1-11-2010

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Recommended Citation

Tomkiewicz, Micha, "On the Feasibility of a Timely Transition to a More Sustainable Energy Future" (2010). *CUNY Academic Works.*
http://academicworks.cuny.edu/bc_pubs/115

Sustainability **2010**, *2*, 204-214; doi:10.3390/su2010204

OPEN ACCESS

sustainability

ISSN 2071-1050

www.mdpi.com/journal/sustainability

Article

On the Feasibility of a Timely Transition to a More Sustainable Energy Future

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Received: 10 November 2009 / Accepted: 5 January 2010 / Published: 11 January 2010

Abstract: The paper uses the framework of the IPAT equation, as applied to CO_2 emission, to decompose the various driving forces in the global energy use. Data from recent history are superimposed on projections of SRES IPCC scenarios to determine if enough sustainable capacity can be built to prevent irreversible ecological deterioration. The conclusion from the analysis is that, in agreement with the IPCC 4th report, until about 2030 there are no large differences between a sustainable scenario and the one that resembles “business as usual”. The sharp divergence that follows stems from different estimates in population growth and in the percentage of use of fossil fuels in the total energy mix. Decomposition of alternative energy options indicate that the rate of increase of alternatives such as hydroelectric and nuclear start with a relatively high base but a growth rate too short for major contribution to a timely replacement of fossil fuels while wind and solar starts from a much lower base but rate of growth, if maintained, that can satisfy a timely replacement.

Keywords: IPAT; greenhouse gases; energy; projections

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1. Introduction

Sustainable Development is now a recognized organizational principle with a Division of the UN Development of Economic and Social Development. Google is coming up with 15 million entries with a large proliferation of definitions with an increasing tendency to regard it as ambiguous and internally self-contradictory [1]. Being a physicist, it is easy to sympathize with these sentiments. However, the issue is too important to be buried in philological ceremonies.

Within the energy context arguments against attempts to globally change our energy choices to a more sustainable alternatives range from denials of major adverse effects of a resulting atmospheric increase in CO_2 concentration to a fatalistic approach that the issue is much too big for a rationale attempt to address it within a time frame that can make a difference.

Within this spirit—our quantitative framework is based on the IPAT [2,3] equation where I stands for Impact, P for Population, A for Affluence and T for Technology.

For CO_2 emission, the identity takes the following form:

$$CO_2 = Population\left(\frac{GDP}{Population}\right)\left(\frac{Energy}{GDP}\right)\left(\frac{FossilFuels}{Energy}\right)\left(\frac{CO_2}{FossilFuels}\right) \tag{1}$$

All the quantities in Equation (1), except for the population, are quantities per year. The Impact here is the environmental impact (CO_2) and GDP/Population (or as it is more often expressed as GDP/Capita) is the measure of Affluence. The rest of the terms refer to the Technology part of the acronym. The next term describes an issue that is often referred to as Energy Intensity. For a given population change, the policy goals are to minimize CO_2 production while at the same time maximize the GDP/capita. The thrust of the challenge from global perspective is to minimize the impact while at the same time to allow growth of the GDP/Capita term. The present inequity of this term between the developed and developing countries is about a factor of 50 with the most populous developing countries show economic growth much faster than the developed countries. The global population is predicted to stabilize at about 9 billion toward the end of the century [4].

Equation (1) was recently reformulated to reflect changes in growth rates. The differential formulation takes the following form [5]:

$$\frac{\dot{I}}{I} = \mu_{I,P}\frac{\dot{P}}{P} + \mu_{I,A}\frac{\dot{A}}{A} + \mu_{I,T}\frac{\dot{T}}{T} \tag{2}$$

where the derivatives are time derivatives and the μ terms are elasticities defined as $\frac{dI/I}{dX/X}$ where x stands for stresses in terms of population, affluence and technology.

Both forms are often seen as tautological but they have served as a useful starting point for the quantification of the driving forces for environmental impact in general and for climate changes in particular.

Table 1 makes a quantitative case for the inclusion of the physical environment as a key restriction on economic development. It balances the assimilation and emission of carbon dioxide by living organisms. This part of the global carbon cycle shows that there is an imbalance between emission and assimilation to the extent that approximates the human contributions, that are not being balanced by assimilation. The spectroscopic properties of carbon dioxide ensure that this imbalance changes the global energy balance that results in an increase in global temperature.

In turn the average global temperature is a key physical parameter that enables living organisms to survive and flourish with no known equivalence in the entire universe.

Table 1. Global assimilation and emission of carbon dioxide into the atmosphere by living organisms in units of billion tons /year (Data extracted from the Carbon Cycle shown in the NASA Earth Observatory site).

Assimilation	Emission
	Microorganisms—222
Marine Biota—185	Marine Biota—185
Land Biota—449	Land Biota—222
	Humans—26

Environmental impacts are not limited to Greenhouse gases, they span a vast area of interactions that uses the physical environment as a damping ground for waste and as source of raw materials to support human developments. Table 1 and similar data on other environmental resources are now convincing most people that there are limits to this practice that once these limits are crossed, our global existence is at stake.

The formal beginning of this realization on a global scale can be arbitrarily traced to the United Nations Conference on Environment and Development (UNCED) (The Earth Summit) that took place in Rio de Janeiro on June 1992. 172 governments took place with participation of 108 heads of states and 2,400 representatives of non-governmental organizations (NGO) and 17,000 participants in the parallel NGO conference.

The resulting documents and the follow-up mechanisms have finally succeeded to put global environmentally issues on the policy agenda to start a global revolution. One of the objectives of this paper is to try to find out how we are doing.

An attempt to quantify the progress was recently made by developing a scoring system for the countries in the world. This effort is being coordinated by Yale and Columbia universities and published annually [6]. The Environmental Performance Index (EPI) has two equally weighted criteria: (1). Reduction of environmental stresses to human health. (2). Protection of ecosystems and natural resources. Six Core policy categories include Environmental Health, Air Quality, Water Resources, Biodiversity and Habitat, Productive Natural Resources, and Climate Change. There is no global entry. The indexing is done through proximity to targets for the various categories and then weighing the contributions of individual categories to the overall criteria. The end result of the scoring is a not surprising high correlation with the wealth of the countries: developed countries at the top and poor countries at the bottom.

It is highly desirable, while not yet attainable, to construct an index with absolute criteria as scale setters. On the most fundamental levels economic development draws on three classes of resources: energy, commodities and labor. Energy and commodities bear directly on the physical environment. Sustainability accounting requires Cradle-to-Grave accounting in terms of limits to earth resources to sustain availability of “raw materials” and limits of earth resources to accommodate disposal of “waste”. This applies both to energy and material products. Appropriate pricing can regulate some of this effort mainly on the supply side. One of the consequences of the Rio conference was to start a major auditing effort to quantify environmental impacts. In commodities this effort is currently focused on the development of full Life Cycle Assessment (LCA) of Cradle to Grave accounting of the environmental impact of each stage of the production, use and disposal; while in energy the effort is focused on energy auditing and carbon footprint accounting. A policy that will move commodities to a sustainable mode will require an increased share of used commodities to be recycled. With energy physics imposes strict limits on our ability to recycle.

The present global LCA effort is focused on the creation of Life Cycle Inventory (LCI) [7] that will be followed by regulation and legislation to limit impact. This effort is just beginning. The rest of the paper will be focused on energy use.

2. Results and Discussion

Energy use analysis of the environmental impact focuses on emission of carbon dioxide as shown in Equation (1). Figures 1–5 show the changes in all the terms in Equation 1 from 1993 to 2007 superimposed on two SRES [8] scenarios that are being used by IPCC [9] as baselines for calculating the environmental impact that contributes to climate change. The two scenarios are A2 and B1 both derived from the Asian Pacific Integrated Model (AIM). The two scenarios were taken from about 40 "possible" scenarios that the SRES calculations follow. The choice of the two scenarios follows IPCC in choosing one that approximates business-as-usual (A2) and one that is the most environmentally conscious (B1). SRES takes pain to discourage the use of "bad" scenario and "good" scenario but in the present context it is inescapable. The A2 storyline and scenario family describes a differentiated world with slower adaptation of technological changes that is consolidated into a series of economic regions in which income differentiations do not narrow. The B1 storyline describes a world with high level of environmental consciousness with globally coherent approach. The actual changes from 1993 to present were compiled based on the BP listings [10].

Figure 1. Real and projected changes in global CO_2 emissions (co_2 emissions expressed in units of 10^9 metric tons of carbon); (data taken from the BP database [10] superimposed on the projections of two SRES scenarios [8]).

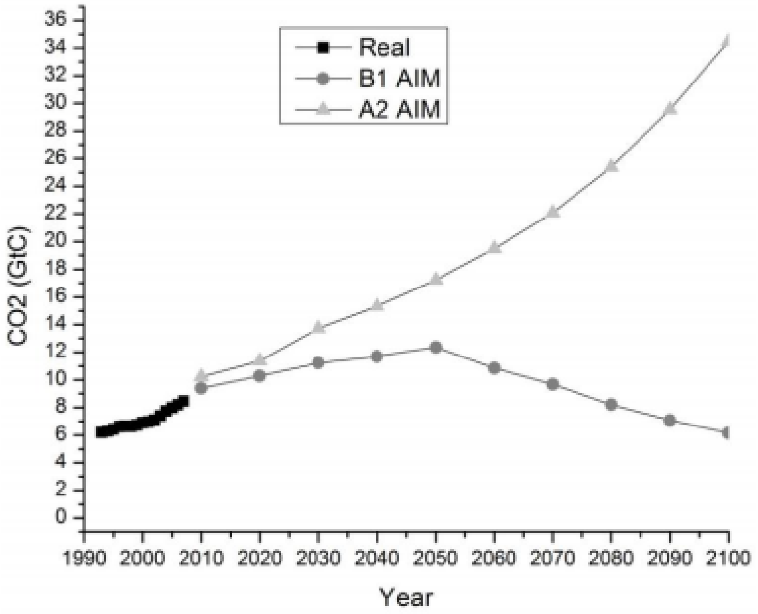


Figure 1 shows the actual CO_2 emissions between 1993 and 2007 superimposed on the A2 and B1 projections by SRES. The units are in Billion tons of carbon. All curves were determined by source emissions (and projections) not by atmospheric concentrations.

To introduce the time element in our environmental transition one needs to determine possible end point. The IPCC did this in its 4th report by converting the emissions into concentration and using a climate sensitivity of 2.5 °C for an expected rise in the average global temperature on doubling the atmospheric CO_2 concentration from the pre-industrial revolution level of 280 ppmv. I use here the optimal assumption that the numbers, shown in Table 1, will stay unchanged for the rest of the century, resulting in about half of the anthropogenic carbon dioxide being sequestered by the land and ocean components of the carbon cycle while the other half accumulates in the atmosphere. Based on this assumption one can estimate that by 2050 both scenarios will exceed the 2 °C average global temperature increase of the IPCC's "red line" in which adaptation can be a viable policy. After mid-century, the A2 scenario takes off quickly reaching concentrations that lead to average global temperature that exceeds the 4 °C increase in which major extinctions are predicted to take place with deadly impacts on the entire ecosystem. In these estimates the sequestered fraction of the emitted carbon dioxide is assumed to remain constant. The oceans are estimated to be responsible for about 65% of that amount—however, the balance is very delicate. The only region of the ocean that sequesters carbon dioxide is the tropics between 14°S–14°N, the rest of the oceans are net emitters [11]. The balance is a small net sequestration. Any changes in the partial pressure differences of the air-sea interface can change the balance. The same is true of the additional sequestration by land—major melting of the permafrost is expected to have a major impact. The time scale for these feedback mechanisms is not understood. The effects of major (larger than 2 °C) global temperature changes on economic development and energy use are also not being considered in these projections. A popular phrase in discussing climate change is that action choices can be grouped in categories that can be labeled as mitigation, adaptation or disaster. Figure 1 and the rest of the article will show that there is a need for intensive mitigation to start now before adaptation can be a credible long term solution.

Figure 2 shows that the major difference between the A2 and the B1 projections is the population increase to about 15 billion by the end of the century, predicted by the A2 scenario, as contrasted with the B2 scenario that expects population to peak in mid-century to about 8 billion, slightly declining thereafter to about 7 billion. The difference in the projected population increase is the major factor in the projected increase in the GDP/Capita that is given in constant US$ as shown in Figure 3 (The real segment of the data are given in constant 2,000 US $). Nevertheless, both scenarios predict a major average wealth increase that raises some valid eyebrows to the inconsistencies with the disaster predictions of Figure 1. This contradiction comes as direct consequence of the inability to include feedbacks into the future scenarios.

Figure 2. Real and projected changes in global population (data taken from the BP database [10] superimposed on the projections of two SRES scenarios [8]).

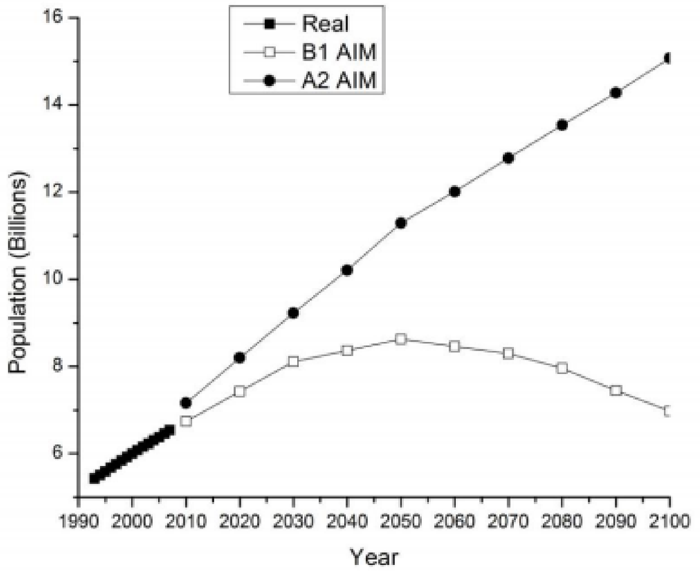
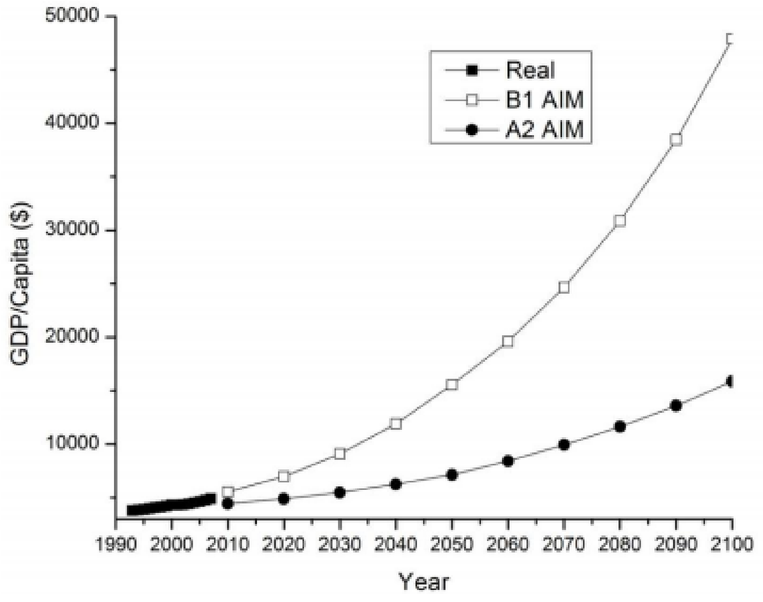
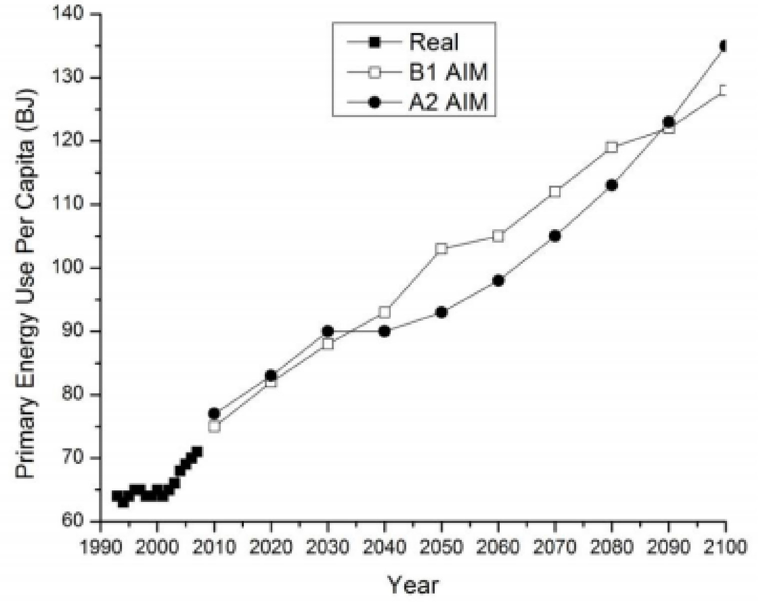


Figure 3. Real and projected changes in GDP/Capita (Source for the real population and GDP is the BP database [10]; data for the GDP are in constant 2000 US$. Projections are based on two SRES scenarios [8]).



The amount of energy required to achieve this projected increase in wealth is shown in Figure 4. Figure 4 presents the data in form of primary energy use per capita. The fascinating aspect of this graph is that the projections for the primary energy use per capita are independent of the scenario. Since the A2 scenario projects population to more than double toward the end of the century while the projection for the B1 scenario projects only a modest change over present population, the total energy needed for the A2 scenario increases proportionally.

Figure 4. Real and projected changes in global primary energy use (energy use in units of 109 Joules); (data taken from the BP database [10] superimposed on the projections of two SRES scenarios [8].



Both scenarios project a continuation of the present trend of major increase in efficiency of using energy as reflected in the decrease of energy intensity. This trend is shown in Figure 5. The large initial offset between the projections for both scenarios remains approximately constant.

Figure 5. Real and projected changes in global energy intensity (units expressed in 10^9 Joules/2,000 US$); (data taken from the BP database [10] superimposed on the projections of two SRES scenarios [8]).

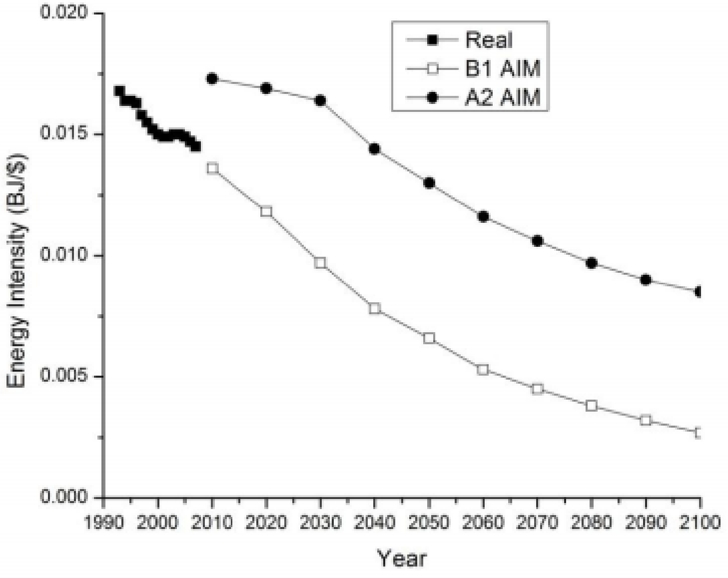
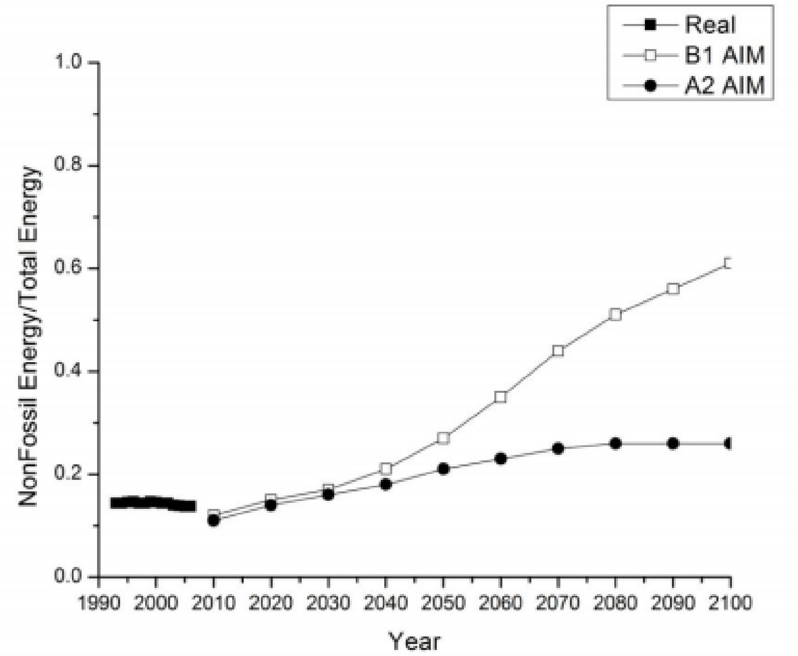


Figure 6 shows the fraction of non fossil fuel energy sources that are presently used and projected to be used in the future. The present trend show that this fraction didn't change much over the last 20 years and in the two scenarios it is projected that by mid-century to slightly increase to about 20% of the total energy. From this date on the A2 scenario does not project much change in this ratio to the end of the century while the B1 scenario projects an increase to about 50%. This is a major difference that together with the projected rise in population are responsible for the difference in projected outcome shown in Figure 1—from atmospheric changes that are predicted to result in manageable environmental changes as predicted by the B1 scenario to the unmanageable self inflicting genocide predicted by the A2 scenario. The rest of the paper will examine if, based on present data, this aspect of the prediction is credible.

Figure 6. Real and projected changes in global use of non fossil fuels (data taken from the BP database [10] superimposed on the projections of two SRES scenarios [8]).

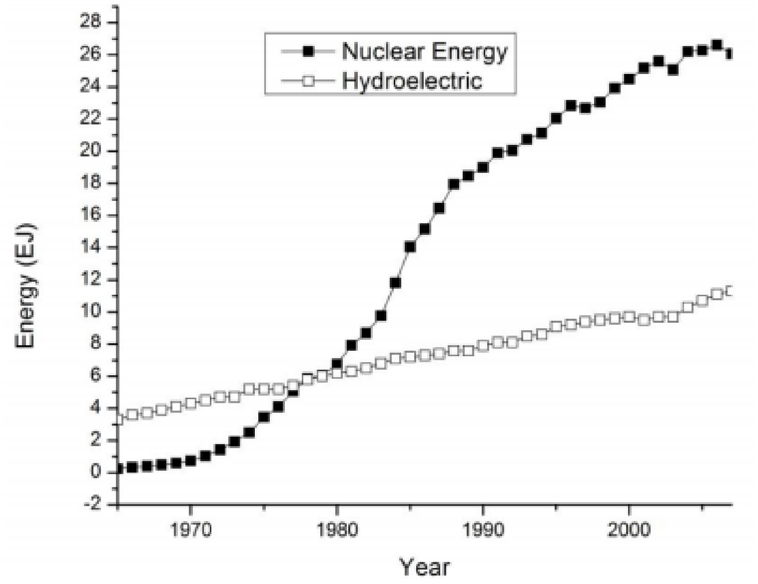


The three components that dominate present Non-fossil energy sources are nuclear power, hydroelectric and a catch-all category that the World Bank designates as Combustible, Renewable and Waste (CRW). The dominant users of CRW are underdeveloped countries that don't have fossil fuels and do not have the resources to import them. In its present form it is not a sustainable alternative to global use of fossil fuels.

Figure 7 shows the history of the global use of nuclear energy and hydroelectric energy. The figure shows that present annual growth rate of these energy sources is under 2% (for nuclear this is the growth rate after 1987 that followed a period of much more rapid growth). This growth rate will not bring us to the 50% non-fossil use required under the B1 scenario or any other scenario that claims to stabilize the atmospheric concentration of greenhouse gases.

Both, the hydroelectric and nuclear power generation method, rely on big projects with long construction time. Construction of a "typical" nuclear power plan can take about 10 years and construction of the largest and most recent hydroelectric plan, the Three Gorges Dam across the Yangtze River in China, has started on December 1994 and is expected to be fully operational in 2010–2011. The Power Plant will have 32 generating units with generating power of 700 MW. The total generating capacity (if fully operational year around) is 0.7 EJ. Nobody expects a repeat of such a project in the coming century.

Figure 7. Changes in global use of nuclear and hydroelectric energies (expressed in Exa Joules); (data based on the BP database [10]).



Direct solar energy conversion methods such as wind power, photovoltaic and photo thermal methods, are emerging technologies that presently are buried within the noise in the global statistics of energy use. However the statistics is based on past and present use. The future looks a bit brighter.

Figure 8. Changes in the global accumulated installed capacity of wind turbines [12] (based on compilation by Earth Policy Institute with 1980–1994 data from Worldwatch Institute, *Signposts 2004*, CD-ROM (Washington, DC: 2004); 1995 data from Global Wind Energy Council (GWEC), *Global Wind 2006 Report* (Brussels: 2007); 1996–2007 data from GWEC, “US, China & Spain Lead World Wind Power Market in 2007”).

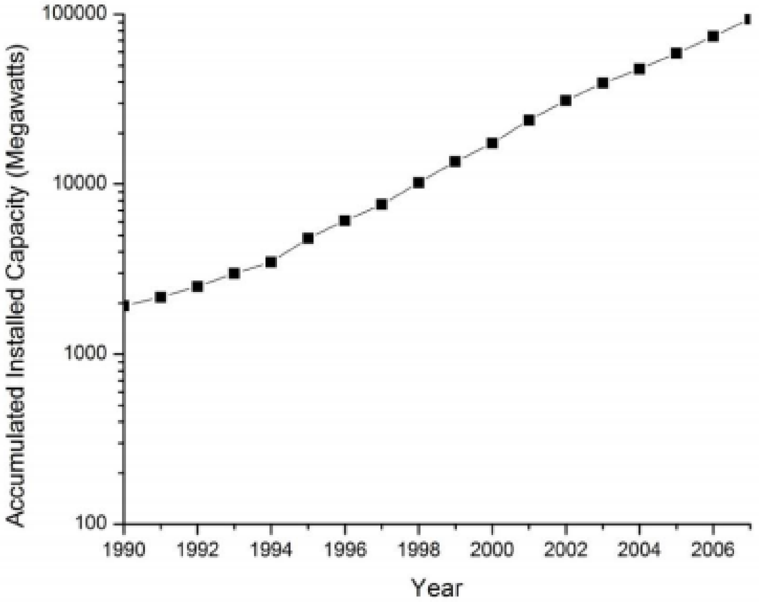


Figure 8 shows the global accumulated installed capacity of wind turbines [12]. The present accumulated capacity of 100 Gwatts, if constantly operating (they are not), is equivalent to 3.1 EJ. This number is still within the noise. However, the growth rate averaged over the last 20 years exceeds 20%. Solar photovoltaic is recording similar growth rates, albeit from a lower level. The expected global energy use in 2050 is around 900 EJ. Maintaining this growth rate for another 15 years will get us to the 50% required 2050 level. This is very ambitious but not impossible. The present price of wind power is competitive with whole sale power prices in the United States [13].

3. Conclusions

Following recent political jargon, the message that emerges out of the data analysis is—“Yes We Can”. The data show that, based on present technology and present growth rates, global energy requirements needed to satisfy economic growth can be implemented on a time scale that allows adaptation to the new environmental conditions. Sustainable technologies that are presently expanding at a rate that satisfies these requirements include wind conversion, photovoltaic and photothermal conversion. This is not an attempt to advocate a single set of solutions for a major substitution of the worlds energy sources to a given, sustainable, zero-carbon footprint alternatives. Small scale high rate of growth almost never extrapolates to a large constituent of an energy mix unless major changes take place. Presently, because of the small scale, availability of raw construction material is not a limiting factor—this will change. Global public acceptance for the transition is essential. Price didn’t enter any of our considerations here—the reason is that major aspects of the price adjustments will be carried out by the fossil fuels and by the developing global attitude that disposal should be an important factor in the price structure. In a sense, since the issue is existential and the time is short and there are no alternative planets with less expensive disposal policies, the discussion should not be whether to pay but only who will pay. This is a question that rests outside the Popperian boundaries of the applicability of the scientific method.

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