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The Worldwide Energy Situation[1]

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Abstract: Energy and growth are intimately related. There will be a pronounced increase in energy demand in the next decades associated with economic development and population growth worldwide. This situation will exacerbate current issues related to the dependency on fossil fuels, its environmental consequences and the mismatch between the geographic distributions of supply and demand. Energy and quality of life parameters for Latin American countries fall between those of the developed economies of Europe, North America, and eastern Asia, and the values of the least developed nations, many of which are in Africa. Quality of life statistics are aggravated by high social inequality in most Latin American countries. Argentina is well positioned compared to other Latin American countries; however, in order to prevent energy-limited growth, Argentina needs to accommodate energy demands associated to population growth as well as increase per capita consumption. A sustainable worldwide energy system will require proper long-term national policies within a global approach, strategic pricing that takes into consideration production costs and life-cycle waste processing, reduced population growth rates, and efficiency and conservation with associated changes in cultural patterns.

Keywords: resources, reserves, life expectancy, infant mortality rate, consumption, power, policy

Resumen: El crecimiento esta íntimamente relacionado con la energía. Se anticipa un alto aumento en la demanda energética en las próximas décadas asociado al desarrollo económico y al crecimiento de la población en el mundo. Esta tendencia confronta la disparidad de la distribución geográfica de fuentes de energía y núcleos de demanda, la dependencia de fuentes fósiles, y consecuencias ambientales. Los indicadores de energía y de calidad de vida para los países de América Latina están entre los valores de las economías desarrolladas (Europa, Norte América y este de Asia) y de los países menos desarrollados (mucho de ellos en África). La desigualdad social en los países Latino Americanos es particularmente alta y empeora las estadísticas de calidad de vida. Argentina esta bien posicionada en comparación a países latinoamericanos; pero para evitar limitaciones en el crecimiento debido a restricciones energéticas, el incremento de la capacidad energética en Argentina debe tener en consideración el aumento poblacional y el aumento de consumo per capita. Una estrategia energética mundial y sostenible demandará políticas nacionales de largo plazo compatibles globalmente, escalas de precios que tengan en consideración costos de producción y de procesado de residuos, reducción en el crecimiento poblacional, y cambios culturales que conduzcan a eficiencia y conservación.

Palabras Clave: recursos, reservas, expectativa de vida, mortalidad infantil, consumo, potencia, política

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[1] *Note: This manuscript documents the first part of the lecture presented at the Argentinean National Academy of Engineering on November 23, 2006. The second part explored the critical role of Geotechnology in solving the energy challenge, from resource recovery and infrastructure development to waste disposal (including carbon sequestration and nuclear waste disposal).*

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Introduction

The mechanical concept of energy relates to the capacity to do work. In society, energy is the capacity to cause change and sustain lifestyles. Plants capture the energy of the sun and have sustained civilizations throughout history. However the dramatic societal changes triggered by the industrial revolution over the last two hundred years have required vast amounts of energy, which coal and later petroleum provided.

Social growth continues today and the non-renewable fossil fuels provide most of the energy (coal, petroleum and natural gas). Increasingly more energy is consumed for transportation (typically from petroleum), heating (natural gas), and electricity (coal, gas, nuclear, hydroelectric and other renewable sources).

Fossil fuel burning is accompanied by the emission of carbon. With the accumulation of carbon dioxide in the atmosphere, there is increased concern for potential dramatic changes in climate.

Therefore, the challenging energy situation we face today is intimately related to the consumption of non-renewable fossil fuels and the emission of CO_2 into the atmosphere. These and other governing factors are explored herein. The situation in Latin American countries, and Argentina in particular, is identified when appropriate. For clarity, scales and simple ratios are used to facilitate the comprehension of otherwise infrequent numbers (For a comprehensive review and parallel analyses see the 2001 and 2007 reports by the Intergovernmental Panel on Climate Change). The database developed as part of this study includes 2003-2006 data compiled from the following sources: British Petroleum Statistical Review of World Energy, Energy Information Administration, International Atomic Energy Agency, International Energy Agency, National Renewable Energy Laboratory, NationMaster, The World Factbook - Central Intelligence Agency, and the United Nations Statistics Division, World Resource Institute.

A Brief History of Energy Resources

Our sources of energy have evolved throughout the history of the earth, beginning 4.5 billion years ago (bya - Figure 1). The first forms of life appeared 3.5 bya; later, bacteria converted the atmosphere from reducing to oxidizing (2.5 bya). More advanced forms of life populated the earth by 1.5 bya. Exuberant life and an atmosphere 50 times richer in CO_2 than current levels were present between 230-and-65 million years ago and led to the rapid accumulation of organic matter in lagoons and marine basins; these later became coal, petroleum and gas accumulations (fossil fuels). Plates drifted, mountains rose and regions that flourished around the tropic often moved near the poles (hence the accumulation of petroleum found in artic climate today).

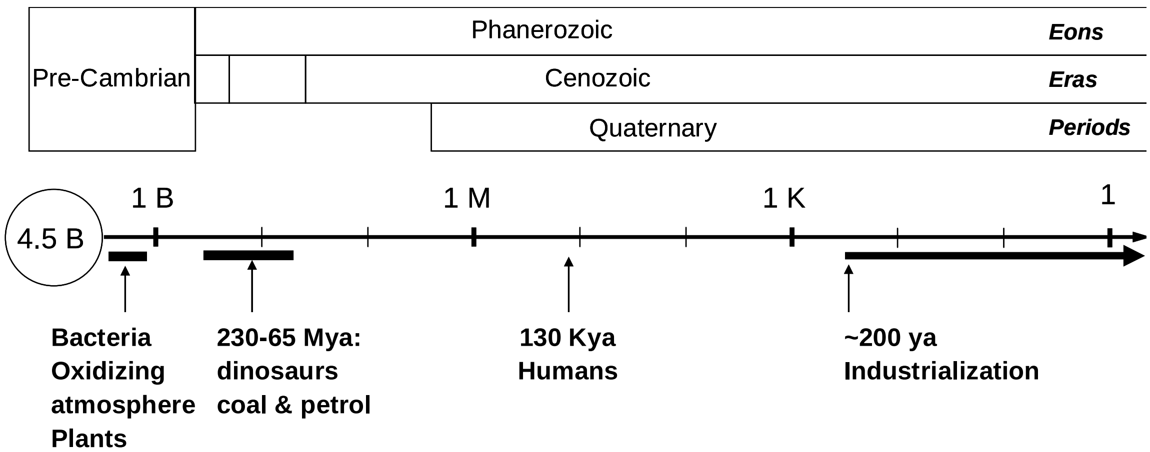

Figure 1: Geological time scales. (Notation: ya= years ago, $K=10^3$, $M=10^6$, $B=10^9$)

Internal radioactivity within the earth (nuclear energy) has maintained a persistent thermal flux towards the surface which manifests in the geothermal gradient (geothermal energy). At the same time, periodic changes have been common, ranging from the four major glaciations and intermediate melting periods during the last 400 thousand years (the ocean water has fluctuated from 50 to 150 m), to the cyclic interaction between the sun, the moon and the earth (tidal energy).

Plants, animals and wood burning have sustained civilizations throughout history, and the sun has remained the main source of energy. Its energy has been captured by plants and accumulated to form coal, petroleum and gas. The sun causes evaporation as well as the wind that transports moisture (wind energy), which eventually precipitates at higher elevations (hydroelectric energy). The efficient capture of solar energy is one of the most appealing alternatives for satisfying today's increasing energy demands.

This brief history of the earth highlights the intimate link between earth processes and all sources of energy we use today: fossil fuels (petroleum, coal, and natural gas), nuclear, and renewable sources (geothermal, solar, tidal, wind, hydroelectric, bio-fuels). A timeline for the earth is attempted in Figure 1 where time is plotted in logarithmic scale to stretch the most recent history and identify those events with the greatest current impact.

Scales in Time and Space

Figure 1 highlights the contrast between the time scale of natural processes and human activity. Furthermore, consider the following time scales for personal and political events

- the news: days
- presidential term: 4-to-6 years
- a generation: 25 years

and compare them against the time scales for natural processes and energy related decisions

- automotive assembly line: 12 years
- energy infrastructure: 20-to-50 years
- lifetime of CO_2 in the atmosphere: hundreds-to-thousands of years
- half-life of Plutonium-239: 24,110 years
- formation of fossil fuel reservoirs: millions of years

Clearly, one of the problems we face in addressing the energy challenge is the short duration of policy and decision makers relative to the long duration of critical energy-related processes.

The comprehension of geometric scales is equally revealing

- the radius of the earth: 6371 km
- the thickness of the earth's skin which is cooler than 1,000˚C is less than 40 km (assuming a 25C/km geothermal gradient), therefore, 98% of the volume of the earth is hotter than 1,000˚C
- most fossil fuels are extracted from the upper 2 km
- 90% of the atmospheric mass is within 16 km from the sea level

The earth is a large hot body. In contrast, the atmosphere is a very thin layer, yet, it receives all carbon emissions that result from burning fossil fuels and is also responsible for thermal balance and weather.

Sources of Energy - Reserves

The main sources of energy worldwide are petroleum (45%), natural gas (25%), coal (25%), nuclear power (2.5%), and hydroelectric (2.4%). Non-hydroelectric renewable sources account for less than 1%. Therefore, 95% of all the energy consumed worldwide is obtained from fossil fuels, primarily because of their low cost under present pricing conditions (Table 1).

"Natural resources" define known amounts of sources of energy that are present under a minimum concentration. "Producible reserves" are the subset of the resources that are economically producible at a given time. While fewer new resources are discovered, technological developments and increasing energy costs expand the boundary of producible reserves. It is estimated that under the current rate of consumption and within the framework of today's technology and pricing conditions, fossil fuel reserves will exceed many generations. Therefore, the energy problem is not about reserves in the short term.

The increased concern about climate change is prompting a new structure of long-term incentives (e.g., 2005 policy in support of nuclear energy in the USA) and penalties (e.g., tax on emitted carbon pending in many European countries) that may eventually alter the economic balance in support of non C-sources.

Table I: Energy Sources - Reserves

Source	**Energy budget**	**Main Use**	**Cost*** **[cent/kWh]**	**Reserves**
petroleum	45%	transport	3-to-8	generations
natural gas	25%	heat & e-power		centuries
coal	25%	electric power		centuries
nuclear power	2.5%	electric power		generations
hydroelectric	2.5%	electric power		almost saturated
renewable (non-hydro)	< 1%	electric power	>20 solar >8 wind	spatially distributed

Note: * cost in US cents

Income and Consumption

The annual consumption of the different energy sources can be combined to determine the rate of energy consumption per person in each country. Let's convert all annual consumption into Joules [J=N.m], compute power or the rate of energy consumption in Watts [W=J/s], and normalize by population size to determine the rate of energy consumption per capita in [W/person]. [3]

Results in Figure 2 are computed on the basis of 2002-2006 data (compiled from various sources listed above). The trend reveals the link between per capita consumption and lifestyles (as reflected by the income per capita). Undeveloped countries, many of them in Africa, plot to the left, and they have some of the lowest consumptions rates in the world. The most developed economies in Europe, North America, Australia, South Korea, and Japan plot to the right, with consumption rates in excess of 3kW/person. Latin American countries are represented as black triangles, and appear near the center of the figure.

The power consumption for an individual that follows a healthy diet is 2000 (kcal/day)/person≈ 100 W/person; in other words, our bodies consume energy at the same rate as a 100 W light bulb. The lower left corner shows the population with less than 100 W/person: 7% of the world population falls into this category. How can they survive? Clearly, they do so under very precarious conditions and without services. They rely on hunting, agriculture and wood for fuel and construction - all sustained by solar energy and natural processes.

[3] Relevant energy conversions include: 1 metric Ton of Coal = 24137 MJ, 1 barrel of oil = 6120 MJ, a cubic meter of natural gas = 38.1 MJ, 1 kWh of electricity is = 3.6 MJ, and 1 J=0.239 cal.

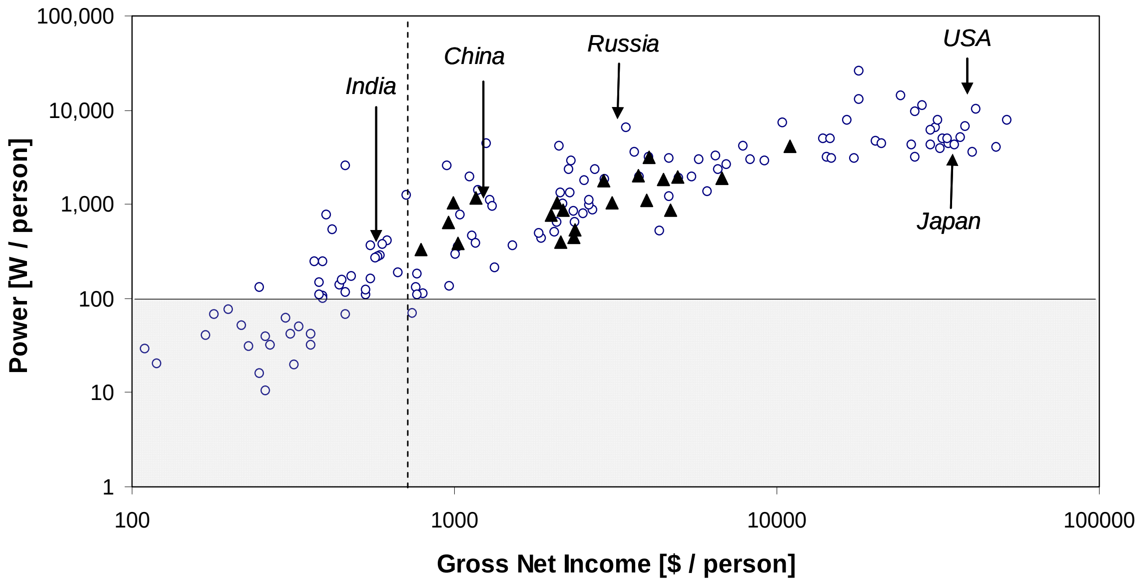

Figure 2: Annual income and energy consumption – Filled triangles represent Latin American countries. Two low boundaries are shown. The 100 W/person boundary corresponds to a 2000 kcal/day: 7% of the world population fall bellow this boundary. The annual 750$/person boundary is shown as a dotted vertical line: 37% of the world population is below this threshold.

The consumption rate in developed/industrialized countries is 30 to 100 times higher than our body's consumption. The excess between consumption and need is used to sustain our lifestyles within today's cultural patterns, and provides for transportation, heating, clothing, construction materials, and all forms of services including medical. Large inefficiencies in these processes are anticipated.

The Role of Each Country in the Global Situation

A country's rate of energy consumption is equal to the product of the population times the consumption per capita. Let's sort all countries according to consumption per capita and accumulate national power consumption and population, starting from the smallest consumers. The resulting trend in shown in Figure 3. It can be observed that:

- The current global energy consumption rate is ~13TW (Note: one tera-Watt = 10^{12} W). This total consumption combines oil, coal, natural gas, nuclear, hydroelectric, and other renewable sources.
- Given a global population of 6520 million people, the average consumption rate per person is 2 kW/person.
- Gaps in the data represent either countries with large populations (quasi horizontal steps) or large consumption per capita (quasi-vertical steps). Notable countries are India (population 1095 million; consumption: 0.4 kW/person), China (population 1314 million; consumption: 1.1 kW/person) and the USA (population 298 million;

consumption: 10.1 kW/person). The impact of the USA on the global energy balance is evident: it consumes about 25% of the world's total consumption with about 5% of the world's population.

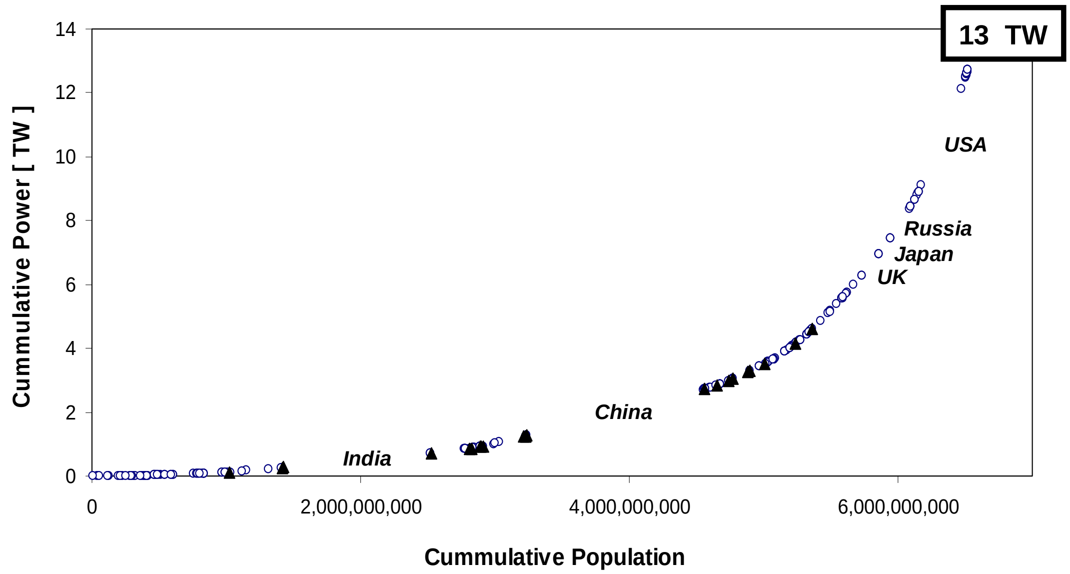

Figure 3: Cumulative energy consumption vs. cumulative population. Countries sorted by per-capita consumption prior to accumulation - Filled triangles represent Latin American countries. The names of countries associated with major increments are shown (horizontal gaps: large population and low consumption; vertical gaps: low population yet high consumption).

The per capita consumption in Argentina is 2.0 kW/person. This is the third highest consumption in Hispanic-America, after Puerto Rico (4.2 kW/person) and Venezuela (3.1 kW/person), similar to Mexico and Chile (1.9 kW/person), and significantly higher than in Brazil (1.0 kW/person).

Rate of Energy Consumption and Quality of Life

A strong pattern emerges when quality of life indicators are plotted against the rate of energy consumption per capita (Note: a better correlation is obtained between quality of life indicators and per capita income). A logarithmic scale is selected to better differentiate countries with low consumption in Figure 4 (however, it collapses together countries with high consumption). The following observations can be made:

- As energy consumption increases, life expectancy increases and infant mortality rate decreases. The data highlights the discrepancy between quality of life in the developed and under-developed economies.
- The correlation is particularly strong for energy consumption lower than 1 kW/person.
- Quality of life parameters reach a plateau at about 3-to-4.5 kW/person. Countries in this consumption range include Israel, Hong Kong, Austria, Denmark, Italy, Switzerland, France, Sweden, Ireland, and Spain. Therefore, excellent quality of life can be attained at this power level with today's technology and cultural patterns.

- Latin American countries fall in the central region of this plot (filled triangles). Argentina is in line with the general trend, but with a relatively high infant mortality rate. On the other hand, Costa Rica and Cuba have exceptional indicators relative to their per capita energy consumption.

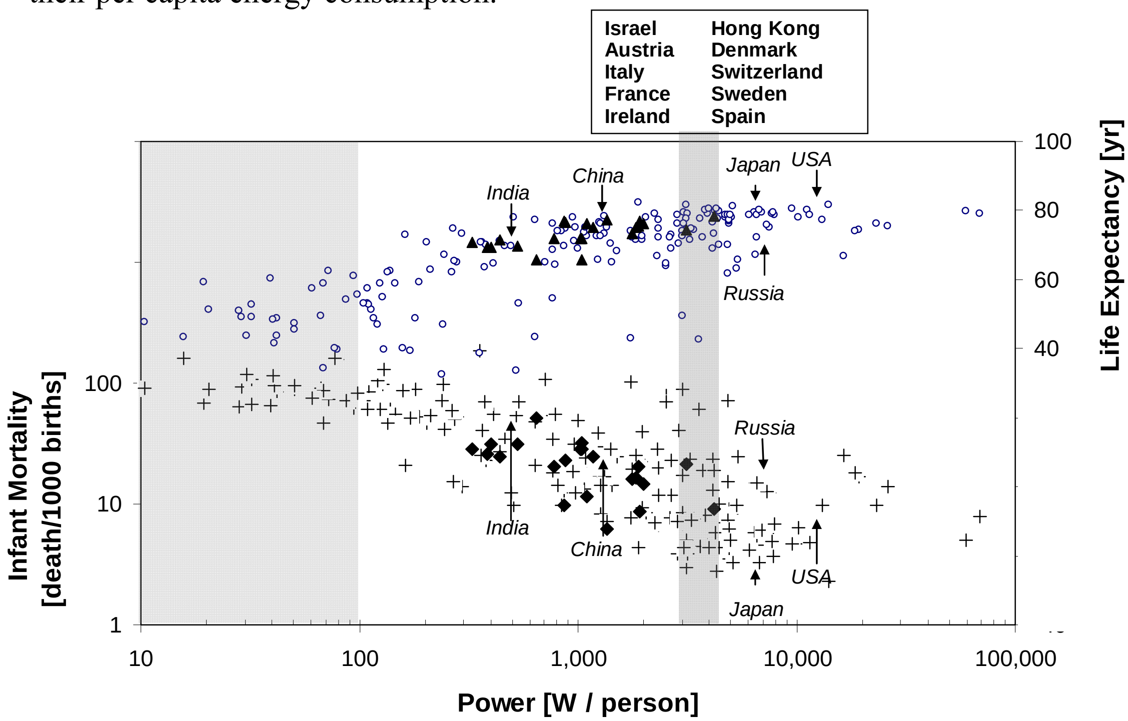

Figure 4: Energy consumption and quality of life - Filled symbols represent Latin American countries. The 100 W/person lower boundary corresponds to a 2000 kcal/day. The intermediate gray region covers the 3-to-4.5 kW/person range.

Life expectancy and infant mortality statistics are similar in Canada and Sweden, yet, energy consumption in Sweden is 1/3 that in Canada. Likewise, similar quality of life parameters are found in Denmark and the USA, but the Danish per capita consumption is 1/3 that in the USA. Therefore, other variables such as cultural and social patterns must be included in the analysis.

Other variables affect quality of life, such as social inequality. Furthermore, social inequality could affect statistical parameters used above to assess quality of life; for example, high infant mortality could be expected in countries with highly polarized societies, i.e., high percentages of poverty (this hypothesis could not be verified with the global database gathered for this study). Social inequality indicators in Latin American countries are among the highest in the world. In most other countries, the richest 20% of the population earns between 4 to 9 times more than the poorer 20%. However, Latin American nations are significantly above this range: Bolivia= 42, Paraguay= 28, Colombia= 25, Brazil= 24, Chile= 19. Social inequality is pronounced in Argentina as well: the richest 20% of the population earns 17.6 times more than the poorer 20%, and the trend shows that social polarization has aggravated in the last two decades (Worldbank, 2006).

Geographic Distribution of Demand, Resources and Infrastructure

There is a general mismatch between the geographic distribution of energy resources and the location of primary consumers. For example, compare the map of the main petroleum producing countries in Figure 5a versus the map of the "largest consumers who are low producers" in Figure 5b. This situation applies to other energy resources, including gas, uranium, and coal to a lesser extent.

The spatial mismatch between sources and demand and associated differences in quality of life bring about delicate political interactions between the large consumers (USA, western European countries, and countries in the eastern Asian belt) and their oil-producing counterparts (Russia, Iran, Iraq, Saudi Arabia, Nigeria, Algeria, and Venezuela). In turn, international events cause ample market fluctuations, such as the Yom Kippur war and the ensuing oil embargo in 1973, or the more recent increase in the price of crude oil since the Iraq war and political changes in Venezuela.

Political and cultural similarities between the USA and Canada add to geographic proximity and strengthen the link between the large USA market and the extensive Canadian reserves of heavy oils.

The overall reserves in Russia are exceptional. While Africa has significant coal, oil, gas and uranium reserves, the continent lacks energy infrastructure and distribution networks. Hence, most African countries face some of the lowest per capita energy consumption rates and quality of life indicators, as presented earlier.

Population Growth

Population growth rates are very high in all African countries and some Latin American countries, as shown in Figure 6a (Argentina has one of the lowest population growth rates among Latin American nations). At current growth rates, some of these countries will double their population in the next ~35 years.

There is an inverse relationship between population growth rates and energy consumption per capita (trend not shown here). Therefore, the energy situation could be exacerbated by the compounded effect of high population growth and increase in energy consumption in countries with currently low consumption per capita. The database compiled for this study is used to explore the coupling of population and consumption and to analyze possible future scenarios; results follow.

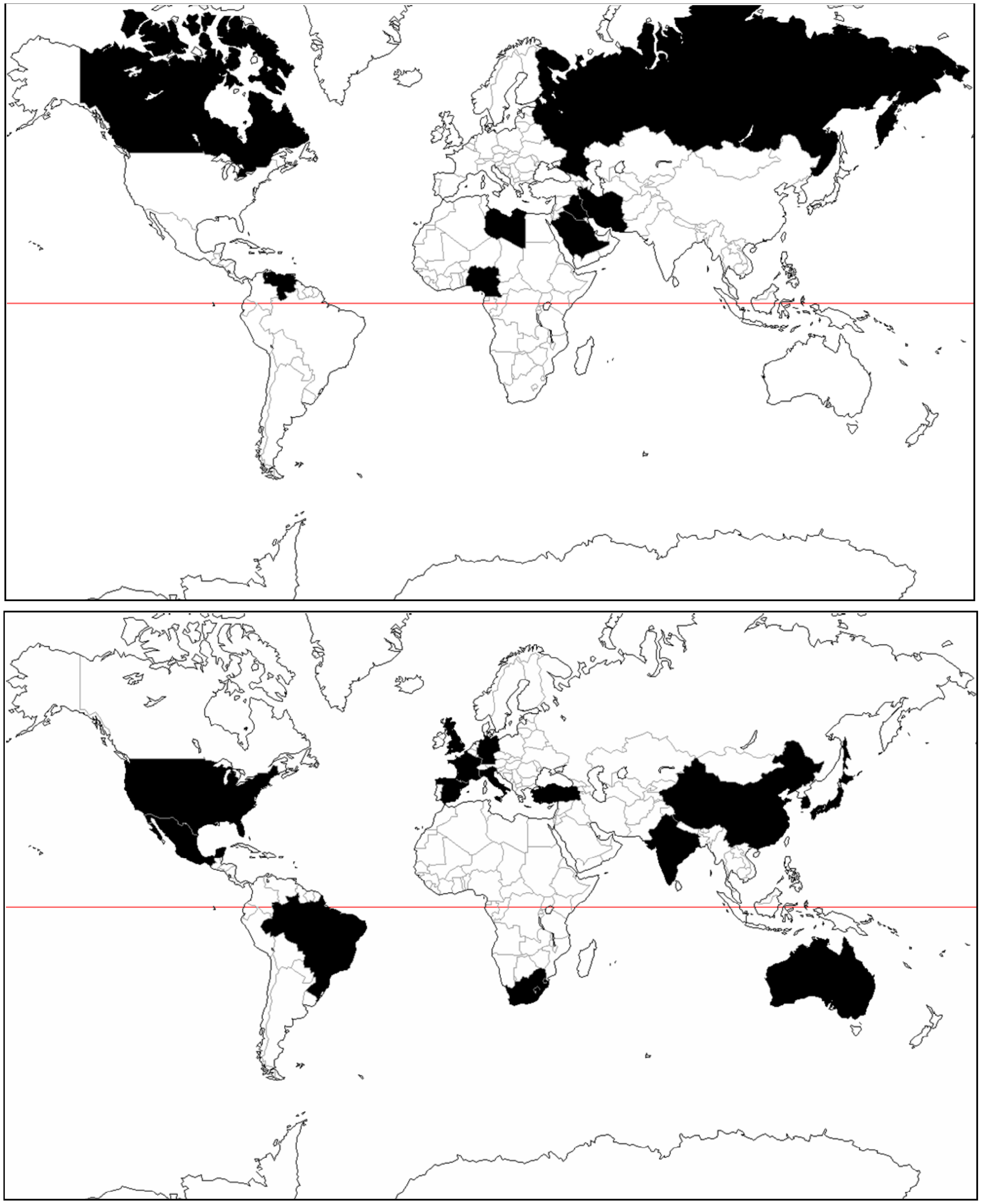

Figure 5: Geographic Mismatch. (a) Main oil producers. (b) Main consumers who are low oil producers.

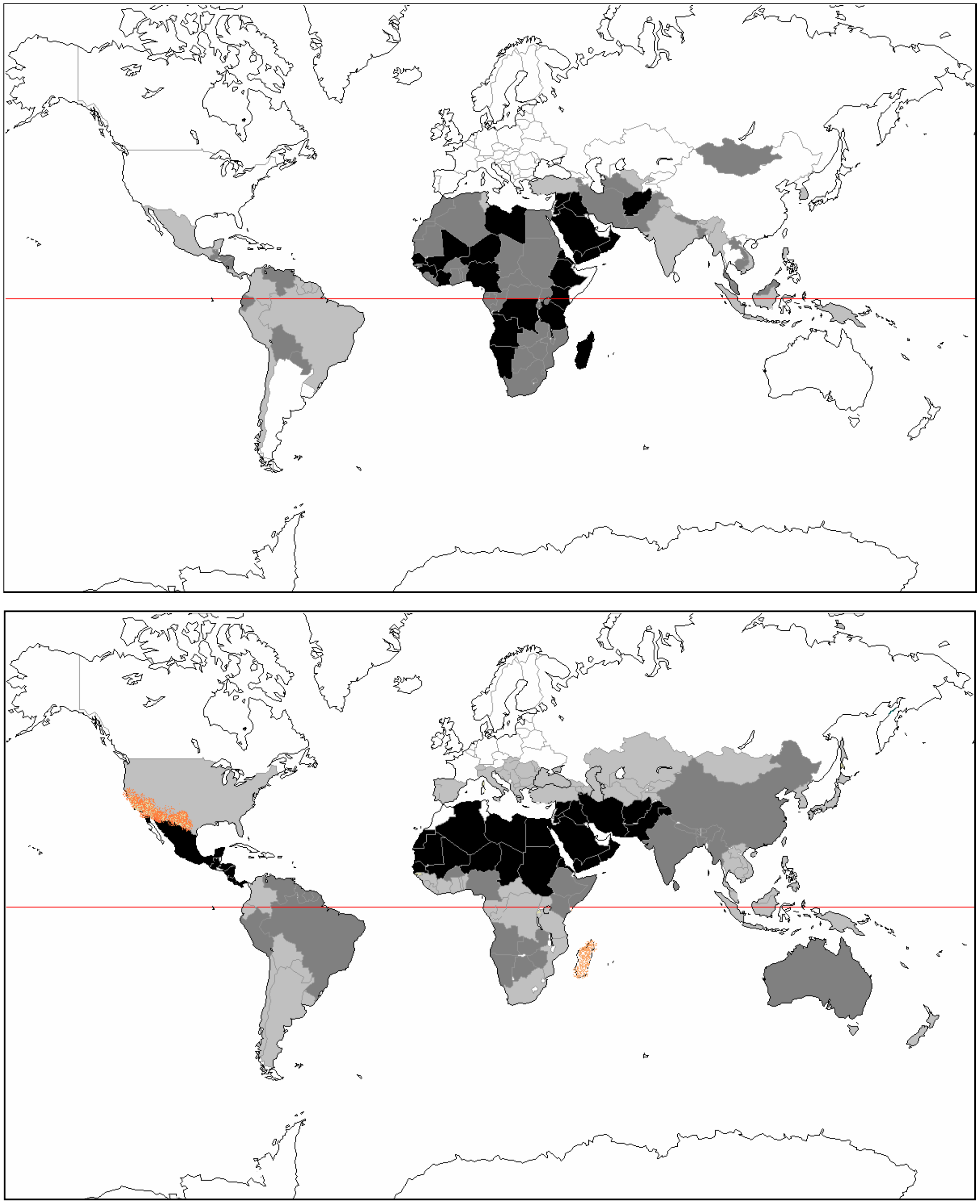

Figure 6: Considerations for future developments – Solar Energy. (a) Counties with highest population growth. (b) Countries with highest insolation. The darker the color the higher the value.

Future Increase in Power Demand – Potential Global Scenarios

The increase in energy demand can be predicted for a 25 year horizon under various hypothetical scenarios (Table II).

Scenario 1: Status quo. At current population growth rates and consumption per capita, the power consumption would increase to 15.2 TW, this is a 17% increase in energy consumption for a 36% increase in population. Given the higher population growth in countries with the lowest per capita consumption, the status quo scenario leads to even lower power per capita in these countries by the year 2032, further aggravating today's dire situation.

Scenario 2: Growth in less-developed countries. If the energy consumption increases to a minimum of 1.5 kW/person everywhere, the world consumption will increase 66% to 21.6 TW. Given the rapid growth in India (currently at 413 kW/person) and China (currently at 1100 kW/person), this predicted growth in demand is not unrealistic.

Scenario 3: Limit over-spending. A reduction in power consumption to ≤ 4 kW/person – a viable option which would not affect quality of life given today's technology and cultural patterns – would reduce the worldwide consumption from 13 TW today to 11.0 TW in the year 2032; this is a -15% decrease in power consumption.

Scenario 4: Limit over-spending combined with growth in less-developed regions. If minor technological developments and changes in cultural patterns support the growth of the less developed economies to a consumption rate of ≥1 kW/person and prompt the reduction in over consumption in developed economies to ≤4 kW/person, the worldwide consumption by the year 2032 would increase only 9% to reach 14.2 TW. This scenario is attainable with relatively minimal negative impact on the lifestyle of the developed economies, yet with a tremendous positive impact on the poorer nations. Important additional benefits could arise from a less polarized world situation. Generally accepted social inequality levels are typically much higher than those assumed in this case, therefore, this scenario appears unlikely.

Scenario 5: Limit population growth. The increases in energy demands in the four previous scenarios compound the effects of population growth and increase in energy consumption which will take place primarily in undeveloped and developing economies. Given the inverse correlation between these two parameters, it could be expected that population growth dramatically exacerbates predictions that are controlled by growth in the developing world. Table II shows results for the four scenarios above when a dramatic restriction in population growth to only 1% or less is imposed on all countries. The increase in energy consumption would be 13% in Scenario 1 (instead of 17%), 53% in Scenario 2 (instead of 66%), -19% in Scenario 3 (instead of -15%), and 1% in Scenario 4 (instead of 9%). Results for the more likely scenarios 1 and 2 suggest that the impact of needed economic growth in undeveloped countries on the global energy balance overwhelms the potential impact of population growth. Nonetheless, the most important benefit from limited population growth is to prevent further straining the very precarious energy and life conditions that already prevail in undeveloped economies.

Table II: Future Power Demand – 25 year Prediction – Scenarios

Scenarios	Assumed National per capita Consumption	Assumed National Population Growth	Power Demand year 2032 [%][b]
1. Status quo	current levels	current rates[a]	17% increase
		≤ 1% everywhere	*13% increase*
2. Growth in less developed countries	≥ 1.5 kW/person (or current levels)	current rates[a]	66% increase
		≤ 1% everywhere	*53% increase*
3. Limit Overspending	≤ 4 kW/person (or current levels)	current rates[a]	-15% reduction
		≤ 1% everywhere	*-19% reduction*
4. Limit overspending and growth in less developed countries	≥ 1 kW/person ≤ 4 kW/person (or current levels)	current rates[a]	9% increase
		≤ 1% everywhere	*1% increase*

Note: (a) at current rates, the world population will increase 36% by the year 2032. (b) Percentage change with respect to today's 13TW consumption.

These hypothetical situations suggest great opportunities associated with conservation among the leading energy consumers, growth among the poorer ones, and reduced population growth. However, in order to have the desired impact, these efforts require concerted global action rather than single-sided national initiatives.

Argentina will require an increase from 80 GW to 102 GW by the year 2032 to satisfy the current population growth rate at a constant consumption rate of 2.0 kW/person. However, if growth is planned to reach 3 kW/person (the apparent energy-limited threshold according to results in Figure 4), the power required to accommodate population growth and increase in consumption will be 160 GW. This is twice higher than today's power.

Carbon Emission and Global Warming

Many natural processes produce carbon emission. Its accumulation in the atmosphere is partially compensated by bioactivity on land and in the oceans. The unprecedented increase in fossil fuel burning since the beginning of the industrial revolution has led to the rapid increases in CO_2 concentration in the atmosphere in the last 200 years, as shown in Figure 7.

Given the strong dependency on fossil fuels (95% worldwide), there is a high correlation between national energy consumption and carbon emission. In fact, the ratio between "non-fossil to total power consumption" is typically less than 6% among the largest energy consumers except in Japan (8%), Canada (14%), France (19%) and Brazil (19%). Argentina derives 7% of its energy from non-fossil fuel sources.

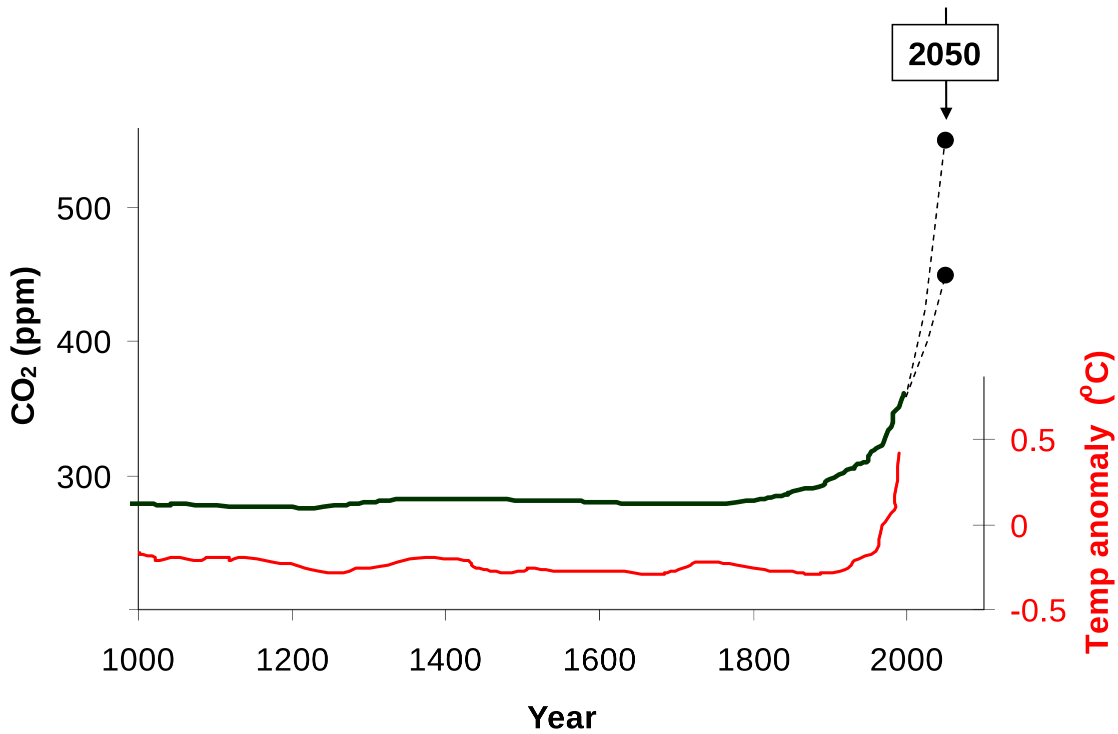

Figure 7: Carbon emission and global warming (highly filtered trend – original data from Mann and Jones 2003; see IPCC 2007)

The USA emits 5.6 ton/person-yr, but at a declining rate. In the meantime, China emits 1.4 ton/person-yr but its per capita emission is increasing. At current rates, China will surpass the USA C-emission within this decade. This situation can be generalized: the rate of increase in carbon emission is much higher in the less developed nations, and their collective emissions will soon surpass the collective emissions of industrialized nations.

Carbon dioxide CO_2 is a green house gas and causes the entrapment of radiation from the sun within the atmosphere leading to global warming. The causal link between CO_2 concentration and temperature appears to be supported by the correlated increase in surface temperature and CO_2 concentration during the last 200 years, suggested in the highly filtered data shown in Figure 7. These trends are based on the instrumental record for the last 120 years complemented with data gathered from ice cores, tree rings, and the inversion of borehole temperature data. While the scientific community tends to lean in support of anthropogenic CO_2 and associated global warming, there are renowned researchers who disagree (Note that water vapor and methane are green house gases as well).

The current concentration of CO_2 in the atmosphere is 380 ppm. Tenants of the global warming hypothesis suggest that a CO_2 concentration of 550 ppm could trigger severe climate effects (see IPCC 2000, and Socolow and Pacala 2006 for comprehensive reviews and analyses). It is estimated that 550 ppm will be reached by the year 2050, unless decisive action is taken by the international community. From this perspective, the interwoven energy, C-emission and global warming puzzle is becoming the first and most important world-wide challenge humanity has ever faced. Determined decision making is lacking, in part due to incomplete understanding of related phenomena, the time scale of the political process compared to natural processes, and concerns about the potential impact preventive decisions may have on the national economies of developed nations without impeding growth in developing nations. In the meantime, there is increasing evidence that social awareness in developed nations is beginning to affect the political agenda.

Different, multi-action scenarios were postulated and modeled as part of the most recent study by the Intergovernmental Panel on Climate Change (IPCC 2007). Results highlight the need for decisive action. Furthermore, a salient conclusion of the study is that more effective solutions will be attained when "global solutions to economic, social and environmental sustainability, including improved equity" are embraced rather than independent national-level initiatives that are based on "self reliance and preservation of local identities".

Overall, solutions will have to involve alternative non-fossil energy sources, reduced population growth in the developing world, conservation and efficiency, and a pronounced reduction in carbon emission in the industrialized world (Note: carbon emission may be reduced by carbon capture and storage CCS – IPCC 2005, Dooley et al 2006).

Non-Fossil Fuel Alternatives: Nuclear?

In the midst of increased concerns for carbon emission and global warming, non-fossil fuel alternatives are gaining increased attention, in particular nuclear power plants. To put this alternative into perspective, let's note that:

- Less than 500 nuclear power plants have been built and operated in the last 56 years since 1951 when electricity was first generated from a nuclear plant.
- Assuming a typical 1 GW plant size, additional 2200 nuclear power plants would be required to produce the 2.2 TW increase predicted in 25 years under the "status quo" scenario explored above.
- There is no nuclear waste repository in operation in the world, and waste fuel is kept in pools. While the critical time for waste fuel is ~100 years, the design horizon for waste repositories is 10,000 years in the USA.

Clearly, even if safe reactors and waste disposal systems are developed to minimize risk and satisfy social concerns (including proper international controls to reduce the threat of nuclear proliferation), the nuclear option alone is not sufficient to address energy needs. In addition, the time required to design, build, and license a plant approaches a decade. Therefore, long term policies are needed to promote investment from the private sector.

If the growth in energy demand in Argentina during the next 25 years were be covered by nuclear energy alone, 22 new 1GW reactors should be in operation by the year 2032 to satisfy population growth, or 80 new reactors to satisfy population growth and increased energy demand to 3 kW/person.

What about solar energy? There are two impediments. The first one is cost, yet, a steady increase in efficiency and reduction in the cost of photovoltaic devices have taken place in the last two decades. The second one is the spatial distribution of insolation which diminishes away from the tropics.

High consumption regions in the northeast USA, Canada, northern Europe, South Korea and Japan have relatively low insolation. Northern parts of Argentina, Chile, South Africa and Australia as well as the southern parts of the USA can clearly benefit from solar energy. Most of the countries with high population growth and currently low per capita consumption throughout Africa and Latin America lie between the tropics of Cancer and Capricorn and have high insolation, which often exceeds a day-average of 300 W/m^2 (Figure 6). Furthermore, being a distributed energy source may be a disadvantage in industrialized nations, but it is an important advantage in developing economies where energy infrastructure and distribution networks are lacking. Therefore, the potential of solar energy becomes particularly attractive in these developing economies, and leap-frog developments may be expected as technological breakthroughs lower installation costs.

Economy vs. Energy Consumption – Trade Balance

The magnitude of the world economy is 40 T$/yr (Tera = 10^{12}), while the worldwide rate of energy consumption is 13 TW. The ratio between the two provides an economic indicator of energy efficiency: a high number implies high economic output relative to the consumed energy.

Selected values follow: worldwide= 0.45 $/kW.hr, USA= 0.47 $/kW.hr, Canada= 0.29 $/kW.hr, UK= 0.78 $/kW.hr, Switzerland= 1.29 $/kW.hr, France= 0.80 $/kW.hr, Denmark= 1.29 $/kW.hr. All large economies in Latin America are below the global world average. In particular, the value of this parameter in Argentina is 0.21 $/kW.hr, which is significantly lower than Brazil (0.34 $/kW.hr) and Mexico (0.41 $/kW.hr).

The economy-to-energy ratio permits converting economic values into energy values. Important implications may follow. For example, the economy-to-energy relation allows us to conclude that expensive high-tech products (e.g., electronics) and services (e.g., medicine) effectively carry higher embodied energy and are more energy intensive than low cost raw materials such as food and even construction materials, contrary to what could be concluded from a cursory observation.

The complete energy life-cycle must also take into account the handling of waste (fly ash, nuclear waste, CO_2) as well as the decommissioning of obsolete energy infrastructure. Legislation in this direction, such as the carbon tax, would shift the balance between different technologies and sources of energy. For a historical example, consider the impact on coal price caused by the USA Mine Health and Safety Act in 1969.

Energy consumption in a given country should be corrected for trade balance: the end-user consumes the embodied energy in the product, rather than the producer that exported it. The negative trade balance effectively increases the per capita consumption in the US, United Kingdom, Spain, France, and Australia, but reduces the per-capita consumption in Germany, China, Russia, Japan, Canada and Brazil. The correction of energy consumption by trade balance cannot be readily computed with the economy-energy ratios above and a more complex analysis is required due to differences in embodied energy in raw materials and in value-added industrial and technological products.

Trade balance also affects the analysis of carbon emission in different countries. To a large extent, the increasing carbon emission in China is related to the production of low cost products consumed elsewhere around the world.

Summary – Closing Thoughts

- Energy is critical for economic development
- A high increase in energy demand is anticipated in the next decades.
- Quality of life indicators such as life expectancy and infant mortality rate are strongly correlated with energy consumption per capita, particularly for the poorer countries with energy consumption lower than about 1 kW/person. Other variables affect quality of life, such as social inequality. Proper changes in national policies can have an important effect on quality of life within current levels of energy consumption.
- It appears that unsurpassed living conditions can be attained with a 3 kW/person consumption within today's technology and cultural patterns. This value appears as a threshold for energy-limited growth. Higher level of energy-efficiency may be attained as a consequence of technological breakthroughs.
- The world population growth will take place primarily in developing countries. Therefore, there is a compounded effect of population growth and increase per capita consumption on energy demands. However, the impact of needed economic growth in undeveloped and developing countries on the global energy balance overwhelms the potential impact of population growth. Thus, the most important benefit from limited population growth is to prevent further straining life conditions in undeveloped countries.
- The most promising strategy for future development involves reduced energy consumption in industrialized countries together with increase per-capita spending and reduced population growth in developing nations.
- The energy resources are adequate to meet demand for several generations. But, there is marked geographic mismatch between the spatial distribution of resources and regions of high consumption.
- The dependency on fossil fuels will continue in the next decades. While the carbon emission per capita has been decreasing in developing nations, the overwhelming dependency on fossil fuels worldwide and the growth of developing economies imply

increased carbon emissions for the next decades. Carbon capture and sequestration will be needed to lessen the current rate of carbon accumulation in the atmosphere.

- The coupling between growth, energy, C-emissions, and climate change has become the most challenging global puzzle humanity has faced. The do-nothing option is no longer an option. In view of the time-scales of political and natural processes, waiting for further developments and theory confirmation appears to be a high risk proposition. Decision making must gain critical national and international relevance.
- Nuclear power can only play a minor role in balancing the expected increase in energy demand in the next decades.
- Solar energy is a promising alternative, particularly for developing nations where high insolation is common and the energy infrastructure is lacking.
- National values of consumption and emission per capita need to be corrected for trade balance and the embodied energy in trade products.
- A sustainable worldwide energy system will require (1) proper long-term national policies within a coordinated global approach, (2) strategic pricing that takes into consideration production costs and waste processing, (3) efficiency and conservation with associated changes in cultural patterns, and (4) reduced population growth rates.
- Energy-related parameters for Latin American countries often fall in between values that correspond to the industrialized economies (Europe, North America, eastern Asia) and the least developed nations (many of them in Africa). Quality of life statistics are aggravated by high social inequality in most Latin American countries.
- Current values show Argentina well positioned in relation to other Latin American countries. However, in order to prevent energy-limited growth, Argentina needs to accommodate energy demands associated to population growth as well as increase per capita consumption. Quality of life indicators, including social inequality, are worse than expected based on per capita energy consumption and can be significantly improved even at current consumption levels. Efficiency, as measured by productivity with respect to energy consumption, is low.

Energy resources, waste handling and the development of the energy infrastructure are intimately related to the earth. Therefore, geotechnology has a critical role to play in addressing the energy challenge[4].

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[4] This is the central theme of the second part of the lecture.

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