New Calculation on the Limits to Growth

Berndt Warm, January 19, 2026

Translated from German with DeepL.com (free version)

Foreword

The book ‘Limits to Growth’ [14] was published 54 years ago. In this book, a group of scientists analysed the global interactions between

• consumption of non-renewable resources

• population growth

• industrial production

• food availability

• environmental pollution

The software tool used to model the system dynamics took into account interactions between systems with non-linear behaviour, delays, feedback loops and exponential growth. The software model [15] was named ‘World3’. The software model predicted that society would collapse sooner or later, as the world's resources are finite and are being slowly but surely depleted. The aim of the authors of the book was not to determine an exact date for the collapse, but to draw public attention to the issue. At the time, the database was not sufficiently researched to make an accurate prediction.

At the time, the book was the subject of heated debate, with supporters and opponents of the theories it presented. Even though the discussion has now completely disappeared from the public eye, people continue to engage with the topic. For example, the World3 program can be used online [18].

About two years ago, a group of scientists led by Arjuna Nebel [1] published a report entitled ‘Recalibration23’ with graphics, which was the result of an update to the ‘World3’ model. They used the model as a tool to predict a date for the collapse.

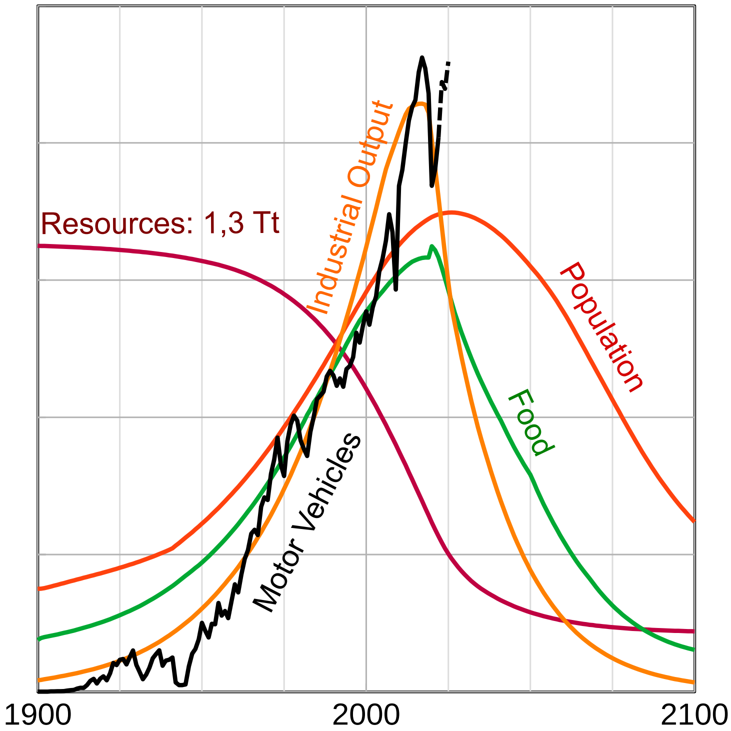

Figure 1: This illustration corresponds to Figure 3 from the report "Recalibration23" [1], supplemented by the author with production data for motor vehicles. The black curve contains the production data, with the solid part of the curve known in 2023 and the dashed part being current. The dashed part does not match the "industrial output" curve.

Looking at Figure 1, which is based on the Nebel Group's report, there should have been a significant slump in the global economy in 2025 or earlier. However, this slump did not occur. The global economy is in trouble, but there has been no slump in car sales, for example. The German economy has many problems, but life in Germany has so far been little affected by them.

I used "PyWorld3-3" to try to find out why this slump did not occur. And I discovered one thing: the more you search for an explanation, the deeper you have to delve into the program, and the more complex the topic becomes. And the clearer it becomes that local differences around the world mean that PyWorld3-3 cannot provide accurate data, but only rough guidelines.

1. The World3 program

The authors Nebel/Kling used a new version of the World3 program. This version, PyWorld3-3, is written in Python. The program can be found on the website [2]:

https://github.com/TimSchell98/PyWorld3-03

I used a version of the Python language called Anaconda [3]: https://www.anaconda.com/download

I used this to perform my own calculations.

The Nebel group's report contains a list of the input variables they adjusted, using current economic data as a basis. The Nebel group found the optimal adjustment by automatically varying the data. I am familiar with the optimisation process from physics and consider it a good way to determine the variables.

I entered the optimal variables mentioned in the Nebel group's report [1] into the PyWorld3-3 program and obtained the same graphs as the Nebel group, with industrial output collapsing in 2025 or earlier (Figure 1).

2. The causes of the deviation

There are things I miss in PyWorld3-3.

a) It does not include renewable energies. Although renewable energy plants can be considered part of industrial goods, this is inaccurate.

b) And it does not provide for the service life of structures. Only the service life of industrial goods is part of the program and is approximately 15.3 years (value of the Nebel group). Structures such as bridges, railway facilities, houses, and schools have a service life of around 50 years, were built during a phase of rising energy consumption, and their slow decay requires increasing amounts of capital and energy for repairs.

First, i checked the production figures for passenger cars and found an error in my data. I had previously used values that were too high for the years 2023-2025 and corrected these figures downwards.

Potential program errors in PyWorld3-3: Errors may exist, but if the program's outputs up to and including approximately 2019 correspond to reality, why should they no longer be correct in 2025?

My conclusion is that Nebel/Kling used questionable economic data to determine the input variables. As a reminder, in 2020 there was an economic slump due to COVID-19, from which the global economy did not largely recover until after 2023. If the data for the last few years (2020-2022) is distorted by COVID-19, the result may also be distorted.

3. Optimizing the input data

The task is therefore to optimise the input variables with new economic data. As a “lone warrior,” I cannot optimise all the data, only selected data. And I have decided to optimise the industrial output with respect to car sales numbers. And I have optimised only one of the variables, namely the number of initial energy resources. These are referred to in the program as non-renewable raw materials.

Consequently, I optimised the number of energy resources so that the “industrial output” calculated by PyWorld3-3 best matches the production of all motor vehicles. The data used by the PyWorld3-3 program all have a physical background; in the case of renewable raw materials, these are tons of raw materials.

Real motor vehicle production peaked in 2017 and will peak again in 2025. The peak in 2025 is slightly higher than it would be without global subsidies for electric vehicles.

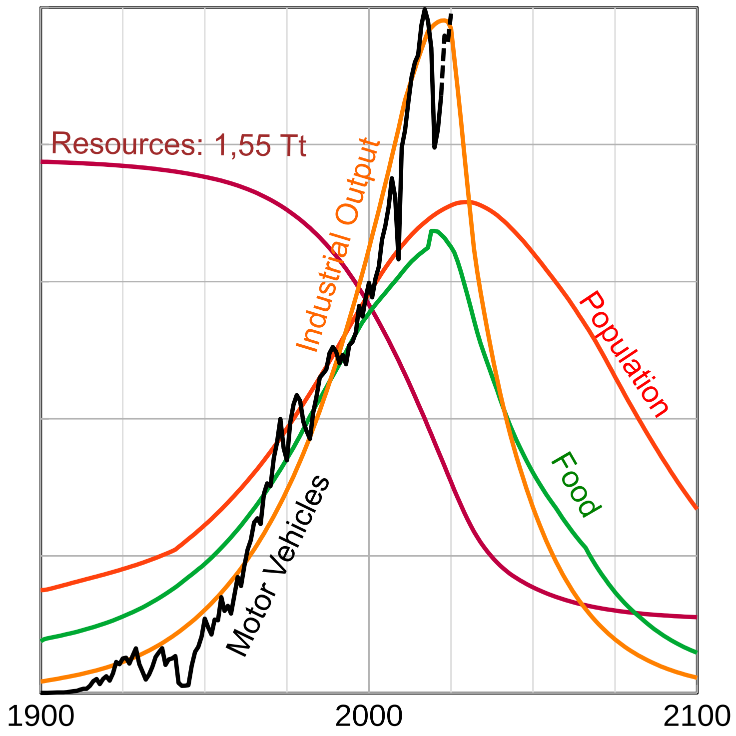

Figure 2: Recalculation using 1.55 tons of energy raw materials. The black curve represents historical car production. Source of data on automobiles: [13] and the author's own statistics for 2025.

This results in an optimal value for energy resources of 1.55 teratons instead of the 1.3 teratons calculated by Nebel/Kling (Figure 3).

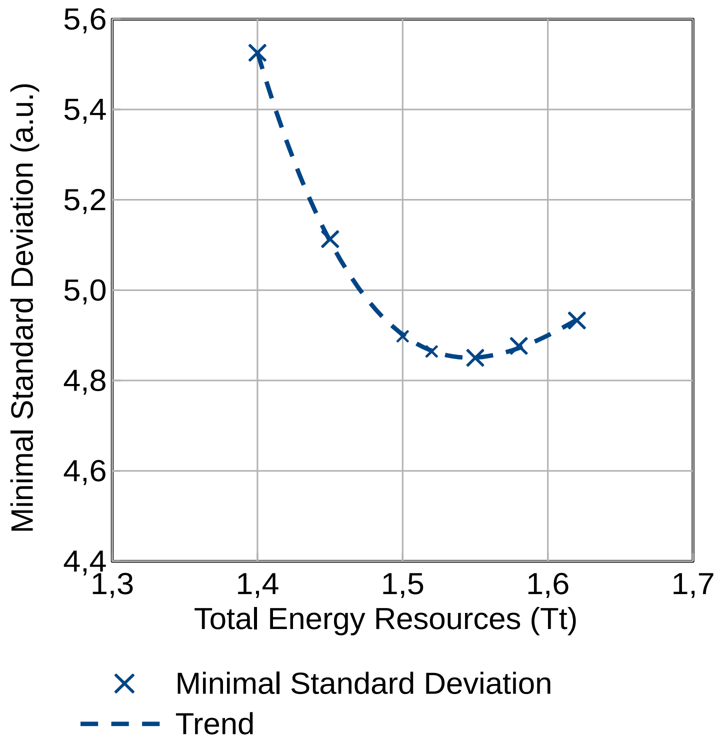

Figure 3: Minimum standard deviation between motor vehicle production and industrial production when the amount of energy resources varies. The minimum is 1.55 tonnes of initial energy resources.

The value of 1.55 teratons is initially an abstract value. How can we check whether 1.55 teratons is a realistic figure? We can do this using the reports from the Energy Institute [6]. These contain data on the consumption of fossil fuels such as coal, oil, and natural gas since 1965. (Figure 13) It is easy to add up this data and determine the consumption in teratons since 1965. The conversion factors used were 7.3 bbl = 1 t for oil and 1000 m^3 = 1.3 t for natural gas. For the period before 1965, I assume that the cumulative total production up to that point is 20 times the value for 1965.

Hubbert linearisation [4] of production data is a common way to make projections for the total production of a resource using current data. The total production of a raw material to date is plotted on the x-axis. The quotient of current production and total production to date is plotted on the y-axis. Normally, this results in a straight line. Its intersection with the x-axis gives the total amount of the raw material.

A Hubbert linearisation of the total energy resources consumed worldwide is shown as a red line in Figure 4. According to this projection, the total amount of energy resources is 2.05 teratons.

The raw material quantity of 2.05 teratons is, so to speak, the maximum extractable quantity possible according to current knowledge, assuming that only geology and nothing else limits production. However, the energy required for extraction is the limiting factor, so the 2.05 teratons are a theoretical maximum value that is guaranteed not to be reached.

Which value between 1.55 teratons and 2.05 teratons is ultimately valid?

If we subtract China's consumption data from the global consumption data, we get a steeper trend line (green line) for the world without China. The explanation for this is that China entered a growth phase relatively late, around 1990. China's Hubbert linearisation (Figure 5) yields a value of 250 gigatons, while the world and China together total 1900 gigatons.

There are other developments that have only recently led to an increase in production volumes: e.g., shale oil in the US (see below, Permian oil field) and Argentina, and the Johan Sverdrup oil field. Therefore, total production is lower; 1,800 gigatons can be considered the maximum possible value.

For me, the values from the Hubbert extrapolations are the most likely quantities of fossil raw materials:

- World without China: 1550 Gt
- China: 250 Gt
- World total: 1800 Gt

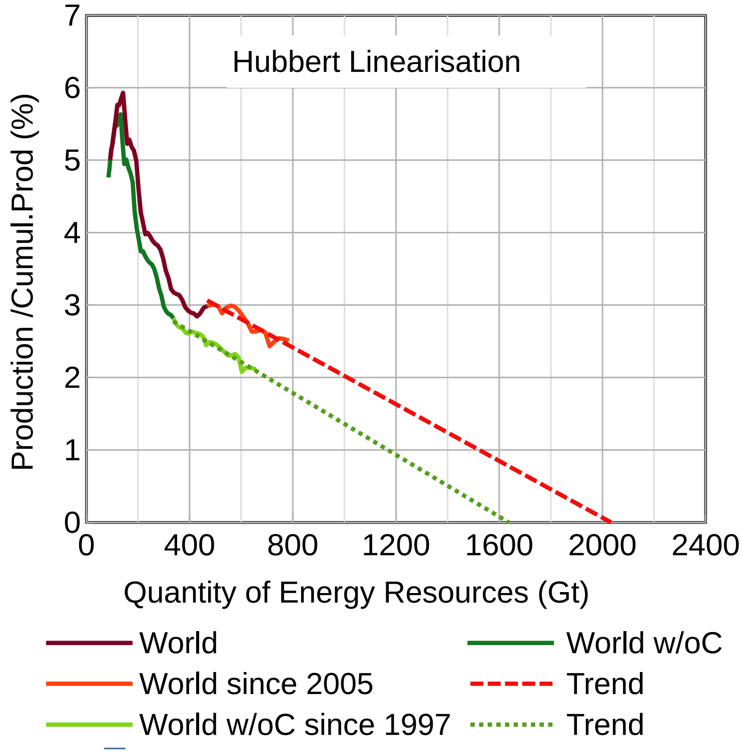

Figure 4: Hubbert linearisation (HL) of the amount of energy resources consumed, based on data from the Energy Institute and OWID. World w/oC is the "World without China".

Equating the data on energy resources from the Energy Institute with the raw material data from PyWorld3-3 poses a problem: Is the data really the same? How big is the difference? Uncertainty remains.

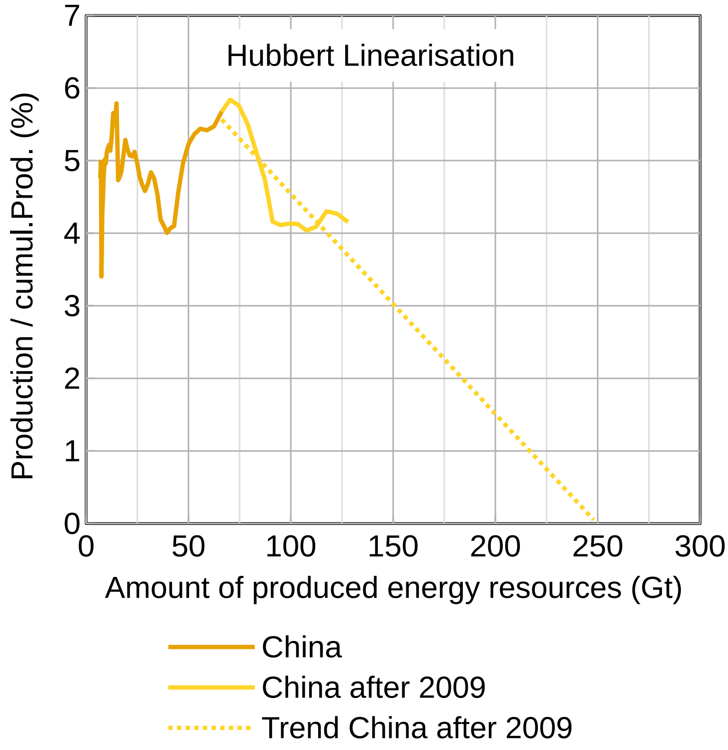

Figure 5: Hubbert linearisation for China, for the sum of the fossil energy resources coal, oil and natural gas.

4. Comparison of further output values from PyWorld3-3 with real data

PyWorld3-3 provides further output data:

Population development: Real population growth [7] varies greatly from place to place. While China is currently experiencing zero growth, Africa's population has been growing exponentially for decades. Regardless of the resource value entered, the PyWorld3-3 simulations show a slowdown in population growth since 2010. This slowdown is also evident in the real data, but only after 2017.

Data on real food production [7] is only available until 2023. OWID has data for “cereals” and “meat” until 2023 and for “fish/seafood” until 2022. There could be a slight decline in “fish/seafood” after 2018, but nothing is apparent for the other two. PyWorld3-3 would indicate a slowdown in food production since around 2015, parallel to population growth.

Inflation-adjusted food prices show no price increase for cereals, but prices for meat and fish/seafood are rising significantly despite inflation adjustment. However, prices are not part of PyWorld3-3.

In contrast to industrial production, real population growth has only declined slightly so far. This raises the suspicion that in the real world, a larger proportion of fossil fuels is currently being used for food production than the PyWorld3-3 program assumes. The available fossil fuels would therefore be slightly higher than 1550 Gt.

5. Local differences

Europe and Germany are experiencing only weak economic growth, China strong growth, and the US somewhere in between. The locally available quantities of fossil raw materials vary considerably. In his book [16], Randers has made separate observations for several regions of the world. Europe and Germany are the first to be affected by the decline in raw materials.

Figure 6 shows Germany's production index. It peaked in 2017/18 and has been falling slowly since then.

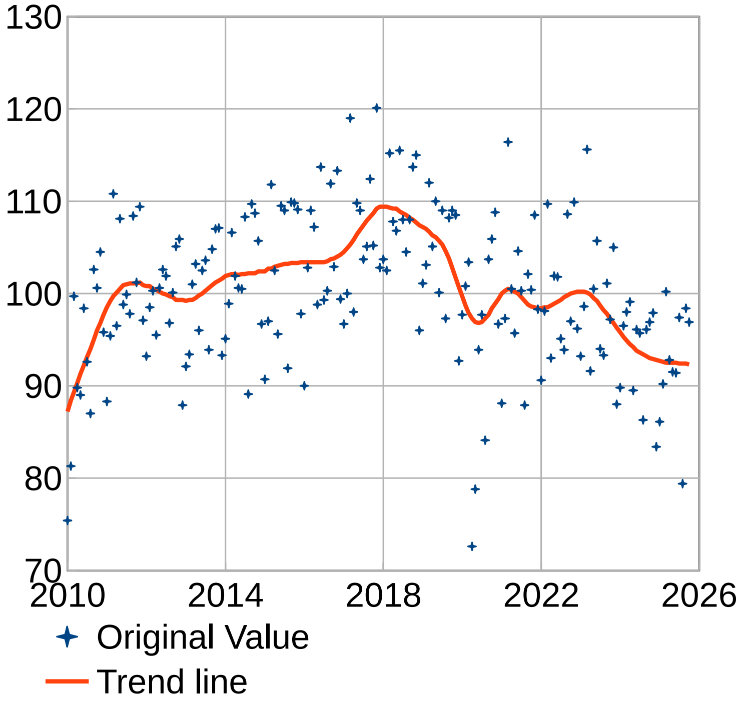

Figure 6: German industrial production index. Normalised to 100 in 2021

Source [8]: Destatis, https://www.destatis.de/DE/Themen/Wirtschaft/Konjunkturindikatoren/Produktion/kpi117.html#355032

6. Checking the quantities of raw materials consumed

Could it really be that right now (in 2025 or 2026) is the peak of fossil fuel production? This is likely to be the case for oil production.

There are two peak values for "crude oil and condensate production" that are almost equal: November 2018 and August 2025 (see Figure 7).

Figure 8 is taken from the website "Peakoilbarrel" (https://peakoilbarrel.com/short-term-energy-outlook-november-2025/) [10]:

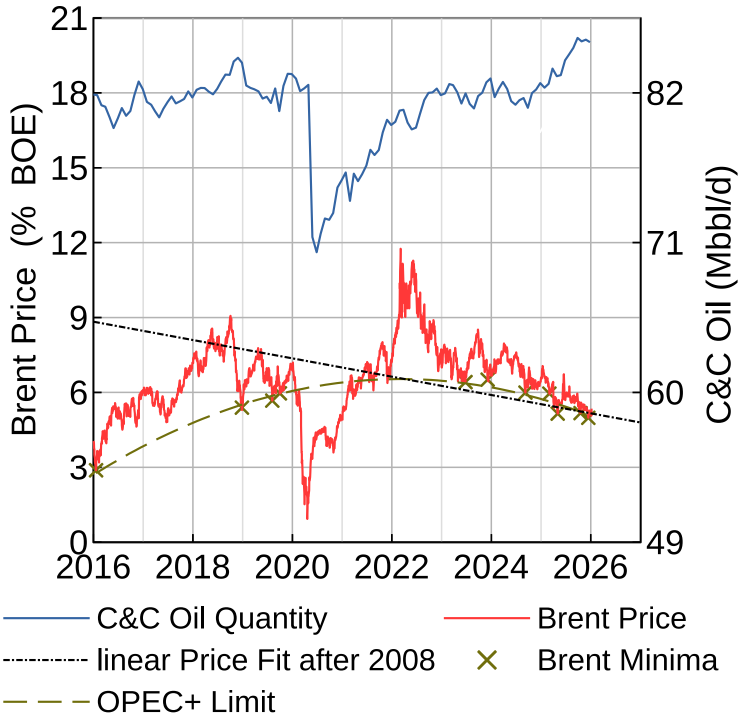

Figure 7: Global crude oil production and oil price with special inflation adjustment based on the energy content of a barrel of oil. The dotted black line is a linear fit to the oil price since 2008.

Notes on Figure 7: The figure shows the amount of crude oil and condensate extracted from the ground, not “all liquids.” The oil price in %BOE is calculated from the Brent price. It is approximately the percentage of energy that the oil producer receives. The dashed black line is a linear fit to the oil price since 2008. The author believes that the oil price will continue to follow this curve in the future. He believes that this curve is just below an upper limit below which oil consumers can earn money from the use of crude oil. The dashed green curve is determined by the dark green crosses. I place a cross at the minimum oil prices. The minimums are themselves a consequence of OPEC's pricing policy. If OPEC considers the oil price to be too low, it reduces production so that the price rises again. The two dashed curves have been almost identical since the beginning of 2021.

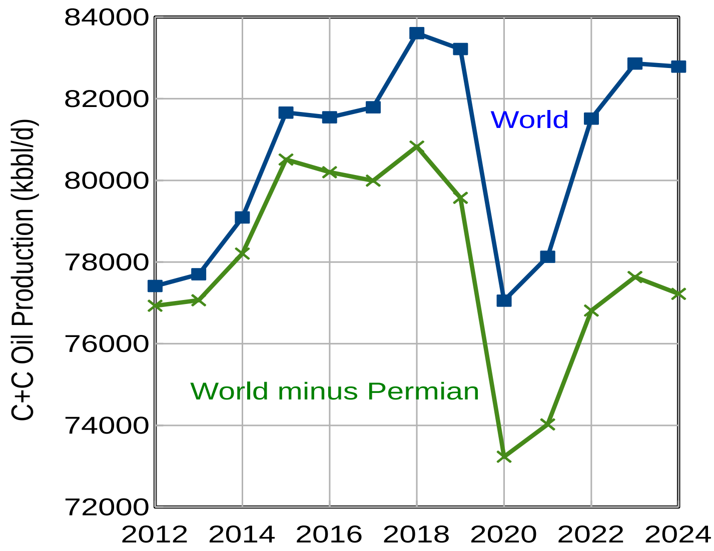

Figure 8: Production curve for the world with and without the Permian oil field [10]

Global oil production is being kept high by virtually a single oil field, the Permian Basin. In the Permian Basin, oil is extracted using fracking. Oil production in this field looks like figure 9

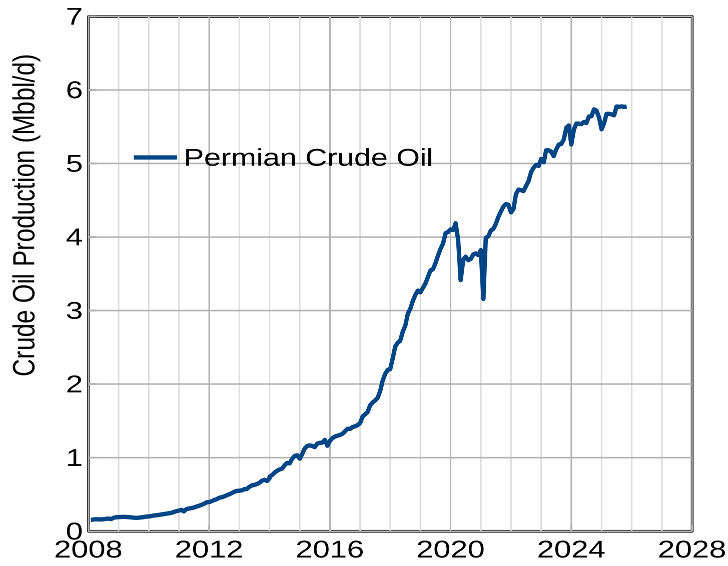

Figure 9: Oil production in the Permian Basin. Data source [11]

This is as close as it gets to a normal distribution curve, and according to Hubbert linearisation, it should start to decline from now on. In January 2026, production in the Permian Basin will slump slightly due to weather conditions, as it does every year. Whether it will actually decline will only become clear in May/June 2026.

This means that it is highly likely that global oil production has now peaked, or may even have already peaked in 2018.

I find coal production in China particularly interesting. China's coal consumption in 2024 accounted for 51.7% of global consumption. Production there must also have peaked around now. Using my own calculations, I have arrived at Figure 10 as the probable production curve for China. Official reports on China [5] assume that Chinese coal production has peaked now or will do so in the near future.

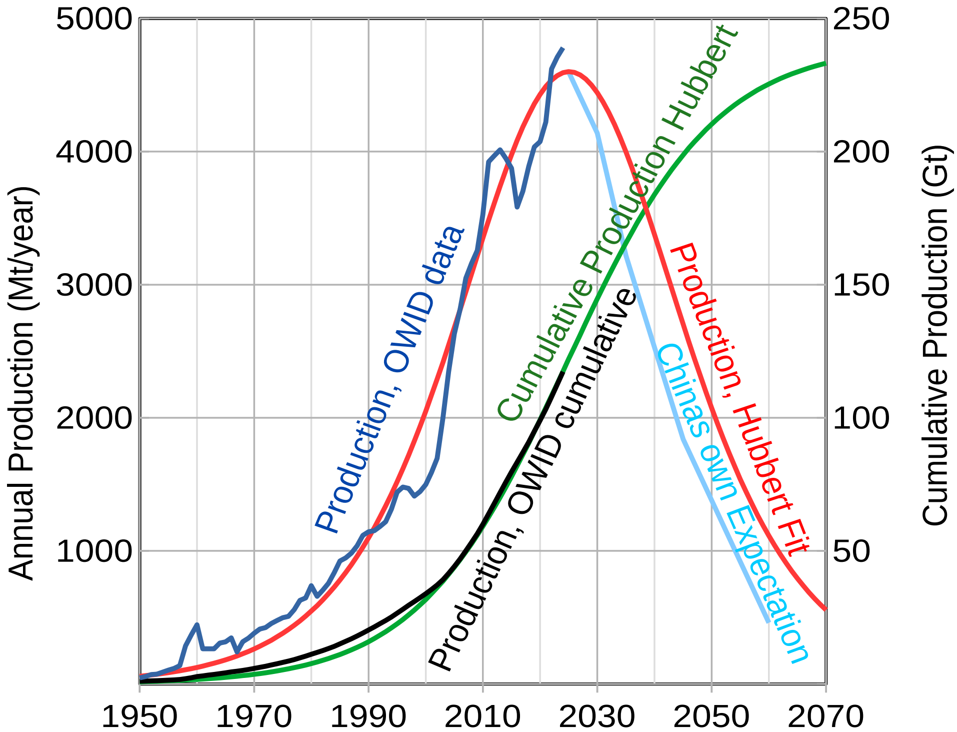

Figure 10 :Approximate expected annual production and cumulative coal production in China, assuming that the data for China in [6] and [9] are correct. The curve 'China's own expectation' has been created using data from [5].

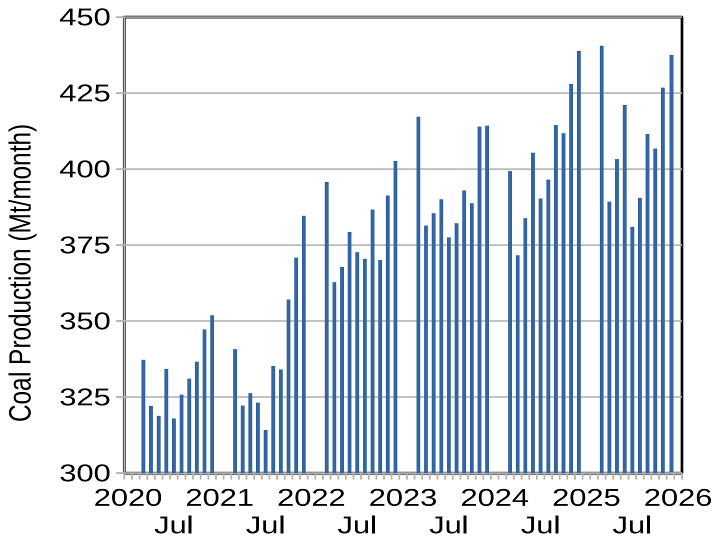

Figure 11: Monthly coal production in China in recent years, from March to the end of each year. Source [12]: https://tradingeconomics.com/china/coal-production. China's coal production in 2025 has increased by approximately 1.7% compared to 2024.

At least in the case of oil and coal production, it looks as if peak production will be reached around 2026. It does not appear that ‘business as usual’ will continue for much longer.

7. Different raw material values

Figure 12 shows a comparison of vehicle production with three initial values for raw materials. Unfortunately, the comparison does not allow us to reliably determine which raw material value is actually the best. Vehicle production could correspond to any of the three values, depending on how vehicle production develops in 2026–2028.

In addition, local differences around the world may mean that some countries are on the downward slope of the 'industrial output' curve, while others are still below the maximum.

But one thing is clear: the world is in a critical phase. It is close to the 'limit of growth'.

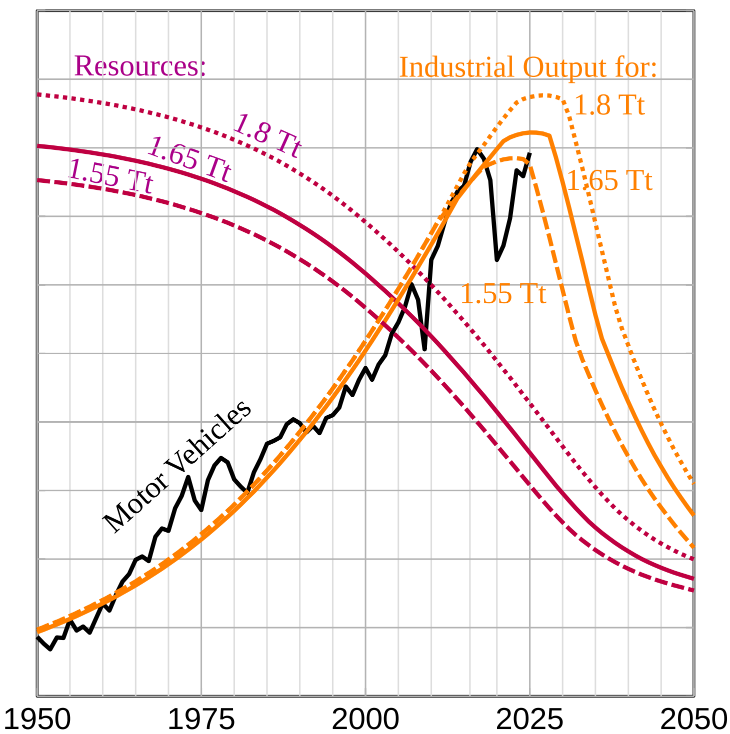

Figure 12: Comparison of motor vehicle production (all motor vehicles) with three values for resources and industrial production.

And as a German who is also familiar with Figure 6, I take these diagrams very seriously. In addition to the war in Ukraine, the German press is discussing the following main problems: lack of economic growth, unreliability of the national railway system, high energy costs, and the poor state of infrastructure. These are all issues that arise from the 'limits of growth'.

Will the decline in industrial production happen as quickly as Figure 12 shows? Jorgen Randers [16] expects the use of renewable energies to result in significantly flatter curves than those shown in PyWorld3-3. However, since the deterioration of infrastructure is not reflected in World3-3, I believe that the decline could also be steep. In short, I cannot judge.

My conclusion: the more you can live your life with less energy, the more energy comes from renewables, the better.

8. Comparison with earlier calculations using the World3 programme

1972: The original report ‘Limits to Growth’ [14] used the values of the US Geological Survey valid at the time as raw material data and thus carried out the calculations for BAU (business as usual), arriving at a maximum of industrial production in 2010. Using double the raw material data (BAU2), the maximum was reached in 2025.

1975: The programme ‘World3’ was described in detail in the book ‘DYNAMICS OF GROWTH IN A FINITE WORLD’ [15]. It was assumed that the total available energy resources were 250 times the consumption in 1970. The ‘Reference run, Fig. 7-8’ calculates a maximum industrial production in approximately 2018 and, for double the amount of resources (Fig. 7-10), a maximum in approximately 2035.

2012: Jorgen Randers published the book ‘2052: The New Report to the Club of Rome’ [16], in which he uses a wealth of new economic data and renewable energies as a basis for making a projection for economic development up to 2052. He sees the transition to renewable energies as the cause of lower consumption of fossil raw materials, not an impending shortage. He expects industrial production to peak (Fig. 4-4) around 2045. According to Fig. 5-3 (CO2 maximum), he expects consumption of fossil fuels to peak in 2030. He predicts that many curves will flatten out slowly rather than falling steeply after peaking.

2020: Gaya Herrington [17] examines the validity of the World3 model for the present day and finds it to be accurate. For existing resources, she uses data from BP's ‘Statistical Review of World Energy (2019)’. Essentially, she confirms the calculations from [15] with maximum industrial production for BAU in approximately 2020 and maximum for double resources for BAU2 in approximately 2035. In the author's opinion, considering double the amount of raw materials (BAU2) is now superfluous, as the data on raw material reserves has improved significantly compared to 1972.

2023: The group led by A. Nebel [1] was the first to attempt to link current economic production with the World3-3 model in such a way that the date for the decline of industry could be determined precisely. Due to the distortion of economic data by Covid-19, they set the raw material data too low (1.3 Tt) and the date too early (2023).

9. Do we still need fossil fuels at all, given that renewable energies exist?

The Energy Institute report contains data on the consumption of renewable energies compared to fossil fuels. According to Figure 13, renewables account for around 17% of the total share. And, to be honest, so far very little fossil fuel has been replaced by renewables; renewables have been added ‘on top’ of fossil fuels.

Renewable energies are more a product of the use of fossil fuels than a replacement for them. It is far from clear whether an industrial world can exist on renewables alone. It is possible that they are only a kind of ‘range extender’.

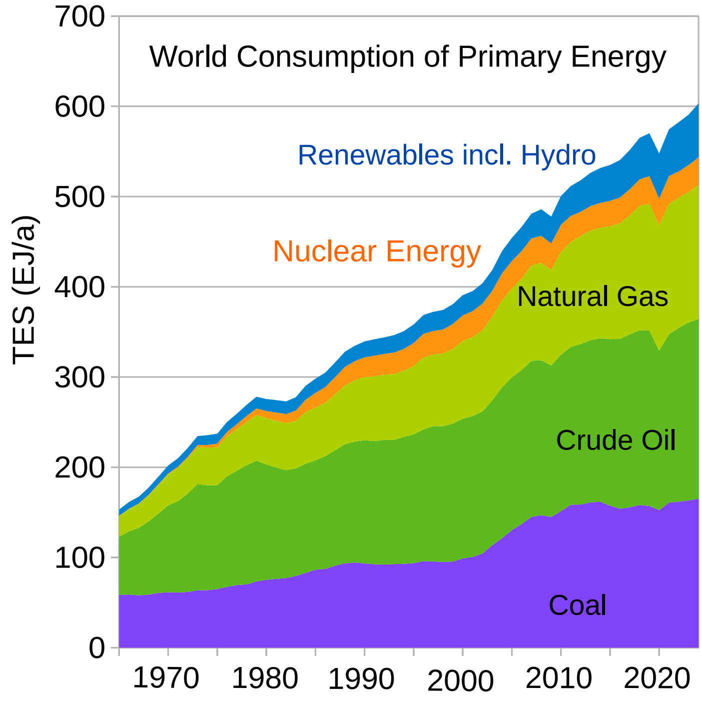

Figure 13: World consumption of all forms of energy (TES: Total Energy Supply), expressed in exajoules.

10. Result

A new calculation using the World3-3 programme is now available. The main change from ‘Recalibration23’ is that the input value for the amount of renewable resources has been increased from 1300 gigatonnes to at least 1550 gigatonnes for the world without China. China can contribute a further 250 gigatonnes. The old value had been distorted downwards by the economic slump caused by Covid-19; the actual amount of resources is higher.

What does it mean that the amount of resources of all fossil raw materials in the world without China is around 1550 gigatonnes? See Figure 2.

Firstly, it means that the world's raw material resources are limited and that around half of them have already been used up.

It means that every single citizen of this planet will have steadily less energy available from now on. Not only that, but maintaining the infrastructure of each country consumes an additional and growing share of the total pie. Germany is particularly affected by this, as it has virtually no fossil fuels other than lignite, has neglected its infrastructure, and car production is an important economic factor. The socio-political consequences of these effects are unimaginable.

Further observation of input and output data for World3-3 is essential, as is publication of the results. This is a basic prerequisite for mitigating the problems arising from future raw material shortages.

11. Literature

[1] A.Nebel, A.Kling, R. Willamowski, T.Schell: „Recalibration of limits to growth: An update of the World3 model“, November 2023, Journal of Industrial Ecology 28(1)
https://www.researchgate.net/publication/375610074_Recalibration_of_limits_to_growth_An_update_of_the_World3_model
[2] The program code of PyWorld3-3 is available here: GitHub - TimSchell98/PyWorld3-03: 2005 updated version of PyWorld3
[3] The programming language Python is available here: https://www.anaconda.com/download
[4] Hubbert Linearisation: https://en.wikipedia.org/wiki/Hubbert_linearization
[5] Chinas planing for coal production: https://www.assetnews4u.com/energy/charting-chinas-evolving-primary-energy-mix-through-2060/
[6] Energy Institute data: EI-Stats-Review-ALL-data.xlsx
https://www.energyinst.org/statistical-review/resources-and-data-downloads
[7] The data base „Ourworldindata“ contains population growth data
https://ourworldindata.org/population-growth and much more.
[8] Destatis, https://www.destatis.de/DE/Themen/Wirtschaft/Konjunkturindikatoren/Produktion/kpi117.html#355032
[9] Historical data for coal production of China: Our World in Data,
https://ourworldindata.org/grapher/coal-production-by-country?tab=chart&country=~CHN
[10] Data for US oil production: https://peakoilbarrel.com/short-term-energy-outlook-november-2025/
[11] Energy Information Agency of USA: https://www.eia.gov/outlooks/steo/xls/Fig42.xlsx
[12] Current production data for coal in China: https://tradingeconomics.com/china/coal-production
[13] Wikipedia: Wirtschaftszahlen zum Automobil,
https://de.wikipedia.org/wiki/Wirtschaftszahlen_zum_Automobil
[14] „Limits of Growth“, Donella H. Meadows, Dennis L. Meadows, Jorgen Randers and William W. Behrens III, 1972; ISBN 0-87663-901-5, ISBN 0-87663-165-0
[15] „DYNAMICS OF GROWTH IN A FINITE WORLD“, Book by Dennis L. Meadows, William W. Behrens III, Donella H. Meadows, Roger F. Naill, Jorgen Randers, Erich K.O. Zahn, August 1975, ISBN 0-9600294-4-3
[16] Jorgen Randers: „2052 Der neue Bericht an den Club of Rome“, erschienen 2012, ISBN 978-3-86581-398-5
[17] Gaya Herrington, 2020: „Update to limits to growth – Comparing the World3 model with empirical data “ ; Journal of Industrial Ecology 2020;1–13

[18] Online simulation for World3 is available here:
https://insightmaker.com/insight/2pCL5ePy8wWgr4SN8BQ4DD/The-World3-Model-Classic-World-Simulation

12. Abbreviations

AMV	**A**ll **M**otor **V**ehicles including trucks and busses, without motor bicycles.
BAU	**„B**usiness **as** **u**sual“ It means that the policies and behaviours of the past will continue to be maintained in the future. BAU calculations are based on the currently known amount of resources.
BAU2	Same as BAU, but with doubled amount of resources.
bbl	Abbreviation for a barrel of crude oil, **bl**ue **b**arre**l.**
BOE	**B**arrel of **O**il **E**nergy. Energy content of a barrel Oil: 1 BOE = 5,86152 GJ
%BOE	Selling price of a barrel of crude oil, converted from US dollars using energy productivity. In practical terms, this is the percentage of energy that the producer receives from 100% of the energy content of the barrel.
C+C	**C**rude and **C**ondensate. Crude oil extracted from the earth. In contrast, ‘all liquids’ is often referred to as the sum of C+C, biofuels, refinery gains and extracted liquefied gas.
C&C	See C+C.
EI	**E**nergy **I**nstitute.
OWID	„Our World in Data“, internet data base.
w/oC	**with**o**ut** **C**hina.

Abbreviations for quantities

Kurzzeichen	Name	Zahlenwert
k	Kilo	10^3
M	Mega	10^6
G	Giga	10^9
T	Tera	10^12
P	Peta	10^15
E	Exa	10^18

1 Gt = 1 Gigaton = 10^9 tons