Climate Change: Economic Growth

And Sustainable Development Through Advanced Technology

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Background

The industrial revolution was driven in large part by technology allowing us to replace biological energy sources (humans, horses, wood fires) with fossil fuels. Figure 1 reveals much of this history. Until the middle of the 19^{th} century, the energy sources of the world would have been easily recognizable by Ramses the first. Almost all power had a biological basis, railroads were new and few had traveled faster than a horse, or made light or heat without setting fire to wood or a plant or animal oil. Coal energy didn't exceed biomass energy until the turn of the century. The real explosion, however, came after the second world war when rising middle class incomes led to explosive growth in personal transportation and homes with modern heating and appliances.

But the exponential growth shown in Figure 1 is plainly not sustainable. The problem is not that the world is running out of fossil fuels. We're reasonably certain that fossil resources are at least a thousand times larger than current annual world energy consumption. The problem is that we are running out of easily accessible, and inexpensive fossil resources and fossil fuels that can be burned cleanly. Most of the world's proven fossil resources are coal. An even more pressing problem, however, is that the consumption of fossil fuels releases CO2 and other greenhouse gases that could create dramatic, and dangerous, changes in the world's climate. The most recent report of the Intergovernmental Panel on Climate Change, endorsed by many of the world's scientific societies – and most recently by the US National Academy of Sciences – concludes that world temperatures might increase 1.4 to 5.8^{o}C (Celsius) triggering sea level rises and creating a non-negligible risk of catastrophic changes – such as affecting major ocean circulation systems such as the gulf stream.

While emissions even at today's levels are dangerous, it is highly likely that emissions will increase dramatically, rather than decline, during the coming decades. During the 21^{st} century, world population will approximately double, the US economy will continue to grow, and other nations will aspire to approach US living standards (see Figure 2). World economic output could be five or ten times larger by the end of the century (see Figure 3)

The challenge of reversing the forces driving rapid growth in energy use and greenhouse gas production is plainly enormous. Innovations will be needed in at least four areas:

Increasing the productivity with which we use energy and materials

Finding ways to produce fuels and electricity with little or no pollution (including production of the carbon dioxide and other "greenhouse gases" that lead to climate change)

Sequestering greenhouse gases in ways that prevent them from reaching the atmosphere, and

Managing the impact of the environmental changes that are already inevitable.

Table 1 gives some perspective on the problem. In prehistoric times, humans managed to eke out a living under their own power – about 0.1kw. Domesticating a horse got you up to about 0.75 KW (at least while the horse was working). Today the average citizen of the world uses an average of about 2 kw – 20 times prehistoric levels, and the average US citizen uses 11.5kw. If world population doubles, keeping energy use at today's levels will require cutting the average consumption rate per person in half – to about 1KW – of slightly more than one horsepower.

Clearly the problem is made much easier if a significant fraction of energy comes from sources that don't produce greenhouse gases. Again, its simple arithmetic to show that if half the world's energy comes from sources that don't produce greenhouse gases (such as renewable energy or coal if the CO2 can be sequestered), we could hold world energy levels constant if average consumption were 2KW – today's average.

Achieving a five-fold increase in economic output per unit of greenhouse gas produced seems like an insurmountable goal. But on closer examination, these increases in productivity are clearly possible. The remainder of this paper will demonstrate that we are not close to the theoretical limits of efficiency in any critical area of energy consumption. And structural changes in the economy can lead to major system-wide gains in efficiency.

Indeed with few exceptions the kinds of innovations needed to increase the productivity of energy and material use are identical to innovations needed to maintain productivity growth – and with it continued growth in incomes. Advances in information technology, biotechnology, nano-technology, advanced materials, and many other areas have the effect of increasing multifactor productivity and lead to simultaneous gains in output for each unit of capital, labor, energy and materials consumed. Moreover, the kinds of market-based policies best suited to achieve spectacular increases in energy productivity are precisely those needed to stimulate invention, innovation, and investment. Environmental policy should therefore be seen as fine-tuning of sensible economic policy – not something inimical to growth. It is, of course, essential to look carefully for places where policies targeted on economic growth may not provide adequate incentives for innovations key to improving the environment. Since environmental benefits can not be captured as income by investors, businesses are likely to under invest in areas of research that can achieve large reductions in emissions at low-cost. This is particularly true for technologies specifically designed to reduce emissions – such as methods of sequestering CO_2 produced by electric generation – but it can be true in other areas as well. There will continue to be a major role for wise public management that embraces both economic and environmental goals.

The New Production Function:

The relationship between value added to the economy and the amounts of energy and materials consumed will change dramatically during the coming decades for four major reasons:
increased productivity of the products (e.g. vehicles and appliances)

structural changes in the economy (e.g. a shifts to information-intensive businesses and away from smokestack industry, shifts to new urban forms). This must include system-wide productivity changes in the production networks that bring products and services to final customers

increased productivity of production facilities (e.g. minimizing waste and ensuring optimum performance of manufacturing plants), and

Structural change in production networks include such things as:

Increasing the efficiency with which manufacturing is linked to distribution and retail systems – decreasing inventory loses and unnecessary warehousing and transportation.

Increasing the efficiency of energy generation and dispatch in ways that minimize the cost of providing customers with services (buildings with onsite electric generation and appliances managed to optimize the performance of a regional electric grid).

Improving the dispatch of vehicles to minimize shipment costs and improving urban designs

Many of these innovations are made possible by the spectacular advances being made in computers, communication, and other information technologies. While it will take time to realize their full potential, it is clear that these technologies can achieve productivity gains at may different levels including:

Intelligent product design of products: advanced design techniques ensure efficient cars, TVs, computers, production machinery
Intelligent production processes: computer-assisted design of manufacturing facilities minimize waste (energy and materials), inventories, discards and defects
Intelligent product operation: advanced sensors and controls to ensure that services are delivered efficiently and only where and when they are needed.

The impact of technical change on US energy use can is already easy to see. Figure 4 shows the continuous decline in energy use per unit of economic activity that has occurred since the 1950s. Figure 3 shows that if no productivity gains had been achieved since 1973, US energy use would be nearly 60% higher than it is today. Efficiency improvements were particularly sharp when energy prices surged in the 1970s but efficiency continued to improve even when prices fell dramatically. The productivity gains in the past few years have been particularly large – and are difficult to explain by price effects. What we appear to be seeing is improving energy efficiency driven largely by the impact of productivity innovations developed for reasons largely unrelated to energy costs.

A Brief Inventory of Opportunities

I'll test these principles by exploring the opportunities in all major sectors of the US economy. Figure 5 reviews the origins of the largest of the greenhouse gases -- CO2. About a third comes from industry, buildings, and transportation. Nearly 44% comes from petroleum.

Transportation

One of the first things that people worldwide do with increased income is to purchase transportation – particularly the freedom and independence provided by personal vehicles (figure 6). The US suffers a particularly grievous problem because we drive more and are shifting to heavier, and less efficient vehicles (figure 7)

There are, however, many opportunities to achieve dramatic improvements in the efficiency of individual cars and trucks, and system-wide efficiencies gained from better dispatch of vehicles and other measures (figure 8)

Vehicle technology

Gains in vehicle fuel economy of cars and trucks are critical. Improving the average fuel economy by only one mile per gallon would 6 billion gallons of gasoline, 9 billion in consumer fuel expenditures, and reduce the US import bill by $3.6 billion.

While progress continues to be made in the efficiency of automobiles and trucks we are far from the theoretical limits. But few of the innovations actually appear as improvements in fuel economy. Low real fuel prices (Figure 4) have not given automakers an incentive to focus on efficiency and they have instead used technical innovations to increase power, vehicle size, and other aspects of performance while staying within mandated energy efficiency standards (27.5 miles per gallon for passenger cars).

This means that opportunities for improving fuel economy remain very large. Only about 15% of the energy in the gasoline actually reaches the wheels. Engines only convert about a third of gasoline's energy to power in the drive shaft. Energy is lost in idling when the car is stopped, in inefficient transmissions, and other sources.

A variety of advanced technologies are available that can lead to efficiency improvements of factors of 3 or more. Fuel cells have or ultra-clean diesel engines have potential to convert a much higher fraction of fuel energy into power at the wheels. There are also many ways to reduce the energy needed at the wheels. About a third of the power is used to push the car through the air – losses that can be reduced through clever aerodynamic designs. About a third is lost to rolling resistance – something that can be addressed through improved tires. And about a third is used to start or accelerate the vehicle; hybrid electric vehicles can recapture some of the energy otherwise lost in breaking and store it for use in restarting the vehicles. Efficiencies can also be gained by using lightweight, strong materials and by using smart control systems to continuously optimize performance – including turning the car engine off when it's not needed – cars typically spend 60% of their time stopped or decelerating.

General Motors, working through the government-industry research partnership PNGV demonstrated a full sized passenger sedan capable of achieving 80mpg (fully three times the efficiency of a comparable conventional vehicle). These technologies are being actively considered by automakers worldwide Toyota and Honda have had hybrid vehicles in sales rooms for a year. Impressive gains in efficiency have been achieved even in these early designs. US automakers have announced their intention to have hybrids on the market in 2003.

Improvements in truck efficiency are also essential for making serious gains in the efficiency of highway transportation. Fortunately, most of the technologies capable of efficiency gains in automobiles can also be used to improve the performance of trucks. The US auto industry may, in fact, introduce hybrid vehicle technology initially in a light truck or SUV.

Air travel is growing at 6 percent a year since leading to rapidly increasing demands for jet fuel. Fortunately improved engine and airframe design, new materials, and a variety of technologies can lead to major gains in passenger miles per gallon for individual aircraft. Improvements in air traffic control and airport management can lead to further savings.

System-Level Improvements

Urban design

Some of the most dramatic opportunities for system-level improvements come from the sharp increase in urbanization worldwide (Figure 9). With creative design approaches it is clearly possible to design urban areas that permit high levels of mobility, and unrestricted access to employment, housing, and recreational activities, without exclusive dependence on automobile or other personal vehicle transportation

The alternatives are ugly. American suburban living and sprawling business districts mean that Americans spend have driven enormous amounts of driving – an average of nearly an hour and a half per day. We may well, however, be approaching the limits of our tolerance for increased driving as the direct and indirect costs of unrestricted sprawl become increasingly apparent. Congestion is the most obvious problem since the number of cars operating on the highway system has increased much faster than the miles of highway available for them to drive on. Americans spend two billion hours stuck in traffic every year at a cost of $40 billion in lost productivity.

Many parts of the American experience are simply not accessible without cars –greatly limiting choice for the large number of Americans who must live without driving.

3 percent of all American households do not own an automobile.

5%of population blind or visually handicapped, 7.4 percent are deaf or hearing impaired, 3.2 percent have some form of lower extremity impairment

40% of persons aged 65 to 74 have some activity limitation, 63.2% of individuals over the age of 74.

New patterns of urban development are already reacting to the growing number of elderly people who would like to minimize their dependence on cars. Developments embodying "new urbanism" design strategies– higher-density, walkable communities -- are enjoying vigorous markets in several parts of the country. These communities provide high levels of access to amenities at vastly reduced rates of energy consumption in transportation – and sharply lower greenhouse emissions.

System-Level Improvements

System-wide improvements in transportation can also be achieved using modern information technologies. Freight companies, for example, are using sophisticated computer models to ensure that trucks travel with full loads for the highest possible fraction of their time. Onboard computers can alert drivers to needed changes in schedules, and even tell them how to avoid delays due to traffic congestion, construction, or poor weather. Intelligent highways can provide updated information about traffic conditions to all drivers, operate traffic signals to minimize congestion, and ensure rapid and accurate response to highway emergencies (ensuring the fastest possible removal of the problem and the best chance of saving lives).

There is no current equivalent of improved dispatching for moving people, but there may well be opportunities. In spite of massive public investments, mass transit keeps losing market share in the US (with a very few exceptions). It would be possible, for example, to introduce a service where a person could use portable, wireless communication devices take bids for any desired trip from taxis, jitneys, and other vehicles. They could choose from a variety of prices and trip times, make an order, and send the new dispatching information to the driver. Any such system would, however, need an unprecedented level of cooperation between private operators, public regulators, and the employees involved.

Clean Fuels

While a variety of options are available for reducing the need for transportation fuels, there are also many options for producing fuels in ways that greatly reduce environmental emissions – including production of greenhouse gases. Liquid fuels can be from the large amounts of organic wastes can be obtained over from farming and forestry operations – world output of these waste products is roughly equal to the world's current consumption of natural gas. Converting this material to fuels isn't easy since most of it is cellulose (sugars held together with very strong bonds). But the biochemistry to break these bonds is available. The system results in no net CO_2 because the amount of CO_2 released when the fuel is used is exactly equal to the CO_2 captured by the plants used to make the fuel in the first place.

Another possibility is the production hydrogen. Hydrogen is an ideal fuel for fuel cells and can be produced from natural gas delivered to filling stations. The problem is that it could cost roughly twice as much as gasoline. But since fuel cell cars could get double or triple the efficiency of standard cars, the cost of driving a mile could actually go down. Hydrogen can also be produced from biological materials or by using electricity from wind or another renewable resource to split water – H_2O. These methods are technically feasible but more expensive.

Hydrogen made from coal would be far cheaper and the US has enough coal to produce hundreds of years of energy. It may be possible to use coal to produce hydrogen and CO_2 and instead of dumping CO_2 into the atmosphere where it can contribute to global warming, pump it into old gas fields or underground aquifers. Some fascinating recent studies suggest that not only is there room in such reservoirs to store the CO_2 produced for centuries, the cost of removing CO_2 would add less than 20%. *Buildings*

Buildings consume about a third of US energy and are responsible for nearly seventy percent of the nation's demand for electricity. Figure 10 shows a range of technologies that can lead to major increases in building energy efficiency. Opportunities for improving the productivity of both products and production systems are particularly large in the construction sector because it has not taken advantage of many the design and management techniques to cut costs while increasing quality that have been used for years in other manufacturing enterprises. It appears possible to cut building energy use by factors of two or more while actually reducing the overall costs of owning and operating buildings.

Building Equipment and Controls

Improvements in appliance technologies have led to dramatic improvements in the efficiency of refrigerators, air conditioners, and many other products since the first energy crisis in 1973 – thanks in no small part to skillful use of regulations. But we are nowhere near the theoretical limits of efficiency.

In a large number of cases improvements in equipment efficiency can lead to large multiplier effects. Take lighting for example Good design can ensure that daylight is used effectively and control artificial lights to maintain uniform lighting levels during the day. The lighting fixtures themselves can produce 3-4 times as much light for each unit of energy consumed using compact fluorescent fixtures and solid-state ballasts. Even greater advances are possible with solid-state lighting. But more efficient lighting also means that less heat is dumped into buildings meaning that chillers can be smaller and cooling energy demand lowered. Improved lighting systems should be able to reduce lighting energy by 59% in new construction and 43% in major retrofits.

The new computers and other information systems themselves can, of course, contribute to electric loads but their impact is comparatively small – about 2% of overall US electricity consumption.

System-Level Improvements

As in other areas, advanced control systems can ensure that building systems operate efficiently – matching lighting and comfort levels to individual tastes and lifestyles. These control systems can also be integrated with electric utility control systems in ways that ensure efficient operation of city-wide systems of electric production and consumption. Time of day meters, for example, allow building owners elect to postpone discretionary consumption until peak demands on the utility have passed. Sophisticated controls are likely to enter the market quickly since advanced communication systems will be installed for other reasons – entertainment, business communication, home medical monitoring, security systems, and other purposes.

Some of the most dramatic gains come simply from applying the kinds of modern, integrated design methods to buildings that have been used in manufacturing for many years. Clearly these methods must be modified to fit the unique circumstances of construction, but there are obvious opportunities. Good integrated designs can cut overall energy by 50-70%. New using computer-based analytic tools permit rapid analysis of the overall structural design (including wind resistance and resistance to seismic shocks), energy use, and overall system costs. Communication systems can speed designs by linking experts that may be located around the country.

Integrated design makes it possible to recognize the value of simple technologies that can lead to large savings. Light colored walls and roofs can make buildings much more comfortable – and much cheaper to air condition. Landscaping can also play a key role (see Figure 11). A large tree can create a cool microclimate providing shade and pumping as much as 40 gallons of water a day into the air, providing evaporative cooling.

The construction process itself can be made more efficient with design for manufacturability methods that minimize use of materials, cut waste on the design site, and ensure precision in components that minimize expensive, and error-prone, work in the field. Components can be constructed to permit fast, failure-resistant site assembly. The pieces should fit without hand-crafting in the field, and it should be easier to put the pieces together correctly than incorrectly. Communication systems can ensure tight links between assemblers and parts suppliers – allowing just in time delivery of precisely manufactured components (B2B) . Paperwork and regulatory delays can be minimized by using paperless communication with inspection and approval agencies (B2G). And advanced technologies – such as tamper-proof onsite video – may greatly reduce or eliminate the need for onsite inspection.

Low Emission Electricity

Innovations will make it possible to achieve large reductions in the energy used in buildings while improving the quality of interior space and cutting costs. But finding ways to generate electricity from low CO2 sources can further reduce greenhouse gas emissions associated with buildings). Hydrogen may provide an option for supplying the fuel needs of buildings.

At present, the least expensive methods for producing electricity is coal or natural gas (Figure 12) but wind power, power provided from biological wastes, and other renewable sources are closing the cost gap rapidly. Wind power in particular is beginning to match the price of new coal plants. Photovoltaic cells won't be fully competitive for several decades, but their ability to be installed in small modules close to where the energy is needed – such as on rooftops, parking lot-shades, and awnings – may make them a preferred source gives them an advantage in smaller applications.

Coal, once thought to be completely incompatible with any strategy for dealing with climate change, may provide a low-cost, low pollution source of electricity if methods can be found for separating CO2 and injecting it permanently into underground storage. One of the most attractive concepts would be to produce hydrogen using the methods just described to power advanced gas turbines. Early analysis suggests that this might only add 15% to the delivered cost of residential electricity.

Distributed power (using natural gas or hydrogen as a fuel) offers another promising dimension of change. Building smaller facilities, matched to the needs of individual buildings or communities, can greatly reduce the financial risks since investors do not need to make billion dollar investments where returns hinge critically on forecasts of future regional demand for electricity and other factors that are difficult to anticipate. Locating clean power generation close to the site where the power is needed also minimizes transmission and distribution costs, and can provide greater reliability if interconnected.

New technologies such as fuel cells and highly efficient gas turbines, offer the prospect of achieving large efficiency gains in comparatively small electric systems. These systems can provide both electricity and use the heat exhausted from power production to supply hot water and other heating needs of the buildng. Small systems avoid the capital risks associated with large utility systems, can be built quickly in response to demand, and reduce the costs and losses of transmission and distribution systems. In the long run, hydrogen may provide an attractive power source for such systems.

Nuclear power may also have a role but appears unlikely to be economically competitive – even if the industry manages to find a design that can overcome public concerns about safety, waste disposal, and the danger of nuclear proliferation. Nuclear generation will probably be limited to large, heavily protected generating stations. Research should continue but the hurdles to be overcome should not be minimized.

Industry

The final third of US energy goes to diverse manufacturing processes and again, the opportunities for huge reductions are significant (Figure 13). Advanced information systems play a key role both in optimizing product design and ensuring efficient operation of production systems.

It's apparent that information technologies and other innovations are reshaping modern economies in ways that are increasingly difficult to document. Figure 14 suggests, for example, that a large share of the large "multi-factor productivity gains" – gains in output not explainable by increasing purchases of labor, capital, energy or other factors -- achieved in the US during the past few years can't be explained by easily measurable investments in new equipment or labor composition. It's likely that the productivity gains were achieved primarily by businesses that have finally figured out how to actually put the new information technology to profitable use typically through deep restructuring of business operations. These "multi-factor productivity gains" translate directly into greater output per unit of energy consumed.

Design improvements and better materials can sharply reduce the materials needed in products (beer cans, for example, can be made with about a third less aluminum than they needed in 1972). New, tightly controlled production systems can ensure that materials aren't wasted. Embedded sensors and controls coupled to computers can ensure that large, complex refineries and other systems are continuously adjusted to maximize performance and safety. Efficient management of such simple things as pumps and fans can make an enormous difference (fluid flows, for example, are typically controlled by operating pumps at full speed and throttling flows with valves instead of changing the speed of the pump).

Enormous opportunities are presented by new methods for mimicking biological production processes. Plants can produce thousands of proteins and other materials from its genetic database, and do so quickly, quietly, and with no pollution. We're beginning to dimly understand how some of this is done and imitate these extraordinary capabilities. While there's controversy about releasing genetically modified materials into the wild, safe manufacturing systems methods based on genetically engineered organisms are already being used to produce valuable products such as pharmaceuticals. And biological materials can be used as the raw materials for plastics, fibers and other materials instead of oil or other fossil fuels. Dupont recently announced their intention of deriving 25% of their revenues from renewable materials. to replace 15% of the fossil fuels they use to make chemicals with biological materials in the next decade.

We have, of course, not mastered the art of self-assembly. Plants of course had the benefit of three billion years of experimentation. Living things can build complex structures – such as stems and flowers– on demand. It may some day be possible to mimic this process and have sophisticated, distributed production systems that permit complex assembly from local materials – only the design information would be moved to the site.

Probably the factor leading to the greatest reduction in energy use per unit of output in industry results from a structural shift from highly material intensive industries such as steel to firms such as integrated circuit manufacturers – that add large amounts of value to small amounts of material. Industry's whose primary product is invention, persuasion, or information produce orders of magnitude more value per unit of resources consumed than traditional businesses.

Policy Challenges

Capturing the kinds of innovation just described depends primarily on managing the economy in a way that ensures the best possible environment for invention and investment made to translate inventions quickly into viable businesses. This is necessary, but is unlikely to be sufficient. Many innovations that could lead to rapid growth in energy productivity and reduction in CO2 emissions will not enjoy adequate private research investment.

The cost of energy does not reflect the environmental costs associated with its use. This will lead to an under investment in research unless energy taxes or other methods force the market to reflect the full cost of energy use.

In many cases the difference in life-cycle costs between a highly efficient-low greenhouse technology and a competing conventional technology will be very small. Investors will be tempted to avoid risk and choose the familiar path.

This tendency is reinforced by the cost of acquiring information needed to make an intelligent decision about an energy related investment. Many firms feel that: "Energy is not my core business" and fail to make the needed investment in analysis even when it would lead to significant returns

Industries responsible for a large fraction of US energy use are often older businesses and some (like the construction industry) do not face the pressures of international completion. Research is not a part of the core culture in many of these industries.

Many of the most dramatic innovations require long-term investments in high-risk technologies with uncertain returns. Public returns to research often far outstrip private returns leading to an under investment in research from private sources (and a strong rationale for public research investment)

A policy built to address these opportunities would include:

A fiscal policy encouraging private investment in research and new plant and equipment based on advanced technologies. This means sound fiscal policy and ensuring that federal deficits don't explode.

A Research and Development policy that provides public support for research where public interests in the outcome outstrip likely private returns. This mans careful balance between basic and applied research and skillful use of research partnerships involving businesses, universities, and government research facilities

A regulatory program that emphasizes competition and performance rather than prescription. This means providing incentives to introduce innovations that achieve environmental goals at the lowest possible price. Finding ways to force markets to consider pollutants (including greenhouse gases) leave the greatest freedom to markets. Taxes or tradeable permits may offer the best solution, but they may not always be politically possible. Carefully crafted performance-based regulation may offer the only practical solutions

Conclusion

There appear to be no technical barriers to achieving factors of 3-5 reductions in the amount of greenhouse gas produced by each dollar of economic activity in the US. The direction of corporate investment in new productivity-enhancing techniques will achieve large savings for reasons unrelated to energy or the environment. But many opportunities for dramatic reductions in emissions will be exploited very slowly because of weak incentives to invest in research that will benefit the public at large – but not necessarily the groups investing in the research. This will require skillfully managed government policy aimed at encouraging inventions that can lead both to rapid gains in US productivity and rapid growth in energy productivity.