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CHALLENGES TO PHASING OUT FOSSIL FUELS AS THE MAJOR SOURCE OF THE WORLD'S ENERGY

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ABSTRACT
Energy-related data for China, India, the United States, and the world were analyzed for the period 2005–2035 to gain insight on (1) the evolution of energy intensity, (2) the pattern of carbon-dioxide equivalent (CO_2) emitted per unit of GDP, (3) reductions in the carbon intensity required to achieve CO_2 emissions comparable to the 1990 Kyoto Protocol's baseline year, (4) key obstacles to transitioning to a world's economy less dependent on fossil fuels. Key findings are: (1) the world's total primary energy use is expected to increase by 56% in the period 2005–2035, (2) the world's rate of GDP growth outpaces its rate of increase in energy use because of a decrease in the energy/GDP ratio, (3) the world's carbon intensity in 2035 must undergo a near 4-fold reduction to achieve emissions equal to those of 1990, (4) there are major obstacles to transitioning to a world much less reliant on fossil fuels.

Keywords: Fossil fuels, greenhouse gases, energy intensity, carbon intensity, renewable energy, nuclear energy, GDP.

1. INTRODUCTION

Concerns over the increase in the concentrations of greenhouse gases (GHGs) in the atmosphere by human action and their potential impacts on the world's climate are prominent in the debate over future sustainable paths of global population and economic growths (see, e.g., Williams, 2008; Custers, 2009; King, 2009; Kurtzman, 2009; Levi, 2009). Two well-publicized studies on the state-of-the-art of climate-change predictions and the likely social, economic, and environmental impacts of global warming during the 21st century are those by the Intergovernmental Panel on Climate Change in 2007 (IPCC, 2007) and Karl et al. (2009). Many other studies have been written on the relation between 20th- and 21st-century climate change and its potential regional impacts on sensitive environments (Sala et al., 2000; Schröter et al., 2005; de Wit and Stankiewicz, 2006; Robinson et al., 2007; Seager et al., 2007; Malhi et al., 2008; Loáiciga, 2009).

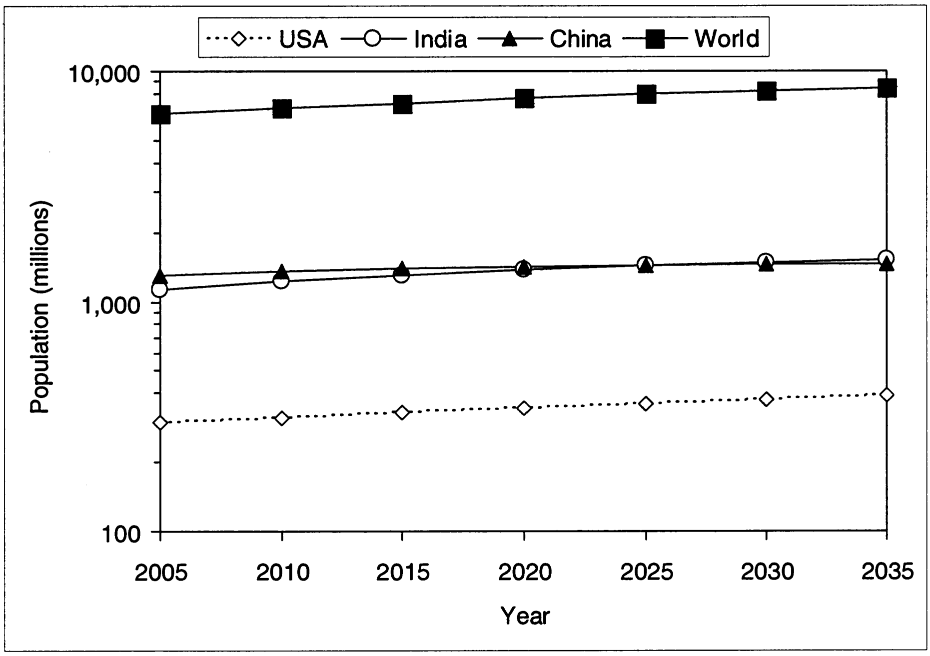

Figure 1: Population in 2005–2035 for the United States, India, China, and the world. (Data source: Loáiciga, 2009; Energy Information Administration, 2010).

At the core of concerns about anthropogenic emissions of GHGs and their role on possible shifts in the world's climate are population growth and economic growth. Figure 1 shows population data and forecasts for China, India, the United States, and the world as a whole for the period 2005–2035. It is seen in Figure 1 that the world will have a population of approximately 8.5 billion (1 billion = 10^9) in 2035, up from 6.5 billion in 2005. India is forecasted to overtake China as the most populous country in 2030. The United States will have approximately 391 million people in 2035, up from 297 million in 2005. Energy use is vital to sustain a growing population and prosperous economy. Today's world economy relies heavily on the combustion of fossil fuels (coal, petroleum and its derivatives, and natural gas) for its energetic needs (Moniz and Kenderdine, 2002; Hightower and Pierce, 2008). The combustion of fossil fuels plus other anthropogenic activities (vegetation burning, for example) have augmented the atmospheric concentrations of several key GHGs (Benka, 2002; Szuromi et al., 2007; Glicksman, 2008; Jacobson and Delucchi, 2009). GHGs are transparent to incoming solar (short-wave) radiation, but trap long-wave (infrared) radiation emitted by earth. Their net effect is to maintain earth-surface temperatures that are higher than those that would occur if the GHGs were absent, the so-called greenhouse effect (see, e.g., Ramanathan, 1988).

The human footprint on GHGs became more acute since the inception of the Industrial Revolution (circa 1750). For comparison, the atmospheric concentration of CO_2 at the height of the last ice age (some 25,000 years before present) was approximately 180 ppmv (parts per million by volume in air). It had risen by the middle of the 18th century to 280 ppmv. It was approximately 285 and 370 ppmv in 1800 and 1990, respectively. It was estimated to be about 385 ppmv in 2010 (Loáiciga, 2009). It is this increase of approximately 105 ppmv since the mid 1700s and the future emissions of GHGs that raises concerns about future adverse dislocations of the relative mild world's climate enjoyed during the Holocene (the last 10,000 years, approximately).

This paper reviews and analyzes (i) data on energy use and GHGs emissions worldwide, in the United States of America, and in China and India, (ii) data concerning the advantages and disadvantages of several energy technologies, and (iii) obstacles on the path to transitioning to a world much less dependent on fossil fuels than today's economy. The United States features the largest economy in the world. China and India are the two most populous countries and their economies are among the largest and fastest growing in developing countries. Some of the energy-use, economic, and GHGs emissions data used in this work were compiled and released to the public by the U.S. Department of Energy's Energy Information Administration in its year 2010 International Energy Outlook (Energy Information Administration, 2010). Other data on energy technologies used in this paper were obtained from various sources to be cited below. The Energy Information Administration's data used in this paper pertain to the period 1990–2035, where the 1990–2007 data represent actual figures and the 2010–2035 data are predictions based on reference-case projections. The reference-case projections of future energy use, economic performance, and GHGs emissions correspond to predictions compatible with historical growth of gross domestic product (GDP) and population worldwide. These projections are the most recent and authoritative of their kind (Energy Information Administration, 2010). This paper's analysis strives to shed light on the following themes for the four comparison regions in the period 1990–2035: (1) the observed and predicted evolution of the energy intensity (or energy used/GDP); (2) the observed and predicted evolution of the CO_2/energy ratio; (3) the observed and predicted evolution of the carbon intensity (or CO_2/GDP ratio); (4) the reduction in the carbon intensity required to achieve CO_2 emissions by 2035 comparable to those of the baseline year 1990 (adopted as a baseline in the 1997 Kyoto Protocol on GHGs emissions); (5) identifying the key challenges to transitioning from a world economy reliant on fossil fuels to another supported by more benign energy technologies.

The analysis carried out to achieve thematic objectives (1)–(5) relies on (i) the observed and predicted use of the main current sources of energy, namely, liquids (that is, petroleum products, natural gas liquids, and biofuels), coal, natural gas, renewables (i.e., solar and wind energy or power –where power is energy per unit time-, hydropower, geothermal power, tidal and wave power, and biomass), and nuclear power, and (ii) information about the intrinsic properties of fossil fuels and alternative energy technologies, where energy technologies are assessed based on (a) their power generation capacities and service lives; (b) their emission or production of GHGs and noxious wastes, (b) their cost effectiveness (that is, does an energy technology's economic benefit exceeds its economic cost and is it competitive in comparison with other technologies?), and (c) their propensity to give rise to irreversible or unmitigable adverse impacts.

GHGs emissions are expressed in the remainder of this paper in terms of CO_2 equivalent, represented herein by CO_2 for the sake of brevity. CO_2 equivalent is the amount of CO_2 by weight that would have to be emitted into the atmosphere to produce the same estimated radiative forcing (that is, energy trapping effectiveness) as a given weight of another radiatively active gas. CO_2 equivalent is calculated by multiplying the weight of the gas being measured (say, N_2O) by its estimated global warming potential (see, e.g., Houghton, 2004). By adding the CO_2 equivalents of GHGs generated by human activities one obtains the total CO_2 equivalent of the mixture of GHGs in the atmosphere.

Economic data in this paper are expressed in equivalent year-2005 US dollars.

2. GROSS DOMESTIC PRODUCT (GDP) AND ENERGY USE

Figure 2 shows the annual GDP in the four comparison regions (the world, China, India, and the United States). GDP is the total monetary value of the goods and services produced in each of the comparison regions. It is seen in Figure 2 that the four comparison regions exhibit sustained growth through 2035. Among them, China is the fastest growing economy. The world's GDP was $45,417 billion in 2005 and is expected to reach $102,057 billion in 2035, for a 2.25-fold rise in the intervening 30 years. In spite of a population less than one fourth of those of either China or India, the United States' GDP exceeds the combined GDPs of China and India through 2035.

Figure 3 shows the use of (total) annual primary energy by the four comparison regions. Primary energy is measured in the form that it is first accounted for in a statistical energy balance (Energy Information Administration, 2010). For example, petroleum can be converted to diesel, which can be converted to electricity. In this case petroleum is primary energy, diesel is secondary energy, and electricity is tertiary energy. Primary energy in Figure 3 is expressed in PWh (1 PWh = 1 petawatt hour = 10^{12} kWh, where 1 kWh = 1 kilowatt hour). Energy use by the four comparison regions increases

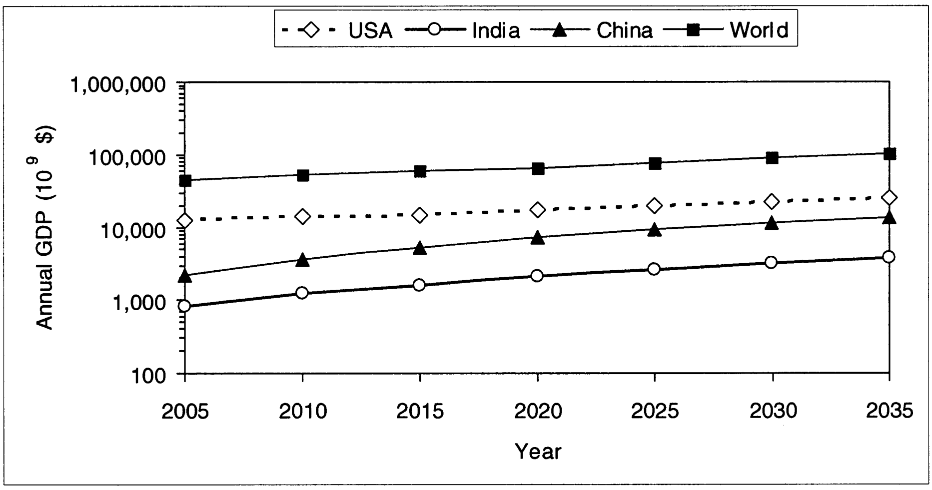

Figure 2: Annual GDP (in billions of year-2005 USA dollars) in 2005–2035 for the United States, India, China, and the world. (Data source: Energy Information Administration, 2010).

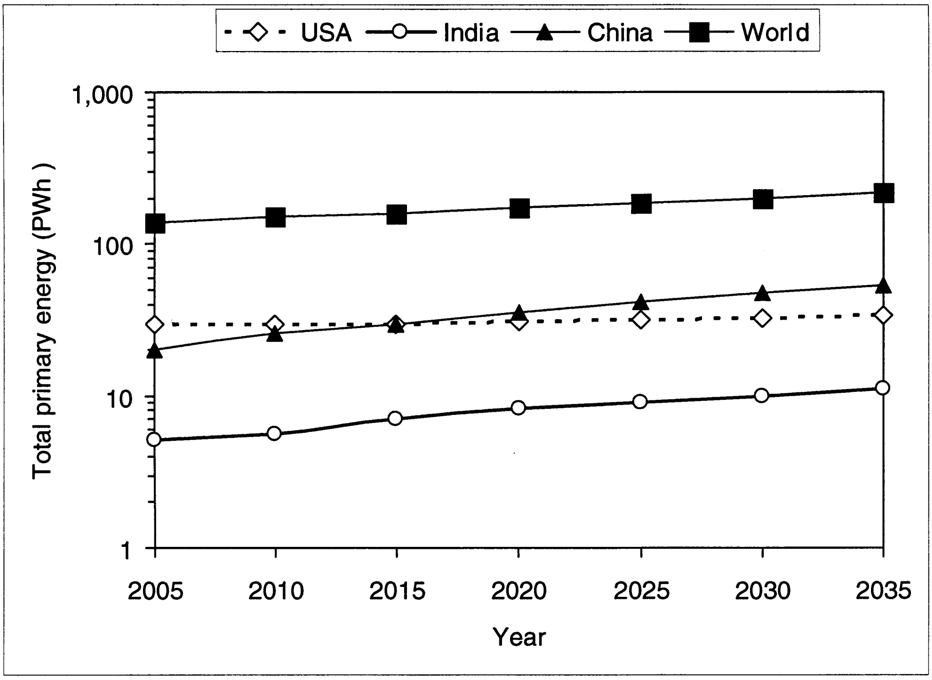

Figure 3: Total annual primary energy (in PWh = 10^{12} kWh) in 2005–2035 for the United States, India, China, and the world. (Data source: Energy Information Administration, 2010).

monotonically through 2035. This is consistent with the concomitant monotonic growth of GDP in the regions.

It is seen in Figure 3 that the worldwide use of primary energy in 2035 (216.5 PWh) is estimated to be approximately 56% larger than what it was in 2005 (138.54 PWh). China's primary energy use would increase nearly three-fold in the same period (from 20.05 PWh in 2005 to 53.31 PWh in 2035). China's energy use will surpass that of the United States by 2015. It is also worth noticing in Figure 3 that the United States exhibits the slowest rate of growth in primary energy use among the four comparison regions in the period 2005–2035, in spite of having a GDP largest than those of China and India. This is explained in the next section in terms of the energy/GDP intensity.

3. ENERGY/GDP INTENSITY

Figure 4 depicts the variation of the energy/GDP intensity for the four comparison regions, expressed in TWh per billion US dollars of GDP (1 TWh = 1 terawatt hour = 10^9 kWh).

The energy/GDP intensity is the ratio of energy used per unit of GDP produced. It is a measure of the use of energy in relation to economic output in a region. Several traits are noteworthy in Figure 4. First, the energy/GDP intensity shows a decreasing trend in all the comparison regions. In, fact, worldwide, the energy/GDP intensity was

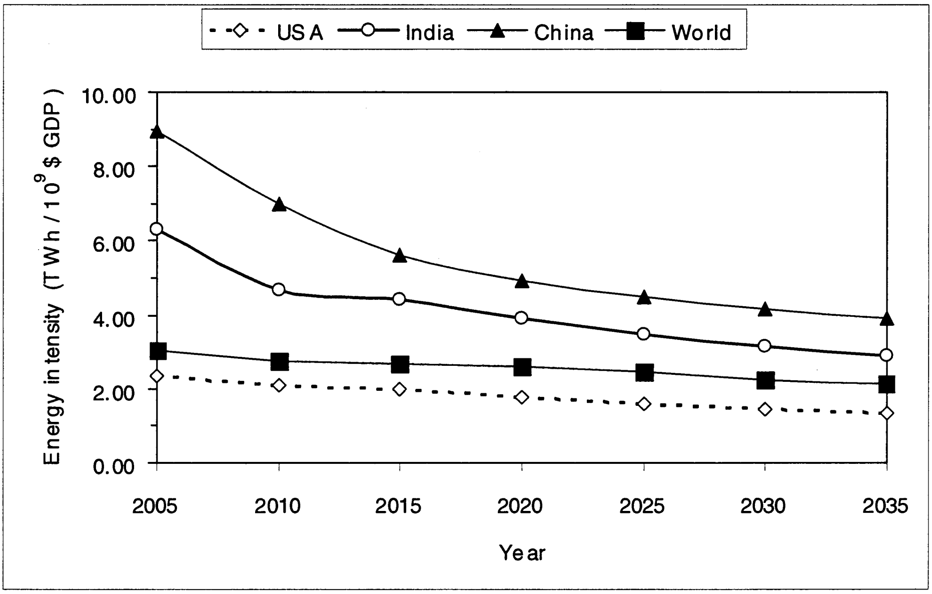

Figure 4: Annual energy intensity (in TWh/ billion year-2000 USA dollar, 1 TWh = 10^9 kWh) in the period 2005–2035 for the United States, India, China, and the world. (Data source: Energy Information Administration, 2010).

3.05 TWh/10^9 \$ in 2005, and is predicted to decline to 2.12 TWh//10^9 \$ in 2035. This represents approximately a 1.4-fold reduction (= 3.05/2.12) in the energy/GDP intensity worldwide in the period of analysis, and it is reflection of the evolution of the world economy towards more energy-efficient goods and services. Second, the United States' energy/GDP intensity is the lowest among the four comparison regions (2.37 TWh/10^9 \$ in 2005 and 1.33 TWh/10^9 \$ in 2035). This explains its relatively low rate of primary energy growth observed in Figure 3. Third, China has the highest energy/GDP intensity among the comparison regions. It features also a pronounced drop in the energy/GDP intensity, from 8.93 TWh/10^9 \$ in 2005 to 3.92 TWh/10^9 \$ in 2035, or a reduction of its energy/GDP intensity by a factor of about 2.3 from 2005 to 2035. Lastly, China and India's energy/GDP intensities are substantially higher than the energy/GDP intensity worldwide.

4. CO_2 EMISSIONS, CARBON INTENSITY (CO_2/GDP), AND CO_2/ENERGY RATIO

The CO_2 emissions in the period 2005–2035 are graphed in Figure 5, where the emissions are expressed in millions of metric tons (1 metric ton = 10^3 kg). All four comparison regions show increasing trends of CO_2 emissions. This rise in CO_2 emissions is the current primary cause of concern about likely associated adverse impacts on climate. The world's emissions in 2005 equaled 28,306 $\times$ 10^6 metric tons and are predicted to be 42,392 $\times$ 10^6 in 2035, tantamount to a 50% increase in emissions from 2005 to 2035. China overtook the United States in the magnitude of

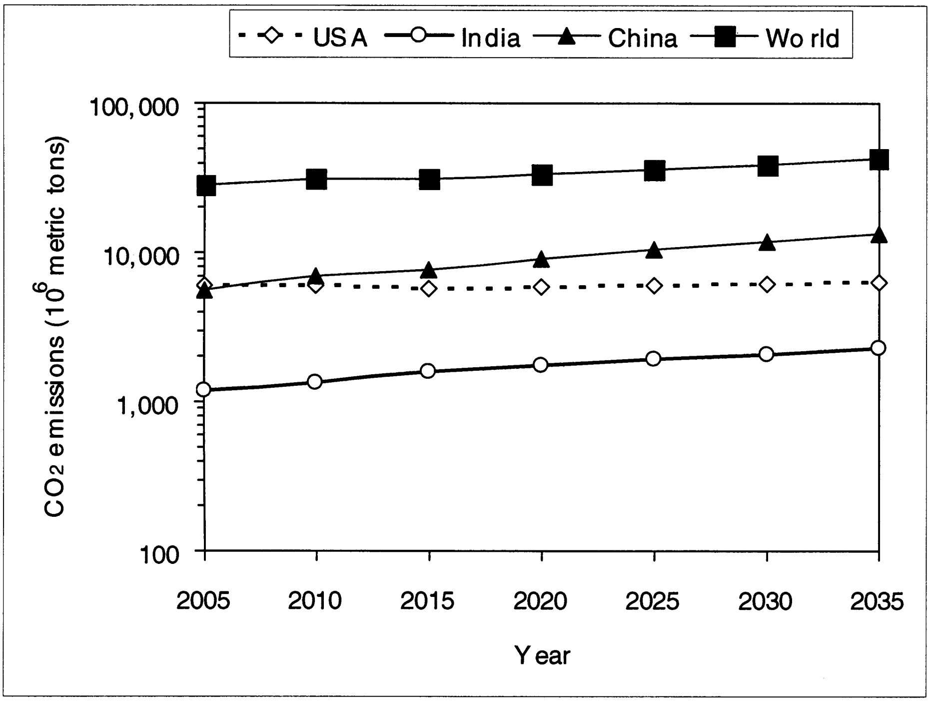

Figure 5: Annual CO_2 emissions (in millions of metric tons) in 2005–2035 for the United States, India, China, and the world. (Data source: Energy Information Administration, 2010).

emitted CO_2 just prior to 2010. India's CO_2 emissions are lowest among the comparison regions. The United States shows the lowest rate of growth in CO_2 emissions in the period 2005–2035 ($5{,}974 \times 10^6$ and $6{,}320 \times 10^6$ metric tons in 2005 and 2035, respectively). The latter observation can be explained in terms of the carbon intensity (= CO_2/GDP) and the CO_2/energy ratio reviewed next.

The CO_2/GDP ratio for the four comparison regions is shown in Figure 6, expressed in millions of metric tons of CO_2 emitted per unit of GDP produced (the latter in billions of year-2005 US dollars). The CO_2/GDP ratio is an indicator of how GHG-dirty the economic production is in a region. It is seen in Figure 6 that the United States has the lowest CO_2/GDP ratio among the four comparison regions (0.48×10^6 metric tons/10^9 \$ in 2005 and 0.25×10^6 metric tons/10^9 \$ in 2035). China, on the other hand, has the highest carbon intensity (2.48×10^6 and 0.98×10^6 metric tons per billion dollars of GDP in 2005 and 2035, respectively). India's CO_2/GDP ratio is lower than China's, but substantially higher that the worldwide intensity. The four comparison regions exhibit declining carbon intensity in the period 1990–2030. This reflects a worldwide shift to the production of less CO_2-intensive products and services.

A related index of relevance in assessing the GHG-laden nature of a regional economy is given by the CO_2/energy ratio, as shown in Figure 7. There, the CO_2/energy ratio is expressed in metric tons of CO_2 emitted per GWh of primary energy used

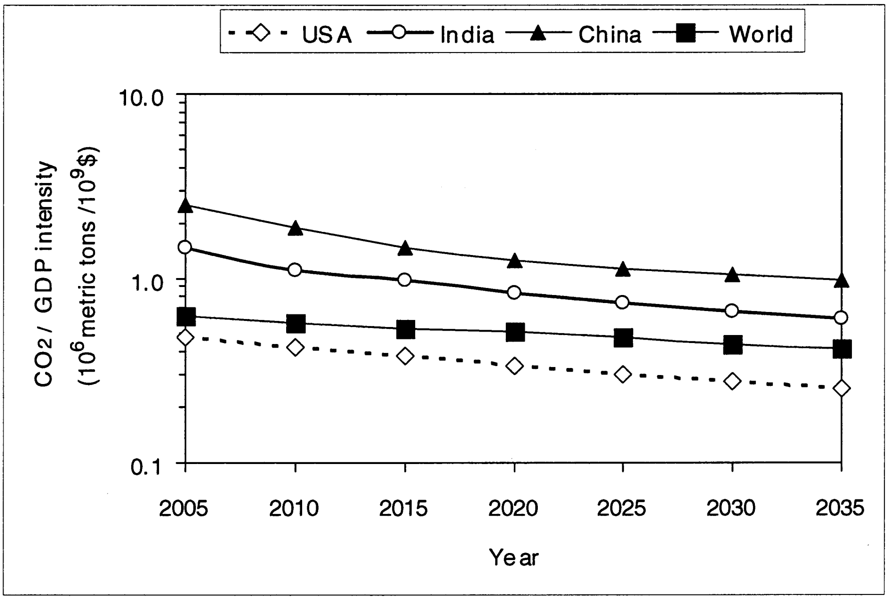

Figure 6: Annual CO_2/GDP intensity (in million metric tons of CO_2 /billion of year-2000 USA dollars) in 2005–2035 for the United States, India, China, and the world. (Data source: Energy Information Administration, 2010).

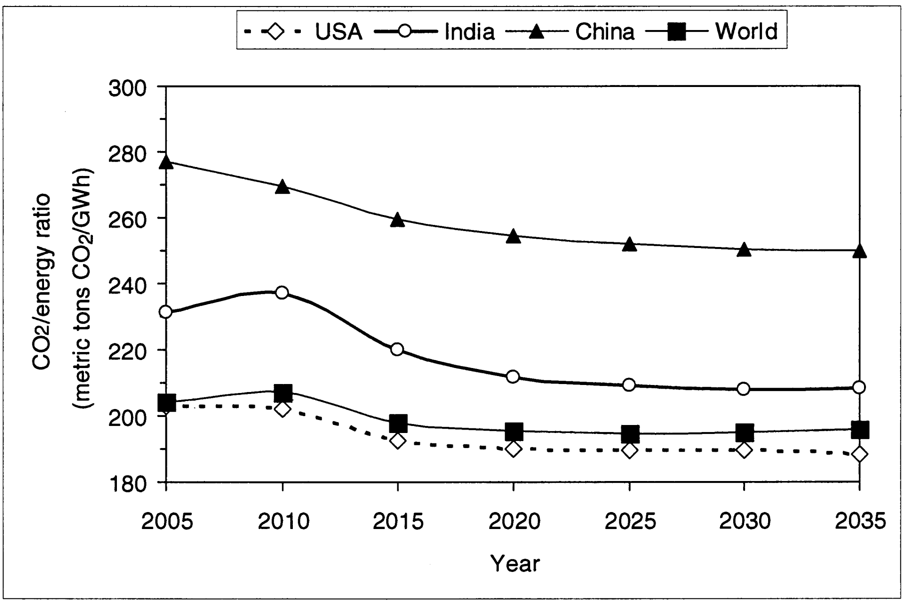

Figure 7: Annual CO_2/energy ratio (in metric tons of CO_2/GWh, 1 GWh = 10^6 kWh) in 2005–2035 for the United States, India, China, and the world. (Data source: Energy Information Administration, 2010).

(1 GWh = 1 gigawatt hour = 10^6 kWh). The four comparison regions exhibit declining CO_2/energy ratio after 2010, with the United States exhibiting the lowest GHG emissions per unit of energy used, and China the highest. India's CO_2/energy ratio is lower than China's but substantially larger than the world's. The world's CO_2/energy ratio is seen to remain approximately constant in the period 2015–2035, at about 195 metric tons/GWh. This is consistent with a rate of CO_2 increase that is nearly identical to the rate of increase in energy use in the period 2015–2035 worldwide.

5. FOSSIL FUELS ARE DEEPLY ROOTED

The extent to which the world depends on fossil fuels for its energy use is portrayed in Figures 8 and 9. Figure 8 shows the percentage of the (primary) worldwide energy use provided by liquids, natural gas, coal, nuclear, and renewables from 2005 through 2035. Liquids encompass petroleum products, natural gas liquids, and biofuels. Renewables include solar and wind power, hydropower, geothermal power, tidal and wave power, and biomass. Notice that renewables and nuclear combined add up to an average of about 16% of the worldwide energy use prior to 2010 and to approximately 19% after 2015. Nuclear energy supplies on average about 6% of the energy use in the period 2005–2035. Liquids, natural gas, and coal, collectively the "big three" fossil fuels that emit GHGs when converted to energy, constitute about 81% of the worldwide primary energy use. The actual amounts of energy used by source are shown in Figure 9, expressed in PWh.

Given the endowment of combined recoverable fossil fuels worldwide, which includes cumulative production, remaining reserves, reserve growth, and undiscovered

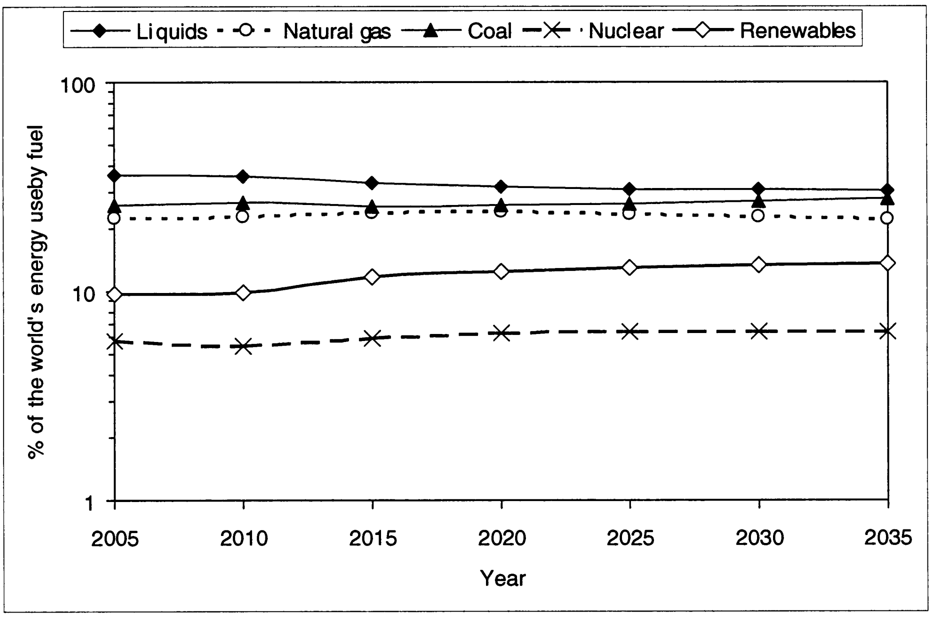

Figure 8: % of the world's energy use by fuel in 2005–2035. (Data source: Energy Information Administration, 2010).

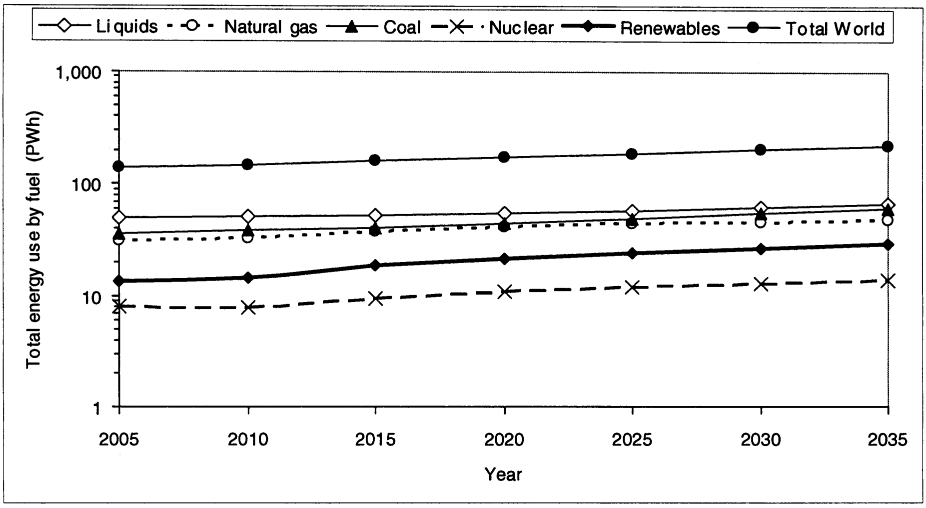

Figure 9: Total annual energy use worldwide by fuel (1 PWh = 10^{12} kWh) in 2005–2035. (Data source: Energy Information Administration, 2010).

resources, they appear viable as a major source of energy from availability considerations alone for the remainder of the 21st century, and possibly beyond (United States Geological Survey, 2000; Ahlbrandt, 2002; Lackner, 2002).

Figure 10 shows the CO_2/GDP ratio in year 2035 that would be required if (i) the CO_2 emissions in that year were a fraction (varying between 0.5 and 1.0) of what they were in year 1990 (the baseline year adopted in the 1997 Kyoto Protocol for controlling GHGs emissions), and (ii) the GDP achieved the reference-case 2035 level worldwide. For comparison, Figure 10 also shows the CO_2/GDP ratio experienced in year 1990, which equaled 0.77 million metric tons per billion US dollars. Thus, if by 2035 the CO_2 emissions were, say, at the 1990 level, the CO_2/GDP intensity in 2035 would have to be 0.21×10^6 metric tons $/10^9$ \$ dollars, or a 3.67 (= 0.77/0.21)-fold reduction in the carbon intensity relative to the 1990 baseline. A reduction of CO_2 emissions by year 2035 to one half of those experienced in 1990 would require a year 2035 CO_2/GDP ratio equal to 0.10×10^6 metric tons $/10^9$ \$ dollars, or a 7.7 (= 0.77/ 0.10)-fold reduction in the carbon intensity relative to the 1990 baseline. This level of reduction in the carbon intensity would require a transformative transition to GHG-cleaner energy technologies used to produce goods and services by year 2035. The following sections delve into the possibilities of such transition.

6. ASSESSING CO_2 EMISSIONS

GDP, the energy/GDP ratio, and the CO_2/energy ratio are related by the following equation that allows the estimation of CO_2 emissions for specified GDP, energy/GDP intensity, and CO_2/energy intensity, and carbon capture and storage (CCS):

$$CO_2 \text{ emissions} = \text{GDP} \times (\text{energy/GDP}) \times (CO_2/\text{energy}) - \text{CCS} \qquad (1)$$

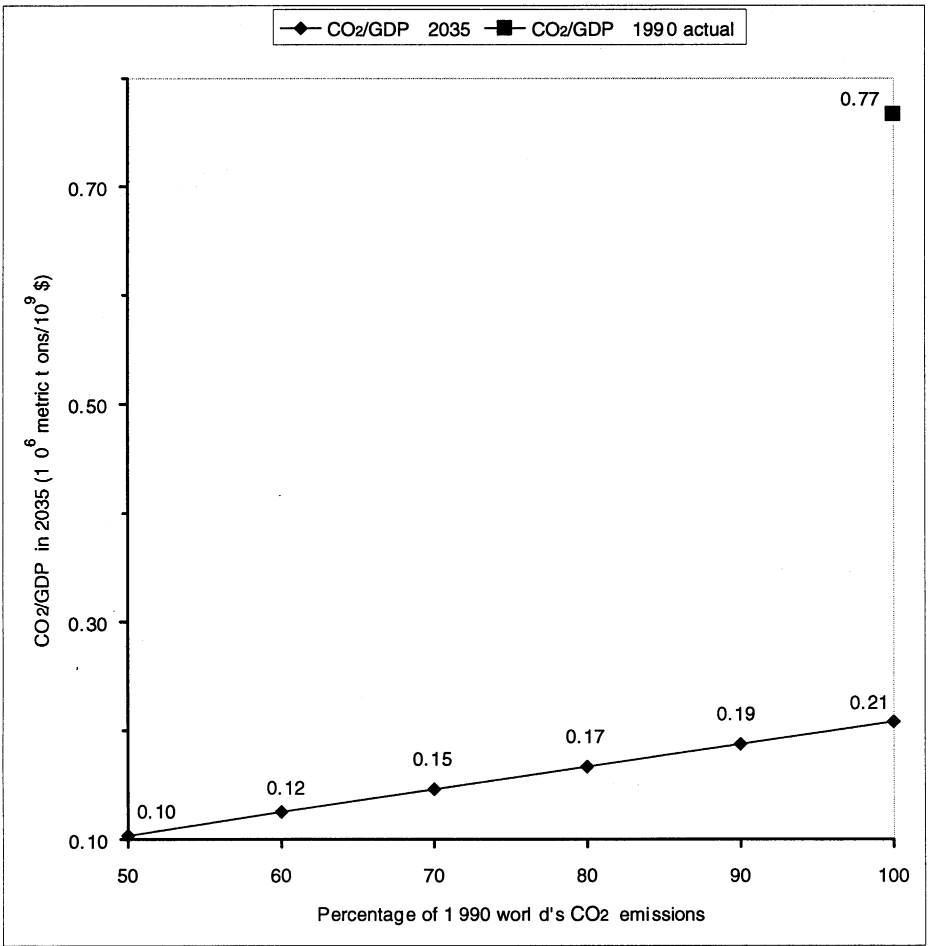

Figure 10: CO_2/GDP intensity in year 2035 required to produce in that year emissions ranging from 50% to 100% of the 1990 CO_2 emissions while achieving the reference-case year 2035 GDP. The 1990 CO_2/GDP intensity in 1990 was 0.77×10^6 metric tons of CO_2/billion dollars.

CCS describes CO_2 that is removed at emission sites or from the open atmosphere (this is the Capture part of CCS) and is subsequently stored in liquid form deep in the earth crust or impaled in frozen form in containers in ocean-bottom sediments (Haszeldine, 2009). The cost and reliability of the emerging technologies for CCS cast substantial uncertainty at present about its effectiveness in removing CO_2 durably and safely from the atmosphere. Assuming negligible CCS, it is worth comparing the year-2035 expected CO_2 emissions with those of 2005 worldwide based on the other variables appearing on the right-hand side of equation (1). The world's GDP is expected to rise from 45,417 billion US dollars in 2005 to 102,057 billion dollars in

2035 (see Figure 2), or an increase by a factor of 2.24 from 2005 to 2035. The energy/GDP intensity is seen in Figure 4 to drop from 3.05 TWh/ 10^9 \$ in 2005 to 2.12 TWh/ 10^9 \$ in 2035. The CO_2/energy intensity is expected to be 196 metric tons per GWh in 2035, and it was 204 metric tons per GWh in 2005, as shown in Figure 7. These amounts imply, according to equation (1), that the world's CO_2 emissions in 2035 would be approximately 1.5 (= 2.24 × (2.12/3.05) × (196/204)) times those of 2005. The interplay among the growth in GDP, the CO_2/energy intensity, and the reduction in energy/GDP intensity (as the world economy transitions to less energy-intensive goods and services), leads to the calculated rise in CO_2 emissions. If follows from the previous calculations that CO_2 emissions in year 2035 could be lowered to those of 2005 if the worldwide energy/GDP and CO_2/energy intensities are lowered by a combined factor of at least 2.24. This is equivalent to reducing the CO_2/GDP ratio by at least 2.24. Greater efficiencies would be required if reductions to the year 1990 emissions are desired.

7. ENERGY TECHNOLOGIES AND THEIR NET ENERGY

Net energy is a concept of importance in assessing the feasibility of energy sources. An energy technology embodies a net energy (NE), which equals the energy produced by the technology (E), minus the input of external energy required to create and operate the energy produced (IE), minus the transmission losses of energy from the production point to the point of use (L, if applicable):

$$NE = E - IE - L \tag{2}$$

A positive net energy is tantamount to requiring that the energy returned exceed the energy invested. Weisz (2004) cites as an example of questionable net energy the case of biofuel ethanol, used primarily for transportation. The production of ethanol from biomass (sugar cane or corn are common raw materials) involves agricultural production and industrial processing that –per unit of mass or volume of ethanol produced- require large and diverse external inputs (IE) that may result in a negative NE (see also, Baldwin, 2002). Another case in point is the production of hydrogen gas (H_2) for use as an energy carrier in hydrogen fuel cells. H_2 is liberated most cheaply from natural gas, albeit with the release of CO_2. Wind and solar power can be used to split water to liberate H_2 without releasing CO_2, but at a higher cost than splitting it from natural gas. Regardless of the method to generate H_2, the input of external energy to produce H_2 for use in fuel cells exceeds the energy that can be produced per unit of H_2 (Service, 2004). The offshoot is that the energy in hydrogen would have a net positive worth only if the cost of the required external energy is less than the value of energy generated from hydrogen fuel cells.

Solar energy and wind energy are examples of technologies in which generated (say, electric) energy (E) is less than the energy content of the external energy source (IE). To illustrate, current photovoltaic cells convert less than 20% of the electromagnetic energy in the solar flux to electricity (Crabtree and Lewis, 2007). Yet, these two technologies become economically viable whenever the worth of produced electricity exceeds the cost of converting their natural, renewable, sources of energy to a usable form.

8. RELIABILITY AND FIRM ENERGY OF ALTERNATIVE SOURCES

Solar energy and wind energy are renewable sources with economic potential when developed under suitable conditions, that is, in well insolated or windy locations as the case might be, and not too distant from delivery points to avoid large transmission losses. Yet, a drawback common to these two sources concerns the reliability of their output. That is, the fact that variable weather or the natural changes in insolation (daily, seasonal) cause uncontrollable fluctuations in energy output. This means that, in spite of high installed energy-producing capacity, the firm energy from these two sources may be low (Pahl, 2007; U.S. Department of Energy, 2010; Storm et al., 2009). Firm energy (also called dependable capacity) is the energy intended to be available at all times during the period covered by a guaranteed commitment to deliver, even under adverse conditions. Firm energy is an important attribute of any source competing with fossil fuels or nuclear power, which can guarantee relatively high firm energy in spite of weather. The importance of firm energy issues from the intrinsic variation of the amount of electric power required in industrialized societies within a day, within a weak, and seasonally. To illustrate this point, Figure 11 shows the fluctuation in daily energy use (or daily load) through a weekly cycle typical of large electric utilities in the United States (U.S. Army Corps of Engineers, 1979; Loáiciga, 2010). Figure 11 shows the graph of hourly energy use during Sunday –the day of lowest load- and Friday –the day of highest load. Notice the pronounced variation of load during Friday, where the ratio of peak load to minimum load is close to 2. Thus, it is paramount for energy providers to know with certainty the level of energy available to meet their variable loads at all times to avoid blackouts and instabilities in the power grid (Johnson, 2009; Petroski, 2010).

Calculations of energy that could be generated with solar (photovoltaic) cells spread over an area of land and based on the sun's irradiance of approximately 1,370 W/m^2 at the top of the atmosphere (and attenuated down to the earth surface) are overly optimistic. For example, Weisz (2004) calculated that the annual energy used in the United States could be obtained from solar cells covering 263,000 km^2 of its territory. This estimate was based on solar irradiance, land area, and the efficiency of converting the energy content of solar radiation to usable (say, electric) energy at ground level. Similar calculations of the theoretical capacity of energy production from solar radiation for the world were made by Crabtree and Lewis (2007). Jacobson and Delucchi (2009) reported the worldwide developable solar power capacity at 580 TW assuming favorable atmospheric conditions and availability of raw construction materials (for photovoltaic cells primarily). This is about 60 times the Energy Information Administration's (2010) projected worldwide net electrical power generation of 9.78 TW in year 2035.

In the same vein, the United States Department of Energy (2010) estimated that 20% of the United States electricity use could be supplied by wind energy by 2030, a twenty-fold increase from its 1% share in 2008 (when its installed capacity was about 21 GW). Jacobson and Delucchi (2009) reported the world's developable wind power capacity range from 40 to 85 TW, or 4 to 8.7 times the 9.78 TW of projected world's net electrical power generated by year 2035. For comparison, in early 2010 the United States, Germany, China, Spain, and India had installed wind power capacities equal to

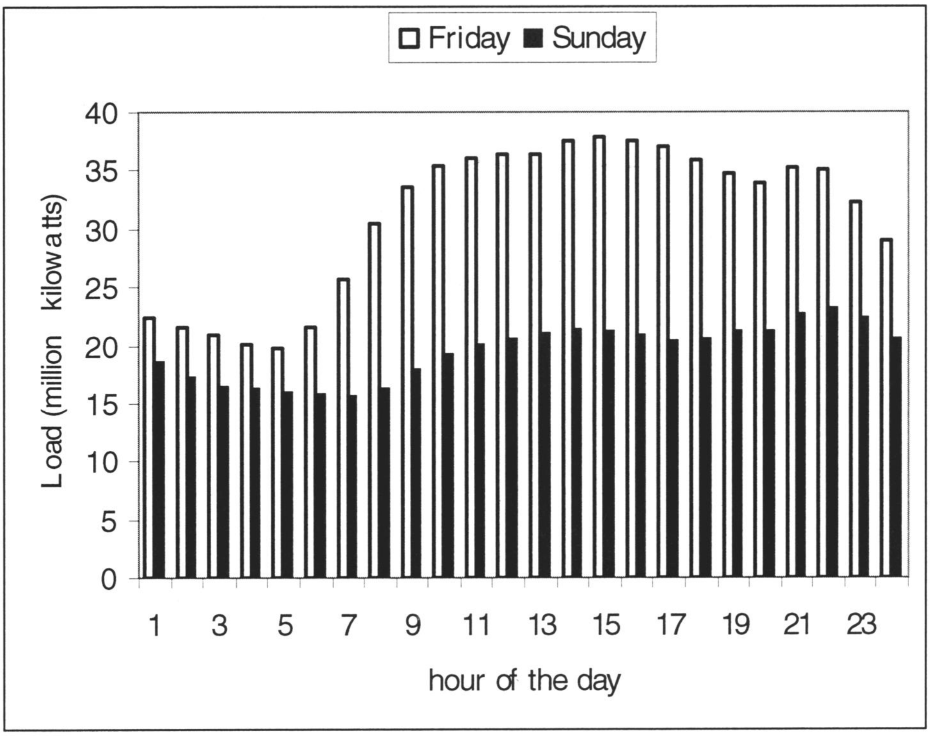

Figure 11: Typical daily load of a large electric utility in the United States during Friday and Sunday. (Data source: U.S. Army Corps of Engineers, 1979, actualized in Loáiciga, 2010).

0.0352, 0.0258, 0.02051, 0.0191, and 0.0109 TW, respectively, these five countries accounting for approximately 73% of the installed wind capacity worldwide (The Economist, 2010). The previous estimates of the rate of rise of the installed wind capacity hinge on several advancements over the current state of affairs: (1) finding suitable sites for wind farms that could generate power, (2) improving the design and power output of wind turbines, (3) developing accurate short-term forecasting of wind conditions ("next day" forecasts or 18-hour to 42-hour lead forecasts) to predict production, and (4) avoiding or mitigating adverse environmental and aesthetic impacts of wind generation.

Uncertainties created by variable weather conditions, the difficulties of storing large amounts of energy for later use during darkness, during periods of still atmospheric circulation, or during periods of peak load, plus the physical limits to the transmission of energy over long distances, and impediments to dotting swaths of land with solar cells and wind turbines pose real limits to the reliance on solar radiation or wind as leading energy sources without the existence of other complementary sources.

Low reliability of output besets all energy technologies that depend on the weather or are vulnerable to climatic variability. Besides solar and wind power, wave power and hydroelectric power are vulnerable to the vagaries of weather or climate.

Hydroelectric power with no storage (called run-of-the river power) is affected by streamflow variations and droughts. Hydroelectric power with storage is threatened by low accretion to storage during droughts (Petroski, 2010). Geothermal energy is renewable but flow-limited. This is so because the subterranean production of heated water vapor –the source of geothermal energy– depends on recharge to groundwater storage, which in turn depends on precipitation. Biofuels derived from crops –such as ethanol- are also dependent in their production process on water availability for irrigation, which may be affected by weather and droughts.

9. ENERGY TECHNOLOGIES AND THEIR CO_2 FOOTPRINT

A new energy technology's CO_2 comparative footprint can be compared with that of an existing technology using the following balance equation (in which CO_2 emitted is measured per unit of energy produced):

$$\begin{aligned} CO_2 \text{ comparative footprint} &= CO_2 \text{ produced directly or indirectly by} \\ &\text{the new technology} - CO_2 \text{ produced by existing technology} \end{aligned} \tag{3}$$

To make the new technology worthwhile from the viewpoint of atmospheric CO_2 balance, its CO_2 comparative footprint must be negative, that is, it must generate, overall, less CO_2 than the existing technology it replaces. An illustration of the principle of CO_2 budgeting for alternative energy technologies can be made by examining the cultivation of fuel biomass, from which ethanol is the most commonly produced biofuel (Brazil being the top producer worldwide, Goldemberg, 2007). On a per unit volume, the combustion of ethanol (the new technology) produces less CO_2 than gasoline (the existing technology, Scharlemann and Laurance, 2008). Yet, the cultivation of fuel biomass (corn and sugarcane are the most commonly used crops) for ethanol production may displace food crops, thus making food scarcer, more costly, and generating CO_2 from the conversion of forest and grasslands to new cropland (Melillo et al., 2009). This conversion may lead to an overall augmentation of atmospheric CO_2 when ethanol replaces gasoline according to several authors (see Scharlemann and Laurance, 2008; Fargione et al., 2008; Searchinger et al., 2008). The CO_2 footprint of ethanol would render it an unsuitable replacement of gasoline in this instance. Furthermore, the energy content of gasoline is about 30 MJ/L (mega Joules per liter), which is higher than the energy content of ethanol (equal to 23.5 MJ/L), making the former more energetically desirable than the latter (Service, 2004).

Cellulosic ethanol has been touted as a substitute to corn- and sugarcane-based ethanol. It relies on cellulosic biomass to produce biofuels. Cellulosic biomass issues from agricultural residues, forestry wastes, and waste paper and energy crops. Yet, cellulosic ethanol remains an experimental endeavor (Himmel et al., 2007).

10. CLEAN ENERGY AND SUSTAINABLE ENERGY TECHNOLOGIES

Clean energy produces manageable wastes or no waste products that might pollute air, water, or land. Such waste products include –but are not limited to- greenhouse gases, airborne toxicants (ozone, carbon monoxide, soot particles, are examples), nuclear (radioactive) wastes, and spent batteries with toxic constituents (i.e., heavy metals). Fossil fuels and nuclear power, which combined produce about 92% of the world's primary energy, emit or generate noxious wastes, the former as GHGs and the latter in the form of radioactive waste. The concept of sustainable energy is more comprehensive than that of clean energy. Specifically, a sustainable energy technology must: (1) produce manageable or negligible levels of noxious wastes or GHGs, (2) produce energy in a cost-effective manner (that is, its economic benefit exceeds its economic cost, and the technology must be competitive when compared with other technologies), (3) avoid irreversible, and unmitigable, adverse (environmental and cultural) impacts, and (4) have an indefinitely long service life. Among the adverse environmental and cultural impacts are those that might be created by reservoirs built to impound water for hydropower generation. These reservoirs may flood cultural, archeological, or ecologically valuable areas. Another example of adverse impacts was presented in previous sections concerning the cultivation of fuel biomass for ethanol production, which may augment atmospheric CO_2 and may lower water quantity and quality (United States National Research Council, 2008). The occupation of swaths of land with solar cells or wind mills may displace organisms or valuable human activities, or disrupt sensitive habitats and flyways. These instances of solar and wind power deployment, albeit being intrinsically clean, cannot be considered sustainable when mitigation alternatives are not available. Evidently, a sustainable energy technology is clean, but the converse is not necessarily true.

Considering the advantages and disadvantages of the key existing energy technologies, one must conclude that the present portfolio of energy sources –about 85% from fossil fuels and the remainder from renewables and nuclear power worldwide- is not sustainable. This is so because of the adverse environmental impacts associated with fossil-fuel GHG emissions, nuclear wastes, and habitat disruption that may occur with hydropower and other aerially-extensive energy developments. Furthermore, the possibility of achieving a future mix of energy technologies that could be considered sustainable remains elusive with the current know-how. Several authors have envisioned future energy production with greatly reduced annual emissions of CO_2. A case in point is Pacala and Sokolow's (2004) roadmap to limit future atmospheric CO_2 concentrations to 500 ± 50 ppmv, or less than twice the pre Industrial concentration of 280 ppmv, by mid 21st century. To that end, however, humans would have to change their approach to building, transportation, and land-use management substantially. Jacobson and Delucchi (2009) proposed a path to sustainable energy by relying on wind, water, and sunlight (WWS) to power the world by 2030. The required socio-economic changes and technological breakthroughs to replace or greatly reduced fossil-fuels dependency are daunting, however. Some authors, in fact, argue that what is needed is a restructuring of the world economy whereby the emphasis is on the reduction of the demand for energy rather than on increasing its supply, while maintaining biodiversity, sustainable habitation, and community well being (Taylor, 2009).

11. THE DILEMMA OF NUCLEAR POWER

Some authors have postulated that nuclear power could become a competitive energy alternative to fossil fuels (see, Sailor et al., 2000). Nuclear power in its present state is not a clean energy technology, for it produces radioactive waste that must be disposed off safely. Yet, its GHG footprint is minimal when compared with fossil fuels. In year 2010 nuclear power accounted for about 5.5% of the total primary energy worldwide. The percentage varies regionally, however. France, for example, generates about 40% of its total primary energy through nuclear power and about 80% of its electricity from the same source (Energy Information Administration, 2010). The former statistics pertain to nuclear fission, an energy technology introduced in the mid 20th century that is now mature. In nuclear fission, energy is released when atoms are split. Proponents of nuclear (fission) power recognize that major obstacles must be overcome prior to its expansion. Those obstacles involve the need for: (1) improved safety in the operation of nuclear reactors, (2) reducing construction, operation, and capital costs of nuclear power, (3) finding safe methods to dispose of nuclear wastes, (4) avoiding nuclear proliferation and preventing nuclear terrorism, (5) expanding the reprocessing of spent nuclear fuel to lengthen the life of available natural nuclear fuel reserves, or natural uranium. Jackson (2007) estimated that at the current rate of fission nuclear power production the known world's reserves of uranium would be exhausted in approximately 50 years.

Overcoming obstacles (1)-(5) is nontrivial, as demonstrated by the fact that nuclear power remains a relative minor source of energy worldwide. A situation that highlights the high-profile politics surrounding the management of nuclear waste is the lack of dedicated, large-scale, geologic repositories for nuclear waste in the United States. Currently, commercial and military nuclear wastes are encapsulated and isolated in situ across the United States.

Jackson (2007) argued that nuclear fusion technology, whereby energy is released when atoms are merged, holds promise to become an energy alternative to fossil fuels in spite of being nascent. The energy contents of typical nuclear fusion and fission reactions are 350,000,000 MJ/kg (mega Joules per kilogram of deuterium-tritium fuel) and 685,000 MJ/kg (mega Joules per kilogram of natural uranium consumed in a nuclear reactor), respectively. These compare with energy contents for crude oil, gasoline, ethanol, and air-dried wood equal to 45 MJ/kg, 39 MJ/kg, 30 MJ/kg, and 18 MJ/kg, respectively. This means that the energy content of fusion fuel is close to seven orders of magnitude larger than the contents of fossil fuels. The fuels for nuclear fusion are deuterium and tritium. The former is obtained from natural water. The latter is produced from lithium, which is found in known deposits totaling 10 million metric tons globally, sufficient to produce the world's energy for many centuries. More advanced fusion reactors would only use deuterium fuel, rendering fusion technology capable of producing the world's energy indefinitely. Jackson (2007) estimated that the amount of nuclear waste produced by fusion power plants would be on the order of one hundredth of that stemming from comparable fission plants. In addition, fusion waste would be less toxic than fission waste, and it would be of short-lived radioactivity (a few decades long), essentially eliminating the need for its geologic burial and greatly reducing the complexity of its management when compared with that of fission waste. In spite of the relatively high energy content of nuclear fusion fuel, the fact remains that this technology is at this time experimental. Time will tell if its touted potential is ever realized.

12. CONCLUSIONS

Demographic, economic, GHG- and energy-related data for four comparison regions were analyzed in this work. The comparison regions were China, India, the United States, and the world. This paper's data analysis has shown that: (1) the world's total primary energy use is expected rise by 56% in the period 2005–2035, with the most rapid growth taking place in China, whose energy use is expected to rise nearly three-fold in the same period; (2) the increase in energy use will fuel a world's GDP that is expected to more than double from 2005 to 2035; (3) in spite of displacing China as the most populous country by 2030, India's GDP is expected to remain the lowest among the four comparison regions in 2005–2035, and so does its energy use; (4) the world's rate of GDP growth outpaces its rate of increase in energy use thanks to a decreasing energy/GDP intensity in 2005–2035, which reflects a transition of the world economy to less energy intensive goods and services in the period of analysis; (5) the United States exhibits the lowest energy/GDP intensity in the period 2005–2035 among the four comparison regions, ranging from 2.37 TWh/10^9 \$ in 2005 to 1.33 TWh/10^9 \$ in 2035; (6) China features the highest energy/GDP intensity among the comparison regions (8.93 TWh/10^9 \$ in 2005 and 3.92 TWh/10^9 \$ in 2035), as well as the fastest rate of decrease of energy/GDP intensity among the four comparison regions; (7) CO_2 emissions are expected to rise in all four comparison regions, with the world's emissions expected to rise by a factor of 1.5 from 2005 to 2035; (8) China surpassed the United States as the country with the largest annual emissions of CO_2 beginning in year 2010; (9) all four comparison regions exhibited a declining CO_2/GDP intensity in the period 2005–2035, and the worldwide CO_2/GDP intensity in 2035 is expected to be approximately 68% of that in 2005; (10) the United States features the lowest CO_2/GDP intensity among the four comparison regions in 2005–2035, and China the highest; (11) the world's CO_2/energy intensity is projected to remain approximately constant in the period 2015–2035, averaging 196 metric tons of CO_2 emitted per GWh energy used; (12) China, India and the United States exhibit declining CO_2/energy intensity in the period 2010–2035, yet, a reduction of CO_2 emissions by 2035 to the 2005 level would require reducing the worldwide CO_2/GDP intensity by a factor of 2.24; (13) the world's portfolio of energy sources is expected to be dominated by fossil fuels through 2035, which are projected to provide about 81% of the world's total primary energy used, while renewables and nuclear are projected to provide about 16% and 3%, respectively, by year 2035; (14) there are major technological, natural, and social obstacles to overcome if a transition to a world economy much less dependent on fossil fuels is to materialize; (15) nuclear fusion has an intrinsic energy content close to seven orders of magnitude larger than those of fossil fuels, yet, it is at present an experimental and unproven technology.

There are current efforts in many countries to reduce their dependence on fossil fuels and increase their reliance on clean or sustainable energy technologies. The weight of the evidence to date shows, nevertheless, that progress in ending the dominance of fossil-fuel energy is slow. There are profound economic and technological reasons behind the persistence of fossil fuels.

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