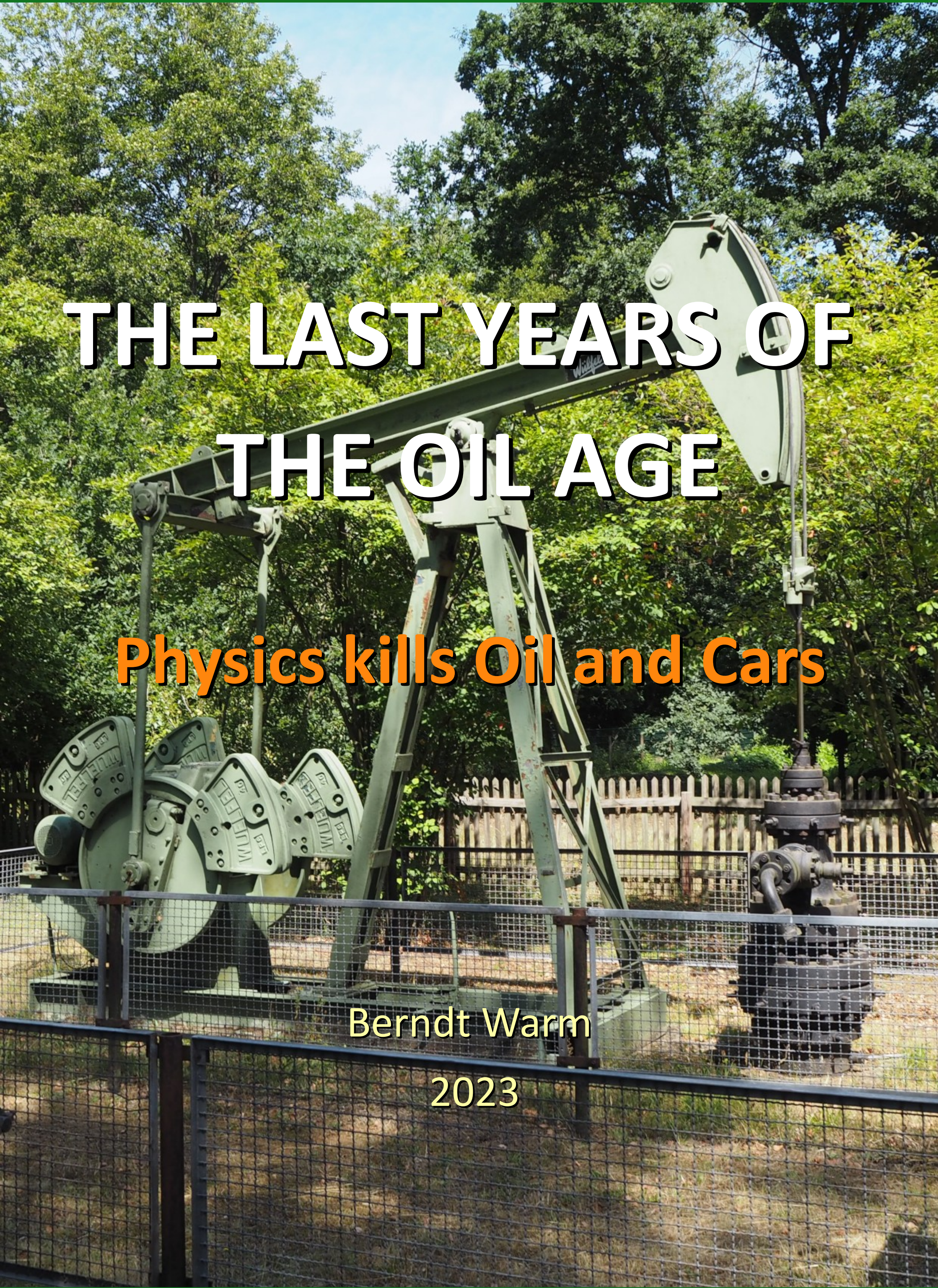


THE LAST YEARS OF THE OIL AGE

Physics kills Oil and Cars

Berndt Warm

2023

THE LAST YEARS OF THE OIL AGE

Physics kills Oil and Cars

Version 1.1

Berndt Warm

Member of ASPO Germany

2023

- September, 19th, 2023
- DOI: 10.13140/RG.2.2.31431.78243

Table of Contents

About the book

This book explains why Peak Oil and Peak Car now are things of the past. The justification is based on a law of physics that has so far received little attention for oil production: the second law of thermodynamics. Diagrams with economic data and explanations of oil production serve as evidence. It is to be expected that oil production and vehicle construction will decline significantly in a few years and will hardly exist in 2035.

At the beginning of the preparation of this report, the energy crisis that has arisen since August 2021 was still a fiction to be expected from the data. Now reality has already caught up with the report.

Acknowledgements

Without support from the following people this book would not have been feasible:

Gunnar Kaestle has been an invaluable discussion partner and has helped to set up the formulas.

Vincent Spreuwenberg checked the logic and the text.

Richard Miller found a lot of errors in the English translation.

A lot of other people, who forced me with contradiction to write with more clarity.

And my wife Ingrid, who tolerated long times with a vacantly man.

1. Introduction

Almost 40 years ago, I was employed by an oil and gas producer in northern Germany. My job was to improve the software of a program that simulated pressure and flow rates for natural gas and oil wells. Thermodynamic equations were part of the program. After half a year I left the company, because I expected a replacement of oil energy by fusion energy and did not see a long-term future in the oil sector.

It was not until about 10 years ago that I began to look at the oil issue again. The ETP model of HillsGroup captured my interest, and I checked its calculations, found many mistakes, but a correct core. Today it is self-evident for me that the thermodynamically calculated energy input is dominant for oil production.

Again, and again I am surprised that this knowledge is not general knowledge. Hundreds of petroleum engineers must have had this insight. I often ask myself if I would not have gained this knowledge much earlier if I had stayed in the oil sector. I'm pretty sure it would have dawned on me by 1990 at the latest. How can it be that something so important is overlooked by mankind?

I distributed a first, albeit very short, version of this report for the first time at the ASPO conference in Potsdam in October 2019. It was only eight pages long at the time. In this report, many additional observations and data on oil production are added. The impact of the Covid-19 pandemic on the curves shown becomes clear; Peak Oil and Peak Car are now recognizable as events of the past. Both peaks are about two years before the start of the pandemic.

1.1. Motivation for writing this report

Oil production will end in a short time; this will have an extreme impact on the life of humanity. The entire transport sector will be transformed or collapsed. The sooner you realize what's in store for us, the better you can prepare for it. My main reason for producing this report is to gain time to switch to a time without oil. The fact that I am writing this book is due to the following things:

• As a physicist, I firmly believe in the validity of the laws of physics, especially the main laws of thermodynamics.

• Of the many physicists in Germany, most have never worked in the oil industry, but i did for a while. The duration was only half a year, but that was enough to get to know certain problems and calculation methods of the industry. My field of work there was software development for the gas flow from boreholes, which is determined by thermodynamic equations.

• I don't make any money from the oil and gas industry or its products and can't get any professional disadvantages from this book since I'm retired.

• As an avid cyclist, I miss the love for the car and the desire to absolutely maintain the car, its amenities and the necessary infrastructure. On the contrary, I am slowly developing an ever-stronger reluctance to seal the landscape through roads, car noise, cities filled with cars and exhaust fumes.

In order to make the statements of this book generally comprehensible, sources are given for all data, as well as the formulas used are explained. Nevertheless, I have had the following experience: I have presented the model and the calculations to many people using the second law. With thermodynamics, the same thing always happens: everyone has their own idea of thermal energy and then starts explaining to me that the model cannot be right. But no one reads the explanation beforehand, based on the second law, which is difficult to understand: If it follows from the second law that oil production is coming to an end, you cannot refute this simply by ignoring the second law.

1.2. Analysis of Data

The following principles have been used in the data analysis:

- Data (prices) are always used in daily resolution. Prices are viewed by other authors on monthly or annual averages. With these averagings, an extremely large amount of information is lost, so that important effects are overlooked.
- Use only original data. Adaption for inflation, for example, can distort data in such a way that it is ultimately impossible to distinguish whether the original value or correction contains or generates information. Therefore, inflation corrections are used only with caution.
- A barrel of oil always contains (almost) the same energy, while a US dollar (USD) has purchasing power that varies from year to year for a variety of reasons. A constant reference is important as a comparative value, so it is preferable to look at the energy first and then convert US dollars in energy terms.
- All data is displayed in the SI system, with a few exceptions. For oil quantities, the barrel is exceptionally used, as all prices refer to it. Kilowatt hours (instead of Megajoules, 1kWh=3.6 MJ) are a legal unit in the EU, although not an SI unit. One liter of crude oil/diesel/gasoline contains about 10 kWh. The value is clear and easy to remember, so kWh is preferred as the unit of energy in

this report.

- Timeliness of data: Oil prices are reported daily, most car sales figures monthly. Unforeseeable economic and political events cause significant fluctuations in prices and sales figures. End date for all charts in this report is spring 2023; more recent values were not used.
- Terminology: Many special terms are used in the oil industry, mostly from the English language. The same applies to thermodynamics. These terms require some time to familiarize yourself with them.
- For an important quantity, namely the water share of oil production, there is only data from individual oil fields. The author is not able to create a curve for this. Without statistically validated input values, output values are unfortunately also questionable. This is especially true for Figure 24 and Figure 17. The author has used diagrams of the Hills Group as a basis.

1.3. The Contents of the Book

This is a book filled with complicated contents about petroleum, money, energy, cars and physics. For people with little time, here is a short overview to help them to concentrate on the most interesting aspects.

- Chapter 2 gives an overview of historic peaks in petroleum production, crude oil prices and car production.
- Chapter 3 describes the usefulness of petroleum.
- Chapter 4 lists data of oil fields.

- Chapter 5 explains the connection between energy and crude oil price. This is important, because the world economy runs on energy, not money.
- Chapter 6 starts with thermodynamics, the part of physics which describes the conversion of one energy form in other forms.
- Chapter 7 is the application of thermodynamics to petroleum production.
- Chapter 8 give additional economic facts. Thermodynamics determines the long-time economic effects of oil, but all short time effects caused by human actions and behaviour are not included.
- Chapter 9 decribes the connection between the prices of crude oil, calculated as fractions of the energy content of a barrel of oil, with car production numbers.
- Chapter 10 lists theories, which are normally used to describe oil price dynamics and car production numbers, and explains their limits.
- Chapter 11 tries to explain why most people never thought about the validity of physics for oil production.
- Chapter 12 contains five different methods to calculate the remaining lifespan of oil and car production.
- Chapter 13 gives conclusions.
- Chapter 14 provides guidance on how to avoid a detrimental outcome for yourself.

1.4. Physics and the Chain of Arguments

For clarity, here is a short assemblage and overview of the arguments dicussed in the book:

- Most of the earth crust below a depth of some ten meters is in thermal equilibrium, according to the zeroth law of thermodynamics. See chapter 4.3 ff.
- According to the second law of thermodynamics, change of a thermal equilibrium requires external energy.
- Oil production changes the equilibrium at the oil reservoirs more and more by transport of oil and water. Thus the change requires more and more energy.
- Calculation of required amount of energy results in more energy than the oil contains, today about 50 percent more.
- The required huge amounts of energy are derived from fossil fuels, oil, coal and natural gas. Even nuclear and reneweable energy are used.
- The required energy is to be delivered by the whole oil producing infrastructure of the world, not by the oil extractors alone.
- The oil using infrastructure must decay as a consequence of the diminishing net energy. Net energy is remains after subtracting the energy for energy production.
- The car production numbers are part of the infrastructure, so they are a good observable to check the theory.
- Car sales peaked in 2017. Despite their sales numbers are influenced by other effects like Cocid-19 and subsidies, the effect of net energy clearly drives the sales down.
- With high probability, car industry and oil industry will vanish in some years.

2. Peaks and Prices

The world's oil production, the number of motor vehicles sold and the price trends for crude oil are important indicators for the global economy. They are almost never considered in context. In this report, they are linked together with the help of physics – more precisely: with the help of the second law of thermodynamics.

2.1. Peak Oil

Peak oil is the maximum of oil production. The earth's oil reserves are finite, so at some point it must be so far that production decreases. In the past, there have often been times when oil production temporarily decreased, but then rose again. According to many experts in the oil sector, one should wait at least five years after a maximum before it can be clearly identified as peak oil.

Figure 1 shows crude oil production in recent years. Shown is C&C (Crude Oil and Condensate). In November 2018 has been a maximum. In 2019, the production was only slightly lower. In 2020, there was a significant slump due to the Covid-19 pandemic. This report explains why the maximum in November 2018 is very likely to be considered the maximum peak oil despite the lack of waiting time.

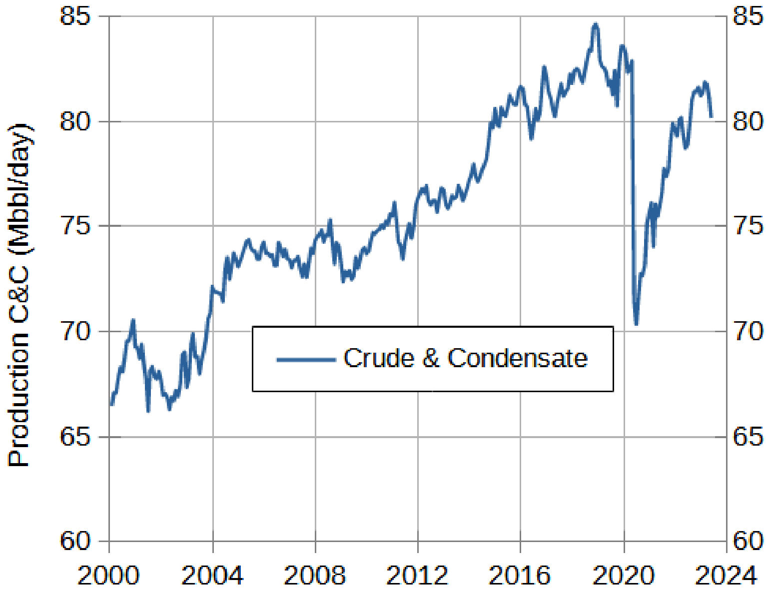


Figure 1: Global crude oil production C&C (Crude andCondensate). Source: EIA [56], OPEC MOMR [30]

2.2. Peak Car

Similar to Peak Oil, we define “Peak Car” as the maximum number of cars produced per year. Global car production has risen steadily in the past. It is to be expected that the number of cars produced with combustion engines will also fall after peak oil. While many people expect a replacement of the combustion cars with electric vehicles, this is at least uncertain, because neither metals (copper, uranium, rare earth metals) nor fossil fuel energy are infinite. (More on electric cars in chapter 9.6)

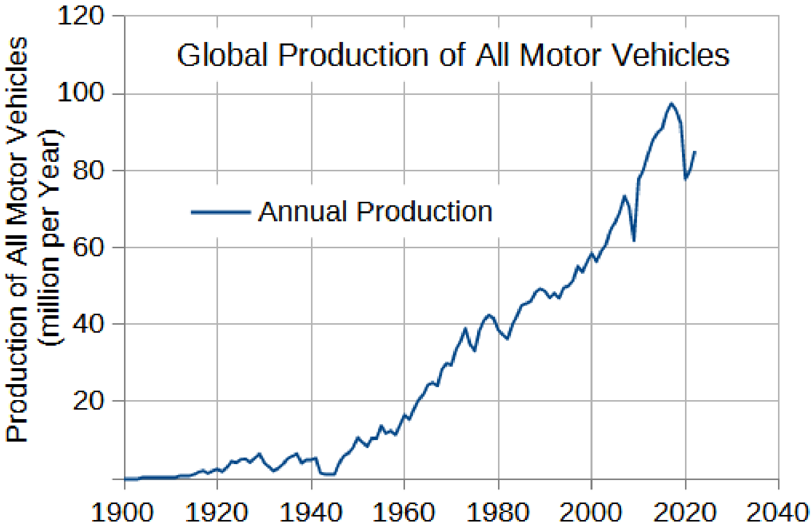


Figure 2: Annual production of motor vehicles; total world (Data Source: Wikipedia, OICA [33]).

Figure 2 shows the monthly totals of all motor vehicle sales in the world. The curve shows a maximum in 2017. In 2018 and 2019, sales fell slightly, at the beginning of 2020 significantly. Overall, the fall until today is about 15% relative to the maximum. As with crude oil, the slump in cars began before the Covid-19 pandemic, it is not caused by the pandemic, but was exacerbated by the pandemic. Supply problems and the shortage of semiconductor devices are blamed for the recent slump in sales.

2.2.1. Was 2017 already »Peak Car«?

In the following, it will be shown that this can be assumed with almost one hundred percent certainty. Observation of the trend of average and maximum oil prices since 2008 shows that. The fall and rise in prices, in turn, is the result of a physical fact, namely the continuous increase in the energy required for crude oil production.

2.3. Crude Oil Prices after 2008 (Peak Crude Price)

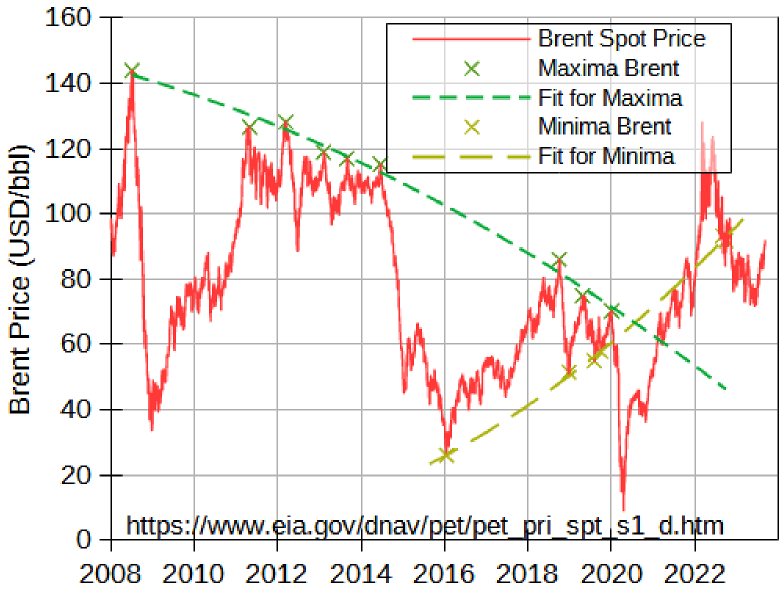


Figure 3: Oil price trend (Brent) since 2008. Dashed green line: connection of maximum values. Dark yellow line with long strokes: connection of minimum values

In 2008, the price of crude oil peaked, it was the next 12 years never so high again. There is a steady up and down of the price, but overall it was slowly getting lower and lower, at least until March 2021. It has been falling since 2008, the maxima (fall: 7.5 $/year) as well as the average value. The case has become faster since 2014, only in 2021 has a change occurred. The fall has been little noticed by the public, despite it contradicted the general assumption that crude oil production is becoming more and more complex and expensive and therefore crude oil must become more and more expensive.

But the fall in prices was not caused by shale oil, not by Trump, not by oversupply or Covid-19, but by physics. The effect is also not caused by chance, but by a law of nature, the second law of thermodynamics. In the following chapters is the explanation.

Since March 2021, the fall in prices has been counteracted by a force that causes higher prices again. This force is the unity of OPEC, which drives up the price through reduced oil production to such an extent that the most important oil-producing state, Saudi Arabia, and others are saved from financial problems and bankruptcy.

2.3.1. Peaks of the Oil Price

A total of 10 points were classified as peak values of the oil price.

Date	Price (USD/bbl)
03.07.2008	143.95
02.05.2011	126.64
13.03.2012	128.14
08.02.2013	118.9
29.08.2013	116.91
19.06.2014	115.19
04.10.2018	86.07
25.04.2019	74.94
06.01.2020	70.25

Table 1: Time and price per barrel of the maxima of the oil price (Brent) Source: EIA [1].

They are marked by green crosses and connected to the dashed green line. Data after 01.01.2021 are considered separately.

03.07.2008: The reason for the increase was the rising global oil consumption, to which production increases did not respond to the same extent. Concerns about weak demand due to the global financial crisis, bad economic news and the resulting decline in demand for oil products caused the oil price to fall sharply in the period that followed. China had recently joined the World Trade Organization (WTO) and was showing an incredible rate of growth. Annual economic growth even accelerated to 14 percent by 2007. Huge infrastructure investments created a significant demand for iron ore. In addition, electricity consumption increased, which also drove up the demand for coal. Diesel generators ensured that China's companies could operate against the backdrop of an inadequately designed power grid.

02.05.2011: In spring 2011 there were two developments that drove up the oil price: the Arab Spring with revolutions throughout the Arab world and the tsunami on 11 March near Japan, which led to the destruction of the Fukushima nuclear power plant. On May 2, American Special Forces killed Al Qaeda leader Osama bin Laden, after which the price of oil fell slightly. It remained at values above $100 for several years.

13.03.2012: From mid-March, news about the euro rescue fund ESM dominated the news. The economy weakened, the oil price fell until mid-2012. In Europe, the economic situation was dominated by the debt crisis and the banking crisis.

08.02.2013: The high price cannot be directly attributed to economic or political events.

29.08.2013: This high price is one of the highest values on the oil price plateau from 2011 to 2014.

19.06.2014: In November 2014, oil consumption rates stopped rising and OPEC announced, that it would not reduce production quotas. Both led to a sharp fall in the oil price in December 2015 to below $30 per barrel

(Brent). The reason for the continued high production was the increasing extraction of crude oil in the USA by fracking. Added to this were the commissioning of many production sources and lower demand due to lower economic growth, especially in China and Latin America.

04.10.2018: OPEC's refusal to increase crude oil production and US President Trump's threats against Iran (termination of the nuclear agreement) drove up the price of oil. The disappearance of the Saudi Arabian journalist Khashoggi put Saudi Arabia under pressure, exemptions for Iranian oil exports for several countries caused the oil price to fall again.

25.04.2019: The oil supply was uncertain. The civil war in Libya escalated rapidly and became bloodier and bloodier. A second factor of uncertainty was the sanctions against Iran. On that day, it was unclear what course Washington would take against Iran in the future: Would the numerous oil export exemptions be extended? This would relieve the oil price, but also take the pressure off Tehran. Tougher sanctions would be in the interest of the hawks in the White House, but would allow gas station prices to climb to unpleasantly high levels. The tensions caused a price peak.

06.01.2020: A trade agreement between the USA and China caused the oil price to rise in the short term, after which the Covid-19 pandemic, which first appeared in China, caused oil prices to fall.

Even after that, there was further increases (Figure 3). The US government's aid programmes totalling nearly 6 trillion USD have led to economic growth, increased oil demand and rising inflation in the US to over 5% per year. Inflation and the production cuts of one million barrels per day by Saudi Arabia were so drastic that from then on OPEC+ became the most dominant factor for the oil price. A new era began. And the war in Ukraine topped the oil price again.

2.3.2. Lows of Oil Prices

Dark yellow crosses and a dashed dark yellow line mark the minima of the oil price in Figure 3. The lows are associated with OPEC intervention if the price becomes too low for it. The low in 2020 is due to the pandemic and not included in the list. In two meetings in 2022, OPEC decided a production reduction, so these dates are included in the table 2. In 2023 a third meeting followed.

Just at the last minimum in the spring of 2020, there was the most violent OPEC reaction with the strongest production cut, but since the demand for OIL had plummeted extremely, the price drop was also extreme.

Date	Price (USD/bbl)
20.01.2016	26.01
27.12.2018	51.49
07.08.2019	55.03
02.10.2019	57.92
05.09.2022	92.83
05.10.2022	93.37
02.04.2023	79.77

Table 1: Timing and price per barrel of oil price minima. Source: EIA [1]

It is striking that the lows are taking on higher and higher price levels. This shows that the OPEC countries need ever higher oil prices to finance their national budgets. (see also International Monetary Fund [2]) .Just like the citizens of Western countries, the citizens of OPEC are not prepared to voluntarily reduce their standard of living. They will continue to fight for higher oil prices in the future.

2.4. Crude Oil Price and Crude Oil Production

Until 2018, the quantities of oil produced increased on average. There was a peak in oil production in November 2018 (blue line in Figure 4), this value has not been reached since. The price of oil is also falling until 2021. Even the attack on Saudi oil facilities and the subsequent production cuts in September 2019 only lifted the oil price briefly, not even touching the

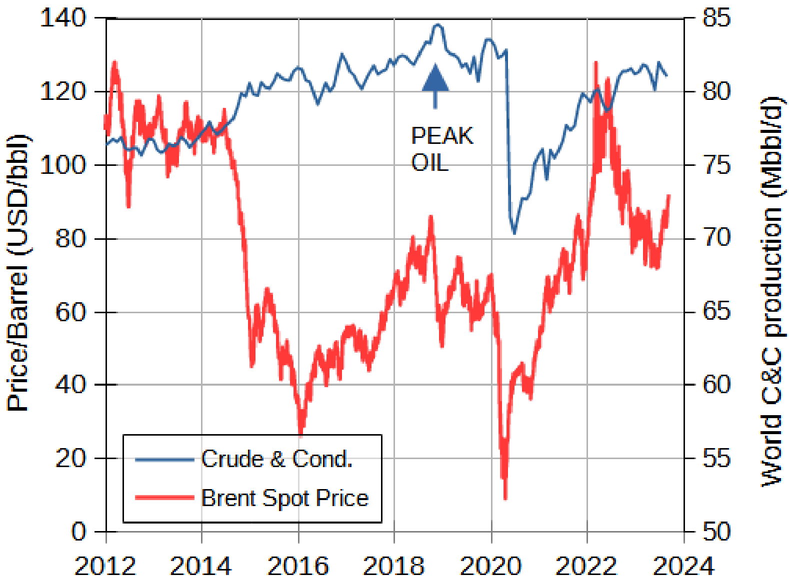


Figure 4: Crude oil price (Brent) and crude oil production. Crude&Condensate production is shown here, which, unlike All Liquids, does not include NGPL, biofuels or Refinery Gain.

Sources: [56] [1]

dashed line of Figure 3. The Covid19 pandemic caused a sharp drop in oil price and production in spring 2020.

Falling oil prices make it unlikely that oil production can reach the prior peak output level again. The global recession is putting pressure on the oil price. Low oil prices make oil producers cut back on investments. Especially the more expensive oil extraction methods such as fracking, oil sands extraction and offshore production are already in decline. The number of bankruptcies in the oil sector has reached an all-time high [3].

Saudi Arabia needs an oil price of around $80/bbl to finance the state budget. To reach this price level, Saudi Arabia's only option is to persuade OPEC+ to reduce oil production. In April 2020, Saudi Arabia significantly increased production to force Russia to also cut production. Since May 2020, OPEC+ production quotas have been extremely reduced, stabilising the oil price at just over $40/bbl. Shortly before the turn of the year2020/2021, the oil price rose again, reaching almost $70/bbl in May 2021.

3. Petroleum

Today, petroleum is one of Germany's most important energy sources. In the transport sector, petroleum products are indispensable as fuels; most means of transport require them. The fuels are concentrated energy in an easily storable and concentrated form; this makes substitution by other energy sources complicated.

The advantage of oil is that it is both an energy source and an energy carrier. Immediately after extracting the oil, one has energy in a usable form; only a few processing steps (refining, blending) are necessary to have an energy carrier for vehicles or heating systems. Other energy carriers are just that – carriers and not energy sources, such as hydrogen or synthetic fuels, on the other hand, are complex to produce with the help of energy sources (biomass, wind power) and additional processes.

An overview of many aspects of petroleum was prepared by Simon Michaux for the Geological Survey of Finland and the EU [4]. The 510-page report is a compilation of information from many sources. His report ends with the statement: **Due to our dependence on oil, it may be the primary, or master raw resource. Because of our dependence on oil, we should consider it our primary raw material**.

3.1. Primary Energy Consumption in Germany

As an industrialised country, Germany consumes vast amounts of energy from a wide variety of sources. Even though the press often gives the impression that a lot of it comes from renewable energies today, most of it is actually from fossil fuels.

In 2019, Germany has an energy consumption of about 13,000 PJ/year with 80.62 million inhabitants. Per capita energy consumption is around 123 kWh/day or 5.1 kW around the clock.

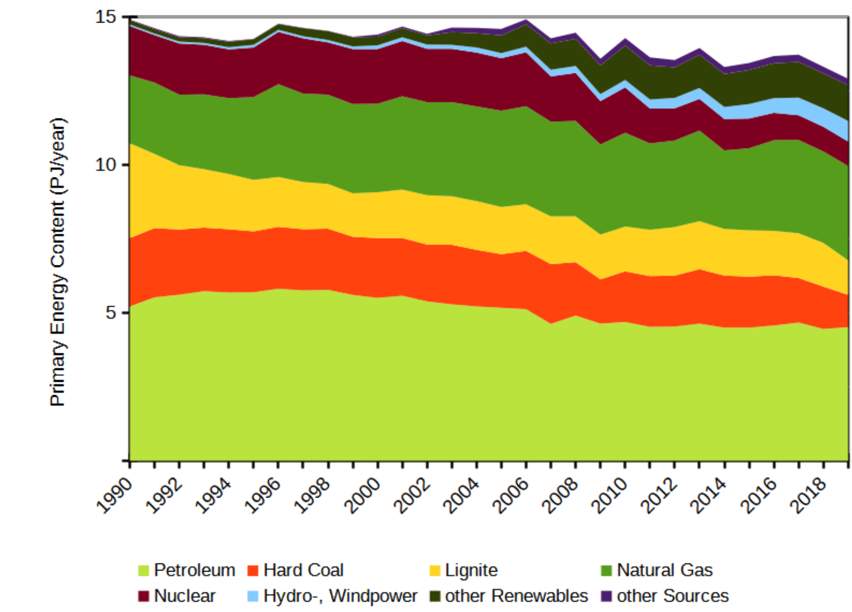


Figure 5: Primary energy consumption of Germany in PetaJoule. Source [4]

According to Figure 5, energy consumption is declining slowly, but has essentially remained constant for decades. The slight decline may be due to the relocation of energy-intensive processes abroad, i.e. the average German has always consumed the same amount of energy for years.

The percentage breakdown of energy sources in 2019 was:

Energy Source	2019
Petroleum	35.3
Hard Coal	8.6
Lignite	9.1
Natural Gas	25.0
Nuclear	6.4
Hydro-, Windpower	5.5
other Renewables	9.4
External Trade Balance	-0.9
other Sources	1.7

Table 2: Percentage shares of energy sources. [5]

As can be seen, crude oil[1] is one of the main energy sources with a share of 35.3 %. Only a fraction of the crude oil used (approximately 2 %) is produced in Germany itself, the main quantity is imported. In 2019, 1,927 kilotonnes (kT) of crude oil were produced in Germany, 85,857 kTwere imported. All importing countries are to be considered important trading partners.

1 The term crude oil is synonymous with mineral oil. In English, the terms crudeoil (crude oil) or petroleum are used. Petroleum, mineral oil, crude oil are used in this book as terms with the same meaning.

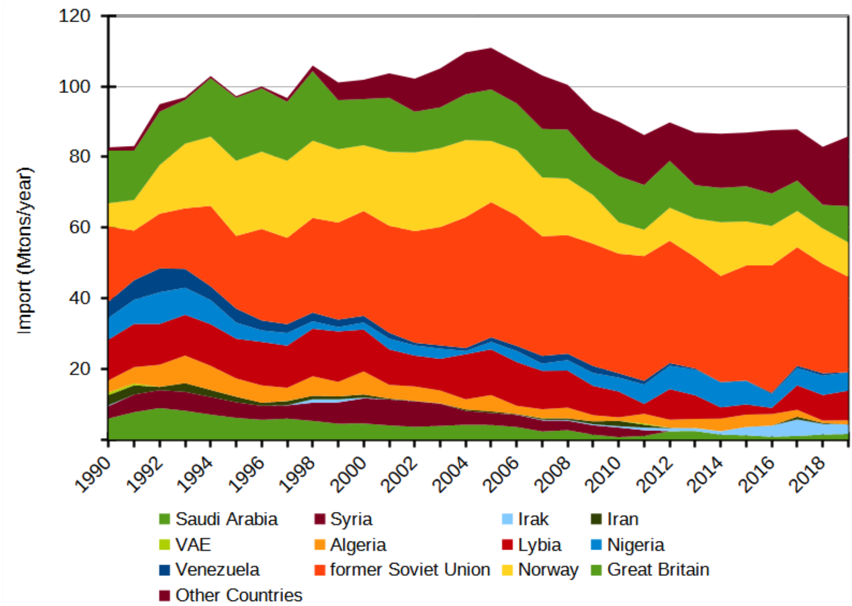


Figure 6: Origin of crude oil imports to Germany in Mega Tons

Source: [4]

Not only unprocessed mineral oil is imported, but also mineral oil products are imported and exported.

3.2. Use of Petroleum

Petroleum is broken down into end products by refineries. The first processing steps are purification, distillation under normal pressure and vacuum distillation with fractionation. Final products are blended from the products of distillation (blending). The percentage distribution of the end products depends on the type of crude oil, the desired amount of end products and other factors.

INLAND SALES	kT
Diesel fuel	37.777
Petrol	18.014
Light heating oil 2)	15.129
Crude petrol	11.269
Jet fuel 3)	10.234
Liquid gas	3.891
Bitumen	2.040
Heavy heating oil	1.806
Total 1)	103.386

Table 3: Sales of petroleum products in Germany 2019, Source: [5]

978 kT of bunker oil for international maritime shipping are also sold, but do not count as domestic sales.

1) Including double counts from recycling

2) Including other heavy residues

3) Including aviation fuel

Crude petrol or naphtha is a relatively light petroleum fraction that is used, among other things, as a raw material for the chemical industry.

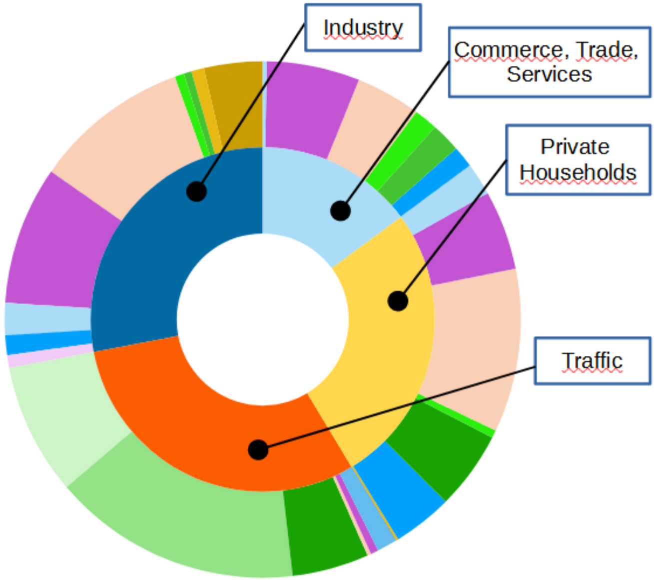


Figure 7: Germany: end energy consumption in sectors. The percentage values and colors are given in the next table.

Industry		2.536
Hard coal	332	
Lignite	72	
Fuel oil	44	
Other petroleum products	53	
Natural Gas	884	
Electricity	785	
District heating	182	
Renewables	111	
Other	73	
Traffic		2.772
Motor gasoline	745	
Diesel fuel	1.413	
Aviation fuel	434	
Natural Gas	22	
Electricity	43	
Biokraftstoffe	114	
Private Households		2.399
Hard coal	2	
Lignite	12	
Renewables	338	
Fuel oil	443	
Other petroleum products	43	
Natural Gas	926	
Electricity	451	
District heating	183	
Commerce, Trade, Services		1.342
Renewables	122	
Fuel oil	167	
Other petroleum products	135	
Natural Gas	368	
Electricity	527	
District heating	24	

Table 4: Final energy consumption by energy source and sector, 2019, Germany, in PetaJoule, Source: [5]

3.3. Petroleum Products in the Transport Sector

From Table 4 we can see that about 93.5% of the energy used in transport comes from petroleum. In other words, without petroleum, transport collapses completely.

There are many efforts to replace fossil fuels with electricity and batteries because of global warming. In the passenger car sector, many such vehicles are already available, and in the truck sector there are initial attempts to replace diesel with hydrogen or synthetic fuels. In the areas of shipping and air transport, no more than functional tests have been carried out.

All these attempts replace the energy carrier, but where the energy stored in the fuel is supposed to come from is more or less nebulous. Hydroelectric, wind and other renewable energies currently account for 15 % of total energy consumption in Germany (see Table 2), so they would have to be seriously expanded.

The construction of vehicles, roads and other infrastructure consumes further large amounts of energy. Building an electric vehicle today costs more energy than building an equivalent vehicle with a combustion engine, which is why it is more expensive. (See Lefs theorem [6]). There is a saying that without government subsidies, no electric car would have been sold anywhere in the world. Road construction without the petroleum product bitumen is possible with concrete, but more expensive than with bitumen.

Today's car concepts based on combustion engines can be summarised as follows: To transport a person weighing about 100 kg, cars weighing about 1500 kg are used. The combustion engine has an efficiency of about 20 %. Car weight and engine efficiency together have an efficiency of 1.2 %. Procuring the fuel roughly halves the efficiency again.

Today's electric-based car concepts can be summarised as follows: To transport a person weighing about 100 kg, cars are used that weigh about 2000 kg, of which 500 kg is the weight of the battery. The electric motor has an efficiency of about 80 %. Car weight and engine efficiency together have an efficiency of 3.8 %. Providing the electricity reduces the efficiency further.

In both concepts, about 97-99 % of the energy used is wasted. And this consideration does not even consider the necessary infrastructure. In a time of energy scarcity, both concepts are not sustainable. The entire transport system will change completely.

3.4. Other Products from Petroleum

Petroleum is one of the most important raw materials. Aside from fuel a myriad of products are made from petroleum. Figure 8 shows some of the product classes. Plastics are largely based on short-chain hydrocarbons derived either from petroleum or natural gas.

The proportion of finished products depends, on the one hand, on the types of crude oil used and, on the other hand, on the processing facilities available in the refinery. For example, light crude oils contain relatively high proportions of light products, i.e. those with low density, such as liquefied petroleum gas, paraffin, petrol and diesel. Heavy crude oils contain larger proportions of heavy products, such as heavy fuel oil and bitumen. In modern refineries, some of these heavy components can be converted into lighter ones, for example by cracking, so that such a refinery can process heavy crude oil.

The internal consumption of refineries is between 5 and 11 % of the energy embedded in the crude oil used, depending on the degree of further processing. Losses also occur, which can be as low as 2 %. In addition, huge amounts of electricity are necessary.

Overall, the following breakdown of the use of petroleum products in Germany can be assumed:

- 60 % for fuels for mobility

- 20 % for heat generation

- 20 % for the production of everyday products, half of which is lost as heat.

Or:

- Approximately 90 % of petroleum is used as an energy source

- Approximately 10 % as raw material

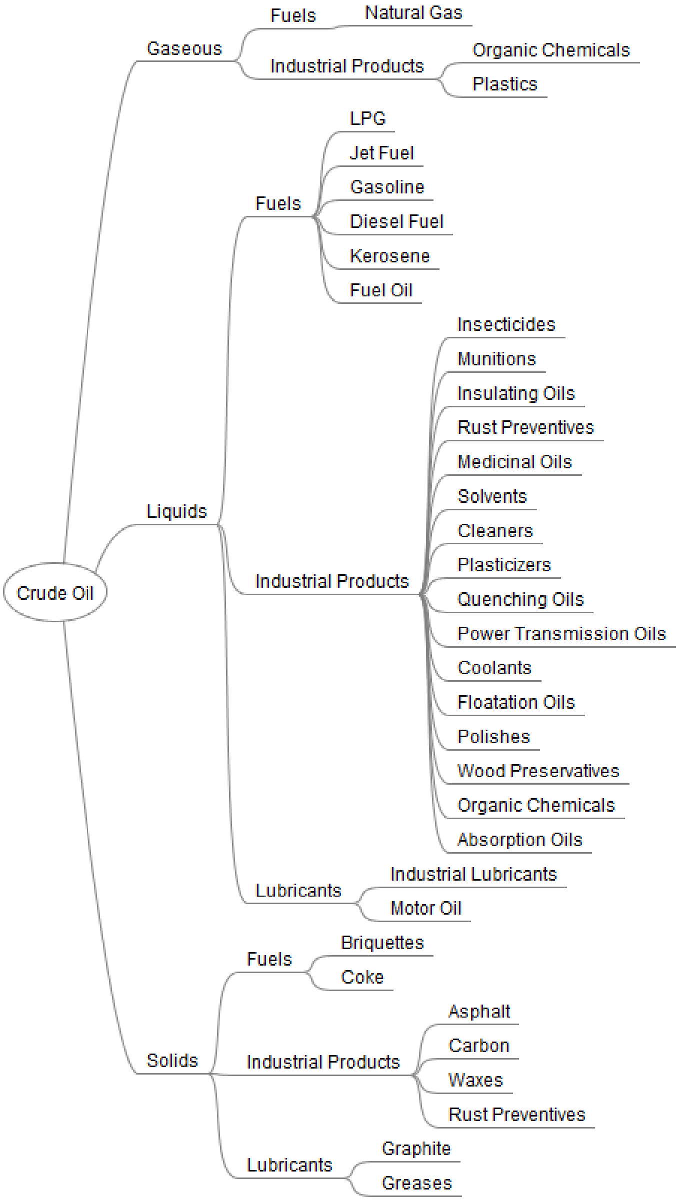


Figure 8: Petroleum products

4. Oil Field Properties

Figure 9: Oil field in Wietze near Celle, Lüneburg Heath, 1920. The oil production towers reached as far as the horizon.

Source: Courtesy of the German Petroleum Museum Wietze.

4.1. World Crude Oil Production

World crude oil production as a function of time is a very well documented measure - the EIA database, for example, contains this curve. The Hills Group uses a fit to this data (skewed parabolic simulation). The fit contains only the data of conventional oil. The unconventional oil types LTG (shale) Oil, Tar Sands, Deep Sea Oil, bioethanol etc. are not included. Therefore, the maximum of this fitted curve is around the year 2003.

The reason for omitting the unconventional oils is that, on the one hand, they are extracted in a significantly different way and, on the other hand, their extraction requires even more energy than conventional oil (see the example of LTG oil in chapter 7.7).

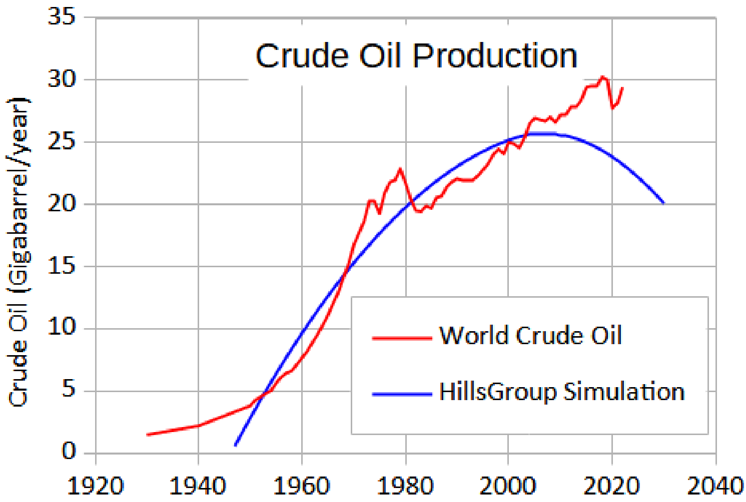


Figure 10: Annual world crude oil production. The curve of the HillsGroup is a skewed parabolic function.

In this book Crude and Condensates (C&C) oil data for oil production are used for calculations, without differentiating between conventional and unconventional oil (red curve in Figure 10). The numbers for all liquids are not used, which include not only C&C oil, but bioethanol, NGPL and refinery gain. The last three kinds are not extracted out of the earth.

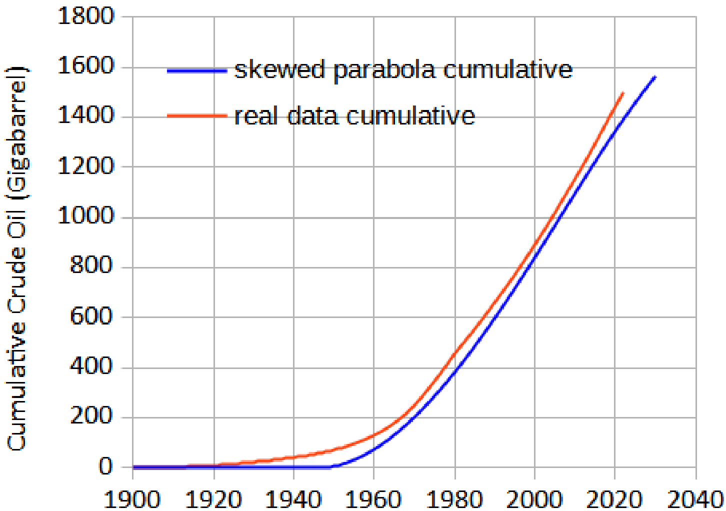


Figure 11: Cumulative global crude oil production with extrapolation. Blue: conventional crude oil, based on the skewed parabola simulation. Red: real data of C&C oil.

4.2. Oil Reserves

Readers familiar with considerations of the length of the oil age and peak oil will have noticed that little has been said so far about oil reserves. Normally, peak oil theories include detailed considerations of the amount of oil found, the amount of oil that may still be found, how much of it is economically recoverable or not, and the result is then put in relation to current oil consumption or extrapolated future consumption. Whole discussion groups deal with this every day. (e.g. Peak Oil Barrel [7]).

Example: Figure 12 shows the current quoted oil reserves. In 2018, the value was 244,049 million tonnes. The annual production of C&C crude oil is about 4,100 million tonnes. From this, one can deduce a static range of about 59 years, if one believes oil is produced with banknotes instead of energy.

These considerations can be dispensed with. The thermodynamic production limit applies regardless of the amount of oil still resting in the earth. Only the temperatures in the oil field and at the earth's surface, as well as the quantities of oil and water extracted, determine the amount of energy needed to extract the remaining oil. Even if an elephant field like Ghawar had ten times as much content: If the energy input is much greater than the energy content, production will come to a standstill. The remaining oil will remain at the bottom.

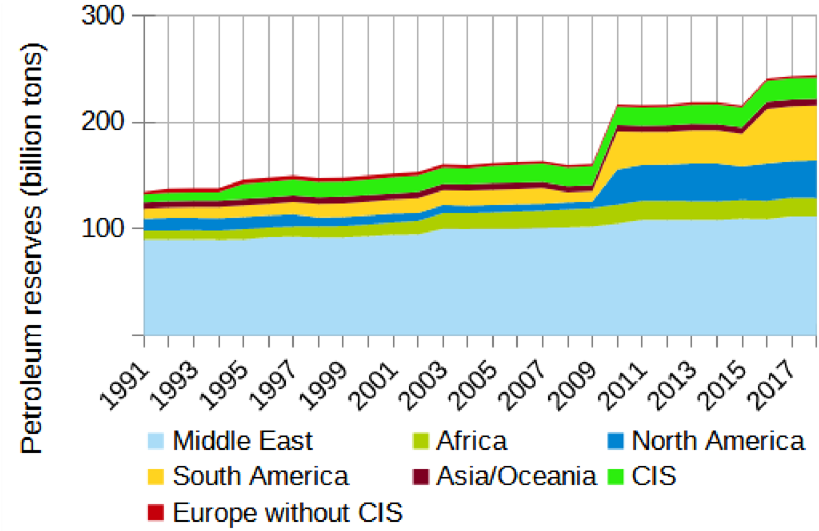


Figure 12: Oil reserves in the world by region. Paradox: Despite production, they are getting bigger every year instead of smaller.

A hint exists, that this process has started: In 2022, Rystad Energy announced a decrease in world recoverable oil reserves by 9% [8], because the production costs are too high.

4.2.1. Oil Discoveries

Figure 13 was compiled from data sets of the companies Wood Mackenzie (until 2015) and Rystad Energy (after 2015) [9] on annual oil discoveries. The 1960s and 1970s saw the most discoveries, after which they slowly decreased. The annual oil consumption is about 30 billion barrels; after 1990, only in three years was more found than was consumed. Since 2011, only about one tenth of the consumption has been discovered.

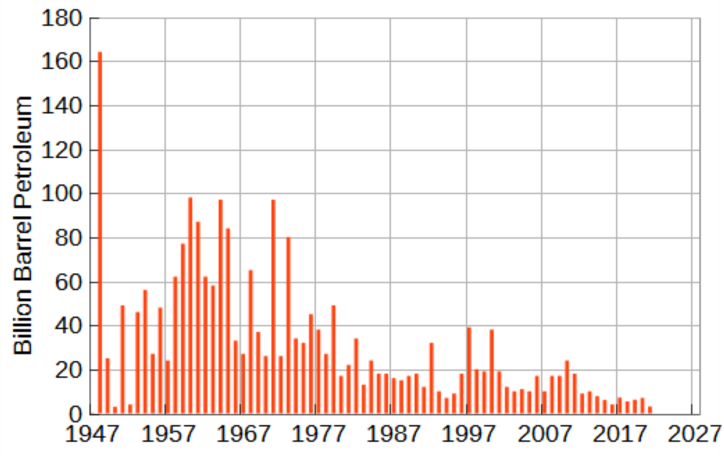


Figure 13: In 1947, only 230 million barrels were discovered, but in 1948, with the Ghawar oil field in Saudi Arabia, there was the largest oil discovery in history.

4.2.2. Capital Investment for Oil Production

Figure 14 has been compiled from the IEA World Energy Investment 2019 and World Energy Investment 2021 [10] reports. Until 2014, oil prices were high and a high proportion of profits were used by oil producers in the upstream sector. Afterwards, investments dropped significantly and reached a provisional minimum in 2020.

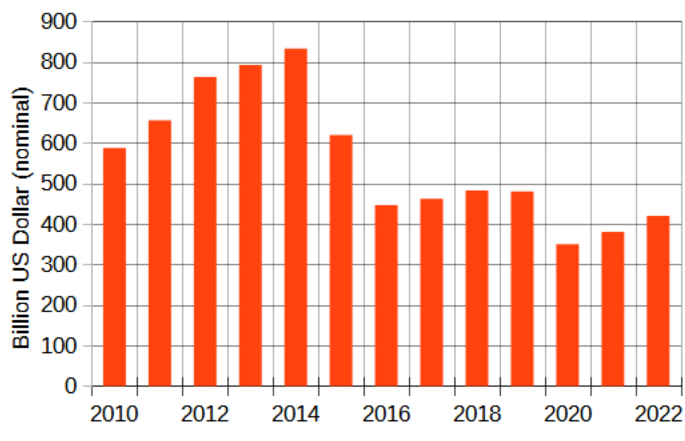


Figure 14: Capital expenditure (capex) in the upstream sector. Source: IEA, World Energy Investment, 2019 and 2022 [8]

In the petroleum industry, the term upstream summarizes the entire process from the geological development of petroleum deposits to the transport of the raw material to the earth's surface and its provision in purified form. Upstream includes all steps leading to the refinery.

The oil industry is in a control loop. Investments will decline if it has low profits. Investments will decline if future profits seem to get low. 2022 has been a good year for the oil industry, because of the war in Ukraine, but this is probably an exception. OPEC cuts production again (03.04.2023) because profits are low.

Oil consumers have less and less net energy for themselves from the energy produced, which means they have less and less money to spend on oil. As a result, profits of oil producers are under pressure. The dilemma cannot be solved.

4.3. Properties of the Earth's crust

Physical properties of the Earth's crust vary locally, just like the properties of oil wells and boreholes. In the following, ranges for the relevant physical quantities are given and a typical value is chosen for the determination of the thermal time constant.

Earth density:

$$\rho = 1700..2700\frac{kg}{m^3}, \qquad \text{selected } is\ 2000\frac{kg}{m^3}$$

Heat capacity of earth material:

$$c = 0.22..0.43\frac{W \cdot h}{kg \cdot K}, \qquad \text{selected } is\ 0.43\frac{W \cdot h}{kg \cdot K}$$

Typical thermal conductivity of earth material:

$$\lambda = 0.47 \ldots 2.1\frac{W}{m \cdot K}, \qquad selected\ is\ 2.1\frac{W}{m \cdot K}$$

Conventional crude oil is typically produced from depths of 500m to 3000m. Well depths:

$$selected \quad d = 1000m$$

4.4. Thermal Relaxation Time

Using the above material values, one can determine the thermal relaxation time for an earth layer. This is the time it takes for a temperature difference to equalise through an insulation layer.

$$T(t) = T_{Start} \cdot exp\left(\frac{-t}{\tau_{Relax}}\right) \qquad \text{Eq. 1}$$

T_{Start} is the initial temperature difference and T(t) the temperature as a function of time. The relaxation time is calculated according to the following formula:

$$\tau_{Relax} = \frac{d^2 \cdot \rho \cdot c}{\lambda} \qquad \text{Eq. 2}$$

Using the material values from above, the time constant for the 1000 m thick layer of earth is as follows

$$\tau_{Relax} = \frac{1000^2 \cdot 2000 \cdot 0.43}{2.1} m^2 \frac{m \cdot K}{W} \frac{kg}{m^3} \frac{W \cdot h}{kg \cdot K} \qquad \text{Eq. 3}$$

of:

$$\tau_{Relax} = 4.1 \cdot 10^8 h = 47000\, Years$$

Since the time constant is large compared to the previous duration of oil production of approximately 150 years, there is very good tempera-ture insulation between the earth's surface and the oil reservoir. For the 150 years of oil production, the above formulas and data result in a depth of heat penetration into the earth of only approximately 56 m.

4.5. Vertical Temperature Gradient in the Earth's Crust

The Earth's core has an estimated temperature of 5500-6000 K. Heat flows continuously from the Earth's core to the Earth's surface and is emitted from the Earth's surface into space by infrared radiation. This amount of heat is about 50 mW/m².

With deep boreholes in Germany, an almost linear temperature gradient was determined. The Earth's interior becomes about 33 K warmer per 1000 m. The value of the gradient is thus:

$$grad(T) = \frac{dT}{dh} \approx 0.033\frac{K}{m} \qquad \text{Eq. 5}$$

Solar radiation causes daily and seasonal fluctuations in the temperature at the earth's surface. However, these fluctuations only penetrate the earth to a small depth. Already at a depth of 20 m, there is an almost constant temperature T_{20m} in most places, which is not subject to seasonal fluctuations. In Germany, the typical temperature at a depth of 20 m is about 11 °C (=284.15 °K).

The equilibrium temperature in the earth's crust has approximately the following value from a depth of 20 m:

$$T_{GL}(h) \approx T_{20m} + grad(T) \cdot (h - 20m) \qquad \text{Eq. 6}$$

T_{20m} and grad(T) are locally different and have to be determined separately for each oil well.

The temperature gradient has been locally unchanged for hundreds of thousands of years, even millions of years. In particular, all heat flows except the flow coming from the Earth's core have balanced out over the years. An equilibrium exists that would hold for hundreds of thousands of years more without human intervention. A temperature equilibrium exists, oil production disturbs the equilibrium.

Geothermal power plants are built in places where the earth's temperature is significantly higher than the normal gradient. Power plants near the gradient line are uneconomic (in other words: energetically inefficient). At equilibrium, energy cannot be extracted.

4.6. Reservoir Temperatures

The reservoir temperature is determined by the depth of the well. The Hills Group has analysed the US well data stored at the EIA against time, plotted it on a graph and fitted it with a straight line. Figure 15 below shows the fit. As with the following diagrams, the fit can be extrapolated into the future. See also Jean Laherrere on depth and temperature distribution [11].

The temperature gradient in the Earth is about 33 K per 1000 m. This gives the curve in Figure 16, which shows the mean tempera-ture difference from the standard reference ambient temperature of 11°C (= 284.15 K) at the bottom of the boreholes.

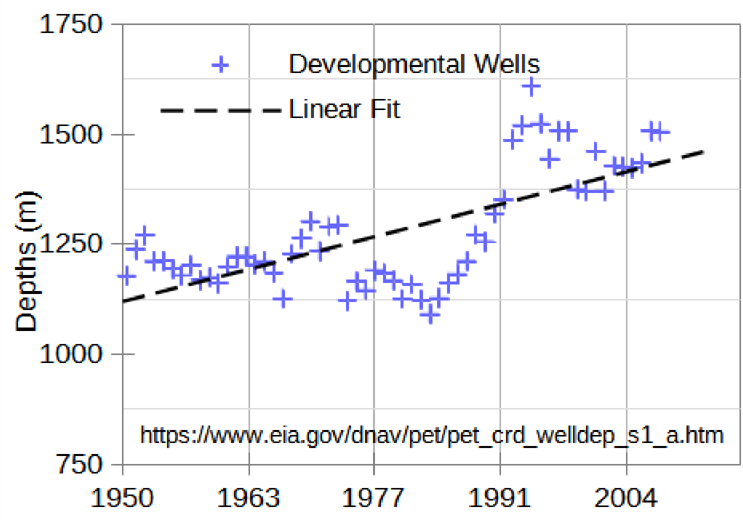


Figure 15: Well depths for conventional oil in the USA as a function of time. Source: EIA

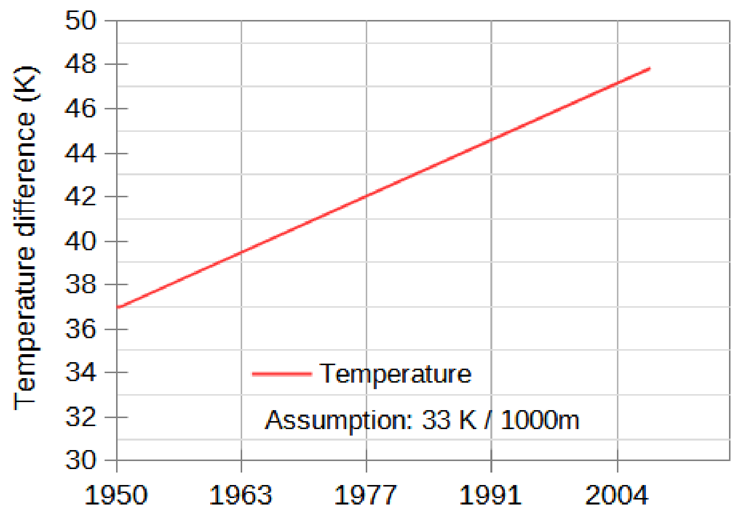


Figure 16: Mean increase in temperature differences (well bottom to 11 C at 20 m depth) of wells in the USA as a function of time, derived from the fit curve of the previous graph.

4.7. Water Cut in Crude Oil Production

Oil wells produce not only oil, most of them produce water as well. The water percentage increases with time. The watercut is the percentage of water that comes out of the well. Since water has a higher mass density and heat capacity, it transports considerably more heat than the same volume of oil.

The water fraction was calculated by the Hills Group using the Buckley-Leverett equation of fluid mechanics. The water fraction as a function of time is much more difficult to determine than the transport curve. In the

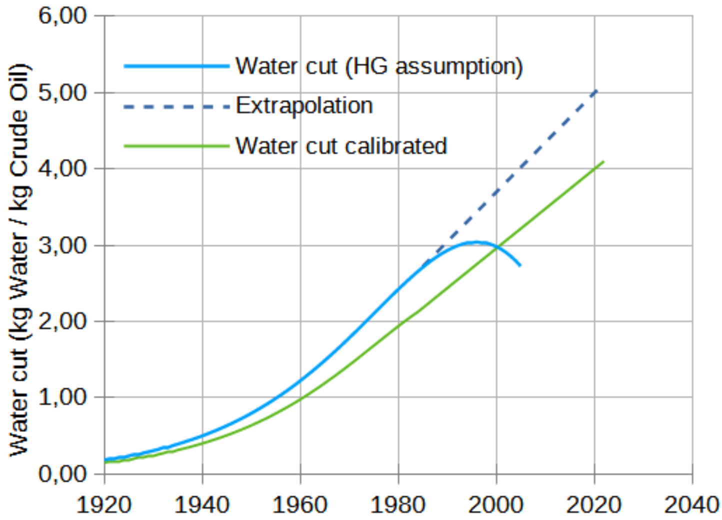


Figure 17: Example of the water content in kg of water per kg of crude oil as a function of time. Thesolid line is determined from the data of the HG group, the dashed line is extrapolated. Unfortunately, there is little data for a realistic curve. The water content today is probably close to 4 kg of water per kg of crude oil.

Hills Group script there is an approximation formula for the water fraction as a function of the percentage extraction from the oil field.

Unfortunately, the extraction of each field as a function of time is unknown. Only the world's oil production to date is available. Furthermore, the curve of water content as a function of extraction is not linear. By analysing a lot of data on oil fields, Hills Group has determined an average water fraction in 2005 to be 54%. The water fraction is given by oil producers as a percentage of litres of water to litres of oil. To determine the mass flow, the proportion must be calculated in kilos of water per kilo of oil. Since the density of water is higher than that of oil, at 46.3 % volume share (watercut) one kilo of water is produced per kilo of oil.

For the conversion of the water content into a function of time, diagrams of the Hills Group were re-engineered and evaluated (Figure 17). The solid blue line corresponds to the HG data. The bending of the curve is not very likely, and probably caused by an error in the HG data. The dashed blue line is an extrapolation from the not bended part of the HG curve.

The solid blue HG function for the water fraction was used for the TNE curve Figure 24. The dashed line has been used in a first approach for Figure 29. Because the energy values derived from thermodynamics and the oil price differed, the water cut has been reduced to adjust the thermodynamic energy values to the price values. This is a sort of calibration. So, the solid green line is used for Figure 29.

Examples for water cut in oil fields:

Daqing is the largest oil field in China. The water cut changes from well to well; it is about 80%-90% [12], probably even higher.

Samotlor is a giant field in Siberia, Russia. It was the sixth largest of the world. Its water cut is about 90% [13].

Ghawar is the worlds largest oil field, located in Saudi Arabia. In 2006 the water cut was 46% [14]. The current value is secret.

5. Oil Price Conversion to Energy Units

As a physicist, i know that all machines, all life, all animals and all plants need energy to run. Without energy in the form of food, nobody will survive for more than some weeks.

In contrast, economists seem to believe the world runs on money. Most money is spent on goods of all kinds, very little is spent for energy. Therefor, energy is unimportant for them.

5.1. Money

But what is money actually? After studying Graeber's book *"Debt - The First 5000 Years"* [15], the following has stuck with me:

1. Money is based on the promise to repay debts. If the promise is fixed on an object (paper), the debt is transferable to other people and becomes money.

2. Money is created out of nothing by central banks. When central banks lend money to someone, they give them something that was not there before. The person thereby becomes a debtor, with the obligation to pay back the interest on it. The money was thus created by the central bank.

3. While private individuals have to pay back the money as well as the interest, this is generally not the case for states and large companies. These take out new loans to repay old ones.

4. Money requires police forces or armed forces. In order to prevent the debtor from refusing to pay interest, it must be possible to force him to pay. For private individuals, the police are sufficient; for states, military forces are necessary. So central banks only work in conjunction with a military. The best example of this is the FED of the USA, which provides

US-Dollar to the whole world, in conjunction with the armed forces of the USA.

5. The value of money is relative. Money gets its value from people's belief in its value and from the situation. A bundle of dollar notes is worthless to a person stranded alone on an island. His banknotes have no value except their calorific value. Or: people consider gold to be valuable. Gold has some use in certain industrial manufacturing processes, but these in no way justify its assumed value. If only one person considers gold (or money) to be valuable, it is valuable.

6. If you have a lot of money, you have a lot of people who owe you. He who owes a lot to others is unfree.

This still does not clarify what money actually is, but one can attribute certain properties to it. Especially the characteristic under point 5 gives rise to the suspicion that money has a lot in common with a **religion**.

5.1.1. Money and Energy

All products that can be bought are paid for with money and produced by using energy. Roughly speaking, the price of a good is proportional to the amount of energy used to produce it. (Lefsches Theorem [6]). This tempts us to equate money with energy or at least a claim to energy.

But: money is not equal to energy. Energy can only be produced by energy (oil production plants, coal mines, solar and wind plants). The central banks can print as much money as they like, but this alone does not create a plant for energy production. Energy can only be produced if the printed money is used to direct energy in such a way that it is used to build plants. Money is thus merely a control instrument for the distribution of energy.

5.1.2. Inflation

Money can buy less from year to year. This effect is called inflation. Inflation is determined from the value of selected items for each year. In Germany, a basket of goods containing a sum of consumer goods is referenced as an example.

The US inflation values tabulated by the World Bank [16] were used to construct the inflation curve in Figure 20 to determine the purchase price of a fictitious basket of US goods.

Inflation has the effect, that oil prices in different years are not directly comparable, the must be adjusted prior to comparison. In this report, the energy productivity is used instead of inflation.

5.1.3. Inflation-Rise in the USA after the Pandemic

In March 2021, the US Congress passed another aid package for the US population worth 1900 billion USD. In total, this means that aid packages totalling approximately six trillion USD have been approved. A side effect of these packages is a significant increase in inflation, not only in the USA, but worldwide. Figure 18 shows that in the USA the energy sector is particularly affected by price increases, i.e. oil, oil products, coal, gas and electricity. The development of price increases is currently in flux and cannot be assessed conclusively.

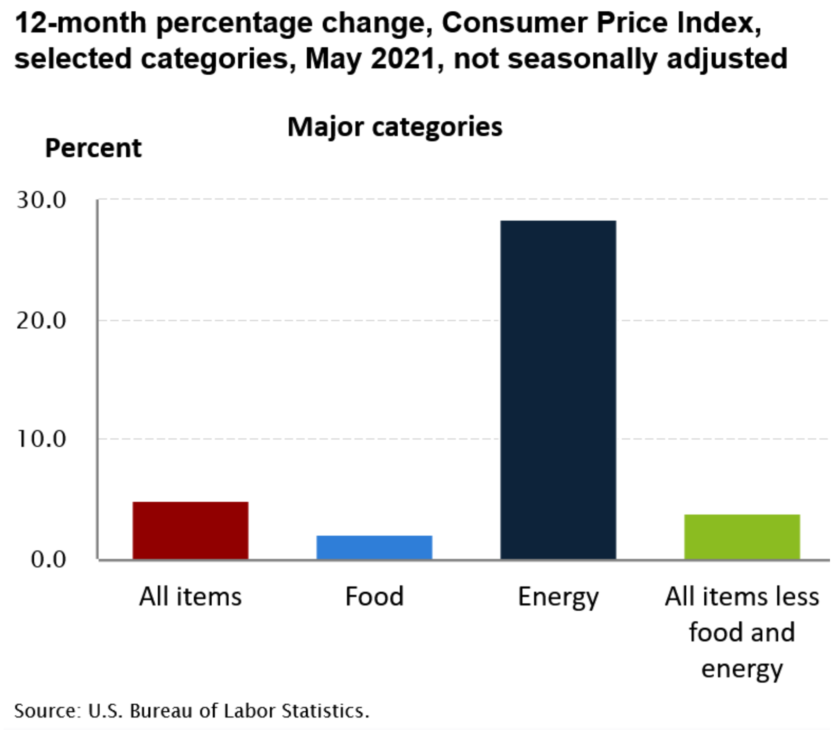


Figure 18: Inflation in the USA, by product group. The mean value of all items is 5 %, as of 15.06.2021. Source: [51] https://www.bls.gov/cpi/, U.S. Bureau of Labor Statistics

5.1.4. Energy Productivity

Even though money and energy are different things, they can be converted into each other using the energy productivity curves (Figure 19). The graph is based on data on global GDP, called Gross Domestic Product or Global Domestic Product, and global primary energy consumption. It shows the GDP to energy consumption ratio. The data used come from the World Bank [16] With the help of this quotient, one can allocate energy per barrel to the prices per barrel.

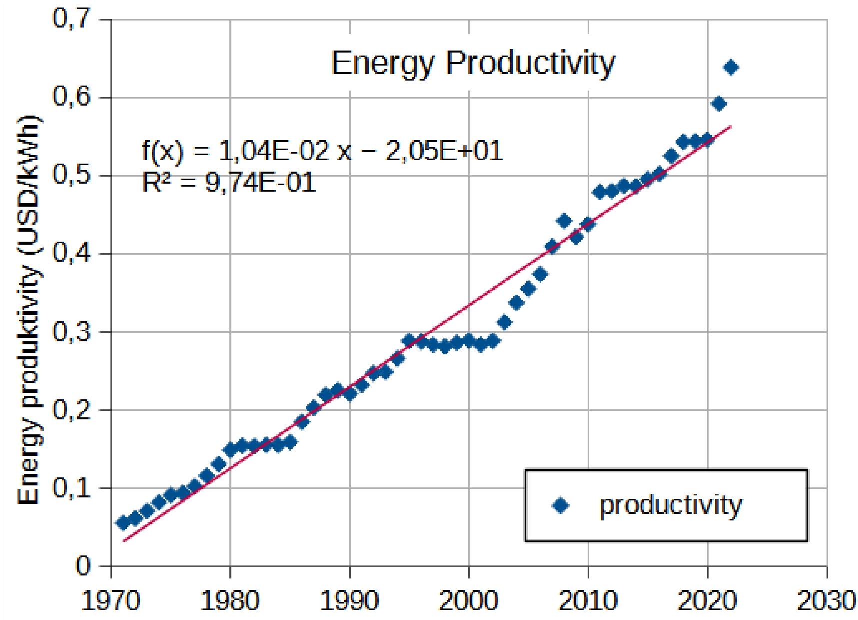


Figure 19: Energy productivity (world GDP divided by world primary energy consumption). The equation of the linear fit is given.

The diagram in Figure 19 shows that over time an ever-higher value is created in GDP with one kilowatt hour of energy. The upward slope of the curve is a consequence of technological progress and inflation. Suddenly rising inflation manifests itself as an upward bend in the curve, especially in 2021 and 2022. The borrowing of the world's states leads to inflation in energy prices in 2021 and later is visible in this curve.

If the curve remains in a horizontal direction, this means that there will be no technical progress or inflation during this period. A downward bend means deflation and regression; this has not happened so far.

However, the diagram should not be understood to mean that the corresponding amount of money is necessary to produce the energy or that the consumer pays the indicated monetary value for his energy. Normally, the consumer spends much less money for the energy than the curve shows. If he had to pay the indicated amount of money for his energy, he would have to spend his entire income on energy and could not buy anything else. The curve is therefore a limit curve for the consumer and represents the maximum he can pay for energy.

Lefs theorem [6] states, that the price of a product is about the same as the energy costs to create the product. For most hardware products this is obviously adequate. For services like medical support the theorems might be questionable, for things like art products it seems invalid.

5.1.5. Determination of an Inflation independent Oil Price

With the help of energy productivity, oil prices can be converted into energy. For the minima of the oil price (see chapter 2.3.2) this results in:

Date	Brent Price USD/bbl	Energy-productivity USD/kWh	Energy needs of oil producers % of BOE
20.01.2016	26.01	0.49	3.0
27.12.2018	51.49	0.51	5.7
07.08.2019	55.03	0.52	6.0
02.10.2019	57.92	0.52	6.3
05.11.2021	82.0	0.24	8.7

Table 5: Energy demand of oil producers at the time of the oil price minima

Petroleum (Crude Oil) production and the price of oil are linked. Oil prices are quoted on the stock exchange in USD/barrel. They are subject to inflation. As a result, a price from 2010 is not directly comparable to the price of 2020, you have to take inflation into account. Inflation levels fluctuate from year to year and have been particularly high since 2021. If you want to compare prices of different years, you have to assume a reference year. Use of a reference year has two disadvantages: 1. It is not standardized; each author uses his own reference year. 2. It is outdated: Who is still interested in the prices related to the year 2000?

An independent frame of reference is needed. For this purpose, the Global Domestic Product (GDP) is used. Dividing GDP by world primary energy consumption results in energy productivity. It is shown in Figure 19. With the help of energy productivity, the price of a barrel of crude oil can be converted into the energy content of the barrel and given as a percentage.

The primary energy content of a barrel of oil equivalent (BOE) is 1 BOE or 1628.2 kWh. BOE is a unit of energy commonly used in the oil industry.

The price of a barrel of petroleum, expressed in U.S. dollars, can be converted into a percentage of the barrel's energy. The conversion factor for this is energy productivity Figure 19. The percentage is calculated by:

$$\%BOE = \frac{Price\left(\frac{USD}{bbl}\right) \cdot 100\%}{EP(t) \cdot 1628.2kWh} \qquad \text{Eq. 7}$$

With:

Price (USD/bbl) : the price of crude oil in US dollars per barrel

EP(t) : the value of energy productivity EP from Figure 19 for the year under consideration.

% BOE : indicates what percentage of the energy content is paid per barrel. Another term for % BOE is "Specific energy content in percent".

Example: Let’s assume: a barrel of Brent oil has cost the consumer $60 in 2020. EP(2020) has been 0.55 USD/kWh. In %BOE we get:

$$\text{Cost of Barrel} = \frac{60 \cdot 100}{0.55 \cdot 1628.2} = 6.7\% BOE \qquad \text{Eq. 8}$$

The advantage of being expressed in %BOE is that the values are not dependent on a reference year. The disadvantage is that values for EP(t) of the last two years have to be estimated and are only inaccurately known because the World Bank publishes the GDP data with a delay.

Energy productivity makes it easy to convert money into energy. This is important, because the economy runs on energy, not money. This difference seems trivial, but is always overlooked. Crude oil is extracted with energy, not money. Money is printed by central banks, and can be produced in any quantity. Energy is finite, at least fossil energy.

5.2. Inflation and Energy Productivity

Inflation and energy productivity both have similar trends. Inflation has 2 underlying effects: Technical progress makes products cheaper, but devaluation of money compensates the first effect.

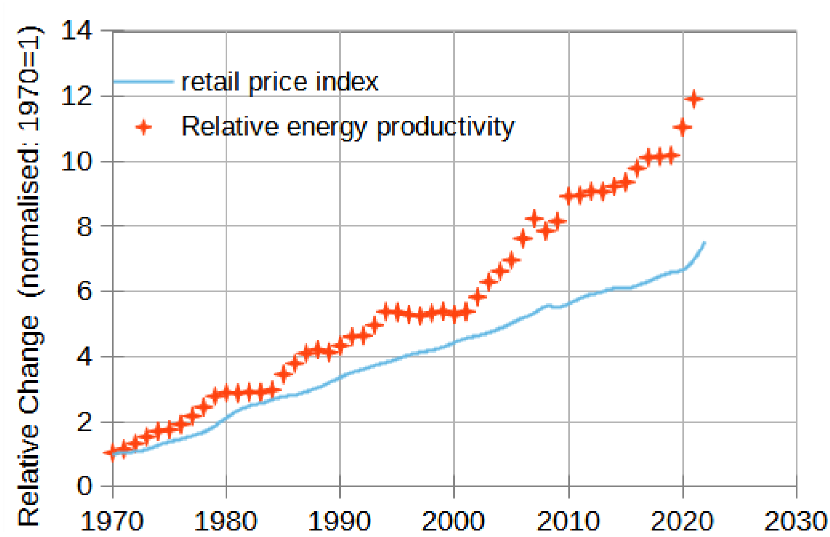


Figure 20: Inflation and energy productivity comparison. Both are set to "1" in 1970.

5.3. Comparison of Fossil Fuel Costs

Each fossil fuel has its own energy content. The fuels are traded on markets with daily changing prices. Figure 21 shows the prices per Gigajoule as a function of time. Before 2021, the GJ from oil was about

4-5 times more expensive than the GJ from gas or coal. In 2022 all fossil fuels have got more expensive. The factor of 4-5 has shrinked to only 2.

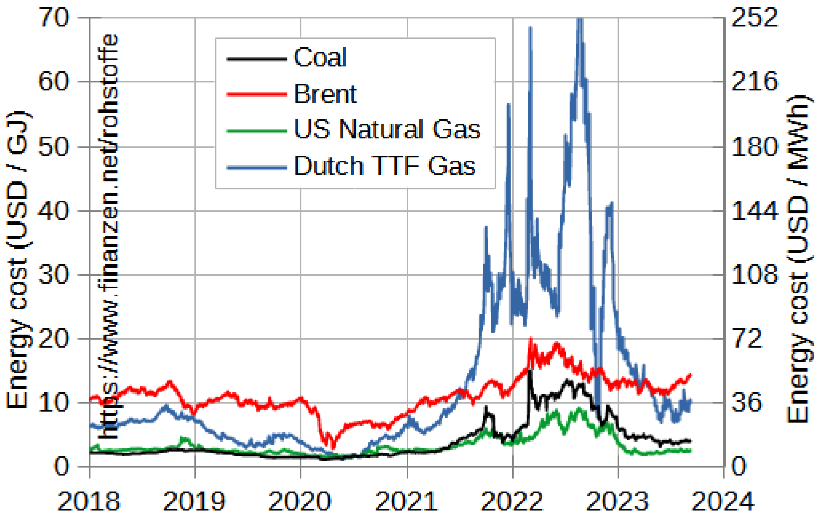


Figure 21: Energy Costs in USD per Gigajoule versus time.

Because very much energy is necessary to produce oil (see chapter 7.8), the rising energy costs of coal and gas will drive the price of oil upwards.

5.4. The Oil Price, measured in BOE

Figure 22 displays the oil price as a function of time, converted from Brent to Percent of BOE. The price maxima from 2008 to 2020 are marked as green crosses. Astonishingly, they are all on a straight line (dashed green). In energy terms, we can conclude:

Imagine, you are the author in December 2019 and look at Figure 22.

There has been an upper limit for oil prices up to 2020. The world economy did not pay more (energy) for oil that this limit allowed. The limit decreases with about 1 %BOE per year.

And a lower limit exists too (dark yellow crosses and dashed line). When the price falls below a certain limit, OPEC reduces the production to drive the oil price high. This lower limit can be seen from 2016 to 2020. The limit increases with about 1% BOE per year.

Since 2020, the oil-producing states have needed more than the global

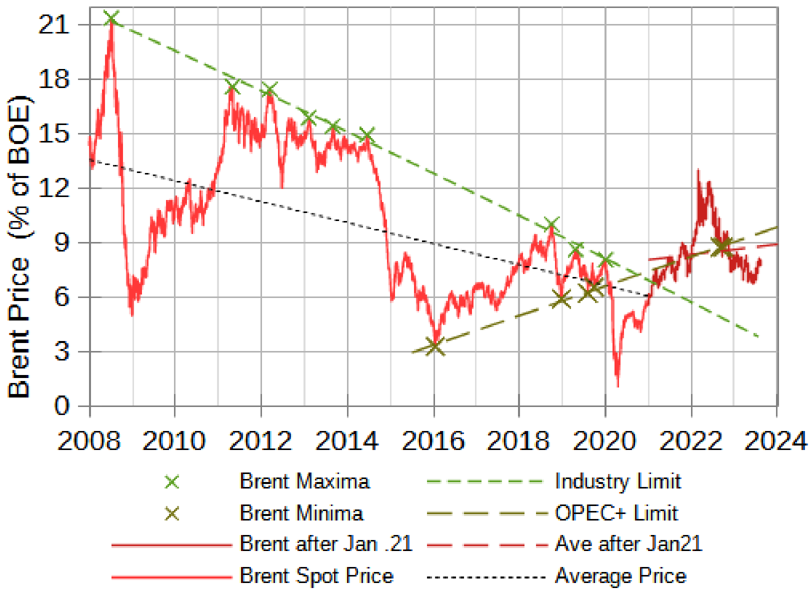


Figure 22: Oil Price, Brent converted to Percent of BOE. The author has set up this graphics at the end of 2019 and continued it afterwards. Please imagine, you are in December 2019 and look at the graphics.

economy can pay. This fact is the background for an extreme potential for conflict.

The world economy's ability to pay for oil allows only about 7 %BOE per barrel in 2020, with a downward trend. If the oil price is above the value that the world economy can pay, a recession and thus smaller oil consumption are the result.

The price demand of the OPEC+ countries is at least 7% BOE per barrel, and the trend is upwards. To realise their desired price, OPEC will cut production.

After 2020, world economies ability and OPECs price demand got a conflict. The average of prices (dashed red line) now follows the dashed dark yellow line. Both dashed lines are almost parallel.

On June 4, 2023 Saudi Arabia announced to cut oil production by 1 Mbbl/d, but the rest of OPEC did not follow. Very volatile oil prices will result.

5.4.1. Four Oil Price Axioms

The discussion of Figure 22 results in:

Axiom 1: Averaged over time, oil consumers have an upper limit for the oil price, they can’t afford each price.

Axiom 2: Averaged over time, oil producers do not sell oil for less than they need to produce it.

Axiom 3: Both limits change with time in defined directions, each with about 1% BOE per year.

Axiom 4: After 2020, Axiom 1 is in conflict with Axiom 2. Oil producers start cutting oil production. The resulting oil prices are unpredictable.

6. Thermodynamics

Thermodynamics is the branch of physics describing the conversion of energy forms from one form to another. To understand thermodynamics fully, detailed study of its laws and a lot of mathematics is necessary. In this book, only a short description of its laws is included, which is copied from/based on Wikipedia articles.

A lot of literature on thermodynamics is available. I prefer the book from Moran/Shapiro: *"Fundamentals of Engineering Thermodynamics"* [17].

The first three laws of thermodynamics have a severe difference to all laws created by humans: They can't be violated. The law of gravity is another example of a law, which can't be violated.

The commandment from the bible *"Thou shalt not kill."* can be found in all laws of the world. Despite that, each day it is violated in hundredths of cases. If caught, the violators get punished according to the local laws.

In contrast, there are no punishments for violation of the second law. That is, because it can't be violated. It is not possible at all.

6.1. The Zeroth Law

The **zeroth law of thermodynamics** is one of the four principal laws of thermodynamics[2]. It provides an independent definition of temperature without reference to entropy, which is defined in the second law. The law was established by Ralph H. Fowler in the 1930s, long after the first, second, and third laws were widely recognized.

[2] https://en.wikipedia.org/wiki/Zeroth_law_of_thermodynamics

The zeroth law states that if two thermodynamic systems are in thermal equilibrium with each other, and also separately in thermal equilibrium with a third system, then the three systems are in thermal equilibrium with each other.

Two systems are said to be in thermal equilibrium if they are linked by a wall permeable only to heat, and their temperature does not change over time.

Thermal equilibrium and thermodynamic equilibrium are not identical expressions. A system in thermal equilibrium can, for example, contain high pressure bottles filled with gas. But this system is not in thermodynamic equilibrium, because it contains stored energy sources.

At most oil reservoirs the vertical temperature distribution is constant and has not changed for millions of years. According to the zeroth law, the earth crust is in thermal equilibrium at most oil reservoirs.

6.2. The First Law

The **first law of thermodynamics** is a formulation of the law of conservation of energy, adapted for thermodynamic processes[3] It distinguishes in principle two forms of energy transfer, heat and thermodynamic work, for a system of a constant amount of matter. The law also defines the internal energy of a system, an extensive property for taking account of the balance of energies in the system.

An equivalent statement is that perpetual motion machines of the first kind are impossible; work done by a system on its surroundings requires

---

[3] https://en.wikipedia.org/wiki/First_law_of_thermodynamics

that the system's internal energy decrease or be consumed, so that the amount of internal energy lost by that work must be resupplied as heat by an external energy source or as work by an external machine acting on the system (so that is recovered) to make the system work continuously.

The law of conservation of energy states that the total energy of any isolated system, which cannot exchange energy or matter with another system, is constant. Energy can be transformed from one form to another, but can be neither created nor destroyed.

6.3. The Second Law

The **second law of thermodynamics** is a physical law based on universal experience concerning heat and energy interconversions[4]. One simple statement of the law is that heat always moves from hotter objects to colder objects (or "downhill"), unless energy is supplied to reverse the direction of heat flow. Another definition is: "Not all heat energy can be converted into work in a cyclic process."

The second law of thermodynamics establishes the concept of entropy as a physical property of a thermodynamic system. It can be used to predict whether processes are forbidden despite obeying the requirement of conservation of energy as expressed in the first law of thermodynamics and provide necessary criteria for spontaneous processes. The second law may be formulated by the observation that the entropy of isolated systems left to spontaneous evolution cannot

---

[4] https://en.wikipedia.org/wiki/Second_law_of_thermodynamics

decrease, as they always arrive at a state of thermodynamic equilibrium where the entropy is highest at the given internal energy. An increase in the combined entropy of system and surroundings accounts for the irreversibility of natural processes often referred to in the concept of the arrow of time.

The second law is the only (macroscopic observable) law of physics which results in a direction for time. Time flow and the second law are inseparable connected.

Historically, the second law was an empirical finding that was accepted as an axiom of thermodynamic theory. The second law has been expressed in many ways. Its first formulation, which preceded the proper definition of entropy and was based on caloric theory, is Carnot's theorem, formulated by the French scientist Sadi Carnot, who in 1824 showed that the efficiency of conversion of heat to work in a heat engine has an upper limit. The first rigorous definition of the second law based on the concept of entropy came from German scientist Rudolf Clausius in the 1850s and included his statement that heat can never pass from a colder to a warmer body without some other change, connected therewith, occurring at the same time.

The second law of thermodynamics allows the definition of the concept of thermodynamic temperature, relying also on the zeroth law of thermodynamics.

The second law can be applied not only to closed systems, but to open volumes, if entropy flows, mass flows and heat transfer in and out of the control volume are considered. In the book of Moran/Shapiro [17] an equation for the *"entropy rate balance for control volumes"* is given:

$$\frac{dS}{dt} = \sum_j \frac{\dot{Q}_j}{T_j} + \sum_i \dot{m}_i \cdot s_i - \sum_e \dot{m}_e \cdot s_e + \dot{\sigma}_{cv} \qquad \text{Eq .9}$$

Because oil production transports heat from oil reservoirs, Eq .9 governs the entropy change for them. The symbols are explained in chapter 7.4.

6.4. The Third Law

The **third law of thermodynamics** states, regarding the properties of closed systems in thermodynamic equilibrium:

The entropy of a system approaches a constant value when its temperature approaches absolute zero.

This constant value cannot depend on any other parameters characterizing the closed system, such as pressure or applied magnetic field. At absolute zero (zero kelvins) the system must be in a state with the minimum possible energy.

6.5. Entropy

In 1865, German physicist Rudolf Clausius, one of the leading founders of the field of thermodynamics, defined it as the quotient of an infinitesimal amount of heat to the instantaneous temperature. He initially described it as *transformation-content*, in German *Verwandlungsinhalt*, and later coined the term *entropy* from a Greek word for *transformation*. Referring to microscopic constitution and structure, in 1862, Clausius interpreted the concept as meaning disgregation.

$$dS = \frac{\delta Q}{T} \qquad \text{Eq .10}$$

A consequence of entropy is that certain processes are irreversible or impossible, aside from the requirement of not violating the conservation of energy, the latter being expressed in the first law of thermodynamics. Entropy is central to the second law of thermodynamics, which states that the entropy of isolated systems left to spontaneous evolution cannot decrease with time, as they always arrive at a state of thermodynamic equilibrium, where the entropy is highest.

Perpetuum Mobiles of the second kind are hypothetic devices, which can't work because they violate the second law.

6.6. Carnot's Cycle, Exergy and Anergy

A Carnot cycle that is a thermodynamic cycle performed by a Carnot heat engine as a reversible heat engine. In a Carnot cycle, heat Q_H is absorbed isothermally at temperature T_H from a 'hot' reservoir (in the isothermal expansion stage) and given up isothermally as heat Q_C to a 'cold' reservoir at T_C (in the isothermal compression stage). According to Carnot's principle or theorem, work from a heat engine with two thermal reservoirs can be produced only when there is a temperature difference between these reservoirs, and for reversible engines which are mostly and equally efficient among all heat engines for a given thermal reservoir pair, the work is a function of the reservoir temperatures and the heat absorbed to the engine Q_H (heat engine work output = heat engine efficiency × heat to the engine, where the efficiency is a function of the reservoir temperatures for reversible heat engines). In fact, Q_H is greater than the magnitude of Q_C in magnitude. Through the efforts of Clausius and Kelvin, it is now known that the work done by a reversible heat engine is the product of the Carnot efficiency (it is the efficiency of all reversible heat engines with the same thermal reservoir pairs according to the Carnot's theorem) and the heat absorbed from the hot reservoir:

$$W = \left(\frac{T_H - T_C}{T_H}\right) Q_H = \left(1 - \frac{T_C}{T_H}\right) Q_H \qquad \text{Eq. 11}$$

Here is work done by the Carnot heat engine, is heat to the engine from the hot reservoir, and is heat to the cold reservoir from the engine. The *Carnot efficiency*, which is a number less than one, is:

$$\eta = \left(1 - \frac{T_C}{T_H}\right) \qquad \text{Eq. 12}$$

A heat engine acts by transferring energy from a warm region to a cool region of space and, in the process, converting some of that energy to mechanical work. The part of the heat $\eta \cdot Q_H$ convertable to work is called *exergy*, the non convertible part $(1 - \eta) \cdot Q_H$ is called *anergy*.

The cycle may also be reversed. The system may be worked upon by an external force, and in the process, it can transfer thermal energy from a cooler system to a warmer one, thereby acting as a refrigerator or heat pump rather than a heat engine.

6.7. Real World Machine Efficiencies

The Carnot engine is the most efficient heat engine which is theoretically possible. The efficiency depends only upon the absolute temperatures of the hot and cold heat reservoirs between which it operates. Theoretical efficiencies for oil burning machines are as high as 71%.

Real world machines have smaller efficiencies. Reasons are for example:

- The machine itself needs heat to reach its operating temperature.
- The machine looses heat through its walls.

- The output gases are hotter than the environment etc.

Single cycle combustion machine efficencies are typical:

Otto motor ICE: 25- 30%

Diesel motor ICE: 35-45%

Hybrid ICE (without plug): 42%

Large ship ICE: 50%

Dual cycle (combined cycle) power plants can reach efficiencies up to 60%, stationary power plants up to 62-64%. Dual cycle machines have one cycle based on combustion, giving about 50 %, and one cycle based on a steam turbine, giving additional 10 %, driven by residual heat from the first cycle.

Typical values for combustion power plants for fossil fuels are:

Oil: 35%, Gas: 60%, Coal: 40%

Estimated average of all: 45%

In this report, 45% efficiency is used for the calculation of exergy generated by machines out of fossil fuels.

6.8. The Fourth Law of Thermodynamics

Physics does not know a fourth law. It comes from biology. From Howard T. Odum comes the principle of maximum power, which is proposed by Hall [18] as the fourth law of thermodynamics. This principle states that not only energy efficiency is important, but also high energy consumption.

In biology, the meaning is simple to understand: Only those animals survive that get to the prey first or are best able to defend the prey against others and then hold out until the next prey with the energy they have absorbed. The principle can be put into words like this (https://de.qaz.wiki/wiki/Maximum_power_principle): "***In self-organising systems, the designs that maximise power consumption, energy conversion and efficiency are selected over time.***" (Howard T. Odum).

For a biological system there are two basically contradictory requirements: On the one hand, it must be able to use as much energy as possible in a sensible way at certain moments, and on the other hand, it must be able to get by with as little energy as possible in the long term. In an environment with many energy sources, organisms will be selected that quickly convert a lot of energy, i.e. the strongest ones. Few energy sources lead to the selection of slow, frugal creatures; fast energy consumers die out. The problem is always to find the middle balance.

The principle of maximum output also applies in economic life: Firms (and states) that convert and consume available energy as quickly as possible thrive best when energy is abundant. The principle of the free market allows companies to quickly find and exploit possible energy sources. As long as energy sources are there, the economy grows fastest with a free market. **When energy becomes scarce and the knowledge from biology can be transferred, the free market economy with its companies also dies the fastest.**

The problem is to find and keep the balance in the transformation process. At the end of the oil age, it will become important to make the transition.

7. Oil Production and Thermodynamics

Crude oil is found in reservoirs at depths of several hundred to over 3000 metres. When a reservoir is found and drilled, the crude oil sometimes comes out of the ground on its own due to pressure from gas dissolved in the oil. After a relatively short time, the pressure is released and the oil is pumped to the surface (Figure 25). At the world's largest oil field, Ghawar in Saudi Arabia, production started in 1951 and gas was injected into the field from 1958 to maintain the pressure. Since 1964/65, seawater has been injected into Ghawar to maintain pressure in the field. For more than 60 years, crude oil has not come out of the ground on its own, but has been extracted using technology and energy. As the field gradually depletes, the effort increases.

When it comes to the energy needed to extract oil, many people only think of the potential energy needed to lift the oil and believe that the temperature of the crude oil extracted is irrelevant.

The first error in thinking about this is: theoretically, no potential energy is needed at all, since the water column is pushing down at the same time.

Error in thinking two: Since the water has a higher density, it would even have to push the oil out of the earth, a continuous flow of crude oil would have to exist, which could even be used for energy production. Since the oil is warmer than the earth's surface, the heat of the oil could be used for energy generation with a machine working according to the Carnot principle. If the water content is high, the mechanical energy gained would even be sufficient to pump more oil upwards.

The belief that the oil temperature is irrelevant ignores an important principle of physics and results in a paradox. The earth's crust below a depth of about 20 m is locally in a temperature equilibrium that cannot change on its own. If energy could be gained by changing this equilibrium, a perpetual motion machine of the second kind would exist. That is not possible.

The fact is that crude oil does not come out of the ground on its own, but a lot of energy is used to extract oil, which ends up as waste heat.

But oil production is not just about moving crude oil upwards, the movement has a second effect: the temperature distribution of the earth's crust changes. And the temperature change requires much more energy input than the movement of the masses. - This report examines the temperature change of the Earth's crust as a result of oil production.

It is not a question of the individual energies required in the production process and their determination and addition. Technological advances that make previously inaccessible oil extractable through additional energy input have no influence on the temperature distribution and are therefore not to be considered separately.

From the point of view of thermodynamics, the process of oil production can be regarded as an irreversible process.

The first law of thermodynamics, the conservation of energy, is not sufficient to describe the extraction process. Waste heat, frictional losses and entropy increase are described by the second law.

Since crude oil does not flow out of the earth on its own, it is clear that there is no natural process. Natural processes are always linked to an increase in entropy without additional energy input from outside.

Looked at the other way around: It is not enough to pave the way for the crude oil to come to the surface by laying a production pipe to the reservoir. The crude oil does not come out on its own, it stays down. Obviously, the entropy of the system is greater when the oil stays down and decreases when it comes out. Only with external energy supply does an overall system result in which the entropy increases.

7.1. Temperature Change of the Earth's Crust

The temperature distribution of the Earth’s crust did not change for millions of years near most oil reservoirs. Despite the temperature has a gradient and the earth interior gets warmer depending on depth, it is a thermal equilibrium according to the zeroth law of thermodynamics. When heat is brought up by transporting oil, the equilibrium is distorted. After the end of oil production, the original temperature distribution will be restored over the course of several tens of thousands of years.

Oil production changes the thermal equilibrium by transporting heat to the Earth's surface, see Figure 23. The Earth's surface heats up; the interior cools down due to water supply. Two areas of the Earth's crust that were previously in thermal equilibrium with their immediate surroundings are brought out of equilibrium. The cooling follows from the law of conservation of energy, because the heat on the surface has to come from somewhere. There is no vacuum at the bottom of the Earth's interior, so water must flow in and is involved in the cooling. Energy (more precisely, exergy, i.e. the technically usable part of the energy) is necessary for the change (Chapter 6.6). The amount of exergy required corresponds exactly to the amount of heat moved.

The second law of thermodynamics states that the energy to change the temperature must be provided by external sources.

The more heat is moved, the higher the exergy required. The exergy expenditure increases with each barrel. Most wells produce water in addition to crude oil. If water is also extracted in addition to crude oil, its entrained heat requires additional exergy input. At some point, this exergy input must become as high as the usable energy content of the barrel or even higher.

The exact calculation of the extraction energy can be found in chapter 7.8 of this report.

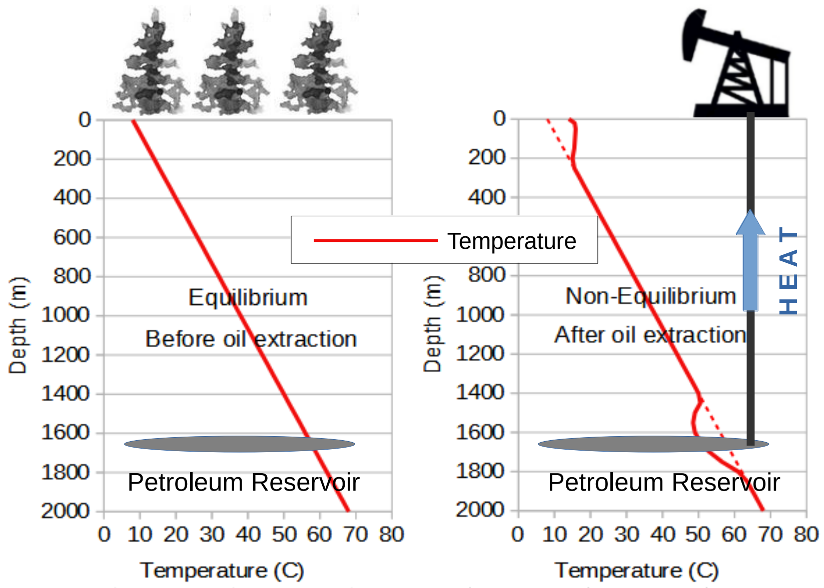


Figure 23: Left: Temperature of the Earth's crust in equilibrium, right after oil production (schematic representation). The local temperature change in the right image can be distributed over wide depth ranges, depending on the type of oil production and the type of water injection. With water injection, the temperature only changes in the vicinity of the oil field.

7.2. Growth of Oil Production Exergy over Time

Figure 24 shows the thermodynamically calculated necessary production exergy as a curve. This diagram has been created by the Hills Group in 2015 and is converted from imperial units to metric units by the author.

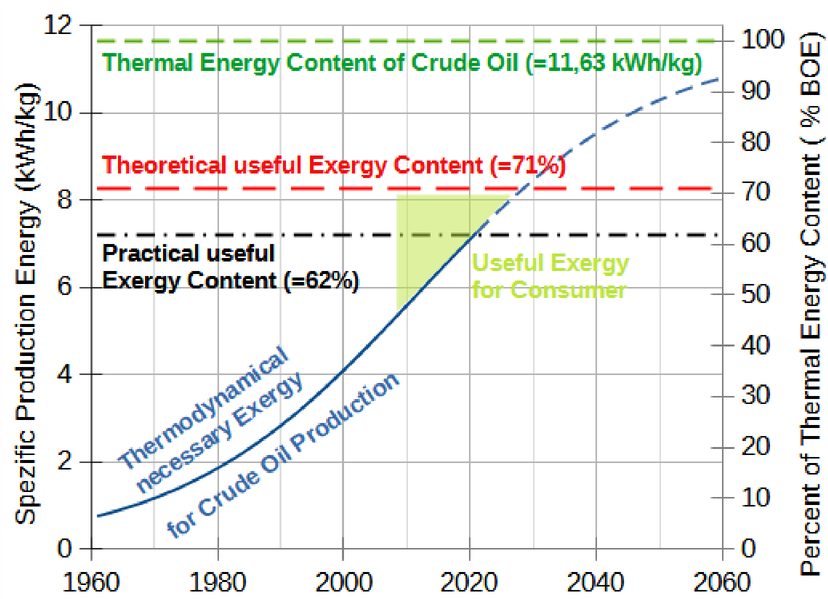


Figure 24: Thermodynamically determined energy expenditure per kg for oil production; oil production energy calculated with the TNE equation Eq. 31.

The exergy expenditure curve shown does not correspond to the usual approach, which only takes the potential energy into account, it is much more comprehensive. This exergy is the minimum exergy that must be expended to produce oil. It is a lower limit; the real production exergy is higher.

The exergy input per barrel extracted increases over time. In 2022, it will be as large as the practically usable exergy content of the oil. In 2029, it will be as large as the theoretically usable energy content. The increase of TNE is in 2020 about 0.14 kWH/year or 1.2 percent per year. Please compare the 1.2 percent with the value derived from the oil price 5.4. Both are almost the same.

When the extraction exergy becomes approximately as large as the energy content of the barrel, oil production will become pointless. Exergy from other sources can prolong the transition process, but not end it completely. The world economy will then stop using oil and the price of the barrel will approach zero.

The exact time of zero entry cannot be calculated because it is influenced, for example, by the use of other forms of energy (coal, gas), the water content of the production is not precisely known, the well depths vary, etc.

The observation, that the temperature of oil reservoirs decreases because water from the earth surface enters in the reservoir, results in two conclusions: First, the earth surface temperature increases by the oil pumped, and second, the thousands of years old temperature equilibrium in the earth crust gets distorted. One attempt to calculate the required energy (ETP=Energy Total Production) has been done first by the Hills Group, but their written report [19] contained a lot of bugs. Because the expression ETP is a little bit misleading, here the expression TNE = “Thermodynamic Necessary Exergy“ is used.

Its time to present an improved version of their formulas, based on the „entropy rate balance for a control volume “, [17], Ch.6, Eq. 6.39):

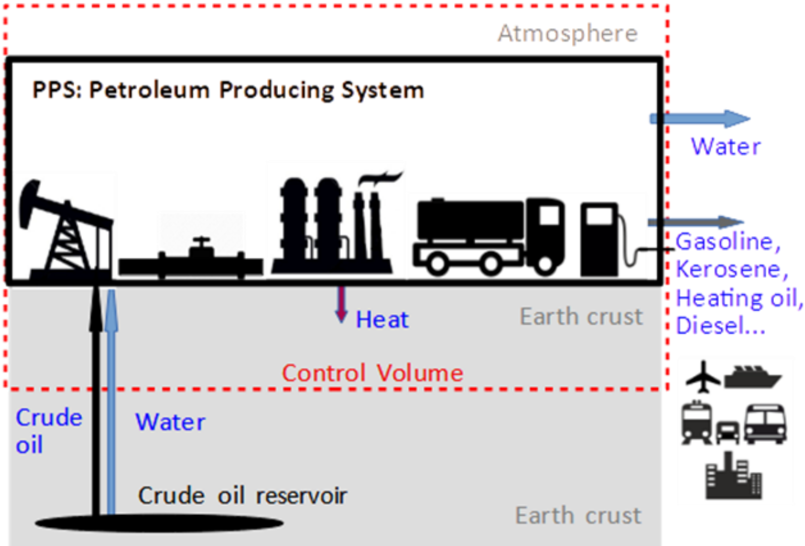


Figure 25: The PPS. Schematic display of the sectors of the oil production. Crude oil and water from the reservoir enter the black encircled PPS. Oil products and water leave the PPS. Heat is stored in the upper layer of the earth crust and the atmosphere, which are included in the control volume together with the PPS. The control volume is part of the earth's crust.

$$\frac{dS}{dt} = \sum_j \frac{\dot{Q}_j}{T_j} + \sum_i \dot{m}_i \cdot s_i - \sum_e \dot{m}_e \cdot s_e + \dot{\sigma}_{cv} \qquad \text{Eq. 13}$$

Remark: In the german language book (B. Warm, [20]) another way to calculate the TNE equation Eq. 31 is described, based on heat transport and temperature change. The result is the same as in this book.

The "entropy rate balance for control volumes" is the second law of thermodynamics in the modern mathematical formulation.

Mass currents, consisting of crude oil and water (index i for „in “), enter the control volume including the Petroleum Producing System (PPS, see Figure 25). The index CV is for „control volume“.

All masses entering the PPS leave it, and entering and exiting masses (Index e for „exit “) are equal:

$$\sum_i \dot{m}_i = \sum_e \dot{m}_e \qquad \text{Eq .14}$$

Because both mass streams are equal, the formula „steady-state entropy rate balance for control volumes“ can be used, with the left term of the equation equal to zero:

$$0 = \sum_j \frac{\dot{Q}_j}{T_j} + \sum_i \dot{m}_i \cdot s_i - \sum_e \dot{m}_e \cdot s_e + \dot{\sigma}_{cv} \qquad \text{Eq .15}$$

The first term on the right side describes the heat leaving the volume through the walls. The second term on the right side is the entering entropy stream, the third is the exiting entropy stream. The last term are the arising irregularities. The spezific entropies s are referred to a reference temperature, for water normally to 0 Celsius respectively 273.15 Kelvin. The values for s are listed in tables, which include pressure and temperature effects.

The control volume in Figure 25 is the PPS extended by the top layer of the earth's crust. The layer should be about 120 m thick, which is twice the thermal penetration depth for 150 years of oil production. The extension is necessary because, as written before, a temperature change of the earth's crust is caused by the oil production. This extension has not been explicitly described by HillsGroup in their calculation, but it makes the following calculation more understandable. The heat transported by the oil warms this layer and does not leave it. Thus, the first term of Eq .15 is zero.

$$\sum_j \frac{\dot{Q}_j}{T_j} = 0 \qquad \text{Eq. 16}$$

Two approximations are now made for the specific entropies: The first is that crude oil and water are assumed to be incompressible fluids. Thus, the specific entropies can be replaced by heat capacities:

$$s_2 - s_1 = c \cdot ln\left(\frac{T_2}{T_1}\right) \approx c \cdot \frac{T_2 - T_1}{T_1} \qquad \text{Eq. 17}$$

The second is that the specific heat capacities of the crude oil are not changed by the refining process. Crude oil essentially consists of a mixture of liquids. Refining separates the mixture "crude oil" into the individual liquids; only a few of the crude oil substances are chemically altered. The heat capacities of the changed substances are similar to those of the starting products.

Then the exiting oil products have the same heat capacities c_e as their source products c_i:

$$c_i = c_e \qquad \text{Eq. 18}$$

For the entropy stream instream flowing into the control volume, this gives:

$$Instream = \sum_i \dot{m}_i \cdot s_i \dots$$
$$\approx ln\left(\frac{T_i}{273.15}\right)[\dot{m}_c(t) \cdot c_c + \dot{m}_w(t) \cdot c_w] \qquad \text{Eq. 19}$$

For the entropy stream exit stream leaving the control volume, this gives:

$$Exitstream = \sum_e \dot{m}_e \cdot s_e \ldots \approx ln\left(\frac{T_e}{273.15}\right)[\dot{m}_c(t) \cdot c_c + \dot{m}_w(t) \cdot c_w] \qquad \text{Eq. 20}$$

and for their difference:

$$\sum_i \dot{m}_i \cdot s_i - \sum_e \dot{m}_e \cdot s_e \approx \left[ln\left(\frac{T_i}{273.15}\right) - ln\left(\frac{T_e}{273.15}\right)\right] \cdot [\dot{m}_c(t)c_c + \dot{m}_w(t)c_w] \qquad \text{Eq. 21}$$

With the calculation rules for logarithms this simplifies to:

$$\sum_i \dot{m}_i \cdot s_i - \sum_e \dot{m}_e \cdot s_e \approx ln\left(\frac{T_i}{T_e}\right) \cdot [\dot{m}_c(t) \cdot c_c + \dot{m}_w(t) \cdot c_w] \qquad \text{Eq.22}$$

Substitution into Eq .15 simplifies it to:

$$0 = \left(\frac{T_i - T_e}{T_e}\right)[\dot{m}_c(t) \cdot c_c + \dot{m}_w(t) \cdot c_w] + \dot{\sigma}_{cv} \qquad \text{Eq. 23}$$

The temperature T_i is the temperature of the petroleum reservoir T_R, and T_e is the ambient temperature T_0. It follows:

$$\dot{\sigma}_{cv} = -\left(\frac{T_R - T_0}{T_0}\right)[\dot{m}_c(t) \cdot c_c + \dot{m}_w(t) \cdot c_w] \qquad \text{Eq. 24}$$

The irregularities in the system are the entropies arising. If entropy arises in the PPS, it means that a corresponding amount of exergy X is converted into anergy (see also Gouy-Stodola theorem). The rate of produced anergy corresponds to a power P. The integral over P is the total produced anergy X.

$$P = \dot{\sigma}_{cv} \cdot T_0 = (T_R - T_0)[\dot{m}_c(t) \cdot c_c + \dot{m}_w(t) \cdot c_w] \qquad \text{Eq. 25}$$

Consequently, the exergy X required to extract the crude oil at the time is:

$$X(t_E) = \int_0^{t_E} (T_R - T_0)[\dot{m}_c(t) \cdot c_c + \dot{m}_w(t) \cdot c_w]\, dt \qquad \text{Eq.26}$$

And the exergy required in a time span is:

$$X(t_E, \Delta t) = \int_{t_E}^{t_E+\Delta t} [P(t)]\, dt \approx P(t_E + \frac{\Delta t}{2}) \cdot \Delta t \qquad \text{Eq. 27}$$

It is equal to the sum of all heat quantities of the previously conveyed materials. At any given time, it is the integral of all previously pumped heat quantities. The approximated term at the right side is valid if P(t) is mostly linear in the time span.

The amount of oil pumped in the period is:

$$\Delta m_c(t_E, \Delta t) = \int_{t_E}^{t_E+\Delta t} \dot{m}_c(t)\, dt \qquad \text{Eq. 28}$$

Dividing the exergy expenditure in the period by the quantity of crude oil produced gives the specific exergy required per unit mass of crude oil. In the numerator of the following fraction, the exergy value is taken for the point in time which lies in the middle of the period.

$$e_{TN}(t_E, \Delta t) = \frac{X(t_E, \Delta t)}{\Delta m_c(t_E, \Delta t)} = \frac{\Delta t \cdot P(t_E + \Delta t/2)}{\Delta m_c(t_E, \Delta t)} \qquad \text{Eq. 29}$$

The exergy per kg of crude oil in each year is thus the exergy required in this period (e.g. year) divided by the mass of oil in the same year. The specific energy e_{TN} for crude oil production is the sum of the thermal energy moved so far divided by the currently produced crude oil mass. The index E of t_E is omitted from now on.

$$e_{TN}(t,\Delta t) = \frac{\Delta t \cdot \int_0^{t+\Delta t} \dot{Q}_{TP}(t)\,dt}{\int_t^{t+\Delta t} \dot{m}_c(t)\,dt} \qquad \text{Eq. 30}$$

This gives the TNE equation:

$$e_{TN}(t,\Delta t) = \frac{\Delta t \cdot \int_0^{t+\Delta t} (T_R - T_0)[\dot{m}_c(t)\cdot c_c + \dot{m}_w(t)\cdot c_w]\,dt}{\int_t^{t+\Delta t} \dot{m}_c(t)\,dt} \qquad \text{Eq. 31}$$

The exergy required for oil production increases over time, depending on the production history. The increasing temperature differences with respect to the earth's surface and the earth's interior historic temperatures are the cause. The energy mentioned here has to be applied by machines, i.e. it is the exergy of the working process of the machines. As more oil is extracted, more exergy is required for each subsequent barrel. Each barrel requires slightly more exergy than the previous one.

Equation Eq. 31 above is similar/identical to Equation 7 in the Hills Group report ([19], page 8). The equation was derived by the Hills Group from the second law in a similar way, using the *"entropy rate balance for control volumes"* as starting point.

Eq. 31 includes one important point: When the denominator (the oil produced in a certain time span) gets small, the specific exergy gets high. In other words: If world oil production decreases, the specific production exergy and thus the oil price must increase. Halving of the oil production doubles the cost of extraction.

7.3. Plausibility Check and EROI

Anyone who sees Figure 24 for the first time cannot imagine such high energy production volumes. One has to consider that this amount of energy applies to the entire extraction process from exploration to extraction, refining, storage and distribution to filling stations.

It is anything but easy to determine all the energy quantities (input energy) that actually occur for oil production. A huge amount of data are required, much of it cannot even be estimated. How much of the training of a steel worker who produces pipeline pipes should be considered? How much of the maintenance of an aircraft carrier that secures a transport route?

The work areas of the oil producing/processing industry (Petroleum Producing System, PPS, Figure 25) can be classified as follows:

a) Oil exploration

b) Oil drilling and production

c) Transport, storage

d) Refining

e) Delivery

f) Supporting industries

A separate estimate for PPS energy expenditure in 2015 showed:

(a) Oil exploration: no data available; can be set to zero by oil producers in case of financial difficulties; assumption: 1%.

b) Oil drilling and extraction: from the EROI of 9:1 ([18], Hall) it follows: ~11 % of crude oil (thermal) energy was used for oil extraction in 2015.

c) Transport, storage: no data available; assumption: 1 %.

d) Refineries: An Evaluation of EIA data [21] resulted in the following values of energy loss in refineries:

- Energy of mass flows input, output:13 % loss
- Biofuels, blenders, hydrogen have a higher input value than the pure calorific value: additional 3 % loss
- Bitumen and plastic raw material (naphtha) do not count as energy output: 13 % loss
- Personnel, maintenance and waste disposal costs; assumption: 2%.

e) Delivery: no figures available; assumption: 5%.

f) Supporting industries: no figures available; assumption: 4%.

According to this estimate, the total losses are: 1 %+1 %+11 %+31 %+5 %+4 %=53 % and thus already in 2015 close to the limit of 62 % for the usable energy share of petroleum. The thermodynamically determined curve in Figure 24 is therefore plausible.

Brandt [22], Hall [23] and others have tackled the task of carefully adding up all input and output energies to determine the EROI (Energy Return on Energy Investment) for oil production. Societal EROI, as defined by Hall, includes all the energy expenditures of the company for oil production, but is not precisely determinable. After reviewing their work, I was always left with an uneasy feeling: Are the data included complete? Are they accurate? Is the time allocation correct? It is hardly possible to reconstruct the results because the amount of work is too large.

7.4. Physical Theory: Thermodynamically Necessary Exergy

The impact of thermodynamics on oil production was first recognised by the Hills Group. This association of consultants to the oil industry produced their calculations under the name ETP model [19]. Unfortunately, the authors' website is no longer accessible. The ETP model has the steady state rate balance as its starting point (see Chapter 11.4.5).

ETP stands for Energy Total Production. ETP is the minimum thermodynamic energy required for oil production and is comparable to the Societal EROI defined by Hall. According to an estimate by the Hills Group, the standard EROI (energy input of oil production companies) was about 20 % of ETP in 1970-2007 ([19], page 25). Instead of ETP, the term TNE (Thermodynamically Necessary Exergy) is more appropriate, as more than just thermodynamically necessary exergy is used in oil production.

The ETP model was never accepted at the behest of the oil industry. Likewise, many supporters of the climate movement had counter-arguments for fear of political discussion Even people who had claimed in the past that peak oil was in 2005-2009 and embarrassed themselves with it, did not dare to agree with the ETP model for fear of a second embarrassment.

With my current level of knowledge, I consider the thermodynamic calculation (TNE model) to be even more accurate. The model makes two essential statements, based on the second law:

- The average oil price must fall for the world economy to function in the way we are used to (to grow).

- The downward pressure on the oil price will lead to the cessation of oil production in a few years.

A wave of bankruptcies of oil producers, also predicted, occurred only to a small extent before 2020, but became stronger in 2020 [3] .

The reduction in oil volumes produced has been evident since November 2018 (see Figure 4), exacerbated by the Covid-19 pandemic. In this figure, a dashed green line is drawn connecting the maxima of oil prices. The green line shows the maximum prices the global economy can pay for crude oil.

In autumn 2018 and early 2020, the price curve reached the green line, and both times the oil price crashed afterwards. In both cases, OPEC+ reacted with production restrictions to drive the oil price higher again. In spring/summer 2021, the next time the green line was reached, including a price crash and production cuts, was to be expected; this time, however, OPEC+ pushed through its price targets, the price rose, and the global economy suffered. See chapter 5.4.1, axiom 4.

It follows from the TNE model that oil production does not end when there is no more oil, but when oil production is no longer energetically profitable. It is not geology that ends the oil age, but thermodynamics. It will become noticeable to the world economy as an economic or financial problem. Economists will later say that the oil age ended because oil production was no longer financially viable.

7.5. The Reversal Point

In 2014, something happened that most oil experts had not expected: The oil price fell from $105 to about $50 per barrel within a short period of time. Almost all experts had assumed continuously rising prices. So far, I know of only four exceptions:

- Frenchman Alexandre Andlauer observed shale oil production in the US and expected an oversupply of oil to cause prices to fall.

- Analyst Gail Tverberg [24] expected oil prices to fall for social reasons: The deepening division of society into rich and poor was bound to make petrol too expensive for poorer classes.

- Steve Ludlum analysed the oil price trend and concluded that the maxima of the oil price and its minima are heading for an intersection at which the oil price will come under such pressure that it will fall.

- Bedford Hill of the Hills Group expected a price collapse based on a thermodynamic analysis. His calculated date was around 2012. According to his calculation, the point at which the extraction energy is exactly half the energy content of crude oil was in 2012. He called this point the reversal point (half-way point).

Each of the four exceptional experts was right, the cause he named had a part in the price decline. In the media, however, almost only the first cause was discussed; most people believed in oversupply. On closer inspection, however, the oversupply thesis was very doubtful: can a production increase of about 3% really trigger a price drop to below 50%? The numerical values are simply too different.

Hill's reasoning for the price drop is that the economy as a whole must always pay 100 % of the energy produced. Before the reversal point, it paid for 100% energy, of which oil production, for example, consumed 45% energy, and the economy as a whole received 55% energy. After the reversal point, the economy as a whole received less (e.g. 45%) than was put into production (55%). From now on, it is cheaper for them not to consume energy, unless energy falls in price. In other words, an oil price drop was inevitable.

However, in the Hills Group report, the word consumer was used instead of world economy. If the word consumer is inserted into the above paragraph, every reader thinks of car drivers as consumers and the text is hardly comprehensible any more. Consumers are not only car drivers, but also companies and the economy as a whole. The Hills Group report was inaccurate at this point.

7.6. Comments on the Hills Group Report

After the Hills Group report was published, it was very heavily discussed in peak oil forums [25]. Most of the discussants had no knowledge of thermodynamics and only paid attention to the price predictions. They were not even able to follow the calculations. The few who were able to do so had a problem with the imperial units of measurement used, which they kept confusing with SI units. A depth of 1000 feet is quite different from 1000 metres. A third obstacle was that the formulas were not written down neatly. This made it easy for opponents to criticise the report.

And there was another effect: The Hills Group did apply the second law correctly and also recognised that oil production is associated with a very high entropy generation. But their physical interpretation was that the entropy is generated by wear and tear on the production equipment. Some of the calculations included in the report suggest that the Hills Group itself was unsure of this interpretation. It did not realise that entropy is necessary to change the temperature equilibrium of the Earth.

Two examples for outside criticism:

- Seppo Korpela [25] has analysed the Hills Group report. For example, he criticised the (actually incorrect) transition in the report from the control-volume-entropy-rate-balance equation to the steady-state-form-of-the-entropy-rate-balance equation ([17], ch. 6) and used that, as well as other errors, to call the report wrong. With his knowledge, however, he could have immediately realised that one could have started with the steady-state form right away and simply deleted the transition.

- Jean Laherrere [26] has criticised, among other things, that a general formula is taken for all oil wells in the world, although each oil well is unique, with specific well depth, temperature distribution and production rate. If the Hills Group had also applied the TNE formula to a single oil well in their report, it would have been clear that it applies to every single well. The result desired by Laherrère could be achieved with a great deal of effort. If you calculate all the oil sources individually and add them up, you might get a result that is a little more accurate at one point.

Ultimately, all theories must be judged by whether they produce results that are consistent with reality. Today, seven years after the publication of the critiques, the agreement can be described as very good (except for a time delay). According to Feynman, the TNE model can thus be described as correct; at least as not refuted. Richard Feynman on the Scientific Method [27]:

In general, we look for a new law by the following process. First, we guess it. Then we compute the consequences of the guess to see what would be implied if this law that we guessed is right. Then we compare the result of the computation to nature, with experiment or experience, compare it directly with observation, to see if it works. If it disagrees with experiment, it's wrong. In that simple statement is the key to science.

7.7. TNE Equation for a single Oil Well

The TNE equation can be used to study individual oil wells or even the entire world oil production. First, it is applied to a single LTO (shale) source.

Example: Typical fracking oil well in the Bakken, production curve from *Drill, Baby, Drill* (Hughes, [28]). The Bakken formation is a subsurface Upper Palaeozoic rock unit in North Dakota (USA), far from volcanic terrain. The earth's crust in this landscape has had millions of years to equilibrate temperatures. LTO is typically found at greater depths than conventional oil, it is at about 3000m depth. The differences with conventional oil are due to the history of how the two types of oil were formed.

Fracking is a process in which a horizontal pipe is laid into an oil-bearing stratum. When water is pumped in and put under high pressure, the rock surrounding the pipe is cracked open. This makes oil-bearing bubbles accessible, the oil flows into the pipe and the oil can be pumped out. In this process, a lot of water is initially pumped into the earth and this has a cooling effect on the reservoir.

The warm oil from the earth warms the surface of the earth. With the oil, a lot of warm water also flows to the earth's surface.

Typical data of an LTO oil well are:

Depth: 3000 m

Oil production as a function of time: see Figure 26.

Water content: volume 50 % [29]. For simplicity, the water content is assumed to be constant. This means that about 1.16 kg of water is produced per kg of oil, and 160 kg of water per barrel of oil.

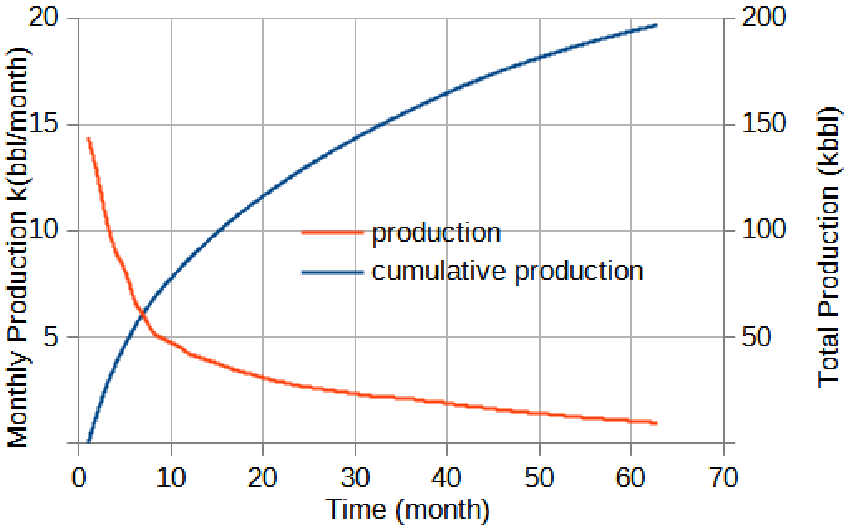


Figure 26: Typical production curve of an oil well in the Bakken. The decline in production is significantly faster than with conventional oil. The somewhat irregular course comes from the template.[20]

Temperature at 20 m depth: 11 °C

Temperature gradient: 0.033 °K/m

Temperature difference to the bottom of the well: 98.3 °C.

Efficiency of the used production energy into exergy: 45 %. (see ch. 6.7)

All data are typical and absolutely realistic.

The TNE equation Gl. 52 is an integral which is replaced by a sum to simplify the following calculation:

$$e_{TN}(n \cdot \Delta t) = \frac{\Delta t \cdot \sum_{i=0}^{n}(T_R - T_0)\,[\dot{m}_C(i \cdot \Delta t)c_C + \dot{m}_W(i \cdot \Delta t)c_W]\Delta t}{\dot{m}_C(n \cdot \Delta t) \cdot \Delta t}$$

Eq. 32

The periods are one month each. In the first month there is no temperature difference from the previous month. The current monthly expenditure in month n is not counted, which is why the summation only runs up to n-1.

With the assumed production curve in Figure 26, 14,400 barrels are pumped out of the earth in the first month, with a weight of 1,972,800 kg, while 2,304,000 kg of water come out of the earth. The heat content

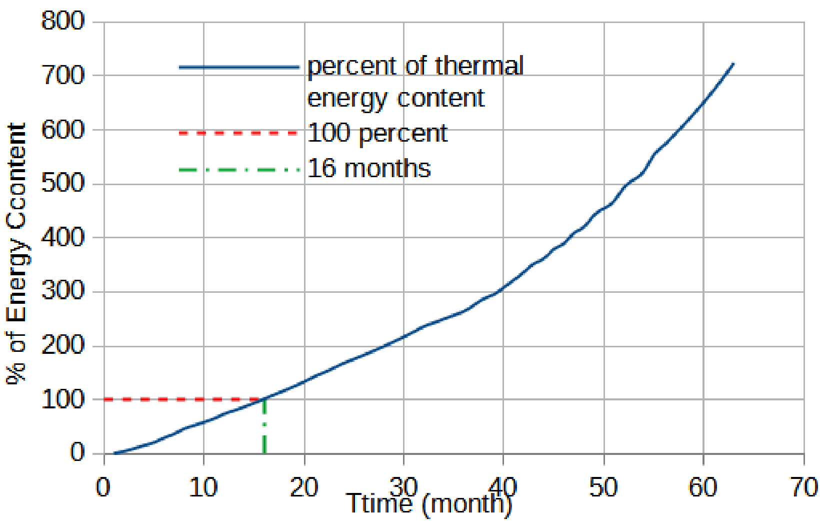


Figure 27: Bakken well: Specific extraction energy as a percentage of the exergy of the crude oil for 45 % efficiency. After about five years, the energy extraction costs are six to seven times higher than the benefits.

of oil and water together is about 1.31E12 J. There are still no heat quantities from the previous month, so $e_{TN}(1)$=0 J/kg.

With the assumed production curve, 12,600 barrels are pumped out of the earth in the second month, with a weight of 1,726,200 kg. At the same time, 2,016,000 kg of water come out of the earth. The heat content of oil and water together is about 1.15E12 J. The heat extracted from the previous month divided by the amount of oil extracted gives an $e_{TN}(2)$ of 761 kJ/kg. $e_{TN}(2)$ is much smaller than the thermal energy content of crude oil of 41.9 MJ/kg, but still 1.8% of it.

In the third month, the amount of crude oil produced is 10,500 barrels = 1438500 kg. $e_{TN}(3)$ is the sum of the two previous months equal to 2.46 E12 J and already 5.0 % of the energy content.

The continuation of this calculation shows that after approximately 36 months the production exergy e_{TN} is exactly as large as the energy content of the crude oil. From now on, more energy is consumed than the extracted oil contains. Production could be stopped from now on if only the current energies are considered.

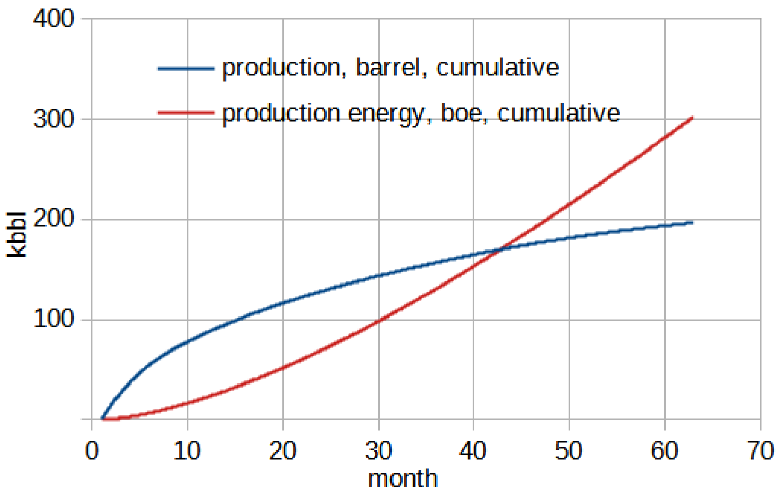


Figure 28: Typical Bakken Source: Cumulative oil production and cumulative energy expenditure. Energy is converted to BOE (= barrel of oil equivalent) and converted with an efficiency of 45% to exergy.

Over the entire lifetime of the source, Figure 28 shows that the cumulative energy produced is almost caught up by the cumulative energy extracted after just over 43 months.

In these calculations, the result is that the extraction of LTO in the Bakken consumes about as much energy per well as it delivers. Why is the crude oil extracted in the first place? It is because the unit of energy from crude oil costs significantly more than the unit of energy from coal or gas. Crude oil is about five times as expensive per joule as coal or gas (Figure 21). If very little expensive oil energy is used in the extraction process, but only cheap energy, a financial gain is possible. However, it is not possible to do completely without oil, because the entire transport sector uses almost only oil as an energy source.

Depending on which numerical values are used, slightly more or less energy is required as input than the output contains. In the example calculation, a water share of 50 % is assumed, but according to Steve St.Angelo [29] the water share is higher. With these figures, it is questionable whether the fracking companies can make a profit at all. Today it looks like many of the companies will not be able to pay back the loans they have taken out.

The hope of the fracking companies that a rise in oil prices can save them is more than deceptive. They can only be saved by a rise in oil prices if at the same time the input energies coal and gas remain cheap - and there is little evidence of this. Figure 21 shows that energy per Gigajoule from oil tends to decrease from a factor of five compared to gas and coal to a factor of two.

Conclusion: Fracking converts one type of energy from fossil fuels into another and produces large quantities of climate-damaging CO_2 gas in the process.

7.8. Update of the TNE Diagram from the HillsGroup

Figure 24 is a diagram, which is the same diagram that the HillsGroup published in 2015, only converted from imperial units to metric units.

With new data, this diagram has been updated. The result is displayed in Figure 29. For it the following data have been used:

- World oil production according to Figure 1. For simplicity, all kinds of crude are used for it, despite unconventional oil has different production schemes. Unconventional oil is oil, for which the extractor spents more energy as for conventional oil.
- Temperature distribution according to Figure 16.
- Water cut according to Figure 17, green solid line. The water cut has been calibrated such that the exergy values for oil production in 2011 and 2019 are the same for Figure 24 and Figure 29. With these values, the necessary exergy for oil extraction rises each year about 1.2%.
- For the calculation of the consumed energy for crude oil production a machine efficiency of 45 % has been used. 45 % seems to be an adequate value, because this value is roughly valid for combustion motors and coal power plants. (See chapter 6.7 Real World Machine Efficiencies).

For the calculation a Matlab routine has been set up.

It follows: **Today the practically used extraction energy for crude oil is about 150 % of oils thermal energy content.**

How accurate is this result?

It all depends on the calibration of the water cut. The values for oil production and oil price are well documented and accurate, so they pose no problem. Water cuts vary from field to field.

But: The urgency to adapt behaviours is not influenced by the exact date of the thermodynamical collapse.

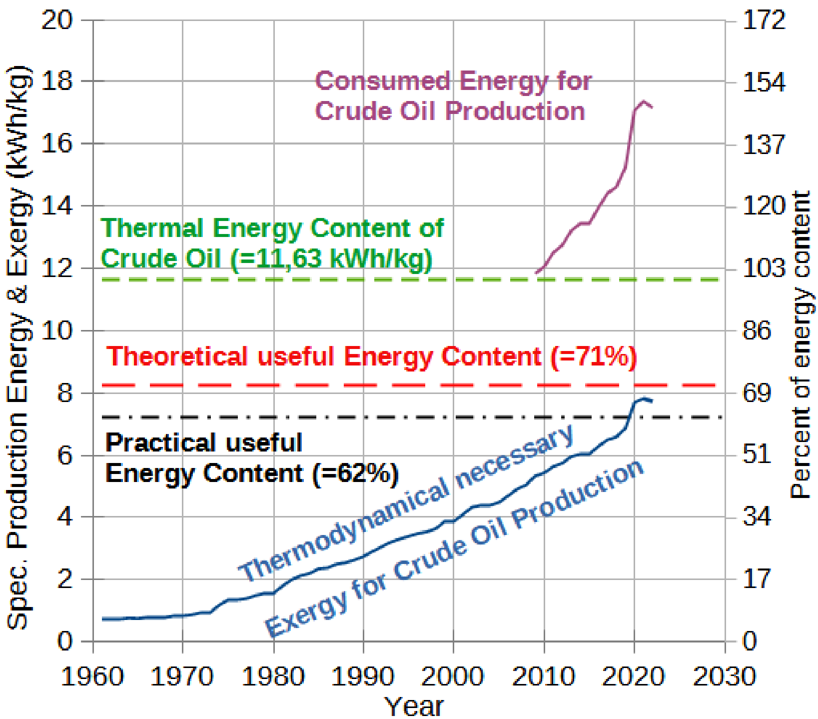


Figure 29: Exergy and energy input for crude oil production determined from the world oil production curve

A little understandable additional result is how little energy is needed in extraction compared to the rest of the fuel production process including transport, refining, distributing etc. A factor of 10 lies in between. Energy losses in refining, subsidies for oil consumers and wear and tear on existing infrastructure will have a share in this, but are difficult to capture numerically. The same applies to biofuel production, subsidies for non-conventional oil and air pollution control measures.

Today, the extraction energies are about a factor of four as high as the exergy that ICE motors extract from crude oil and significantly higher than values of the known EROI calculations. Since EROI calculations do not take thermodynamics into account, the difference is to be expected.

8. Economic Realities

8.1. The Struggle of OPEC and OPEC+

OPEC is the Organisation of the Petroleum Exporting Countries, based in Vienna. The countries belonging to OPEC vary according to their production quota; currently thirteen countries belong to the cartel: Algeria, Angola, Equatorial Guinea, Gabon, Iran, Iraq, the Republic of Congo, Kuwait, Libya, Nigeria, Saudi Arabia, the United Arab Emirates and Venezuela. Five OPEC members (Saudi Arabia, Iran, Kuwait, Venezuela, and United Arab Emirates) are among the ten largest oil producers in the world. In total, OPEC member states produce about 30 per cent of the world's oil production and hold three quarters of the world's oil reserves (own data).

Since the end of 2016, OPEC has been working with eleven non-OPEC countries to gain more influence on the oil market. These countries include Russia and Mexico, for example. OPEC's cooperation with these countries is called OPEC plus. The important producer country USA is not part of it.

OPEC's goal is a monopolised oil market that can protect prices on the world market by setting production quotas for the individual OPEC members and regulating oil production. Through the artificial shortage or increase of oil production, the price of crude oil worldwide is to be depressed, stabilised or raised by agreement of all OPEC member countries so that it lies within a defined target price corridor. This target price corridor is variable, but is considered a benchmark over a longer period of time.

However, it also happens that individual members do not adhere to the fixed support quotas, but pursue their own economic and political goals [30].

OPEC and OPEC+ meet every six months to coordinate oil policy. Additional meetings are held in the event of critical situations in the oil sector. OPEC publishes current data on the oil market in the Monthly Oil Market Report [31] [30].

8.2. Saudi Arabia's oil dependence

Saudi Arabia is one of the dominant countries in OPEC and can usually rally the votes of the other Arab countries behind it.

Saudi Arabia's oil exports make it one of the richest countries in the world; it ranked 14th in the world by gross domestic product per capita (adjusted for purchasing power) in 2016, and 36th in the Human Development Index in 2019. Thanks to its wealth, the country can afford to provide its population with generous social benefits, ensuring political stability at home. Increasing pressure on the national budget due to the drop in oil prices since the beginning of 2015 has forced the country to diversify its sources of income. The Vision 2030 reform project aims to realise this.

In 2000, 12.3 % of the oil produced worldwide came from Saudi Arabia. The reserves amount to 35 to 36 billion tonnes or 262.7 billion barrels, which is 25% of all known oil reserves in the world [32].

Saudi Arabia's main economic driver is crude oil. It is the only significant export. Saudi Arabia can be seen as a pure oil factory, similar to a car factory. Saudi Arabia supplies crude oil to the world and receives all other goods in return. The entire population is more or less involved in the process of oil production.

Saudi Arabia is currently involved in a war with Yemen, which in turn is supported by Iran. Counterattacks by Yemen often target Saudi oil facilities, for example on 14 September 2019.

8.2.1. Outlook

OPEC+ has several times increased oil prices by restricting production. Today (June 2023) the dashed green line (Figure 22) has been clearly surpassed, where up to now there has always been a demand destruction. All previous price maxima are connected by the green line, with a high probability there will be another collapse leading below the line. As with the three previous sharp price collapses, there will be an occasion that masks the internal dynamics, the falling affordability of oil.

The OPEC+ fight against falling oil prices has been waged with reductions in crude oil production since the beginning of 2017. However, each reduction leads to a decrease in revenues for the OPEC countries. Every success is thus a small Pyrrhic victory. At some point, the Pyrrhic victories will lead to intolerable revenue losses. Then the OPEC alliance will break up and the oil price will plummet. The standard of living in the OPEC producing countries will decline.

On June 4, 2023, Saudi Arabia did announce an oil production cut, but the other OPEC+ members did not follow. A bad sign for the alliance.

The consequence of revenue losses is that investments in oil production infrastructure will cease. This in turn limits the possibilities to produce oil. A cycle is set in motion that will bring about the end of oil production. The voluntary cuts in production by Saudi Arabia since February 2021 are suspected of not being voluntary at all.

8.3. The Covid-19 Pandemic

The decline in oil production and the decline in car production in 2020 are almost exclusively attributed in the media to the Covid-19 pandemic. The fact is that the peaks of both were well before the declines began. Oil production peaked in November 2018, while car production peaked in 2017.

After the outbreak of the Covid-19 pandemic, lockdowns in almost all countries led to the disruption of supply chains and the temporary closure of car factories and the suspension of air travel as a precautionary measure. As a result, the oil price plummeted. OPEC+ wanted to counteract the drop in prices with production cuts, which succeeded after some back and forth. In September and October 2022, OPEC+ again agreed on production cuts.

In April 2021, the oil price rose to the levels of January 2020 and higher. This price is so high for some countries that they are experiencing economic difficulties: In India, there have been farmers' protests for months against high petrol and diesel prices, among other things, and in Lebanon, all generator power plants have already been shut down because the fuel can no longer be paid for.

The Covid-19 pandemic was not the cause, but a kind of fire accelerator for the thermodynamically induced energy crisis. That is why oil production and car production increased after the pandemic, but could not return to pre-Covid-19 levels.

9. Costs of Oil and Car Production

From the increasing energy consumption, economic problems can be expected, especially for the oil-consuming infrastructure, i.e. first of all for the car industry. The problems exist and are massive, as the following figures show. Car sales numbers are monthly published in many countries, and they allow a continuous observation of infrastructure effects. But they are influenced by other economic effects too, like Covid-19, wars and subsidies.

Figure 32 and Figure 35 to Figure 38 have the following structure:

The x-axis is in each case the monthly average oil price (Brent, [1]) converted to energy, using the energy productivity value for the month (Figure 19). The y-axis represents the average number of cars sales over the last 12 months. The average value was chosen because car sales and production fluctuate greatly from month to month. Figure 35 is similar, but since only annual figures from Saudi Arabia are available, the averaging is omitted.

The type of presentation was chosen to show oil price and car sales in one chart and as a means to identify development trends.

9.1. Car sales in Europe and USA

The sales numbers for Europe and USA [33] have similar characteristics. Both had a maximum in 2018 and 2016 and go slowly down. They had their minimums in 2022 and now go up a little bit, but are still below the values of 2014.

The Covid-19 pandemic had a strong influence on the sales numbers in 2020, driving them down. In 2021, a recovery followed, but only of short

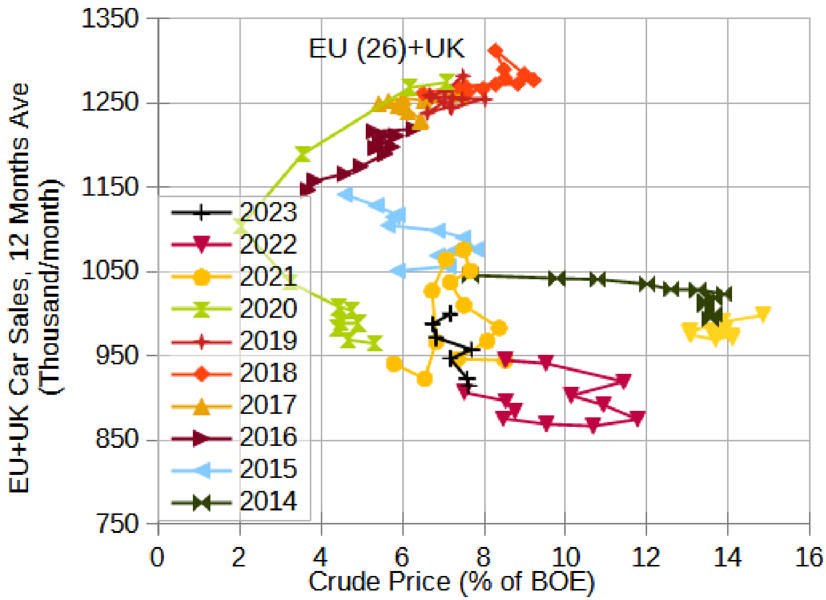


Figure 30: Sales of passenger cars in Europe: EU(26) plus United Kingdom. Source: ACEA [53] and SMMT [52]. The three points 12/2022, 01/2023 and 02/2023 are almost identical.

duration. Problems in the supply chain (semiconductor chips) have played a part in the slump since July 2021. The rise of sales in the first half of 2023 has much to do with subsidies for electric vehicles. In the USA, crude oil releases from the Strategic Petroleum Reserve supported car drivers and the car sales increase. Similar declines in car sales are seen in Japan, Mexico, Argentina, Brazil and many other countries.

The car sales numbers for both regions behave according to the TNE model. The charts on motor vehicles show that not only oil producers are affected, but also the oil-consuming infrastructure:

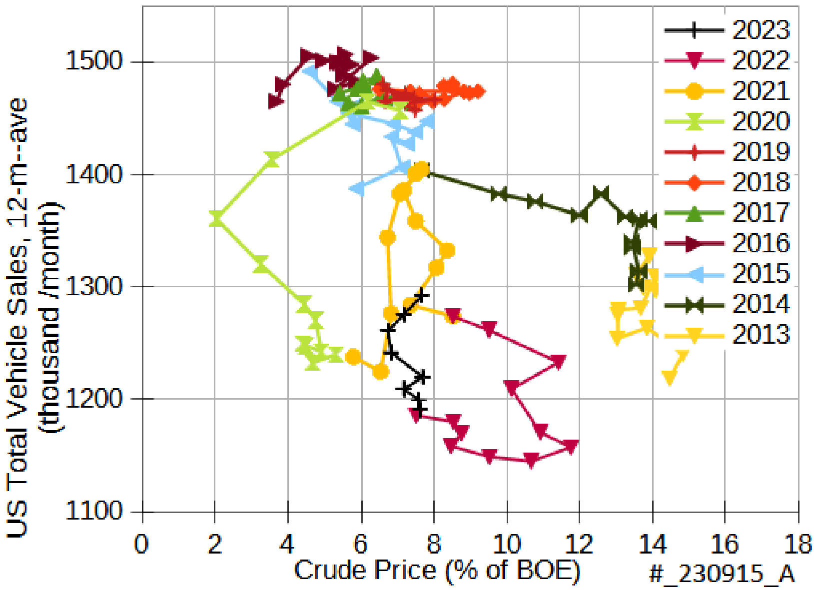


Figure 31: Sales of All Motor Vehicles in the USA.

9.2. Car sales in Germany

German car production started to collapse in mid-2018 (Figure 34, source: [34]). The Covid-19 pandemic acted like an accelerant there. Until the end of 2020, only exports were affected by the slump; new car registration figures in Germany were only influenced after that (Figure 33). Massive subsidies for electric cars and hybrids have recently not only increased the percentage of electric vehicles, but also caused sales figures to rise again. The recovery of the supply chain is a second reason for the rise.

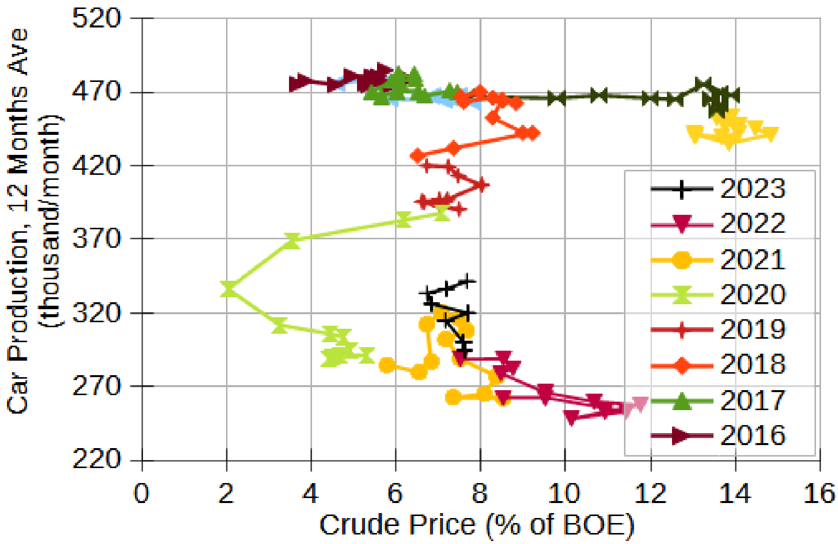


Figure 32: Car production in Germany

Figure 32 shows that German car production is moving rapidly towards the TNE model. The diagram Production as a function of time Figure 34 emphasises the speed: if the trend that has been in place since the beginning of 2018 continues, no more passenger cars will be produced in Germany as early as 2030.

The trend is driven by stagnating oil production and lack of energy, not by technologies such as the transition to electric drives. For explanation, see chapter 10.4 “IntroductionThe Osborne Effect”, discussing the delay between the maximum of car production and the introduction of electric drives.

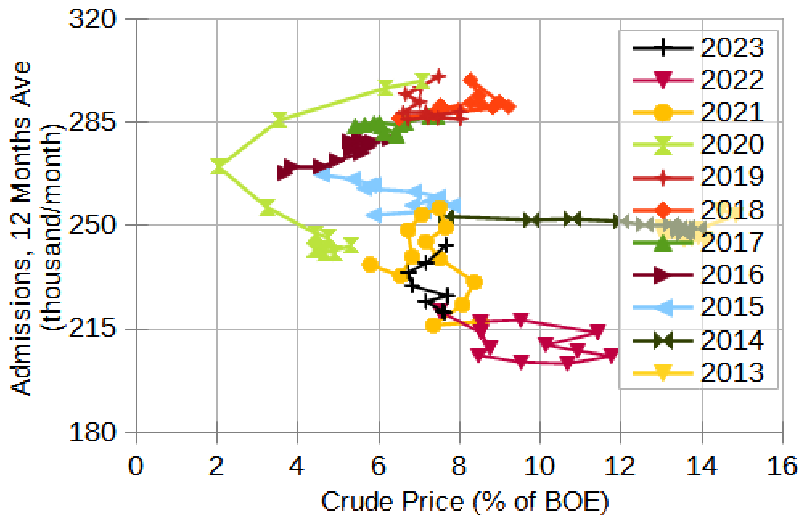


Figure 33: New car registrations in Germany

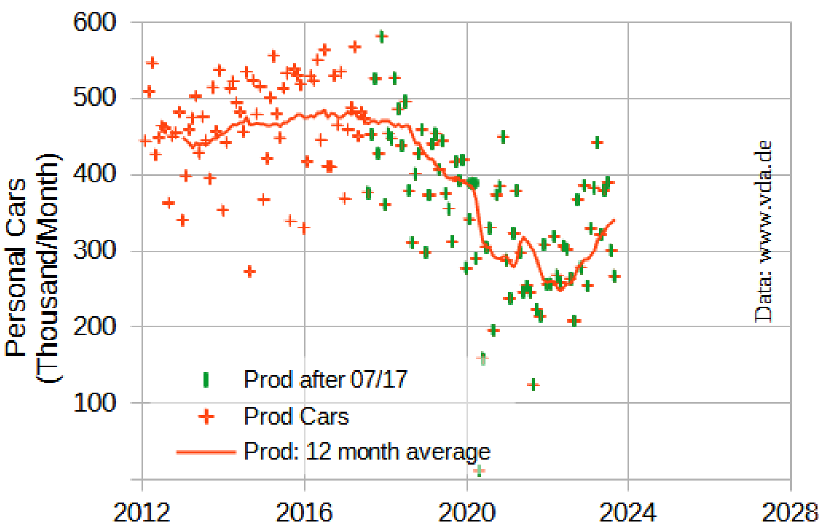


Figure 34: Car production in Germany versus time. Source: VDA [34]

9.3. Car Sales in Saudi Arabia

The chart for Saudi Arabia (Figure 35, source: [35]) shows how car sales there increase when oil prices are high, but fewer cars are sold when oil prices are low. The trend is the exact opposite of Europe. Saudi Arabia is in economic distress, when oil is too cheap.

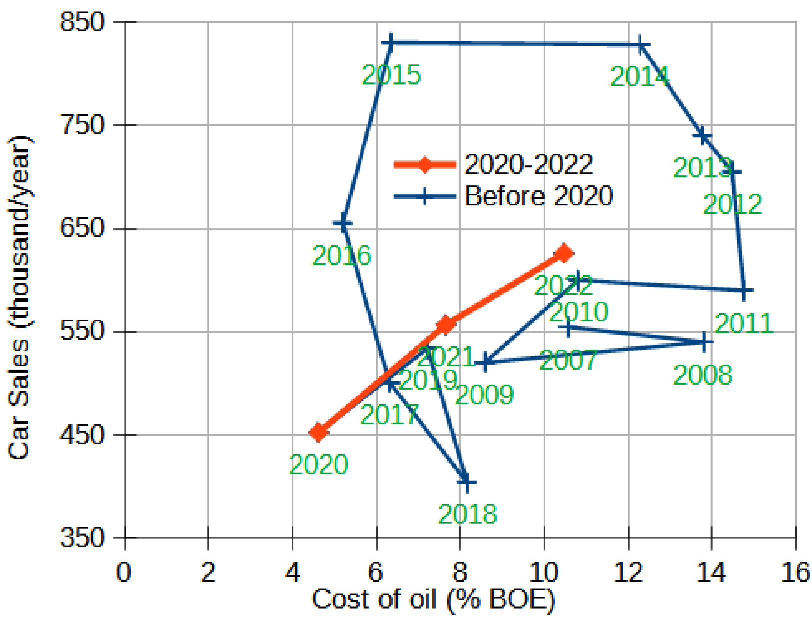


Figure 35: Personal car sales in Saudi-Arabia. Source: CEICDATA [35]

9.4. Car Sales in India and China

Car sales in India were highest in 2018 (Figure 36; Source: [35]). In 2019, they declined, a sign of economic problems. In 2020, there was a very sharp drop, due to the Covid-19 pandemic. In 2021, they continued to decline, followed by a period of slow recovery. In contrast to many other countries, in April 2022 they started to rise again. Probably India has access to cheap Russian oil, with a price discount caused by the war in Ukraine.

China's car sales (Figure 37, source: [35] and [36]) clearly show how sales rise when oil prices are low and collapse when oil prices are high. The first slump started in early 2018 and intensified during the Covid-19 pandemic. By the end of 2020, China's economy had begun to recover as the Covid-19 pandemic had little impact and oil prices were low. Oil prices above $70/bbl in the second quarter of 2021 are slowing the economy for a second time.

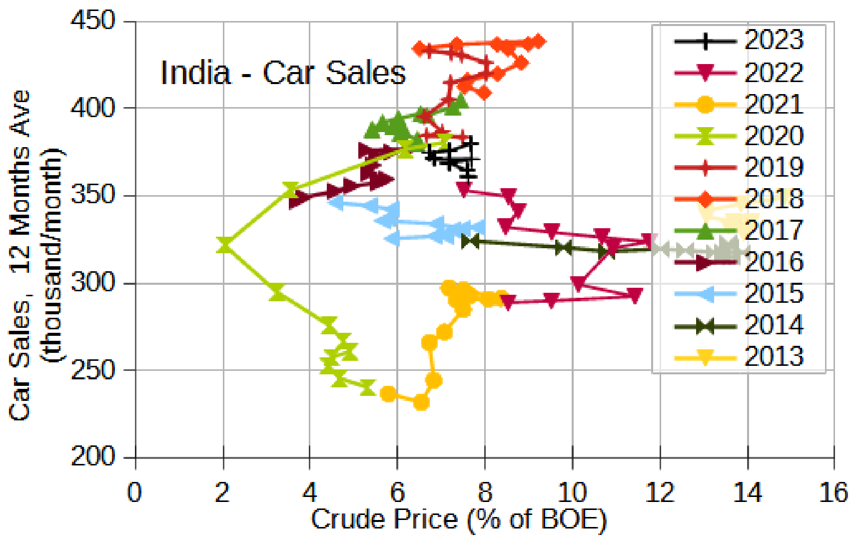


Figure 36: Sales of motor vehicles in India (passenger cars plus commercial vehicles); vehicle figures from CEICDATA [35] and FADA [55].

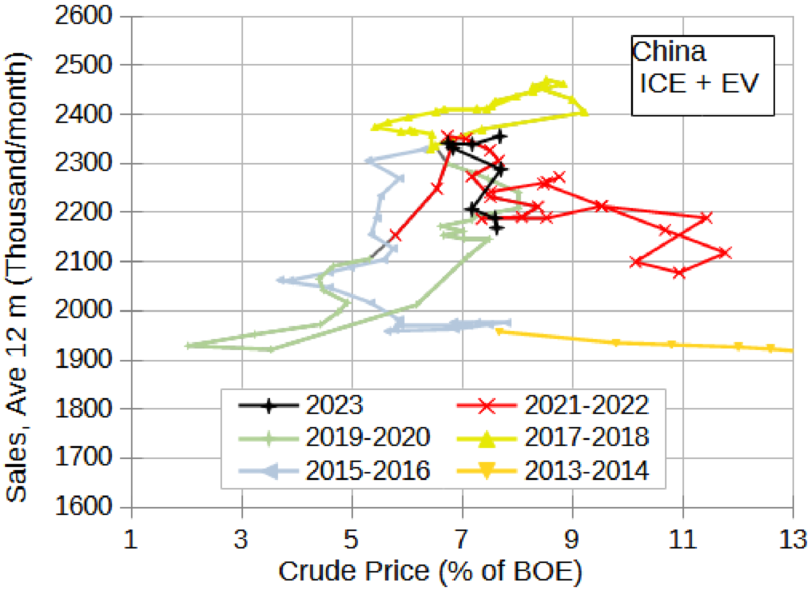


Figure 37: Sales of motor vehicles in China. Source CAAM [36]

Both countries, India and China, do not show a car sales decrease in 2022. Both derive about 50% of their total energy consumption from coal. Because the cost of energy per gigajoule derived from coal is cheaper than the gigajoule derived from oil (Figure 21), they have a cost advantage. And both probably have access to cheap Russian oil. India is known to buy the Russian oil, refine it and sell the diesel to Europe.

In addition, in China authorities have tried incentives to revive demand, with the central government halving purchase tax to 5% for cars priced at less than 300,000 yuan ($45,000) and with engines no larger than 2.0 litres. That tax break has affected purchasers of close to 1.1 million vehicles, bringing a tax loss of 7.1 billion yuan ($1 billion) for the government, the official People's Daily said.

Many policies have been aimed at encouraging sales of new-energy vehicles (NEVs). In May and June, some local governments began offering subsidies for trade-ins of gasoline vehicles for electric cars.

And, the size of a lot of EVs sold in China is much smaller than the size of EVs sold in Europe and USA.

9.5. Sum of Car Sales in Five Large Regions

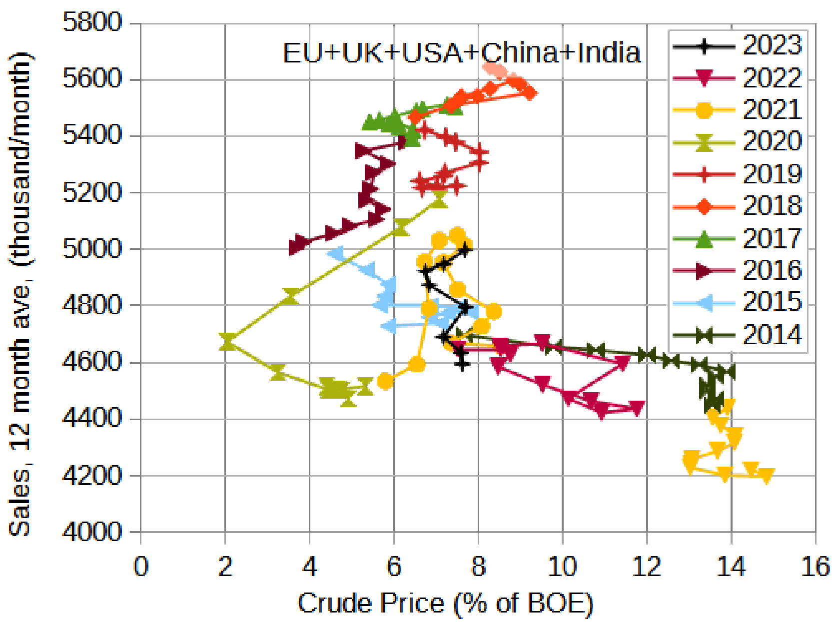


Figure 38: Sales of motor vehicles in the EU, United Kingdom, USA, China and India. These regions contain about 80% of worldwide sales.

Without subsidies for EVs, the car sales numbers in 2022 and 2023 would be smaller.

9.6. Electric Vehicles

As in Germany, sales of electric cars in China are heavily dependent on subsidies. In Germany, massive subsidies, especially for company vehicles, have caused the share of electric vehicles in registrations to increase significantly compared to internal combustion vehicles in 2019 to 2022. Current subsidies are (May 2023): USA up to 7500 USD per BEV; Germany up to 6500 Euro per BEV; China no tax for BEVs (normally 10%). Figure 39 shows global sales of cars with electric drive systems [37]. Sales are increasing exponentially.

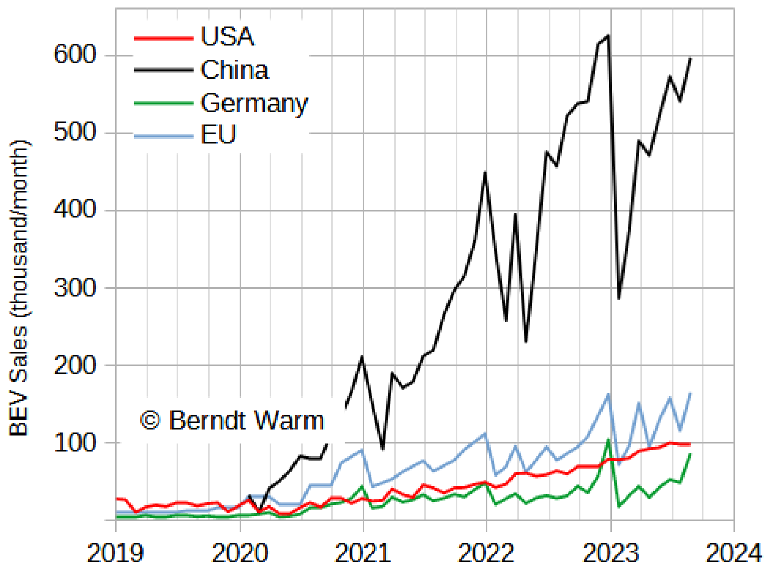


Figure 39: Sales numbers of Battery Electric Vehicles (BEV) in four regions. The maxima at the end of each year show the influence of subsidies, typically ending in December. Sources: ARGONNE [54], CAAM [36], VDA [34], ACEA [51].

Figure 40 is based on statistics from the International Organization of Motor Vehicle Manufacturers [38], linked to data for BEVs and PHEVs from Cleantechnica [37]. Battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) are only a fraction of all new cars. Figure 40 makes it clear that even today electric cars represent only a fraction of all new car sales, about 15%. The fall in total car sales is much faster than the rise in electric car numbers. The problem for car production is not that there is a lack of fuel, but that there is a lack of energy.

If customers lack the money, instead of buying an expensive car with an internal combustion engine, they will not buy a car with an electric motor at the same or an even higher price, but no car at all. The time of energetically inefficient locomotion is coming to an end, regardless of the type of drive.

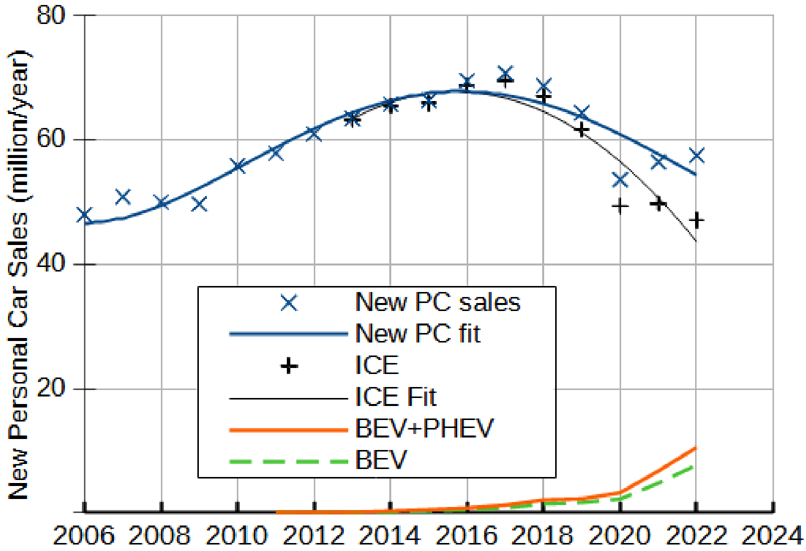


Figure 40: Passenger car sales worldwide. Chart based on data from the OICA [38] and Cleantechnica [37].

9.7. Maximum Oil Price for the Purchase of Motor Vehicles

Figure 30 shows a drop in sales when oil prices are high, but with a delay. The drop can be evaluated numerically by plotting the monthly change in sales figures against the oil price. In the time period 2017-2019 high oil prices were connected with low car sales (see Figure 41). This connection has vanished for the last years, because Covid-19 and car subsidies have

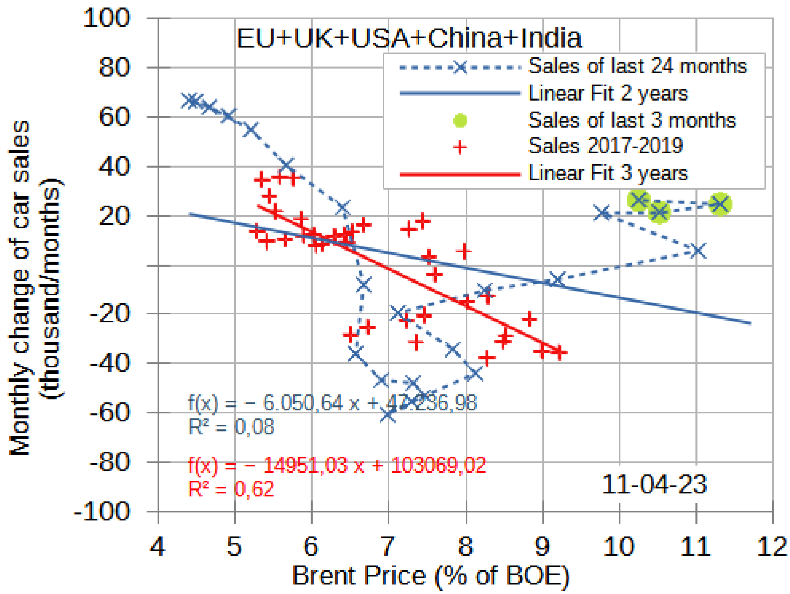


Figure 41: To calculate oil prices correlated with a decline in car sales. The straight line equations and the coefficients of determination R^2 are given.

effects.

The data used in Figure 41 are the sales numbers relative to an oil price, which is delayed by 8 months. The result is a group of points that can be approximated by a straight line. Determining the intersection of the straight line with the line y=0 yields the oil price, above which the sales figures of motor vehicles decrease.

Due to the Covid-19 pandemic and car subsidies, the period of the last 24 months has a wild variation of data points, giving a low correlation value R^2. The correlation for the time period 2017-2019 has been higher, $R^2=0.62$.

Result: There are oil prices that are too high for car buyers. These maximum values have the tendency to fall over time. But other effects can have more importance.

The following applies to the threshold values for willingness to buy motor vehicles (see chapter 6.3):

Time Span	Limiting price	Energy productivity	Limit
	USD/bbl	USD/kWh	% BOE
2014-2016	110	0.47	13.3
2017-2019	59	0.50	6.7
2020-2022	50	0.53	5.3
2021-2022	82	0.61	7.0

Table 6: Threshold value of petroleum costs and energy per barrel above which the willingness to buy motor vehicles decreases.

The 24 months up to March 2023 show a limit of 7.8%BOE, significantly higher than for the time period 2021-2022 with 5.3%BOE. The author has expected, that the limit remains constant. He believes, the higher sales numbers are caused by the massive subsidies for EVs in many countries. The subsidies have not only resulted in higher sales of EVs, they have encouraged buyers to purchase earlier than planned.

10. Economic Theories

In 2020, the author tried to get an explanation from German-speaking economic institutes as to why, in their opinion, the oil price has been falling since 2008. The BMWi[5], DIW, WIFO, IFO and the Öko-Institut Freiburg were contacted by e-mail. Only the BMWi replied and explained that because of the Covid-19 crisis no one could take care of an answer at the moment, but that the relevant department would be informed. The others ignored me. The BfR and EBV answered a question about the risk of falling oil prices by saying that they were not competent for risk estimations. Due to work overload, the BGR also did not want to answer my enquiry as to whether thermodynamics should be considered in reserve calculations.

Economic theories on maximum oil production can be summarised in a few words: At some point, production will be so expensive that it will no longer be worthwhile. That is the insight of mainstream economists. There is no more to be found in the mainstream, no details of when this might be, and no details of mechanisms of action, control loops, etc. In addition, there is the firm belief that oil must become more expensive when it becomes scarce. But since it has been getting cheaper for a long time, it cannot be scarce at all. So, there is no problem.

---

[5] BMWi: Federal Ministry for Economic Affairs and Energy (Berlin); DIW: German Institute for Economic Research e. V. (Berlin); WIFO: Austrian Institute of Economic Research (Vienna); IFO: Leibniz Institute for Economic Research (Munich); BfR: Federal Institute for Risk Assessment (Berlin); EBV: Petroleum Stockholding Association (Hamburg); BGR: Federal Institute for Geosciences and Natural Resources (Hannover).

Even after studying the subject for a long time, I am always amazed at so much ignorance. Only a few economists (Gail Tverberg [24], Tim Morgan [39], Blair Fix [40]) have more substance to offer.

Below I suggest some reasons why economists have these thought patterns and cannot break out of them.

10.1. The Law of Supply and Demand

Prices are determined by supply and demand. This assertion is clearly correct. When analysing past price fluctuations, it is always either changes in supply or demand or both that cause a price change. Often it is just the belief that one of the two will change, which is then called speculation.

Take the September 2019 price jump triggered by the Abqaiq bombing on 14/09/2019 as an example. On the news of the bombing, oil prices went up significantly (from $55 to $62.7/bbl). The world was worried that oil shortages might occur. When the Saudis repaired their facilities, the price fell back to the old level. Already at the beginning of October, the price had fallen by $10/bbl. Tankers transporting oil from Saudi Arabia to all over the world are on the road for about four weeks. So there was no real change in the oil supply, this price jump was purely speculative.

The case shows how the law of supply and demand works. It also shows with several features why one cannot use the law of supply and demand to make predictions with it. Apart from the bombers, no one knew that an attack would take place. Neither the occurrence nor the time nor the amount of the price jump can be explained by this law. Since no one knew beforehand how great the damage would be and how long it would take to repair it, the duration of the price jump could not be explained beforehand either.

This law cannot be used to explain medium- or long-term changes in the oil market. - Oil cost around $110/bbl in mid-2014, and only $75/bbl in mid-2018. How can supply and demand explain this difference?

The law of supply and demand is completely unsuitable for making statements about price developments in the future. Who knows the political developments of tomorrow? The old statement about the weather: '*The weather will be the same tomorrow as it is today'* has a higher accuracy than all predictions based on the law of supply and demand. The truth is: price fluctuations are triggered by various causes: political events, catastrophes, diseases and physical effects. When you try to lump everything together and find a commonality, supply and demand comes out.

Unlike physical laws, this law cannot be disproved. If tomorrow an apple were to fly from the bottom to the top without any external force, the law of gravity would be disproved. A fairly simple proof to disprove the law of gravity. For the law of supply and demand, such a proof is not even theoretically conceivable. Neither the supply nor the demand of the future can be predicted, let alone their effects on the price. Feynman [27] has also found non-refutable laws elsewhere and classifies them as vague theories and useless.

10.2. Substitutability

The logic of economists goes something like this:

- As oil production becomes costlier, the consumer must pay more for it in the medium term.

- If oil becomes rarer, it becomes more expensive.

- At some point, the price will be so high that alternatives to oil (wind energy, solar energy) will become competitive.

- From then on, the alternatives will be bought by consumers.

- Then oil will no longer be needed as an energy source; oil production will come to a standstill.

- In a free market, this process runs by itself; it is regulated by the invisible hand of the free market.

- State intervention in this process (e.g. by subsidising alternative energies) can only disrupt it.

My opinion on this:

- Oil is a source of energy. Consumers use it to earn money with it.

- An energy source is fundamentally different from a consumer good.

- If you can't earn anything from oil anymore, you won't use it.

- Since the net energy decreases as the energy required to extract it increases, oil prices have to fall at some point.

- If oil costs more money than people can earn using it, oil use will rapid fall.

- If one does not develop a cost-effective alternative energy source, all petroleum-dependent and energy-consuming applications will cease to exist.

- The impact on everyone's living conditions will be severe.

In the article from Kümmel et al. [41] the following anecdote is mentioned: At a conference on natural resources, a younger economist pointed out that because of the first law of thermodynamics, energy could not be substituted by capital at will. A highly respected American economist interrupted him and said: "You must never say that. There is always a way for substitution ..."

And the first law is still easy to understand compared to the second law.

10.3. Liebigs Law of the Minimum

Liebig's law of the minimum, often simply called **Liebig's law** or the **law of the minimum**, is a principle developed in agricultural science by Carl Sprengel (1840) and later popularized by Justus von Liebig. It states that growth is dictated not by total resources available, but by the scarcest resource (limiting factor). The law has also been applied to biological populations and ecosystem models for factors such as sunlight or mineral nutrients.

Liebigs law of the minimum is contradicting the economists assumption of substitutability. If crude oil becomes scarce, Liebigs law predicts a demise of oil-powered transports. Proponents of substitutability will expect a timely replacement of oil by another fuel. I myself think, Liebigs law will be valid.

10.4. The Osborne Effect

Up to now, I have found only one explanation from economists for the falling number of car sales: That’s the Osborne effect [42]. The Osborne effect is something I experienced in my professional life, but for a totally different product. For cars, the explanation goes like this: Electrical Vehicles are much better than fossil fuel vehicles. Unfortunately, today they are more expensive than their fossil counterparts. But their prices will drop, caused by the progress of technology.

Consumers know that. If they want to buy a new car, they will wait until the cheap electrical version is available. For car manufactures, this is very disadvantegous, because a gap arises with little car sales. After some years, the cheap cars are available and the gap vanishes. The sales numbers return to their normal growth.

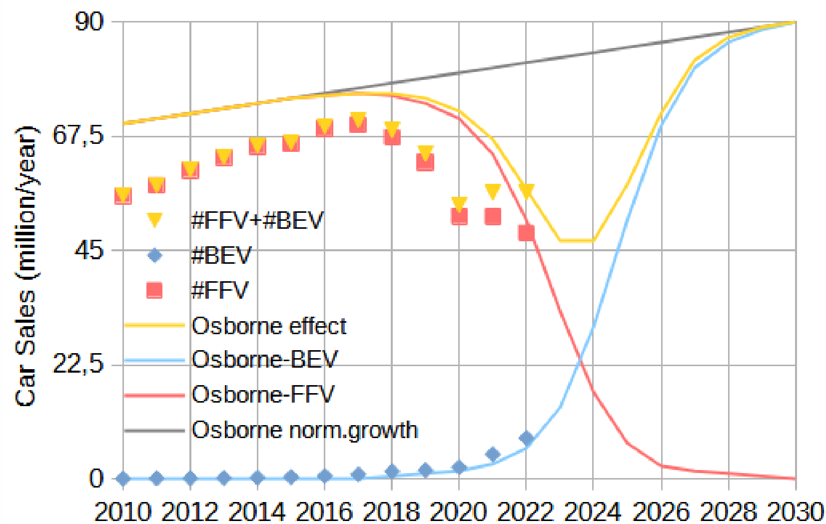


Figure 42: Osborne effect for the car industry. The solid lines are theory, the symbols show the worldwide real sales numbers.

The solid gray line on top shows the normal growth of car sales, going upward. The solid blue line shows the predicted sales of BEVs (battery electric vehicles). The blue squares are the real sales, and they follow the theory. The solid red line shows the predicted sales of FFVs (fossil fuel vehicles). The red squares show the real sales numbers. They drop, but two years earlier than predicted. The sum of BEVs and FFVs are the yellow line and symbols.

Prediction and real numbers are not the same, but similar. The difference in the diagram does not allow to refuse the Osborne effect for cars.

But a detailed view on the car sales numbers show, using the first derivation of the sales numbers that the sales began to drop as soon as 2013. Much before BEVs became relevant. This is a sign, that the Osborne effect is not crucial.

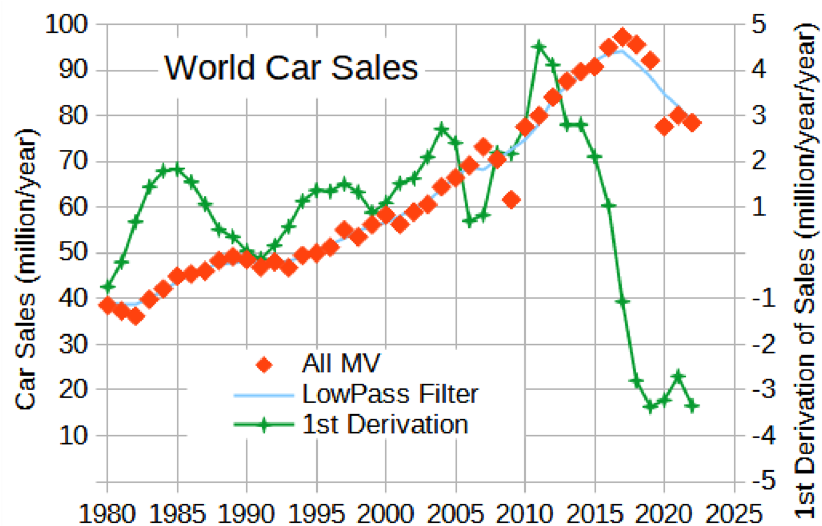


Figure 43: Car Sales numbers and first derivation of sales numbers. A low pass filter is applied to the sales numbers before derivation.

A second sign come from the sales numbers of China. China is able to produce significantly more BEVs than predicted. A lot of them are small and cheap cars (Chery QQ Ice Cream, Wuling Hongguang). China shows that cheap BEVs are possible. That is a sign that people do not wait for BEVs until they are as cheap as FFVs.

10.5. Lessons from history

While economists largely ignore energy as an economic factor, historians present in their works the connection between available energy or raw materials and the rise and fall of nations. Examples are the works of Tainter [43] and Turchin/Nefedev [44].

Most people who have grown up in the Western economic region have internalised a belief in progress. They assume that wealth and technology are continuously improving and that the economy is always growing. They expect to have a little more of everything every year. They may have learned at school that there was once a Roman Empire and a Mayan civilisation and that both perished, but both seem so distant that they can have nothing to do with life today.

10.5.1. Secular Cycles

The historians Turchin and Nefedev [44] have a different opinion on this. They have studied the development of civilisations in more detail. According to their research, history takes place in cycles. Each cycle (Figure 44) consists of a growth phase (expansion), a stagflation phase, a depression phase and an inter-cycle phase that lasts until the next growth phase.

A civilisation in the growth phase has enough space, food and land so that the population can multiply. At some point, the population has grown so much that the available land and food are just enough. The population becomes so large that the carrying capacity of the land is reached. Then the stagflation phase begins, where growth still exists but per capita wealth slowly falls. In this phase, the yield of agriculture deteriorates due to overexploitation. The depression phase (crisis phase) follows. The poorer living conditions of the population lead to social conflicts and wars. Due to the cramped living conditions, epidemics occur more frequently. The population decreases. At some point, there is enough land to produce food for everyone again, and the inter-cycle phase begins. Its duration is indefinite, lasting until a breakthrough in technology or otherwise.

A typical duration of a cycle can be 200-300 years, about 100 years for expansion, about 50-60 years of stagflation and about 50-70 years of depression. Turchin and Nefedev show this cycle for eight epochs in history.

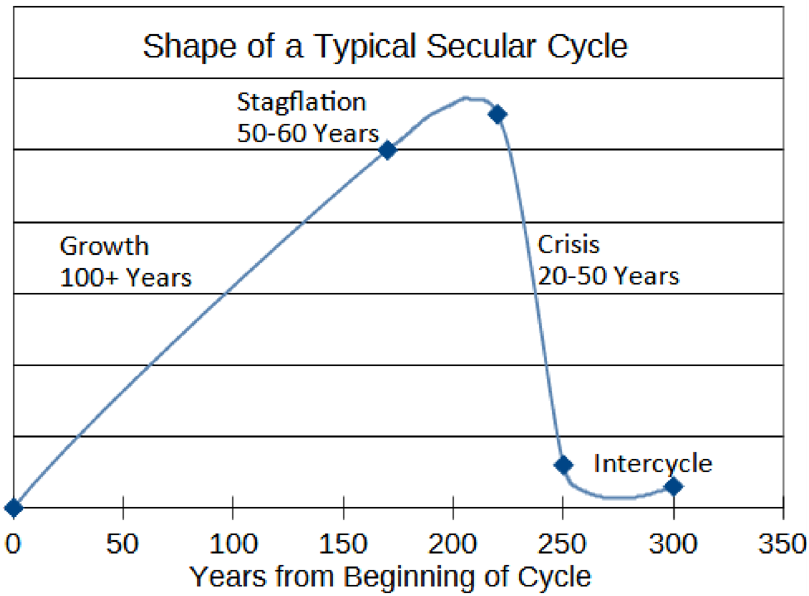


Figure 44: Form of a typical secular cycle according to Turchin/Nefedev

In contrast to earlier epochs, the current epoch, the petroleum age, does not only affect a local group of people, but all of humanity. The epoch began around 1860 with industrial extraction in Wietze and Drake Spring. Looking at the petroleum age from Turchin's point of view, humanity is now in the beginning crisis phase. In history, pandemics are typical for crisis times. So, the Covid-19 pandemic is a sign of this. Other signs are the rise of populism and social unrest in various countries.

10.5.2. Collapse of Complex Civilisations

Tainter [43] has dealt with the rise and fall of civilisations. This fate did not only catch Romans and Mayans, but he assumes several hundred affected civilisations. He also focuses on the raw material situation (food supply).

Civilisations grow as long as they have enough raw materials. At some point, the locally available raw materials run out, and the procurement of raw materials requires more effort (by transporting the materials from far away, building irrigation systems or other things). To cope with the effort, the members of the civilisation specialise through division of labour. Tax systems are introduced, elites establish themselves. The civilisation acquires a complex structure. The complex structure allows for further growth, but goes hand in hand with a growth in complexity. More transport routes become necessary, middlemen appear, water sources dry up and have to be replaced, and thieves make guards necessary for security. At some point, the complex system becomes an end in itself. Further increases in complexity make it more ineffective. Then, when a crisis comes (drought, disease), the whole system collapses and disappears. Parallels to the supply problems of the car industry and other economies in 2021 are unmistakable.

Tainter explains his thoughts using the Roman Empire, the Mayans and others. He writes that only one civilisation out of hundreds was able to stop collapse by reducing complexity: The Eastern Roman Empire. All the others collapsed.

It is no problem to find the complexity described by Tainter in our lives today (bureaucracy, standardisation systems, tax law, supply chains of goods, etc.).

The most complicated machines in today's world are the internationally networked supply chains. They require sophisticated communication systems, vast numbers of vehicles, banking, specialists to operate the systems and vast amounts of energy. It is to be expected that this machines will be the first to sputter.

Current examples from the pandemic:

- The EU has been desperate to drive down the price of vaccines, but has failed to recognise the need to build factories as a prerequisite for vaccine procurement and has frittered away. Vaccines arrive later than desired.

- Bureaucracy delays effective disease control when vaccines sit in warehouses because high-priority vaccinees are not reached.

- In March 2020, the auto industry failed to manufacture because components from China were not available due to lockdowns.

- In spring 2021, semiconductor chips to build cars were missing because orders in Taiwan were cancelled during the first manufacturing freeze.

What will happen when less and less oil is available in our economic system? An economic order built on credit must actually collapse; a thoroughly bureaucratised social order cannot resist it. Not a pretty prospect.

10.6. The Peak Oil Movement

Peak oil is the term used to describe the maximum level of oil production. Since the earth is finite in size, oil reserves must also be finite. This means that without any doubt, at some point in time production will decrease and then approach zero.

The first person to formulate this fact into a theory was Marion King Hubbert. He had analysed individual oil wells and found that their cumulative production trend could be described in idealised terms by a logistic function (also called a sigmoid function, see Figure 45). The current production looks like a standard distribution. Based on his results, he concluded in 1956 that the oil production trend in the USA could be represented by a logistic function and that the maximum must occur around 1970, based on an estimate of the recoverable oil quantity of 200 billion barrels. He was right (Figure 46). After 1970, US oil production fell.

$$cumul.production(t) = G \cdot \frac{e^{(\frac{t-t_0}{\beta})}}{1+e^{(\frac{t-t_0}{\beta})}} \qquad \text{Eq. 33}$$

(Sigmoid-Funktion)

G: Value for total cumulative production

t: Time

t_0: Time of maximum production

β: Factor that determines the width of the curve.

The denominator of the sigmoid function is an exponential growth function. Since it is also in the numerator, growth is followed by shrinkage.

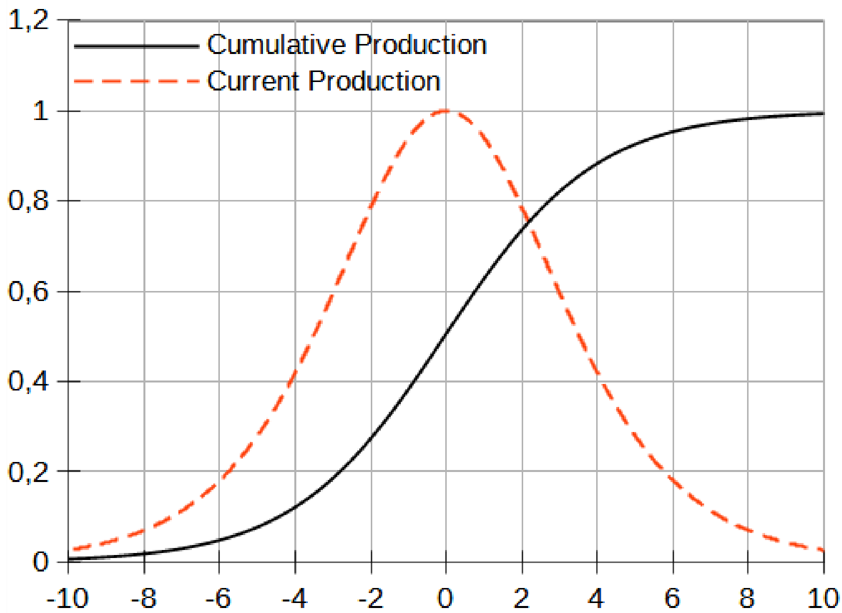


Figure 45: Idealised production curves, set up using the Sigmoid function. Both curves are normed to “1”.

Hubbert also predicted that the world's oil production would peak in the year 2000. He assumed that oil would be replaced as an energy source by nuclear energy. This prediction did not come true. And something else happened: first, oil production in Alaska was added, and later, US shale oil production increased so much that the maximum US oil production was exceeded in 2016 and continued to increase until 2019.

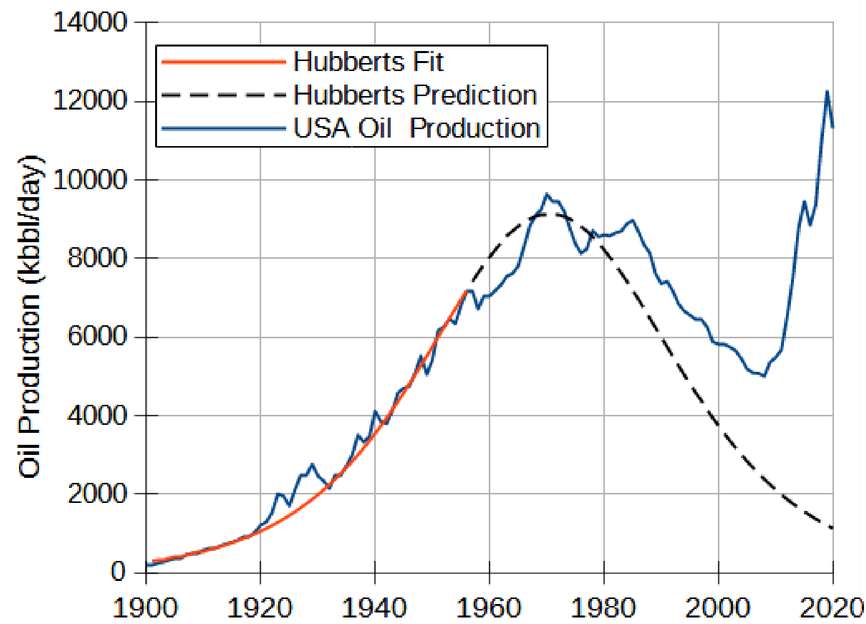


Figure 46: Hubberts prediction, done in 1956, for the oil production of the USA.

In contrast, the author does not expect that the world oil production will follow a Hubbert curve, because the largest oil fields have been exploited first (**best first**), and smaller fields followed. A triangle function is the most probable outcome for the sum of individual productions (compare Figure 47 with Figure 10).

Hubbert was the forerunner of a group of people who were waiting for peak production followed by decline: the peak oil movement. The website "The Oil Drum" [45] contains a large number of articles on peak oil from the years 2005-2013, which dealt with the production maximum. The supporters of the movement had in common that they waited for oil prices to rise according to the Hotelling rule. In 2008, the oil price was so high that everyone believed the maximum had almost been reached.

When production continued to increase in the years after 2008 despite high oil prices, interest in peak oil decreased. In 2013, The Oil Drum was discontinued and has only been usable as an archive since then. The oil price collapse in 2014 and the unforeseen boost of production by light tight oil hit the movement heavy. People who spoke loudly of decreasing production rates and increasing oil prices back then are cautious today. They no longer dare to recognise a production peak as such without waiting about five years to see if production does not rise again.

In 2001, the ASPO (Association for the Study of Peak Oil and Gas) was founded by the British petroleum geologist Colin J. Campbell. This initiative was the inspiration for the founding of ASPO Germany and ASPO Switzerland in 2006 (dissolved at the end of 2018). ASPO is a worldwide network of scientists, economists, politicians and journalists that draws the public's attention to the assumed global peak oil and gas production. Furthermore, its timing as well as the decline in production rates is investigated, information is provided about the possible effects and approaches to solutions are discussed, sometimes controversially. The author joined ASPO in 2016.

Today, peak oil is almost only a topic of conversation among geologists. Economists are firmly convinced, because of low oil prices, that oil must be available in large quantities. Reserve considerations, such as those carried out by Jean Laherrère [11] and Dennis Coyne [7], state that about half of the oil originally present on earth is still left.

In recent years, some people have come to believe that the maximum oil production will not be determined by the supply side, but by the demand side. They expect peak oil demand when electric vehicles replace combustion engines. Oil energy will then be substituted by renewable energy. The peak described in this book is not peak oil demand, but peak oil affordability.

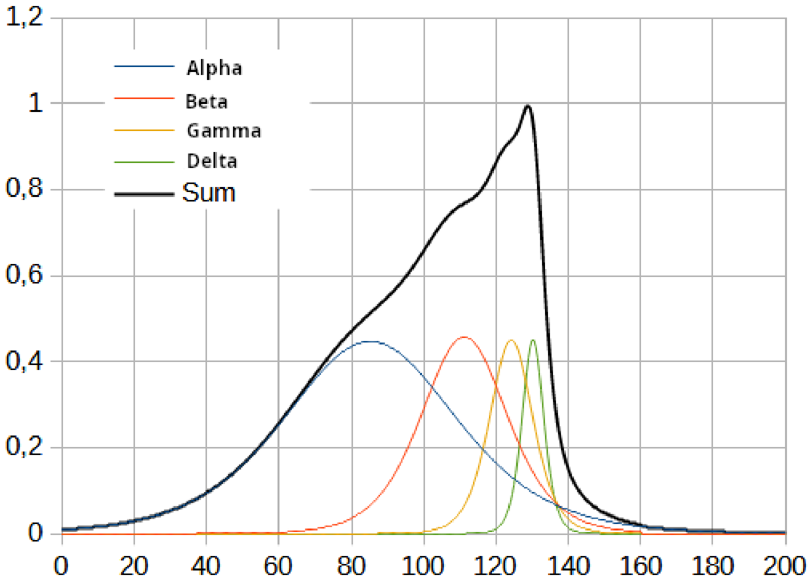


Figure 47: Addition of four Standard Distributions, designated alpha, betam, gamma and delta. The addition of standard distributions does not result in a fifth standard distribution, but in a triangle. If a mechanism exists which sorts the distributions with respect to size, a Seneca cliff results for the sum.

11. Miscellaneous

11.1. Psychology

"Man prefers to believe what he prefers to be true."

(Francis Bacon)

The chapter on psychology was included because two things are hardly comprehensible to the normal mind:

- Anyone who looks at the oil price curves from 2008 to 2020 should have alarm bells ringing. Many economists expect the price to rise because of rising production costs, but it was falling. Every economist should at least try to clarify this issue.

- A law of physics says that the oil age must end soon. Unfortunately, this fact is unknown to most people. And those who know the law believe it somehow does not apply to oil production.

Even people who see major problems coming for humanity due to climate change, pollution, soil erosion, resource depletion, overfishing of the oceans, waste through consumption and overpopulation believe, when referring to thermodynamics, that it does not apply to oil. How can this be?

I have found the following explanations so far:

- A large part of the elite more or less earns its living with oil, e.g. the management of oil companies, car manufacturers, banks and insurance companies. These managers did not get into their leadership positions because they are selfless, but because they think of themselves first and foremost. Even the discussion about an oil production peak can ruin a car manager's balance sheet for the next quarter, which is why the topic is never brought up.

- Politicians are elected when they promise their voters a positive future. A maximum production of crude oil followed by a renunciation of the car is anything but positive. The politician who raises this issue might as well look for a new job right away.

- Even green politicians have nothing to do with peak oil. If someone raises this issue, he torpedoes another favourite green issue: the climate catastrophe. If there is no more oil available in the near future, it will be difficult to continue emitting much CO_2. (But I'm sure it will still work.) You could only address peak oil as a Green if you were absolutely sure that the thermodynamics were right. But how much green politicians have the science background for that?

- Economists have rarely mentioned or taken note of energy in their formulas for the future of economic development. How are they supposed to understand the effects?

- Engineers and scientists should actually be able to check and verify or even refute the thermodynamic considerations. In the meantime, I have the impression that specialisation has gone so far in this field that people no longer dare to have and express opinions for things outside their special field. This seems to be especially true for researchers at institutes and universities. Almost none of the people who have examined the ETP model (or TNE model) more closely and affirmed it, and whom I know, were employed at a university.

- Journalists with a science background are rare.

- And then there are the ordinary citizens. Most of them want to stick to the previous life and no changes. Only the house and the car should be a little bigger for them in the future, the flight can go a little further away.

Reduction is out of the question. Even if you know that CO_2 emissions are harmful, you don't reduce them; let the others do it first.

- What they all have in common is that in an increasingly complicated world, knowledge of facts is increasingly being replaced by belief in facts, as the vast amount of detail becomes more and more confusing. It is becoming increasingly difficult to distinguish facts from alternative facts. Supporters of alternative facts are vocal and can influence or at least confuse others.

Actually only a few nature lovers (and a special personality type (Tom Murphy, [46]) can relate to the issue of peak oil and give it some thought.

11.2. Global Warming and Peak Oil Production

The majority of scientists who study the Earth's climate are convinced that the increasing emission of greenhouse gases, together with the change of the Earth's surface from a natural landscape to a useful landscape, will lead to global warming. The author of this book is of the same opinion. I have spent much of my professional career studying absorption of radiation in the infrared spectral range by the atmosphere. My own impression is that it has become warmer in Germany during my lifetime. The multitude of facts such as the warming of the Arctic, increase of CO_2, methane and other gases in the atmosphere, reduction of polar ice areas, thawing of the tundra, disappearance of glaciers are clear: man-made global warming exists.

What will be the impact on global warming if oil is no longer produced? Since oil is extremely important for the entire transport sector, traffic will be significantly reduced. Especially heavy transport by truck and ship will be affected, as there are still no alternative propulsion systems for either.

Ships used to be moved by coal, but these ships no longer exist. Without heavy traffic, much less coal will be transported and thus not used.

However, since people want to maintain their standard of living and thus their energy consumption, lower-quality fuels such as lignite and wood will be burned more intensively. Natural gas will also continue to be burned and in larger quantities. Consequently, CO2 emissions will decrease, but only slowly. Burning lower quality materials increases emissions of other greenhouse gases. I believe that efforts to reduce greenhouse gases to combat global warming will not become superfluous, but will remain a permanent task.

11.3. Proof of the Validity of Thermodynamics for Oil Production

The reader who has followed up to this point will ask himself at some point: The argumentation on thermodynamics and oil production sounds logical, but where is the proof that it is really true?

Unfortunately, there is no proof. In physics, there is no proof for theories in the first place, that is always the case. The only thing that exists in physics are refutations of theories. A theory in physics is valid until its opposite is proven.

After all, a refutation of the TNE theory would be possible:

1. a energy source with a very high EROI would be found, making the TNE model obsolete.

2. a special combination of oil price, oil production and car production in a stable economic situation. For example, if all get high or all get low **in a stable situation**.

If the oil price rises significantly above the maximum value without inflation being the cause, and car sales rise, the evidence to the contrary would be provided. However, since inflation data are only reported with a lag of about one year, one can only be sure some time after the price rise.

If a theory is used to make a prediction that arrives later, this supports the usefulness of the theory, but is not real proof. - Not even if other theories predicted the opposite and were wrong. If one looks at movements in the oil market, one can find such evidence of usefulness. Certain effects show that the TNE model is very useful, but one can also assume other causes for these effects:

1. The fall in oil prices due to thermodynamics in the summer of 2014 was predicted by the Hills Group. In public, however, only the increase in US oil production due to fracking is seen as the cause.

2. In spring 2020, OPEC+ production cuts brought the oil price close to the maximum value. It was expected since September 2019, based on the TNE model, that the price would crash significantly and OPEC+ would cut production. The Covid-19 pandemic broke out in spring 2020, the price plunged, OPEC cut, but everyone believes the pandemic is the only cause.

3. Car sales have been falling since 2017, but the German public sees completely different facts instead of energy problems as the cause: the rise of electromobility, the pandemic and supply chain problems.

4. Oil production had a maximum in November 2018; in the public the maximum is seen as a coincidental phenomenon, the pandemic is seen as the only cause of the reduced demand for oil.

Meanwhile, I am of the opinion that thermodynamics will probably be seen as the cause of the movements in the oil market only after much delay (if at all). The physical effect happens in the background, current political or economic issues overlay it and will always be considered the cause. Only in retrospect (more about ten years later), when the big picture is there, will the thermodynamic effect also be recognised as such by the public.

Ockham's razor (research principle of scholasticism) is unfortunately no help. It says: Of several sufficient possible explanations for one and the same state of affairs, the simplest theory is to be preferred to all others. For a physicist, the law of nature, the second law, is a very simple explanation, for everyone else it is far too complicated.

12. Remaining Life Span of Oil and Car Industry

Petroleum production and driving are connected like Siamese twins. Without fossil fuels, hardly any vehicle moves. Petroleum provides the energy for the drive. Petroleum also provides energy for oil production. Worldwide, almost only combustion engines are used for motor vehicles, the proportion of electric vehicles is in the percentage range (according to wikipedia: 1.4% worldwide). Siamese twins can sometimes be separated, otherwise they live and die at the same time.

Based on openly accessible data on car manufacturing and petroleum production, the lifetimes of this twin were determined in several ways. The mathematical methods used are standard methods for data evaluation. The calculation methods and results are presented, but no details of the calculations[1].

Methods:

1. from the worldwide production of motor vehicles

2. from the price of oil

3. from the monthly production of passenger cars

4. from the German car data

5. from the Entropy Balance Equation for Open Systems[2]

12.1. Lifespan Determination from the worldwide Production of Motor Vehicles (Method 1)

This method uses the number of motor vehicles built worldwide since 1900. The number is shown graphically in Figure 48. The data come from https://de.wikipedia.org/wiki/Wirtschaftszahlen_zum_Automobil.

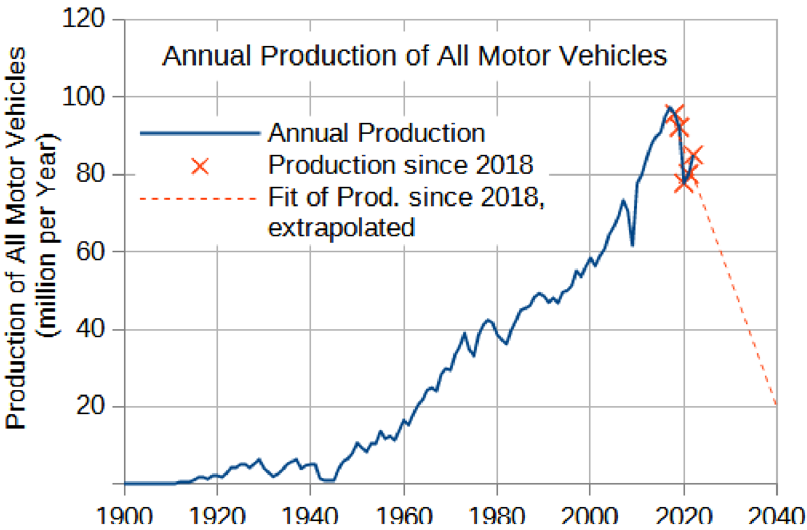


Figure 48: Annual Production of All Motor Vehicles with extrapolation

The maximum production was in 2017, since then it has been declining. A linear fit to the last five points hits the zero line around 2040. The last of the five points has a large influence on the intersection point. Because the car production number in 2022 have been modified by car subsidies, the intersection point is uncertain. This means that if the previous trends continue, vehicle production will end about 2035-2045.

One method for estimating the production that will still be possible in the future from previous production data is Hubbert linearization. It is used in mining to predict the expected future residual production of a mine or oil well. For this purpose, the previous summed up production is taken for the x-axis. For the y-axis, the current annual production is taken for each year, divided by the previous total production. If the last data are

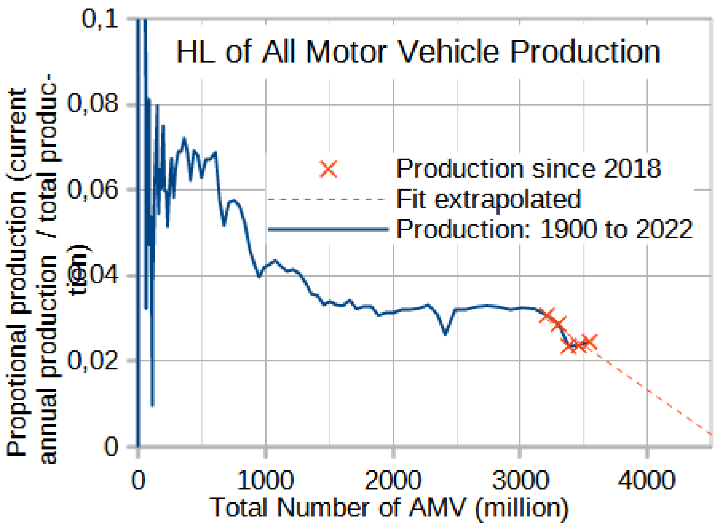


Figure 49: Hubbert Linearization of the global all motor vehicle production.

approximately on a straight line, its cutting axis with the x-axis is the total expected production.

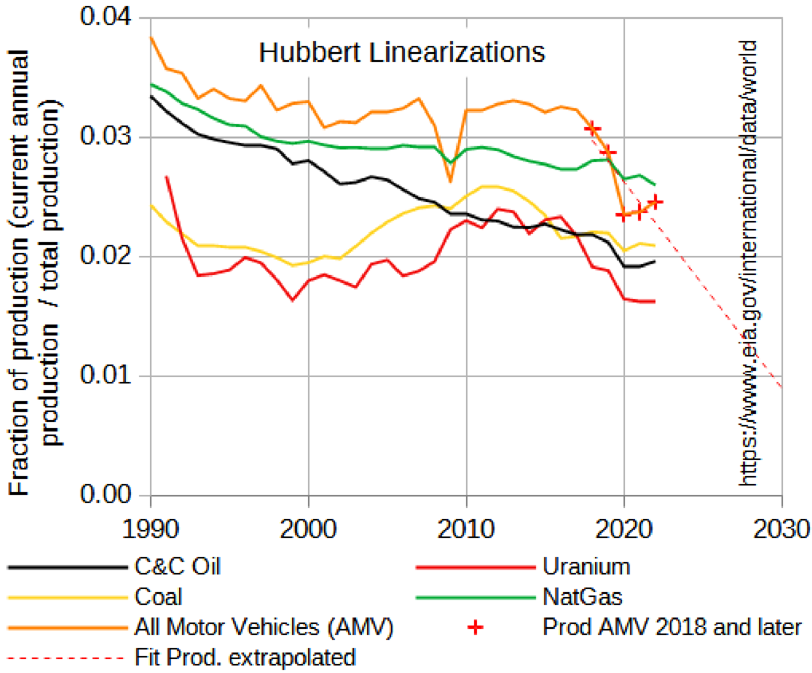


Figure 50: Hubbert Linearizations for all motor vehicles and fossil fuels. To combine all elements in one diagram, the x-axis is here the year instead of the total production.

For motor vehicles, the total production to date is about 3550 million vehicles, the expected total production is about 4500 million vehicles. So about 950 million vehicles can still be built.

If one applies the Hubbert linearizations against time and summarizes fossil energy raw materials and motor vehicles in a diagram for the fossils, the steep drop in production is only recognizable in the case of motor vehicles and uranium. The other energy raw materials fall off much more slowly.

Uranium is a special case. Up to 1990, it has been produced mainly for nuclear weapons. Much of the weapon material has been reused for nuclear power plants up to today, reducing the amount of new production. The global fleet of nuclear power plants is old and will be decommissiioned in the near future, and only some new are built. So, it can be expected, thar uranium demand and production will decrase further.

The most likely cause of the difference between the behavior of motor vehicles and fossil energy raw materials is: Gross is still a lot of raw materials extracted, but the net energy of the raw materials is running out. The production effort is becoming too high. The number of vehicles is determined by the net energy, not the amount of raw materials.

An interesting question is the effect of net energy on uranium. Is its production depending on the net energy of oil and coal, despite it is itself an energy raw material?

Result: The extrapolation of the production data of motor vehicles show that from about 2035 no more vehicles will be produced worldwide.

12.2. Lifespan Determination using the Oil Price (Method 2)

At the end of 2018, the author made the observation that the peaks of oil prices are pretty much on a straight line (dashed green line in Figure 22). The straight started in 2008 and lasted until 2021, thirteen years. The straight line falls by 1.1%BOE/year.

It was not until the beginning of 2021 that the oil price came back above the straight line and has continued to rise ever since. Just as there was an upward limiting line, there was one that limited the price of oil downwards (dashed dark yellow line in Figure 22). It started in early 2016 and has been on the rise ever since. Both lines crossed in mid-2020.

The author interprets the line of maxima as the oil price that the industrialized countries can afford to the maximum while maintaining their lifestyle. He interprets the line of minima as the price of oil that the producing countries need to keep their economies running. In mid-2019, the author noticed this crossroads and expected a crisis in 2020, although he was completely unclear what kind of crisis it would be. He didn't expect Covid-19.

The price of oil has been somewhat below until 2021 and well above the green line since 2022. First, OPEC raised prices because its countries' economies needed the money. Then the war in Ukraine caused a further increase. On 05.09.2022, OPEC decided to cut production because the oil price became too low for them.

The inhabitants of the industrialized countries are now realizing that their lifestyle is at risk. The line of the maxima will reach the zero line (0%BOE) around mid-2027. From then on, the inhabitants of the industrialized countries can no longer afford oil without giving up many things of daily life. The demand of the oil producers is then about 13-14 %BOE. These two values are incompatible.

Result: The extrapolation of oil prices shows that from 2022 the lifestyle in the industrialized countries will degrade, and that after 2027 the inhabitants of the industrialized countries will hardly be able to pay for oil or its products.

12.3. Lifespan Determination from the Monthly Production of Passenger Cars (Method 3)

Figure 51 contains several prominent areas:

- In 2013 and 2014, car sales increased at approximately 14%BOE of oil prices. (red ellipse)
- In 2018, sales began to fall at 8-9%BOE. (green ellipse)
- In 2021, car sales did increase at oil prices of 6%BOE to 7%BOE, after a period with only 2-5%BOE. (red ellipse)
- In 2021, at 7%BOE oil price sales numbers collapse (green ellipse) and then remain low in 2022.
- The recovery in the second half of 2022 and begin of 2023 has much to do with subsidies for EVs (red ellipse). We can be sure, without subsidies the recovery would be smaller. The future will show, how important and stable the recovery is.

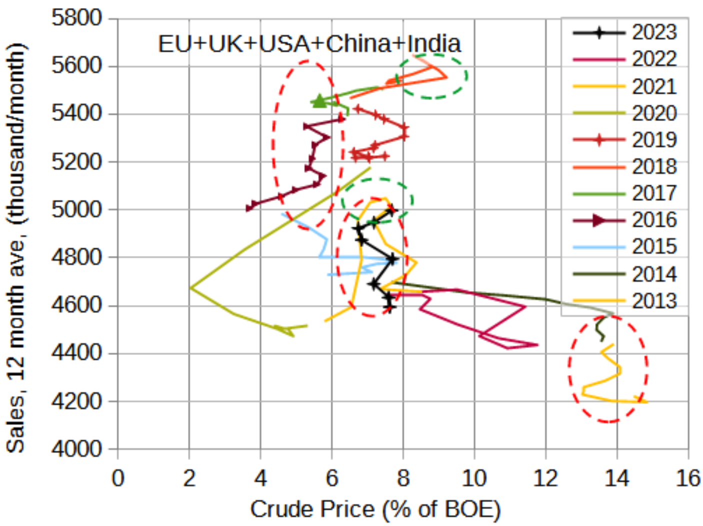


Figure 51: Car Sales in 5 important regions versus Oil Price.

While in 2013 the relatively high price of 14 %BOE was conducive to the desire to buy, in 2021 an increase was possible at only 6 %BOE. In 8 years, the "beneficial price" decreased by 8%BOE, i.e. one percent BOE per year.

In 2018, car sales fell at 8-9%BOE, in 2021 at 7%BOE. Here, the "limiting oil price" fell by 2%BOE in 3 years.

The extrapolation of the trend means that in 2027 the "conducive price" will be 0 %BOE, i.e. hardly anyone can afford a car anymore. Electric vehicles are usually more expensive than comparable cars, so the transition to electric vehicles will not slow down this trend.

Result: The extrapolation of sales data relative to the oil price shows that in 2027 and later world car sales will go down fast.

12.4. Lifespan Determination from the German Car Production Data (Method 4)

Car production and the export of passenger cars from Germany have been declining since 2018. The 2020 Covid-19 crisis, the semiconductor supply crisis and the Ukraine war are often cited in the press as the culprits. However, since the decline began in 2018, the explanation is incomplete.

Since the data are very scattered, it takes at least several months before upward and downward tendencies in the curve are recognizable. In Figure 52, the data have been projected into the future since 2018 using linear fits. Both fits cut the straight y=0 around 2030 and say that from 2030 no more cars will be produced in Germany.

Result: The extrapolation of the German production data implies that no more cars will be produced in Germany in about 2030.

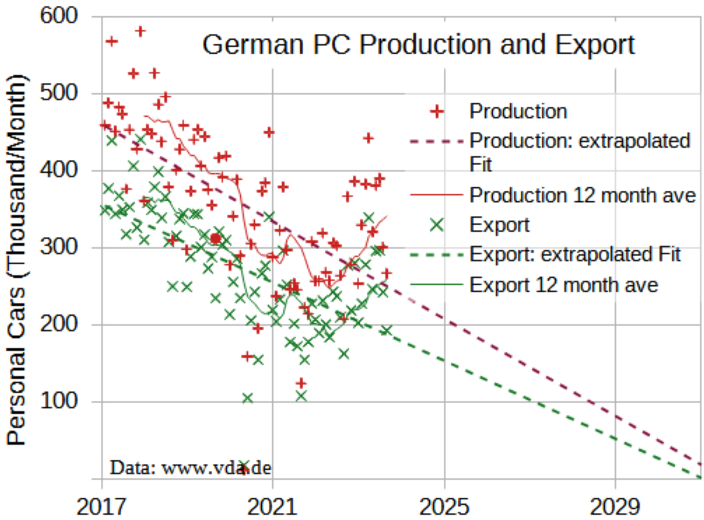


Figure 52: Germany: Car production and Export. The increase of production and export in 2023 has stopped in August 2023.

12.5. Lifespan Determination from the Entropy Balance Rate for Open Systems (Method 5)

The earth's crust is usually in a temperature equilibrium near the oil fields. Oil production transports heat from the Earth's interior to the Earth's surface. The petroleum pumped upwards is replaced by water from the Earth's surface, which cools the Earth's interior.

The temperature equilibrium of the earth gets disturbed. In chapter 7 “Oil Production and Thermodynamics” the calculation of the required exergy expenditure using the entropy rate balance has been carried out, resulting in Figure 29.

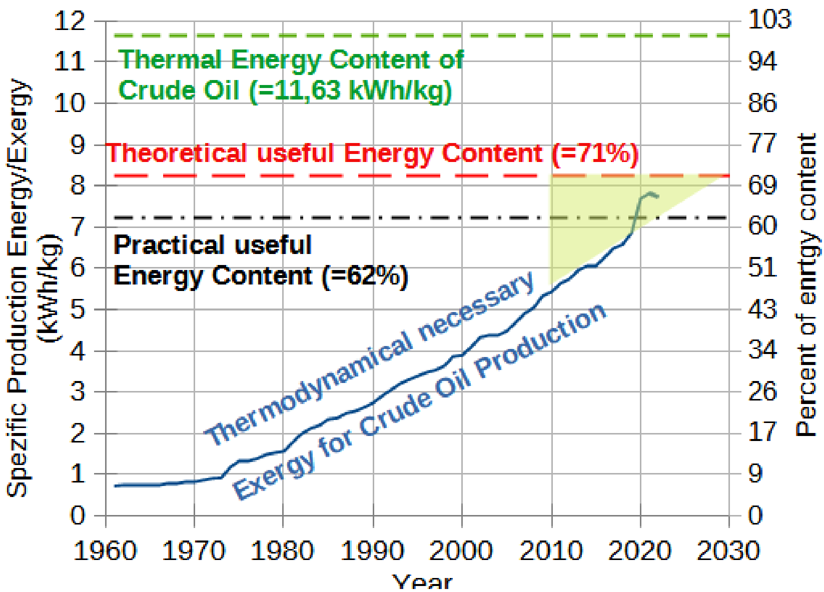


Figure 53: Production exergy for oil. The green triangle indicates the exergy remaining for consumers.

The thermodynamically necessary exergy (TNE) for oil production (= distortion of the thermal equilibrium) increases continuously over time. The distance of this curve to the theoretically or practically usable portion is the remaining exergy for the oil user. The green triangle in Figure 53 indicates the exergy left for the consumer for the relevant range from 2008 to 2027.

The exergy required to change the temperature equilibrium is continuously increasing and will reach the value for the practical exergy content of crude oil in 2021, and the theoretically usable exergy content in 2029. The difference in exergy between 2021 and 2029 is about 10%, i.e. 1.25%BOE/year.

Result: In the years 2028 – 2029, the exergy expenditure for oil production will be higher than the exergy content of crude oil[6]. Then oil production no longer makes sense in terms of energy.

12.6. Comparison of the Results of Methods 2, 3 and 5

Method 2 (Figure 22): The slope of the dashed green line connecting the price maxima is -1.25 %BOE/year. The line will hit the zero line in 2027.

Method 3 (Figure 51): The propensity to buy cars decreases by -1%BOE/year. According to this diagram, world car sales will decrease fast after 2027. See also chapter 5.4.1 Four Oil Price Axioms.

Method 5 (Figure 24, Figure 53): The increase in oil production exergy (TNE) is currently 1.25 %BOE/year. The theoretically usable exergy content will be achieved in 2029.

The three methods provide almost exactly the same results for the slope and the end date[7]. This accuracy is astonishing, because in method 5 there are two inaccuracies due to the principal reasons:

- Crude oil is largely extracted using other energy carriers, e.g. from natural gas and coal.
- Real efficiencies of gasoline and diesel engines are well below the 71 percent that are theoretically achievable.

The inaccuracies should actually lead to the fact that the real figures from the economy have deviations from the calculation. However, real numbers and calculations are almost identical.

The likely explanation is that consumers pay for the oil at maximum as much money as they can generate with it themselves. And their earnings are proportional to their share of the barrel's exergy. Their share is the theoretically usable exergy minus the exergy used for the extraction (Figure 24).

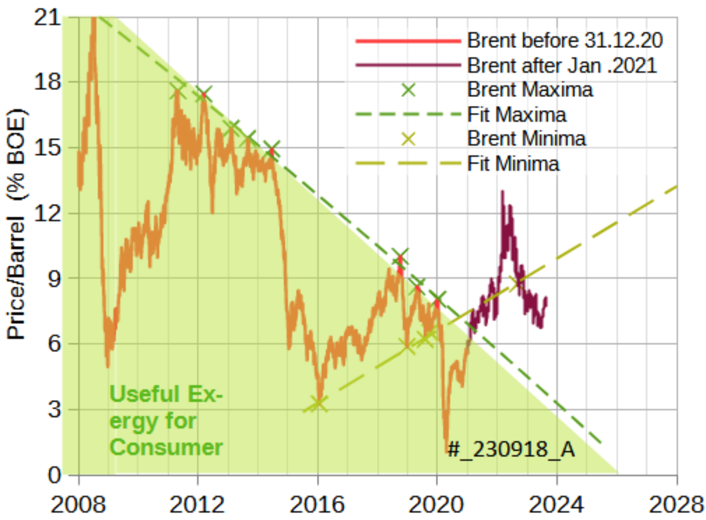


Figure 54: Maximum oil price line converted to Percent of BOE. The green triangle shows the thermodynamical calculated exergy remaining for oil consumers per barrel.

If the thermodynamically necessary exergy (TNE) remaining for consumers for an efficiency of about 67% is entered into the oil price curve, Figure 54 results. It shows a remarkable agreement of the maximum oil prices with the theoretical curve. The dashed green curve of method 2, which connects the maximum values, is almost exactly on the thermodynamically calculated one. In most cases, however, less is paid than the limit value allows.

The very good agreement between calculation from physics and economic data demonstrates the validity of the thermodynamic calculation. It also provides an explanation for the linearity of the price maxima curve (dashed green line in Figure 54): The underlying thermodynamic calculation results in an almost linear course of the conveying energy in the relevant period.

The fall in the price of crude oil from 2008 to 2020 with the extreme price increase since 2021 is an absolute alarm signal! Soon there will be no more crude oil affordable, no matter for which economy in the world!

12.7. Note for Car Lovers

Overall, my results are very bad for car lovers, especially for the drivers of powerful fast cars and SUVs. But there is hope. I do not want to rule out the possibility that light vehicles with an unladen weight of less than 700 kg will be a means of transport in the future, powered by renewable energies such as solar and wind energy. But this is only possible

• If renewable energies are being expanded at full speed. Example: If gas becomes expensive, one should not reduce the price burden on consumers, but gas consumption, and invest the saved money in renewables.

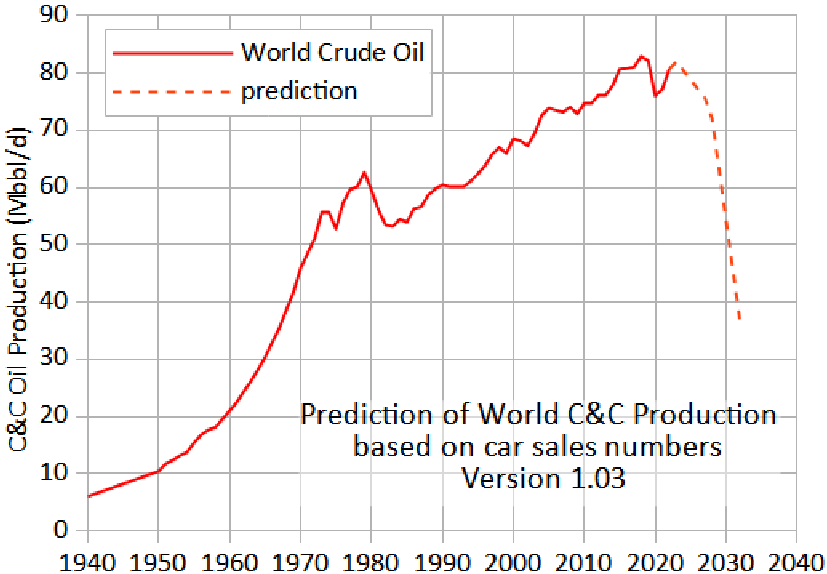
• If the expansion of renewable energies is scalable. On the one hand, there are legitimate doubts as to whether the required raw materials (metals) are available on earth. On the other hand, fossil fuels are needed for expansion, which are limited in any case[8].

• If legislation and traffic rules are adapted to light vehicles. As things stand today, drivers of such vehicles must be very willing to take risks. If a 2-ton car collides with a light vehicle, the 2-tonner has a slight sheet metal damage, the driver of the light vehicle is unlikely to survive.

• If the mentality of drivers changes. This is probably the most difficult point.

12.8. Prediction of Future Oil Production

Based on the past car sales numbers and the five methods, it is possible to make a prediction for the future C&C oil production (Figure 55). It is to be expected, that the crude oil production will remain roughly constant until 2027, because people spent their money on oil products



The last*Figure 55: Prediction for Oil Production* to continue the life style they are used to. They only forgo to buy new cars. After 2027, they will be forced to forgo oil products which get too expensive. Oil production will decrease then very fast.

The amount of remaining petroleum in Figure 55 is slightly below 300 Terabarrel, if summed up. 300 Terabarrel is the same number RystadEnergy [47] has determined as P1 (Producing plus Approved) oil reserves in a report of June 2023.

12.9. Summary of the Calculations

Procedures 1, 2 and 4 are extrapolations of economic data of the past. Method 3 is a link between oil prices and car production. Method 5 is a calculation based on a law of physics.

The five calculation methods result in:

1. End of world motor vehicle production about 2035-2040.
2. Oil affordability problems for consumers beginning 2027.
3. Fast decrease of worldwide sales of motor vehicles after 2027.
4. End of German vehicle production about 2030.
5. Fast decrease of oil production after 2028.

The results are not the same, but in the end the same thing comes out. All five procedures show that vehicle production and oil production will continue to collapse in the coming years. Vehicle production will disappear first. Oil production later, as the world's existing fleet will continue to consume crude oil, even if no new vehicles are added. It is to be expected, that the crude oil production will decrease slowly until 2027, and after that very fast. That means: Oil will be extremely expensive by 2027!

It is, of course, sometimes easier to predict longer-term outcomes than more immediate events. As it applies to economics, this means that *what* will happen is a great deal clearer than *when* it will happen.

And my personal impression: The effects i expect all come true, but later than i estimate. Examples:

- OPEC cuts production since 2022, but too slow to rise prices to 90 USD.
- Oil production remains high and does not fall, because OPEC cuts production less than expected.
- Worldwide car sales go down, but subsidies are able to rise them again.
- In India and China, energy from coal and and cheap oil from Russia have the effect of rising car sales.
- In Germany, energy from renewables stabilizes the economy. Rising energy prices have resulted in a recession, but car sales are still high.

In total, because consumption of energy delivered by coal and renewables increases, oil consumption decreases slower than the pure thermodynamic consideration implies. But not much.

13. Conclusions and Extrapolation

13.1. Thermodynamics and the Peaks

The thermodynamic calculation is based on the following:

- The earth's crust was in temperature equilibrium before oil production.

- Oil production destroys the equilibrium.

- Because of the destruction of the temperature equilibrium, external energy must be supplied.

The thermodynamic calculation shows that the energy required for oil production becomes greater and greater. The effect is irreversible. The world economy's ability to pay for oil approaches zero if there is no net energy left over from oil production. - You don't pay for something you have nothing of.

The price of oil has been falling since 2008 because the energy required for oil production is rising. Soon a limit will be reached because the expenditure is bigger than the energy content of the oil. Then the world economy will stop spending money on oil.

In earlier peak oil discussions, two points used to be considered as possible triggers for the peak:

- Geology will determine the peak, because oil reserves are limited.

- Economics will determine the end, because at some point oil production will become too expensive.

Today it is clear that the second argument is decisive.

The peak of oil production in November 2018 is very likely to be peak oil because of thermodynamically ever-increasing energy expenditures.

Oil products are the main fuel for the world's means of transport. Less and less energy remains as net energy from crude oil production. As net energy falls, so does the ability of consumers to afford consumer goods, since almost all products are produced using energy. This, of course, primarily affects oil-consuming consumer goods, i.e. cars. It is no coincidence that oil production peaked at almost the same time as car production. Oil production and oil-consuming infrastructure are so closely linked that the maxima of both must coincide.

The peak in vehicle production in early 2018 is highly likely to be Peak Car because of the link with oil production.

What will happen: Oil-producing countries and those producing oil-consuming infrastructure are increasingly experiencing economic difficulties. But not all countries suffer equally. Germany has declared an economic recession, starting at the end of 2022. At present, it is impossible to distinguish how much of the recession is due to the Covid-19 pandemic or the war in Ukraine, and how much is due to oil affordabilty. Only when energy from oil is a niche product the recession can end.

13.2. Extrapolation of Oil Price and Oil Production

Figure 56 shows oil price converted to percent of BOE and includes the price minima. The limits for car purchases are also plotted. The fits at minima and maxima crossed in autumn 2020. Since then, the oil price can only be too low for OPEC and too high for the world economy. At most, only one can be happy with the price.

The fine dotted blue line, which starts at the peak of production in November 2018, is a linear fit to the crude oil production curve since November 2018. The fit also suggests a continuous slow drop in production for the near future.

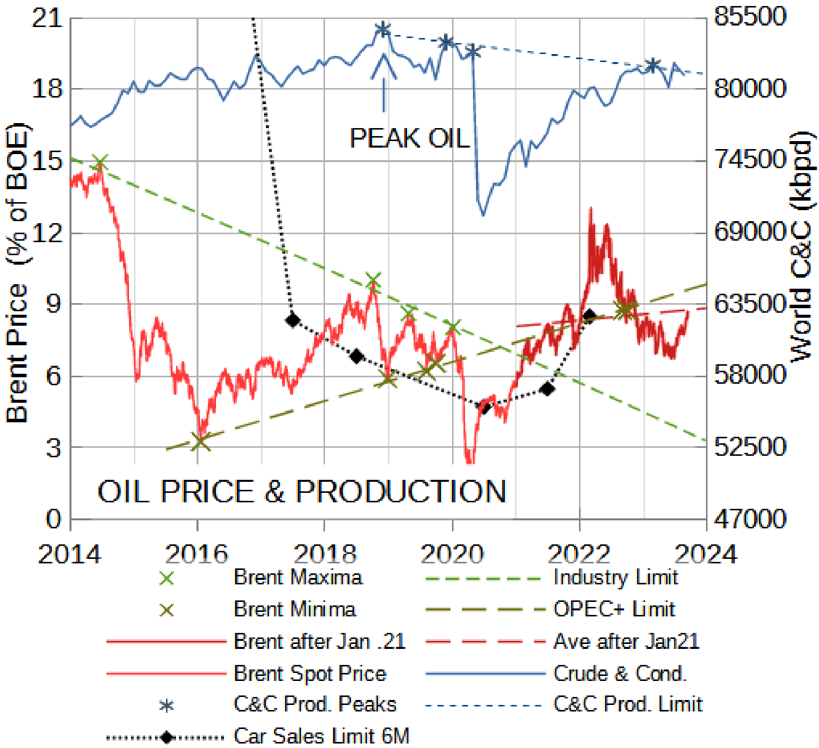


Figure 56: Extrapolation of Oil Price and Oil Production

Today, it seems impossible to project the curves of the diagram in the near future out of the following reasons:

- The war in Ukraine could continue or end with a peace treaty, thus driving the oil price up or down.
- A second war in Taiwan, Moldavia, or other countries could

originate.

- Iran and Saudi Arabia could end their hatred and finish the war in Yemen.
- A worldwide recession or a banking crisis are possible.
- OPEC+ has cut their production in the last months. The oil price is too low for them, and they might impose further cuts. See chapter 5.4.1, axiom 4. *Addition, 05.04.2023: Three days ago, OPEC+ announced further production cuts.*

All these reasons can drive oil price and oil production up and down. The next months will be govered by politics, not by thermodynamics.

In the end, all that remains is to wait and see.

14. Crisis management

Unfortunately, I have not yet found a patent remedy on how to deal with the coming crisis. Let's start with a common procedure used to avoid problems with risky technology: a petroleum loss risk analysis.

14.1. Risk Assessment for the Loss of Oil

For most technical equipment today, manufacturers are obliged to assess possible risks that may occur when using the equipment before placing it on the market. The procedure is as follows:

1. Determination of possible hazards result from previous equipment, similar equipment, empirical values, FMEA analyses or others.

2. Probabilities of occurrence are determined for all possible hazards identified in this way.

3. Possible damages are determined for all possible hazards identified in this way.

4. Then, risk reduction measures are defined to reduce the probabilities and possible damages.

5. If the remaining risks exceed the benefits of the device, it must not be placed on the market.

Applying this procedure to petroleum production results in:

Point 1: That a loss of oil to the world economy may occur can be safely assumed to be a risk due to the finite size of all oil fields. There is a predecessor: The Soviet Union has probably been damaged as a state by a local and temporary peak oil (Reynolds, [47]). Exactly the same applies to Venezuela and other states where political mistakes have also triggered crises.

Point 2: The probability of occurrence is 100 %. A law of physics says that we are already in the loss process and that this will be completed in a few years, probably around 2030.

Point 3: Possible damage:

- In extreme cases, loss of means of transport: many cars, all trucks, most ships and aircraft.

- Decline of associated industries (car manufacturing, tourism, deep sea fishing).

- Collapse of home heating supplies to dependent consumers.

- Loss of agricultural vehicles. Famines due to lack of food.

- Loss of the raw material base of the chemical industry.

- Loss of tax revenues from these industries.

- Destruction of the economic and social base, first in poorer countries like Venezuela, Lebanon, Syria, etc.

The damage potential of these points is huge, we do not include others.

Point 4: Risk mitigstion: The probability of occurrence is 100%, only postponing the time of occurrence seems possible. There are ways to do this:

- Voluntary use of other energy sources.

- Voluntary reduction of oil consumption.

- Reduction of all energy waste.

In Germany, the first two ways have been discussed for some time in the context of climate protection. Figure 5 shows that the switch to alternative energy sources will take much longer than 10 years. Other possible energy sources could be nuclear or fusion power plants. With a time horizon of 10 years, the use of fusion energy is out of the question, since at least 40 years of development time are still needed. Building new nuclear power plants takes about 20 years and is not a solution for many reasons.

Figure 5 shows that in the years 2010-2020 there is no trace of a reduction in oil consumption, and voluntary restrictions will not work in the next 10 years either.

The third way is also tried, e.g. by insulating houses or by increasing taxes in the transport sector. But in 10 years, this won't achieve much either.

It seems that neither the probability of occurrence nor the time of occurrence can be influenced. The measures taken so far are much too slow for a time frame of 10 years.

Point 5: All that remains is damage reduction as a risk mitigation measure. To begin with: squaring the circle will be child's play compared to defining and enforcing harm reduction measures.

In order to define measures, one must first have a well-founded idea of what the world will look like after the oil age. Not wishful thinking, but a reality-based goal. The measures should then be such that the transition to the goal is facilitated.

The idea of the people affected by the damage is exactly the opposite: Everything should remain as it is. Measures should be such that the status quo is maintained.

Example: In Baden-Württemberg, there are currently about 500,000 jobs with car manufacturers and suppliers. After the oil age, there will perhaps still be light vehicles, for the production of which an estimated 100,000 jobs will suffice. Unions, politicians, workers will try at all costs to preserve the 500,000 jobs. Today, people believe that this can be done by switching to electric vehicles. The resource situation is seldom considered. Tesla has build a new car factory in Brandenburg with the help of state subsidies. Politicians and workers' representatives will try to get similar subsidies for Baden-Württemberg.

But it won't work without fossil energy. Electric vehicles are very likely to be a dead end. This means that not only two federal states are on the wrong track. The passenger car of today's design has no future. The money would be much better spent elsewhere on damage reduction.

Real damage reduction would mean:

- Concentration of financial aid on the unaffected means of transport: trams, trains, bicycles and light vehicles.

- Affected industries should be left to the free market and no longer be subsidised.

- Promote research into potential future technologies, e.g. hydrogen.

- Trying out unconventional solutions, e.g. work at home office.

- Expansion of renewable energy.

- Preservation and support of desired areas: Food supply, medical care, etc.

Last point: The main risk of the oil age is that oil will run out without replacement. It cannot be reversed. You have to come to terms with it. The first thing to do is to recognise that it is coming to an end.

14.2. What is to be done?

There is no “one-size-fits-all” solution. You can only adjust your own life to it:

- Make yourself independent of oil.

- Live in such a way that you have short distances to work and shops.

- Use the train/bicycle.

- Use a low-energy house.

You can try to influence political directions:

- No subsidies for the car industry.

- Promote public transport.

- Make infrastructure independent of the car.

- Promote renewable energies.

- Ensure food and medical supplies.

Many of the measures are the same as those needed to combat the climate crisis. However, there is less time available than for combating the climate crisis. The personal measures should be tackled by each individual quickly; the governmental ones will come too late.

Discussions with friends on this topic always resulted in the principle Carpe diem. Seize the day!

14.3. Technologies of the Future

I live near a city that is now almost 1000 years old. The city walls, most of which still exist today, were built before the oil era. This city will still exist in a few hundred years when there is no more oil for a long time. There are some technologies that I expect to play a role in the future. Some of them still need to be tested for feasibility and scalability.

- Hydrogen can be produced by wind and solar energy and, like natural gas, can be stored in underground caverns.

- The existing natural gas pipeline network can be used and converted to distribute the hydrogen.

- External combustion devices based on micro gas turbines (Green Box by Louis Arnoux [48], Brayton process) can be used locally to generate electricity and heat simultaneously. It would be ideal if these could be used with different fuels with little or no modification.

- Microturbines can be used to build a decentralised power supply, as they automatically allow power/heat/electricity coupling.

- Bicycles with or without electric drive are ideal for getting around.

- For car enthusiasts: light vehicles with hydrogen or electric drive can be used for medium distances.

- Railways for long-distance journeys.

Many of today's favourites will become superfluous:

- Two-tonne cars, whether internal combustion or battery-powered.

-High speed motorways.

- Aviation.

- The oversized house heated everywhere. Substitute: jumpers.

- Shopping.

- Disposable products.

Not going to work:

- Replacing the vast amounts of energy from fossil fuels with renewables. There is simply far too much energy used for that.

- Circumventing the problem of disappearing fossil fuels with technologies that consume vast amounts of raw materials.

- Centralised energy supply: Central systems require large infrastructures (raw materials, maintenance). The waste heat from large power plants also accumulates centrally and is difficult to use. In addition, they are too prone to failure. The future belongs to decentralised systems.

- Fusion energy: When I started my university education, many people believed that in 40 years there would be fusion power plants to replace nuclear power plants. In the meantime, I am retired and it is still 40 years until fusion. I no longer give it a chance.

- Growth: Growth always means growth in raw material consumption. The future belongs to sustainable, static systems.

The task will be to get by with energy in the order of estimated 30% of today's consumption.

15. Terms and Definitions

ACEA	European Automobile Manufacturers Association, https://www.acea.be
All Liquids	All liquids added together: Crude and condensate plus NGPL plus Refinery Gain plus biofuels
BEV	Battery Electric Vehicle
Biofuels	Fuels produced by agriculture, which are counted in All Liquids.
Brent	Crude oil grade; traded in Europe and USA, also worldwide
CEICDATA	Database on the internet, contains a lot of economic data, also on car production
C and C	Crude oil and Condensate.
EIA	Energy Information Administration, US-Institute
Entropy	Expression from thermodynamics: quantity of heat divided by temperature; entropy production corresponds to waste heat generation.
EROI	Energy Return on Investment.
Exergy	Exergy is the part of the energy that can be used mechanically, the part that cannot be used is called anergy.
ETP Model	Study published by the Hills Group that was the first to point out thermodynamic limits to oil

	production: ETP= Total Production Energy; the term ETP is used in this report for historical reference, otherwise the term TNE is used.
FED	Federal Reserve Bank, Central Bank of USA
FRED	Federal Reserve Bank of St.Louis database, https://fred.stlouisfed.org
G$	Gigadollar = 1.000.000.000 USD. One Trillion USD.
GDP	Gross Domestic Product (BIP, Bruttoinlandsprodukt) or Global Domestic Product
HG	Hills Group, Group of consultants for the oil industry
ICE	Internal Combustion Engine
IEA	International Energy Agency
Conventional oil	Conventional petroleum reservoirs are accumulations of larger quantities of petroleum in a trap structure in reservoir rock.
LTO	Light Tight Oil – the correct name for shale oil.
MOMR	Monthly Oil Market Report of OPEC
NGPL	Natural Gas Plant Liquids: liquid hydrocarbons that are produced together with gas from gas wells
OICA	Organisation Internationale des Constructeurs d’Automobiles

OPEC, OPEC+	Oil Producing and Exporting Countries, Cartel of oil-producing countries; OPEC+ refers to OPEC plus other countries (mainly Russia).
Peak Car	Maximum of car production
Peak Oil	Maximum crude oil production C&C, the term was coined by Colin Campbell
PHEV	Plug-in-Hybrid electrical Vehicle
PPS	Petroleum Producing System, all industry involved in oil production
Refinery Gain	Increase in volume of liquids due to refining; requires energy input in addition to crude oil to be produced
Shale Oil	Term incorrectly used in common parlance for oil extracted by fracking; the correct term would be LTO (light tight oil), because the term shale oil applies to shale oil, which has hardly been extracted to date, if at all.
Specific energy expenditure	Energy expenditure per kg
TNE	Thermodynamical Necessary Exergy
UK	United Kingdom
Unconventional oil	This includes shale oil, tar sands, deep-sea oil. Biologically produced fuels such as ethanol are not included.
Upstream Producer	Company that extracts the crude oil from the earth and delivers it cleaned and unprocessed

VDA	German Association of the Automotive Industry; publishes monthly data on car production in Germany (Vereinigung der Deutschen Automobilindustrie)
WTI	West Texas Intermediate, Crude oil grade, traded in the USA

15.1. Symbols in Formulas

bbl	Abbreviation for blue barrel (blue is the colour of the cask cover). kbbl is 1000 barrel, Mbbl is one million barrel
E	Energy
E_{TN}	Exergy required by thermodynamics
e_{TN}	Spezific exergy required by thermodynamics (per unit of mass or volume)
kbpd	Kilo Barrel per Day; daily production in 1000 barrel per day
qe, Qe	Electric charge
Q	heat
c	Spezific heat capacity (J/kg/K)
T_R	Average reservoir temperature (K or C)
T_0	Average environment temperature ~11 °C (=284,15 K)

t	Time
dt	Time span (for example month or year)
m	Mass
S	Entropy
W	Work
P	Power, energy per unit of time
Point above a symbol	Derivation with repect to time
Index C	Crude oil
Index W	Water
Index S	Surface (of earth)
Index R	Reservoir
Index 0	Start value 0

15.2. Numerical Values

Units: The world calculates in the international SI system with metre, kilogram, litre, second, etc. There are only a few exceptions. For example, the oil industry uses the imperial system with feet, pounds, gallons, barrels and others. In the imperial system, it must be taken into account that British and US units may differ.

Feet: 0.3048 m

Pound:	0.453 kg
Barrel volume:	158.897 Litres (=42 US-Gallon)
US Gallon:	3.785 Litres

Energy:

There are tons of energy units. The SI system requires joules, but the kilowatt-hour is also an SI unit. Examples are:

1 kWh = 3.6 MJ

1 PJ = 277777777.8 kWh

1 BTU = 1055.06 J (British Thermal Unit)

The BOE is an energy unit, but has some conversion complictions. It comes in two versions:

HHV – higher heat value. Includes the heat to condens water from gas to liquid.

LHV – lower heat value. Without condensation heat. Seems to be more applicable for machines, which release gaseous water.

Because the condensation temperature is not fixed, LHV can vary in definitions. And it depends on the density (API grade) of the oil, resulting in different definitions.

1 BOE = 6.1 GJ HVV, or about 5.5 GJ LHV

The United States EIA proposes to use, that 1 kg crude oil has a thermal heat content of 41.868 MJ.

Typical values of crude oil (can vary significantly depending on the type and API grade):

1 kg crude oil = 11.630 kWh LHV or 41.868 MJ LHV

1 BOE = 1628.2 kWh LHV

1 litre crude oil weighs 0.883 kg, a barrel of oil weighs ~140 kg.

Heat capacity: 1884 J/kg/K

Water:

Mass density: 1.0 kg/litre

Heat capacity: 4190 J/kg/K

Earth:

Temperature gradient: ~ 33 K/1000m

Ambient temperature: ~25° C

Earth temperature 20 m below ground: ~11°C

Earth mass density: $\rho = 1700..2700 \frac{kg}{m^3}$

Heat capacity of earth material: $c = 0.22..0.43 \frac{W \cdot h}{kg \cdot K}$

Typical thermal conductivity of earth material:

$$\lambda = 0.47 \ldots 2.1 \frac{W}{m \cdot K}$$

The letters and prefixes of the SI units mean:

E: Exa = 10^{18}

P: Peta = 10^{15}

T: Tera = 10^{12}

G: Giga = 10^9

M: Mega = 10^6

k: kilo = 10^3

m: milli = 10^{-3}

Bibliography

[1] U.S. Energy Information Administration, “Petroleum & Other Liquids, Spot Prices,” U.S. Energy Information Administration, 2023. [Online]. Available: https://www.eia.gov/dnav/pet/pet_pri_spt_s1_d.htm. [Accessed 23 February 2023].

[2] IMF - international Monetary Fund, “Table 6: Breakeven Oil Prices,” 2019. [Online]. Available: https://data.imf.org/regular.aspx?key=60214246. [Accessed 04 April 2023].

[3] Haynes and Boone, LLP, „Energy Bankruptcy Reports and Surveys,“ 2020. [Online]. Available: https://www.haynesboone.com/publications/energy-bankruptcy-monitors-and-surveys.

[4] Michaux, Simon, “Oil from a Critical Raw Material Perspective-Report 70/2019,” GTK Geological Survey of Finland, 2019. [Online]. Available: http://tupa.gtk.fi/raportti/arkisto/70_2019.pdf. [Accessed 22 08 2021].

[5] Bundesministerium Wirtschaft, “energiedaten-gesamt-xls,” 2020. [Online]. Available: https://www.bmwi.de/Redaktion/DE/Binaer/. [Accessed 2021].

[6] LEF, (Pseudonym), “Das Lefsche Energie Theorem,” Schwarze Tafel der Philosophie, 2008. [Online]. Available: http://lt.accb.de/das-lefsche-theorem/energie-vorrede/. [Accessed 21 03 2023].

[7] D. Coyne, “Peak Oil Barrel,” 11 03 2023. [Online]. Available: https://peakoilbarrel.com/. [Accessed 11 03 2023].

[8] Rystad Energy UCube, “Total recoverable oil worldwide is now 9% lower than last year, threatening global energy security,” 01 07 2021. [Online]. Available: https://energynorthern.com/2022/07/01/total-recoverable-oil-worldwide-is-now-9-lower-than-last-year-threatening-global-energy-security/. [Accessed 11 03 2023].

[9] P. Hacquard, M. Simoën, E. Hache, “Is the oil industry able to support a world that consumes 105 m barrels,” Oil & Gas Science and Technology, https://doi.org/10.2516/ogst/2019061, 2019.

[10] International Energy Agency, “World Energy Investment 2021,” International Energy Agency, June 2021. [Online]. Available: https://www.iea.org/reports/world-energy-investment-2021. [Accessed 11 03 2023].

[11] J. Laherrere, “Extrapolation of oil past production to forecast future production,” ASPO France, 2018. [Online]. Available: https://aspofrance.org/2018/10/03/updated-extrapolation-of-oil-past-production-to-forecast-future-production/. [Accessed 12 09 2021].

[12] L. Renqing, “Development of enhanced oil recovery in Daqing,” *Journal of Petroleum and Gas Engineering Vol. 4(2),,* pp. 46-50, 01 02 2013.

[13] Wikipedia, “Samotlor Field,” Wikipedia, 19 03 2023. [Online]. Available: https://en.wikipedia.org/wiki/Samotlor_Field. [Accessed 19 03 2023].

[14] Seeking Alpha, “Saudi Arabian Oil Is Running Out And That Will Affect Long-Term Oil Markets,” Seeking Alpha, 14 08 2017. [Online]. Available: https://seekingalpha.com/article/4098775-saudi-arabian-oil-is-running-out-and-will-affect-long-term-oil-markets. [Accessed 19 03 2023].

[15] G. David J, Debt - The First 5000 Years, New York 2011: Melville House, 2011.

[16] Worldbank, “Inflation, consumer prices (annual %),” [Online]. Available: https://data.worldbank.org/indicator/. [Accessed 2021].

[17] Michael J. Moran, Howard N. Shapiro, Fundamentals of Engineering Thermodynamics, John Wiley & Sons, Inc..

[18] C. Hall, Energy Return on Investment, Springer International Publishing AG, 2017.

[19] HillsGroup, Depletion, Report# HC3-433, 2015.

[20] B. Warm, Die kurze Endphase des Ölzeitalters: Erdöl, Autoproduktion und Thermodynamik, Hamburg, 2021.

[21] EIA, “EIA - Refinery & Blender Net Production,” Energy Information Agency, 12 03 2023. [Online]. Available: https://www.eia.gov/dnav/pet/pet_pnp_refp_dc_nus_mbbl_m.htm. [Accessed 12 03 2023].

[22] A.R. Brandt, Y.Sun, S. Bharadwaj, D. Livingston, E.Tan, ,D.Gordon, „Energy Return on Investment (EROI) for Forty Global Oilfields“.*PLoS ONE 10(12): e0144141. .*

[23] Charles A.S. Hall, , Jessica G. Lambert, Stephen B. Balogh, „EROI of different fuels and the implications for society," *Journal of Energy Policy,* 2013.

[24] G. Tverberg, "What's Ahead? Lower Oil Prices, Despite Higher Extraction Costs," 2013. [Online]. Available: https://ourfiniteworld.com/2013/11/15//whats-ahead-lower-oil-prices-despite-higher-extraction-cost/.

[25] S.Korpela, „On the Thermodynamic Model of Oil Extraction by the Hill's Group," 2017. [Online]. Available: http://peakoilbarrel.com/on-the-thermodynamic-model-of-oil-extraction-by-the-hills-group/.

[26] J. Laherrere, "Comments on the data of the Hill`'s Group ETP model," ASPO FRANCE, 2017. [Online]. Available: https://aspofrance.files.wordpress.com/2017/03/jl_2017_com hill.pdf.

[27] R. Feynman, "Feynman on the Scientific Method," [Online]. Available: https://sites.google.com/site/barrykort/feynman-on-the-scientific-method. [Accessed 05 04 2023].

[28] J. Hughes, Drill, Baby, Drill, CreateSpace Independent Publishing Platform, 2013.

[29] S. St.Angelo, "BIG TROUBLE BREWING AT THE BAKKEN," SRSRocco Report, 2018. [Online]. Available: https://srsroccoreport.com/big-trouble-brewing-at-the-bakken-rapid-rise-in-water-production-signals-red-flag-warning/. [Accessed 26 08 2021].

[30] WIKIPEDIA, “WIKIPEDIA OPEC,” WIKIPEDIA, [Online]. Available: https://en.wikipedia.org/wiki/OPEC. [Accessed 23 February 2023].

[31] OPEC, “Monthly Oil Market Report,” OPEC, [Online]. Available: https://www.opec.org/opec_web/en/publications/338.htm. [Accessed 23 February 2023].

[32] WIKIPEDIA, “WIKIPEDIA SAUDI ARABIA,” WIKIPEDIA, [Online]. Available: https://en.wikipedia.org/wiki/Saudi_Arabia. [Accessed 23 February 2023].

[33] FRED, “FRED Motor Vehicles,” Federal Reserve Bank of St.Louis, [Online]. Available: https://fred.stlouisfed.org/categories/32993. [Accessed 23 February 2023].

[34] VDA, “Verband der Automobilindustrie,” Verband der Automobilindustrie, [Online]. Available: https://www.vda.de/de/presse/Pressemeldungen. [Accessed 23 February 2023].

[35] CEICDATA, “CEICDATA - Motor Vehicle Sales,” Motor Vehicles Sales, [Online]. Available: https://www.ceicdata.com/en/indicator/india/motor-vehicles-sales. [Accessed 23 February 2023].

[36] CAAM, “CAAM Sales of Automobiles,” China Association of Car Manufacturers, [Online]. Available: http://en.caam.org.cn/Index/show/catid/52/id/1632.html. [Accessed 23 February 2023].

[37] Z. Shahan, “Global Plugin Vehicle Sales,” Cleantechnica, [Online]. Available: https://cleantechnica.com/2021/02/08/global-plugin-vehicle-sales-up-43-in-2020-european-sales-up-137/. [Accessed 23 February 2023].

[38] OICA, “Global Sales Statistics,” International Organization of Motor Vehicle Manufacturers (OICA), [Online]. Available: https://www.oica.net/category/sales-statistics/. [Accessed 23 February 2023].

[39] T. Morgan, “Surplus Energy Economics,” Tim Morgan, 24 02 2012. [Online]. Available: https://surplusenergyeconomics.wordpress.com/2021/02/24/191-the-map-unrolled/. [Accessed 15 03 2023].

[40] B. Fix, “Economics from the top down,” Blair Fix, 03 12 2020. [Online]. Available: https://economicsfromthetopdown.com/2020/12/03/as-we-exhaust-our-oil-it-will-get-cheaper-but-less-affordable/. [Accessed 15 03 2023].

[41] R. Kümmel, D. Lindenberger, W. Eichhorn, “Energie, Wirtschaftswachstum und technischer Fortschritt,” *Phys. B1.53 (1997) Nr. 9, p. 869-875,* pp. 869-875, 1997.

[42] M. Vinkhuyzen, “The Osborne Effect On The Auto Industry,” 25 February 2019. [Online]. Available: https://cleantechnica.com/2019/02/25/the-osborne-effect-on-the-auto-industry/. [Accessed 22 February 2023].

[43] J. Tainter, The Collapse of Complex Societies, Cambridge University Press, 1990.

[44] P. Turchin, S.A. Nefedov, Secular Cycles, Princeton University Press, 2009, p. 339.

[45] The Oil Drum, "The Oil Drum - Discussions about Enegy and Our Future," 31 10 2013. [Online]. Available: http://theoildrum.com/special/archives. [Accessed 11 03 2023].

[46] T. Murphy, "Do the Math - Programmed to Ignore?," 14 04 2015. [Online]. Available: https://dothemath.ucsd.edu/2015/04/programmed-to-ignore/. [Accessed 11 03 2023].

[47] RystadEnergy, „Recoverable oil reserves top 1,600 billion barrels," RystadEnergy, 29 June 2023. [Online]. Available: https://www.rystadenergy.com/news/recoverable-oil-reserves-billion-barrels-warming-planet. [Zugriff am 2023 September 2023].

[48] D.B.Reynolds, Cold War Energy: The Rise and Fall of the Soviet Union, Alaska Chena, 2016.

[49] L. Arnoux, "nGENI GREEN BOX NEW TECHNOLOGY: Solution To The Thermodynamic Oil Collapse," Steve St.Angelo(SRSROCCO), 2020. [Online]. Available: https://srsroccoreport.com/ngeni-green-box-new-technology-class-solution-to-the-thermodynamic-oil-collapse/. [Accessed 22 09 2021].

[50] US Bureau of Labor Statistics, [Online]. Available: https://www.bls.gov/cpi. [Accessed 15 06 2021].

[51] SMMT, “SMMT Vehicle Data Car Registrations,” Society of Motor Manufacturers and Traders (SMMT), UK, [Online]. Available: https://www.smmt.co.uk/vehicle-data/car-registrations/. [Accessed 23 February 2023].

[52] ACEA, “ACEA Press Releases,” European Automobile Manufacturers’ Association, [Online]. Available: https://www.acea.auto/nav/?content=press-releases. [Accessed 23 February 2023].

[53] FADA, “FADA Press Releases,” Federation of Automobile Dealers Associations India, [Online]. Available: https://www.fada.in/. [Accessed 23 January 2023].

[54] U.S. Energy Information Administration, “International Data Petroleum and Other Liquids,” U.S. Energy Information Administration, 2023. [Online]. Available: https://www.eia.gov/international/data/world/petroleum-and-other-liquids/monthly-petroleum-and-other-liquids-production. [Accessed 23 February 2023].

[55] Argonne National Laboratory, “Monthly sales data for electric vehicles,” Argonne National Laboratory, 20 September 2023. [Online]. Available: https://www.anl.gov/esia/light-duty-electric-drive-vehicles-monthly-sales-updates. [Accessed 20 September 2023].

Front and back pictures: Oil pumps in the German Petroleum-Museum Wietze, Germany

This book explains why Peak Oil and Peak Car now are things of the past. The justification is based on a law of physics that has so far received little attention for oil production: the second law of thermodynamics. Diagrams with economic data and explanations of oil production serve as evidence. It is to be expected that oil production and vehicle construction will decline significantly in a few years and will hardly exist in 2034.