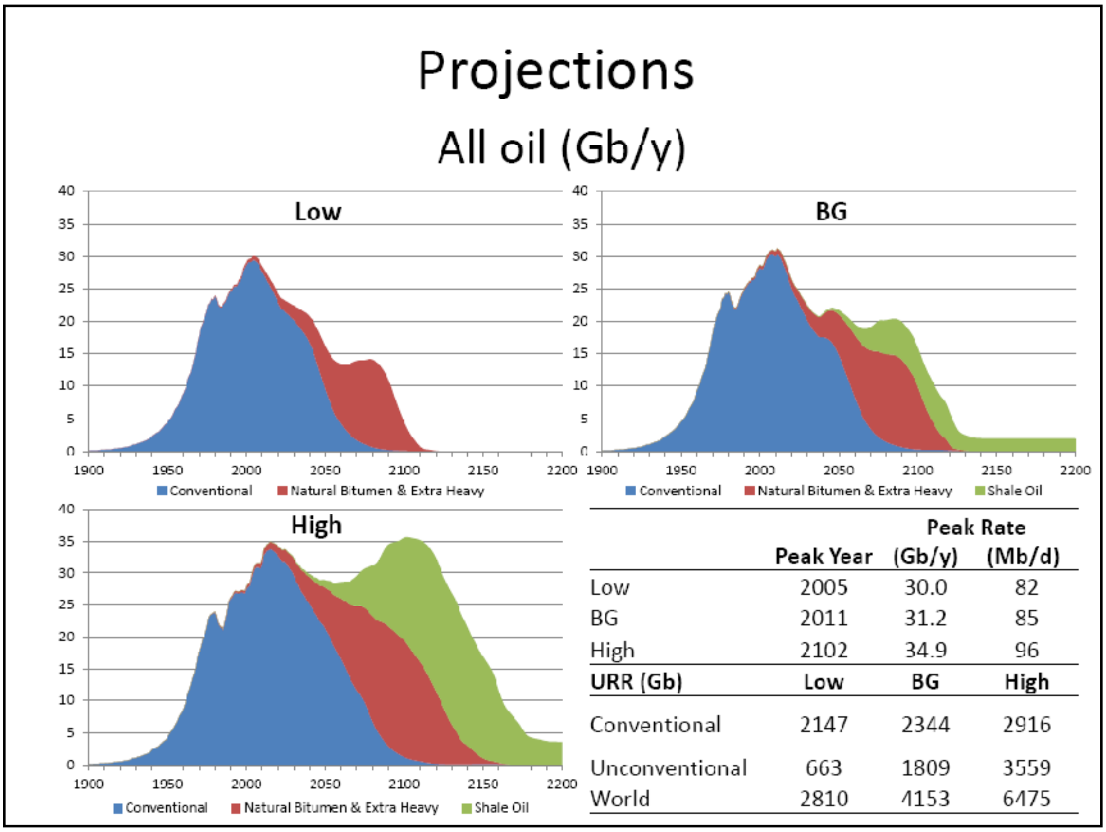

Figure 7.8.: Projections of all oil (conventional and unconventional) production Source: (Mohr & Evans, 2012)

The recent overtaking of the growth in discoveries of ***deepwater oil*** from other discoveries (see [Fig. 6.3.]) indicate that oil companies are forced to look in more and more extravagant places for new reserves. Extraction of deepwater oil, although it does not directly belong to “unconventional” resources as it is generally a light crude, incurs similar problem of low EROEI and environmental concerns, as heavy oil and tar sands. The 2010 oil spill which followed the explosion at BP owned “Deepwater Horizon” platform at Macondo Prospect in Gulf of Mexico, indicated once more how difficult and how dangerous such operations could be and to what

[18] The Model is free to download and to test at ISF of University of Technology Sydney website: “**Geologic Resource Supply-Demand Model**” .

kind of disastrous results they could lead. Nevertheless we could expect the explorations of seabed for oil will continue with Arctic Ocean, becoming the next battleground (Wikipedia, 2012).

Deepwater oil is defined (depending on an organization, i.e. US Government, CERA) as oil fields under the water depth of more than 1000 to 2000 ft (300-600 meters) (IHS CERA, 2010). Total reserves are estimated to be in the range of around 10% of the total global reserves, i.e. between 100 and 150 billion barrels of oil (Laherrere J. , Updating world deepwater oil & gas discovery, 2012).

The production from all offshore deepwater oil rose from 1.5 mb/d in 2000 to more than 5 mb/d in 2009 (IHS CERA, 2010).

The current forecasts from deferent experts on the subject show the range from 8 Mb/d peaking in 2017 (Wood Mackenzie, based on just current projects) and then declining to 2 Mb/d in 2030; to 12 Mb/d and becoming a plateau from 2020 to 2030 by CERA (**Fig. 7.9.**):

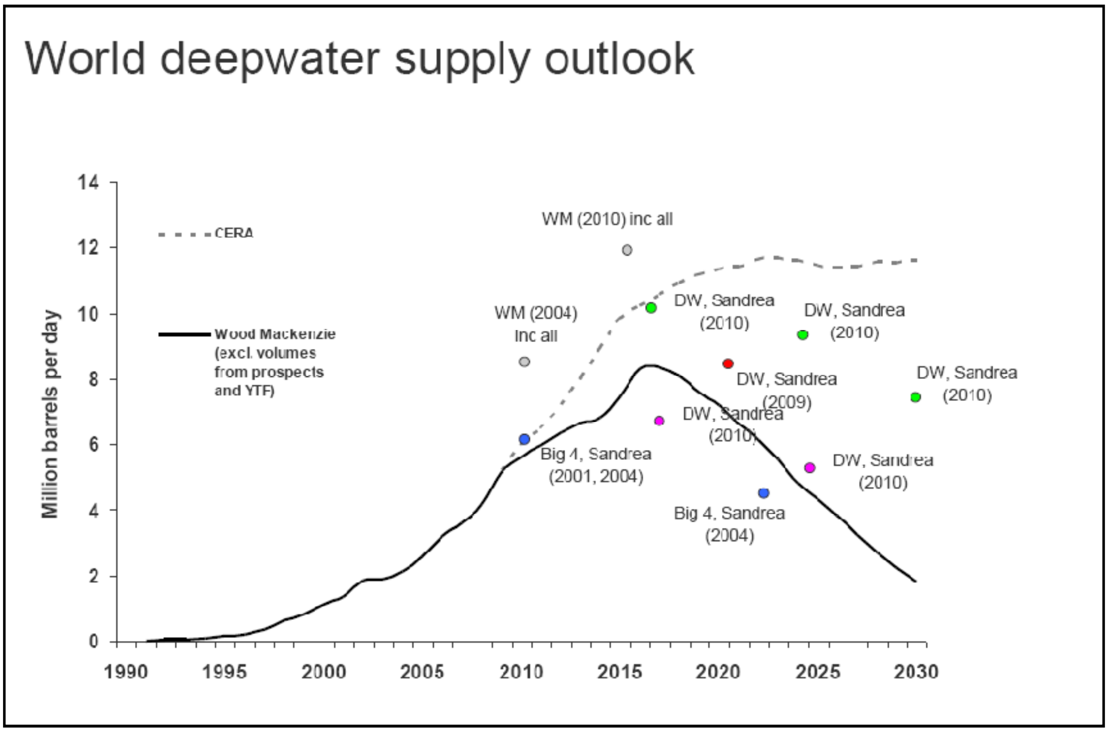

Figure 7.9.: World deepwater supply outlook. Source : CERA and Wood Mackenzie. Source: (Sandrea, 2010).

Laherrere J. (2012) estimates 6.7 Mb/d production for all deepwater in 2010 and using URR of 150 Gb runs Hubbert model and comes up with peak of 11.5 mb/d around 2024, declining to 2 Mb/d by 2050. (**Fig. 7.10.**):

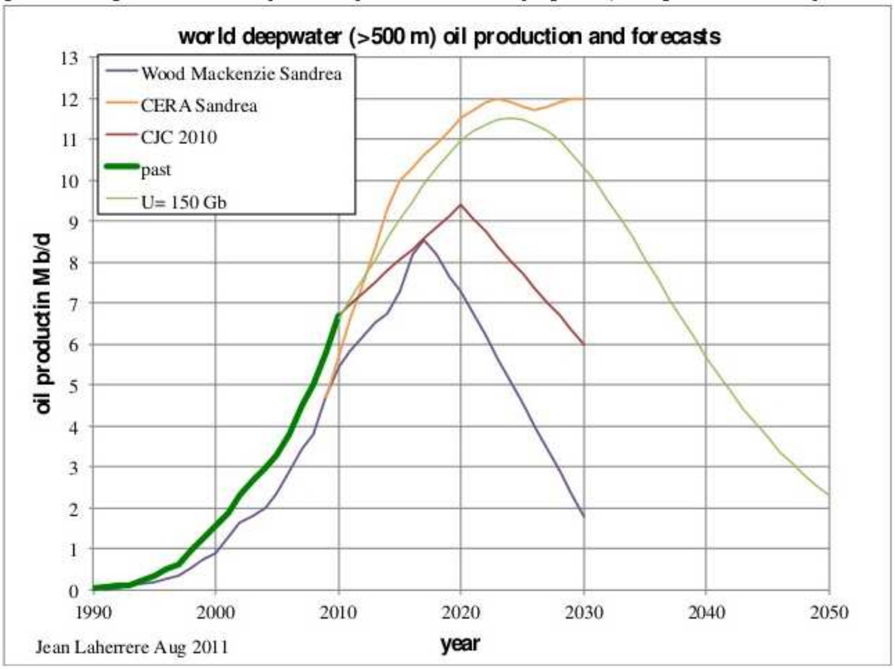

Figure 7.10.: World deepwater oil production and forecast for an ultimate of 150 Gb, compared with the forecasts by CERA and WM. Source: (Laherrere J. , 2011)

It has to be noted that above projections are subject to logistical constrains such as availability of rigs – currently 80% of all deepwater rigs are for hire by one company "Petrobras" (Bloomberg, 2008), lack of trained personal and long lead times from discovery to production (**Fig. 7.11.**):

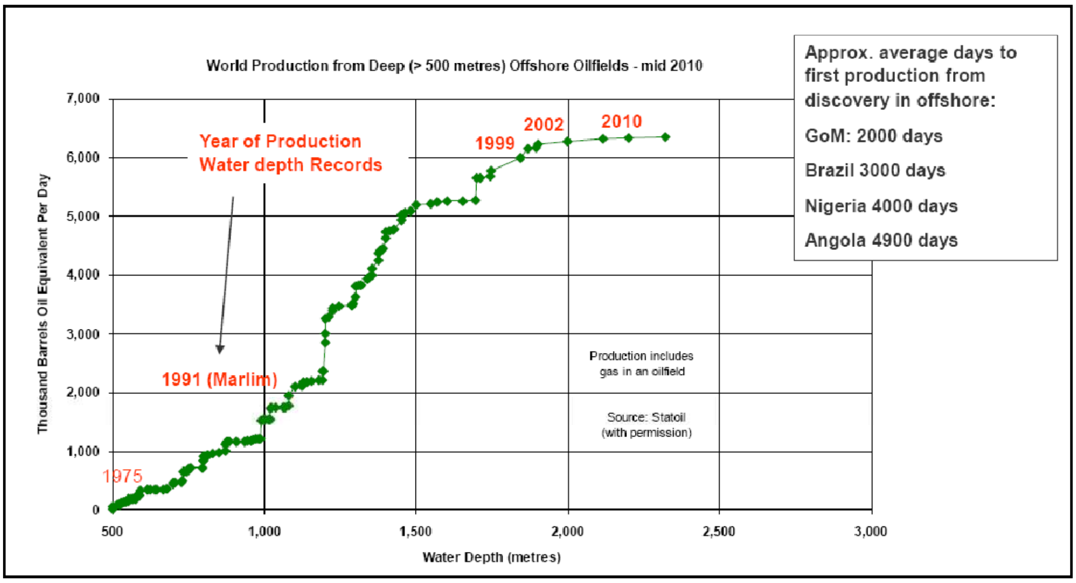

Figure 7.11.: Progressive development of production technology. Source: (Sandrea, 2010) Statoil.

Needless to say that the current high level of oil prices has to stay constant into the foreseeable future for investments into exploration and production to remain profitable for oil companies (**Fig. 7.12.**):

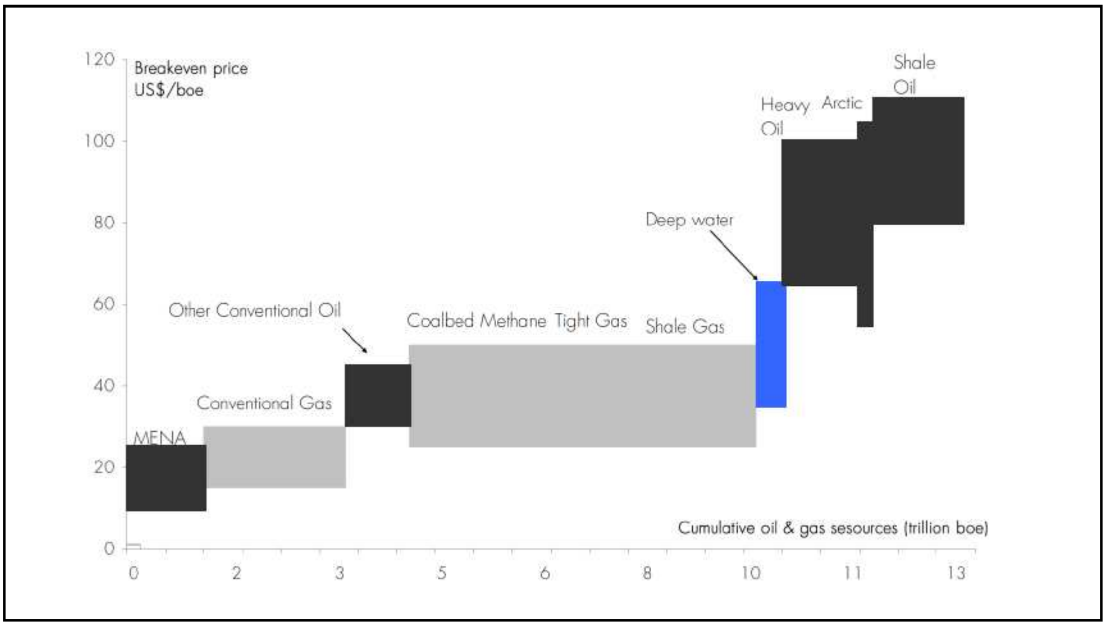

Figure 7.12.: Breakeven price for production of deferent types of oil and gas. Source: (Ibid).

On the balance of things if economic concerns will win over environmental fears, the production from deepwater oil fields can contribute to slowing the decline in production from the existing fields and perhaps bring some additional yearly production capacity to the global oil supply, although not sufficient to become a “game changer” in the race for alternative replacement to conventional oil.

7.1.3. Natural Gas and its derivatives as an alternative

The use of natural gas as a feedstock for production of liquid fuels (namely diesel) is a similar to CTL process and based on Fischer-Tropsch techniques with additional purification and transformation before conversion and upgrading after. The resulting output yields gives typically about 70% of ultra-clean diesel out of one barrel of oil using around 283 m^3 of natural gas as a source (Slaughter, 2007).

There are currently three GTL plants in full operation in the world using the Fischer Tropsch (F-T) process. Two are located in South Africa operated by Sasol and PetroSA (under Sasol licence) and one in Malaysia, operated by Shell.

The Sasol's Oryx GTL plant, that has been build at a cost of 1 billion US$, was opened in Qatar, but not operating yet at its full 34 kb/d design capacity (**Fig. 7.13.**). Shell's Pearl project with the capacity of 140 kb/d in Ras Laffan (also Qatar) began its operation last year, although at a cost overrun above the reported budget of 18-19 billion US$ (Shell, 2012).

Figure 7.13.: The ORYX GTL (gas-to-liquids) plant at Ras Laffan in Qatar. Source: Sasol's website.

The other planned factories (**Fig. 7.14.**) were not that lucky and most projects suffered cancellations and planning delays.

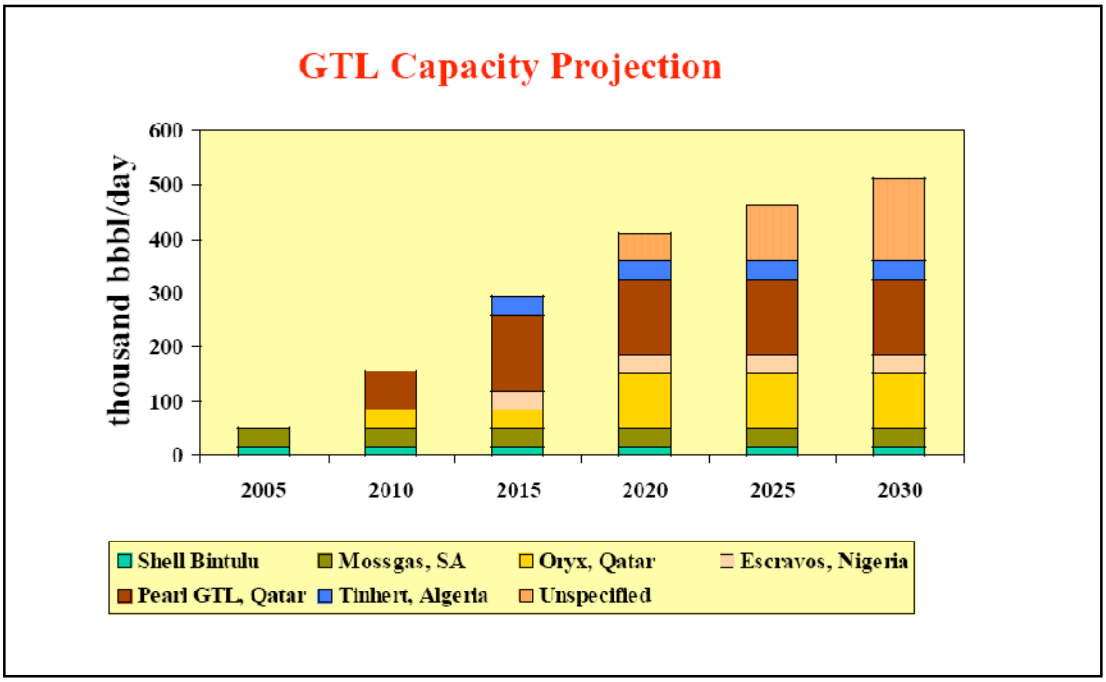

Figure 7.14.: GTL capacity projections. Source: (Slaughter, 2007).

That is why, perhaps, EIA downgraded its forecast for production of GTL in 2030 from 2.6 mb/d in IEO 2006 to 0.3 mb/d in 2008 version of IEO (Paul, 2008).

IEA WEO2010 gives GTL only slightly better chances in filling up the gap, left by diminishing light crude (**Fig. 7.15.**):

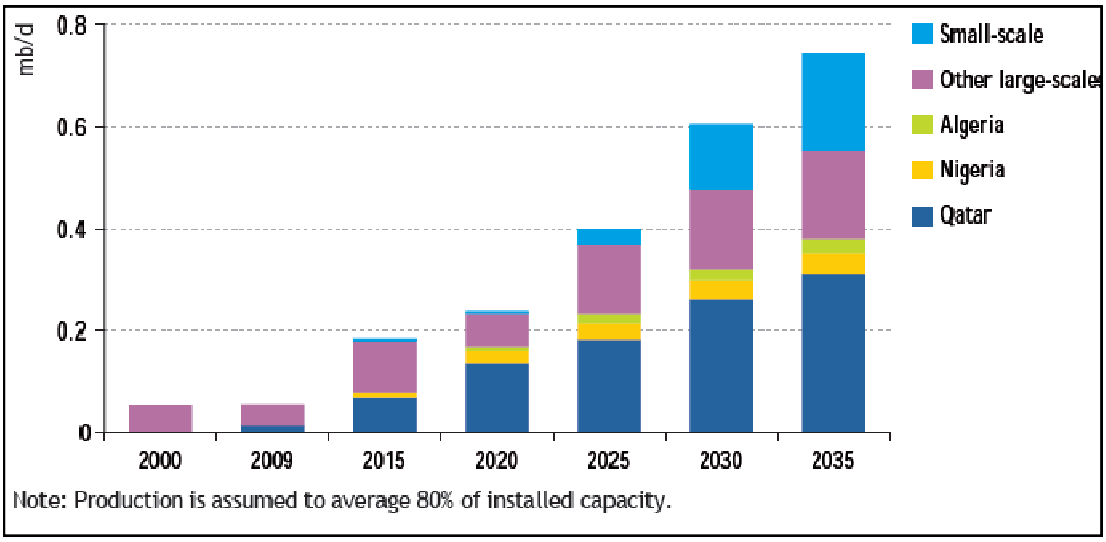

Figure 7.15.: GTL production by source in the New Policies Scenario. Source: (IEA, 2010)

Using GTL plants – if they can be scaled down - can be economically advantageous in places, where gas or associated oil fields are so remote, that building a pipeline makes no commercial sense. Then this type of facilities can help to “monetize” otherwise flared or left underground gas. Whether this would make sense in energetic terms, when 40% of gas is being “consumed” within process of conversion is another matter (Chandra, 2012).

From the environmental point GTL technology on its own (without CCS) is also more damaging as about a quarter of the gas is turned into CO_2 during synthesis process, resulting in well-to-wheels emissions of GTL diesel being 10% to 15% higher than those of diesel refined from conventional crude (Wang & Huang, 1999).

The other option within existing technologies, of course, is a direct use of natural gas or its components in their compressed or liquefied form as CNG, LNG or LPG.

Compressed Natural Gas (CNG) is a known and relatively widely used substitute to oil derivate fuels (gasoline, diesel) and “auto-gas” (propane/LPG). It is produced by compressing natural gas (mainly composed of methane, [CH_4]) to less than 1% of its atmospheric volume at 200 to 248 bar.

It is slightly more environmentally friendly fossil fuel as it releases 20 to 28 % less $CO_{2eq.}$ on a WTW basis than that of diesel or gasoline[19] (**Fig. 7.16.**):

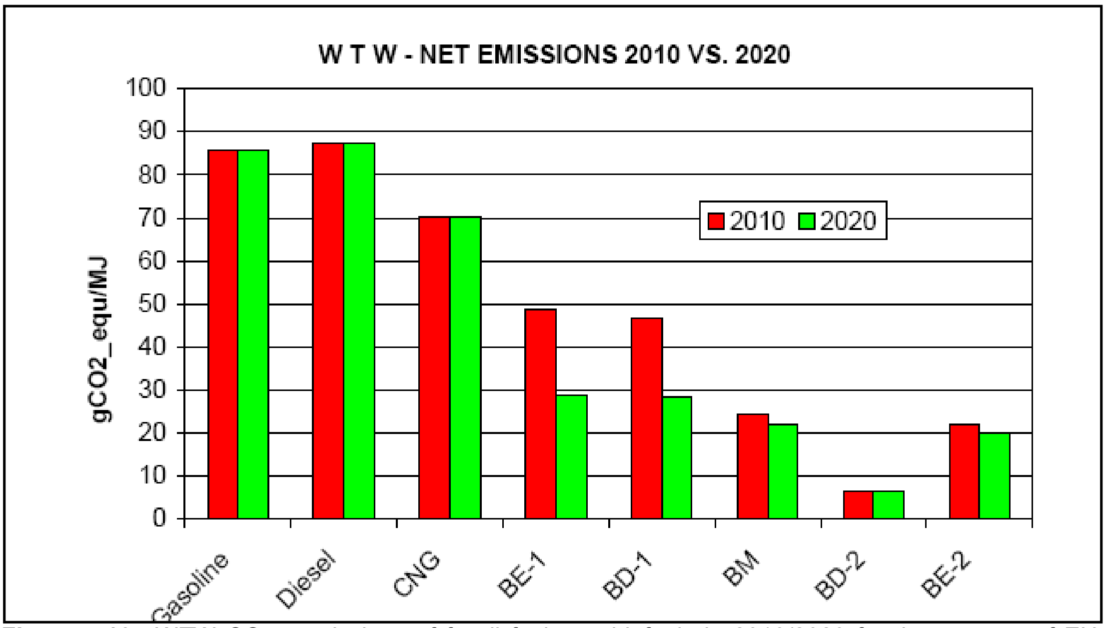

Figure 7.16.: WTW CO_2 emmissions of fossil fuels vs. biofuels in 2010/2020 for the average of EU countries. Source: (Ajanovic, et al., March 2011).

Currently there are 16.5 million vehicles worldwide using natural gas as fuel, consuming on average 2.26 million m^3 of gas a month (NGV Journal, 2011).

According to the data from WEO 2010 (IEA, 2010), tripling the total amount of vehicles, running on CNG will bring additional "savings" of nearly 1mb of oil per day. Increasing the total fraction of the global HGV fleet using CNG from 1.5% in this Scenario to 5% should bring additional reduction in oil use by 0.6 mb/d.

Small part (10%) of these NGV is running on ***LNG***. ***LNG Technology*** is mainly used currently to transport the otherwise stranded gas to the distribution centres – LNG Terminals connected to pipeline network. Because of the larger reduction in volume via liquefaction process, its higher energy density (**Fig.7.17.**) than that of CNG makes it a better solution for use in HGV and busses, requiring longer haul journeys between refuelling.

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[19] See also (California Air Resource Board, 2010).

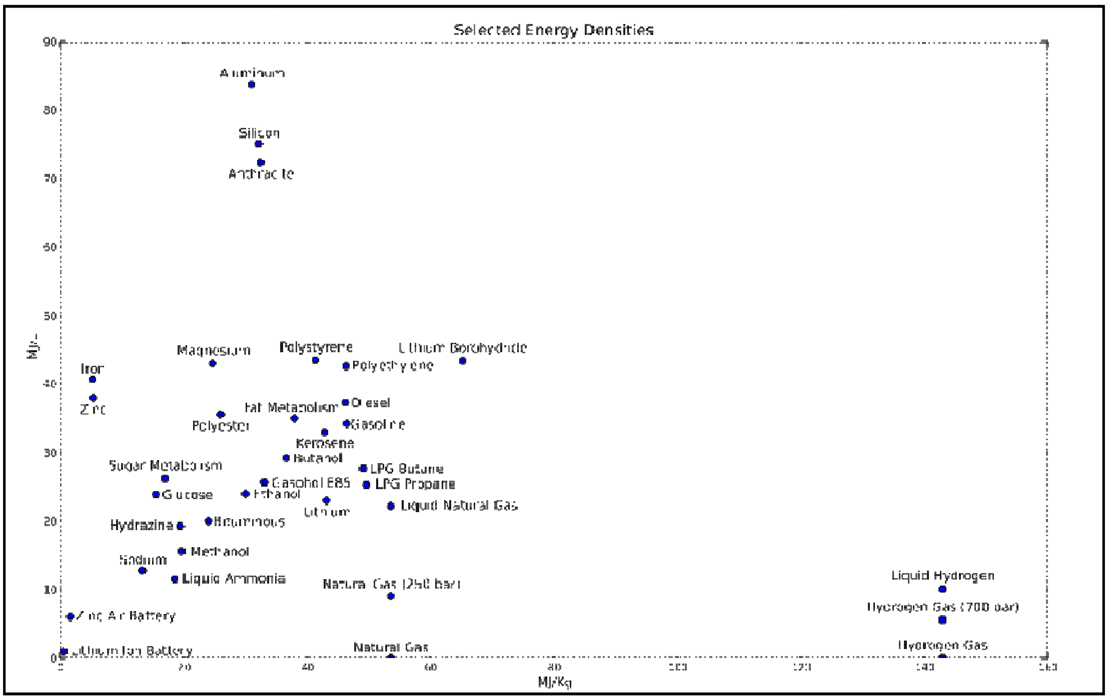

Figure 7.17.: Selected Energy Densities for different types of fuel and material. Source: (Wikipedia, 2012).

LNG has similar if slightly higher to CNG GHG characteristics albeit 5% to 10% lower conversion efficiency (Wang & Huang, 1999).

The main drawback to using LNG as well as CNG as a wide replacement to crude derived fuels is the infrastructure investments and although the current number of fuelling stations is constantly growing around the world The IEA WEO2010 estimates that the tripling of the current NG fleet will only bringing “saving” of over 1 mb/d in 2035 in comparison to 300 kb/d as in 2009 (IEA, 2010) (**Fig. 7.18.**):

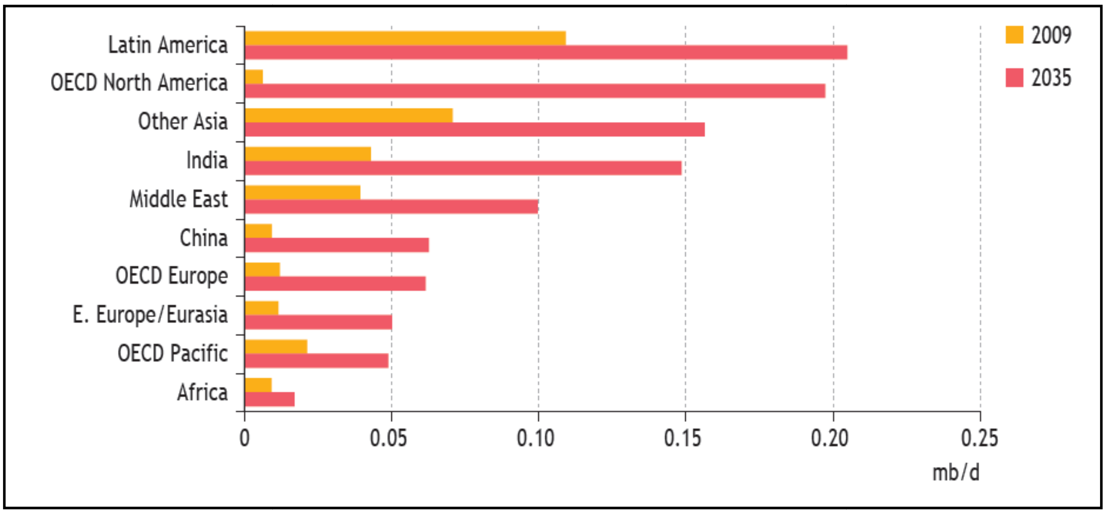

Figure 7.18.: Oil savings by the use of natural gas in road transport by region in the New Policies Scenario. Source: (IEA, WEO 2012).

LPG or ***“autogas”*** as it is popularly known is another gaseous alternative to diesel and petrol in transportation. It is well known and established fuel, which is currently used in over 13 million vehicles worldwide. (NGV Journal, 2011).

LPG is a mixture of mainly propane and butane and has 2.5 times higher calorific value as natural gas. Its slightly lower energy density then diesel or petrol (**Fig.7.17.**) means however that its fuel consumption is 10-15% higher. LPG is currently produced in oil process refineries as well as in natural gas processing plants where it is stripped from the “wet” gas as the latter is pumped out from the ground.

Its ease of storage and transportation means that it is used in many other applications such as cooking and home heating as well as refrigeration apart from as a vehicle fuel and therefore cannot be assumed to play a major role in substituting other liquid fuels, even if the gas production is to grow in the future.

7.2. Biological alternatives to oil as transport fuel

Biofuels have received much attention recently in the wake of tightening supplies and high oil prices. They are deemed by many as a way out of double edge sword of dwindling supplies of crude and rising GHG emissions. The opponents of mass production of biofuels voiced concerns however about land competition with food production, CO_2 emissions associated with direct or indirect land use change, high investment costs and low energetic returns. Nevertheless IEA projects in their New Policies Scenario fourfold increase in use of biofuels for transportation from just over 1 mb/d today (**Fig. 7.19.**) to 4.4 mb/d by 2035, covering 8% of total world demand (IEA, 2010).

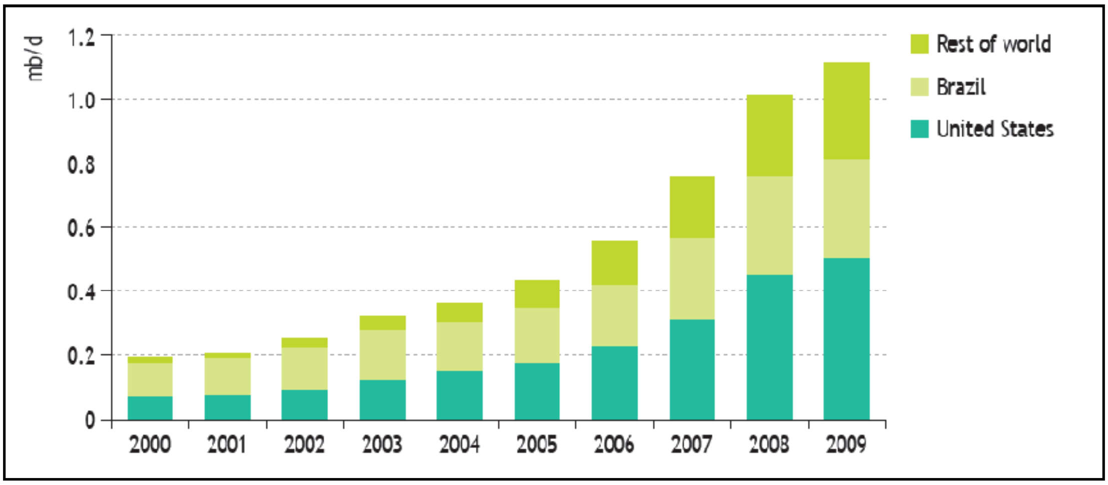

Figure 7.19.: Biofuels production in key regions. Source: (IEA, 2010).

Currently just a couple of technologies compliment to the production of biofuels. They are production of bioethanol from corn or sugarcane and of biodiesel from vegetable oils or animal fats.

7.2.1. Bioethanol

Bioethanol is an alcohol made by fermentation of mostly carbohydrates produced in sugar or starch crops (Friedl, 2010). Cellulosic biomass, derived from non-food sources such as grass or trees, is also being developed as a feedstock for ethanol production. There is currently however no commercial plant production in the world, although a number of research facilities exists it Europe and USA. IEA in its WEO 2010 does not expect for cellulosic biomass plants to make any significant contribution in ethanol production before 2020, eventually rising the production to almost 1.6 Mb/d by 2035 (IEA, 2010).

At this moment of history, however, almost all bioethanol production is concentrated on American continents, with USA and Brazil producing just over 90% of the total worldwide and the rest is being in almost equal share divided by EU, China and India.

Bioethanol production is currently supported by the government financing to the tune of 13 billion US$ in 2009 (IEA, 2010) and "suffers" from very low EROEI – from 1.3:1 to 2.3:1, depending on calculations (Shapouri, et al., 2010). Its contribution to GHG reduction is also questionable as the production process requires high energy input, currently mainly from natural gas. Additionally, changing precipitation patterns on the warming planet put extra strain on water use in production of ethanol. The continued growth success of the bioethanol industry in the USA is under question as calls to the Senate requesting to withdraw multi-billion subsidies are finally succeeded (World Street Journal, 2012), especially under current (2012) drought situation.

Although bioethanol production from sugar cane in Brazil yields higher EROEI of 5.5:1 to 10.7:1 (worst/best case scenario) (Smeets, Junginger, Faaij, Walter, & Dolzan, 2006) and contributes to 80% reduction in GHG emissions, if used locally, there are still open questions remaining regarding land use change; soil erosion, water usage, biodiversity loss. The current working conditions on Brazilian sugar cane plantations remain in the sharp focus of public attention as well.

Bioethanol can be currently added to petrol in 1:10 ratio without any technical problems. The increase of this ratio, although not impossible, would require technological adjustments to car engines as well as infrastructural changes to petrol delivery stations.

7.2.2. Biodiesel

Biodiesel is the most common biofuel in Europe (**Fig. 7.20.**):

	Ethanol		Biodiesel		Total	
	Mtoe	kb/d	Mtoe	kb/d	Mtoe	kb/d
United States	21.5	470	1.6	33	23.1	503
Brazil	12.8	287	1.2	25	14.1	312
European Union	1.7	38	7.0	140	8.7	178
China	1.1	24	0.3	6	1.4	30
Canada	0.6	13	-	-	0.6	13
India	0.1	3	0.1	2	0.2	5
Other	0.9	20	2.7	51	3.6	72
World	38.7	855	12.9	257	51.6	1 112

Figure 7.20.: World biofuels production in the world, 2009. Source: (IEA, 2010).

It is produced from oils or fats using transesterification and is a liquid similar in composition to fossil/mineral diesel. Transesterification is the principal method of converting vegetable oils into biodiesel, during which relatively viscous TAGs are reacted with methanol in the presence of a catalyst to produce fatty acid methyl esters (FAME) which resemble petroleum-based diesel fuel, along with a glycerol co-product (Darzins, Philip., & Edye, 2010).

For 2008 the largest amounts of biofuels are found in Germany, France, Austria and Lithuania. The average for the EU-27 amounted to 3% in 2008. In the European Union by 2020 10% of energy used in transport should be from renewable energy sources, certified biofuels in practical terms (Ajanovic & et al., March 2011).

To qualify as a renewable fuel, savings on GHG reductions of over 35% have to be achieved. Currently only rapeseed biodiesel qualifies under this rule with imported soya bean and palm oil diesel falling below this rule. (IEA, 2010). This could change for the worse, however, if land use change factors are included into calculation in the future, as intended by EU Commission (van Renssen, 2012). As far as energetic balance is concerned, then just for the final product (excluding byproducts and energy for their production) biodiesel from soya beans “returns” at the ratio of 7.3:1 (Hill J., et al., 2006).

Currently biodiesel – in the same manner as bioethanol in gasoline - is mixed into fossil diesel at a rate of between 5% and 10%. Potentially this mixture can be increased to 20%. Further modifications to engine are required if the percentage of biodiesel is to exceed this barrier. Other potential drawbacks are land use change, as once mentioned above, and downstream aquifers pollution with fertilizers and associated chemicals.

As mentioned before, although a lot of research is being currently undertaken into the development of the second and the third generation of biofuels, these technologies are not envisaged to play a significant role in providing replacement for crude derivatives in transportation in the next 10 to 15 years and even thereafter their contribution could be marginal (IEA, 2010).

7.3. Changing the Energy Carrier

7.3.1. Electricity

Electrification *of* current transport system offers considerably "saving" potential from current dependency on oil. Electric engine is 2 to 3 times more efficient than ICE and nearly maintenance-free. Electrification process could encompass three main sectors of transportation: private, public and goods. From the environment perspective electrification of transport services offers potential "savings" in GHG only when combined with increase in production of electricity from renewable sources.

Electrification of goods transport is only feasible in switching from road to rail and public transport is already offers high levels of electrically or gas driven stock and further improvements in this area although needed, will bring only limited reduction in oil use. Electrification of private transport offers by far the greatest reduction in petroleum consumption that is why it is worth looking at it in more detail.

There are few technologies that are currently available to private motorists. Battery electric vehicles (BEV) are driven by electricity stored in the carried on board of the car batteries. These could be lead-acid, nickel-cadmium, lithium-ion, nickel-metal hydride, sodium-nickel chloride. There are issues concerning availability, production, recycling and disposal of these elements, but this topic has not left the world of academia, as there are currently only around 60 000 EV projected to be sold in 2012 in comparison with over 60 million of ICEV's. This is not going to change much in the near future according to IEA projections (**Fig. 7.21.**):

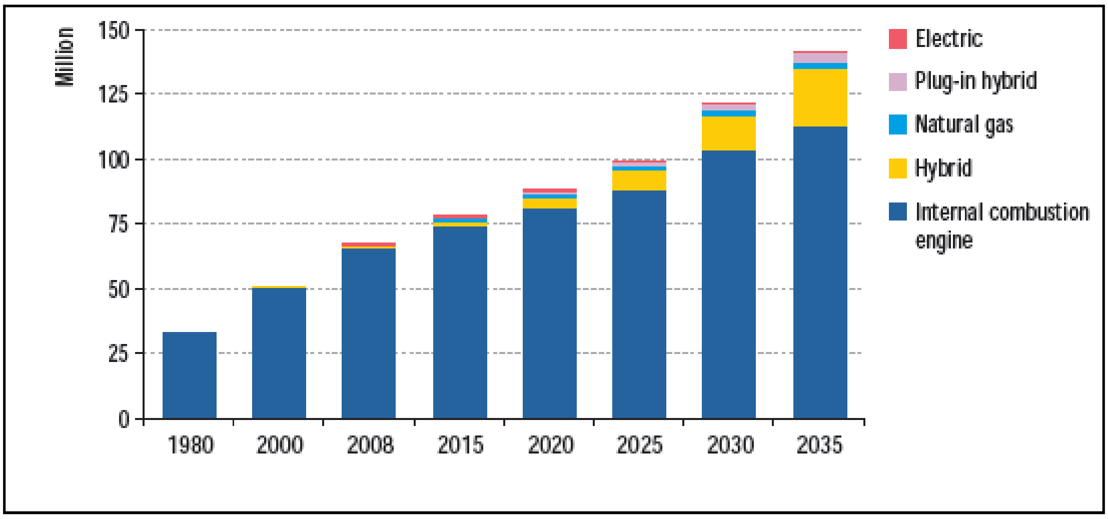

Figure 7.21.: Passenger light-duty vehicle sales by type according to New Policies Scenario. (IEA, 2010).

The main drawbacks preventing the sharp rise in uptake of BEV by consumers is the smaller driving range between recharging of around one fifth in comparison with similar ICE car; long recharging time and high up-front cost related with the battery costs. Unless at least the last two can be addressed by the industry, this trend is not expected to change in the near or medium term future.

Ecological benefit analysis on the WTW basis shows no significant difference between GHG emissions left by ICEV or BEV, if BEV is charged using electricity from UCTE Coal Mix. Performance is improved twice when electricity is provided by new natural CHP gas plants and, of course, emissions are nearly zero, when just RES electricity is a source of the battery power (Ajanovic & et al., March 2011).

Hybrid vehicles, using different type of technological approaches: plug-in hybrid, range-extenders and so on, are assumed to occupy a higher percentage in overall vehicle sales in New Policies Scenario (**Fig. 7.21.**). This trend, plus technological advances in development of the ICE, spurred by policy incentives and rising fuel costs could bring the average fuel consumption of light duty vehicles sold worldwide from 9.7 l/100km of fuel in 2009, to 7.6 l/100km in 2020 and 6.7 l/100km in 2035 (**Fig. 7.22.**):

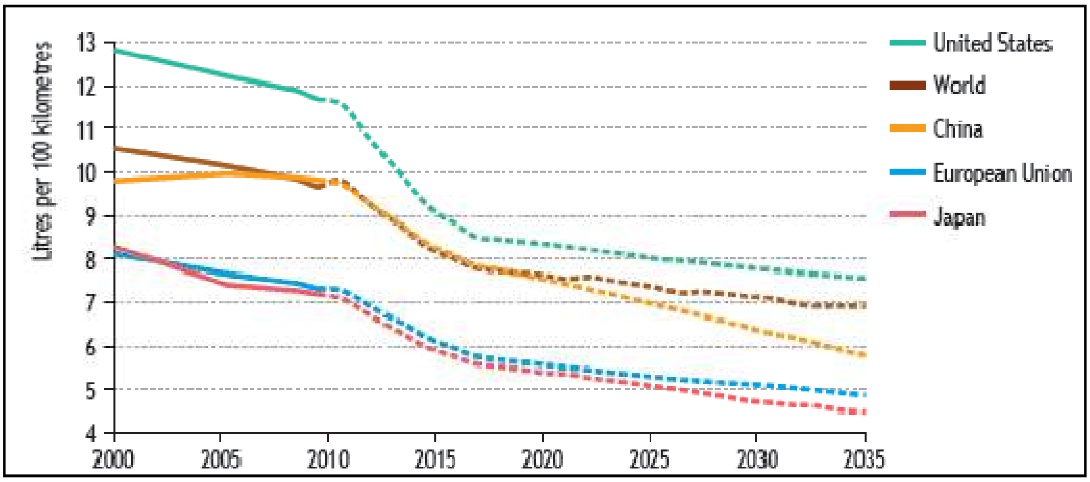

Figure 7.22.: Average fuel economy of new passenger cars by region in NPS. Source: (IEA, 2010).

Whether resulting efficiency savings will translate in lower consumption – owing to [Jevons paradox]() – is open for debate, as people are known to tend to buy larger cars and travel longer distances, when they can afford it (Ajanovic & Haas, 2011).

Much will depend on consumer behaviour in developing BRIC economies, but with the growing trend of more and more consumers in these countries aspiring to ownership of private vehicle the world average oil consumption per capita is likely to grow to 0.25 toe/capita/a. (**Fig. 7.23.**):

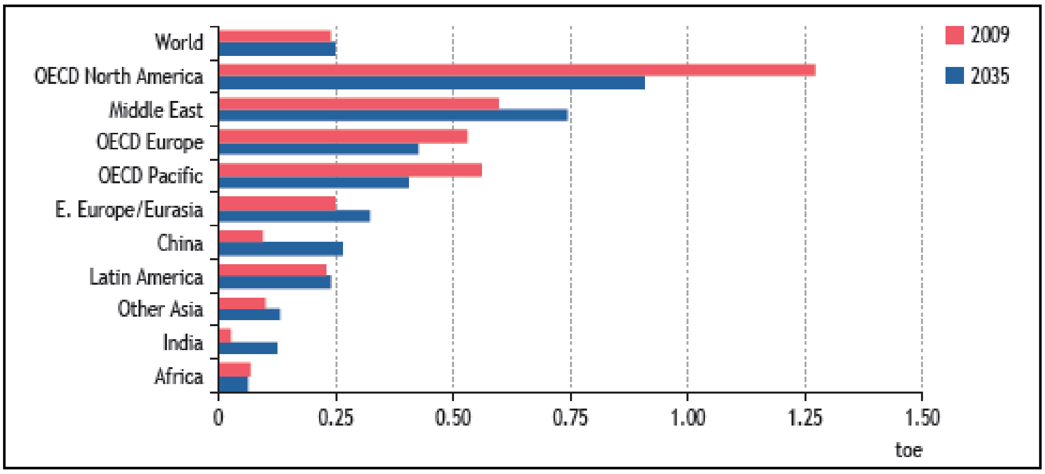

Figure 7.23.: Road transportation per-capita oil consumption by region in NPS. Source: (IEA, 2010).

This seemingly unstoppable growth in private car ownership can only be reversed by physical constrains in the cities (parking/road space/ecology), economic considerations (rising fuel costs/congestion charging) or political intervention – time limitation on use, like the one practiced in Athens, or purchase limitations, like the one being recently in the news from China.

Developing existing and creating a new electrified public transport infrastructure in growing cities across the planet can bring down $CO_{2.eq.}$ per person per kilometre travelled, helping significantly to improve air quality in modern megacities. Electrically-powered transportation reduces final energy use by more than a factor of three, as compared to gasoline-powered vehicles (International Institute for Applied Systems Analysis, 2012). And of course the best reduction can come from so called nega-miles travelled, or switch to walking and biking in the cities.

The projected 5%-6% growth of truck sales (IEA, WEO 2010) in the total share of increasing transport figures (**Fig. 4.2.**) will easily swallow any potential savings from switch to hybrid or gas propelled engines in this sector. The use of rail and river transport can take some pressure of the HGV market, but to what extent and at which cost is subject to further research and acceptance of longer delivery times by the industry.

7.3.2. Hydrogen

Another energy carrier, that has been extensively researched as an alternative replacement of carbohydrates in the world economy is hydrogen. Because of its highly reactive nature hydrogen, like electricity, needs to be produced either with the help of either steam methane reforming or electrolysis of water technologies. Other processes exist and many more are being researched driven by the fact that unlike electricity hydrogen can be stored and transported in its liquefied/compressed form.

The fact that it is difficult and expensive – both in economic and energetic senses - to produce has slowed hydrogen based technological development to the point that it has never left the world of experimental and chemical industry or the world of academia.

Additionally, producing hydrogen from methane does not address the finite problem of fossil materials at least in the long run. Secondly it leaves open the question of what to do with by-produced GHG. Finally, it is an energy sink process, which could only make sense in the world of abandon cheap energy, and not in the one that is struggling to replace what is simultaneously being depleted.

The second, most widely used, method of water electrolysis albeit more environmentally friendly, leaves open the high cost in energy and infrastructure.

Using electricity to create hydrogen to drive our cars, leaves open the viability question of using electricity direct to charge car batteries. Moreover the costs of infrastructural transition to hydrogen economy are prohibitively high at the best of times, let alone at a time of the peak oil looming on the horizon. Such transition, even if implemented, and some countries are trying to – Iceland for one, would take at least 20 years of concentrated effort to achieve (Sullivan & Brown, 2009). All current indications are that our industrial civilisation has neither will, nor time or money to go down this route.

8. Transition Strategies

8.1. Time window

When and if (!) the western industrialized society and by this description I mean business community, media, general public and political classes, will come to realization and acceptance of the enormity of the problem we facing when discussing options at hand and transition strategies available to us it is surely important to know the time scale on which we can rely when making a decision. As discussed above, the exact timing of peak or plateau, followed by eventual decline in oil extraction is only possible to determine with hindsight. The comprehensive report on "Global Oil Depletion" by United Kingdom Energy Research Centre made a thorough review of some 700 scientific articles on this subject and came to the conclusion (Ibid, *p. 165*) that "On current evidence… a peak of conventional oil production before 2030 must be considered likely", and that "…on the balance of the 'above' and 'below' factors involved… there is a significant risk of a peak in conventional oil production before 2020." (Sorrell, et al., 2009).

8.2. Transition period

The development of the alternative energy solutions to mitigate the consequences of the decline in oil extraction require an unprecedented up to now level of investment and long lead times to implement technological changes needed to be adopted by the economy. The pioneering Hirsh Report suggests minimum 20 years adaptation period of successful transition (**Fig.8.1.**):

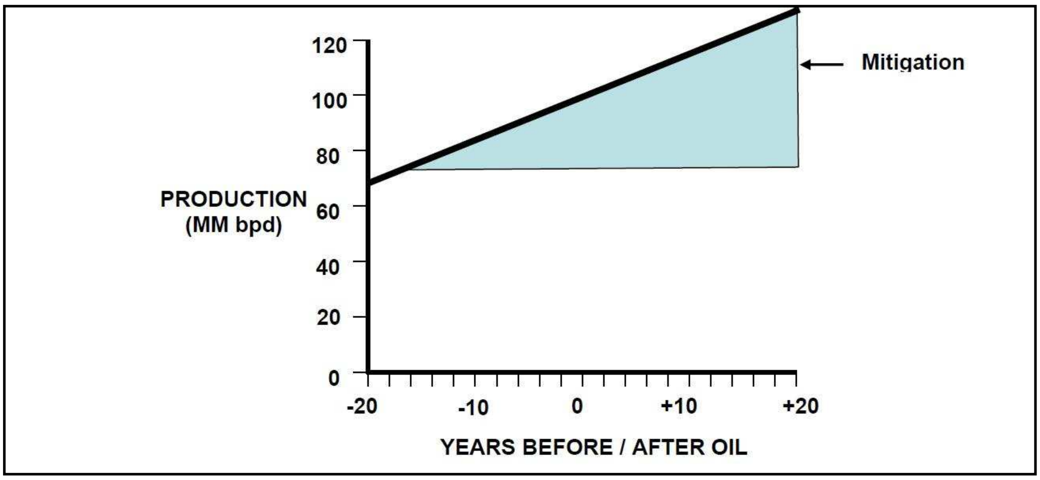

Figure 8.1.: Mitigation crash program 20 years before peaking. Source: (Hirsch et al., 2005)

The Report also points to the asymmetric risks of mitigation and stresses that “…the failure to act on a timely basis could have debilitating impacts on the world economy:

- Mitigation actions initiated prematurely will be costly and could result in a poor use of resources.
- Late initiation of mitigation may result in severe consequences. (Ibid. *pp. 59-60*).

8.3. Range of scenarios

What this mitigation can look like in reality? I propose to have a look at 4 scenarios under following assumptions:

On the production side:

- the conventional (easy/sweet/light crude) oil has peaked at around 70 million barrels a day in 2006 (IEA, 2010) and
- undulating plateau with modest gains from EOR, unconventional oil and NLG is following for 10 years after which the terminal decline sets in.
- This decline after peak production of all liquids in 2016[20] will follow a slow decline in 4 possible paths:

1.	Scenario_P1	- linear drop of 0.5% year on year
2.	Scenario_P2	- linear drop of 0.5%, increasing by extra 0.5% every 5 years
3.	Scenario_P3	- dropping 0.5% exponentially
4.	Scenario_P4	- linear drop of 0.5% with a doubling rate every 5 years

[20] DOE EIA.Report "Long Term World Oil Supply", (Wood & Long, 2000), has projected 12 possible scenarios for oil production peaking based on USGS estimates of world conventional resource base. Hirsch Report takes 2016 year of peaking as the most plausible scenario, stating however (p. 69) that USGS figures are overly optimistic. Based on the review of the literature mentioned in §5.2. I assume Hirsch figure to be right and run my model calculations based on that assumption. The fact that mitigation process takes a generational life-time and that increasing or decreasing the resource base by the amount of consumed to-date oil “only” moves the date of peak oil by a decade, makes the exact date less relevant figure, rather a “point-zero” from which irreversible changes start to occur.

These scenarios will be compared by the demand curves following other 4 possible assumptions:

On the demand side:

1.	Scenario_C1	- BAU (1.3% growth - av. during 2000-2010)
2.	Scenario_C2	- modest growth of 0.5% year on year[21]
3.	Scenario_C3	- Steady State - growth of 0.0% year on year
4.	Scenario_C4	- Decline 0.5% year on year

These relatively modest decline scenarios (individual fields follow more steep curves of around 4% on average (Hamilton, Oil Prices, Exhaustible Resources, and Economic Growth, 2011)) intend to demonstrate the scale on which the alternative solutions have to be found in order to replace declining production of crude oil (**Fig. 8.2.**) even on these modest assumptions:

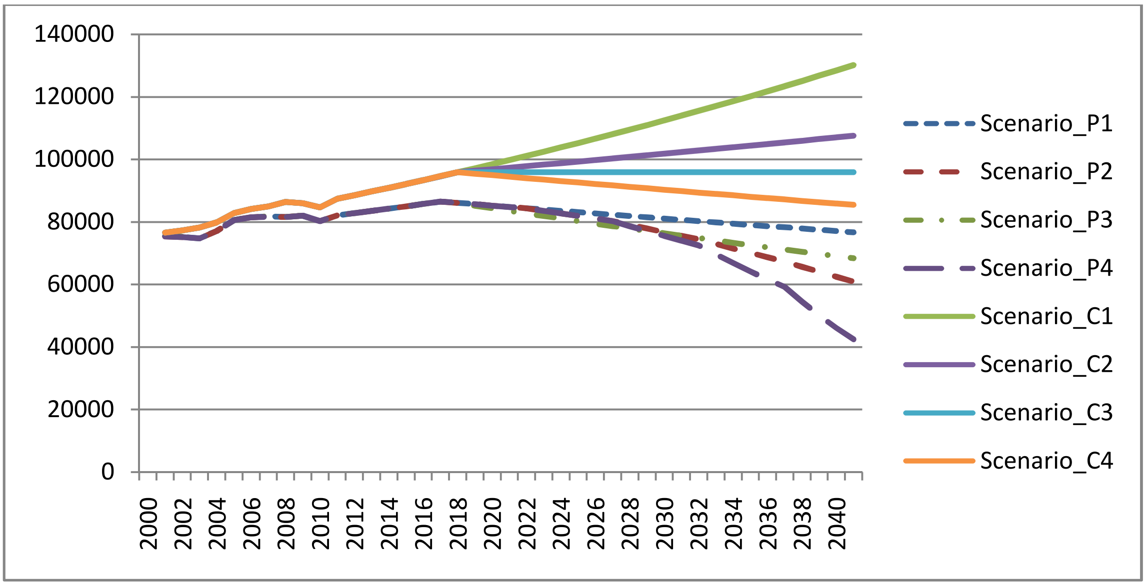

Figure 8.2.: Consumption vs Production (000' b/d) in 8 extrapolated curves. Data source: (BP, 2012).

[21] BP 2012 Energy Outlook 2030 (BP, January 2011) projects 1% for example.

The result of these extrapolations gives us 4 possible scenarios with 16 different outcomes. (**Fig. 8.3. - 8.6.**):

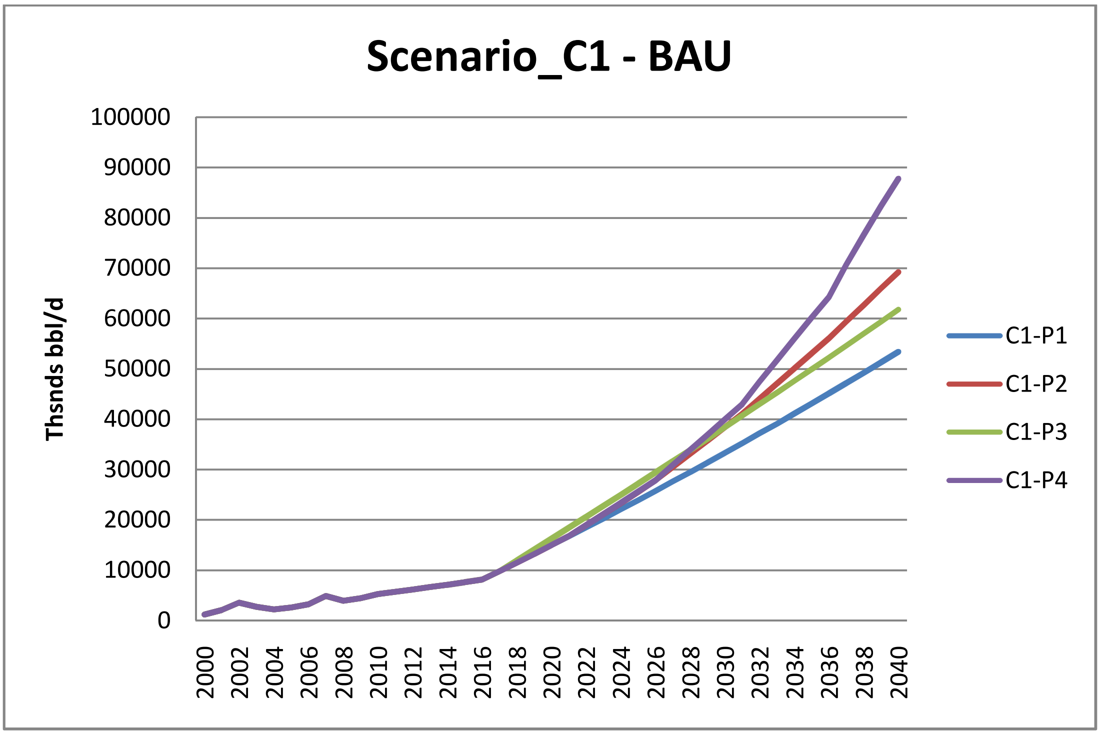

Figure 8.3.: Difference in consumption demand and production under BAU Scenario.

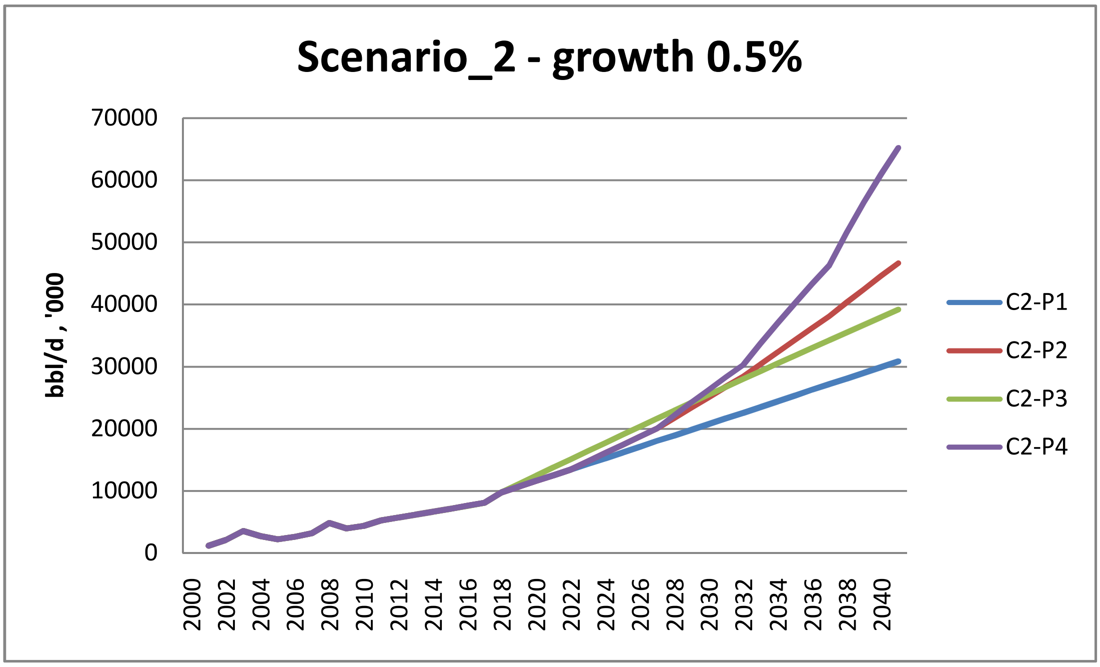

Figure 8.4. Difference in consumption demand and production under 0.5% growth Scenario_C2.

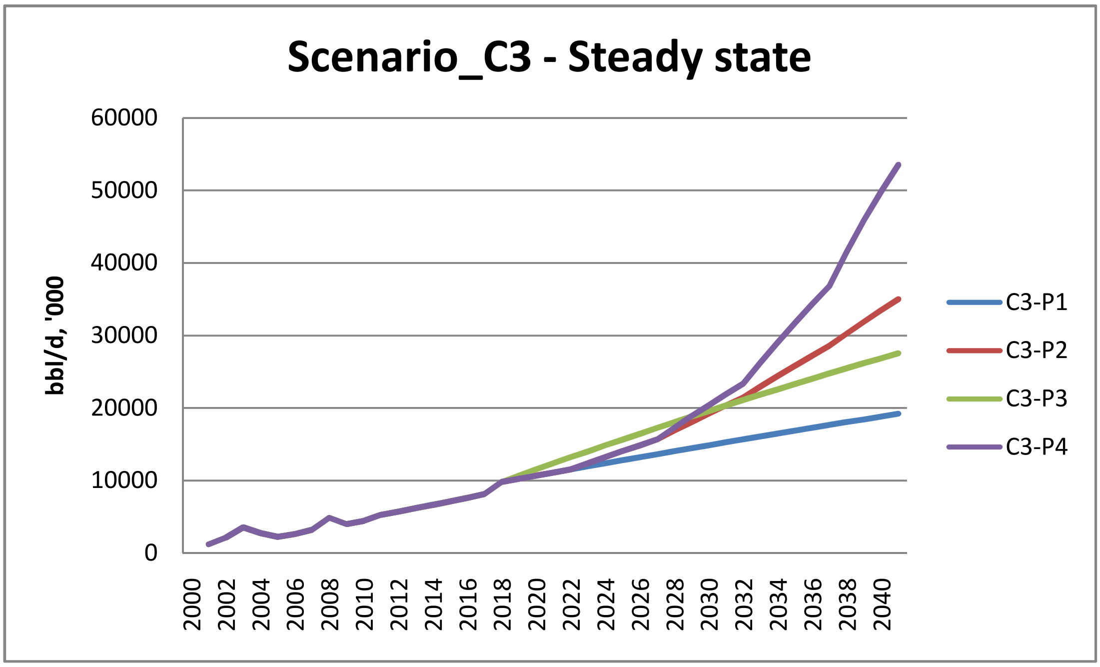

Figure 8.5.: Difference in consumption demand and production under "Steady State" Scenario_C3.

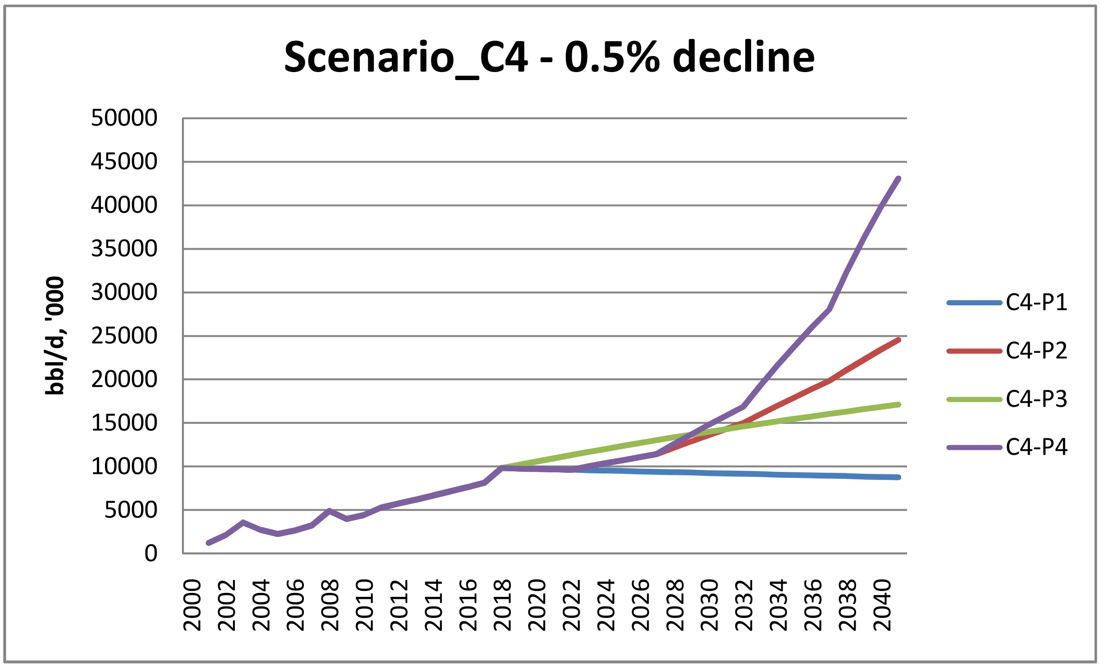

Figure 8.6.: Difference in consumption demand and production under 0.5% decline Scenario_C4.

8.3.1. Exclusion Zone

Since the "Steady State" and "De-growth" economies would require serious structural readjustments to the current global financial, trade and economic systems and since the impact and consequences of such readjustments are difficult to calculate within the scope of this work I would leave these scenarios out of the current discussion and return to them as possible options only in the conclusion.

This leaves us with two possible developments: “Business as Usual” and “Slow Aggregate Growth” in the world economy scenarios.

8.3.2. Business as Usual Scenario

In The “BAU” scenario, even the most optimistic assumption on small continuous yearly decline in extraction of 0.5%, yields the gap of over 25 mb/d between production and demand in just 10 years and reaching over 43 mb/b in 20 (**Fig. 8.7.**):

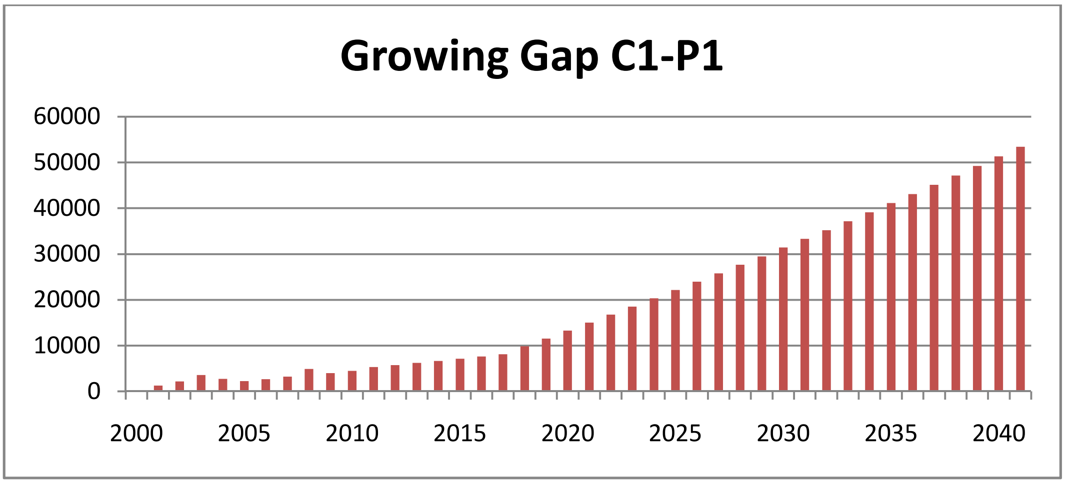

Figure 8.7.: The difference between consumption and production in the most optimistic case in „BAU“ scenario (000’ of b/d).

What it means in real terms that the combined effort of the whole humanity is needed to replace the declining oil production within one decade equal in size to modern Russia and Saudi Arabia – No.1 and 2 respectively in world oil league of producing countries – put together, if the growth in consumption levels world is experiencing today are to be sustained.
The mitigation actions proposed by Hirsch and his co-authors in his 2005 Report lead to production equivalent of 21mb/d in 10 years from the start of mitigation.[22]

[22] Hirsch Report assumptions – even by its own admission - are very generous. For example he extrapolates heavy oil/tar sand crash program from Canadian and Venezuelan reserves without any consideration to ecological, economical, energetic or geopolitical factors. His CTL program assumes yearly construction of five plants capable of production of 100,000 b/d for the duration of 20 year program without logistical or raw material assessment. His GTL program make “jump” from nothing to 2 mb/d in just 3 years, admitting however the complications of having to take into account “the need to consider the total world energy system”. His EOR projections stems from the 3% assumption on 100 Mb/d peak recoveries. But most importantly, the Report does not take any notice of the imperative to reduce CO_2 emissions and associated with it costs and possible delays.

However, even if these "brave" assumptions fail to fill the gap in the most optimistic case for the "BAU" scenario, it becomes obvious that this development of the events also will be very unlikely to succeed in the world of restrained supplies as growing prices would destroy demand for goods and services.

8.3.3. Mild Growth Scenario

This leaves us with the last from four proposed scenarios of slow aggregate growth in demand of 0.5%. (**Fig. 8.8.**):

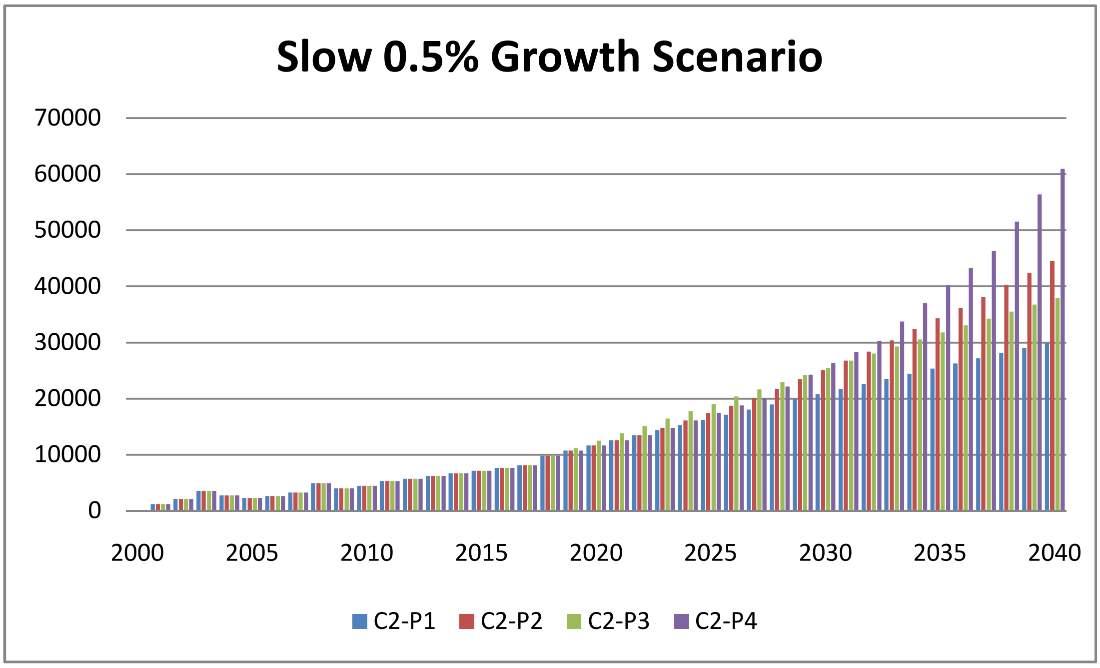

Figure 8.8.: The difference between slow 0.5%/annum consumption growth and four depletion curves.

Please, note that this 0.5% growth in our Scenario is just a shade over a half of 0.9% that the latest BP Energy Outlook 2030 predicts for oil consumption in the next 20 years; reaching the total consumption of over 102Mb/d (BP, January 2011). IEA World Energy Outlook 2011 is even more cautious with its latest predictions of 99 mb/d by 2035[23]. In their "New Policies" Scenario, it uses exactly 0.5% increase in oil demand year on year till 2035.[24]

In its Introduction to "Oil Market Outlook", IEA quietly admits – without using the word "peak" - that crude oil supply "increases marginally to a plateau of around 69

[23] IEA World Energy Outlook 2011, page 103.

[24] Ibid. page 104.

mb/d (just below the **historic high of 70 mb/d in 2008***) and then declines slightly to around 68 mb/d by 2035. Nonetheless, gross capacity additions of 47 mb/d – **twice the current OPEC Middle East production**** – are needed just to compensate for declining production at existing fields.”[25]

However nowhere in the Report is mentioned or explained how this staggering amount of oil will be found and brought on-stream, bearing in mind that most of the ageing giant oil fields – especially OPEC ones - are expected both by IEA and BP Reports to be the chief sources of this extra oil.

8.4. Aggravating factors

8.4.1. Energy Trap

The other important phenomenon that is worth mentioning in conjunction with energy economy transformation is the effect coined by Professor T. Murphy, so called “Energy Trap” (Murphy T. , 2011).

The gist of it is that once the available energy sets into decline, the required amounts and quality of energy needed to perform transition and investment into new economy will be more economically difficult and politically controversial to obtain. In other words, if we have not used the available energy – oil in our case, to invest into the transformation of the economy when we had the surplus for growth, it becomes virtually impossible to overcome immediate imperatives of sustaining the current level of economic development and maintain existing infrastructure, when the enabling resource is in decline.

8.4.2. Seneca cliff

One more effect of the declining resource is important to keep in mind when assessing transition scenarios. It is formulated by Professor Udo Bardi and describes the dynamic system behaviour model that makes the descending slope of the supply curve to be steeper that the ascend (**Fig. 8.9.):**

[25] Ibid. page 103

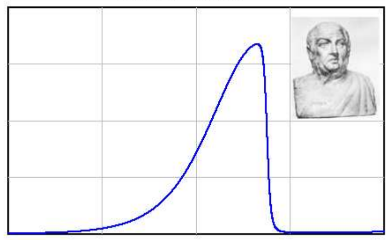

Figure 8.9.: Seneca Cliff. Source: (Bardi U. , 2011)

It is caused by the time lag of the "pollution", which could be lower EROEI or unaccounted externalities, build into the system and calling in on its debtors, i.e. economy, exactly at the inconvenient time of the resource decline.
The result of these effects is a sudden or quickened collapse after the initial high point is reached.

8.4.3. Climate change

It is scientifically determined (Solomon, et al., 2007) that anthropogenic influence on global warming is taking affect, and it is also internationally acknowledged (UNFCCC, 2009) that the resulting increase in temperature should be contained within 2°C in order to avoid catastrophic changes to the planet's climatic behaviour.
To facilitate this the participants of the Copenhagen Accord 2009 agreement as well as other interested parties of The United Nation Environment Programme issued a synthesis Report "Bridging the Emissions Gap" in November 2011 (UNEP., 23 November 2011).

The Report claims that "in order to have the likely chance of keeping within the 2°C limit this century, emissions in 2020 should not be higher than 44Gt of CO_{2eq} (Ibid., *p. 7*).

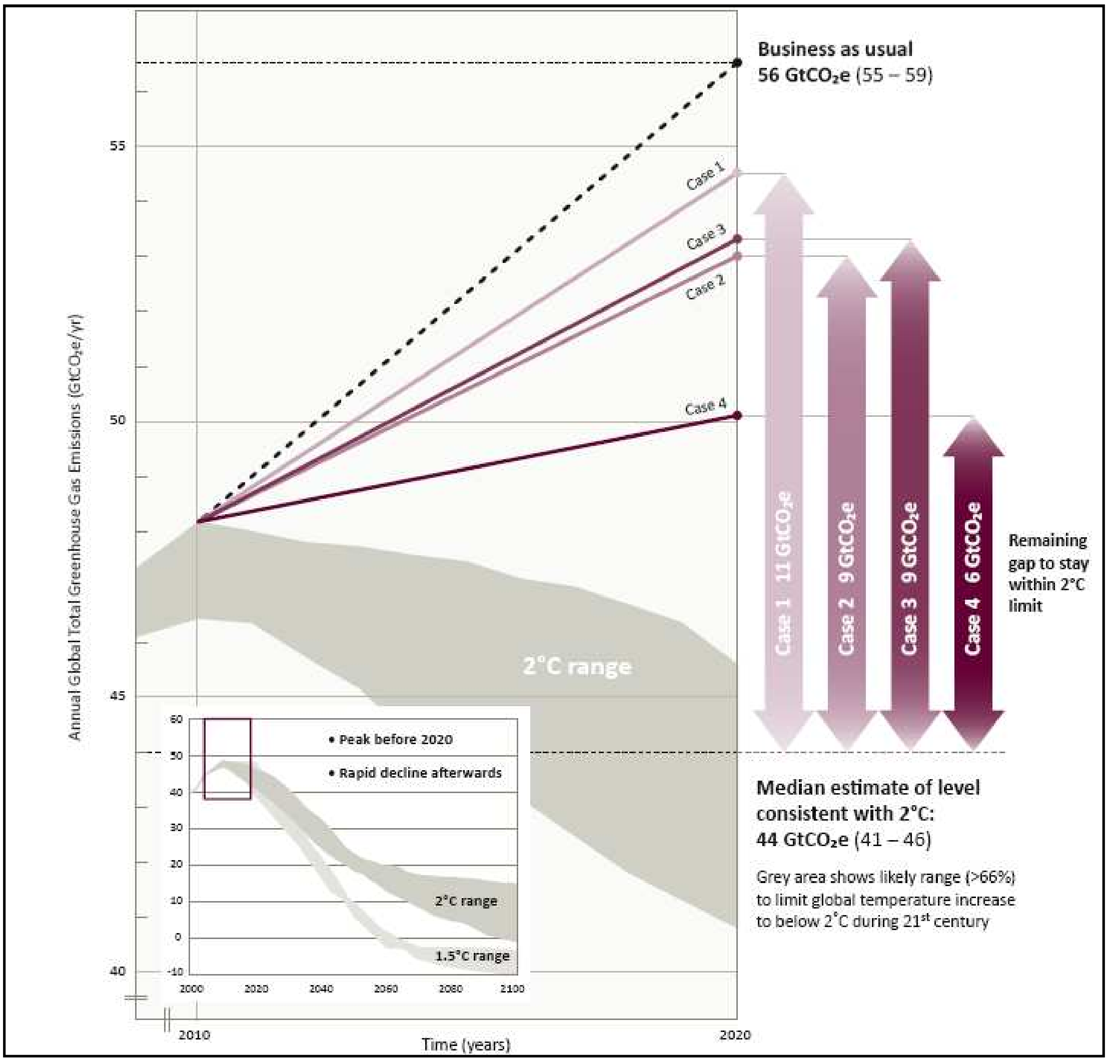

Figure 8.10.: The emissions gap. 2020 Scenario. Source: (UNEP, 2011)

Total anthropogenic emissions at the end of 2009 were estimated at 49.5Gt of $CO_{2eq.}$ (Montzka, et al., 2011). Just over a third of this amount comes as a result of petroleum usage (EIA, 2012).

Even in the “worst case” scenario of peak oil development (“P3” - Production dropping 0.5% exponantialy), the resulting difference in production between 2020 and 2009 will lead to 4.43% increase in GHG emissions, which would clearly do little to contribute to achieving required reduction.

If we take a look at Production Scenario No.4 (“P4” - dropping 0.5% with a doubling rate every 5 years), which gives us the lowest production figures at the end of the series – 53% of 2009 level and a “savings” of 6,125Gt of $CO_{2eq.}$ – **considering there is no other alternative fossil fuel substitution is used to balance back the**

losses, - humanity will still be struggling to “find” necessary reduction to keep within the UNEP curve (**Fig. 8.11.**):

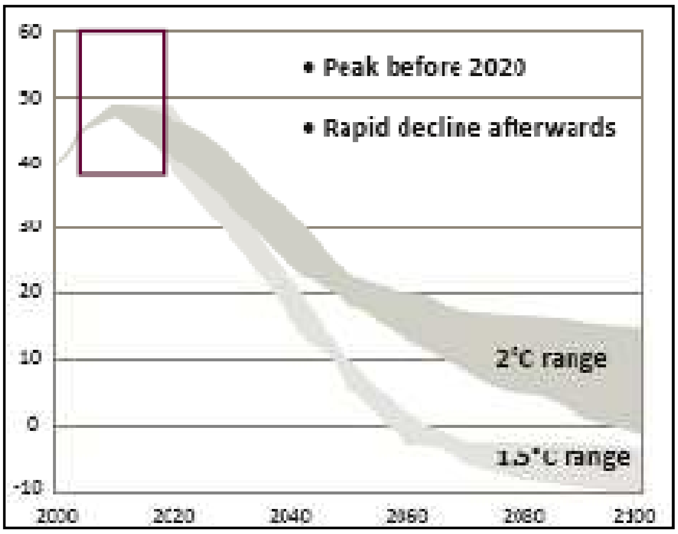

Figure 8.11.: The emissions gap. Long term scenario. Source: (UNEP, 23 November 2011)

The conclusion is that the physical oil shortage alone, even without any effort in large scale implementation of solutions on substitution through other fossil energy carriers, would not be sufficient to plug the necessary emissions reduction gap, needed to fulfil the Copenhagen Accord requirements.

The only “hope” will be then the resulting from “oil shock” slumping behaviour of the economy, leading to further reduction of energy consumption in all sectors, bringing another minus 20% of total on top of the reduction resulting from the lack of available oil.

How would this economical shrinking look like and what consequences it could bring to the welfare of the people of the planet is left to speculation beyond the scope of this work, but my guess is that it will not be a “soft landing”. Most of these reductions will have to come from industry, transport and agriculture and will be forced closures rather than as a result of efficiency gains, bearing in mind the “Energy Trap” phenomenon.

8.4.4. Plugging the gap with lower EROIE

Even if we are to disregard possible implications to global warming phenomenon from the growing use of fossil fuels or its alternatives through associated GHG emissions, even if we are to postpone real action to mitigate increasing levels of $CO_{2eq.}$ in the atmosphere like the world leaders seemed to agree to in Durban (Reuters, 2012), would it help the world economy to continue on its growth path, bearing in mind falling EROIE of oil and that lower quality (in energetic terms) fuels are to be used as substitutes?

As mentioned before in §6.3. higher ratio of lower quality grade oil, being pumped out from further and more difficult to get to places far away from refineries and/or consumers, as more and more "unconventional" replacements in the overall production mix will inevitably "translate" in lower energy yields (net energy), available to the industrialized society for reinvestment and consumption.

If this logical trend is to continue outpacing technological advances, as recent researches indicate (**Fig. 8.12.**) at what point our industrialized civilization will start experiencing fundamental problems?

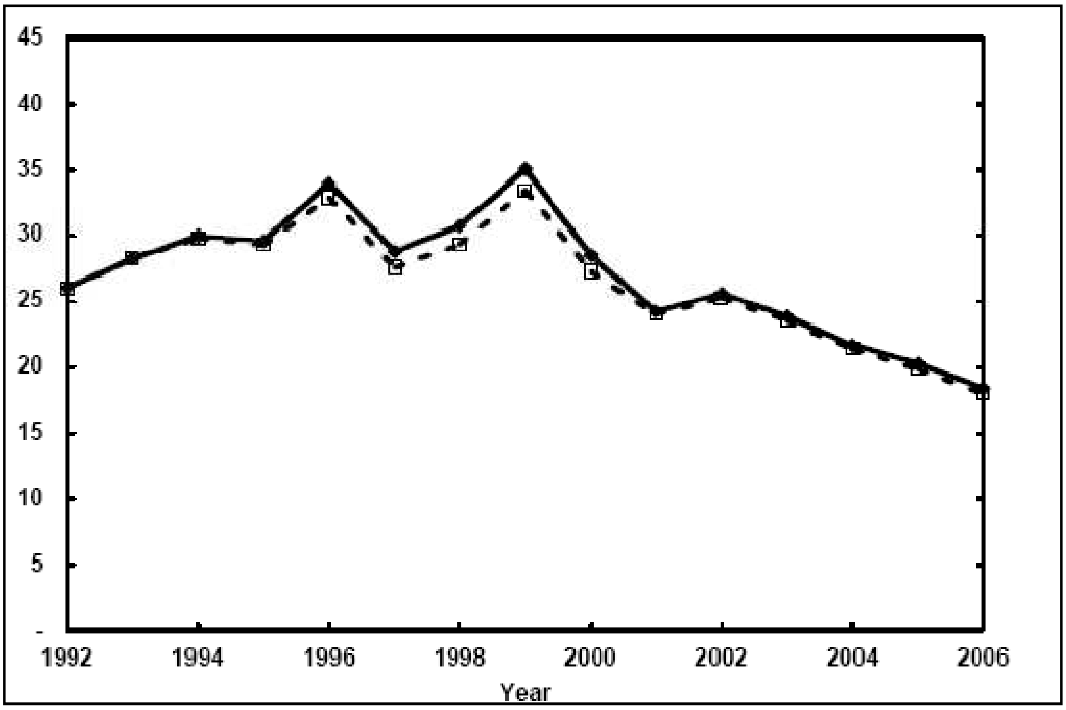

Figure 8.12.: ERoEI for oil and gas production worldwide. Source: (Gagnon, Hall, & Brinker, 2009).

It is estimated that our society needs minimum EROI of 3:1 to continue with oil extraction to provide transportation service and a minimum EROI of 5:1 from our main fuels, if we are to support current level of what we call civilization (Hall, Balogh, & Murphy, 2009).

The current worldwide energy balance of oil extraction is estimated to be around 18:1 (Gagnon, Hall, & Brinker, 2009). It is further claimed that lowering EROIE to less than 10:1 ratio will drive the production price steep up the exponential curve (**Fig. 8.13.**):

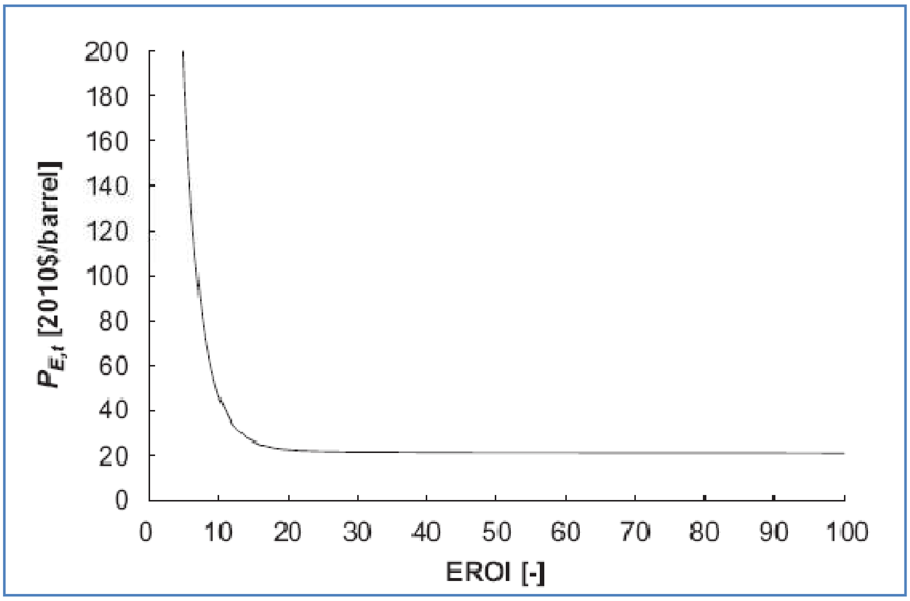

Figure 8.13.: Model for oil price as a function of EROI using present-day correlations. Source: (Heun & de Wit, 2011).

By this rational, it is not so important how much oil is still left in the ground, or when we hit the extraction peak, as – given the data that we have already peaked in EROI in 1999 and on the right side of the downward slope since last 10 or so years – how much time left before the combined EROI reaches the inverted cliff from which the escalating cost in production will destroy most of the existing demand for the service it provides. This time frame, which as available research suggests (Cleveland C. , 2005), (Heun & de Wit, 2011) to having linear correlation with EROI will determine available for the society adaptation period within which it will have to make a transition away from the fossil fuels to another way of organizing productive economic activity.

Whether we succeed or not in this transition is a matter of optimistic versus pessimistic view on human condition. One is for sure: if we are to disregard the "writing on the wall" and are to miss this, with every day slipping into history opportunity, the transition may never happen at all as there will be very little left to transition into.

9. Conclusions

In this work I have tried to demonstrate the fundamental difficulties our society faces as we are confronted by the imperative to transition our economy to low carbon future. I have specifically concentrated on the energy component of the economy as a creation source behind the production of goods and services. Oil in particular is on the top of the list in the table of primary energy providers as “enabling” and “connecting” fuel due to its universality in the use of the internal combustion engines designed to drive our machinery around the globe.

The investigation of the current academic consensus gives us an opportunity to guesstimate the high likelihood of coming supply crunch within next decade. Given the size of the world economy and the technological, logistical, political and economical constrains, the adaptation period to the declining supply of crude oil products could take a generational time span. Although some adaptation efforts are currently taking place – Europe being the leading economical power on this front – most of the important energy producing and consuming nations are showing lack of ambitions to tackle this “problem of the century”. As it is with climate change, the adaptation to the new economic reality will cost more in terms of economic disruption the longer serious efforts are postponed.

The range of the options to provide “soft landing” is further narrowed by the necessity to take into account the problem of the global warming. This complexity only dissolves the ability of the world political powers to come to the consensus, further procrastinating the decision making process.

In the absence of the international agreement on consolidated effort, the tightening supply of available oil on the free market will inevitably translate into price hikes, resource nationalism, resource grabs and associated with them violence. This will in turn make the reaching of the common ground more and more difficult, breaking the world in fractions of those who have the energy resources and those who want them. Such divisions will further destabilise global economy, disturbing the long established trade links, forcing further economic disruption. If not timely and consistently addressed, this disruption could be followed by social instability, bringing the political changes reminiscent to those of a hundred years ago.

It is easy to underestimate the seriousness of the predicament we are facing at the beginning of this century. If one looks outside one’s window, it would seem that the planet is spinning around as it always was. However, the complex global society such as ours today has grown very quickly and inorganically on the dopamine of cheap energy. The sudden or even minimal decrease of the amount of this “drug” pumping through the veins of the world economy could have serious repercussions on the health of our civilisation.

To avoid this happening, we need first to admit to this existing serious and present danger on the world wide platform of opinion making. This will help us to step over denial and bargaining syndromes of psychological reckoning with the unpleasant fact. This has to be done as soon as possible to avoid unpleasant shocks and possible societal collapses once the inevitable has occurred.

When this transformation is achieved, it would be easier to stare the reality in the face and start looking for the solutions. The recognition that our world is enclosed within a finite planet, on which indefinite growth will inevitably lead if not to planecide, but to collapse of current ecology, is essential “pill” to swallow if we want to continue on our civilisational path. We will need to see this challenge as an opportunity to rediscover the meaning of being a human being on the planet Earth.

A lot of intellectual effort is being put into formulating new concepts and designing accounting practices, which will help our civilization to whine itself from the infinite growth meme towards sustainable development. Concepts like LCA (ISO 1999), MIPS (Ritthoff, et al., 2002), EROEI, GAIA theory of James Lovelock, and holistic approach of Herman E. Daly and Ernst F. Schumacher to sustainable human economy functioning within the given parameters of ecosystems as well as pioneering works on effects of thermodynamic laws within the economic processes by Nicholas Georgescu-Roegen, – all are out there, ready for the wide society to embrace as mainstream thinking as soon as the die-hard “drill, baby, drill” attitude to the environment will become to majority of the people on the planet as obviously insane and not worth killing and dying for.

In the words of the founder of TTI movement, Rob Hopkins: “We need local solutions to the global problems”. If your world is to “become smaller”, it should not necessarily mean it could not become a better place to live.

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Appendix 1

List of oil countries past peak production and the ones that are still growing in mb/d.

Country	Peak Prod.	2008 Prod.	% Off Peak	Peak Year
United States	11297	7337	-35%	1970
Venezuela	3754	2566	-32%	1970
Libya	3357	1846	-45%	1970
Other Middle East	79	33	-58%	1970
Kuwait	3339	2784	-17%	1972
Iran	6060	4325	-29%	1974
Indonesia	1685	1004	-41%	1977
Romania	313	99	-68%	1977
Trinidad & Tobago	230	149	-35%	1978
Iraq	3489	2423	-31%	1979
Brunei	261	175	-33%	1979
Tunisia	118	89	-25%	1980
Peru	196	120	-39%	1982
Cameroon	181	84	-54%	1985
Other Europe & Eurasia	762	427	-44%	1986
Russian Federation	11484	9886	-14%	1987
Egypt	941	722	-23%	1993
Other Asia Pacific	276	237	-14%	1993
India	774	766	-1%	1995
Syria	596	398	-33%	1995
Gabon	365	235	-36%	1996
Argentina	890	682	-23%	1998
Colombia	838	618	-26%	1999
United Kingdom	2909	1544	-47%	1999
Rep. of Congo (Brazzaville)	266	249	-6%	1999
Uzbekistan	191	111	-42%	1999
Australia	809	556	-31%	2000
Norway	3418	2455	-28%	2001
Oman	961	728	-24%	2001
Yemen	457	305	-33%	2002
Other S. & Cent. America	153	138	-10%	2003
Mexico	3824	3157	-17%	2004
Malaysia	793	754	-5%	2004
Vietnam	427	317	-26%	2004
Denmark	390	287	-26%	2004
Other Africa	75	54	-28%	2004
Nigeria	2580	2170	-16%	2005
Chad	173	127	-27%	2005
Italy	127	108	-15%	2005
Ecuador	545	514	-6%	2006
Saudi Arabia	11114	10846	-2%	2005 / Growing
Canada	3320	3238	-2%	2007 / Growing
Algeria	2016	1993	-1%	2007 / Growing
Equatorial Guinea	368	361	-2%	2007 / Growing
China	3795	3795	-	Growing
United Arab Emirates	2980	2980	-	Growing
Brazil	1899	1899	-	Growing
Angola	1875	1875	-	Growing
Kazakhstan	1554	1554	-	Growing
Qatar	1378	1378	-	Growing
Azerbaijan	914	914	-	Growing
Sudan	480	480	-	Growing
Thailand	325	325	-	Growing
Turkmenistan	205	205	-	Growing
Peaked / Flat Countries Total	-	49597	-	**60.6% of world oil production**
Growing Countries Total	-	32223	-	**39.4% of world oil production**

Appendix 2

Scenario Calculable.

Growth in oil Production	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
In Thousands brl/day	75381	75169	74700	77075	80567	81486	81729	81544	82015	80278
In % year on year	1.0087	0.9972	0.9938	1.0318	1.0453	1.0114	1.0030	0.9977	1.0058	0.9738
In % to 2000	1.0000	0.9972	0.9930	1.0225	1.0688	1.0810	1.0842	1.0818	1.0880	1.0650
Scenario_P1	75381	75169	74700	77075	80567	81486	81729	81544	82015	80278
Scenario_P2	75381	75169	74700	77075	80567	81486	81729	81544	82015	80278
Scenario_P3	75381	75169	74700	77075	80567	81486	81729	81544	82015	80278
Scenario_P4	75381	75169	74700	77075	80567	81486	81729	81544	82015	80278
Scenario_P5	75381	75169	74700	77075	80567	81486	81729	81544	82015	80278
Growth in Consumption	76605	77304	78230	79823	82837	84128	84959	86420	85980	84714
In % year on year	101.3%	101.9%	101.2%	102.0%	103.8%	101.6%	101.0%	101.7%	99.5%	98.5%
In % to 2000	100%	101.9%	102.2%	104.2%	108.1%	109.8%	110.9%	112.8%	112.2%	110.6%
Scenario_C1	76605	77304	78230	79823	82837	84128	84959	86420	85980	84714
Scenario_C2	76605	77304	78230	79823	82837	84128	84959	86420	85980	84714
Scenario_C3	76605	77304	78230	79823	82837	84128	84959	86420	85980	84714
Scenario_C4	76605	77304	78230	79823	82837	84128	84959	86420	85980	84714
Matrix	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**
C1-P1	1234	1134	3567	2748	2259	2641	3229	4885	3984	4436
C1-P2	1234	1134	3567	2748	2259	2641	3229	4885	3984	4436
C1-P3	1234	1134	3567	2748	2259	2641	3229	4885	3984	4436
C1-P4	1234	1134	3567	2748	2259	2641	3229	4885	3984	4436
C2-P1	1234	1134	3567	2748	2259	2641	3229	4885	3984	4436
C2-P2	1234	1134	3567	2748	2259	2641	3229	4885	3984	4436
C2-P3	1234	1134	3567	2748	2259	2641	3229	4885	3984	4436
C2-P4	1234	1134	3567	2748	2259	2641	3229	4885	3984	4436
C3-P1	1234	1134	3567	2748	2259	2641	3229	4885	3984	4436
C3-P2	1234	1134	3567	2748	2259	2641	3229	4885	3984	4436
C3-P3	1234	1134	3567	2748	2259	2641	3229	4885	3984	4436
C3-P4	1234	1134	3567	2748	2259	2641	3229	4885	3984	4436
C4-P1	1234	1134	3567	2748	2259	2641	3229	4885	3984	4436
C4-P2	1234	1134	3567	2748	2259	2641	3229	4885	3984	4436
C4-P3	1234	1134	3567	2748	2259	2641	3229	4885	3984	4436
C4-P4	1234	1134	3567	2748	2259	2641	3229	4885	3984	4436
Replacement Methods										
Vehicle Fuel Efficiency										
Coal Liquids										
Tar Sands										
EOR										
GTL										
Total savings										
Growth in oil Production EIA	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**

Growth in oil Production	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
In Thousands brl/day	82092	82812	83536	84266	85002	85745	86495	86062	85632	85204
In % year on year	1.0226	1.0087	1.0087	1.0087	1.0087	1.0087	1.0087	0.9950	0.9950	0.9950
In % to 2000	1.0891	1.0986	1.1082	1.1179	1.1276	1.1375	1.1474	1.1417	1.1360	1.1303
Scenario_P1	82092	82812	83536	84266	85002	85745	86495	86062	85632	85204
Scenario_P2	82092	82812	83536	84266	85002	85745	86495	86062	85632	85204
Scenario_P3	82092	82812	83536	84266	85002	85745	86495	86062	85254	84354
Scenario_P4	82092	82812	83536	84266	85002	85745	86495	86062	85632	85204
Scenario_P5	82092	82812	83536	84266	85002	85745	86495	83975	81530	79155
Growth in Consumption	87382						-2519	-2446	-2375	-2305
In % year on year	103.1%									
In % to 2000	114.1%									
Scenario_C1	87382	88549	89732	90930	92145	93376	94623	95886	97157	98465
Scenario_C2	87382	88549	89732	90930	92145	93376	94623	95886	96356	96848
Scenario_C3	87382	88549	89732	90930	92145	93376	94623	95886	95886	95886
Scenario_C4	87382	88549	89732	90930	92145	93376	94623	95886	95407	94930
Matrix	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
C1-P1	5288	5737	6196	6664	7142	7630	8128	9824	11535	13261
C1-P2	5288	5737	6196	6664	7142	7630	8128	9824	11535	13261
C1-P3	5288	5737	6196	6664	7142	7630	8128	9824	11963	14111
C1-P4	5288	5737	6196	6664	7142	7630	8128	9824	11535	13261
C2-P1	5288	5737	6196	6664	7142	7630	8128	9824	10734	11644
C2-P2	5288	5737	6196	6664	7142	7630	8128	9824	10734	11644
C2-P3	5288	5737	6196	6664	7142	7630	8128	9824	11152	12494
C2-P4	5288	5737	6196	6664	7142	7630	8128	9824	10734	11644
C3-P1	5288	5737	6196	6664	7142	7630	8128	9824	10255	10683
C3-P2	5288	5737	6196	6664	7142	7630	8128	9824	10255	10683
C3-P3	5288	5737	6196	6664	7142	7630	8128	9824	10683	11533
C3-P4	5288	5737	6196	6664	7142	7630	8128	9824	10255	10683
C4-P1	5288	5737	6196	6664	7142	7630	8128	9824	9775	9726
C4-P2	5288	5737	6196	6664	7142	7630	8128	9824	9775	9726
C4-P3	5288	5737	6196	6664	7142	7630	8128	9824	10204	10576
C4-P4	5288	5737	6196	6664	7142	7630	8128	9824	9775	9726
Replacement Methods										
Vehicle Fuel Efficiency				0	75	100	133	178	237	316
Coal Liquids				0				500	1000	1500
Tar Sands				0	500	801	1068	1424	1898	2531
EOR				0					2559	2556
GTL					421.875	562.5	750	1000	1060	1103
Total savings				0	997	1464	1951	3102	6755	8006
Growth in oil Production EIA	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**

2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
84778	84354	83932	83512	83095	82679	82266	81855	81445	81038	80633	80230	79829	79429	79082	78637	78244	77853	77464	77076	76691
0.9950	0.9950	0.9950	0.9950	0.9950	0.9950	0.9950	0.9950	0.9950	0.9950	0.9950	0.9950	0.9950	0.9950	0.9950	0.9950	0.9950	0.9950	0.9950	0.9950	0.9950
1.1247	1.1190	1.1134	1.1079	1.1023	1.0968	1.0913	1.0859	1.0804	1.0750	1.0697	1.0643	1.0590	1.0537	1.0484	1.0432	1.0380	1.0328	1.0276	1.0225	1.0174
84778	84354	83932	83512	83095	82679	82266	81855	81445	81038	80633	80230	79829	79429	79082	78637	78244	77853	77464	77076	76691
84778	84354	83512	82679	81855	81038	80230	79032	77858	76691	75546	74419	73941	71493	70074	68683	67320	65654	64019	62444	60898
83512	82679	81855	81088	80230	79429	78637	77853	77075	76307	75546	74793	74047	73308	72577	71853	71136	70426	69734	69028	68340
84778	84354	83510	82679	81848	81030	80120	78613	77045	75502	73592	72312	69811	68627	64154	61388	59124	54393	50043	48040	42550
76849	74611	73438	70328	68380	66391	64260	62496	63665	58800	57383	55518	53901	53121	50837	49337	47890	46496	45141	43826	43560
-2238	-2173	-2110	-2048	-1989	-1931	-1875	-1820	-1767	-1715	-1666	-1617	-1570	-1524	-1480	-1437	-1395	-1354	-1315	-1276	-42550
99780	101113	102463	103832	105218	106624	108048	109491	110955	112435	113537	115439	117001	118563	120147	121752	123378	125026	126696	128388	130103
97332	97819	98308	98799	99253	99790	100289	100790	101294	101801	102310	102821	103335	103852	104371	104893	105417	105945	106474	107007	107542
95886	95886	95886	95886	95886	95886	95886	95886	95886	95886	95886	95886	95886	95886	95886	95886	95886	95886	95886	95886	95886
94435	93983	93513	93046	92580	92117	91657	91199	90743	90289	89837	89388	88941	88497	88064	87614	87176	86740	86306	85875	85445
2020	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**	**2040**
15002	16759	18531	20319	22124	23944	25782	27636	29508	31397	33304	35229	37172	39134	41115	43115	45134	47173	49232	51311	53412
15002	16759	18051	21152	23364	25580	27818	30459	33101	35744	38391	41040	44059	47070	50073	53068	56058	59072	62067	65044	66294
16268	18433	20609	22794	24989	27194	29411	31638	33877	36128	38391	40666	41954	45156	47570	49859	52243	54399	56972	58359	61763
15002	16759	18953	21157	23370	25594	27828	30876	33910	36933	39545	42947	47389	51736	55993	60164	64253	70631	76653	82348	87746
12554	13465	14376	15287	16198	17110	18023	18935	19849	20762	21677	22591	23507	24422	25339	26256	27173	28092	29011	29930	30851
12554	13465	14795	16120	17439	18752	20059	21758	23441	25110	26763	28402	30394	32358	34297	36230	38098	40091	42446	44563	46643
13810	13139	16453	17751	19063	20360	21652	22937	24215	25493	26765	28018	29289	30544	31794	33040	34281	35518	36730	37976	39202
12554	13463	14797	16124	17446	18760	20069	22175	24251	26298	28318	30309	32733	37036	40217	43305	46393	51150	56411	60967	65185
11109	11533	11954	12374	12752	13207	13621	14032	14441	14848	15254	15657	16058	16457	16854	17249	17643	18034	18423	18810	19196
11109	11533	12374	13207	14032	14848	15657	16854	18034	19196	20340	21468	22945	24393	25812	27203	28567	30233	31858	33441	34988
12374	13207	14032	14848	15657	16457	17249	18034	18810	19579	20340	21094	21840	22579	23310	24034	24750	25460	26163	25858	27547
11109	11533	12376	13211	14038	14857	15667	17271	18844	20384	21894	23374	26275	29059	31732	34258	36762	41492	45844	49847	53530
9678	9629	9581	9533	9486	9438	9391	9344	9297	9251	9205	9159	9113	9067	9022	8977	8932	8887	8843	8799	8755
9678	9629	10001	10366	10726	11076	11427	12166	12890	13598	14291	14970	16000	17003	17980	18931	19856	21086	22278	23431	24547
10943	11304	11559	12007	12351	12688	13020	13346	13666	13982	14291	14596	14895	15189	15477	15761	16040	16313	16582	15846	17105
9678	9629	10003	10370	10732	11088	11437	12583	13700	14787	15845	16876	19330	21669	23900	26026	28051	32345	36263	39835	43089
422	563	750	1000	1250	1563	1953	2441	3052	3265	3494	3739	4000	4280	4580	4900	5243	5611	6003	6423	6873
2000	2500	3000	3500	4000	4500	5000	5500	6000	6500	7000	7500	8000	8500	9000	9500	10000	10500	11000	11500	12000
3375	4500	6000	8000	8400	8820	9261	9724	10210	10721	11257	11820	12411	13031	13683	14367	15085	15839	16631	17463	18336
2543	2531	2505	2480	2456	2431	2407	2371	2336	2301	2266	2233	2188	2145	2102	2060	2020	1970	1921	1873	1827
1158	1216	1276	1340	1407	1477	1551	1629	1710	1796	1886	1980	2079	2183	2292	2407	2527	2653	2786	2925	3072
9498	11309	13532	16320	17513	18791	20172	21665	23308	24583	25903	27271	28678	30139	31667	33234	34875	36573	38342	40185	42108
2020	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**	**2040**