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Unsolved: Climate Change Problem

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ABSTRACT

The Zero-dimensional Energy Balance Model is introduced to calculate courses of global mean temperature increases for the stationary higher limit values of 1.5 ⁰C, 2.0 ⁰C and 3.0 ⁰C compared to the pre-industrial time. In particular, mean stationary temperatures for sea surface, land surface and entire surface of the earth are calculated and compared, also with temperature anomalies.

The problem of the Carbon budget will be discussed. Its solution is a real challenge for mankind.

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The Zero-Dimensional Energy Balance Model

It was developed by the Russian climatologist, geophysicist and geographer Mikail Ivanovich Budyko (1920–2001) and the American-British climate re- searcher and astronaut Piers John Sellers (1955–2016).

The physical model is based on the balance of heat power: the difference between the heat gain P_{gain} absorbed by the earth via solar radiation and the heat Ploss lost via radiation results in the earth heating up.

Its description in this section is a shorted version from [1].
All physical quantities are exclusively globally averaged scalar quantities, which is why we speak of a zero-dimensional model.

The quantity of heat of a body of mass *M* with absolute temperature *T* measured in Kelvin and specific heat capacity *C* is

$$Q = C \cdot M \cdot T. \qquad (1)$$

In the case of the earth, *C* is the specific mean global heat capacity of the affected layer of the earth's surface per degree and kg.

The time-dependent rate of change in the quantity of heat per unit of time $\frac{dQ}{dt}$ (physically a power) is described by the following heat equation of a heat- exchanging body of arbitrary shape:

$$\frac{dQ}{dt} = P_{\text{gain}} - P_{\text{loss}}. \qquad (2)$$

The total mean solar radiation (Total Solar Irradiation TSI) onto a surface perpendicular to the sun's rays outside the atmosphere is

$$S_0 = 1370 \frac{\text{W}}{\text{m}^2}. \qquad (3)$$

The total constant mean power of the short-wave solar radiation absorbed by the earth is given by

$$P_{\text{gain}} = \pi R^2 \cdot S_0 \cdot (1 - \alpha).$$

Here πR^2 is the cross-sectional area of the earth with radius R. Moreover, $\alpha \approx 0.32$ is the portion of the reflected radiation, the so-called planetary albedo, that is, 32% of the solar radiation is reflected.

Why a circular disk? The sun's radiation on the small surface elements of half the sphere's surface is in general oblique, not perpendicular. Therefore, only the surface area of the illuminated sphere projected onto the plane perpendicular to the irradiation counts for the power.

The total power loss caused by the outgoing long-wave radiation is given by the

Stefan-Boltzmann law

$$P_{\text{loss}} = 4\pi R^2 \cdot \varepsilon \cdot \sigma \cdot g \cdot T^4.$$

Here
$\varepsilon = 0.97$ is the emissivity, which specifies how much radiation the earth emits compared to an ideal black body,

- $\sigma = 5.67 \cdot 10^{-8} \frac{\text{W}}{\text{m}^2\text{K}^4}$ is the Boltzmann constant,
- *T* is the mean temperature on the earth's surface measured in Kelvin,
- $4\pi R^2$ is the area of the entire earth's surface (because radiation takes place in all directions.

The decisive radiation factor $g < 1$, which can be influenced, models the greenhouse gas effect. It reflects the fact that the emission temperature in the real atmosphere – that is, the temperature that one would see from space – does not correspond to the temperature on the earth's surface.

The reason is that a large portion of the infrared radiation emitted by the earth's surface does not leave the atmosphere because it is absorbed by greenhouse gases, mainly water vapor and CO_2, that are present in the atmosphere. These particles radiate the absorbed energy in all directions, including downwards back to the earth. As a result, the earth's surface heats up and, by convection, the entire atmosphere heats up as well. Due to this greenhouse effect, the average temperature on the earth's surface is higher than without an atmosphere.

In the convective atmosphere, the temperature decreases with increasing alti- tude, mainly because the air expands adiabatically with decreasing pressure.

Due to the infrared radiation back into space, which depends on the altitude, the earth system can maintain the balance between incoming and outgoing radiation even in the presence of greenhouse gases. With the current concentration of greenhouse gases, the infrared radiation into space takes place at an altitude of about 5 km.

In our present simple energy-balance model we consider the heat loss via infrared emission with a radiation factor of $g < 1$.

Note that its exact value depends on many feedbacks in the earth system. For instance, an increase in the amount of water vapor in the atmosphere reduces the radiation factor g.

The instantaneous rate of change in the earth's heat energy per unit of time (physically a power) follows from Equation (1):

$$\frac{\mathrm{d}Q}{\mathrm{d}t} = C \cdot M \cdot \frac{\mathrm{d}T}{\mathrm{d}t}.$$

The mass *M* of the layer of the earth's surface, which is involved in the heat exchange, is given by

$$M = 4\pi R^2 \cdot \Delta R \cdot \rho,$$

where ΔR is the surface layer's mean thickness and ρ its average density. With the heat equation (2), this results in

$$4\pi R^2 \cdot \Delta R \cdot \rho \cdot C \cdot \frac{\mathrm{d}T}{\mathrm{d}t} = P_{\text{gain}} - P_{\text{loss}}.$$

Dividing the equation by $4\pi R^2$ yields the first-order nonlinear differential equation for the unknown function T (t), also found in, Section 3.2.1 [2]:

$$C_E \cdot \frac{\mathrm{d}T}{\mathrm{d}t} = \frac{S_0}{4}(1-\alpha) - \varepsilon \cdot \sigma \cdot g \cdot T^4.$$

The constant $CE = \Delta R \cdot \rho \cdot C$ can be interpreted as the average specific heat capacity per square meter, because its dimension is $[C_E] = \mathrm{J/(K \cdot m^2)}$.

A first-order differential equation not onl $\frac{\mathrm{d}T}{\mathrm{d}t}$ ıvolves the unknown function $T(t)$, but also its first derivative . The task consists in finding a solution that is a function $T(t)$ (not a number).

According to the climate science, the prevailing solar radiation power $\frac{S_0}{4}(1-\alpha)$ increases by the so-called radiative forcing

due to feedbacks in the atmosphere, mainly caused through carbon dioxid is aproximately

$$\Delta F = 5.35 \frac{\mathrm{W}}{\mathrm{m}^2} \cdot \ln\left(\frac{\mathrm{c}}{\mathrm{c}_0}\right).$$

Here $c_0 = 280$ ppm[1] is the relative pre-industrial CO_2 reference pollution. In 2025, the global average annual CO_2 concentration c reached a record high of 425 ppm CO_2 in the atmosphere. In 1960, the concentration c was 317 ppm. During 64 years, it increased by about 30 %, mainly caused through the burning of fossil fuels.

Remark
The contribution of radiative forcing of the other greenhouse gases such as methan, laughing gas and others is small in comparance with the effect of CO_2, because erosols have a negative, cooling effect.

For 2024, we have

$$\Delta F = 5.35 \frac{\mathrm{W}}{\mathrm{m}^2} \cdot \ln\left(\frac{425}{280}\right) = 2.23 \frac{\mathrm{W}}{\mathrm{m}^2}.$$

[1]ppm is the abbreviation for parts per million, [1]ppm = $10^{-6} = 1/10^6$ = 1 millionth, comparable to 1 percent = 10^{-2} = 1 hundredth and 1 per mille = 10^{-3} = 1 thousandth.

Hence the nonlinear differential equation with radiative forcing is given by

$$C_E \cdot \frac{\mathrm{d}T}{\mathrm{d}t} = \frac{S_0}{4}(1-\alpha) + \Delta F - \varepsilon \cdot \sigma \cdot g \cdot T^4. \qquad (3)$$

The quantity ΔF depends logarithmically on c and therefore changes only slightly. Let us, in a first approximation, consider ΔF to be constant. That is, we equate the right-hand side of the differential equation (2.3) to zero. Us- ing the numerically given parameters that depend on the radiation factor g, we obtain the following time-constant solution

$$T_\infty(g) = \sqrt[4]{\frac{1370(1-\alpha)/4 + \Delta F}{\varepsilon \cdot 5.67 \cdot 10^{-8} g}} - 273 \quad \text{in}^\circ\mathrm{C} \qquad (4)$$

with the mean global albedo α.
Expressed in physical terms, this is a stationary solution.

Mean Temperatures

Global Temperatures for Different Scenarios

The clear signs of human-induced climate change reached new heights in 2024, which was likely the first calendar year to be more than 1.5 ◦C above the pre-industrial era, with a global mean near-surface temperature of 1.55 0.13 ◦C above the 1850-1900 average [3]. Record greenhouse gas concentrations combined with El Nin˜o and other factors drove 2024 to a record heat: the warmest year in the 175-year observational record.

The year 2024 was 1.55 ◦C above the pre-industrial temperature of 13.7 ◦C. Let the temperature anomaly (increase since 1850-1900) at the beginning of 2025 be 1.50 ◦C. Therefore, the absolute mean global temperature was

$$T = 273.1 + 13.7 + 1.5 = 288\ ^\circ\mathrm{C}$$

Due to (4), the stationary temperature increase $\Delta_\infty(g)$ with $\alpha = 0.32$ from the beginning of 2025 on is given by

$$\Delta_\infty(g) = \frac{256}{\sqrt[4]{g}} - 288 \quad \text{in } ^\circ\mathrm{C}. \qquad (5)$$

Without greenhouse gases (i.e., g = 1), we would have the mean surface tem- perature $\Delta_\infty(1) = 256 - 288 = -32$ ∘C!

Solving Equation (5) for the radiation factor g results in

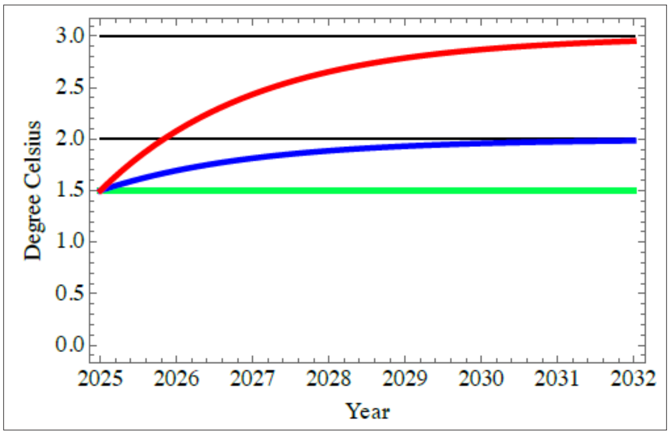
$$g = \left(\frac{256}{\Delta_\infty + 288}\right)^4. \qquad (6)$$

The g-values for the much-discussed scenarios $\Delta_\infty = 0$ ∘, 1.5 ∘, 2.0 ∘, 3.0 ∘C are:
$g_0 = 0.624$, $g_{1.5} = 0.6115$, $g_{2.0} = 0.6073$, $g_{3.0} = 0.600$.

We estimate CE with averaged parameters:

$$C_E \approx 40\ \mathrm{m} \cdot 1500\ \frac{\mathrm{kg}}{\mathrm{m}^3} \cdot 3440\ \frac{\mathrm{J}}{\mathrm{kg}\cdot\mathrm{K}} = 2.06 \cdot 10^8\ \frac{\mathrm{J}}{\mathrm{m}^2\cdot\mathrm{K}}.$$

Here are the solutions for the mentioned three scenarios:



Albedos
Albedo is the fraction of incoming short wave solar radiation that is reflected back to space. We have to distinguish two different kinds:

- **Surface Albedo:** Defined as the ratio of reflected to incoming solar ra- diation measured at the Earth's surface just above the ground.
- **Planetary (Bond) Albedo:** The entire ratio of reflected to incoming solar radiation, calculated from Top-of-Atmosphere (TOA) radiation measurements, i. e. satellites observe looking down on the entire Earth- atmosphere system. The reflection include the clouds as well as the surface reflection.

NASA Earth observatory summarizes decades of satellite measurements (e. g. CERES, EBAF) with a mean planetary albedo of $\alpha = 0.30 \pm 0.01$, a mean Land-only planetary albedo of $\alpha_\ell = 0.32 \pm 0.01$ and a mean Sea-only plane- tary albedo of αs = 0.28 0.01, including the clouds, which have an essential influence (for example the open sea without clouds has the low mean albedo of 0.06).

The Albedo over land is a weighted mean of surfaces with different albedos (Examples without clouds: snow 0.8-0.9, desert 0.3-0.4, forest 0.345). The rela- tively small difference between αs and αA shows that the effect of the clouds is dominant.

The absolute planetary albedo has decreased during the decade 2013-2022 by 0.34%, the average of 0.33% (CERES) and 0.35% (ERA5). The relative decrease was 0.34/0.3 = 1.1 %. The year 2023 showed a mean absolute decrease of 0.44% per decade.

Some causes are lower clouds and loss of higher reflective surfaces throuhg melt- ing sea ice and snow.

Stationary Temperatures for Land and Sea Surfaces
We choose ΔF = 3.0 W/m². For a better understanding, we consider (4) as function f of the variable α and linearize at the point α = 0.32 with

$f(\alpha) \approx f(0.32) + f'(0.32)\cdot(\alpha - 0.32)$, where f' is the derivative of f:

$$T_\infty(g) \approx \left(\frac{254}{\sqrt[4]{\varepsilon \cdot g}} - 273\right) - \frac{92.2}{\sqrt[4]{\varepsilon \cdot g}} \cdot (\alpha - 0.32) \quad \text{in °C.}$$

For an emissivity of ε = 0.98 and g1.5 = 0.6115 we get

T∞(g1.5) ≈ 15.3 − 105 · (α − 0.32)

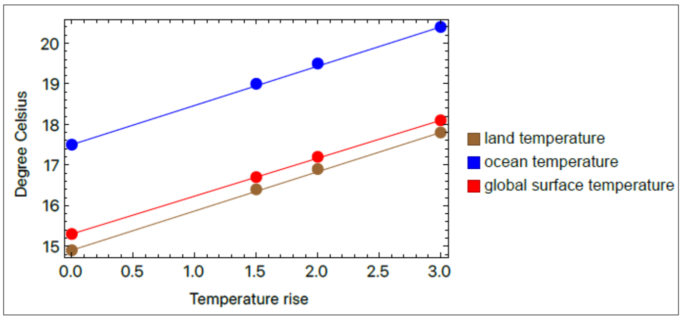
This linearly dependence manifests the sensible dependence of α: A difference of the albino of Δα = 0.01 causes a change of about 1 ∘C.

Formula (4) delivers the following table of temperatures T∞(g) for the 4 scenarions $g = g_0, g_{1.5}, g_{2.0}, g_{3.0}$ with the given albedos α and emissivities ε:

Mean Stationary (limit) Surface Temperatures

Scenario ΔT∞	sea surface α = 0.28, ε = 0.99	entire surface α = 0.306, ε = 0.985	land surface α = 0.32, ε = 0.97
0 °C	17.5 °C	15.3 °C	14.9 °C
1.5 °C	19.0 °C	16.7 °C	16.4 °C
2.0 °C	19.5 °C	17.2 °C	16.9 °C
3.0 °C	20.4 °C	18.1 °C	17.8 °C

Graphical representation (Blue for sea surface, Black for entire surface and brown for land surface):



Here is an analysis for the graph: Substitution of (6) into (4) results in the linear dependence (0 ≤ Δ∞ ≤ 3):

$$T_\infty(\Delta_\infty) = \frac{100}{256}\sqrt[4]{\frac{1370(1-\alpha)/4 + 3}{\varepsilon \cdot 5.67}} \cdot (\Delta_\infty + 288) - 273 \quad \text{in°C.}$$

The numerical value of the factor (the slope of the line) on the left is 1.000 for all numerical pairs (α, ε) in the second line of the previous table: The three lines are parallel.

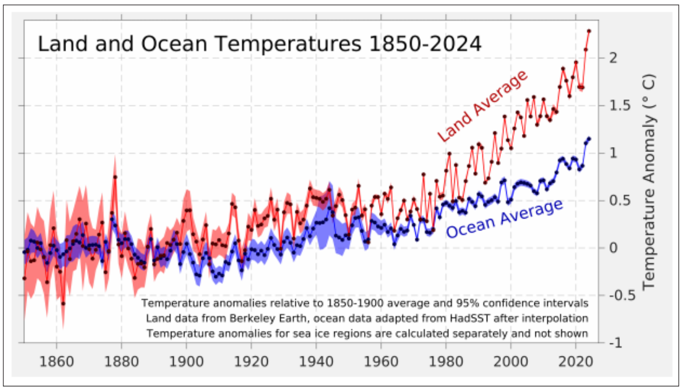
An increase of the scenario Δ∞ by +1.00 ◦C leads to an increase of the global mean surface temperature of +1.00 ◦C for all three surfaces.

The temperature difference between sea surface and land surface is always 2.6 ◦C.

NASA's satellite data for 2024: the mean global temperature was 1.47 ◦C above the pre-industrial mean value. Therefore in 2025, the mean global surface tem- perature is 13.7 + 1.5 = 15.2 ◦C, which is compatible with the value 15.3 for the scenario 0 ◦C of the previous table.

According to Berkeley Earth's analysis, 2024 was the warmst year on record since instrumental measurements began in 1850. The global average tempera- ture anomaly was 1.62 0.06 ◦C above the 1850-1900 pre-industrial period (with a temperature of 13.7 ◦C.) This marks the first time their dataset has recorded an annual average exceeding 1.6 ◦C and the second consecutive year surpassing the 1.50 ◦C threshold established by the Paris Agreement.

Finally, let us consider the temperature anomalies (the temperature increases) in comparence with the pre-industrial period 1850-1900 from Berkeley Earth:



On a first glance, the comparence seems to be contradictory to the former results with higher temperatures of the sea. But the fact that the temperature anomaly of the sea is lower than that of the land surface is primarily due to the differences in how land and ocean absorb, store and release heat. The main causes are:

- Water has a 2-4 times higher specific heat capacity than soil, dersert or rock: this means oceans can absorb more heat without warming up as quickly. Land heats up and cools down much faster than the ocean for the same heat input.
- **Evaporating Cooling:** Over the ocean, much of the incoming heat is used for evaporation, not temperature increase. This latent heat loss moderates ocean warming. Over land, most heat goes directly into raising tempera- ture.
- **Vertical Mixing in the Ocean and Ocean Circulation:** Oceans mix heat vertically, especially in the upper layers (about 100-200 m), which dis- tributes energy downward. Ocean currents can transport heat away from the surface and redistribute it globally. Both effects dilutes surface warm- ing over a much greater depth compared to land, where heat mostly affects just a thin layer.

Of cause, the temperatures, depending on time and geographical situation varies enormous:

- In August 2024, the average surface temperature of the Mediterranean Sea reached 30°C.
- In June 2025, one measured a temperatue of 30.1°C in the Straights of Florida.
- On land, temperatures clearly over 50⁰C were measured in extremly hotdesert regions (USA: Death valley; Middle East: Iran, Kuwait, Pakistan.)In European Russia, extreme cold temperature appear, such as below-50⁰C.

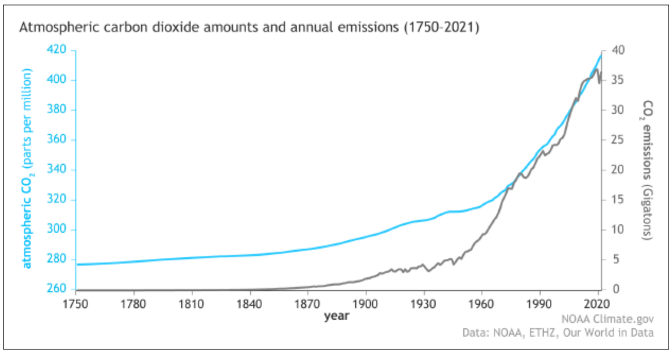
Carbon Budgets for Various Scenarios

Graphs and data are taken from, where more informations can be found [1].

Emissions

The atmosphere does not decompose any pollutants. It accumulates the emis- sions, like a liquid container into which water is repeatedly poured.

The following diagram taken from shows the CO_2 concentration in parts per million ppm and the annual CO_2 emissions in Gt (black curve)[2]: [4].



The total mass of CO_2 emitted during the time interval from 1840 to 2024, over a period of 184 years, is equal to the sum of all annual emissions and is 1,945 Gt CO_2.

Emissions during the period of 2018-2024

year	2018	2019	2020	2021	2022	2023	2024
Gt CO_2	36.7	36.7	34.8	37.1	36.8	37.1	37.4

The mass of CO_2 emitted during the COVID year 2020 only contributed to a reduction of around 6% relative to the previous years 2018 and 2019.

According to the Max Planck Institute on November 13, 2024, increased land use will add another 4.2 Gt CO_2. This results in total emissions of 41.6 Gt CO_2 for 2024, about 11 % of global anthropogenic CO_2 emissions.

[2]Gt means Gigatons = 10^9 tons

Key sources of Land-use-related CO^2 emissions are:

- Deforestation: Cutting down trees reduces the number of carbon sinks, and the burnig or decay of cleared vegetation releases CO_2.
- Forest degradation: Logging or damage that doesn't fully remove forests can stil emit carbon due to soil disturbance and loss of biomass.
- Peatland drainage: Peatlands store vast amounts of carbon. When they are drained for agrigulture or development, they releas CO_2 as the organic matter dcomposes.
- Soil carbon loss from agriculture: Converting forests or grasslands to crop- land or pasture disturbs soil, leading to oxidation of soil organic matter and CO_2 emissions.

Data

Compared to the mass of the carbon atom C, the mass of the CO_2 molecule is greater by the factor 2 (16 + 12)/12 = 3.67, because the relative atomic masses of the oxygen atom O and the carbon atom C are 16 and 12, respectively.

From [5]: p 994 and p.1016:
The Cumulative Anthropogenic Emissions CAE (fossil and land use change) "
for the time span 1850 until end of 2024 totalled CAE = 703 GtC (2580
Gt CO_2). That is 474 GtC from fossil emissions and 229 GtC from land use changes.

For 2023 the emission was 11.10.9 GtC. For 2024, it is projected 11.4 GtC,
2% above 2023."

The following diagramm, taken from Table 8, p.2663 in [6], contains actual data from June 2025:

Estimated Remaining Carbon Budgets in GtC from the Beginning of 2025

Avoidance probability	17%	33%	50%	67%	83%
1.5 ◦C	87	54	35	22	8
1.6 ◦C	169	114	84	65	44
1.7 ◦C	248	174	134	106	79
2.0 ◦C	488	357	286	237	188

The remaining number of years until the budget is used up, can be obtained by dividing through 11.4.

If in the near future, humans would use an annual emission of 11.4 GtC (as projected in 2024) then for the security of 50%, the remainig time span from 2025 on would be about 3, 7, 12 or 25 years for the temperature increases of 1.5, 1.6, 1.7 and 2.0 ◦C After that Net zero emissions had to be achieved abruptly: an unrealistic situation

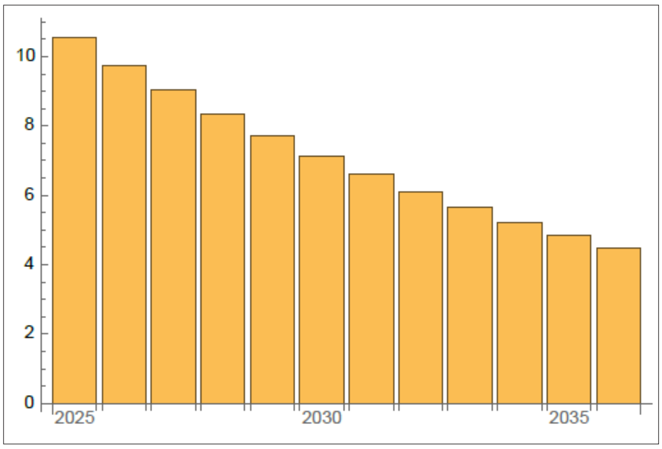
Decreasing Percentage Emissions

If the emission quantity, starting from the value 11.4 GtC for the year 2024, were to decrease by p% annually, then in the following n years, starting with 2025, the total emissions quantity in GtC would be the geometric series

$$A_n = 11.4 \cdot (m + m^2 + m^3 + \dots m^n) \quad \text{where} \quad m = 1 - \frac{p}{100}.$$

The emission Gap Report of UNEP (UN Environment Program) from October 2024 concluded: The global emissions would need an annual drop of 7.5% from 2025 through 2035 to get us back on track for 1.5◦C. Cuts of 37% are needed by 2030 (0.9256 = 0.63), 58% are needed by 2035 (0.92511 = 0.42).

Annual drop of 7.5 % emissions in GtC



From the beginning of 2025 until the end of 2035, the accumulated emission would be A11= 81 GtC. But the budget of 35 GtC for the security 50% is much smaller. Consequence: the report 8 months earlier was too optimistic for the limit temperature of 1.5 ◦C!

Therefore, we refer to the higher limit temperatures of 1.6 ◦C and 1.7 ◦C.

Limit Temperatures 1.6 ⁰C with 50 % Security

For the duration of the 12 years from the beginnig of 2025 until the end of 2036, the total emission would be 85 GtC with an emission in 2035 of$11.4 \cdot m^{11} = 4.8$ GtC.

This means, that the budget for the security of 50 % is completely used up. An abrupt stop of the emission of 4.8 GtC had to be realized from 2036 on!

Limit Temperature 1.7⁰C (see previous table). C with 50 % security The budget is 134

The total emissions for the 21 year period from the beginning of 2025 until the end of 2045 with m = 0.925 would be 11.4 ($m + m^2 + m^3 \dots m^{21}$) = 122 GtC with a remaining small budget of (134-122) GtC = 12 GtC.

But implementing an annual percentage decrease of 7.5% and after 2036 a complete stop is a massive challenge!
Reason: The emission during the COVID year 2020 relative to the previous year 2019 fell only by 6% (see diagram on page ??) and during the following years 2021 and 2022, they remained at the level of 2019!

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