THE FALLACY OF PURE EFFICIENCY GAIN MEASURES TO CONTROL FUTURE CLIMATE CHANGE

Alberto Di Fazio, September, 20, 2000
Astronomical Observatory of Rome and Global Dynamics Institute

Starting from the first decades of the 19th century, with the industrial revolution, mankind (or rather part of it) has experienced a great expansion in science, technology, and economy. The onset of mechanized production, as well as the concept of investment and economic feedback, together with a strong link (financial and political) with scientific and technological development, were the cause of the exponential growth of the World Industrial Product (WIP). The latter quantity is the generalization of the more known GDP, in real terms (i.e. cleaned of inflation), to the world level. Moreover, the WIP is computed in the so-called "physical equivalent", i.e. it is not in mere monetary terms, which depend on the contingent market price, but expressed in equivalent of a pool of goods, materials, fuels, high-tech prime materials, etc., that are vital to human technological and economical development. For these reasons, the growth of the WIP marks the economic growth in real physical terms at world level. The growth has accelerated in the last century and we can see the historic data plotted in Fig.1. A part from temporary stops or oscillations due to wars and/or oil shortages ("oil shocks"), the overall trend has been rather stable, being an increasing exponential with the extremely rapid doubling time of only about 17 years. The economic growth has brought in - of course - growing needs of raw materials, growing pollution rates, growing use of wood (with consequent growing deforestation rate) and - most important to the growth itself - a fast-increasing need of energy.[2] We know that more than 95% of the energy used by human kind is obtained by burning fossil fuels (oil, gas, coal) and we also know that burning the above mentioned carbon-based fuels inevitably produces carbon dioxide (CO_2). For these reasons, the economic growth - i.e. the exponentially increasing WIP - has implied a correspondingly exponentially increasing emission rate of CO_2 in the atmosphere (see Fig. 2) and an exponentially increasing CO_2 concentration since about 1800 (see Fig. 3). Having understood the evident logical connection that has held so far between the economic growth and the growth of the CO_2

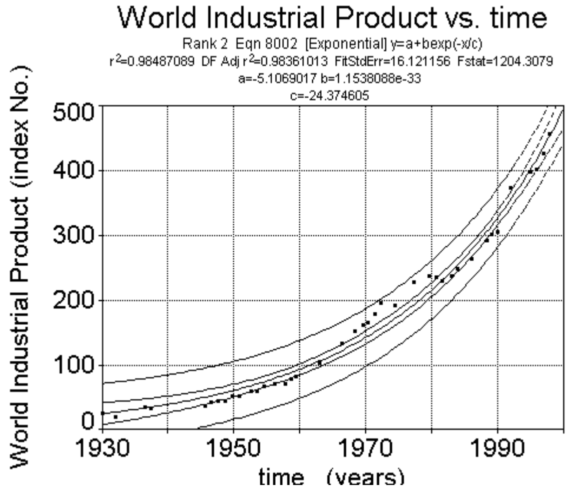

Figure 1 The World Industrial Product (deflated world "GDP" in real value - i.e. in physical equivalent). The unit is an index number, set as base=100 in 1963. To obtain - with good approximation- the value in US$ (1990 value) multiply by 212.1 billion. Doubling time≅17 years. Data: The World Bank (hereafter WB); stats.: GDI[1].

---

[1] GDI: Global Dynamics Institute, a new institute of Italian scientists - members of staff of several Italian governmental scientific Intitutions - working on climate change.

[2] up to now - since the economic growth has been due essentially to the industrialized countries - the contribution of the developing countries to the growing raw materials and energy consumption rates has been quite low, compared to the developed countries. This has been true notwithstanding the exponential growth of the population, mainly from the developing countries. The described situation will not hold anymore in the coming near future (roughly 2 decades from now) when the consumption rates of some leading developing countries will become comparable with those of the industrialized countries (or greater).

emission rate, let us evaluate quantitatively the “strength” of the implied correlation: we can do this by looking at Fig. 4. The correlation between the WIP and the CO_2 emissions is astoundingly high, as the correlation coefficient is r≅0.995, i.e. practically 1 (total correlation).

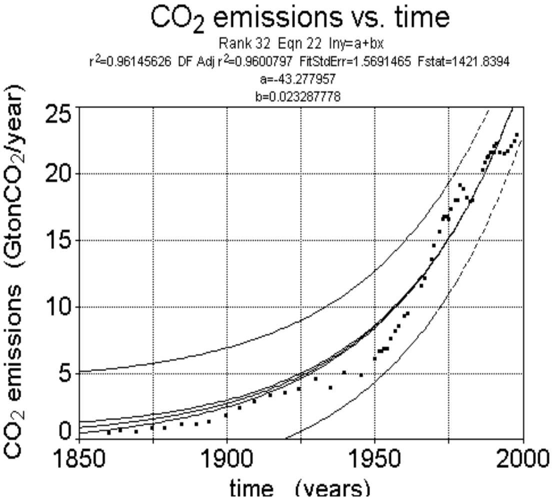

Figure 2 The CO_2 emissions (in CO_2 mass units: to obtain GtonC - i.e. Carbon units - multiply by 12/44 ≅ 0.2727). Doubling time≅29 years. Data: CDIAC; stats.: GDI.

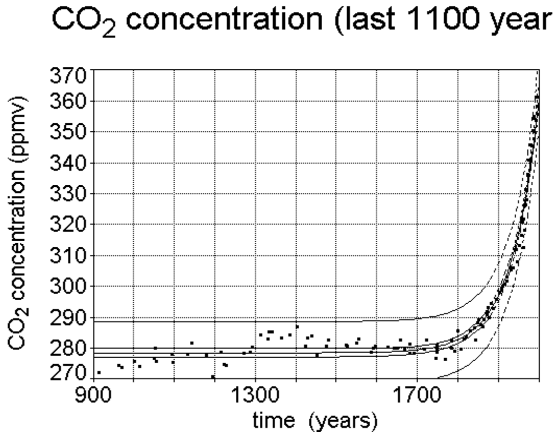

Figure 3 The natural CO_2 variations and the anthropogenic increase after the industrial revolution in 1800. In this graph, and in all the others showing a best-fit curve to the data, the continuous lines above and below the fit are the 99% confidence levels (inner lines) and the 99% prediction levels (outer lines from the fit). Data from the IPCC (1995); CDIAC[3]. Statistics: GDI 1997

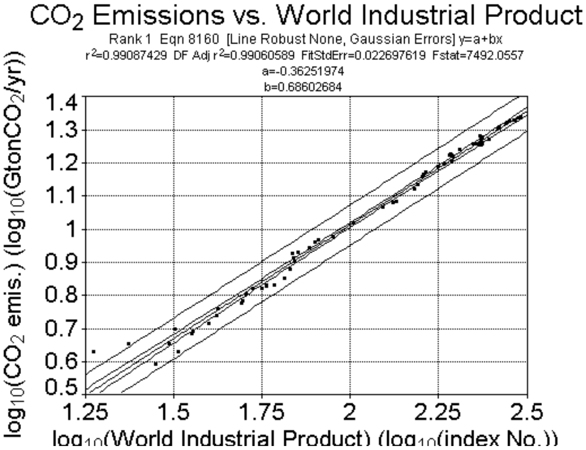

Figure 4 The impressive, strong correlation between the global CO_2 emissions and the world industrial product. The implied correlation coefficient is r≅0.995. Data from: CDIAC; WB. Correlation and stats.: GDI.

We now know the implications of such a rapidly growing rate of input of the atmosphere. The last report of the IPCC[4] (IPCC Second Assessment Report[5]) has clearly shown a whole series of impacts and damages to the environment, to the agriculture, to human health, and to the economy, that are likely to take place as a consequence of the climatic changes induced by the greenhouse effect produced by the increased CO_2 concentration in the atmosphere. In particular, if we continue “*business-as-usual*” (BAU), the atmospheric sea-level temperature will reach in the next century levels not seen in the latest 35 million years (see Fig. 5, which shows a data set on temperature, relative to the earth’s climate as it was more than 100 million years ago.).

Before we continue our description of the link among CO_2 emissions, technology, and economy, we must stress the speed of the above described process of input of CO_2 in the atmosphere.

---

[3] CDIAC: Carbon Dioxide Information Analysis Center

[4] IPCC: Intergovernmental Panel on Climate Change, estabilished in 1988 by the General Assembly of the UN with the World Meteorological Organization and the United Nations Environment Programme, and with the collaboration of the ICSU (International Council of Scientific Unions)

[5] SAR: Second Assessment Report, IPCC, 1996, Cambridge University Press

The equilibrium temperature attained by the atmosphere depends on the concentration of several greenhouse gases (GHG) in the atmosphere itself, through what is known as the natural greenhouse effect. The latter guarantees, e.g., that the present average temperature on the planet is about +15°C instead of about -20°C (below zero). From the palaeoclimatological data in our possession, we know that about 100-180 million years ago most of the carbon (which was found stored -at the beginning of 1800- in the ocean and in the fossil fuel deposits) was initially in the atmosphere, under the form of CO_2.. The surface of the earth was covered with forests. The temperature was about 10°C warmer than now, the sea level was very likely about 70-90 meters higher than now, and there were practically no ice caps in the polar regions. In other words, it took 100-180 million years, for the photosynthesis to remove a large portion of the carbon from the atmosphere, storing it into the plants' tissues under the form of several kinds of C-H chemical bonds, and contemporaneously storing solar energy in such forms of reduced[7] carbon (the C-H bonds). An analogously long time took the process of uptake of CO_2 in the oceans. The fossil fuels now used by humanity have been created from decomposition and putrefaction processes of the chlorophyllian mass of those forests that removed a large part of CO_2 from the atmosphere. The fact is that - since the industrial revolution - we are putting back that carbon into the atmosphere, burning fossil fuels in order to get energy, in only 100-150 years. Humanity is thus displacing the carbon back into the atmosphere at a rate which is *a million times faster* that the natural inverse process described above, which stored the carbon and the energy. The climate equilibrium states are thus perturbed at an umprecedented rate, and can imply a possibly "runaway" and/or devastating enhanced[8] greenhouse effect: the unsustainability of such human process of energy generation is scientifically evident.

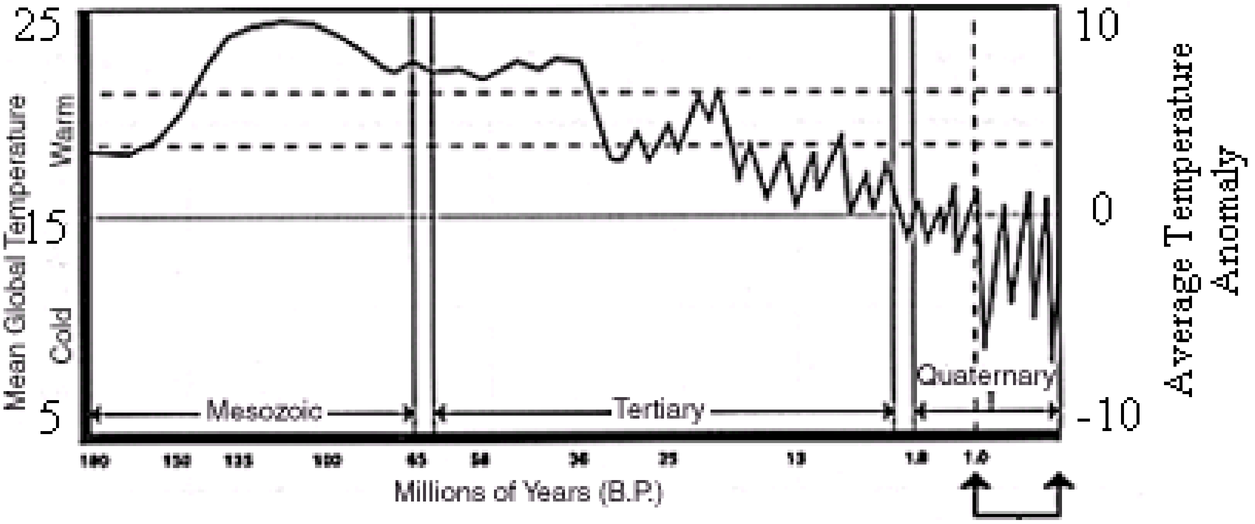

Figure 5 Global palaeoclimatic temperature behaviour from 180 million years before present up to now, in three different time scales. The Vostok ice core data cover roughly the last half (440,000 years) of the 1 million year interval marked with the arrows. (Data from, e.g., IUCC[6], CDIAC or NGDC)

---

[6] IUCC: Information Unit on Climate Change, now IUC: Inf. Unit. for Conventions/UNFCCC Secretariat

[7] reduced carbon: Carbon is in the reduced form in the bond with hydrogen, as the bond-electron is closer to carbon than to hydrogen. Carbon is in the oxidized form in the bond with oxygen (e.g. in the CO_2 molecule) as the bond-electron in the C-O bond is displaced towards the oxygen atom.

[8] enhanced greenhouse effect, so called in order to distinguish it from the natural one. The enhanced greenhouse effect is the process which is caused by the anthropogenic GHG emissions, and which produces the climatic changes that humanity is trying to mitigate.

We now show how mankind, through a fast scientific and technological development, has bettered the efficiency of the energy generation process by building machines that obtained more and more “work” per quantity of fossil fuels burnt (or the same work -usable energy- burning less fossil fuels, i.e. reducing the waste in unusable thermal energy). We should here explain that the work - and potential energy - are the fundamental ingredients to produce economic wealth. In other words, the GDP - or WIP at world level - is proportional to the usable forms of energy available - work and potential energy. An evident physical variable to measure efficiency in using fossil fuels is then the usable energy per unit of fossil fuels burnt. Equivalently, another variable is: world industrial product per unit of emitted CO_2 ($/ton$CO_2$). This is the variable beloved by economists and politicians, although we will show that it hides some crucial physical facts that invalidate most of the current economic analyses on the efficiency gain policies thought to be useful to combat climate change. In Fig. 6, we can see how the efficiency has indeed increased in the present century, under the effect of technological development and economic growth. How long can the efficiency still grow? The cathegoric (almost religious) answer of most of the mainstream economists is: *forever*! We must note that most of the politicians also think so, which can be certainly recognized as the strongest ever ideology present in the planet’s politics.

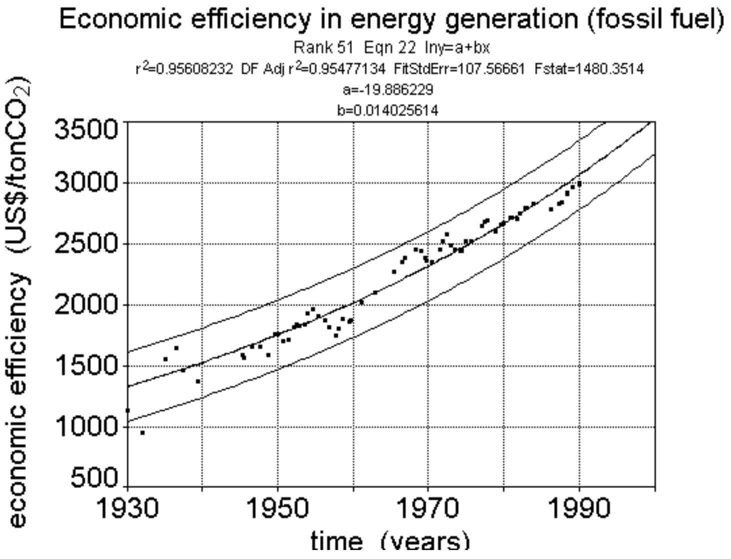

Figure 6 The historical increase of the economic efficiency in the generation of energy through fossil fuel burning. In 1995, the corresponding thermodynamic efficiency, η_T, is approximately: η_T=0.25 (or 25%). This leaves only a few decades of increase allowed by the Second Principle of Thermodynamics.

Let us finally analyse - in a quantitative fashion - the myth of the so-called “efficiency gains” policy.

In the process of defining policies of CO_2 emission reduction (and, in general, what is known as the Quantified Emission Limitation and Reduction Objectives) great emphasis is being put by several economic environments (e.g. the IMF, the World Bank, as well as several governments) on the possibility of reducing CO_2 emissions: i) without renouncing to the massive use of fossil fuels; ii) without limiting or reducing the growth rate of the World Industrial Product (WIP). In this regard, it is pointed out that increasing the efficiency of the energy production, and thus increasing the amount of industrial product per unit emissions - i.e. increasing the quantity ΔWIP/ΔE [9] (in $/ton), where WIP is in G$/year and E are the emissions in Gton/year - we obtain obviously the same WIP burning less fossil fuels, and thus emitting less CO_2. In principle - and *remaining only within the economic assessment*- the above statement seems to be more than obvious. But, alas, actually **it is not so.** In fact, the quantity $\varepsilon=\Delta$WIP/ΔE , which is usually defined as the “economic efficiency”, is actually related to the **thermodynamic efficiency, η.** The quantity ε is simply proportional to the thermodynamic efficiency η: $\varepsilon=\eta k/\alpha_c$, where k is a thermodynamic constant and α_c is simply the carbon content of the used fuels. As it is well known from the Second Principle of Thermodynamics, the thermodynamic efficiency η can never reach the value 100%, and - in the real world - it is actually limited to values at most of the order of

---

[9] the ratio ΔWIP/ΔE is the amount of industrial product (a sort of deflated, “absolute” GDP) produced per CO_2 emitted.

60%-80%. This fact, *induced by a natural law,* together with the fact that the WIP is growing (since about 150 years) exponentially with a doubling time of about 17 years (i.e. an e-folding time of ≈25 years) causes the emissions to be reducible **only by a very limited amount: a factor ≈ 2-3.5.**[10] In fact, the present thermodynamic (TDN) efficiencies, reached after the previous 150 years of industrial and technological development, range in the interval [15%-50%]. The first value in the range is characteristic of the thermal engines presently installed in the motor vehicles and in the cargo ships, while the latter one corresponds to the best presently obtainable TDN efficiency of high-technology experimental high-temperature gas turbines. Being the maximum value obtainable for η less than ≈ 80% - and this turns out to be wildly optimistic - we can easily see that *only a very modest factor can be gained in reducing the emissions by mere efficiency gains.* In order to quantitatively perform this assessment, GDI has set up a numerical code - the "Effqelro97". Using this program, we have computed various scenarious for the emissions and for the resulting CO_2 concentrations. This has been done assuming that the growth rate of the WIP is kept business-as-usual, i.e. under the assumption that the governments do not slow down or modify their countries' economic growth rates. In fact, we are here trying to assess the magnitude of pure efficiency enhancements in attempting to reduce CO_2 emissions, in other words, in trying to reduce the emissions $E=WIP/\varepsilon$ only by increasing the denominator ε[11]. To the regret of most economists, this is of course *an impossible battle,* as the numerator, the economic growth rate, is required to grow forever, and in exponential fashion, while the denominator, the efficiency, can "only" grow by a factor 2-3.5! Furthermore, in order to study the *maximum reduction possible* without reducing the economic growth rate and/or reducing the amount of fossil fuel consumption rate, we consider the maximum possible reduction of coal and oil usage, in favor of natural gas. In fact, the latter has the lowest emission coefficient among the possible fossil fuels (~15 Kg C/GJ [12]against ~26 for coal and ~20 for oil). In doing this calculation, we optimistically assume that: *i)* all the industrial sector (responsible for ~16% of the CO_2 emissions) could be run on natural gas, as well as all the thermoelectrical power generation sector (23% of the total sources) and all the residential sector (~16%), while: *ii)* the transportation sector can be run on natural gas only in its land traffic fraction (~73% of the total transportation sources, which means ~16% of the total CO_2 emissions); *iii)* the deforestation and agricultural sector -of course- cannot be switched to natural gas. These assumptions allow us to switch from the present contributions to CO_2 emissions due to coal, oil, and natural gas (respectively 34.6%, 42.3%, 23.1%) to the "best" attainable fractions, namely 10% for coal, 12.3% for oil, and 77.7% for natural gas. Taking into account the above fractions and the relative emission coefficients, we obtain a maximum possible reduction factor of the emissions if we use the fractions described above. The fact that the obtained reduction factor is indeed the maximum possible is also strengthened by the super-optimistic assumptions made on the amount of natural gas usable. The obtained factor is ~1.28, which corresponds to a ~29.9% emission reduction through the use of natural gas wherever possible. The latter reduction is attained, of course, *only if* the shift to natural gas were applied *immediately.* In fact, any delay would increase the emissions, reducing or eventually making the gain vanishing, if the delay is too long and the economic growth too fast.

The results are very clear and instructive, and are shown in Figs 7,8, and 9. They correspond, respectively, to the following scenarios:

A) the governments start in the year 2000 policies aimed at increasing the efficiency, and succeed in bringing it to the natural maximum limit in 20 years (a 210% increase in efficiency in 20 years!); contemporaneously, a gradual shift to the use of natural gas (as described above) takes place

---

[10] Although this is a "very limited amount" with respect to the ever-growing GDP, which doubles every 17 years, it still represents an enormous efficiency increase with respect to the efficiency gains presently considered by the economists and by most politicians: the amount we mentioned corresponds to a max efficiency gain of 250%.

[11] ε: the economic efficiency in \$/tonCO_2

[12] Kg C/GJ: kilograms of carbon per billion Joule.

in the same period (Fig. 7a: resulting emission trajectory; Fig. 7b: resulting CO_2 concentration). The drastic efficiency gain measures achieve a delay of only 24 years for the moment when the CO_2 concentration reaches 500 ppmv;

B) same as above, but starting in the year 2010, as the US government seemed to be backing at AGBM5[13], and as implied now by the Kyoto Protocol. The 10 years delay in starting to push the efficiency gains to their natural limit lowers the maximum attainable increase in efficiency to 139% . The above mentioned delay is lowered to less than 19 years (results in Figs 8a and 8b);

C) as above, but starting in 30 years from 1995, as proposed by some of the scenarios by WRE[14], who claim that continuing now to increase business-as-usual, while reducing "in the future", will allow much faster and low cost measures, based on better technology available by then. Adopting such a large delay, and accounting for the limit imposed by the Second Principle of Thermodynamics, lowers the maximum obtainable efficiency gain to a mere 90%[15]. The efficiency gains - delayed by 25 years with respect to scenario A) - accomplish a negligible delay in the growth of the CO_2 concentration (results in Figs 9a and 9b).

---

[13] AGMB5: the fifth session (1997) of the climate negotiations of the "Ad-hoc Group on the Berlin Mandate", a task-group estabilished at the UN climate summit in Berlin, 1995, in order to strengthen the commitments of the industrialized countries to reduce their CO_2 emissions.

[14] WRE: Wigley, Richels, and Edmonds, see IPCC SAR.

[15] WRE probably did not take into account that, in 30 years from now, the technology may be better, but the BAU growth in the economy may request - in order to abate the emissions - efficiency gains larger than the maximum allowed by the Second Principle of Thermodynamics.

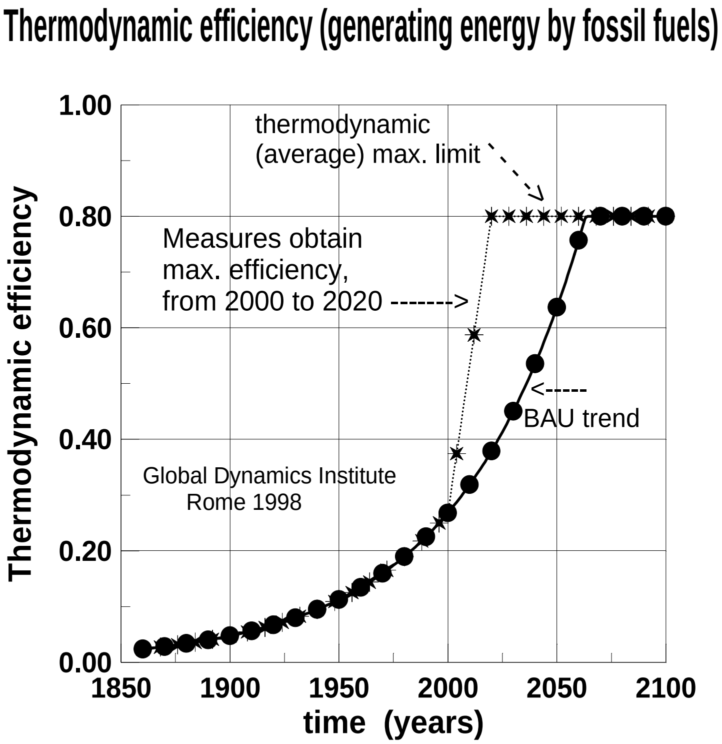

Figure 10 The thermodynamic efficiency, corresponding to the economic efficiency in energy generation from fossil fuels (see Fig. 6), vs. time in years. The curve marked by full circles is the present BAU trend, while the line marked by the stars represents the political-economical measures to push the efficiency to its physically allowed maximum, starting in the year 2000 and ending in 2020. See scenario A. Data computed by GDI, 1997.

In all Figs. 7-9, the units used for the emissions are Gton/year of CO_2: to convert to the units GtonC/year (e.g. used in the IPCC SAR) the emissions have to be multiplied by the ratio 12/44 (the ratio of the atomic weight of carbon to the molecular weight of the CO_2 molecule).

In Fig. 10, we can see the evolution of the thermodynamic efficiency as it is pushed to its physically allowed maximum, in the assumptions of Scenario A. The horizontal line at 0.8 marks the maximum attainable TDN efficiency due to the Second Principle of TDNs).

For all scenarios the maximum η was taken η=80%. It is well-known that -for any kind of machine and/or burner- the exhaust gases come out of the combustion chamber at the temperature characteristic of the given oxidation reaction, i.e. several hundred degrees C. Furthermore, the materials out of which the combustion chambers are made can be more or less heat-conducting, but -on one side- there can be no materials which do not conduct heat at all, as the brownian motion is based on atomic collisions and reticular oscillations, and -on the other side- the substantial cooling needed to avoid structure distortion and melting will necessarily carry out substantial fractions of energy. *All this is at the expence of the amount of work produced by the machine.* In the light of all these reasons, the above value for the TDN max efficiency (η) used in our calculations, 80%, is extremely optimistic. Moreover, the real possibility of implementing the needed new technologies, the actual costs needed to implement the technological enhancements, the actual possibility for the consumers to massively buy the new more efficient equipment, and, finally, the feasibility of the implementation of the new technologies within the proposed time-frames, makes the examined scenarios even more optimistic.

From the results of the computations corresponding to scenarios A), B), and C), displayed in Figs.7,8, and 9, we can easily see that the policies based **only** on the efficiency gains, as well as those based on the additional shift to natural gas **do not allow any significant - or appreciable - control of the coming climate crisis.** Of course, increasing the efficiency is a positive factor- but it is not at all determinant in solving the problem. The real - and inevitable - conclusion is that: *either we switch to non-fossil fuel sources of energy or we limit the world industrial product, or both in some proportion.* **Nature -*not* the tecnological know-how or the markets - offers no other choice**.

It is now clear that relying on efficiency gains and technological shifts alone, the governments and the economic institutions in the negotiation process are certainly underestimating what will be the resulting magnitude of the greenhouse effect and all its consequences on the ecosystem, the society, the health, the future of our species.

Alberto Di Fazio is a theoretical astrophysicist at the Astronomical Observatory of Rome, where he investigates star formation and galaxy formation via multiphase radiative hydrodynamical modelling. A. Di Fazio directs the Global Dynamics Institute, a new institute of Italian scientists working on climate change, accredited at the Conference of the Parties to the UNFCCC.

E-address: difazio@oarhp1.rm.astro.it

CO2 Emissions (Gton / year)

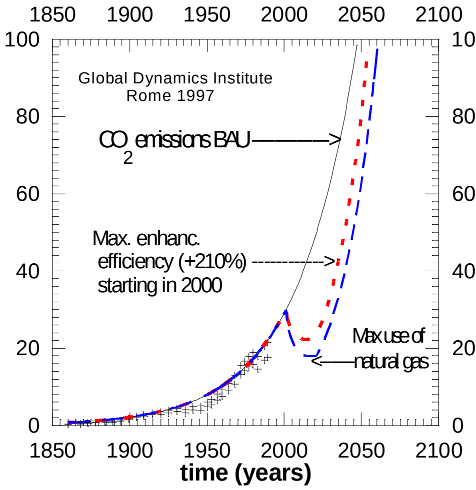

Figure 7a: measures start in 2000, and reach max. effic. (+210%) and massive use of nat. gas in 2020

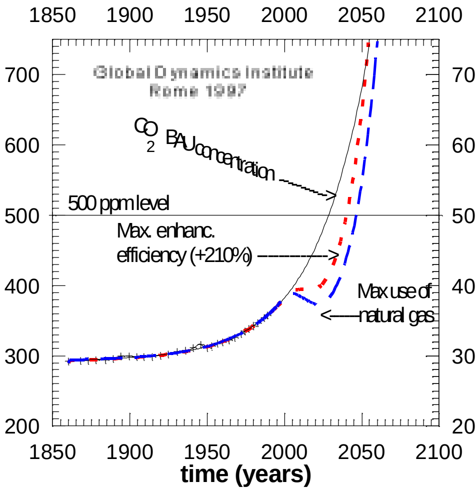

Figure 7b: With respect to no measures, CO_2 conc. reaches 500 ppmv with a delay of only about 24 years.

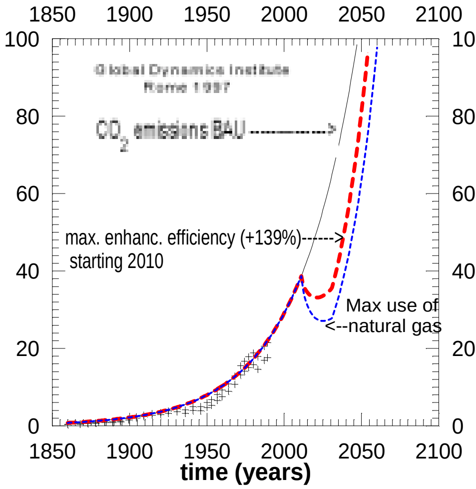

Figure 8a: measures start in 2010, the max. efficiency gain attainable is now only 139%, reached in 2030.

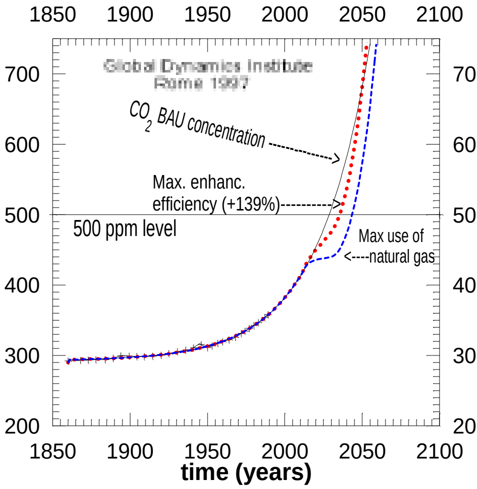

Figure 8b: The obtained delay in reaching 500 ppmv is reduced to less than 19 years

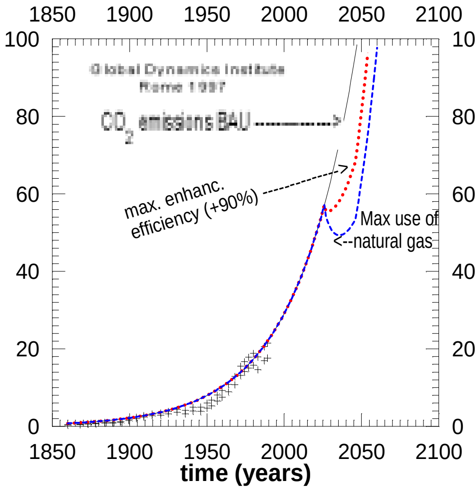

Figure 9a: measures delayed until 2025 impose max efficiency gains attainable then (+90%) and massive use of natural gas. Max efficency reached in 2045. To convert to GtonC/year, multiply by 12/44 ≅

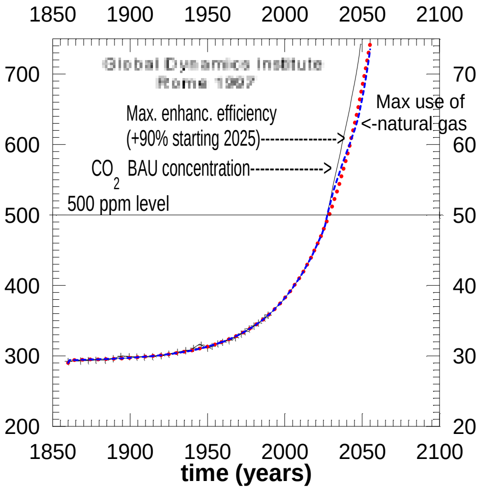

Figure 9b: compared to no measures, the delay in reaching 500 ppmv becomes negligible, due to the high increase of the WIP (world industrial product) meanwhile.

CO2 Concentration (ppmv)