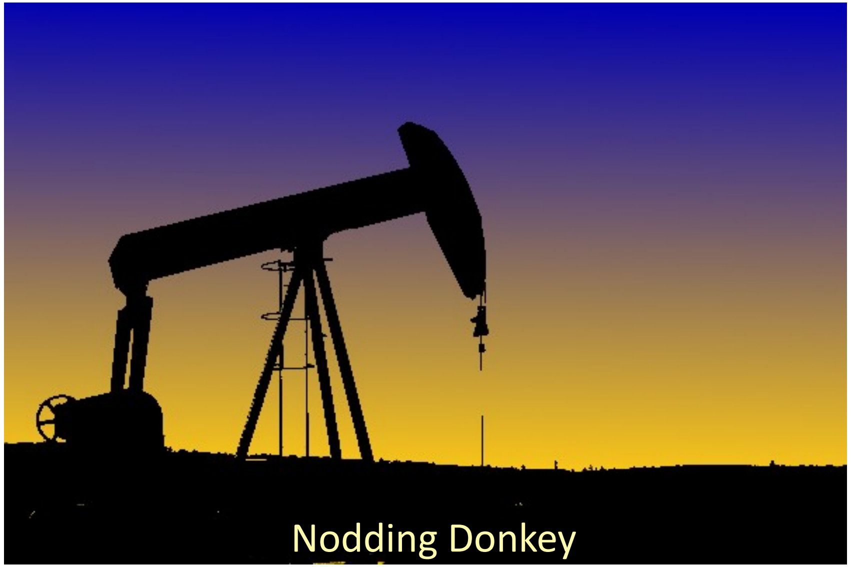
Temperature Effects impacting Earth cause severe Limits for Oil Production


Nodding Donkey

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Nodding Bird - No Perpetuum Mobile

Heat as a Side Effect of Oil Production

Abstract

- The goal of oil production is the extraction of a useful energy carrier out of earth.
- With each barrel of oil, some heat is extracted out of the earth.
- The heat is unvisible, not audible, it does not smell : But it is a kind of waste contaminating the environment.
- Over time, the heat has a added up to a very large pile of waste.
- This waste forms a temperature wall, hindering future oil production.
- Surmounting the wall costs energy, reducing the usefulness of the extracted oil.
- In some years, the wall so high that oil production gets senseless.

Introduction

Preface:

• The Hills-Group has developed an equation for the calculation of the energy required for oil production (see: The Hills Group, *„Depletion: A determination for the world's petroleum reserve“,* page 8, Eq #7)

• This ETP-equation predicts, that in the year 2029 the energy required will be as large as the useful exergy of oil

• The ETP-equation has been derived by using the second law of thermodynamics

• The derivation has a disadvantage: it is understandable only for people with a good background in thermodynamics

• In this set of slides an alternative approach for the equation is developed, which is (hopefully) simpler to understand

• In a very different way, the same equation is derived

The Second Law of Thermodynamics

This law can be described with a lot of phrases.

A well-known phrasing is:

„The entropy of an isolated system can only increase“

A quantitative modern phrase used by engineers is the „entropy rate balance equation for control volumes“, which allows dimensioning of gas turbines etc.

One verbalization is:

„If two objects are in thermal equilibrium, cooling one and heating the other can be done only with external energy supply“

Two Pots of Water

Each pot contains one liter of water, each at 50 °C.
They are in thermal equilibrium in a closed system.

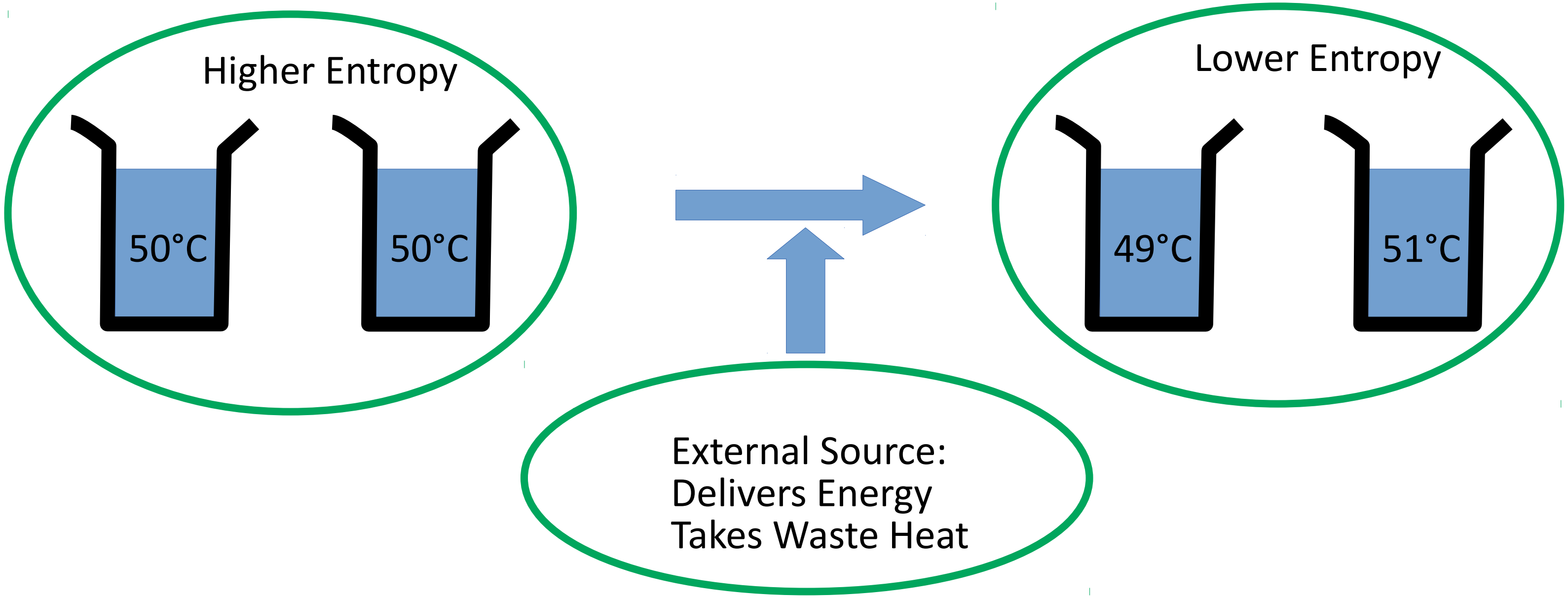
After some time one is at 51 °C, the other at 49 °C.
This can‘t happen by itself, because this state has a lower entropy than the equilibrium state has.

Consequence:

The energy to heat one and cool the other one must have been supplied by an external energy source.

It does not matter how the change has happened, the result tells us:

„External Energy has been necessary“



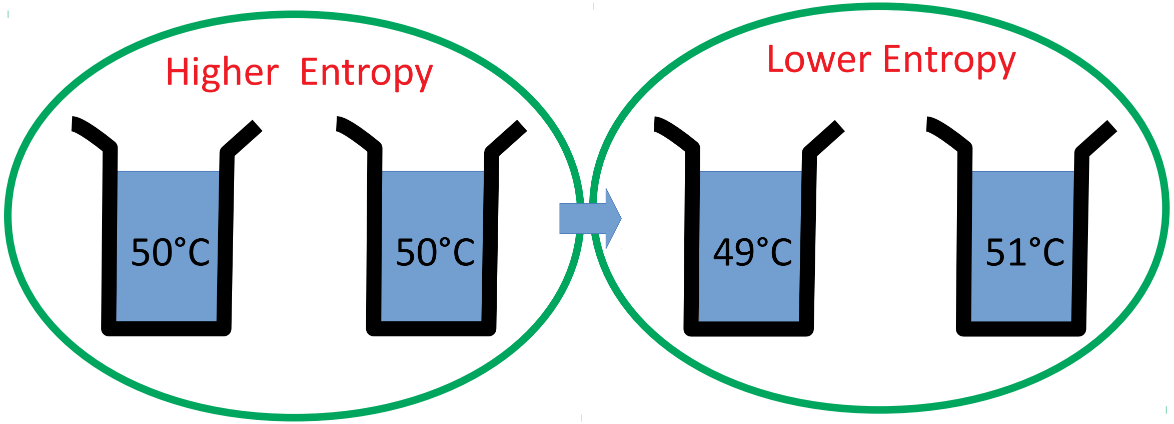
Expert Page: Two Pots of Water

Entropy change of material by temperature change from $T_1 \rightarrow T_2$

$$\Delta S = m \cdot c \cdot \ln \frac{T_2}{T_1}$$ (Eq. 1)

with:
- m: mass of material (kg)
- c: heat capacity of material (J/(kg · K))

m = 1 kg
c: specific heat capacity H_2O = 4.19 kJ/(kg · K)



Entropy change of right system is negative:

$$\Delta S = m \cdot c \cdot \ln \frac{273+49}{273+50} + m \cdot c \cdot \ln \frac{273+51}{273+50}$$

$$\Delta S = m \cdot c \cdot \left(\ln \frac{322}{323} + \ln \frac{324}{323} \right) = -0.9585\text{e-}6 \cdot m \cdot c$$

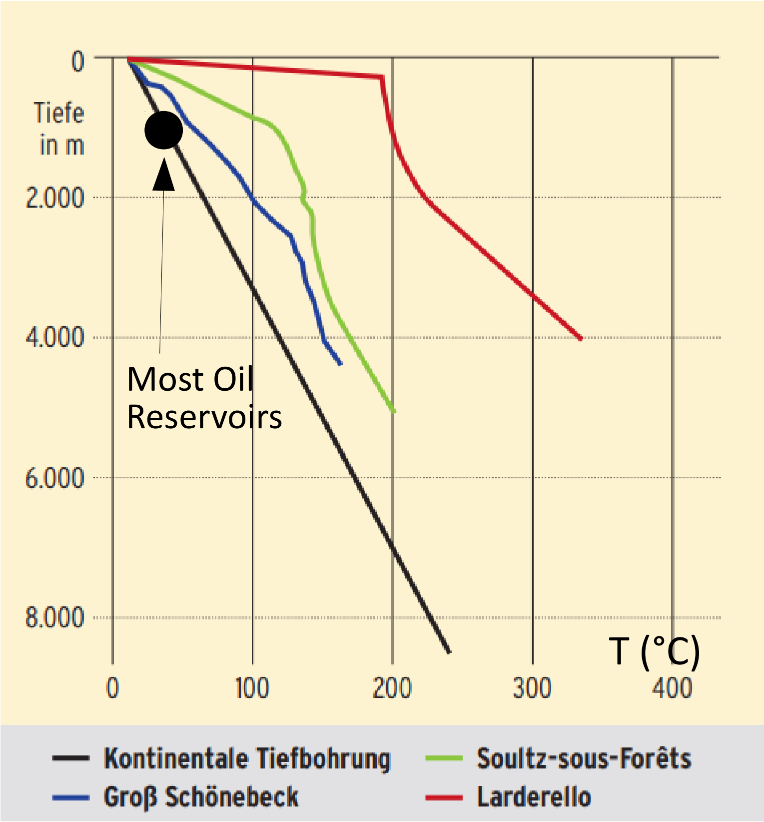
$$\Delta S = -0.9585\text{e-}6 \cdot 1\, kg \cdot 4.19\, kJ/(kg \cdot K)$$

$$\boxed{\Delta S = -4.0\text{e-}5\, kJ/K}$$

This process requires external energy and heat supply

see: Moran/Shapiro „*Fundamentals of Engineering Thermodynamics*“

Geothermal Power Plants



Earth Temperature Increase with Depth

Temperature of the earth interior

- The black line is the temperature gradient in the earth interior, determined with a drill hole.
- All realized geothermal power plants are on the right side of the black line. The colored lines show temperature curves for three of them.
- The more distant from the black line, the better the efficiency of the plants.
- Power plants near the black line have got bankrupt sooner or later.
- No power plants have been realized on the left side of the black line.
- The black line poses a limit for technical useful temperature gradients.

Source: (BMU: „Geothermische Stromerzeugung“)

Thermal Equilibrium

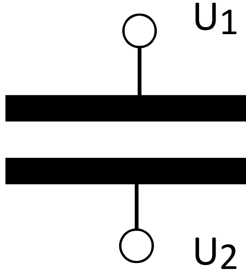
Temperatures in thermal equilibrium are matched

- Two objects in thermal equilibrium have the same temperature
- Without external influence, they will hold their temperature, no heat will flow from one to the other
- To make one object warmer than the other, energy must be spent.
- The amount of energy can be calculated using mass, heat capacity and temperature difference of the object

The earth is in thermal equilibrium

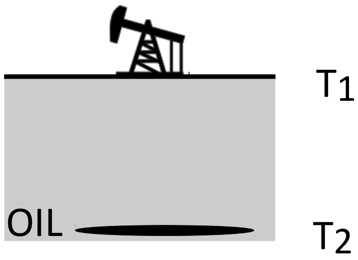
- In millions of years the earth has developed a thermal equilibrium (except vulcanic areas)
- The earth core has a temperature of about 5500° – 6000° Celsius
- The earth surface in some meter depth has an average temperature of about 11° Celsius in Germany (corresponds to the average annual temperature)
- The gradient of the earth temperature amounts about 35 Kelvin per 1000 m of depth
- The temperature distribution did not change in hundred thousands of years
- The gradient hides the thermal equilibrium of surface and interior
- Weather and seasons lead to short term fluctuations on the earth surface, which have no influence on the earth interior

Work for Change of Temperature



$$dW = -q \cdot dU$$

$$W = \int_0^Q U(q)\,dq = \frac{1}{2} C U^2$$



$$dW = -m \cdot c \cdot dT$$

$$W = ?$$

Earth and a Capacitor

- Conventional Crude Oil reservoirs have typically a depth of more than 1000 m and have temperatures in the range of 30°C-60°C
- A 1000 m thick layer of earth has a typical thermal relaxation time in the order of 47000 years (see below)
- Earth surface and earth interior can be compared with two plates of an capacitor, isolated by the earth layer
- A constant current q into the capacitor results in a constant increase of the voltage U
- An increasing voltage U of the capacitor requires an increasing work W for further voltage increases
- A constant heat current by oil from the earth interior ending in the earth surface with heat capacity m*c results in a constant temperature T increase
- The higher the temperature, the larger the work W to achieve additional temperature increases

Expert Page: Thermal Relaxation Time

$$T(t) = T_0 \exp\left(\frac{-t}{T_R}\right) \quad \text{(Eq. 2a)}$$

$$T_R = \frac{d^2 \cdot \rho \cdot c}{\lambda} \quad \text{(Eq. 2b)}$$

$$T_R = \frac{1000^2 \cdot 2000 \cdot 0.43}{2.1} m^2 \frac{m \cdot K}{W} \frac{kg}{m^3} \frac{W \cdot h}{kg \cdot K}$$

$$T_R \approx 4.1 \cdot 10^8 h = 47000 \, years$$

Equation for thermal relaxation time

- Time in which a temperature difference decreases to 36.8% of the initial value
- Earth specific density:

  $\rho = 1700..2500 \, kg/m^3$, here $2000 \, kg/m^3$

- Earth heat capacity:

  $c = 0.22..0.43 \, Wh/kgK$, here $0.43 \, Wh/kgK$

- Earth heat conductivity:

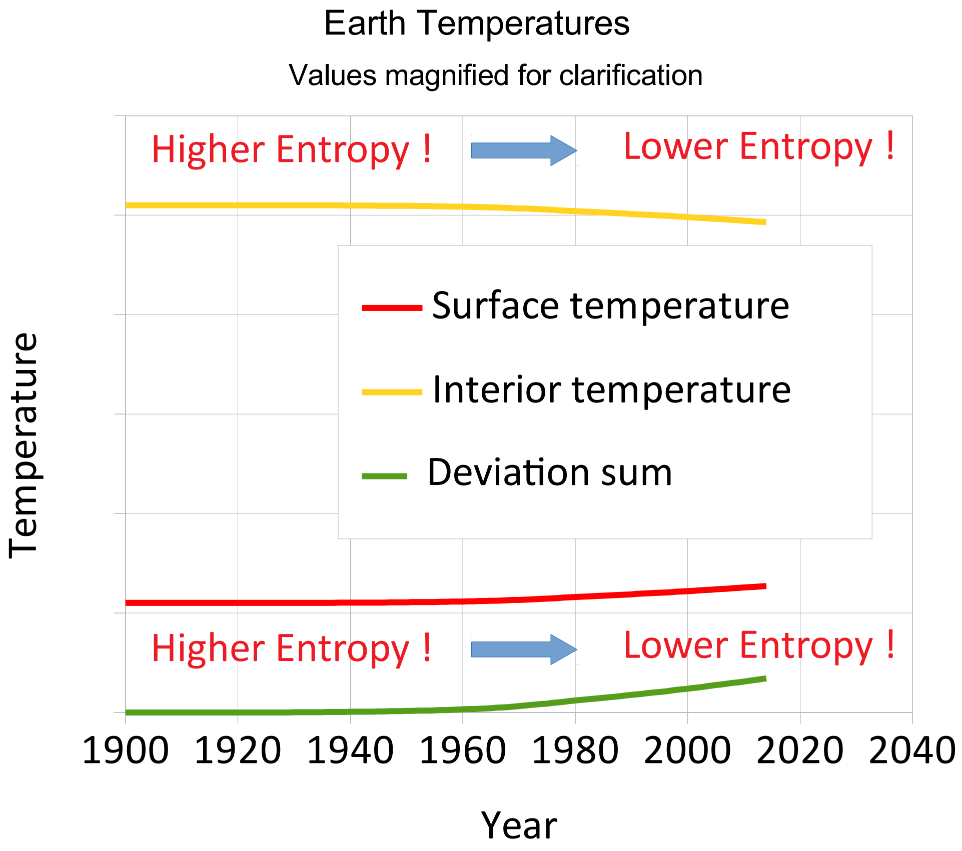
  $\lambda = 0.47..2.1 \, W/mK$, here $2.1 \, W/mK$

- Typical depth of oil reservoirs:

  $d = 1000 \, m$ and more

- 160 years of commercial oil extraction are neclectable compared to the relaxation time

Oil production and Thermodynamic Equilibrium



Oil production and heat transport

- Oil production results in heat transport from the earth interior to the surface.
- The thermodynamic equilibrium of the earth gets disturbed. The distortion requires the input of energy
- The surface gets a little bit warmer compared to the natural state. The interior gets a little bit cooler.
- The difference of both deviations increases over the years.
- This results in an always increasing energy expenditure, necessary to disturb the thermodynamic equilibrium and to extract oil.

Expert page : Oil production and Thermodynamic Equilibrium

Entropy change of earth material by temperature change from $T_1 \rightarrow T_2$

$$\Delta S = m \cdot c \cdot \ln \frac{T_2}{T_1}$$

with:

m: mass of earth material (kg)

c: heat capacity of earth material (J/(kg · K))

Neither mass nor specific heat capacity of involved fraction of the earth are known. Lets assume 0.1 K temperature change.

We assume an oil reservoir temperature of 323 K, and an earth surface temperature of 284 K, 1400 m reservoir depth, and an gradient of 35 K/1000m:

Elimination of the temperature difference caused by the gradient results in a „degradiented“ reservoir temperature of 323-49 K=274 K, giving an entropy change:

$$\Delta S = m \cdot c \cdot \ln \frac{273.9}{274} + m \cdot c \cdot \ln \frac{284.1}{284}$$

$$\Delta S = -1.3\text{e-}5 \cdot m \cdot c$$

The entropy change caused by oil production is negative:

$$\boxed{\Delta S < 0} \qquad \text{(Eq. 3)}$$

Oil Production requires external energy and heat supply.

Experts homework:
What results for the oil flow, if the degradienting is invalid ?

Quantitative Discussion of Temperature Increase

Assumption: Each year the same mass of oil and water is produced

- Year 0: Oil production heats the earth exterior by a small temperature, no temperature difference must be overcome
- Year 1: Oil production heats the earth exterior by a second small temperature, the first small temperature difference must be overcome, requiring a little energy
- Year 2: Oil production heats the earth exterior by a third small temperature, two small temperature differences must be overcome, requiring twice the little energy
- Year n: Oil production has heated the earth exterior by a n small temperatures, all of the small differences must be overcome, requiring much energy

Each year the same amount of oil is produced, but the energy required per mass unit of oil gets larger and larger. At some point in time the energy required per kg of oil is larger than its energy content !

=> then oil production gets senseless.

Numeric Example for Temperature Increase

Assumption: Each year the same mass of oil and water is produced

- Year 0: Oil production heats the earth exterior by a small temperature, no temperature difference must be overcome
- Year 1: Oil production heats the earth exterior by a second small temperature, the first small temperature difference must be overcome, requiring a little energy
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Each year the same amount of oil is produced, but the energy required per mass unit of oil gets larger and larger. At some point in time the energy required per kg of oil is larger than its energy content !

=> then oil production gets senseless.

Expert page: Emergence of a Temperature Increase

Oil extraction accounts for the transport of masses $m_i(t)$ with a total heat content q(t) to the earth surface

$$q(t) = (T_R - T_0) \cdot \sum_i m_i(t) \cdot c_i \qquad \text{(Eq. 4)}$$

Heat transport from the earth interior results in a small temperature increase relative to the equilibrium between earth surface and earth interior.

The increase $T(t)$ is the heat divided by the earth thermal capacity :

$$T(t) = \frac{q(t)}{m_S \cdot c_S} \qquad \text{(Eq. 5)}$$

T(t) is small, but not neglectible.

This process exists for a lot of years k now.

$$\sum_i m_i(t) \cdot c_i = m_C(t) \cdot c_C + m_W(t) \cdot c_W \qquad \text{(Eq. 6)}$$

Index C: crude oil
Index W: water
Index S: surface (of earth)
c: spec. heat capacity [J/kg/K]
T_R: average reservoir temperature [K]
T_0: average environment temperature ~25° C [=298,15 K]

Expert page: Integral Temperature Increase

The heat transport as a function of time is:

$$\dot{q}(t) = (T_R - T_0) \cdot \sum_i \dot{m}_i(t) \cdot c_i \qquad \text{(Eq. 7)}$$

In the year k the total heat Q(k) transported to the earth surface from the begin of oil extraction is:

$$Q(k) = \int_0^k \dot{q}(t)\,dt = \int_0^k (T_R - T_0)\left[\sum_i \dot{m}_i(t) \cdot c_i\right] dt \qquad \text{(Eq. 8)}$$

And the total temperature raise is:

$$T(k) = \frac{Q(k)}{m_S \cdot c_S} \qquad \text{(Eq. 9)}$$

Because the earth surface mass m_S is very large, the temperature raise is very small and not measurable.

Expert page: Annual Temperature Increase

In the year k+1 the heat transport is:

$$\delta q(k+1) = (T_R - T_0) \cdot \sum_i \delta m_i(k+1) \cdot c_i \qquad \text{(Eq. 10)}$$

δ: prefix for annual value

In this year the additional temperature increase $\delta T(k+1)$ is:

$$\delta T(k+1) = \frac{\delta q(k+1)}{m_S \cdot c_S} \qquad \text{(Eq. 11)}$$

Resulting in a total temperature increase of:

$$T(k+1) = \frac{Q(k)}{m_S \cdot c_S} + \frac{\delta q(k+1)}{m_S \cdot c_S} = \frac{Q(k+1)}{m_S \cdot c_S} \qquad \text{(Eq. 12)}$$

Expert page: Work Required to increase the Temperature

The work $\delta W(k+1)$ in the year k+1 to generate the temperature change is to be calculated from the temperature difference times heat capacity of the earth surface

$$\delta W(k+1) = m_S \cdot c_S \cdot T(k+1) \qquad \text{(Eq. 13)}$$

$$\delta W(k+1) = m_S \cdot c_S \cdot \frac{Q(k+1)}{m_S \cdot c_S} = Q(k+1) \qquad \text{(Eq. 14)}$$

This is the amount of work necessary to generate the temperature difference in the year k

Division of $\delta W(k+1)$ by the amount of crude oil m(k+1) produced in the year k+1 results in the annual work (=energy) required per mass unit of crude oil.

$$e(k+1) = \frac{\delta W(k+1)}{\delta m_C(k+1)} = \frac{Q(k+1)}{\delta m_C(k+1)} \qquad \text{(Eq. 15)}$$

Discussion of Result

- The exergy per kg e(k) of crude oil in each year is the work required in this year divided by the mass of the oil in the same year.

$$e(k)=\frac{\int_0^k (T_R - T_0)[\dot{m}_C(t)\cdot c_C + \dot{m}_W(t)\cdot c_W]dt}{\delta m_C(k)} \qquad \text{(Eq. 16)}$$

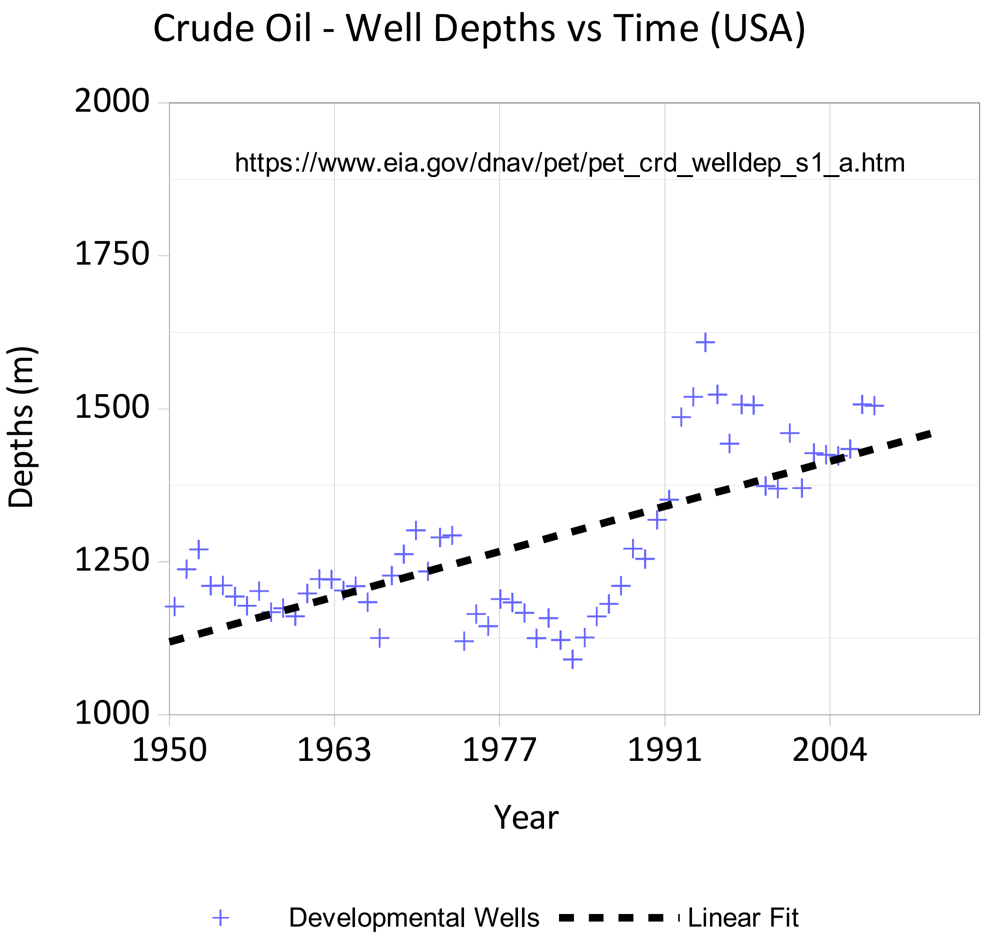
- The work required for oil extraction increases with time, depending on the history of extraction. The increasing temperature difference between earth surface and interior is the cause.

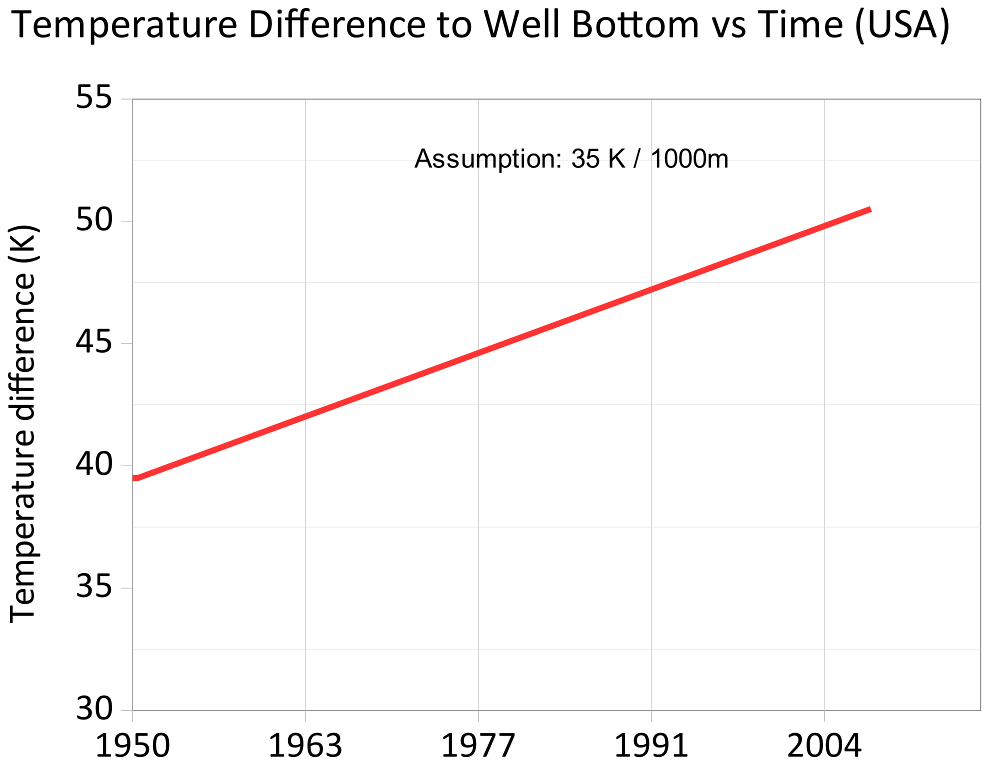
- The more oil is produced, the more exergy is necessary for each following barrel. Each barrel requires a little more exergy than the previous barrel.

- (For experts: To determine the necessary energy, the exergy e(k) is to divided by the efficiency of the process converting energy to work. (here 62%, the practical useful part of oils thermal energy content)).

- The equation above is identical to the Hills Group report (page 8, Eq #7). It has been solved in the HG report, using the data displayed in the following slides.

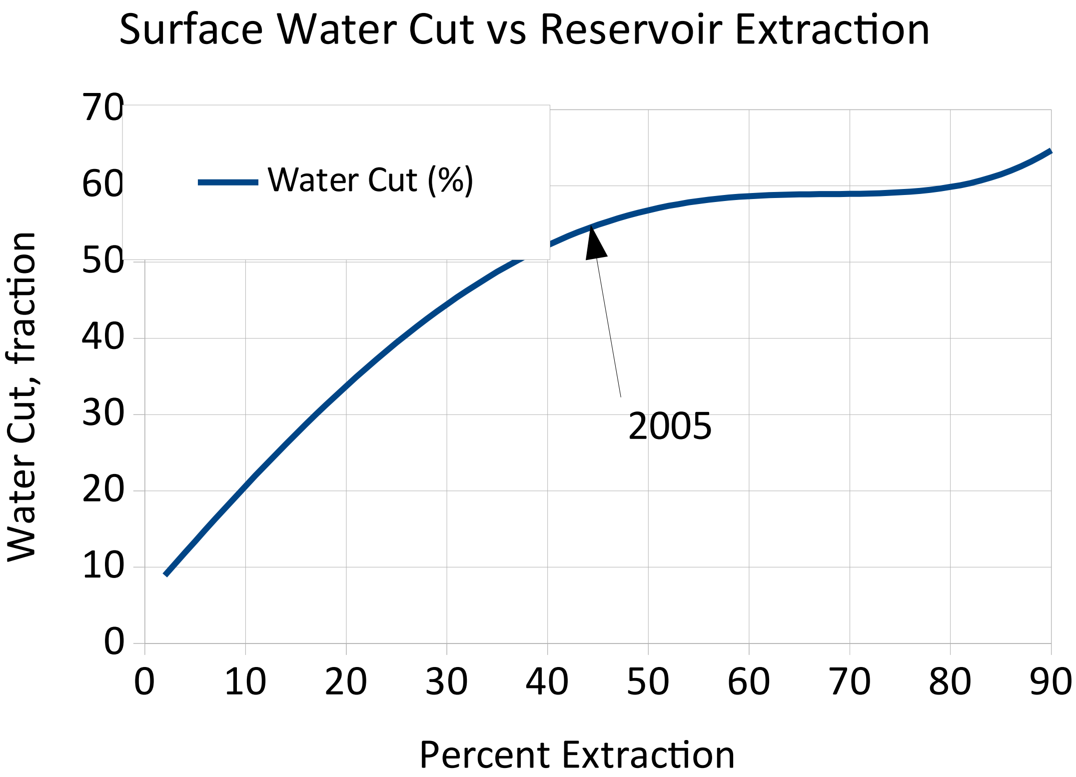
Reservoir temperature





The medium depth of the wells increases as a function of time, as well as the medium temperature at the well bottom.

Water cut

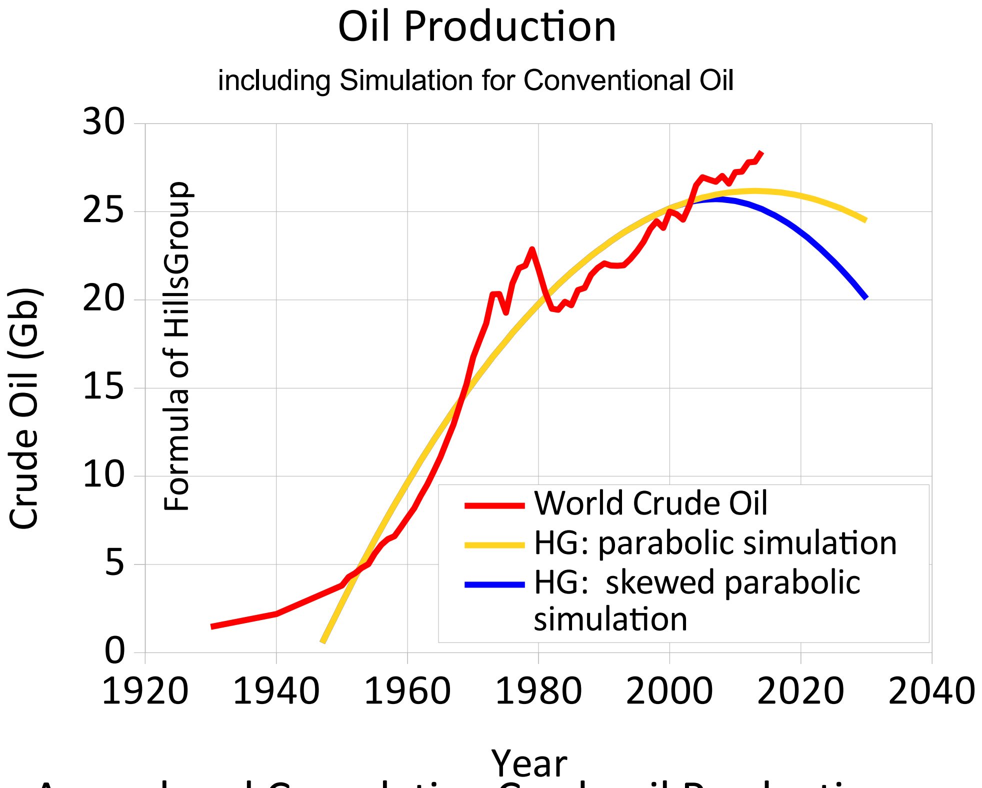


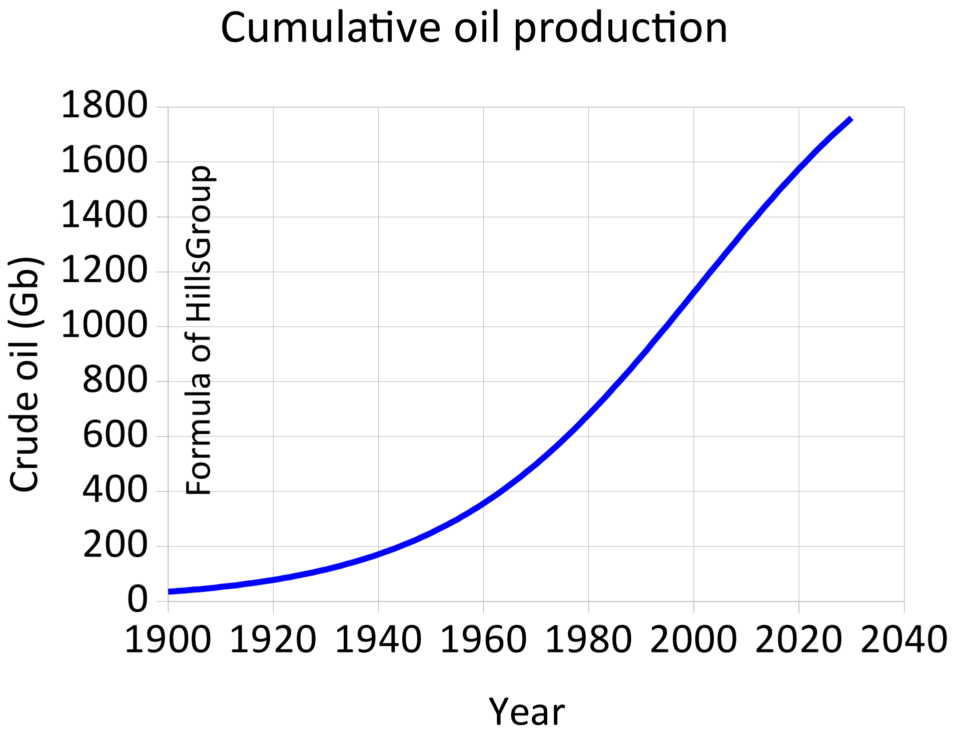
„Water cut“ is the percentage of water which flows together with crude oil out of the well. [1] Because water has a higher mass density and heat capacity, it transports significant more heat than the same volume of oil.

The „water cut“ gets calculated by HG using the Buckley-Leverett equation of the fluid mechanics. The resulting function is balanced such that the „water cut“ has been in the year 2005 equal to 54%.

See: Halliburton, „Oilfield water management“, http://www.halliburton.com/en-US/ps/solutions/clean-energy/oilfield-water-management/default.page?node-id=hgjyd44q

Crude oil Production

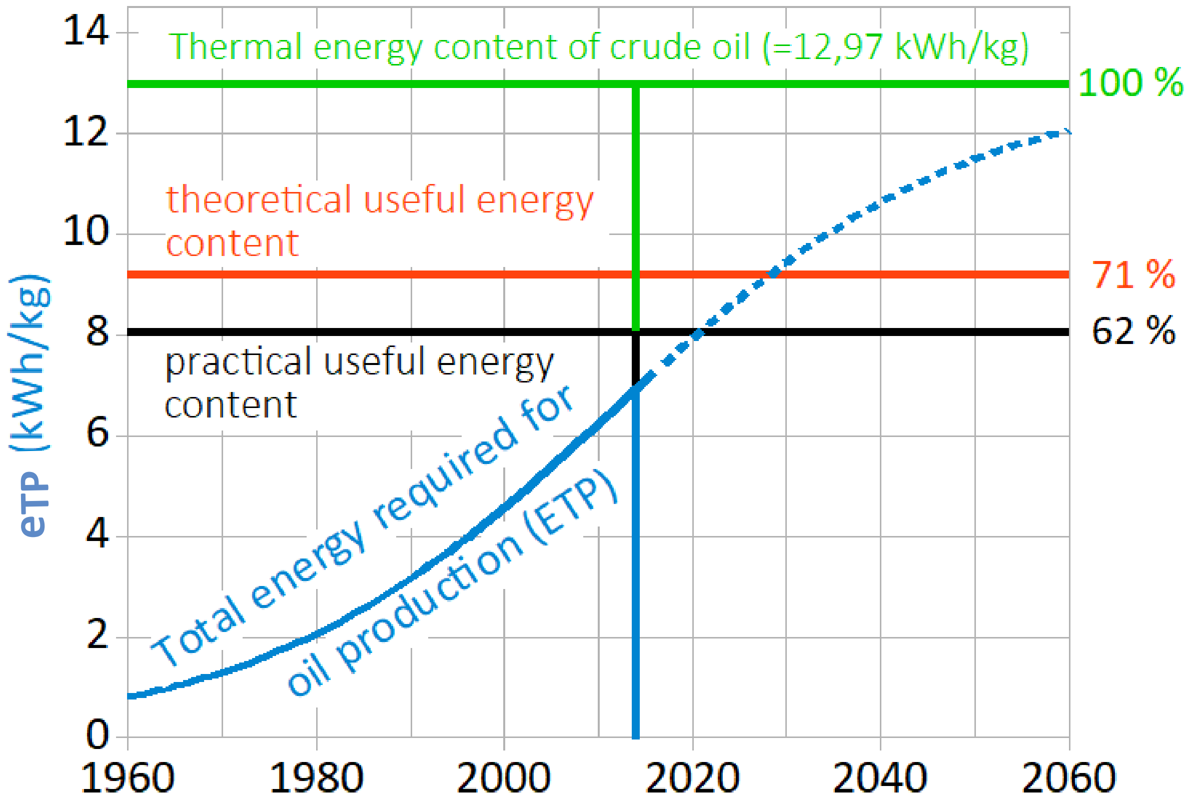




Annual and Cumulative Crude oil Production

Source: 1950-1964 compiled by Worldwatch Institute from U.S. Department of Defense and U.S. Department of Energy data; 1965-2014 data from U.S. Department of Energy, Energy Information Administration, International Energy Statistics Website, June 2015. (Additional resources: www.eia.doe.gov)

ETP-Model – Diagram



Grafic Display of $e_{TP}(t)$

- The creation of a temperature disequilibrium within earth requires a very high energy expenditure
- $e_{TP}(t)$ requires today (2017) about 56% of the thermal energy content of crude oil
- 2029 will the specific production energy be as high as the theoretical useful value of the energy content of crude oil (carnot process)
- At the latest in 2029 crude oil production will make energetical and economical no sense
- Even 2022 is critical

ETP - Modell

A law of physics tells us:

In some years oil production will hit a severe limit.
Physics laws can‘t get violated.

Fatih Birol: ***Leave oil before it leaves us***

Neclecting the Temperature Gradient

We assume an oil reservoir temperature of 323 K, and an earth surface temperature of 284 K, and neclect the gradient of 35 K/1000m:

$$\Delta S = m \cdot c \cdot \ln \frac{T_2}{T_1}$$

with:

m: mass of earth material (kg)
c: heat capacity of earth material (J/(kg · K))

Lets assume 0.1 K temperature change, caused by oil transport from the reservoir to the surface. This corresponds to an entropy change of:

$$\Delta S = m \cdot c \cdot \ln \frac{322.9}{323} + m \cdot c \cdot \ln \frac{284.1}{284}$$

$$\Delta S = +4.2\text{e-}5 \cdot m \cdot c$$

The entropy change caused by oil transport gets positive.

If a process leads to an higher entropy state, it can run by itself, without external enery spending.

This would result in a never observed effect: If a hole is drilled, and at the bottom of the hole is a liquid (oil without gas) warmer than the surface, the liquid must creep out of the hole by itself !

=> Neclecting the gradient is erroneous.

Questions and Answers #1

Q1: Why do you analyze thermal differences ?

A: I have made a thermodynamic analysis of oil production. Each machine, each animal, each plant, each motor works corresponding to the laws of thermodynamics. I have done a natural thing.

Q2: Why don‘t you see that chemical energy of oil dwarfes thermal differences ?

A: The thermal differences are small, but they accumulate. The following image might explain it:

Oil production has the consequence of extraction of heat out of the earth. Oil extraction causes a kind of environmental pollution, caused by garbage (heat). Each barrel of oil is accompanied by a small package of garbage accumulating on earth. The oil producers put them on a pile. The pile gets higher with each package, and over time the packages get larger (because of increasing water cut and temperature difference).

Now the pile is so high, that throwing the packages on top of the pile requires a lot of energy.

Questions and Answers #2

Q3: Why do you believe thermal differences limit pumping oil, not depth and gravity ?

A: In words: At the beginning of oil production more than hundred years ago only the gravitational energy had to be overridden. After some months the thermal differences required more energy than the gravitational energy. Now, after more than hundred years, the energy required to overcome the temperature difference for a barrel is nearly as high as the chemical energy contained in the barrel of oil.

In formulas: Slides 14 to 18 show the calculation, giving the high energy values i mention.

Q4: The cooling of the crust by water injection or other means would be negligible given the immense mass of the Earth.

A: Eq 14 shows see that mass and thermal capacity of earth cancel on denominator and numerator. Therefore, the thermodynamic work to extract oil is independent of the mass. If the mass of would be not so high, for example only 1000 million tons, other persons would have done my calculation years before me. The nearly „infinite“ mass has hidden the facts.

Questions and Answers #3

Q5: Any oil geologist would say that the energy necessary to pump a given amount of oil from a given depth has remained constant. Most fields didn't even have to be pumped in the inital stages of exploitation, as they flow under their own pressure.

A: This is a thermodynamic analysis, not a geological. From a different branch of science. A comparable geological analysis should include a societal EROI analysis as defined by Charles Hall.

Q6: The temperature effects from this calculation are small compared to real day temperature changes. They seem neclectable. The whole calculation seems theoretical and not reality-based.

A: The formulas are based on the 2nd law of thermodynamics, which is always valid. It is a very strong and important law. To say, the law is not valid, because the effects are too small, is careless. In contrast, it requires very good reasons to conclude that the law can‘t be applied.

Questions and Answers #4

Q7: Why you care to calculate “the work … to generate the temperature change” between oil and water in the subsurface (higher temperature) and the surface ?

A: Oil and water are substances, which transfer their heat short time after they leave the well to the earth surface. This changes the earth temperature equilibrium => gives a state of lower entropy => requires external energy.

This temperature change is a side effect of oil production, which is unavoidable, never considered, but requires energy.

Q8: The heat from the oil can be used as heat machine, so the heat is beneficial ?

A: The slide for geothermal power plants contains info about the power plants: Soultz-Sous-Forets, Groß Schönebeck and Lardarello, the colored lines are the temperature gradients at their position, with the endpoint at working depths. After studying some of this diagrams, i made the observation, that nobody tries to build a power plant along the black line. The argument was always, that they are too expensive. This seemed to be one of the cost/energy intermixtures, where costs are mentioned, but the energy relations don‘t work. Most oil reservoirs are near the black curve. So i‘m quite sure that your proposed heat engine might work for a short time, but will be too expensive thereafter.

Questions and Answers #5

Q9: Why do you speak of thermal equilibrium ? Plate tectonics and oil formation are processes which always have changed the earth and its interior ?

A: Its depending on the time scale and location. Oil production lasts for 160 years. Oil formation has happened about 200 to 500 million years ago. Times of hundred thousand to a million years have been long enough for reaching thermal equilibrium. Most of the areas of oil reservoirs are not in tectonic critical areas.