A quantitative (out)look at the future of energy

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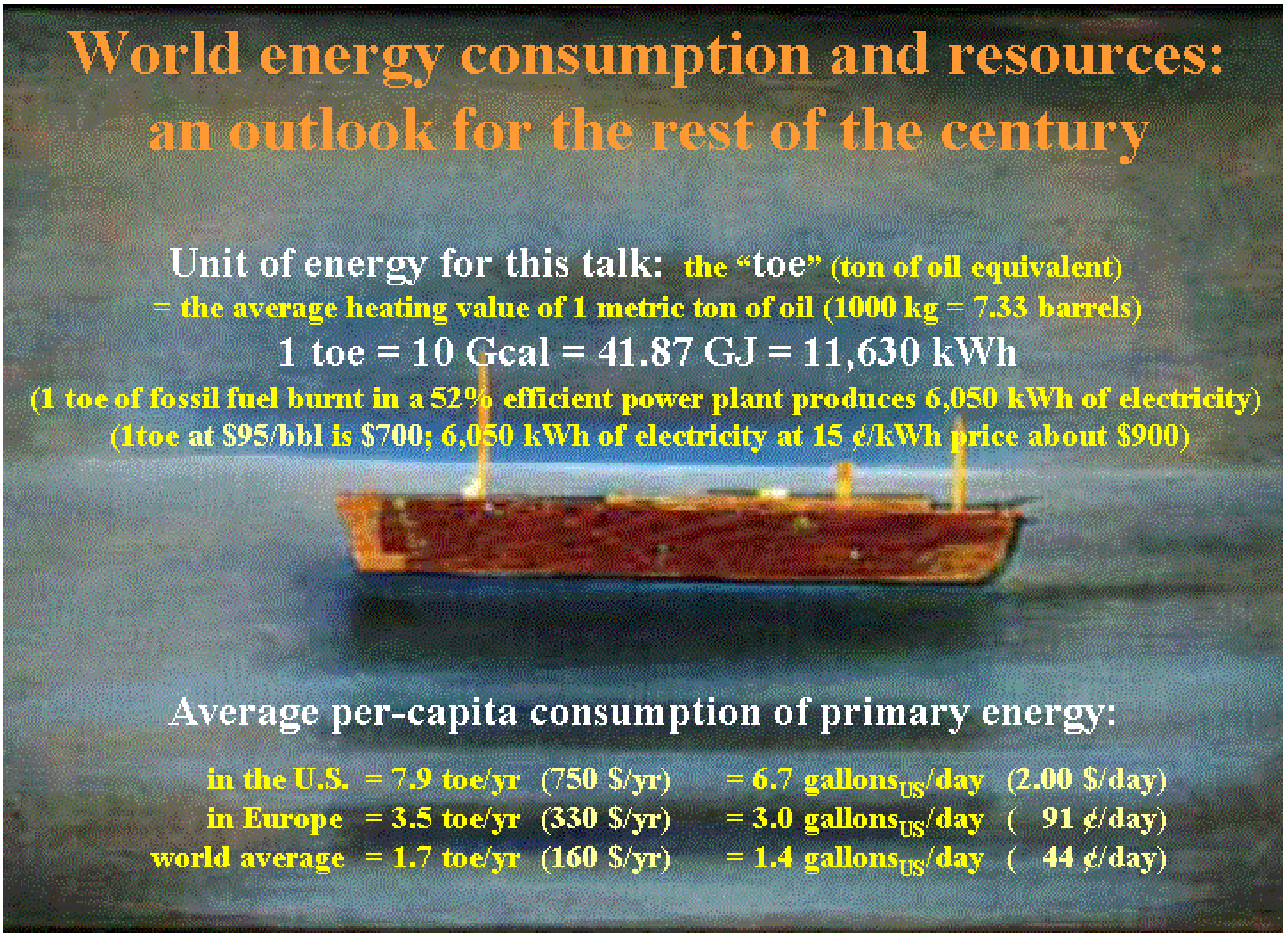
World energy consumption and resources: a plausible outlook for the rest of the century. The numbers you should know before you venture to talk about energy, let alone to take decisions...

Text and Slides of the talk delivered at MIT by Prof. **Gian Paolo Beretta** (Università di Brescia, Italy) during IAP on Friday, Jan.11, 2008, Room 6-120, 9:00-10:30 am.

The **discussion** is not transcribed below, but the VIDEO of the discussion, and the VIDEO and AUDIO of the entire talk are available at http://web.mit.edu/beretta/www/Energy-MIT-IAP-Jan08-text-and-slides.htm

The first part of the talk is based on the following article and references therein (please refer to it if you need to quote from this talk): G.P. Beretta, World Energy Consumption and Resources: an Outlook for the Rest of the Century, International Journal of Environmental Technology and Management, Vol. 7, 99-112 (2007). Also this reference can be downloaded at the link given above.

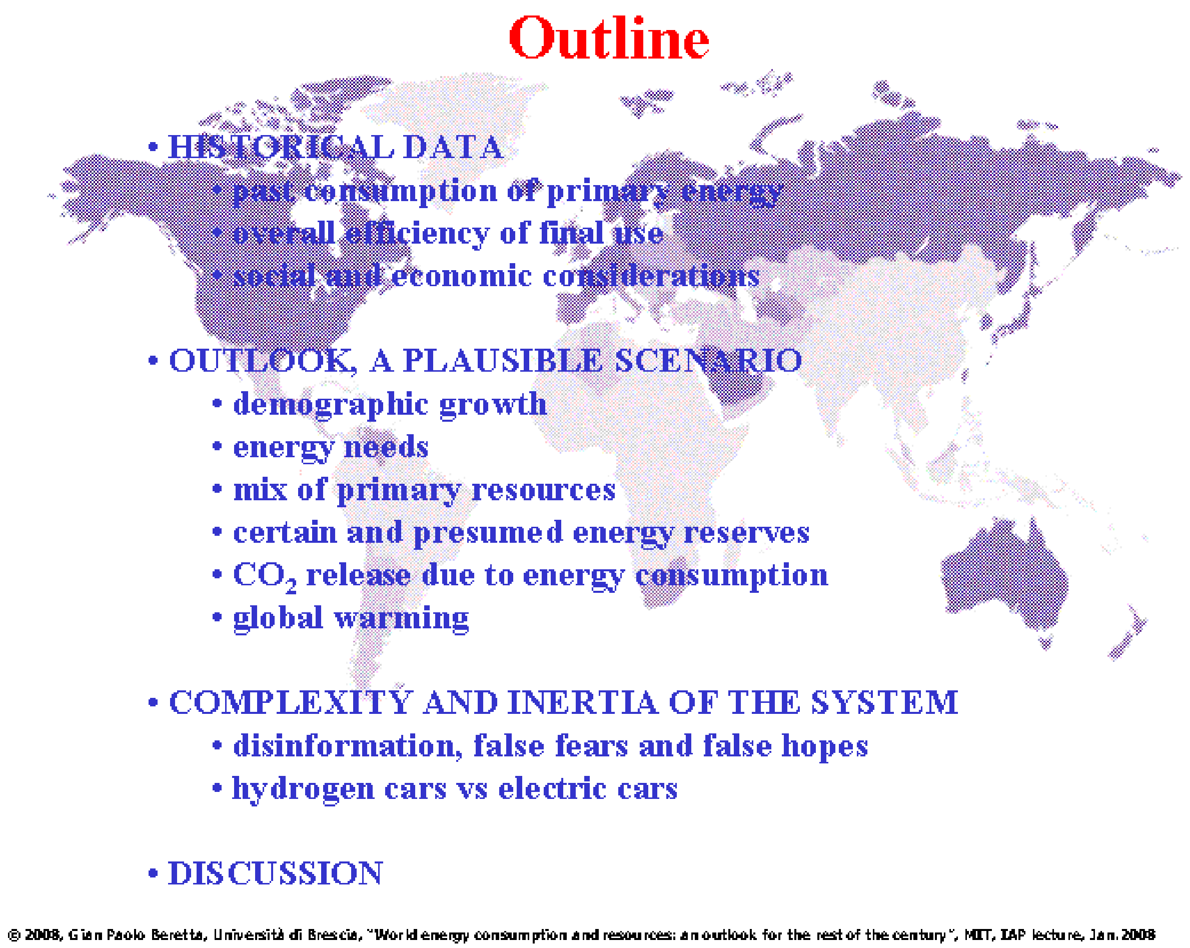


1.

Before we start, this initial slide defines the unit of measure of energy that is best suited for the purposes of our discussion today: the ton of oil equivalent. The toe. That is, the average heating value of one metric ton of oil, which is about 7.3 barrels. In more standard units, this amount of energy is equivalent to 10 billion calories, about 42 billion Joules, about 12000 kWh. Just to fix ideas, if one toe of primary energy is used in a 52% power plant, it produces slightly over 6000 kWh of electricity; if the primary energy source used is indeed oil, at $95/bbl it costs $700, and the electricity produced sells in Massachusetts at about $900.

The current global yearly consumption is about 11 billion toes. Not a very gentle tiptoeing on the surface of our planet!

The average per-capita consumption of primary energy is 7.9 toes per year in the US, almost seven gallons per day. In Europe it is less than half. The world average is less that a quarter.

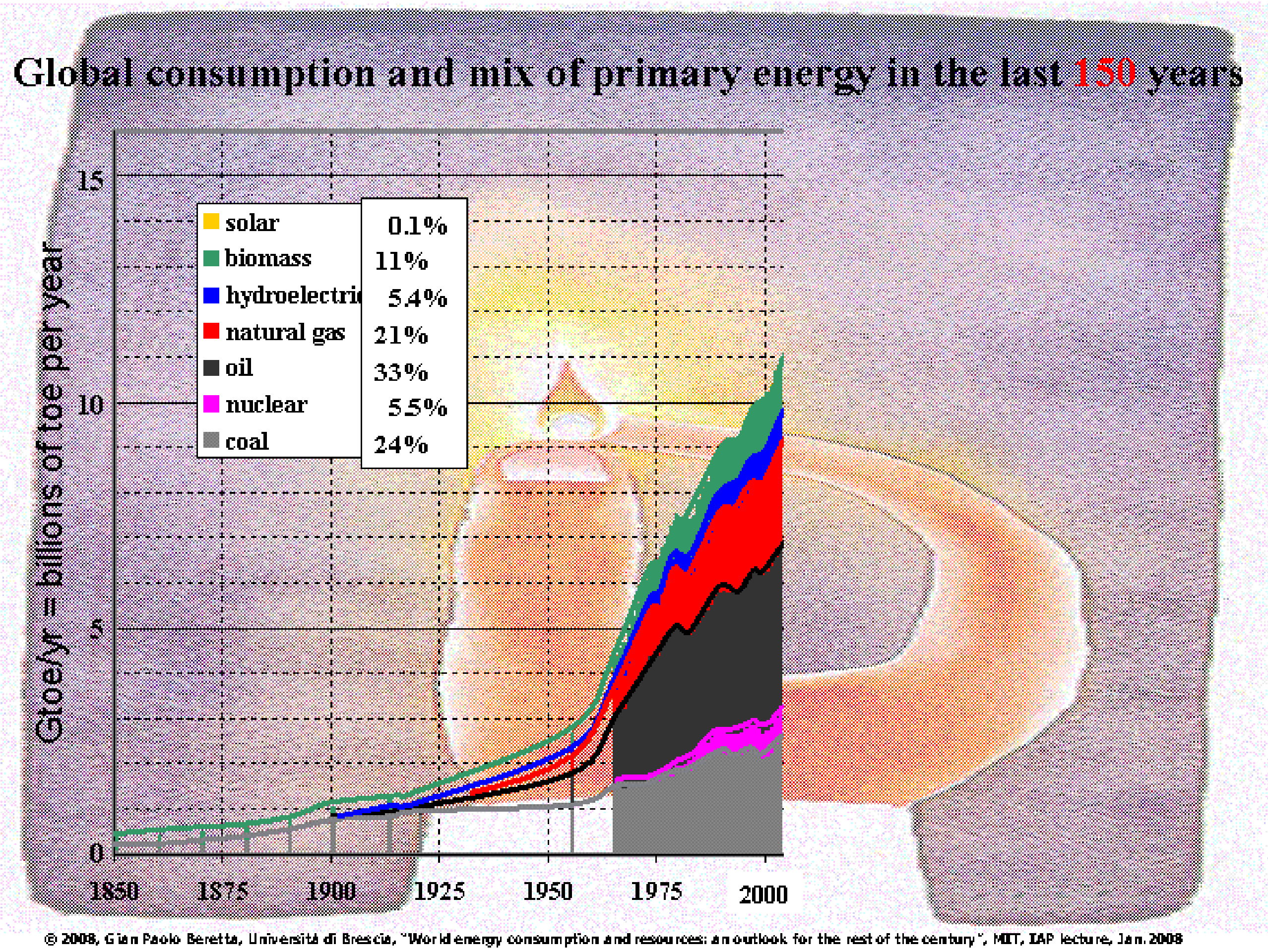


2.

The outline of the talk is as follows. We first review historical data on past consumption of primary energy, and on the overall efficiency of final use. We then single out some social and economic data and considerations useful for an outlook, to infer a plausible scenario about demographic growth, energy needs, and mix of primary resources. We then compare this scenario with data on currently proved and presumed energy reserves on our planet, to decide whether we are really running out of fuel as media and politicians keep saying. Next, we use the scenario to infer how much carbon dioxide we will release due to primary energy consumption during the rest of the century, and what impact this will have on global warming.

We will conclude with some comments on the complexity and the inertia of our energy and economic system, and about the dissipative role of disinformation, false fears and false hopes of simple solutions. As an example, I will show the numbers on a comparison between the energy and global warming perspective impact of hydrogen cars vs electric battery cars.

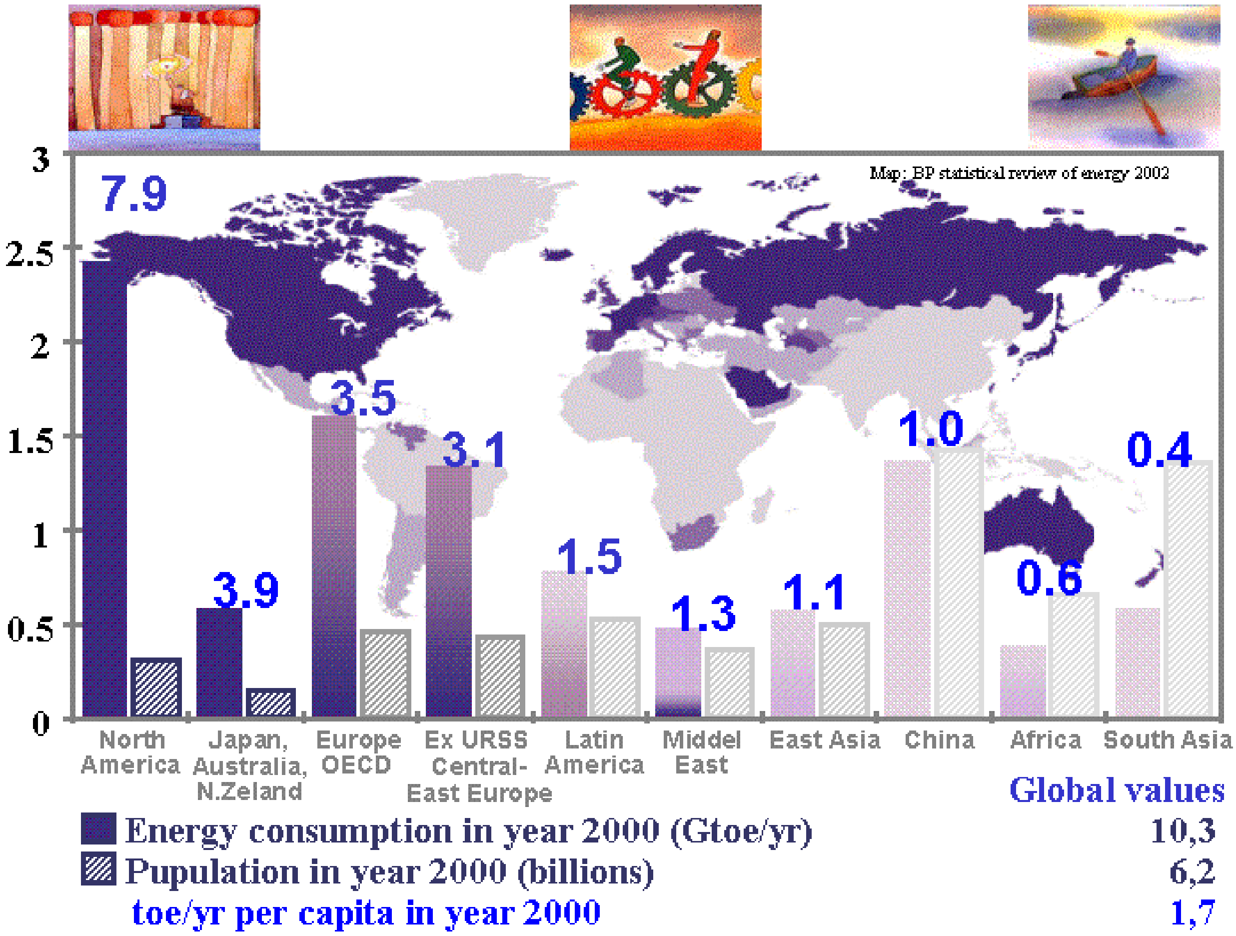
I will talk for about 45 minutes and then we will have plenty of time for discussion.



3.

Let's start with the global energy consumption over the last 150 years. Today, the global demand of about 11 billion toes per year is covered for 78% by fossil fuels (33% oil, black in the figure, 21% natural gas, red; 24% coal, gray), 5.5% by nuclear fuels (violet), 17% by renewable sources, mainly hydro (blue), 5.5%, while the remaining 11% are non-commercial biomasses (green), like wood, hay and other forage which in rural-economy countries are still the main resource. These rural biomasses are not counted in the usual energy statistics by oil companies, but in a global framework they should be considered, because at least 2 / 3 of human kind still lives in rural and craft economies not much different from those of the european middle age. Consider hay for animal feed. Not more than 150 years ago, in the United States two-thirds of the mechanical work came from horses, and in 1925 the horses were still about 30 million.

The direct use of solar energy (yellow in the graph) is currently estimated at about 10 million toes (millions, not billions) and so, on the scale of this chart it is invisible, since it meets less than one thousandth of the global need.

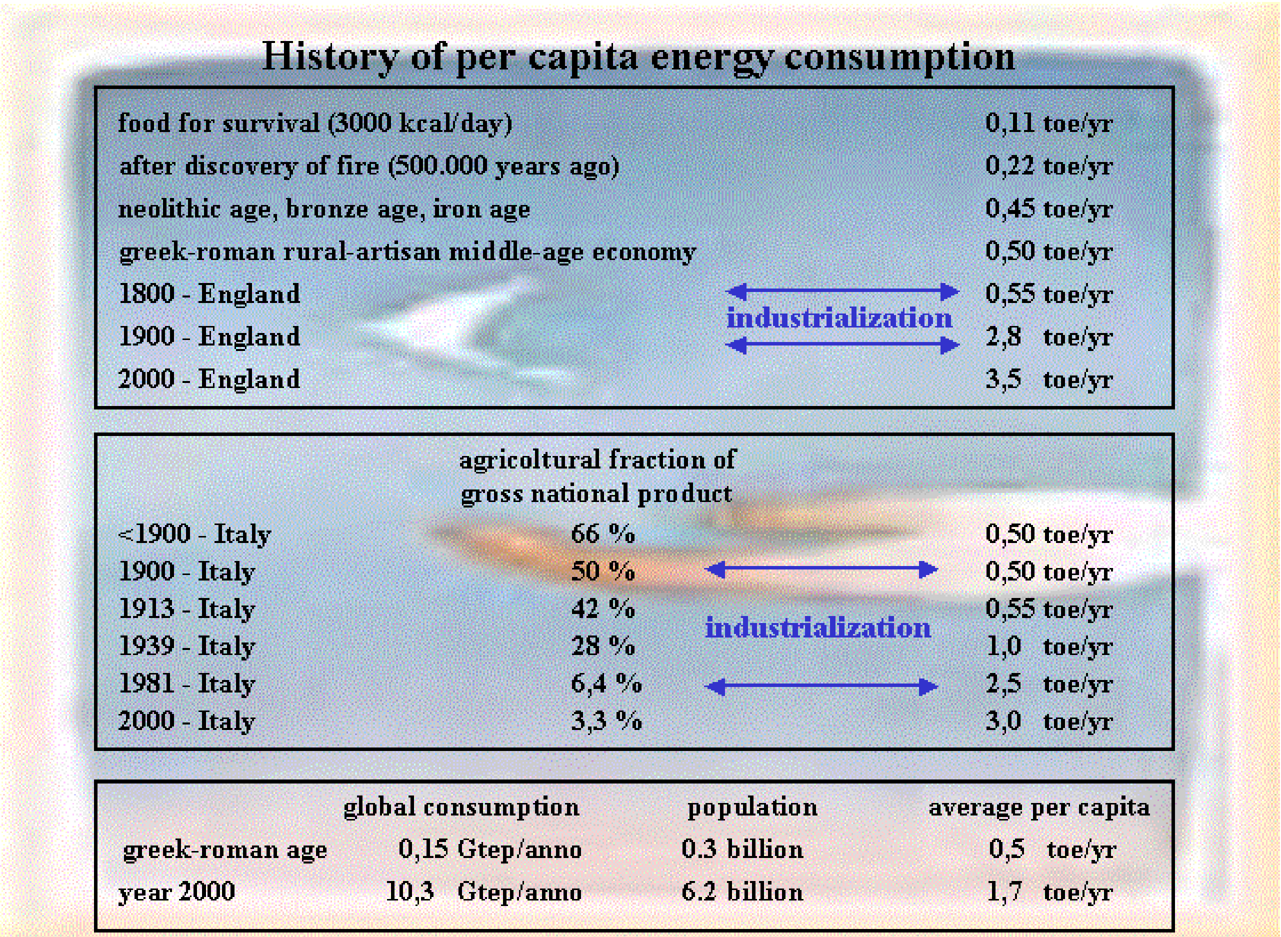


4.

In this chart, which refers to year 2000, nations are divided into 10 groups homogeneous by type of economy, industrial development and intensity of energy consumption. For each group of nations, the left bar is the yearly consumption in billion toes; while the right bar represents the population, in billions; and the number in blue at the top indicates the intensity of energy consumption, expressed in toes per year per capita. Globally, in year 2000, about 6.2 billion souls consumed about 10.3 billion toes, with an average intensity of 1.7 toes per year per capita.

The graph shows very pronounced disparities in the intensity of consumption. It varies widely from country to country, depending on many factors such as the different geographical and climatic conditions. For example, Sweden has a harsh climate that requires a high level of energy for heating, moreover its geography and low population density require moving people over long distances with high consumption also for transportation. Similar problems characterize Canada and the United States with the addition of a strong need for air-conditioning of buildings due to moisture levels in the summer months. By contrast, for example, Egypt does not need winter heating, nor air conditioning during the summer because the weather is dry, and also the average trip distances are small, because the population is condensed in a narrow strip along the Nile and its Delta. Another important factor is the technical economic and organizational efficiency in exploiting the resources, which depends on the political-economic system internal to the individual nations. For example, the bureaucratic mentality that has dominated collectivized economies

such as the former Soviet Union, where everything was subjected to meticulous central planning, causes strong dissipations, and this is not due to technological backwardness, nor to lack of internal vitality. In fact, in less than two decades, following the reorganization of former Soviet Union states, their per capita consumption has halved, and reached the same average intensity of most European countries.
But, beyond the political and climatic diversity, the main factor that determines differences in per capita energy consumption, is the level of development and industrialization, as we can infer by considering the historical trends.



History of per capita energy consumption

food for survival (3000 kcal/day)		0,11 toe/yr
after discovery of fire (500.000 years ago)		0,22 toe/yr
neolithic age, bronze age, iron age		0,45 toe/yr
greek-roman rural-artisan middle-age economy		0,50 toe/yr
1800 - England	industrialization	0,55 toe/yr
1900 - England		2,8 toe/yr
2000 - England		3,5 toe/yr

	agricoltural fraction of gross national product		
<1900 - Italy	66 %		0,50 toe/yr
1900 - Italy	50 %	industrialization	0,50 toe/yr
1913 - Italy	42 %		0,55 toe/yr
1939 - Italy	28 %		1,0 toe/yr
1981 - Italy	6,4 %		2,5 toe/yr
2000 - Italy	3,3 %		3,0 toe/yr

	global consumption	population	average per capita
greek-roman age	0,15 Gtep/anno	0.3 billion	0,5 toe/yr
year 2000	10,3 Gtep/anno	6.2 billion	1,7 toe/yr

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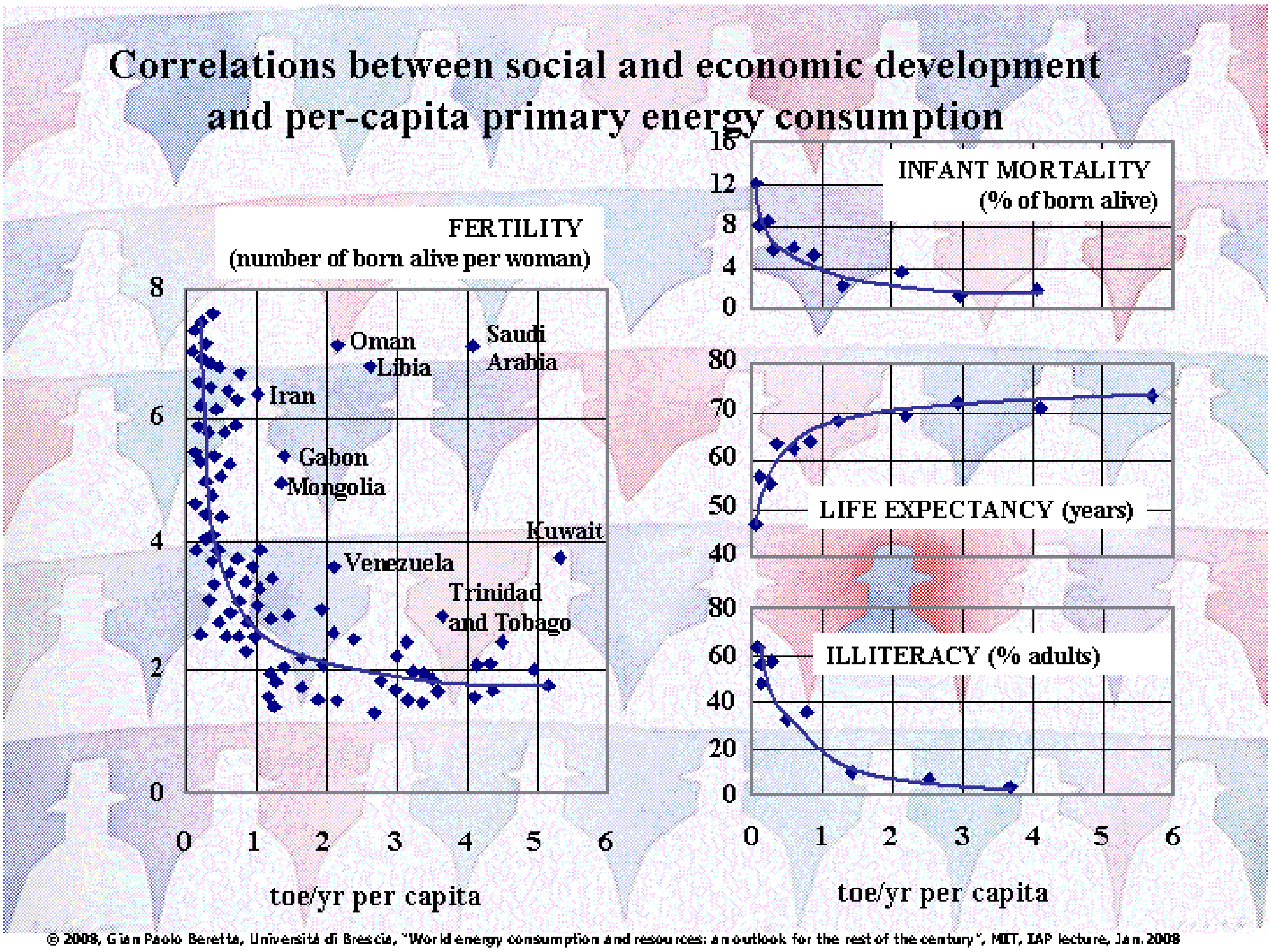
5-1.

If we consider the bare survival, an active human body requires about 3000 kilocalories per day (... about half of that is enough for my daughter, but that's another story...), equivalent to about 0.11 toes per year It is estimated that with the discovery of fire 500,000 years ago, the per capita requirement doubled to 0.22 per year. Another doubling, to 0.45, is attributed to the Neolithic, due to additional consumption to heat the homes that replaced the natural caves, to feed animals, for which it was necessary to cultivate the fields, and later to extract and work bronze and iron. Within the Roman Empire, the increase in demand was counterbalanced by the progressive improvements in the efficiency of use. With the use of water to power mills, wind propulsion to power ships and then also wind mills, with the use of oil and bituminous products for lighting, the per capita consuption settled to about

0.5 toes per year, and did not change much until 1800. But then the transformation from rural to industrial economy in very delimited geographic areas, beginning with England, involved a rapid increase in the demand for coal, up to 2.8 toes per year in 1900 in England. In the next century, in western Europe, following complete industrialization, even where GDP more than doubled, the per capita energy demand grew only up to 3.5 toes per year. So, industrialization is really a key factor in attempting a reasonable forecast.

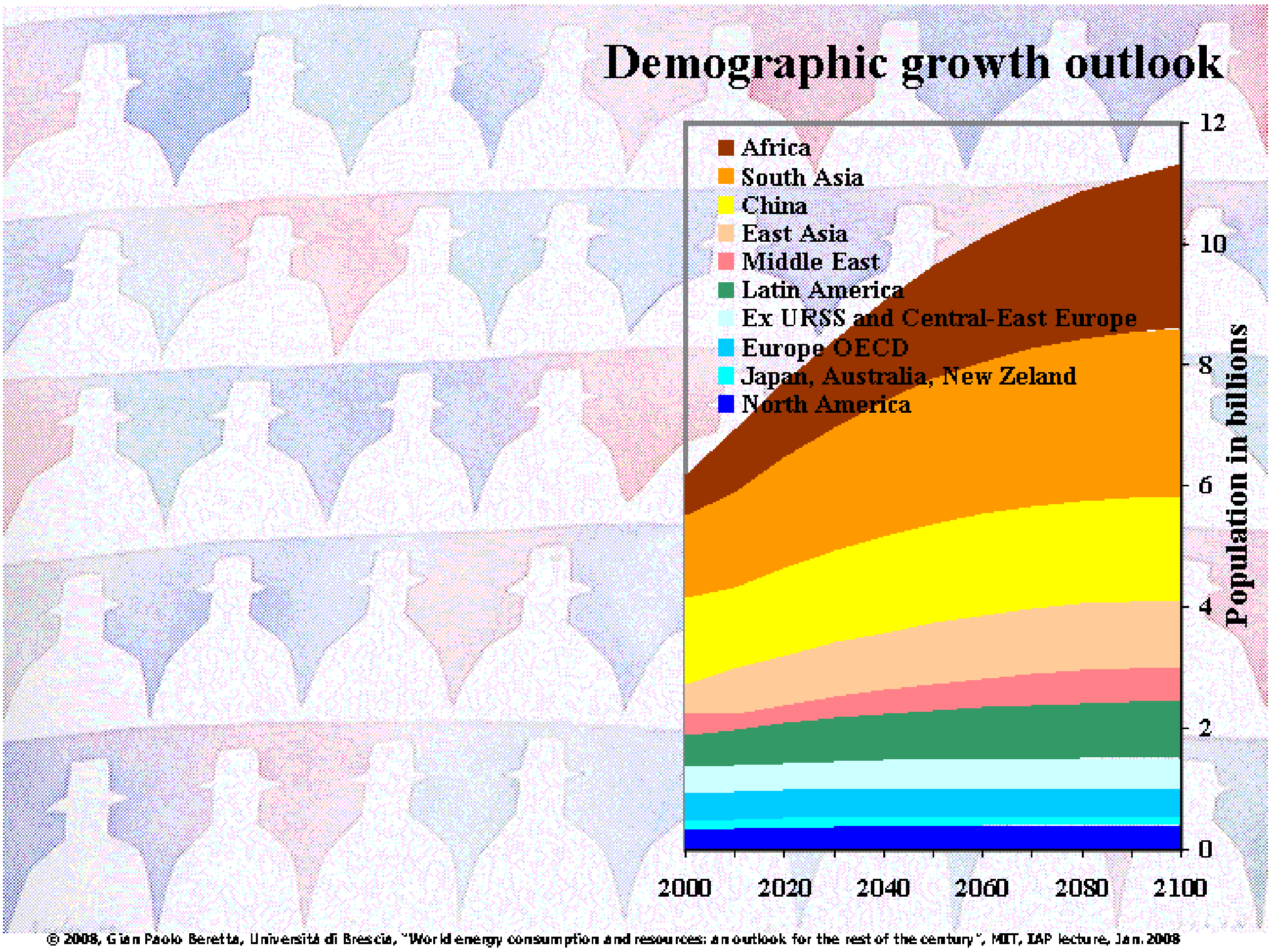
5-2.
For example, consider the case of Italy. In rural-and-craft greek-roman economy, the agricultural product was about 2 / 3 of the gross product, in 1900 it had fallen to almost half, without a substantial change in the per capita consumption of energy, mainly from sources still almost only renewable. In 1913 the gross agricultural product had instead fallen to 42%, meaning that industrialization had started, and the consumption rose to 0.55 toes per year. In 1939, 28% and 1 toe / year, with the increase all shifted towards the consumption of fossil fuels instead of renewables. In 1981 the agricultural product had fallen to 6.4%, the process of industrialization was almost complete, the gross product per capita had increased fivefold since 1913, and, like in England during industrialization, the per capita energy consumption rose to 2.5 toes per year.

5-3.
Overall, in the last two thousand years, the global demand of energy had a 70-fold increase, the population a 20-fold increase and the per capita consumption little more than a 3-fold increase (from 0.5 to 1.7 toe per year). The transition from renewable energy sources (wood and forage) to massive use of fossil fuels, has accompanied and allowed the processes of development and industrialization, which allowed profound changes in the quality of life.



6.

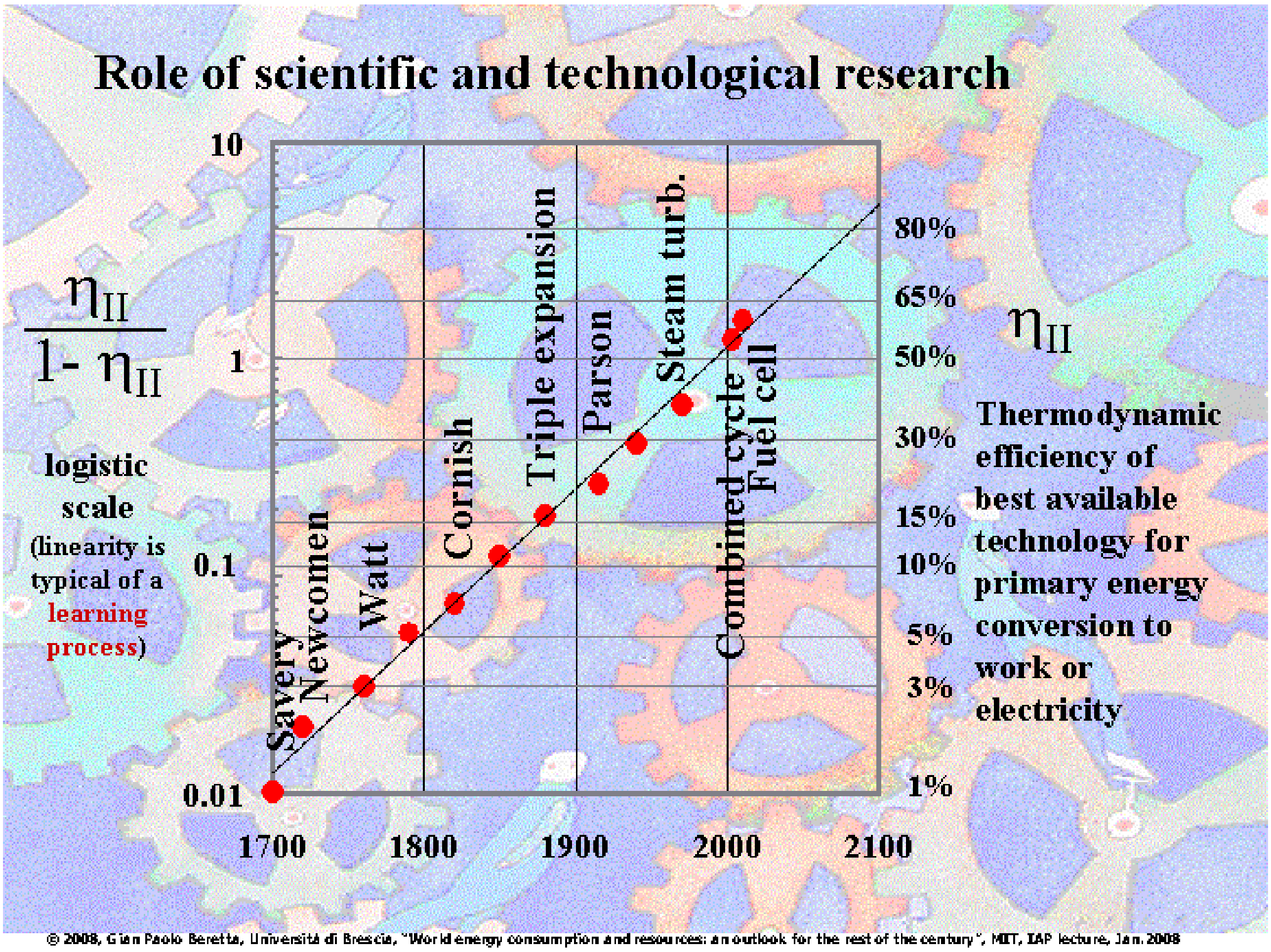
There is a strong inverse correlation between the per capita consumption of energy, and various factors and indicators of social and economic development, especially the fertility rate and hence the rate of population growth. Energy allows improvements in the standard of living, broad access to health care, use of contraceptives, longer life expectancy, services that increase the level of literacy and access to information, working opportunities for women, and, importantly, a lesser need to have children and numerous families to ensure the survival of the unproductive members, children and the elderly. The per capita energy consumption emerges therefore at the same time as an index and as an instrument of social and economic development. Countries with high standards of living and higher per-capita consumption, have very low or no population growth. Underdeveloped countries have high growth rates, sometimes doubling the population every 25 years. An important stage in the development seems to be the passing of the 1 toe threshold. Social conditions improve, life expectancy reaches 70 years, fertility decreases and population growth slows down.



7.

Clearly there is no room on Earth for an indefinite population growth. Most studies agree with the estimate that a sustainable future for our planet requires the global population to stabilize around twice the current population and that this will occur in the next 100 years. But population growth rates will vary greatly from region to region on the planet, depending, as we have seen, on the current stage of development. On this basis, the chart shows the expected population growth for the rest of the century, for each of the 10 groups of countries we already saw.

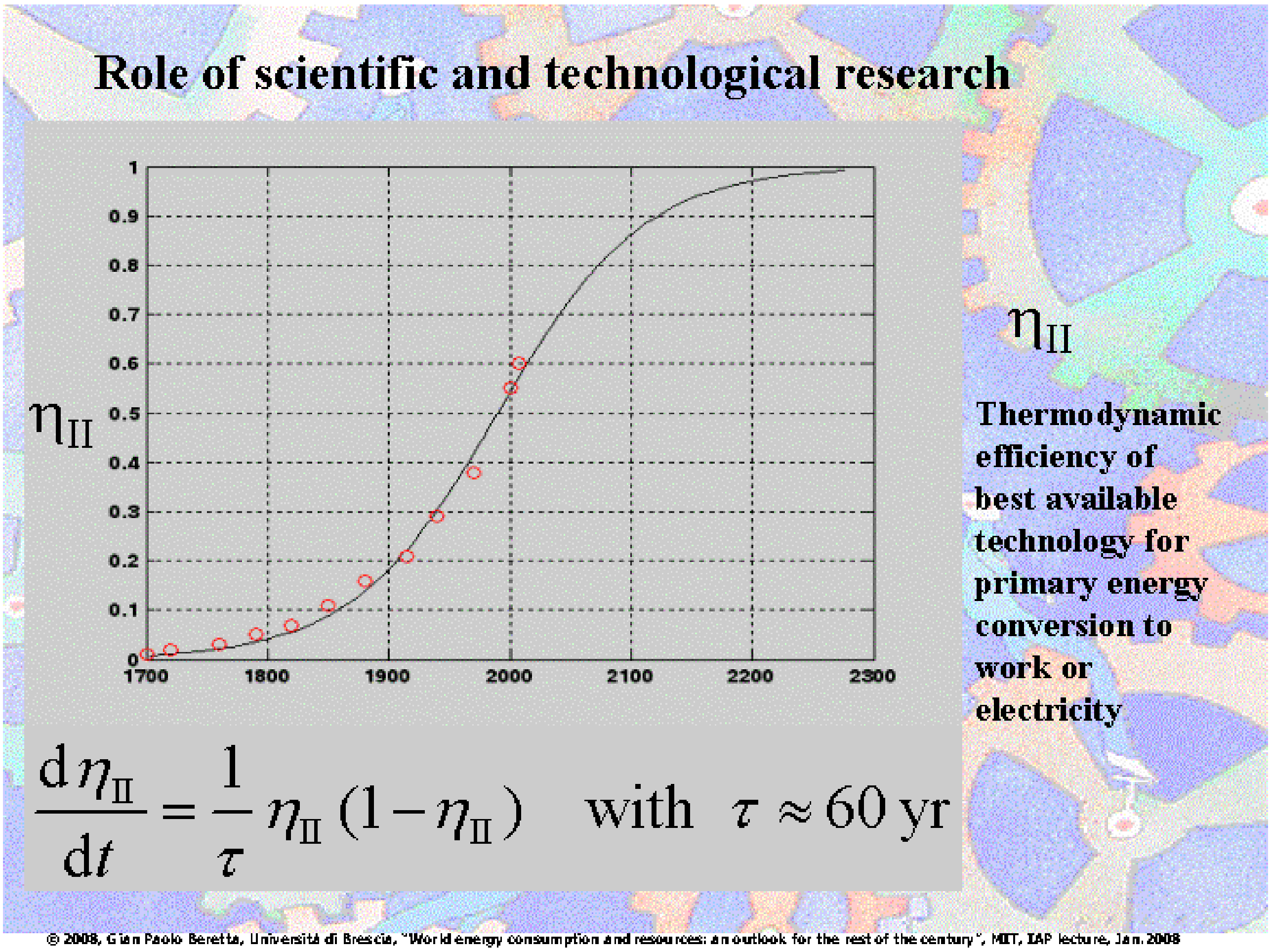
We will pass from 6 to 11 billion people. Growth will stabilise in all countries, soon after they pass the threshold of 1 toe per year per capita. Africa and South Asia today host a third of human kind, at the end of century they will host a half. North America, Japan, Australia, New Zealand, Europe and Former Soviet Union states, will drop from todays overall 22% to only 13%.



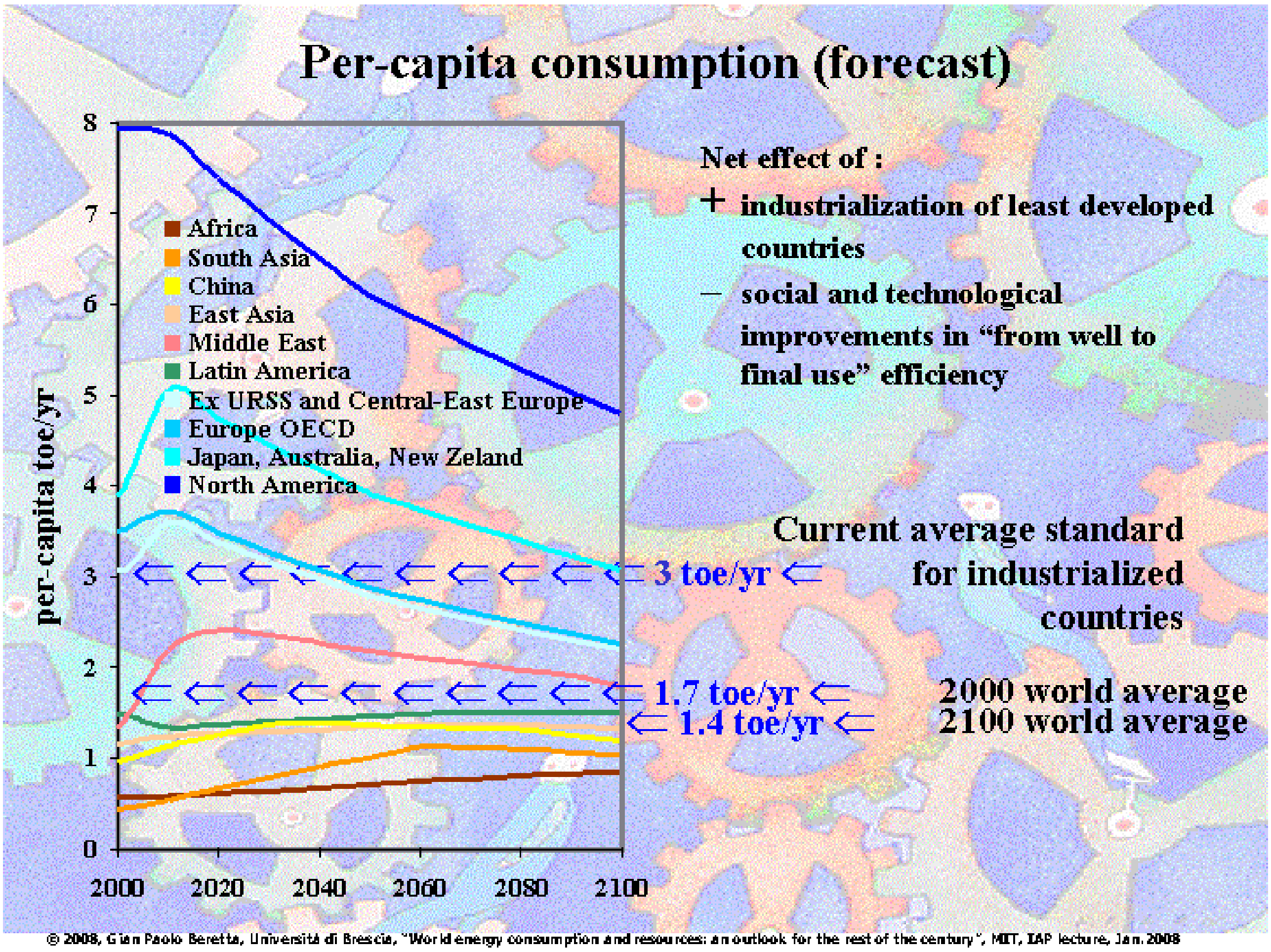
8.

While this social and economic development takes place, also technological development continues. The efficiency of exploitation of energy resources, and of end uses of energy carriers will continues to improve.

This graph shows how technical and scientific research has resulted in a steady improvement of energy conversion machines, according to a process that follows the logistic laws typical of all human learning processes. The chart spans the last 300 years. On the right scale, it shows the regular growth of the thermodynamic effectiveness of the best available technology for fossil-fuel primary-availability conversion into mechanical work and electricity, from the first steam engnes at the dawn of the industrial revolution in England, to the modern combined-cycle power plants and fuel cells, which now exceed 60%. We are talking here of the thermodynamic effectiveness which is sometimes also called 'second-law or exergy efficiency'. The fact that it is a remarkable straight line on this scale, is a typical feature of any learning process. The importance of this correlation of historical data, is that it shows that progress will continue, and by the end of the century, we will have energy conversion technologies, with thermodynamic effectiveness well over 80%. The scale of this graph is not linear in the effectiveness itself, but in the logarithm of the ratio of the effectiveness to one minus the effectiveness, as shown on the left logarithmic scale of the graph. If we were to show effectiveness versus time on a linear scale, the graph would look as follows.



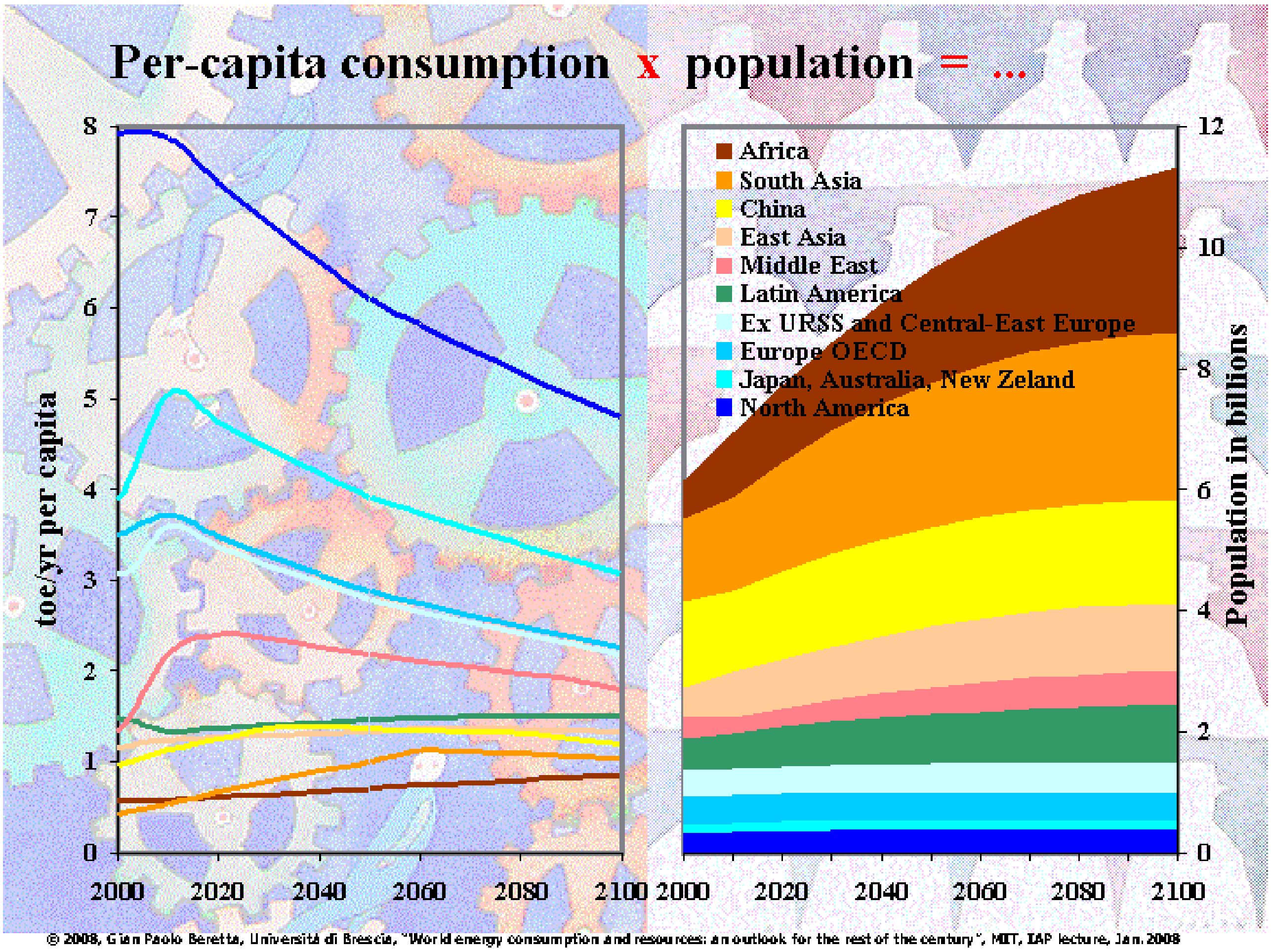
9.
The typical S-shaped curve of a learning process. Where growth is at any time proportional to the current efficecectiveness and the current room for improvement, and the time constant turns out to be about 60 years. Sixty years to change the ratio of eta to one minus eta by a factor of e. Sixty years to go therefore from the current 60% to 80%. This graph is very exciting, especially for people like me who work in thermodynamics: you see, we are still just past a half of our learning process about understanding and mastering the laws of thermodynamics. That's why we thermodynamicists are still going to be in business for a while.



10.

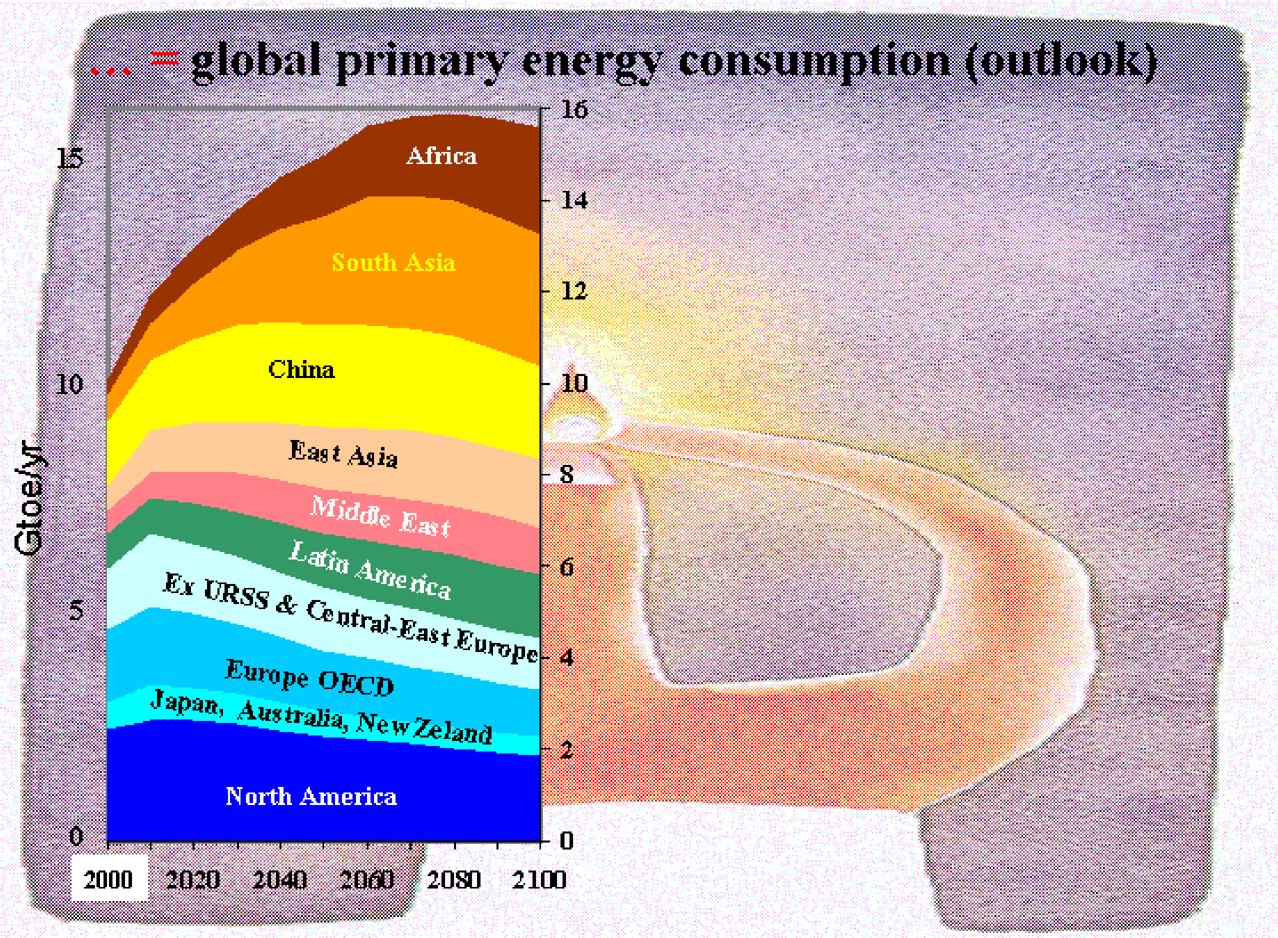
Similar improvements will of course obtain also in all the end-uses of energy, so that at the end of the century the overall life-cycle efficiency will be doubled, that is, the current standard of living, possible today in Europe with a per capita consumption of 3 toes per year, will require only 1.5 toes per year.

The graph shows the trend for the per-capita consumption in the 10 groups of countries already cited. Efficiency improvements, will cause a steady decrease in countries that are already industrialized, and will partially mitigate the increase for developing countries, intrinsic in their process of industrialization. Overall, from the current 1.7 world average, we will end the century with a world average of only 1.4, in spite of the vaste industrialization of most of the globe.



11.

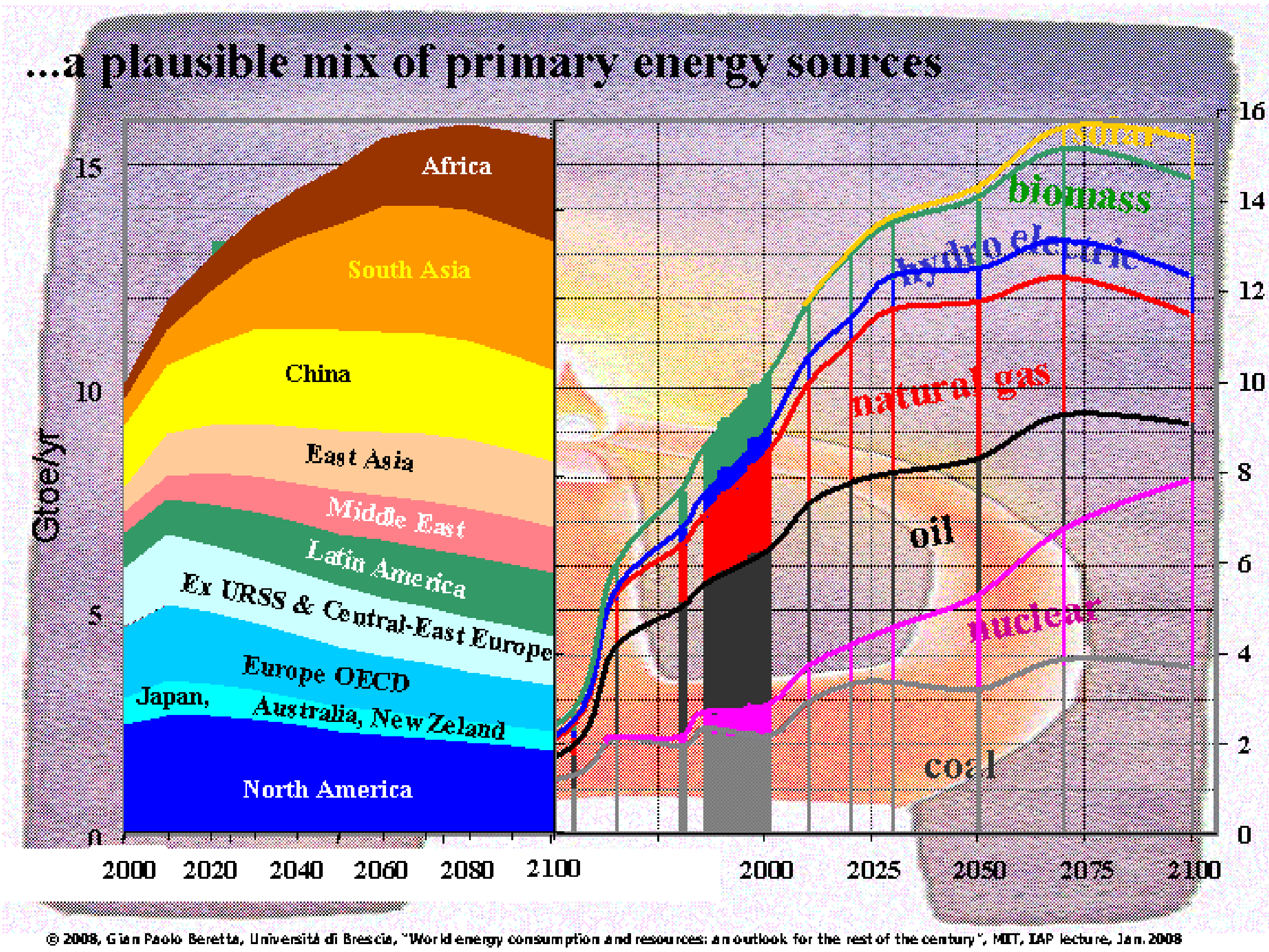
Well, we can now combine this chart with the one about demographic growth we just saw. We multiply, for each group of nations, the per capita demand by the expected population. Thus we get an estimate of the energy needs for each group of nations.



12.

Here's the resulting scenario. The global demand will keep growing quickly for a few decades, but then will stabilize at the end of the century to a value of about 16 billion toes against the current 11 billions. The contribution of the most industrialized nations will still grow slightly in the first two decades, but then reduces to 3 / 4 of their current needs. Compared to global needs, however, the marginal impact of today's most industrialized countries will fall from 60 to 28%. Instead, Africa and South Asia will rise from 10 to 33%.

Given this forecast of energy needs, an even more disputable affair is to predict how the mix of energy resources used to satisfy them, will evolve. The various possible scenarios depend on many variables, especially the geopolitical context that will develop.



13.

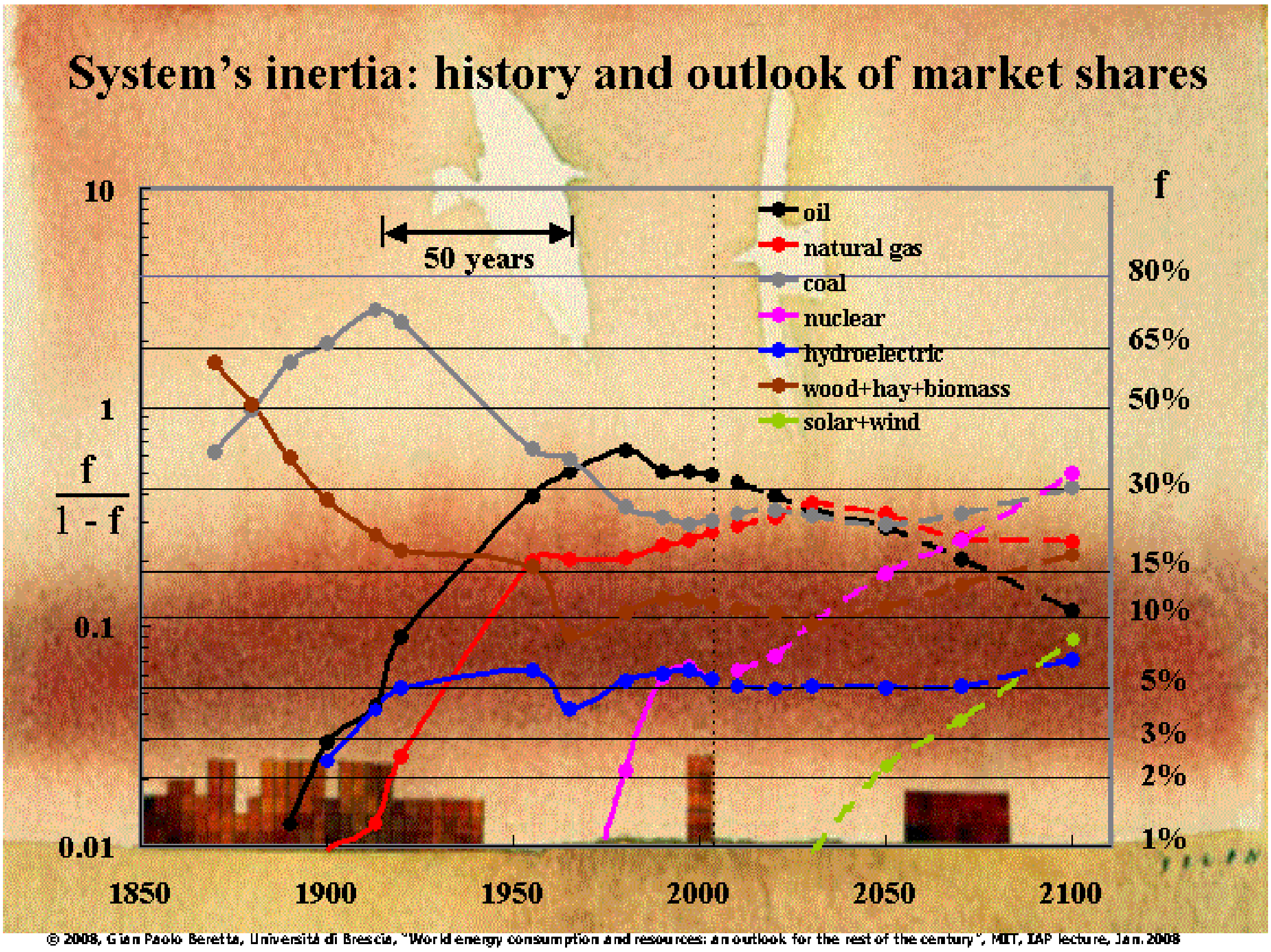
Here is a possibility, very balanced I believe, although quite optimistic in some ways.

The consumption of coal will continue to grow because it will be used with increasingly clean technologies. Nuclear energy will continue to grow in the (optimistic) hypothesis that the geopolitical context will stabilize, allowing for ways to manage the military risks, and that technology will solve current environmental safety and radioactive waste management concerns.

Oil consumption will peak around year 2020 and then will start to very slowly decline, due to the progressive but slow depletion of the current wells, and the decreased rate at which new wells are found. Natural gas and 'clean' coal will take up oil's role and will become the predominant resources of the century. Still uncertain is the role that non-conventional oil resources such as tar sands, bituminous shales, heavy crudes and methane hydrates will have.

Renewable energy consumption will increase, thanks to increasing exploitation of hydroelectric resources, increasing 'sustainable' uses of biomasses and solid wastes.

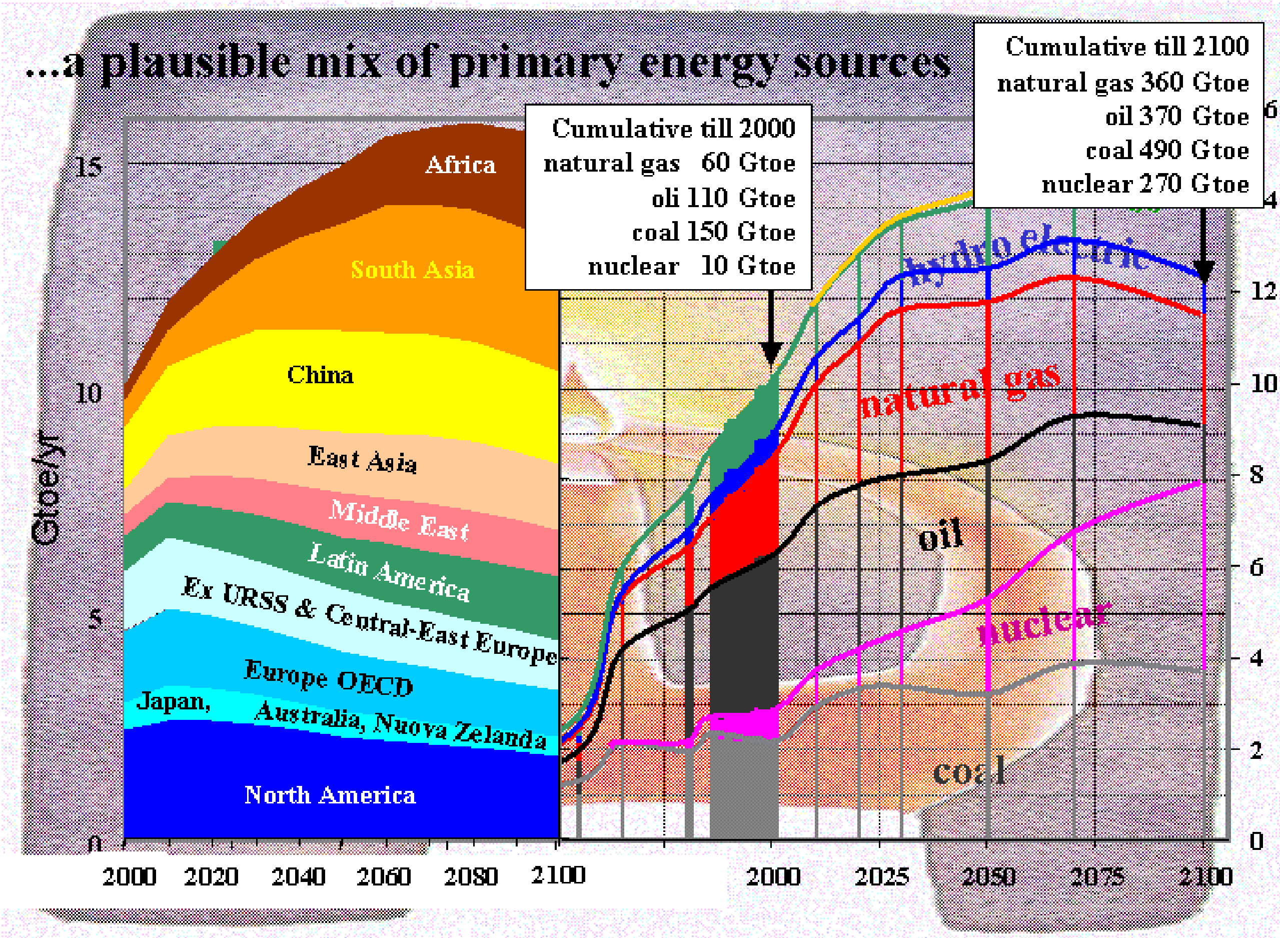
Direct solar power, wind power, tidal power and other renewable, or better, quasi-inexaustible resources, will certainly increase, but most likely will keep their current marginal role for the entire century, although the learning curve of these technologies will also climb up and hopefully contribute more significantly.



14.

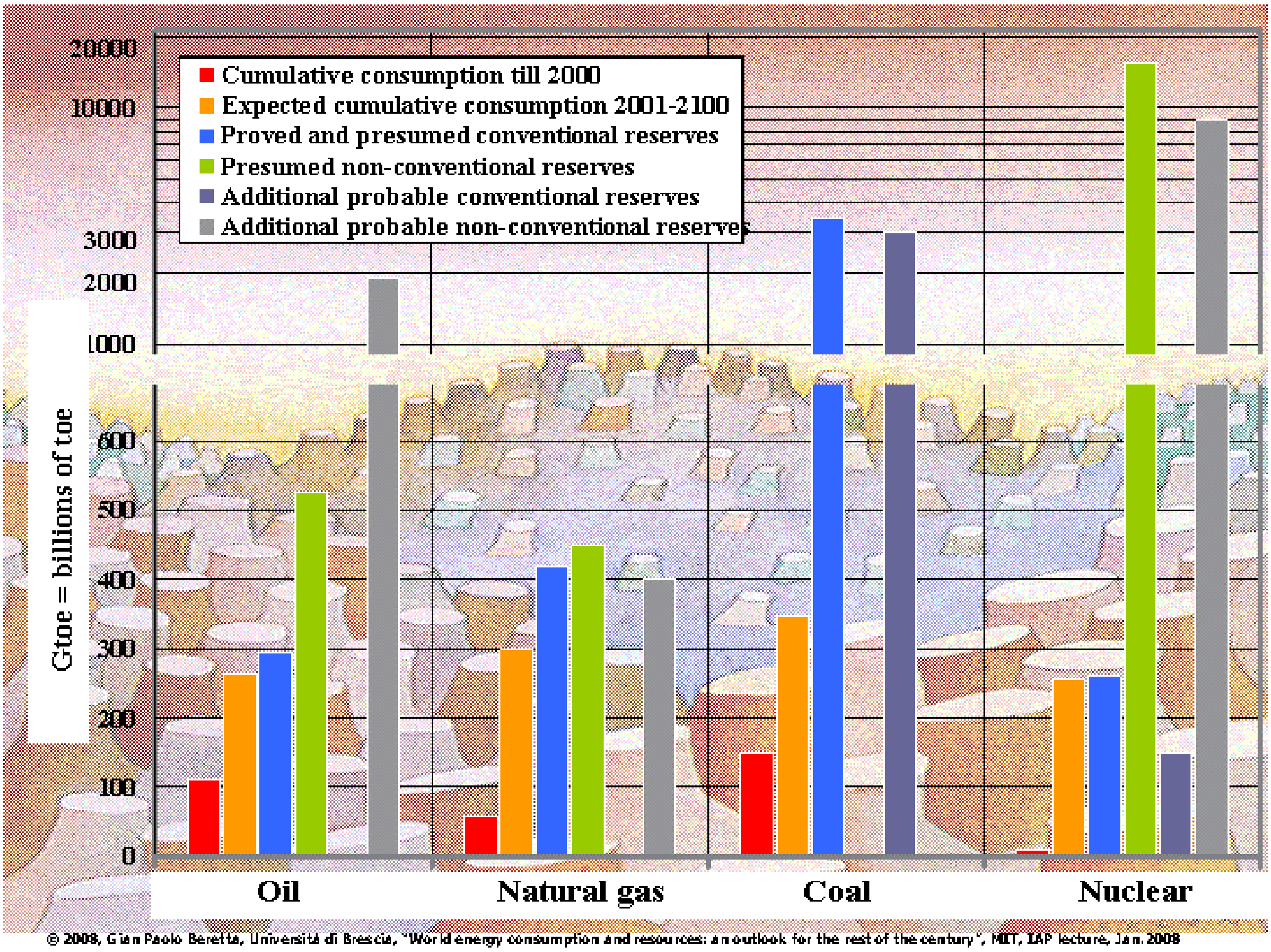
The scenario just presented as a pausibile mix of resources for our mid term future is obviously debatable, no one has the crystal ball, it is nevertheless compatible with what is shown in this graph. The historical trends of market shares of the various primary sources, extrapolated with the scenario just discussed, again shown on a logistic scale, namely a scale linear in the log of f over one minus f, where f if the market share of each resource.

The laws of the market have resulted in the gradual competition and replacement of resources, from wood and rural biomasses to coal, from coal to oil, to the current mix of sources that sees gas about to overtake oil. The slopes on this chart warn about the huge inertia of the economic and energy technology system. We need tens of years for a new resource to reach a significant market share. The very life of production facilities ranges from 20 to 40 years. It is obvious that the inertia of the system involves long response times and long-term returns of investments.



15.
A practical consequence of the inertia of the system, is that any uncoordinated local or national energy policy, not well-weighted and well-concerted internationally and globally, cannot possibly change the course of the system. Not only such a local energy policy would be ineffective and dissipative, but it could even reduce the confidence of operators in the stability of the economic and regulatory context in which they are called to make investments.

Well, from the scenario and the mix of resources we forcast, we can now calculate the cumulative consumptions per resource at the end of the century. These are written in the top right box. Compare them with the cumulative consumptions so far, in the box at the center. In the next slide, we will compare these numbers, with current estimates of the available reserves, of fossil and nuclear fuels, to decide if we have enough resources to satisfy the predicted energy demand for the rest of the century.



16.

Here is the histogram that compares past consumption and future demand with the known reserves of oil, natural gas, coal and nuclear fuels. The red bars indicate how much we have already consumed up to the last century, the orange bars how much we will consume in the current century (according to the scenario proposed), and the blue bars indicate conventional reserves, that are considered either proved or highly probable.

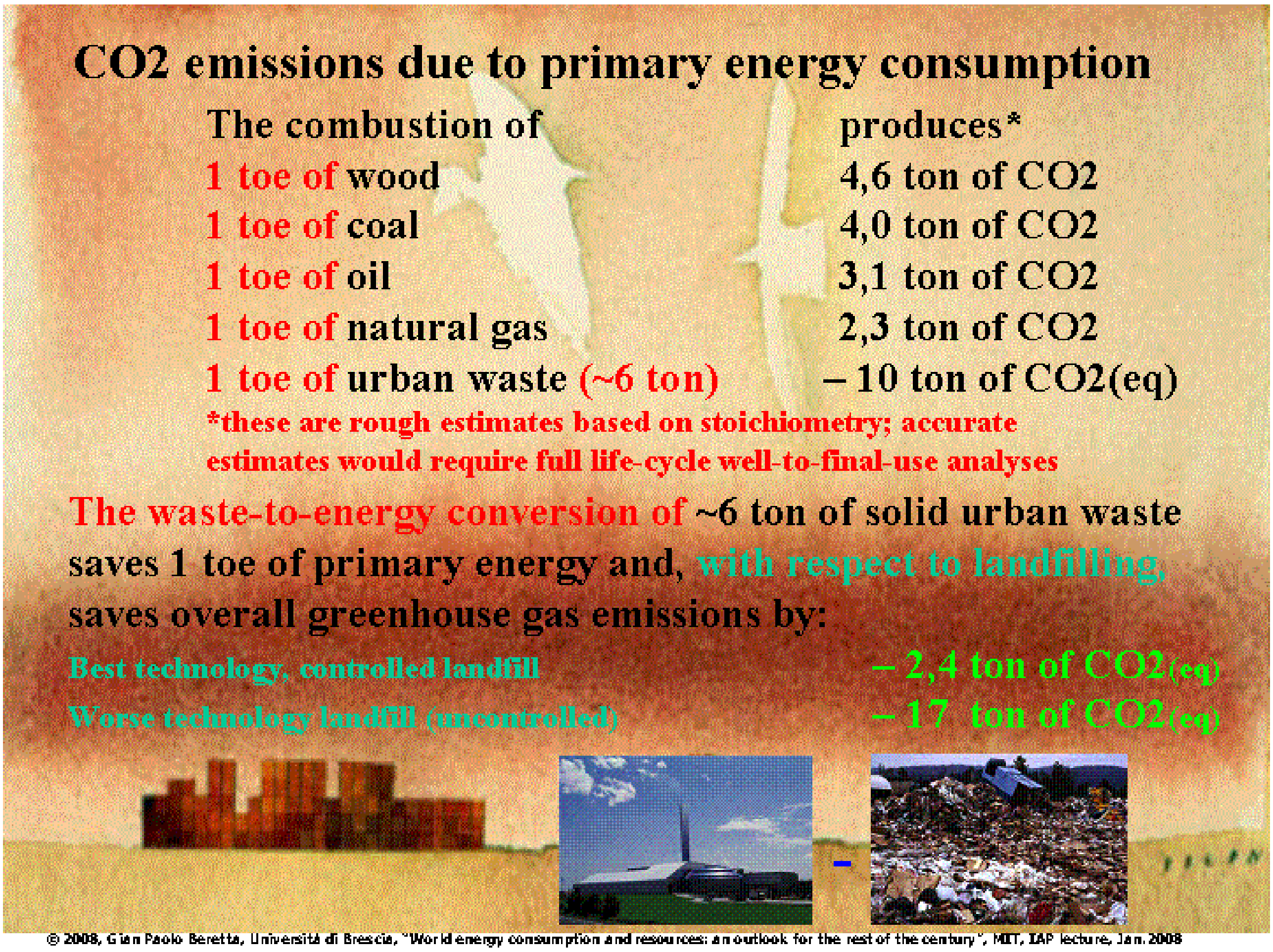
Further bars indicate resources that with today's methods are considered non conventional and not potentially recoverable, but that presumably could be developed on the time scale we are considering, such as the use of tar sands, bituminous shales, heavy crudes and methane hydrates, as well as breeding fission technologies and the Thorium cycle.

It is quite clear that reserves will last well beyond the current century.

Thus the allegation that primary energy reserves are scarse, which is constantly repeated by the press, by politicians at all levels with obvious demagogic purposes, and by aggressive futurologists whose sole interest is to sell their books and speeches, is clearly false and unfounded. There is no shortage that will prevent or impede the impressive social and economic development expected in this century by the emerging countries. When a resource gets scarce, the markets will adjust, but we will not remain out of fuels for very long time.

And we didn't mention nuclear fusion here as an option, because of the difficulties it encounters in the labs and because of the decades that will separate physics laboratory demonstration, from engineered industrial installations, and from gaining a sizable share of the market. In any case, we all know that reserves for fusion would be plentiful, as Lithium is a most abundant element.

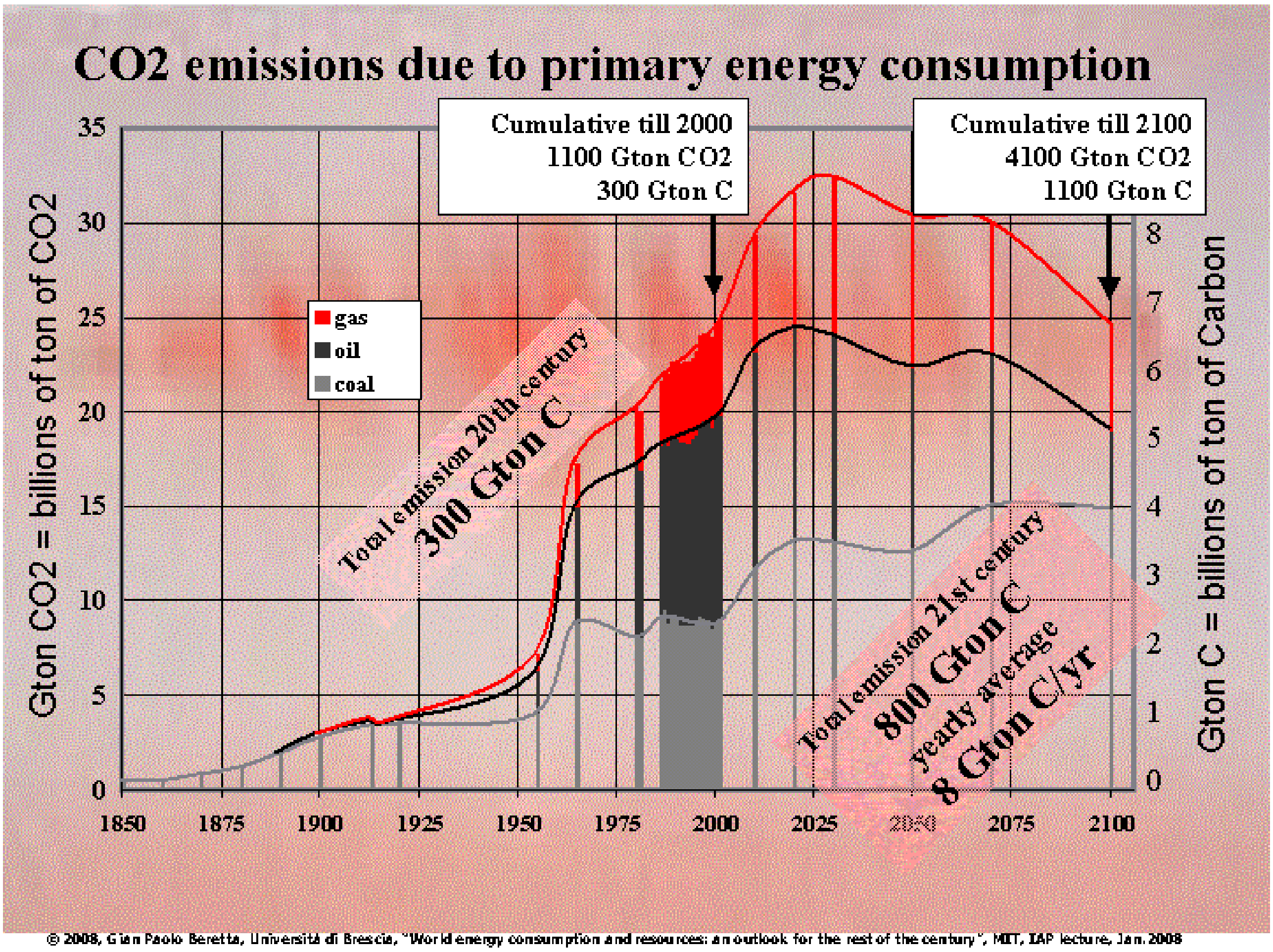
So, the concern is not scarsity, but rather the fact that in the long-term the second most abundant resource (after breeding nuclear fission) is coal. Well-known environmental concerns derive from the well-founded hypothesis, that the amounts of greenhouse gases introduced in the atmosphere by anthropic exploitation of fossil fuels, may significantly influence the thermal balance of our planet, affecting clima and melting polar ice-caps. This hypothesis is in fact pushing towards more energy consumption to seize and confine part of the carbon dioxide released by the use of fossil fuels.



17.

Indeed, for each toe of primary energy obtained by oxidation of fossil fuels, the carbon dioxide emission can be estimated to a very first approximation, by simple stoichiometry. It is 4.6 tonnes of CO_2 for wood, 4 for coal, 3.1 for oil and 2.3 for natural gas. Better numbers would require considering the full life-cycle from-well-to-final-use of each of these fuels. In the next slide, we will apply these rates to estimate the overall CO_2 emissions implied by our scenario.

Before that, however, I would like to make a brief digression on the role of waste-to-energy technology, with respect to greenhouse gas emissions. Municipal wastes are composed for almost 80% of biomasses, and as such they can be considered a mainly renewable resource. In Brescia, in Italy, where a top technology, very clean, waste-to-energy power plant has been operating for ten years now, 1 toe of primary energy is saved for every 6 tons of waste which is burned. With respect to landfilling, depending on the quality of the landfilling technology, 1 toe of primary energy saved by burning the 6 tons of wastes, results in saving also about 10 tons of greenhousegas emissions. This is the estimate based on the current average landfilling technology in Italy. So, waste to energy does contribute positively. But the contribution is limited. Even if we burnt all our wastes in power plants like the Brescia one, the primary energy savings would not exceed 2%, but the GHG savings would be of the order of 5%.



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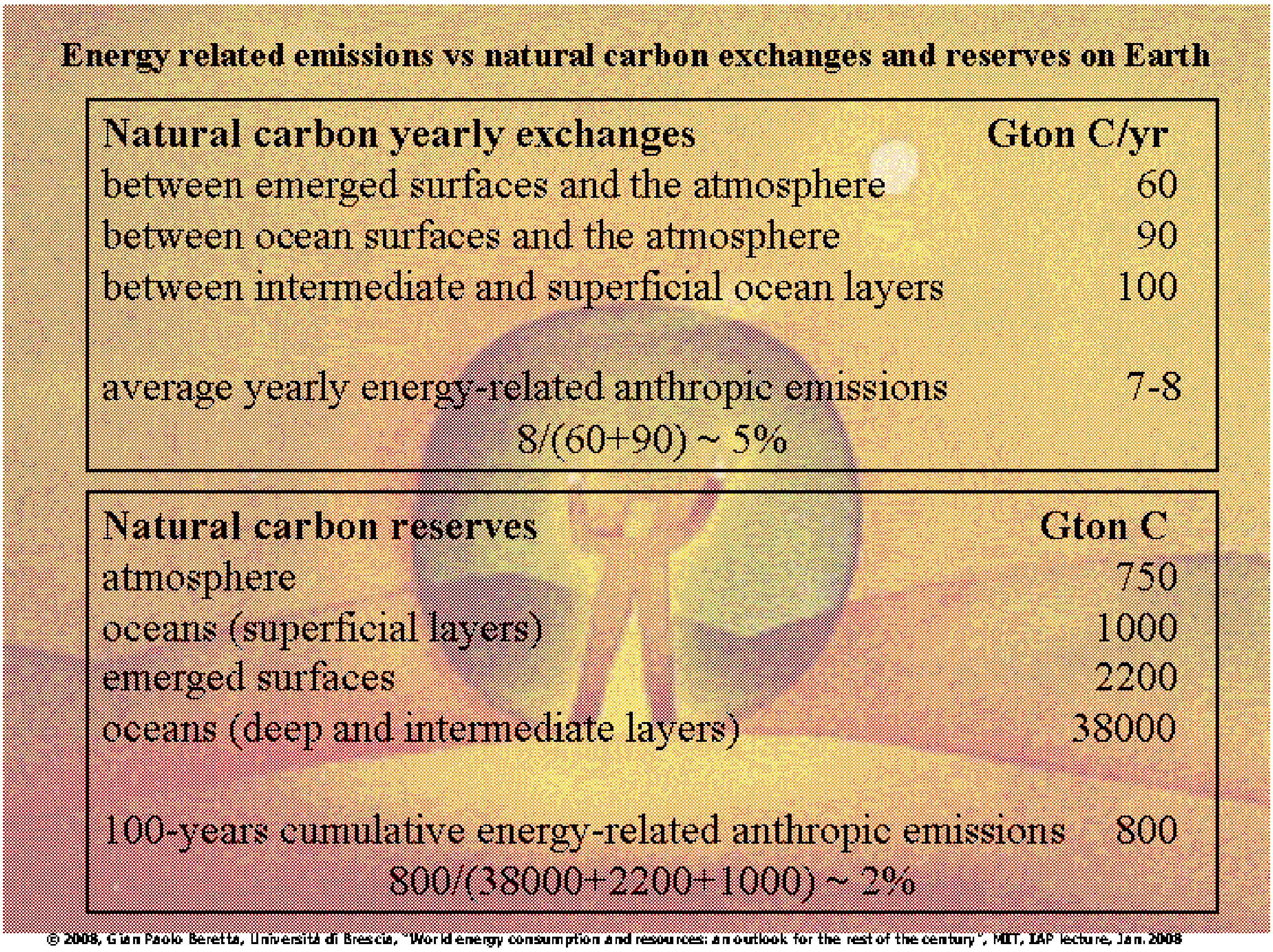
18.

Ok, back to the anthropogenic CO2 emissions for the next century.

This is the scenario of CO2 emissions due to fossil fuel consumption according the scenario we have developed. If during the last century human kind has released a total of 300 billion tonnes of carbon in the form of CO2, in the current century we will release another 800 billion tons, an average of 8 billions per year. And it will be more, if the optimistic assumption of an acceptable resolution of the problems of nuclear energy should not come through.

This anthropogenic release, which arises from primary energy consumption, is certainly not a negligible amount, but it is a relatively small fraction of the complex natural balances and exchange mechanisms, by which carbon accumulates on the surface of our planet and in the ocean depths, determining the natural concentration of CO2 in the atmosphere.

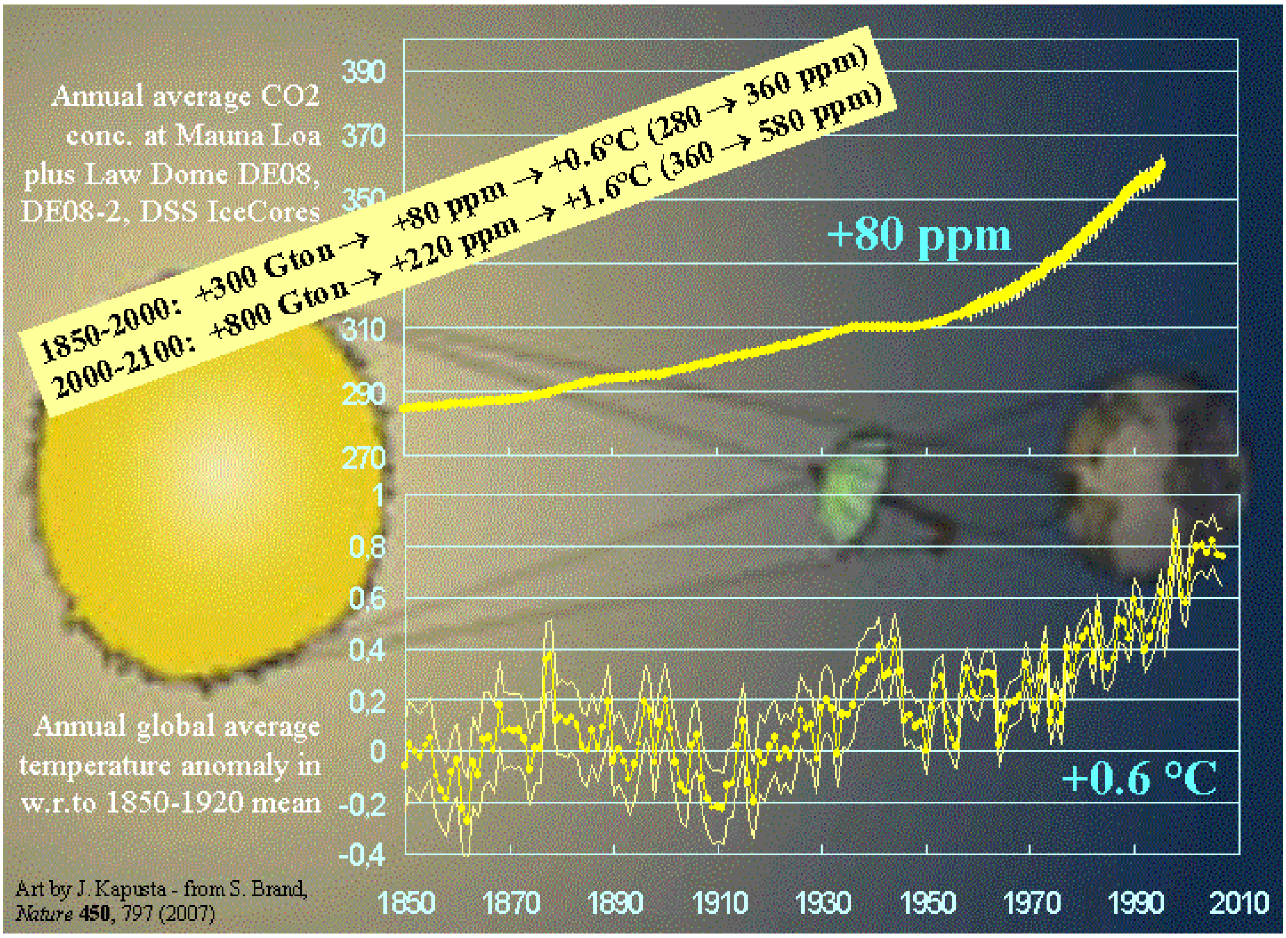


19.

The 8 billion tons of annual, anthropogenic, energy-related emissions, are about 5% of the amounts exchanged every year in the natural carbon cycles, regulated by the production of biomass for photosynthesis, decomposition of biomass plants and animals, and mass exchanges accompanying seasonal temperature changes. Every year, the atmosphere exchanges 60 billion tons of carbon with the land surface and 90 billions with the upper layers of the oceans. The yearly exchanges in the ocean between the surface layers and the intermediate and deep layers are about 100 billion tons, and they are important because carbon dioxide, which is heavier than both air and water accumulates in large and stratified amounts in the ocean's depths.

So much so, that one of the ideas for segregating the CO2 produced from oxidizing fossil fuels, is to separate it from the products of oxidation, solidify it to the so-called dry ice from, and then drop it down in the ocean depths (8-9 thousand meters) where the absence of convective mixing and the high pressures, maintain very large and stable viscous lakes of liquid carbon dioxide.

Today the atmosphere contains about 750 billion tons of carbon in the form of CO2, the surface layers of the oceans contain 1000 billion tons of carbon, and the earth's surface 2200, while the deep ocean layers contain 38000. So, the overall cumulative anthropogenic emissions during this entire century, 800 billion tons, amount to slightly less than 2% of the overall natural reserves of carbon, but are about 20% of the surface amounts.



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20.

So, of course, what matters are the rates at which the natural mechanisms can metabolize the amounts of CO2 we inject. Of the 300 billion tons we emitted during the past century, only about 45% have been metabolized. We infer that from the fact that the remaining 55% have accumulated in the atmosphere, causing an increase in CO2 concentration of 80 ppm, from 280 to 360. Assuming the phenomenon is still in its linear phase, as suggested by the fact that the anthropic contribution is a small fraction of the natural metabolism, we infer that of the additional 800 billion tons that we will inject in this century, still only about 55% will remain in the atmosphere, meaning that the concentration will go up another 220 ppm, to a final 580. Considering the apparent direct proportionality between increase in CO2 concentration and increase in average surface temperature, we will have another scary 1.6 degrees Celsius temperature increase, on top of the 0.6 degrees already occurred, with all the climatic changes that will follow.

So, differently from what I thought when I wrote the paper I circulated, I now changed my mind, and I am now convinced of the existence of scientific evidence that anthropic emissions are to be held responsible for the climatic changes. Arguments about the unprecedented rates of increase have convinced me. However, the doubt remains that the enormous costs and efforts, also in terms of additional primary energy consumption, that are necessary to obtain significant reductions in greenhouse gas emissions, could be easily rendered vain by small fluctuations in the many broad natural mechanisms that regulate the thermal equilibrium of our planet.

21.

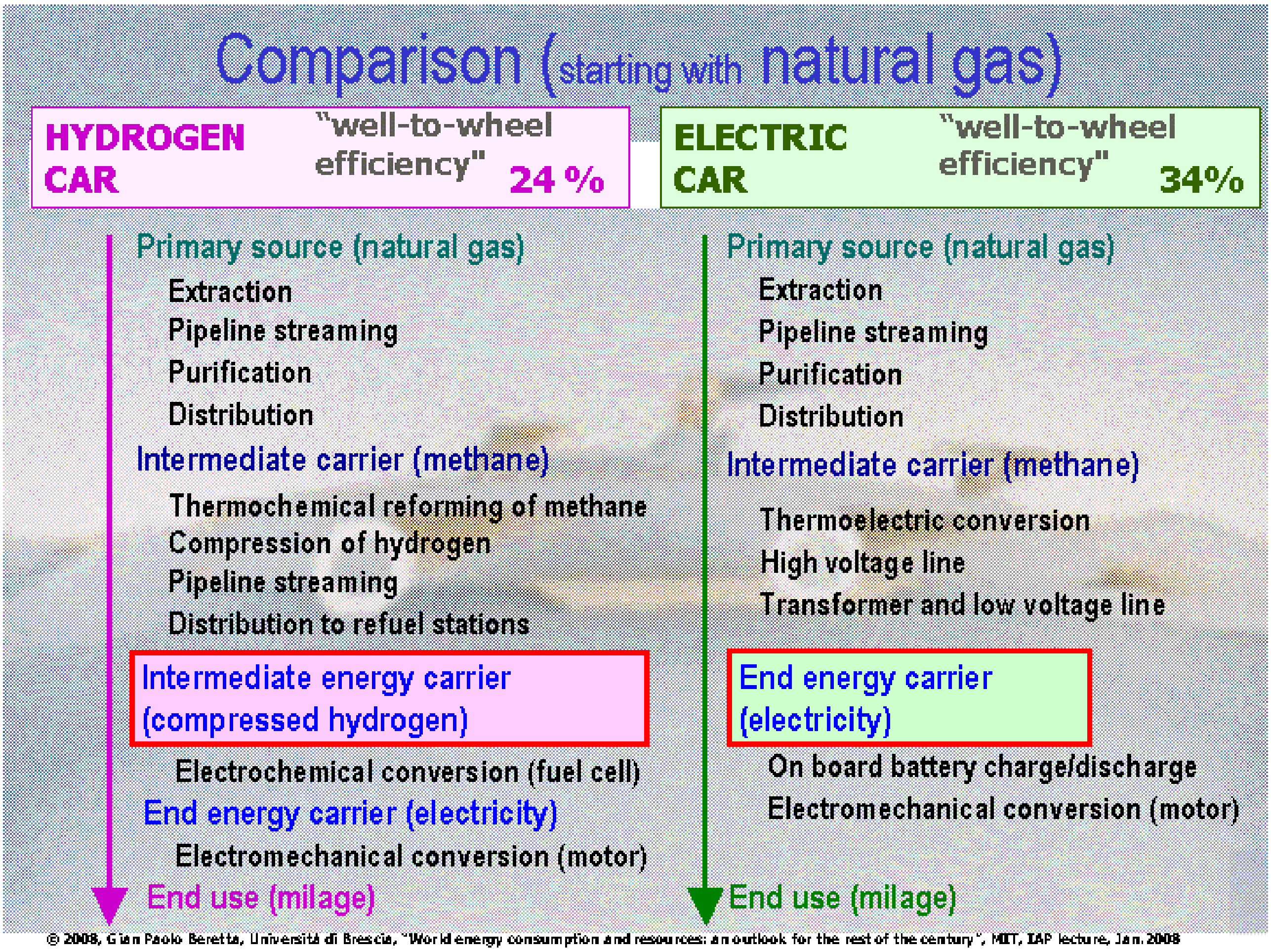
In any case, legislators, politicians, media, and ultimately the people, should not lean on disinformation or cheap futurology, and should not be tempted by false promises of easy solutions, of the complex energy and environmental problems we face. Decision makers and everybody else should never forget the characteristics of complexity, inertia and globality, of the social and economic context, in which the energy and environmental problems are embedded.

For example, especially in Europe, in the name of sustainable development, we have been spending a lot of research money to chase the mirage of the so-called hydrogen economy. The idea that the synthetic production of hydrogen fuel from water, could serve as an energy carrier, alternative and better than electricity, is in my view illusory and misleading.

I look forward to your comments and to the discussion which I hope will follow, as I am quite open to hear you comments, and I am eager to learn from you, if I should change my mind about this too. Therefore, to provoke some discussion, I will conclude my talk by showing the numbers, that convince me, that a hydrogen economy centered on hydrogen cars, is a bad idea, both from the point of view of energy consumption and of climate change. The numbers I found, from prominent sources, seem to suggest quite clearly that an economy based on electricity and electric battery cars, is much more energy efficient and environment friendly.

Of course, hydrogen may be the most abundant element in the Universe, and there is no doubt that it is a great fuel, if handled with care, but nowhere on Earth we have hydrogen wells. Hydrogen on Earth is not a primary source of energy, yet most european laymen, due to bad information, have unfortunately been convinced that hydrogen, is the source of energy of the future.
Of course in this room we all know very well that if we want to produce hydrogen, we must consume a primary resource. Just as we do to produce electricity.

Electricity is an energy carrier, that we have been using for over a hundred years, central to past as well as current industrialization processes. Electricity is a non-polluting energy carrier, in the sense that where it is used for a variety of end uses, it does not produce local pollution. But we do pollute, and do consume primary energy, in the power plants where the electricity is generated.
For hydrogen, the picture is exactly the same. Hydrogen too is a non-local-polluting energy carrier, if it is used in a fuel-cell to power an electric car. But to make the hydrogen, we do pollute, and do consume primary energy.
So, to decide whether to invest on hydrogen or on electricity, we must study the entire life cycle from well to wheel, and we must compare the two energy carriers on equal grounds.



22.

Here is such a comparison, in a scenario in which the primary energy source is natural gas. Forget the details. The problem of an energy life cycle that passes through the production of hydrogen, is that it generally has more intermediate processes, and more irreversibilities than going through electricity. According to these perspective estimates, worked out by internationally recognized experts, the well-to-wheel efficiency of a hydrogen car will hardly ever exceed 24%, compared to the 34% of an electric battery car. This means that in the best perspective, the hydrogen car will consume 43% more primary energy than the battery car. The local pollution will be zero in both cases, but mind that if the primary energy source to produce hydrogen or electricity is a fossil fuel, this also means 43% more greenhouse gases and other pollutants.

Comparison (starting from eolic or solar photovoltaic)

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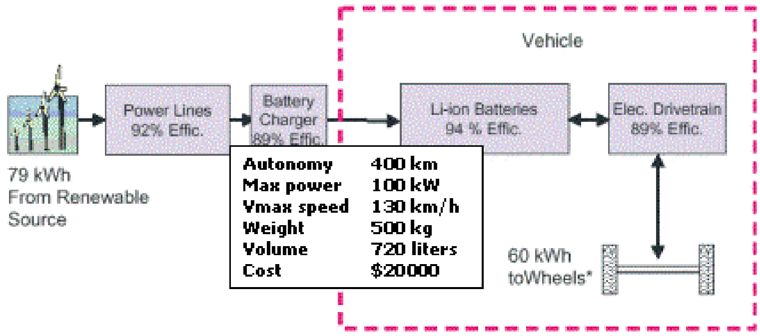


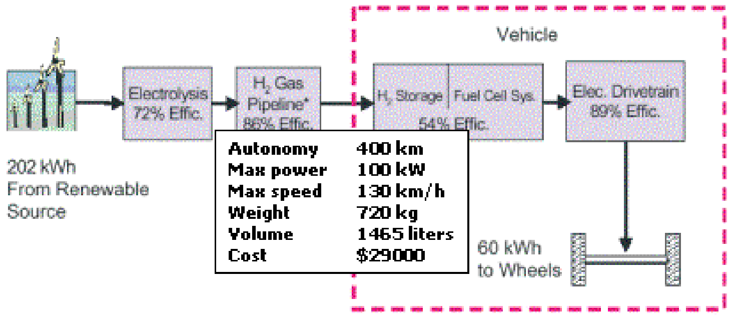
*The BEV regeneration capability reduces the 60kWh requirement by 6kWh while achieving the same range

Fig. 1. Well-to-wheel energy pathway for battery electric vehicle.

ELECTRIC CAR

well-to-wheel efficiency

62%*



* "Pipeline" includes losses from compression, expansion, storage and distribution

Fig. 2. Well-to-wheel energy pathway for fuel-cell vehicle.

HYDROGEN CAR

well-to-wheel efficiency

27%*

23.

Well. It is often said, that hydrogen is really ideal for use with renewables, solar photovoltaic and wind power, or with hydro and nuclear power, and that it helps reducing greenhouse gases in a fully renewable or nuclear scenario. But this too seems to be contradicted by the conclusions of the experts. If the hydrogen is produced by electrolysis, using electricity from renewable sources (or nuclear electricity), the comparison is even worse: 27% instead of 62%, which means that the consumption of primary energy of the hydrogen car is 130% more than that of the battery car; it consumes more than double. And note that these estimates were done on the basis of the same autonomy, power, and cruise speed of the car.

Comparison of various car scenarios

"well to wheel" primary energy consumption w.r.to electric car

Energy scenario	Primary source	Main energy carrier	On board	Propulsion system	$(\eta_e - \eta)/\eta$
Mix of traditional sources	Various*	Electricity	batteries	electric	0%
	Oil	Diesel oil	tank + batteries	hybrid: electr.+Diesel	+1%
	Coal	Synthetic LD Diesel oil	tank + batteries	hybrid: electr.+Diesel	+7%
	Oil	Gasoline	tank + batteries	hybrid: electr.+Otto.	+19%
	Natural gas	Compressed methane	tank + batteries	ibrido: elettr.+Otto	+27%
	Coal	Synthetic FT Diesel oil	tank + batteries	hybrid: electr.+Diesel	+30%
	Oil	Liquid petroluem gas	tank + batteries	ibrido: elettr.+Otto	+31%
	Various*	Compressed H2 from thermoch.	H2 tank + fuel cell	elettrico (fuel cell)	**+43%**
	Natural gas	Compressed methane	tank+reformer+fuel cell	elettrico (fuel cell)	+46%
	Various*	Liquid H2 from thermoch..	H2 tank + fuel cell	elettrico (fuel cell)	+69%
	Oil	Diesel oil	tank	Diesel	+70%
	Oil	Gasoline	tank	a scoppio	+95%
	Coal	Methanol	tank+reformer+fuel cell	electric(fuel cell)	+132%
	Various*	Compresse H2 from electrolysis	H2 tank + fuel cell	electric(fuel cell)	+156%
	Various*	Liquid H2 from electrolysis	H2 tank + fuel cell	electric(fuel cell)	+199%
Renewables	Hydroelectric / Solar photovolt. / Wind / Tides	Electricity	batteries	electric	0%
		Compresse H2 from electrolysis	H2 tank + fuel cell	electric(fuel cell)	**+130%**
		Liquid H2 from electrolysis	H2 tank + fuel cell	electric(fuel cell)	+172%

Assmed η_{grey}= 90%. Outlook data on performace in part from: M.A.Weiss, J.B.Heywood, A.Shafer,V.K.Natarajan, *MIT report* no.LFEE 2003-01 RP; F.Kreith, R.E.West, *Transportation Quarterly*, Vol.56, 51 (2002); S.Eaves, J.Eaves, *Journal of Power Sources*, Vol.130, 208 (2004).

* Various = oil / coal / natural gas / nuclear / biomass / solar thermal

24.

This table puts the estimates we just mentioned, together with the many other potential combinations for automotive traction. If we start from the more likely traditional mix of primary sources, the perspective numbers proposed by automotive experts, confirm that the electric battery car is the least consuming, immediately followed by various hybrid car combinations. The best hydrogen car combination consumes 43% more, as we have seen. If we assume an unlikely hypothetical scenario of all renewable primary sources, the picture for hydrogen cars is even worse, as the best combination consumes 130% more, as we have just seen. This means that for the same mileage, we would need more than twice as many windmills and twice as many fields covered by photovoltaic cells.

And notice that these are just the numbers for energy, without accounting for the additional burden to build up the necessary infrastructures, the market penetration, and the safety measures that a hydrogen economy would require.

Sure, the development of electric battery vehicles still requires a lot of research, and infrastructure investments for upgrading the distribution network, and also to recharge the exhausted batteries, but a good part of the technology is well known and established. In addition, based on the existing electricity network, the diffusion of these vehicles for limited distances, can start right now and build up gradually. Indeed, some cities in urban areas where environmental benefits justify the higher costs, have already adopted fleets of battery vehicles. Research can focus on the development of better batteries, and more efficient recovery of the kinetic energy dissipated during braking of the car.

25.

So, all these numbers, show that energy is a complex and global problem, characterized by large inertia and influenced by geopolitical difficulties. If we want to change the direction of such a large and heavy ship, we must schedule and coordinate the maneuver well in advance. Local manoeuvers, if not well coordinated on the global scale, will hardly be effective. It is a difficult equilibrium to maintain, between the short-term time scale of the political world and the long-term time scale needed to direct and attract investments in the proper coordinated directions.

26.

In the meantime, one of the best investments we can make is in research, fundamental and applied, technological and scientific, in all directions, to continue our learning process, and guarantee that indeed sixty years from now, we will have power plants with a net thermodynamic effectiveness over 80%, and we will greatly improve on all our end uses of energy.

27.
With this, I thank the foundation Jean-Michel Folon, for publishing the evocative works of art of this great belgian artist, from whom I have freely drawn all except one of the backgrounds of my slides (http://www.folon-art.com/). And I thank you all for your attention, and look forward to your comments.

APPLAUSE

Click here to see the **VIDEO (wmv)** of the discussion that followed the talk (be patient...: after about one minute, the camera will turn and stay on the audience)