Proceedings Climate 2008/Klima 2008. Available: <http://www.climate2008.net/?a1=pap&cat=1&e=61>

Limitations of Greenhouse Gas Mitigation Technologies Set by Rapid Growth and Energy Cannibalism

J.M. Pearce

Department of Mechanical and Materials Engineering

Queen's University

Contact:

Joshua M. Pearce

Department of Mechanical and Materials Engineering

Queen's University

60 Union Street

Kingston, ON Canada K7L 3N6

Tel: 613-533-2754

Fax: 613-533-6610

pearce@me.queensu.ca

Abstract

As the unacceptable results of continued fossil fuel combustion on climate change become ever clearer, a need to dramatically reduce greenhouse gas (GHG) emissions by aggressive energy conservation and immediate transitioning global civilization to alternative energy sources has become evident. Many energy technologies are capable of displacing significant volumes of fossil fuels. Unfortunately, neither the enormous scale of the current fossil fuel energy system nor the necessary growth rate of these technologies is well understood within the limits imposed by the net energy produced for a growing industry. This technical limitation is known as energy cannibalism and refers to an effect where rapid growth of an entire energy producing or energy efficiency industry creates a need for energy that uses (or cannibalizes) the energy of existing power plants or production plants. Thus during rapid growth, the industry as a whole produces no net energy because new energy (or conserved energy) is used to fuel the embodied energy of future power plants or production facilities. Such life cycle analysis is also valid for GHG emissions. All current technologies are dependent to some degree on fossil fuel energy and thus also contribute to emissions. This paper expands earlier work to generalize the GHG emission neutral growth rate limitation imposed by energy cannibalism to any renewable energy technology or any energy efficiency technology. Conclusions and recommendations are made from the analysis to assist decision makers in optimizing deployment of technologies on large scales to reduce GHG emissions to safe levels without overshoot.

Keywords: alternative energy, embodied energy, energy efficiency, greenhouse gas emissions, life cycle analysis

1. Introduction

The scientific consensus on climate change articulated by the Intergovernmental Panel on Climate Change (IPCC) is that humanity's rampant combustion of fossil fuel for energy and the resultant carbon dioxide (CO₂) emissions, a powerful greenhouse gas (GHG), has resulted in global climate destabilization (2007). Humanity is warned that if we maintain our current trajectory towards continued climate destabilization, Earth will reach a tipping point from which it will not recover (Hansen, et al., 2008; Hoffert et al., 2002). As discussed throughout this conference, global warming is already occurring, and if combustion of fossil fuels continues, global temperatures are projected to rise catastrophically by the end of the century. This potential catastrophe exists because climate change in the long term is likely to exceed the capacity of natural, managed and human systems to adapt (IPCC, 2007). The idea that it is in the global public's best interest to begin to look for sources of alternative energy and improve our energy efficiency has become widespread (Curry, et al., 2007; Leiserowitz, 2006; Pacala and Socolow, 2004). This has created a call for an aggressive strategy to prevent serious harm to the global environment and the long-term viability of the human experiment by deploying vast quantities of alternative energy (Hoffert, et al., 2002; Kutscher, 2007; Pearce, 2002). Similarly aggregating small reductions in GHG emissions by utilizing energy efficiency technologies can also have a substantial positive global impact (Hoffert, et al., 2002; Pacala and Socolow, 2004; Pearce and Russill, 2005; Pearce and Miller, 2006; 2007; Pearce, et al., 2007). Unfortunately, neither the enormous scale of the current fossil fuel energy system nor the necessary growth rate of either energy efficiency technologies (EETs) or alternative energy technologies (AETs) is well understood with the boundary

conditions set by the net energy produced during growth of an industry. This technical limitation is best described as an “energy cannibalism” (Pearce, 2008), which refers to an effect where rapid growth of an entire energy producing (or energy conserving) industry creates a need for energy that cannibalizes the energy of existing GHG emission mitigating power plants (or EET manufacturing plants). In this paper the scale of the energy problem will be quantified, the necessary growth rates will be discussed for a generalized GHG emission mitigating technology (AET or EET), and a generalized process will be derived for determining the energy cannibalism for a given technology. Finally, conclusions and recommendations are made from the analysis to assist decision makers in optimizing deployment of technologies on large scales to reduce GHG emissions to safe levels without overshoot.

2. The Challenge of Energy Scale

2.1 Replacing Existing Fossil Fuel Energy Infrastructure

The late Richard Smalley tried to educate the public on the enormous scale of the problem facing society as it attempts to replace fossil fuels. He pointed out that the global economy consumed the equivalent of 220 million barrels of oil per day (2005). This is an enormous amount of energy, which is made easier to put in perspective by considering it in electricity terms; it is equivalent to 14,500 GigaWatts (GW). With a typical nuclear plant having about 1GW of capacity, contemporary civilization would need 14,500 nuclear power plants to maintain the status quo. For reference there are 434 nuclear reactors totaling around 349 GW operating in 32 countries in 1999 (International Atomic Energy Agency, 2000), which produce only about 17% of the world’s electricity (ICJT, 2001). Roughly 90% of all of our energy (not just electricity) comes from fossil fuels. Fortunately, the entire energy infrastructure does not need to be replaced. To stall climate change current global GHG emissions must be cut by about 60% (Hansen and Sato, 2004). Thus, if the non-GHG emitting energy were to be supplied by any of the AETs (e.g. solar, wind, geothermal, etc.) or a combination of AETs an additional 7,481 GW of AETs would need to be constructed to meet *today’s* energy needs while preventing additional climate change.

2.2. Rate of Energy Demand Increase

The construction of more than 7,000 GW of additional AETs (or the equivalent reduction from EETs) is a formidable challenge, but the GHG emission induced climate challenge is being significantly complicated by rapid increases in energy needs as developing countries elevate themselves out of poverty and those in developed countries increase their consumption of remaining fossil fuel supplies at an astonishing rate. The United Nations forecasts the global population will reach 8.5 billion by 2050 and plateau at 10 billion by 2075 (Leeson, 2002) with 80% of this increased population expected to reside in urbanized areas. This increase and shift in demographics is expected to lead to rapid growth in energy demand. The need for a new non-fossil fuel-based energy source is evident from comparing the standard of living, which is dependent on energy, in the most developed countries and developing countries. Although the population of the developing world is five times that of developed nations, they consume less than 40% of the world’s energy supply (World Energy Council, 2001). Therefore, the climate challenge is being significantly complicated with the developing world’s continuing transition into a developed world’s standard of living requiring more energy consumption.

The World Energy Council project that in a high growth world in which economic growth and energy consumption steadily increases, the global primary energy consumption could reach 24.8 gigatons oil equivalent (Gtoe) by 2050 compared to 9.0 Gtoe in 1990. Again converting these values to electrical energy units, with 1 toe per 11,630 kiloWatt Hour (kW-hr), and dividing by the hours in a year means that we will need roughly 33 TW. To put this number in perspective, between 1960 and 1986, 1 TW-year of electric energy produced in the United States generated approximately 10 trillion dollars of gross national product (World Energy Council, 2004). Another way to look at the challenge is to consider solving the problem with nuclear power plant construction. If all of the world energy growth and the global demands of non-GHG emitting energy were to be provided by nuclear power in 2050, roughly 26,000 nuclear power plants having a 1GW capacity would need to be constructed (Pearce, 2008). If we assume that construction of plants begins in 2010 and is concluded by 2050, 650 new nuclear power plants must be built and put into operation each year or roughly 1.8 per day for the next 40 years. This enormous increase in energy demand represents a major challenge to current energy infrastructure. Not only must the magnitude of the energy demands be met, but they must be met in a way which will avoid further CO₂ forcing of the climate system. The new means of sustainable energy production must be cheap, clean, renewable and from a CO₂-free source (Pearce, 2002; Smalley, 2005).

3 The Challenge of Rapid Growth and the Cannibalization Effect

3.1 Life Cycle Analysis for Embodied Energy

In order to determine true sustainability, all energy technologies (either sources or conservation devices) must undergo a comprehensive life cycle analysis (LCA). LCA is a means of quantifying how much energy and raw material are used and how much (solid, liquid, and gaseous) waste is generated at each stage of a product's life (Pearce and Lau, 2002). Ideally an LCA would include measured quantification of material and energy needed for: raw material extraction, manufacturing of all components, use requirements, generation or conservation (if any), end of use (disposal or recycling), and the distribution/transportation in between each stage. Complete LCA's are difficult to perform on any technology, because there are always limits to the information available. For the purposes of determining energy cannibalism, the important sub-section of the LCA is given by embodied energy invested (over the entire life cycle), E_E , in the device. As this paper will demonstrate the scope and scale of LCA and E_E studies must increase enormously to provide decision makers with the information to make informed decisions about allocating resources to reduce GHG emissions.

3.2 Energy Payback Time and GHG Emission Conservation Payback Time

All current technologies are dependent to some degree on fossil fuel energy and thus also contribute to GHG emissions. In order for either an EET or an AET to have a net negative impact on GHG emissions of the energy supply, first it must produce enough emission-less energy or conserve enough energy to offset the emissions that it is responsible for, and then it must continue to produce energy or conserve energy to offset emissions from existing or potential fossil fuel plants. This can become challenging in view of rapid growth discussed in section 2.2 because the construction of additional AET production

plant (or the fabrication of many EET devices) to enable the rapid growth rate, creates emissions that cannibalize the GHG mitigation potential of all the power plants (or EETs) viewed as a group. To illustrate this point it is helpful to view all AET or EET plants of a given type as a single aggregate plant or ensemble and look at its ability to mitigate emissions as it grows. This ability is first dependent on the energy payback time (t_{EP}) of the plant, or the amount of time it takes for a given device to produce (or conserve) as much energy as it took to construct. For a generic energy producing technology (or energy conserving technology), an installed total capacity, C_T (in GW), produces (or conserves):

$$E_T = t \cdot C_T = t \cdot \sum_{n=1}^N C_n \quad (1)$$

of energy per year, where t is the time the plant is running at capacity in hours in a year, C_n is the capacity of an individual power plant or EET and N is the total number of plants or EETs.

If we assume that in the same year the industry of that technology grows at a rate, r , it will produce an additional capacity of rC_T . The amount of energy that the industry produces (or conserves) is obtained by multiplying by the time and is thus $rC_T t$. For simplicity assume that the additional capacity does not produce (or conserve) its energy, $rC_T t$, in that year but only in subsequent years. The time that the GHG emission reduction technology takes to pay for itself in terms of energy it needs over its life cycle, or the t_{EP} , is given by embodied energy invested (over the entire life cycle), E_E , divided by energy produced (or fossil fuel energy saved), $E_{P/S}$. Thus t_{EP} , as measured in years, is:

$$t_{EP} = \frac{E_E}{E_{P/S}} \quad (2)$$

The same analysis is true for GHG emissions. If a given AET or EET causes GHG emissions during its manufacture and use it has a finite time that it must operate to achieve climate forcing neutrality.

3.3 Energy Cannibalism

The energy needed for the growth of the entire technology ensemble is given by the cannibalistic energy E_{Can} :

$$E_{Can} = \frac{E_E}{E_{P/S}} r C_T t \quad (3)$$

Regardless if the technology is an energy producer or conserver, the technology ensemble will *not* produce any net energy if the cannibalistic energy is equivalent to the total energy produced. So by setting equation (1) equal to (3) the following results:

$$\frac{E_E}{E_{P/S}} r C_T t = C_T t \quad (3)$$

and simplifies to set equation (2) equal to the inverse of the growth rate:

$$\frac{E_E}{E_{P/S}} = \frac{1}{r} = EPT \quad (4)$$

Equation 4 shows that the growth rate of either an AET industry or EET deployment may not exceed the reciprocal of the t_{EP} to have a positive net energy. For example, if the energy payback time is 5 years and the capacity growth of either a AET or EET ensemble is 20%, no net energy is produced and no GHG emissions are offset. This is because the same analysis is again true for GHG emissions. The embodied GHG emitted in order to provide for the AET or EET divided by the emissions offset every year must be equal to one over the growth rate of the AET or EET simply to break even. This cannibalism of energy for new AETs or EETs has a profound effect on their ability to assist in the mitigation of GHG emissions.

3.4 An Example of Energy Cannibalism Limiting Growth Rates

In order to understand the effect of energy cannibalism on the growth rate of an AET or EET it is instructive to consider a concrete example where a single technology produces all of the necessary energy for society except for energy produced via fossil fuel combustion with a tolerable amount of GHG emissions (e.g. GHG emissions that can be absorbed safely by the biosphere). It has been argued that future non-GHG emitting energy could largely be provided by solar photovoltaic (PV) cells, which convert sunlight directly into electricity, powering of a sustainable society (Pearce, 2002). As it is clear that humanity is already producing more GHG emissions than the sustainable rate, the deployment of a renewable energy source should be accomplished in a way so as to not add additional GHG emissions to the atmosphere while fossil fuel plants are taken off line. Thus, the growth rate in the deployment of solar PV would be limited by the neutral growth rate set by the t_{EP} and equation 4. The energy LCA for solar photovoltaic cells depends on both the balance of system (BOS), type of solar cell, efficiency and region where it is deployed (to account for the variations of solar flux). A number of detailed studies on the energy requirements of the three types of PV materials which make up the majority of the active solar market: crystalline silicon, polycrystalline, and amorphous silicon were reviewed and summarized. This review found that depending on the specifics of the array the t_{EP} was between 1 to 5 years (Pearce and Lau, 2002). This is equivalent to a growth rate maximum between 100% and 20%. This is significant limit to consider as the PV industry has been growing rapidly, maintaining a growth rate of ~20% on the average, while in the last five years the average annual growth rate has climbed to 35%. The faster t_{EP} values were generated from lower embodied energy processing (thin films), roof mounted systems, higher efficiencies, and favorable climates (e.g. Arizona), while the slower t_{EP} values are generated for high embodied energy processing (crystalline silicon), large solar farm arrays, with low efficiencies located in unfavorable regions. This analysis provides several useful conclusions. First, even a technology with an strong ecological balance sheet, such as PV, must continue to adapt to reduce E_E . Currently, the PV industry is moving towards a greater percentage of thin film solar cells and roof mounted systems are becoming more socially acceptable. Both of these trends will act to reduce E_E and thus decrease t_{EP} by equation 2. Second, although there continue to be steady improvements in conversion efficiency, which will improve $E_{P/S}$, solar flux also has an enormous impact on $E_{P/S}$. This would indicate that energy policy meant to accelerate deployment and raise r , would function best to concentrate first in regions of high solar flux. As evidenced by the current haphazard government support for PV throughout both the world, and in individual countries like the U.S. and Canada, it is

clear that there needs to be a shift in policy away from simplistic economics to more subtle energy and emissions considerations.

4. Energy Cannibalism Induced Growth Rate Restrictions at the Climate Tipping Point

The restrictions of energy cannibalism are not limited to complex 'hi-tech' technologies; even far more mundane technologies such as home insulation has a maximum climate neutral growth rate. The limit set by energy cannibalism for insulation, as for many EETs and AETs, not only varies widely because it is highly geographically dependent (e.g. weather, local energy sources, and human behavior), but also has largely not been determined. Some alternative energy technologies, such as the example of solar photovoltaic cells, have considerable literature dedicated to LCAs and embodied GHG emissions (Pearce and Lau, 2002; Fthenakis and Alsema, 2006; Fthenakis, et al., 2008), but the majority of energy conserving or producing technologies have not been scrutinized as thoroughly. To combat GHG emissions on an appropriate mass scale, full LCAs and t_{EP} s must be calculated for all candidate technologies. For leaders to make informed, intelligent decisions about which AETs and EETs to deploy on a large scale this data is imperative.

This work becomes increasingly important as civilization approaches the tipping point in climate stabilization. If humanity wishes to preserve a planet similar to that on which civilization developed and to which life on Earth is adapted, paleoclimate evidence and ongoing climate change suggest that atmospheric CO₂ concentration will need to be reduced from its current 385 ppm to at most 350 ppm (Hansen, et al., 2008). This CO₂ concentration is determined by a limit of 1°C global warming (relative to 2000, 1.7°C relative to pre-industrial time), aiming to avoid practically irreversible ice sheet and species loss (Hanson, et al., 2007). This 1°C limit, with nominal climate sensitivity of 3/4°C per W/m² and plausible control of other GHGs (Hansen and Sato, 2004), implies maximum CO₂ concentration of approximately 450 ppm (Hansen et al., 2007), which must not be crossed before stabilizing at a lower concentration. This physical limit to global CO₂ concentration places enormous boundary conditions on the ability to deploy any AETs or EETs on a scale necessary to reduce fossil fuel use and drive the CO₂ concentration below 350 ppm. Given the current trend of increased energy use for economic development, additional GHG emissions necessary for the massive growth of AETs and EETs to offset fossil fuels may not be tolerable. As Hanson et al. note, if the present overshoot of this target global CO₂ is not brief, there is a possibility of instigating irreversible catastrophic effects (2008). Thus, to prevent additional climate forcing while mass deploying AETs and EETs on the global scale the condition of equation (4) for the aggregated for all AETs and EETs and must be met as follows:

$$r_{limit} = \frac{\sum_{i=1}^N E_P + \sum_{j=1}^M E_S}{\sum_{i=1}^N E_{E_{AES}} + \sum_{j=1}^M E_{E_{EES}}} \quad (5)$$

Here r_{limit} is the maximum rate of growth of the reduction of GHG emitting energy obtainable with the use of all available EETs and AETs while ensuring that the net energy remains positive. This limit in the growth rate of non-GHG emitting energy sources also sets the limit for the time to which the anthropogenic climate forcing can be stabilized without radically shifting human economies. Considerable further work is needed to quantify this limit by calculating t_{EP} s of all potential AETs and EETs to determine the optimal mix of technologies for driving down CO₂ concentration below 350

ppm. This appreciable work needs to be developed quickly on a global scale as each passing year makes the problem of replacing fossil fuels before reaching the 450ppm absolute limit of CO₂ concentration that much more challenging. These results indicate a need for a consideration of a global “energy economy” - an economy based on a real physical value of energy rather than on a subjective valuation of worth, in order to make informed decisions to ensure a stable climate for all nations and the biosphere.

The cannibalization effect, however, is more complicated than the simplest results above would indicate. With each AET power plant constructed, the embodied GHG emissions of the next plant (or EET) will be reduced because the fraction of non-fossil fuel based energy has increased. As the embodied GHG emissions is decreased and the effective growth rate can be increased. It is also likely that sources of energy that have lower mass CO₂-eq. per unit energy rates than fossil fuels will be deployed at an expanding rate as economies of scale drive down cost as production increases (e.g. solar photovoltaic cells) (Pearce, 2005; Pearce, 2006). This will speed the decrease in the embodied GHG emissions for any type of AET or EET ensemble. Similarly for each EET device deployed the total amount of energy needed is reduced, which reduces the necessary r to meet a climate neutral energy state at a specific point in time. Thus the growth rate needed for stabilization of the earth's climate can be pushed below r_{limit} with a suitable deployment of EETs. Full vetting of this concept will need to be completed in the future as all AET and EET candidates are identified and full LCAs are completed for each geographical location.

5. Conclusions

This paper has shown that the GHG emission neutral growth rate of both energy conserving technologies and alternative energy technologies are constrained by the energy cannibalistic effect. To grow while remaining net GHG emission energy reducers, AETs and EETs must grow at a rate slower than the inverse of their payback time. To overcome this effect, the technologies with the fastest energy payback times should be deployed first in the appropriate regions. In addition, every effort should be made to increase the efficiency, and thus energy produced (or conserved) of all candidate AETs and EETs. Complete LCAs should be run for all candidate AETs and EETs as quickly as possible. The results of these studies should be made globally available to help decision makers encourage the best technological development in their own countries to combat global climate destabilization.

References

- Curry, T.E., Ansolabehere, S., and Herzog, H., (2007), “A Survey of Public Attitudes towards Climate Change and Climate Change Mitigation Technologies in the United States: Analyses of 2006” Publication No. LFEE 2007-01 WP MIT Carbon Sequestration Initiative.
- Fthenakis V.M. and Alsema E., 2006. “Photovoltaics Energy Payback Times, Greenhouse Gas Emissions and External Costs: 2004-early 2005 Status”, *Progress in Photovoltaics: Research and Applications*, Vol. 14, pp.275-280.

Fthenakis V.M., Kim H.C. and Alsema, E. 2008. "Emissions from Photovoltaic Life Cycles", *Environmental Science and Technology*, Vol. 42, No. 6, pp. 2168-2174.

Hansen, J. and Sato, M. (2004) "Greenhouse gas growth rates", *Proceedings of the National Academy of Sciences of the USA*, Vol. 101, No. 46, pp.16109–16114.

Hansen, J., Mki. Sato, R. Ruedy, P. Kharecha, A. Lacis, R.L. Miller, L. Nazarenko, K. Lo, G.A. Schmidt, G. Russell, I. Aleinov, S. Bauer, E. Baum, B. Cairns, V. Canuto, M. Chandler, Y. Cheng, A. Cohen, A. Del Genio, G. Faluvegi, E. Fleming, A. Friend, T. Hall, C. Jackman, J. Jonas, M. Kelley, N.Y. Kiang, D. Koch, G. Labow, J. Lerner, S. Menon, T. Novakov, V. Oinas, Ja. Perlwitz, Ju. Perlwitz, D. Rind, A. Romanou, R. Schmunk, D. Shindell, P. Stone, S. Sun, D. Streets, N. Tausnev, D. Thresher, N. Unger, M. Yao, and S. Zhang, (2007) "Dangerous human-made interference with climate: A GISS modelE study", *Atmospheric Chemistry and Physics*, Vol. 7, pp. 2287-2312.

Hansen, J., Sato, M., Kharecha, P., Beerling, D., Masson-Delmotte, V., Pagani, M., Raymo, M., Royer, D. L., Zachos, J. C. (2008), "Target atmospheric CO₂ : Where should humanity aim?" (Submitted on 7 Apr 2008) Available: <http://arxiv.org/pdf/0804.1126>

Hoffert, M. I., Caldeira, K., Benford, G., Criswell, D.R., Green, C., Herzog, H., Jain, A.K., Kheshgi, H.S., Lackner, K.S., Lewis, J.S., Lightfoot, H.D., Manheimer, W., Mankins, J.C., Mauel, M.E., Perkins, L.J., Schlesinger, M.E., Volk, T., and Wigley, T.M.L. (2002) "Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet", *Science*, Vol. 298, pp. 981-987.

I.C.J.T. (2001) "Nuclear Power Plants in the World 2001", The Nuclear Training Centre (ICJT) is part of the Jozef Stefan Institute, Available: <http://www.icjt.org/an/tech/jesvet/jesvet.htm> (Visited May 19, 2008).

International Atomic Energy Agency (2000) "Nuclear power reactors in the world", *International Atomic Energy Agency Reference Data Series No. 2*, April Edition, IAE, Vienna, Austria.

Intergovernmental Panel on Climate Change (IPCC), (2007), "Climate Change 2007", S. Solomon et al., Eds., Cambridge Univ. Press, New York.

Kutscher, C.F. (editor) (2007) "Tackling Climate Change in the U.S. Tackling Climate Change in the U.S. Potential Carbon Emissions Reductions Efficiency and Carbon Emissions Reductions from Energy Efficiency and Renewable Energy by 2030", American Solar Energy Society.

Leeson, G. W. (2002) "The Changing Face of the Population of Europe: Geographical Distribution, Urbanization, Depopulation, and International Migration", Nordegio, Stockholm, Sweden.

Leiserowitz, A. (2006) "Climate Change Risk Perception and Policy Preferences: The Role of Affect, Imagery, and Values", *Climate Change*, Vol. 77, No. 1-2, pp. 45-72.

Pacala, S. and Socolow, R. (2004) "Stabilization Wedges: Solving the Climate Problem for the Next 50

Years with Current Technologies”, *Science*, Vol. 305. No. 5686, pp. 968-972.

Pearce, J. M. (2002) “Photovoltaics – A Path to Sustainable Futures”, *Futures*, Vol. 34, No. 7, pp. 663-674.

Pearce, J. and Lau, A. (2002) “Net Energy Analysis For Sustainable Energy Production From Silicon Based Solar Cells”, in R. Cambell-Howe (Ed), *Proceedings of American Society of Mechanical Engineers Solar 2002: Sunrise on the Reliable Energy Economy*.

Pearce J. M. (2006) “Catalyzing Mass Production of Solar Photovoltaic Cells Using University Driven Green Purchasing”, *International Journal of Sustainability in Higher Education*, Vol. 7, No. 4, pp. 425 – 436.

Pearce J. M. (2008) “Thermodynamic Limitations to Nuclear Energy Deployment as a Greenhouse Gas Mitigation Technology”, *International Journal of Nuclear Governance, Economy and Ecology*, Vol. 2, No. 1, pp. 113-130.

Pearce, J. and Russill, C. (2005) “Interdisciplinary Environmental Education: Communicating and Applying Energy Efficiency for Sustainability”, *Applied Environmental Education and Communication*, Vol. 4, No. 1, pp. 65-72.

Pearce J. M. and Miller, L. L. (2006) “Energy Service Companies as a Component of a Comprehensive University Sustainability Strategy”, *International Journal of Sustainability in Higher Education*, Vol. 7, No. 1, pp. 16-33.

Pearce, J. M., Johnson, S. J., and Grant, G.B. (2007) “3D-Mapping Optimization of Embodied Energy of Transportation”, *Resources, Conservation and Recycling*, Vol. 51, pp. 435–453.

Smalley, R. 2005. “Future Global Energy Prosperity: The Terawatt Challenge”, *Materials Research Society Bulletin*, Vol. 30, pp. 412-417.

World Energy Council (2001) “Lunar Solar Power System: Industrial Research, Development, and Demonstration” University of Houston, USA. 18th Congress, Buenos Aires, October, 2001.

World Energy Council (2004) “Energy Data Centre: Global Energy Scenarios to 2050 and Beyond” Available: <http://www.worldenergy.org/wec-geis/edc/scenario.asp> (Visited May 19, 2008).