How Far Energy Efficiency?

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ABSTRACT

Analysts agree about the need for developing both new and cleaner energy resources. At the same time, some argue that energy efficiency can provide only a minimal role in meeting future energy needs. Hence, energy supply is encouraged while energy efficiency is supported only minimally. Analysts Douglas Lightfoot and Christopher Green suggest in a series of papers, for example, that there are practical limits that will constrain the rate of efficiency improvement to no more than about one percent per annum over the next 100 years. This paper explores the assumptions that underpin such "practical limits" and concludes that efficiency gains perhaps could more than double the rate suggested by Lightfoot and Green. The question is not one of practical limits; rather, the issue is one of choosing to develop energy paths that allow greater system efficiencies to emerge.

Introduction

Whatever we believe about the world energy future, there will be a huge shortfall in the availability conventional resources by roughly 2030 (Hall et al. 2003; Hoffert et al. 2002; Metz et al. 2001). "The world is not remotely running out of total energy, but it is (slowly) running out of major nonrenewable sources such as coal, oil, gas, and (more quickly) the arable land environment and healthy air quality urban environment" (Abt 2002). A huge investment in research and development, infrastructure, and technology will be needed to ensure adequate energy availability. This is true whether we are talking about unconventional fossil fuels, a hydrogen economy, renewable resources, nuclear energy, or energy efficiency. In that context, we should explore the mix of energy investments that will deliver economic robustness, environmental quality, and energy security (Hanson et al. 2004).

The magnitude of future energy supplies needed to support a growing economy depends critically on how efficient the economy might be. A more efficient economy requires less total energy than a comparatively inefficient one. For that reason, a large number of studies have suggested ways of increasing overall energy efficiency, especially through the period 2030 or so. At the same time, several analysts have begun to argue that long-term efficiency gains are limited. This paper reviews a number of concerns raised and provides another look at the argument.

The Argument

In their recent series of papers Douglas Lightfoot and Christopher Green comment that future energy requirements depend crucially on the long-term average annual rate of decline in world energy intensity (Green & Lightfoot 2002; Lightfoot & Green 2002, 2003).[1] In this case, energy intensity is measured by the number of British Thermal Units (Btus) per dollar of Gross Domestic Product (GDP), or equivalent world GDP. The authors note their papers are an attempt "to remove much of the uncertainty surrounding the size of the contribution that declining energy intensity could make towards replacing fossil fuels and, thereby, a contribution towards stabilizing the level of carbon dioxide in the atmosphere."

The Lightfoot and Green further note that the rate of energy intensity decline depends on two aspects: (a) energy efficiency, and (b) long term structural change in the economy. Energy efficiency refers to improvements in fuel economy, power plant heat rates, building operations, and industrial processes. Structural change refers to shifts in economic activity away from energy-intensive manufacturing industries to lower energy-intensive sectors such as business services. Using what they claim to be "the physical limits to increases in energy efficiency," Lightfoot and Green calculate "the maximum attainable global average energy efficiency increase for the 110 years between 1990 and 2100." According to their estimates, the overall average decline in energy intensity by the year 2100 will be about 41 percent of what it was in 1990. This total reduction in energy intensity is equivalent to an average annual rate of decline of 0.80 percent for 110 years.[2] Including the impact of structural change on the economy, they suggest that energy intensity may approach a practical limit of about 1.0 percent annually through the year 2100.

The implications of such "practical limits" are significant. If we assume that worldwide GDP grows at an average annual rate of 2.3 percent (not an unreasonable assumption over a 110-year time horizon as Lightfoot and Green assume in their papers), a 1.0 percent decline in the world's energy intensity implies that total energy supplies in 2100 will need to grow to about four times as large as in 1990. On the other hand, a 2.0 percent decline in energy intensity implies annual energy requirements that are only 1.3 times the 1990 levels. Hence, the potential for efficiency improvements can be a very big deal.[3]

In the review and analysis that follows, I highlight four critical problems with the Lightfoot-Green assessment. These include: (1) use of incomplete data; (2) an inconsistent estimation of changes in energy intensity within an inappropriate analytical framework; (3) failure to establish the physical limits of efficiency improvements as they claim they set out to do, discussing only "assumed" limits; and finally, (4) allowing no apparent room for innovation over the 110-year period covered in the analysis. When their analysis is corrected for these serious weaknesses, a substantially different conclusion emerges. With the right mix of market conditions, prices, and policy signals it appears that the rate of improvement can – within practical limits – perhaps double the maximum rate identified by Lightfoot and Green. Again, depending on the level of innovation both in technology development and within the marketplace itself, it is not inconceivable that this rate may be tripled for long periods of time.[4]

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[1] Lightfoot and Green discuss this issue in terms of the climate change perspective, but the logic follows the same path for energy since climate change is a function of carbon dioxide (CO_2) concentration brought about by growing use of fossil fuels.

[2] Note that (0.41^(1/110) – 1) * 100% = -0.8%.

[3] Here we have [(1 - 0.02) * 1.023]^110 = 1.32 times the 1990 level of worldwide energy demand.

[4] Whether from a mathematical or a physical perspective, the rate of a decline in energy intensity may be less of a problem than is generally assumed. For example, current US energy intensity is about 10,000 Btus per dollar of GDP (Energy Information Administration 2003c). Hence, a two percent decline in 2004 means an absolute reduction of about 200 Btus per dollar of GDP. In the year 2100, however, a two percent decline compared to the projected intensity in the year 2099 would be less than 30 Btus.

Energy Efficiency in Perspective

Over the period 1990 through 2003, the US energy intensity has actually declined at an annual rate of 1.7 percent. Indeed, energy efficiency (defined as the decline in energy intensity) has provided almost two-thirds of the increase in the nation's "energy supply" since 1990![5] Clearly, the US economy has shown an ability to reduce energy intensity at a significantly greater rate than the practical limits suggested by the Lightfoot-Green hypotheses. Hanson and Laitner have shown in a forthcoming article that the "business-as-usual" rate of decline in the US energy intensity might average 1.7 percent through the year 2050. In addition, they note the adoption of moderate energy policies might extend that rate of decline to 2.4 percent per year also through 2050 (Hanson & Laitner 2004). One analyst (Blok 2002) further indicates that efficiency improvements might increase by 5 percent over the next twenty years. Moreover, the World Energy Council suggests that worldwide industrial energy intensity might decline by more than two percent per year over the period 1990 through 2020 (Levine et al. 1995).

Still the question of efficiency improvements is a long-term one. Are there practical limits, as hinted by the Lightfoot-Green hypothesis, which constrain the decline in energy intensity to about one percent per year for the 110-year period through 2100? On the other hand, have such constraints have been overstated or poorly understood? More positively, have areas of opportunity been overlooked that might actually allow the kind of improvements suggested by Hanson and Laitner to continue beyond 2050 through the year 2100?

Even when corrected for an inappropriate analytical framework, the Lightfoot-Green perspective appears to be unnecessarily constrained by the assumption of Carnot efficiency limits that apply only to the combustion of fossil fuels. In fact, the majority of future efficiency gains are likely to be the result of improvements in chemical processes rather than fuel combustion.[6] Hence, the analysis that follows strongly suggests that, when we transform the analytical framework away from an outmoded paradigm of *Promethean Fire* to one of *Chemistry in Action*, the potential rate of improvement can approach or perhaps even exceed two percent per year. Referring to energy efficiency as one of the main technological drivers of world-wide sustainable

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[5] According to the latest data from the Energy Information Administration (Energy Information Administration 2003c), the nation's energy intensity was 12.6 kBtus per dollar of GDP in 1990. Had the technology and market structure remained frozen at the 1990 level of intensity, total energy use would have grown at the same rate as GDP. Preliminary estimates for 2003 suggest an economy that is 44 percent larger today than in 1990. This implies an estimated energy consumption that is 44 percent larger today than in 1990. Hence, using the benchmark of a 1990 frozen efficiency, energy use should have risen from 84.6 quads in 1990 to about 122.1 quads today. Yet, preliminary estimates show that, in fact, consumption will be only 97.8 quads through 2003. In other words, had the demand for energy services been met only through increased energy supply, the US economy would have required 122.1 less 84.6, or 37.5 quads of additional energy supply compared to 1990 levels. Actual energy use grew by only 97.8 less 84.6, or 13.2 quads. Thus, new supply provided only 35 percent of the new energy needs while energy efficiency, or reduced energy intensity more properly, provided 65 percent of increased demand for energy services.

[6] One example of potential efficiencies is cited in (Astumian 2001). The author notes that nanoelectromachines can imitate what protein pumps and motors do in living cells – "convert chemical energy into mechanical work with almost 100 percent efficiency." Another recent article references ultralow power levels of such devices that use "a millionth to a billionth the amount of power used for conventional transistors" (Roukes 2001). This is not to say there aren't substantial difficulties in developing practical devices that are commercially viable. Rather, it is to point out that, at worst, the practical limits have yet to be defined. As Michael Roukes further notes, "we are only *beginning* to acquire the detailed knowledge" that will be at the heart of future technologies (emphasis in the original).

development, one group of analysts suggest a technical potential for energy efficiency of almost one order of magnitude that may become available during this century (Goldemberg 2000). As we shall also see, this assumes the right mix of incentives and an appropriate set of policy signals that, together, might support a greater rate of improvement than might be found in a typical reference case or business as usual projection.

Incomplete or Inappropriate Data

A review of the references cited by Lightfoot and Green quickly reveals a serious omission of significant research available from the national energy laboratories and the current literature. For example, despite the availability of significant industrial and commercial sector data for OECD countries and for many developing countries (see, for example, (Goldemberg 2000; Levine, Martin & Price 1995), they assume that commercial buildings will use energy like the industrial sector. This is wholly wrong both on a sectoral basis and in terms of important differences between developed countries compared to economies in transition. They further assume that the industrial sector will look and evolve like the chemical industry. This also is wrong. They completely overlook the potential improvements available from technologies such as combined heat and power (CHP) systems.[7]

Inappropriate Estimations of Changes in Energy Intensity

For purposes of a more detailed analytical review, let's use the example of passenger cars as but one example of inappropriate estimation of potential efficiency gains. Lightfoot and Green, defaulting to US data, suggest that fuel economy for cars will increase 300% by the year 2100, going from 27.5 to 110 miles per gallon (MPG). According to their papers, this implies a 75% reduction in fuel consumption such that energy intensity of cars will be 25% of the value in 2100 as in 1990. Over a 110-year period, this calculation implies a -1.3% annual rate of change in energy intensity for passenger cars.

But let's examine the Lightfoot-Green analysis more closely. First let's note that in 1990 the average car had 10,500 vehicles miles traveled (VMT) per year according to historical data from the Energy Information Administration (Energy Information Administration, 2003b). At that level of annual travel, a 300 percent increase in fuel economy implies going from a gasoline consumption of ~382 gallons down to ~95 gallons per year.[8] Over a period of 110 years this implies an annual rate of change of -1.3 percent in energy use.[9] So far so good.

As we just noted above, Lightfoot and Green assume that GDP will grow 2.3% per annum. As we shall see, the decline is even greater from an energy intensity perspective (again, measured as energy use per dollar or GDP). Under the Lightfoot-Green scenario, the total

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[7] Perhaps as an indication of research bias, they misstate in a companion paper (2002) both the current CHP system efficiencies and the long term potential of CHP technologies — in spite of significant documentation to the contrary. For example, the author has personally visited several different facilities with system efficiencies in excess of 70 percent. At the same time, the industrial documentation for the NEMS model shows 8 CHP systems which now maintain average system efficiencies that range from 65 to 78 percent (Honeycutt and Unruh 2003) rather than the 40 to 50 percent cited by Lightfoot and Green in their companion paper.

[8] Dividing 10,500 miles per year by 27.5 miles per gallon implies total gasoline consumption of ~382 gallons. Similarly, a fuel economy of 110 mpg requires only 95 gallons.

[9] This is estimated as [(95/382)^(1/110)-1]*100%= -1.3%.

economy will be about ~12.2 times larger in 2100 compared to 1990.[10] Hence, we have to divide the 95 gallons by 12.2 that will give us approximately 8 instead of 95. The new change in intensity, then, is -3.5% per year.[11]

Even if we assume a rebound and/or growth effect such that VMT grows at about three-fourth the rate of GDP,[12] or about 1.7% annually which increases VMT to 67,100 miles per annum, the annual rate of decline in energy intensity for cars (rather than improvements only in fuel economy) is still -1.8%.[13] Finally, the actual on-road average for cars was 20.2 mpg in 1990 (in the US according to EIA). Assuming all of the above, the annual rate of decline would then be -2.1%. This is a significantly different annual rate of change than -1.3% — which is also significantly different than -0.8%.

From this discussion we can quickly see that measuring the change in energy intensity – again, measured as the number of Btus per dollar of GDP – involves much more than estimating the change in the specific energy consumption associated with a particular good or level of service. It also involves changes in the production of goods or the levels of service provided by that specific energy consumption. Hence, *the anticipated energy intensity should be more properly thought of as the specific energy consumption of a given unit of service times the total level of service that is provided as it is divided by the GDP*. Using the transportation example once again, we might note a more appropriate calculation as follows (with values rounded to the nearest thousandth):

$$E/GDP_{2100} = 20.2 / 110 * 1.017^{110} / 1.023^{110} = 0.184 * 6.387 / 12.199 = 0.096$$

In this example, the new index of fuel economy of 0.184 is multiplied by the more than six-fold increase in travel that, in turn, is divided by more than 12-fold increase in economic activity. Therefore, if we assume the 1990 level of energy intensity is 1.000, the new level of energy intensity in 2100 is not 0.184 but 0.096. On an annual basis then, the change in energy intensity is not -1.5 percent, but -2.1 percent. In other words, if the level of service provided (in this case reflected in vehicle miles traveled) is less than the growth in GDP, then the new level of energy intensity will be less than that estimated from the anticipated efficiency gains (dividing the old MPG by the new MPG).

This same simple error appears to be repeated for the other end use sectors in the Lightfoot-Green papers. In residential buildings for example, the assumption is that efficiency gains will reduce building intensity down to a value of 0.26. However, the mid-level projection of worldwide population growth appears to be on the order of 0.6 percent through 2100. Even if we assume a doubling of this number to reflect greater wealth and smaller household sizes over time, 1.2 percent is still less than the projected 2.3 percent growth in GDP. Compounded over a 100-year period, growth in residential household activity is only 30 percent of the assumed

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[10] Or, 1.023^110 = ~12.2.

[11] In this case we are assuming that the 8 gallons will provide us with 12.2 times greater economic activity in 2100 than the 382 gallons in 1990. The calculation, therefore is [(8/382)^(1/110)-1]*100%= -3.5%.

[12] This link between VMT and GDP growth rates is suggested, for example, by data from the Annual Energy Outlook 2003 (Energy Information Administration 2003a).

[13] Multiple drivers traveling further on an annual basis, and using more cars, might bring about this magnitude of increase in total vehicle miles. However, as we shall see later in this analysis, there is every reason to believe that the demand for travel may not grow as large as 1.7% per year as new production techniques will allow travel to remain closer to home or closer to production sites.

growth in world GDP.[14] By definition, then, the energy intensity from an energy efficiency index is 0.26 * 0.30, which equals 0.078, for an annual rate of declined approximately equals to -2.3 percent.[15]

The Practical Limits Are Only "Assumed"

An equally troubling aspect of the Lightfoot-Green hypothesis is they never actually describe or document the physical or the "practical limits" to energy efficiency that might actually constrain the rate of improvement. In the case of passenger cars, for example, they merely "assume" that 110 mpg is the maximum attainable improvement in fuel economy. According to the Rocky Mountain Institute's Hypercar concept, future fuel economy could be 200 MPG (Lovins 1996).[16] Other reports cite similar numbers (Smil 1999; VonWeizsacker et al. 1997). By way of comparison, if we think in terms of the useful chemical energy of gasoline such that it can be converted fully to the kinetic energy necessary to move a two-ton car at a speed of 60 miles per hour, we would need only 0.005 gallons of gasoline (to go 60 miles) instead of perhaps the two or more gallons consumed by an average car today.[17] So by their own stated objective, Lightfoot and Green failed to deliver a useful analysis of the "documented" practical limits in the case of cars.

But from an economy-wide perspective there are a growing number of engineers and analysts who are beginning to explore the possibility of an order of magnitude gains in energy efficiency (Goldemberg 2000), in effect reducing material requirements by a factor of 10 (Schmidt-Bleek 1999). If translated as reducing energy intensity to 10 percent of year 2000 levels, then we might suggest the possibility of a 2.3 percent decline in the rate of energy consumption per dollar of world GDP.

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[14] In this case we have (1.012^110 / 1.023^110) * 100% = 30%.

[15] We might inquire how growth in the level of service might actually be smaller than GDP. One answer is productivity. In fact, we sometimes explain GDP growth as a combination of a growth in population or labor force times productivity growth. In the Lightfoot-Green example discussed above, a 2.3% annual growth in world GDP can be explained as a 1% growth in population times a 1.3% growth in productivity improvements. Alternatively, it might be a 0.6% growth in population times a 1.7% growth in worldwide productivity. Following that logic, then, the worldwide energy intensity for any given year might be defined as (Btus per Unit of Service * Total Level of Service) / (Population * Productivity). We can say more generally, as long as the growth in goods or level of services is smaller than GDP, the change in energy efficiency improvements will always result in a larger change in energy intensity. Of course, the reverse is also true.

[16] Although perhaps an extreme estimate of potential fuel economy, it is worth noting that the RMI Hypercar concept won the 2003 World Technology Award for Environment, suggesting a level of credence with the Lovins estimate that might not be accorded to Lightfoot and Green (Hypercar Inc., June 2003).

[17] Drawing from a physics textbook (Romer 1976), the kinetic energy is equal to ½ mv^2. With units in so-called meter-kilogram-second (MKS) format, we might obtain, in joules: KE = 0.5 * (2 tons * 907.2 kg / 1 ton) * (60 miles/hour * 0.447 m/sec / 1 mile/hr)^2 ~ 650,000 joules. Since there are about 130 million joules per gallon, the energy required is about 0.005 gallons. Even if we incorporate the maximum thermodynamic efficiency (as distinct from Carnot efficiency), probably greatly than 90 percent (measured as the change in Gibbs free energy divided by the change in enthalpy at standard temperature and pressure), the energy required is still a very small amount. This, of course, does not include added fuel consumption for accelerating or going up hills or steep inclines; nor does it include idling time or the myriad reasons that energy may be siphoned away from the immediate task of moving passengers. The only purpose here is to illustrate the difference between energy required versus current levels of inefficiencies.

At the same time, the decline in energy intensity is not limited only by technological constraints. There are social interactions and institutional/market arrangements that can also impact energy intensity as well. For instance, mode shifting, car pooling, telecommuting, and land use patterns might all interact to reduce VMT compared to standard reference case projections. This is especially true should climate change, gridlock, and air pollution concerns further catalyze the so-called "smart growth" initiatives. Such outcomes can have a significant impact on further decreases in energy intensity. To continue with the example of passenger cars, if the VMT growth rate falls to 1.0 percent annually, the energy intensity associated with light cars might decline 2.5 percent annually. The same set of weaknesses associated with passenger cars unfolds with all of the other technologies and sectors in the Lightfoot and Green paper. In other words, patterns of use within buildings and industry can equally affect changes in energy intensity.

No Room for Innovation over the 100-Year Period

Perhaps not surprisingly, Lightfoot and Green appear to overlook the many significant advances in materials science, electronics, nanotechnology, software, and systems integration that are likely to have profound impacts on energy use. The growth in the number of books, reports from the national laboratories, journal articles, and technology magazine headlines that highlight major technological advances are a first indication. But developments within industry itself point to exciting advances that promise both reduced material consumption and energy efficiency gains. None of these is reflected in the literature cited by Lightfoot and Green.

Carbon nanotubes, for example, were first discovered in 1991 — only one year after Lightfoot and Green's assumed reference case year. Nanotubes are a new class of materials formed from graphite-like sheets of carbon rolled into exquisitely small cylinders. They are incredibly light synthetic materials with a potential electrical conductivity that is 50-100 times better than copper. Their structures are potentially 100 times stronger than steel and about 1,000 times thinner than a human hair. DOE and lab scientists are working on ways to incorporate nanotubes into new composite materials, making them much stronger than existing fiber-reinforced composites.

Nanotubes encapsulated with chemicals might some day be used to deliver medication to specific parts of the body or to separate reactant chemicals. Fuel cells converting hydrocarbon fuels directly into electrical energy for use in remote locations will most likely incorporate large membranes of nanotubes. A computer based on nanotube devices would be extremely compact, fast, and powerful (U.S. Department of Energy 2003). The world of materials science (Ball 1997) and biomimicry (Benyus 2002) offer a rich set of current innovations and of innovations yet to come that might greatly impact energy intensities worldwide.

Let us turn our attention to buildings and their present level of energy consumption and explore the impact of potential innovation in residential and commercial buildings. Of notable interest is the goal of the Climate Change Technology Program which recently announced a target of zero net energy consumption in new buildings by 2025 (Climate Change Technology Program 2003). The sub-goals are 70 percent reduction in energy use with 30 percent of remaining consumption being met through onsite generation. Assuming the year 2100 is sufficient time for all building stock to reduce consumption to 30 percent of 2003 levels, this might imply a change in building consumption of -1.2 percent annually. Again, when we note that the economy will be substantially larger in 2100, the implied change in energy intensity might be on the order of –2.3 percent.[18]

As aggressive as a 2.3 percent decline in energy intensity might appear to be, we may not be done yet. For example, the goal of the Climate Change Technology Program is also to provide the balance of energy needed through photovoltaic energy systems and other onsite technologies. At the same time, the capabilities of materials science suggest that such systems might be integrated into the structural components of building materials. Examples include light emitting polymers and a composite of roofing membranes and photovoltaic cells. Given that possibility, let us make three additional assumptions at this point: (1) two-thirds of the remaining energy needed in buildings is provided by structural building materials rather than separate energy systems; (2) both the efficiency improvements and the multipurpose structural materials reduce system-wide energy production losses; and (3) that the level of service provided by homes grows 1.2 percent per year while the economy grows 2.3 percent per year. With these additional assumptions calculated over a 97-year period, the rate of decline might actually grow closer to 4.0 percent.[19] At the same time, however, such system-wide efficiency improvements might actually promote a much faster growth of GDP would which, in turn, lower the rate of decline in energy intensity.

Perhaps to provide a more moderate perspective, and to highlight the potential impact of new products and new materials, the evidence suggests that we may need 50 percent less material to support a dollar of economic activity in the year 2100. This reduction would be made possible by the increased strength and functional capabilities of new materials, but also because many of the new materials may be serving multiple functions. Moreover, there are indications that the production of such materials may also require 50 percent less energy than present requirements. Hence, the energy needed for the production of materials would then be only 25 percent of today's requirements. Since these reductions are already expressed as a function of energy intensity, the annual rate of change implied by the 25 percent lower energy intensity is -1.4 percent, less dramatic than the changes suggested in the buildings and transportation sectors but still significantly greater than the -0.8 percent rate of change suggested by Lightfoot and Green.[20] Again, The Factor of 10 Club (Schmidt-Bleek 1999) might suggest a possibility of -2.3 percent decline in energy intensity which is the same as the rate of growth in the economy.

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[18] Here, the assumption is that the number of buildings grows about twice the rate of world population, or about 1.2% per year, with the world economy expanding by 2.3% as before. In this case, however, all of the economic activity takes place over a 97-year time horizon (from 2003 that is the formal setting of the zero net energy goal for buildings to 2100). Although awkwardly shown in a highly aggregate format, the energy intensity calculation would be: [(0.3 * 1.012^97 / 1.023^97)^(1/97) - 1] * 100% = -2.3%. Of course, if the number of buildings grows faster or slower than the population growth rate, the results would change. But that becomes a problem of demographics and markets rather than one of practical limits on efficiency gains.

[19] It takes energy to produce energy. Various estimates of production losses suggest that wellhead to home, the value of natural gas might be 90 percent of the *in situ* Btu content. Similarly, the production, processing, and transportation of coal to electric utilities involve energy use. Moreover, the current efficiency of the U.S. electricity grid appears to be about 31 percent for the system as a whole. Improving on-site efficiencies, therefore, will reduce losses from energy production. Based on current EIA data (Energy Information Administration 2003a) and other sources, for example, it appears that a typical home requires about 190 Btus of energy for every 100 delivered to the home. A combination of reducing building losses to 30% of today's energy use, together with onsite production of power, might improve system-wide efficiencies such that we use only 5% of today's requirements. Thus, we might have an annual change in energy intensity of [(0.05 * 1.012^97) / 1.023^97]^(1/97) - 1] * 100% = -4.1%.

[20] We earlier established that a 2.3 percent growth rate over 110 years would generate an economy that is about 12.2 times larger than in 1990. So, [(0.25 / 12.2)^(1/110)-1] * 100% = -3.5% change in energy intensity per year.

Hence, total energy use might remain the same as today, even while the economy is substantially larger in the year 2100.

Without pointing to any one specific family of technologies or systems of technologies, it is very clear that further advances are possible. This may be all the more so with appropriate funding, prices, invention, and entrepreneurship — all of which Lightfoot and Green seem to overlook.

Exploring a New Paradigm for Efficiency Improvements

There is little question that energy is used inefficiently. Even with the substantial improvements that are possible with today's class of technologies, energy will continue to be used inefficiently. This is because, at present, the current generation of energy technology uses energy primarily as *heat* rather than as *chemical energy*. Contrary to what Lightfoot and Green might otherwise imply, there is no law of nature that demands that things must done using the current technology.

In a penetrating study written for the Foresight Institute, one analyst commented that the current mindset might be termed what we already referred to as the "Promethean paradigm" (Gillett 2002). But, he notes, "fire turns out to be a clumsy and messy way of manipulating the world." Adopting a materials science or *chemistry in action* perspective, valuing energy for its chemical-based potential rather than its heat-based reaction, we open the way for large-scale efficiency improvements well beyond the one percent annual rate of change suggested by Lightfoot and Green.

Fuel cells are a near term example of using chemical energy without "thermalizing" it. At the same time, this is only the beginning. As Gillett further comments:

> Because arranging matter with conventional technology is difficult, matter organizers ("factories") have traditionally been large-scale, capital-intensive affairs to which raw materials are brought, and from which finished products are exported. This obviously requires an enormous transportation infrastructure; one of course that now subsumes the entire world. For example, bauxite, a tropical soil, is mined in Jamaica and sent to Norway for processing into aluminum (the electrolytic process for extracting aluminum requires vast amounts of electricity, and Norway has abundant cheap hydropower). Then the aluminum metal is sent around the world to be further fabricated into finished products. If the promise of distributed fabrication can be achieved — "matter as software" — this energy-intensive transportation network will become largely obsolete.

Casual readers may be first think of "matter as software" as something that is more a product of 20th century scriptwriters for television's long-running Star Trek series than a possibility for real world technology. In fact, the concept is already being developed to custom-make products using only a digital file — whether created by an engineer or by a scan of a physical object — as the basis for manufacturing. The matter-as-software technologies will both fabricate materials — for example, plastic or metal from powders, or nylon from resin — and shape them into parts. In short, they are a direct bridge between the virtual world of design and the physical world of manufacturing (Amato 2003). As Gillett has noted, this possibility has tremendous implications for both manufacture and transportation of products. Less thermal energy will be wasted and fewer ton-miles of goods will be shipped.

Another result of the present clumsy approaches to matter arranging is the unintended manufacture of unwanted byproducts. With little control over occurrences at the nanoscale, conventional synthetic processes yield a suite of molecular products, of which typically only one or two may be desired. The other products become waste that must be discarded or treated. That adds to both the environmental and the energy burden. Many ore minerals are not oxides as assumed by some analysts, but they are in fact sulfides. Metal sulfides react *exothermically* with oxygen. Thus, according to the laws of thermodynamics, we could use sulfide ores as fuels and get metal as a by-product!

Biosystems are far ahead of current Promethean technology. Even though we loosely speak of "burning" food for energy, biological systems are not heat engines and so are not limited by Carnot efficiency in the same way as power plants or gasoline engines. Rather than converting the energy of chemical fuel (i.e., food) to heat, and converting only some of that heat to work as it flows to a cooler body, living things oxidize their fuel non-thermally, via a cascade of molecular-scale mechanisms that approach the reversible limit set by the difference in free energy. Since they carry out their chemical processes isothermally in the range 25-40° centigrade or so, the irreversible losses are also much lower. Biosystems are capable of their remarkable feats of separation because they do not rely on phase changes. Instead, molecular mechanisms literally carry out separations molecule by molecule. Such molecular separation is both far more efficient and capable of extraction from considerably lower concentrations (Benyus 2002).

Energy could be used vastly more efficiently in technological processes 100 years from now. Within the next several decades, energy efficiencies can be improved several times today's clumsy technologies. Within the century we can imagine efficiency improvements by at least an order of magnitude or more; and in some cases, we can envision efficiency improvements well below the thermodynamic limits. In effect, the high energy densities of conventional fuels are a "brute force" compensation for the inefficiencies with which they are used. Bringing the full spectrum of our knowledge of materials science and *Chemistry in Action* may make today's unknown possibilities more tangible and more widely available (Jochem 1991) than is assumed by the substantially more limited view of the Lightfoot-Green hypothesis.

Conclusion

The evidence suggests that the Lightfoot-Green hypothesis is based on an inappropriate estimation of practical limits on the average rate of decline in energy intensity. In fact, Lightfoot and Green have neither documented what the practical limits might be, nor have they properly characterized the data and the analytical framework in which such an assessment might be undertaken. On balance, it appears that "practical limits" may be twice or even three times that described in their papers. This is especially true as the analysis is more properly broadened to reflect changes in demographic, social, and cultural norms. And it may be broadened even more when we think in terms of policies and price signals that can accelerate the pace of innovation and market penetration.

Most analysts are in full agreement about the need for developing new energy resources, whether hydrogen, renewables, nuclear or unconventional fossil fuels. Given both the economic and environmental impacts of future energy technology choices, the question should be asked whether it is appropriate to arbitrarily limit technology development by excluding energy efficiency as among those choices. Rather, this is more a matter of market, energy prices, and public policies rather than any real or practical limits. Indeed, it is entirely conceivable that we can increase the scale of the world economy by a factor of 12 as suggested by Lightfoot and Green, but actually use less energy than required by today's technology.

Given the critical need for new energy technologies, and against the backdrop of many different social objectives — ranging from improved national security and environmental quality to concerns about equity and growth in economies in transition, we might ask the question: "Why limit the growth of any technology whether a form of energy supply or energy efficiency?" Rather than espousing practical limits of one technology compared to another, it would make more sense to encourage the appropriate market conditions and public policies that accelerate innovation across all technologies. From that point, we might then allow the market and public policy decisions to determine which mix of technologies best satisfy the range of social objectives expressed in the marketplace.

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References

Abt, Clark. "The Future of Energy from the Perspective of the Social Sciences," R. N. Cooper and R. Layard, What the Future Holds: Insights from Social Science. Cambridge, MA: The MIT Press, 2002.

Amato, Ivan. "Instant Manufacturing." Technology Review, November 2003, pp. 56-62.

Astumian, R. Dean. "Making Molecules into Motors." Scientific American, July 2001, pp. 57-64.

Ball, Philip. Made to Measure: New Materials for the 21st Century. Princeton, NJ: Princeton University Press, 1997.

Benyus, Janine M. Biomimicry : Innovation Inspired by Nature. Perennial, 2002.

Blok, Kornelis. "Improving Energy Efficiency by 5% and More Per Year?," Utrecht, The Netherlands: Utrecht University, 2002.

Climate Change Technology Program. "Technology Options for the near and Long Term: A Compendium of Technology Profiles and Ongoing Research and Development at Participating Federal Agencies," Washington, DC: U.S. Department of Energy, 2003.

Energy Information Administration. "Annual Energy Outlook 2003: With Projections to 2025," Washington, DC: U.S. Department of Energy, 2003a.

____. "Monthly Energy Review," Washington, DC: U.S. Department of Energy, 2003b.

____. "Short-Term Energy Outlook," Washington, DC: U.S. Department of Energy, 2003c.

Gillett, Stephen L. "Nanotechnology: Clean Energy and Resources for the Future," Palo Alto, CA: Foresight Institute, 2002.

Goldemberg, Jose ed. World Energy Assessment: Energy and the Challenge of Sustainability. New York, NY: United Nations Development Programme, United Nations Department of Economic and Social Affairs, and World Energy Council, 2000.

Green, Chris and Lightfoot, H.D. "Achieving CO2 Stabilization: An Assessment of Some Claims Made by Working Group III of the Intergovernmental Panel on Climate Change," Montreal, Canada: Centre for Climate and Global Change Research, McGill University, 2002.

Hall, Charles; Tharakan, Pradeep; Hallock, John; Cleveland, Cutler and Jefferson, Michael. "Hydrocarbons and the Evolution of Human Culture." Nature, 2003, 426(20 November), pp. 318-322.

Hanson, Donald A. and Laitner, John A. “Skip”. "An Integrated Analysis of Policies That Increase Investments in Advanced Energy-Efficient/Low-Carbon Technologies." Energy Economics, 2004, forthcoming.

Hanson, Donald A.; Mintzer, Irving; Laitner, John A. "Skip" and Leonard, J. Amber. "Engines of Growth: Energy Challenges, Opportunities, and Uncertainties in the 21st Century," Argonne, IL: Argonne National Laboratory, 2004.

Hoffert, Martin I.; Caldeira, Ken; Benford, Gregory; Criswell, David R.; Green, Christopher; Herzog, Howard; Jain, Atul K.; Kheshgi, Haroon S.; Lackner, Klaus S.; Lewis, John S., et al. "Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet." Science, 2002, 298, pp. 981-987.

Honeycutt, T. Crawford and Unruh, Brian. "Model Documentation Report: Industrial Sector Demand Module of the National Energy Modeling System," Washington, DC: Energy Information Administration, U.S. Department of Energy, 2003.

Hypercar Inc. "Hypercar Is Winner in the 2003 World Technology Awards," Basalt, CO, June 2003.

Jochem, Eberhard. "Long-Term Potentials of Rational Energy Use - the Unknown Possibilities of Reducing Greenhouse Gas Emissions." Energy Environment, 1991, 2(1), pp. 31-44.

Levine, Mark; Martin, Nathan and Price, Lynn eds. Energy Efficiency Improvement Utilising High Technology: An Assessment of Energy Use in Industry and Buildings. Paris, France: World Energy Council, 1995.

Lightfoot, H. Douglas and Green, Christopher. "Energy Intensity Decline Implications for Stabilization of Atmospheric CO2 Content." Energy, 2003, (forthcoming).

____. "Energy Intensity Decline Implications for Stabilization of Atmospheric CO2 Content," Montreal, Canada: McGill Centre for Climate and Global Change Research, McGill University, 2002.

Lovins, Amory B. "Hypercars: The Next Industrial Revolution," 1996 IEV Symposium. Osaka, Japan, 1996.

Metz, Bert; Davidson, Ogunlade; Swart, Rob and Pan, Jiahua eds. Climate Change 2001: Mitigation: Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge UK: Cambridge University Press, 2001.

Romer, Robert H. Energy: An Introduction to Physics. San Francisco, CA: W.H. Freeman and Company, 1976.

Roukes, Michael L. "Plenty of Room, Indeed," Scientific American. September 2001, 48-57.

Schmidt-Bleek, Friedrich. "The Factor 10/MIPS-Concept: Bridging Ecological, Economic, and Social Dimensions with Sustainability Indicators," United Nations University, 1999.

Smil, Vaclav. Energies: An Illustrated Guide to the Biosphere and Civilization. Cambridge, MA: MIT Press, 1999.

U.S. Department of Energy. "Examples of Recent DOE S&T Achievements: Carbon Nanotube Technology," 2003.

VonWeizsacker, Ernst; Lovins, Amory B. and Lovins, L. Hunter. Factor Four: Doubling Wealth -- Halving Resource Use. London, England: Earthscan Publications, Ltd., 1997.