End-Use Energy Technologies

A CORE ELEMENT OF A GLOBAL ENERGY TECHNOLOGY STRATEGY TO ADDRESS CLIMATE CHANGE

A TECHNOLOGY REPORT FROM THE SECOND PHASE OF THE GLOBAL ENERGY TECHNOLOGY STRATEGY PROGRAM

GTSP

Global Energy Technology Strategy Program

End-Use Energy Technologies

A CORE ELEMENT OF A GLOBAL ENERGY TECHNOLOGY STRATEGY TO ADDRESS CLIMATE CHANGE

PHASE 2 FINDINGS FROM AN INTERNATIONAL PUBLIC-PRIVATE SPONSORED RESEARCH PROGRAM

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May 2007

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TO THE READER

This report reflects research conducted as part of the Global Energy Technology Strategy Program (GTSP) at the Joint Global Change Research Institute and in collaboration with partner research institutions around the world. The first phase of the GTSP began at a time when the importance of a technology strategy in addressing climate change was unappreciated. GTSP Phase 1 made the case that a technology strategy was an important part of a larger strategy to address climate change and needed to be included along with the other major components: climate science research, adaptation to climate change, and emissions mitigation.

The second phase of the GTSP recognized that to craft a global energy technology strategy it was important to develop a deeper understanding of potentially important technologies and technology systems, and to embed that knowledge in the context of the larger global energy and economic systems. In Phase 2 we identified six energy technologies and technology systems with the potential to play a major role in a climate-constrained world: CO_2 capture and storage, biotechnology, hydrogen systems, nuclear energy, other renewable energy, and end-use technologies that might be deployed in buildings, industry and transportation. Knowledge gained in each area has been integrated into a larger global energy-economy-climate frame. That combination of depth of study and integrated assessment produced a unique strategic perspective and a bounty of fresh insights. In this document, we have distilled and summarized some of the most salient.

The past nine years have flown by and, looking back from the present, it is amazing to see how far we have come. The GTSP has accomplished much, but much work remains. As we enter Phase 3, we will build on the knowledge gained thus far. We will continue to deepen our understanding of technology and we will continue to integrate that understanding into a larger energy and economic context. And, we will add a new dimension to our work to provide a deeper understanding of the *regional* and *institutional* contexts in which technology is developed and deployed.

Our research has been supported by numerous firms, nongovernmental organizations, and government agencies. Their support has enabled us to continue to explore the implications of designing and implementing a technology strategy. Moreover, we have received the help of many peer reviewers, who throughout the process of developing this document provided their expertise and advice. And for that support we are grateful. Of course, the views and opinions of the authors expressed herein do not necessarily state or reflect those of the sponsoring, participating institutions, or reviewers and any errors that remain are our own.

Jae Edmonds
May 2007

End-Use Energy Technologies

The focus of this chapter is on services for businesses and individuals that require energy. Energy services, also called energy end-uses, include demands such as cooling, heating, and lighting homes; transporting people and freight; and heating and powering a range of industrial processes. The set of energy services across the economy and the set of end-use technologies that provide them are extremely diverse.

Efficiency gains in end-use technologies reduce the demand for energy to provide the specific energy service, e.g., lighting; allow the use of carbon-free energy sources; and reduce the losses of energy in the process of converting primary fuels to electricity and delivered fuels. More efficient end-use technologies also help to conserve natural resources, reduce the impact of energy production on the environment (air quality, other pollution), and enhance energy security.

The importance of increased electrification in response to a CO_2 stabilization policy is one of the key findings of our research on end-use energy. The development of improved, more cost-effective, end-use energy technologies that use electricity can reduce emissions through both efficiency improvements and the use of electricity from low-carbon emission sources.

The opportunities for improving and deploying end-use technologies vary substantially across the portfolio of end-uses in the buildings, transportation, and industrial sectors.

Buildings Sector

- Make substantial efficiency gains in specific end-uses such as solid state lighting and heat-pump-based technologies for space conditioning, but also through integrated building design.

- Develop smart appliances that could also help stabilize the grid, increasing reliability and perhaps facilitating the deployment of non-dispatchable renewable energy.

Transportation Sector

- Realize the substantial potential for efficiency gains in light-duty vehicles, with further opportunities for shifting to low-emission technologies such as electricity, hydrogen, and biofuels. The deployment of hydrogen will depend substantially on the development of fuel cell, and hydrogen storage and distribution technologies.

- Improve battery technologies to benefit all electric-based vehicles, whether fuel-cell, hybrid, or plug-in hybrid.

Industrial Sector

- Re-engineer industrial processes to require less energy services, such as the use of membrane technologies for chemical separation processes that would use much less heat and steam.

- Explore burning commercial biomass as a non-fossil option where processes still require high temperatures for steam or heat. For some applications, the economic response may be to continue using fossil fuels even while paying an emissions penalty.

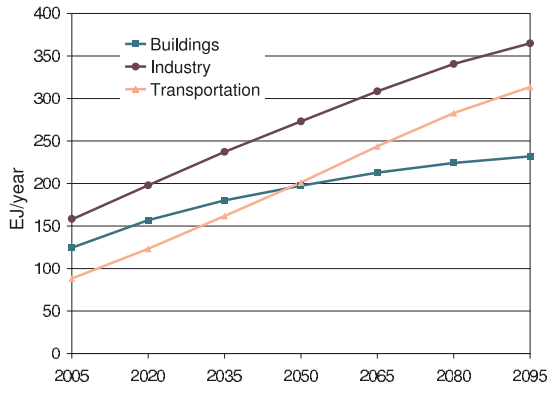
A GLOBAL PERSPECTIVE ON END-USE ENERGY DEMANDS

End-use energy consumption patterns in the future will be governed by several interacting forces, including increasing prosperity, particularly in the developing countries; changes in urban land-use patterns; greater ease of long-distance travel; the spread of emerging end-uses, such as computing and information technologies; and the development of new and improved end-use technologies.

In GTSP, we performed detailed modeling and analysis of end-use energy demand in the United States. We used the insights gained from the detailed U.S. analysis to inform our modeling of end-use demand for the rest of the world, taking into account regional-specific determinants, such as socioeconomics, population density, technology, and regional climate. Figure 1 shows a future scenario of energy end-use demands that we have constructed for the GTSP considering these interacting forces.

In this scenario, demand for energy increases substantially in the transport and industrial sectors. In the buildings sector, end-use demand growth is relatively lower, but still significant. Most end-uses in buildings are now met by electricity, natural gas, and fuel oil. However, most of the buildings end-use services could be served by electricity. The end-use services in the industrial sector are more diverse, and the potential to switch away from fossil fuels to electricity may be more limited.

These aggregate characteristics demonstrate the potential scale of the challenge that climate change provides. Fuel mixes may shift over time, providing very different opportunities for climate change mitigation across sectors. The relative importance of the sectors is itself not static. However, within each sector are a multitude of different energy end-use services, each of which may evolve in very different ways over time and across regions and have very different challenges and opportunities for improved technology and climate change mitigation.



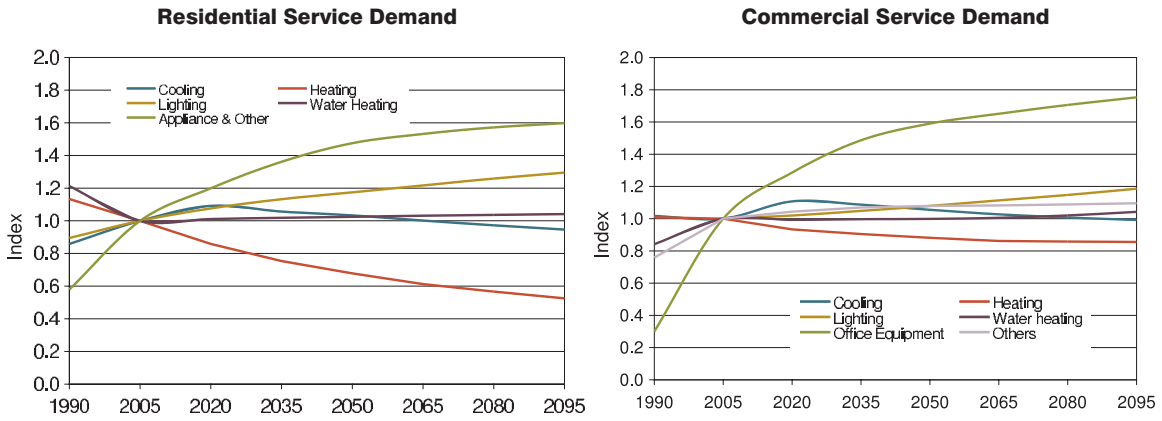
▲ **Figure 1.** GTSP scenario of global energy end-use demand growth by end-use sector. Transportation and industry see the largest growth in energy use.

BUILDING ENERGY SERVICES AND END-USE ENERGY TECHNOLOGIES

The buildings sector includes a diverse set of buildings types, from detached family homes to condominiums and apartments, as well as commercial buildings such as shopping malls, high-rise offices, and refrigerated warehouses (Figure 2). Although end-uses differ among these types and purposes of buildings, several are common across building types and can explain most building energy use. These end-uses include space heating, space cooling, water heating, and lighting. Beyond this set are a range of additional end-uses, such as appliances and information technologies, which we have aggregated together in a category called "other."

In the United States and elsewhere, the mix of end-uses has evolved over time and will continue to do so throughout the century. Figure 3 shows a future scenario of building service demands, indexed to the demand in 2005 (i.e., the value in 2005 is set to 1). The demand for "other" technologies, which includes appliances and information technologies such as computers, has increased substantially over the past 15 years, and will probably continue to do so over the coming decades. Most of the technologies for meeting these service demands use electricity, which will help to continue the trend of electrification in the buildings sector.

▲ **Figure 2.** Demand for energy services in commercial buildings will grow over the century as incomes rise across the globe.



▲ **Figure 3.** A future scenario of U.S. building service demands by end-use (indexed to 1 in 2005). Demands for energy for appliances and other electronic equipment are the biggest source of growth.

Information technology, appliances, and other end-uses generate heat within buildings as an unintended byproduct of their use; this reduces the need and demand for space heating but increases the need and demand for space cooling. Fifty years ago, space cooling did not constitute a meaningful demand for energy. With improving technologies and people moving to traditionally hotter climates, space cooling is now one of the major building end-uses in the United States. In the future, the demand for space cooling will surely expand dramatically in developing countries such as India that have the need, but not yet the resources to meet the need.

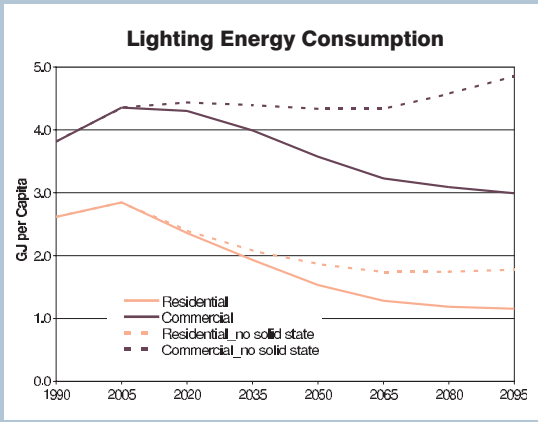
End-use efficiency gains present a substantial opportunity to reduce the CO_2 emissions that result from service demands in the buildings sector. Space heating may rely more heavily on highly efficient heat pump technologies rather than furnaces and electric resistance heating. Space cooling will continue to be based on existing technologies, but there are opportunities to improve the efficiency of current cooling equipment.

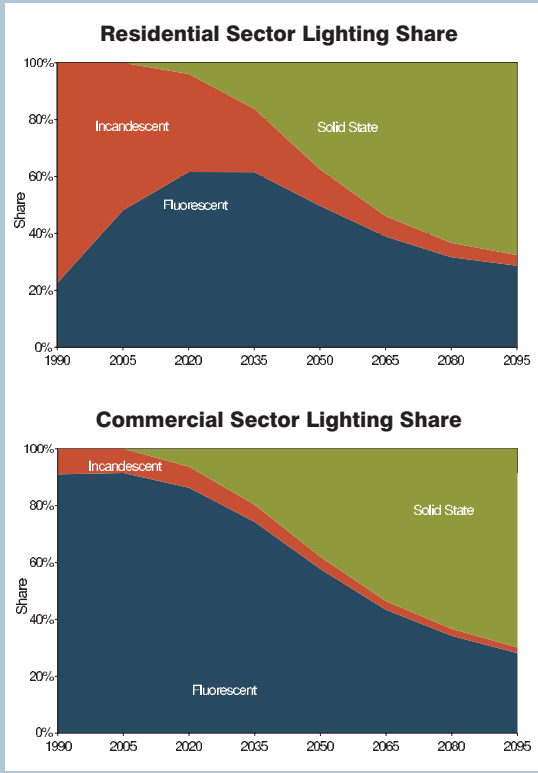
Better insulation and windows can be used to improve building shell performance, which will reduce the needs for heating and cooling. Solid state lighting could substantially reduce the energy requirements for lighting (see Box 1). Controls can better utilize heating, cooling, lighting, and other technologies so that they provide services only where and when they are needed.

Many end-uses are already primarily supplied by electricity, including space cooling, lighting, and the rapidly growing end-uses of information technology and appliances. The primary opportunity for additional electrification is in heating, where electric heat pump technologies could both increase efficiency and allow for a shift from fuels such as natural gas and fuel oil, as well as the substantial quantities of biomass used in developing countries.

As future energy costs rise, many opportunities for increased efficiency may be undertaken irrespective of climate concerns. The role of building energy technologies in mitigating climate change will be to further reduce the energy required to provide building services in an expanding global economy and to further push the trends toward electrification.

Box 1. Solid state lighting could result in dramatic gains in lighting efficiency. Today, lighting is predominantly provided by fluorescent lights and incandescent lights. Fluorescents provide the majority of lumens in the commercial sector; incandescents provide the majority in the residential sector. The increased market share of fluorescent lights in the future will reduce lighting energy use.The introduction of solid state lighting could lead to large-scale deployment and associated additional energy demand reductions in both sectors.



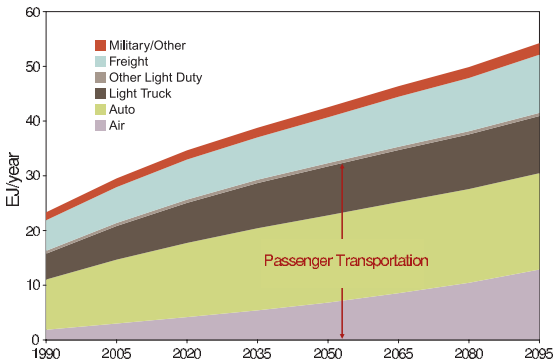


TRANSPORTATION ENERGY SERVICES AND END-USE TECHNOLOGIES

Transportation energy services are used to move people (passenger transportation) and products (freight). Although freight constitutes an important demand for transportation energy, passenger transportation is today the dominant consumer of transportation energy (Figure 4). The most important modes of passenger transportation are light-duty vehicles in ground transportation and airplanes for air travel. Light-duty vehicles—that is, automobiles and light trucks—are the largest source of energy use in the transport sector in today's industrialized nations and are the fastest growing segment in developing nations. The second-largest source of transportation energy use is heavy-duty trucks providing freight services, followed by airplanes for both freight and passenger services. In the United States, energy use by light-duty vehicles, freight trucks, and airplanes contributes to 59, 17, and 10 percent, respectively, of total transportation energy use. Modes such as buses and trains make up a much smaller component of transportation energy consumption.

▲ **Figure 4.** Automobiles and light trucks for passenger travel, and heavy-duty trucks for freight consume the vast majority of energy in today's transportation sector.

The distribution of modes varies today across different regions, and it will evolve as well in the future as a function of a variety of interacting forces. As people become more affluent, their time becomes increasingly valuable and they increasingly value faster modes of transportation. Increasing global prosperity, accompanied by the expansion of the air travel infrastructure more generally will lead to a rapid expansion of air travel and associated energy consumption over the coming century. Air travel in the United States could replace freight trucks as the second-ranked source of fuel consumption before the middle of the century (see Figure 5).



▲ **Figure 5.** A future scenario of U.S. transportation energy demand growth by end-use category. Air travel and freight are expected to grow as incomes rise.

Globally, the biggest driver of increasing transportation energy consumption will be the developing countries. If countries like China and India emerge as projected, then transportation demand will dramatically increase as these countries take on the transportation characteristics of developed economies.

Despite the diversity of end-uses, liquid fuels such as gasoline are far and away the dominant source of energy for transportation applications because they are so portable. For this reason, without efforts to constrain carbon, the transportation sector will probably remain largely dependent on liquid fossil fuels. Advances in hydrogen production, batteries, and fuel cells could change this. In addition, liquid biofuels can be directly substituted for liquid fossil fuels.

Despite the diversity of end-uses, liquid fuels such as gasoline are far and away the dominant source of energy for transportation applications because they are so portable.

Vehicle Technologies. A wide range of technologies may be available to improve efficiency in the transportation sector as well as to allow for substitution either to bio-derived liquid fuels or to energy carriers such as electricity or hydrogen. Ethanol or natural gas can be used in existing vehicle technologies with minimal modification, thus achieving lower emissions at little cost. Options available or in development include advanced diesel, alternative fuel, hybrid and plug-in hybrid, electric, and fuel-cell vehicles. Opportunities are also available in air travel and freight, but these may be more limited.

Diesel engines provide an opportunity for efficiency gains in liquid fuel use. The drawback of traditional diesel engines is that they produce more pollutant emissions than gasoline engines, including particulate matter, nitrogen oxides, hydrocarbons, and sulfur. Advances in diesel technology have produced new diesel engine vehicles with emissions and performance characteristics similar to gasoline engine vehicles but with significantly higher fuel economies. "Clean" diesel vehicles are expected to gain market share in the United States and globally.

Hybrid vehicles that combine an electric motor and related system with a combustion engine have fuel economies that are two and half times greater than a comparable gasoline engine vehicle. Hybrids are rapidly gaining market share.

Plug-in hybrid vehicles are a variation on the hybrid vehicle concept that further improves vehicle fuel economy. Larger battery packs that can be recharged through an electrical outlet are incorporated into the hybrid vehicle so it can be utilized for local travel in an all-electric mode. The extended range in an all-electric mode combined with a combustion engine burning gasoline, diesel, ethanol, or other fuel has the potential for even higher fuel economy and lower greenhouse gas emissions than the hybrid vehicle. The plug-in hybrid technology is just emerging; multiple technical and economic issues remain to be resolved, but demonstration vehicles have shown fuel economy as high as 100 miles per gallon. Even accounting for greenhouse gas emissions from central station electricity, the overall improvement to the total systems efficiency of the plug-in hybrid vehicle could result in further reductions in total greenhouse gas emissions.

Fuel-cell vehicles represent yet another future transportation technology option and possibly one with the potential for the highest fuel economy and lowest greenhouse gas emissions, although these are substantial technical hurdles. See the report, *Hydrogen Systems* for a further discussion.

The Importance of Batteries. Common to hybrid, plug-in hybrid, and fuel-cell vehicles is their use of electricity for motive power. Therefore, the development of more effective storage and control of electricity and related systems is crucial to their success.

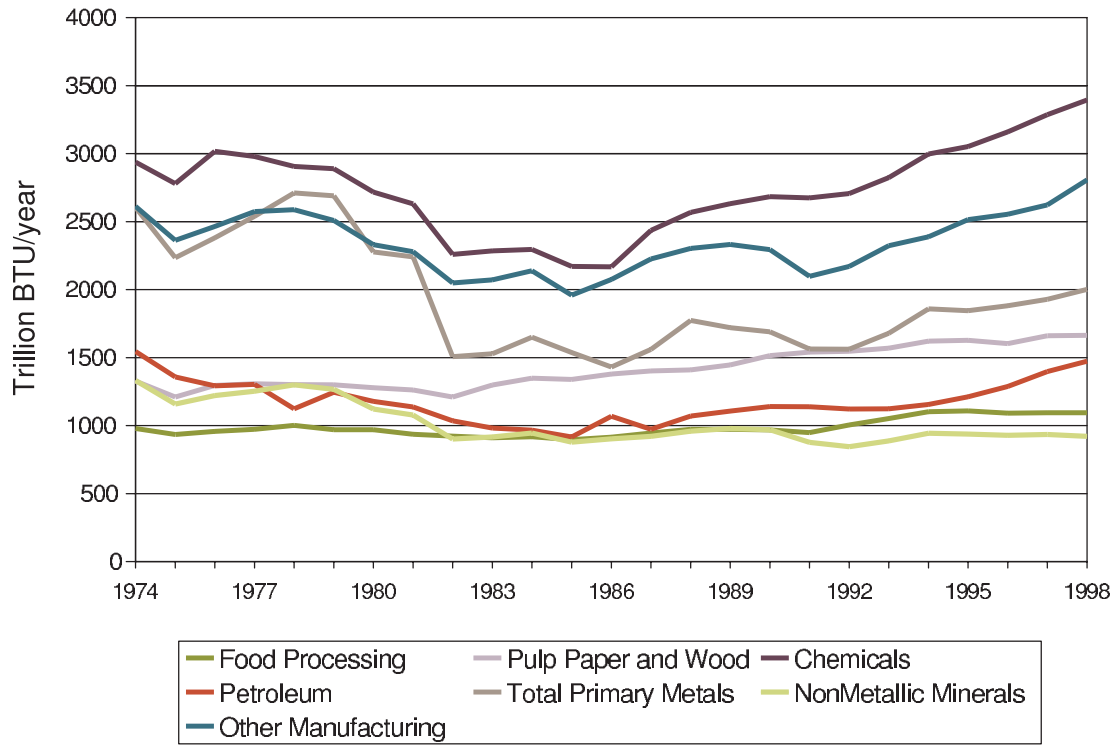
Although they have to improve further to become commercially viable, new batteries are emerging with improved performance and lower costs. New lithium ion batteries that have more power; can recharge faster; and are lighter, more reliable, safer, and cheaper are being introduced to the marketplace. Further battery developments would enable the increasing electrification of the transportation sector, with potentially wide-reaching impact on the electricity market and society as a whole.

INDUSTRIAL ENERGY SERVICES AND END-USE TECHNOLOGIES

The industrial sector spans an enormous and heterogeneous range of individual industries. Energy consumed to produce goods ranging from food products, furniture, petroleum, automobiles, and computers is all considered industrial sector energy consumption. In the United States, total industrial energy consumption has not grown relative to what it was 30 years ago. However, as Figure 6 shows, consumption has grown steadily over the past decade in key energy-intensive industries such as chemicals and petroleum refining.

Heavy industry has been shifting its energy-intensive manufacturing from developed to rapidly developing regions of the world. A climate policy limited to developed nations could accelerate that trend, with implications for changing emissions profiles and policies. The international scope of climate policies is critical to controlling emissions from the industrial sector. Otherwise emissions can be shifted rather than reduced.

Despite the heterogeneity of the industrial sector, most of the demand for energy across all industries is driven by the demand for a small set of key, common energy services such as process heat, steam, machine drive, and chemical feedstocks. This commonality of energy services means that mitigation efforts can focus on a key subset of energy technologies.



▲ **Figure 6.** U.S. industrial energy consumption. Although total U.S. industrial energy consumption has not been growing, key energy-intensive industries such as chemicals have been growing steadily.

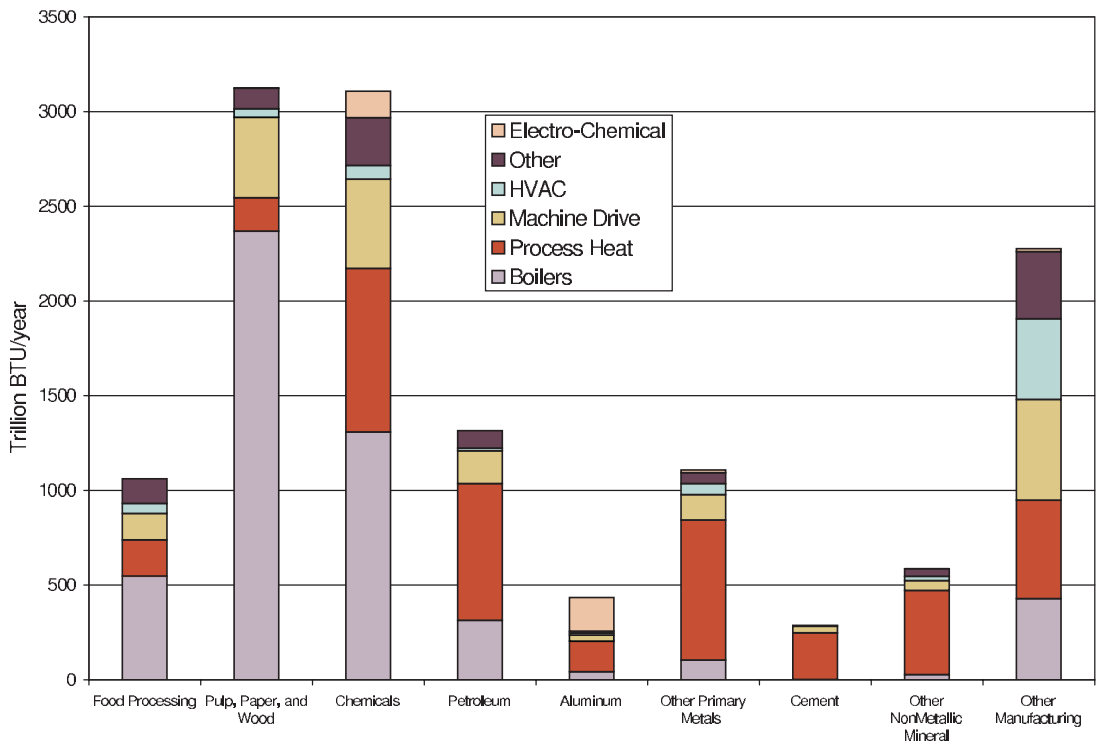
As shown in Figure 7, pulp and paper, chemicals, and food processing are major consumers of steam (from boilers). Several industries, including chemicals, petroleum, and metals, also require process heat (dry heat rather than steam).

Electricity provides most of the energy for electrochemical; machine drive; and heating, ventilation, and air conditioning (HVAC) services in industry. Process heat has been mainly generated by natural gas, because a clean-burning fuel is required for this service. Electricity can also be used to generate process heat in some applications, but it is limited by the cost.

In contrast, steam can be generated using a number of fuels, and the fuel mix for steam does vary across industry, based on availability of fuels (Figure 8). Currently, the pulp and paper industry relies on biomass, since it has access to waste products. Some coal and oil are also used, but many industries still rely on gas. Under a climate policy, emissions could be reduced by using commercial biomass to generate steam in more industries.

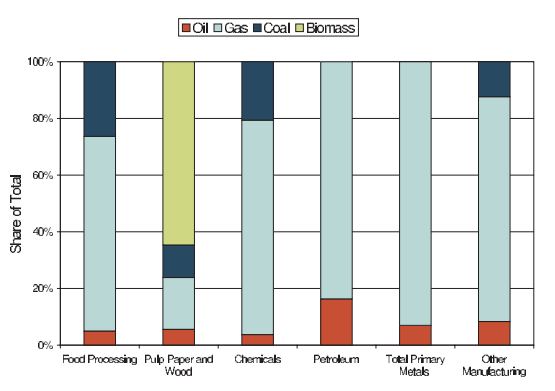
Many of the specific technologies that produce basic industrial energy services such as heat and machine drive are already highly efficient. For example, current efficiencies to produce steam or heat from burning natural gas exceed 80 percent, while the efficiencies of electric motors exceed 90 percent.

Because of the high energy efficiencies of the service technologies, future reductions in industrial energy intensity are more likely to come from redesigns and fundamental changes in the processes used to manufacture industrial products—for example, a re-design of a manufacturing system or an advance in materials so that less heat or steam is required to produce an item. The potential for process changes is more industry-specific than the more generic industrial energy services, although there are some promising new processes like membranes that would reduce the steam requirements for separation in industries such as chemicals and petroleum.



▲ **Figure 7.** U.S. manufacturing industrial energy consumption, by industry and energy service, 1998. The mix of energy end-use services required to manufacture products varies substantially.

Cogeneration of electricity along with steam and heat increases the net energy efficiency of the system; electricity is generated from steam and heat that would otherwise be wasted. This electricity could be used on-site or sold to the grid. Cogeneration would not reduce direct emissions and energy use in the industrial sector, but it could reduce economy-wide emissions by reducing the amount of fossil fuels used elsewhere in generating electricity. Cogeneration is best suited to large facilities with a steady demand for steam or heat.



▲ **Figure 8.** U.S. fuel consumption for steam by industry. Steam can be generated by various fuels, and different industries have used what is available and economic.

In a carbon-constrained world, however, CO_2 limits may eventually reach a point that cogeneration with fossil fuels is not economical, since it can not compete with electricity from non-fossil sources such as nuclear, wind, and solar. Cogeneration from commercial biomass may then become the choice.

Although electrification will be an important response to a climate policy, some industries may continue to require burning fuels when intense sources of heat or steam are needed. It may be possible, although expensive, to electrify some of these requirements. Burning commercial biomass to generate steam and gasifying biomass to create biogas for process heat may be the best non-fossil options. For some applications, the economic response may be to continue using fossil fuels even while paying a high emissions penalty.

In addition to emissions from burning of fossil fuels, some industries (such as cement, Figure 9) also have a substantial amount of direct CO_2 emissions as a by-product of their materials processes. Under an efficient carbon policy, potential mitigation of these emissions must also be considered, through means such as materials substitution or CO_2 capture.

▲ **Figure 9.** Cement production and emissions. In addition to the emissions from energy consumption, a cement factory has direct process emissions of CO_2 that result from its conversion of limestone. Mitigation of process emissions of CO_2 and other greenhouse gases must also be considered in an economically efficient policy.

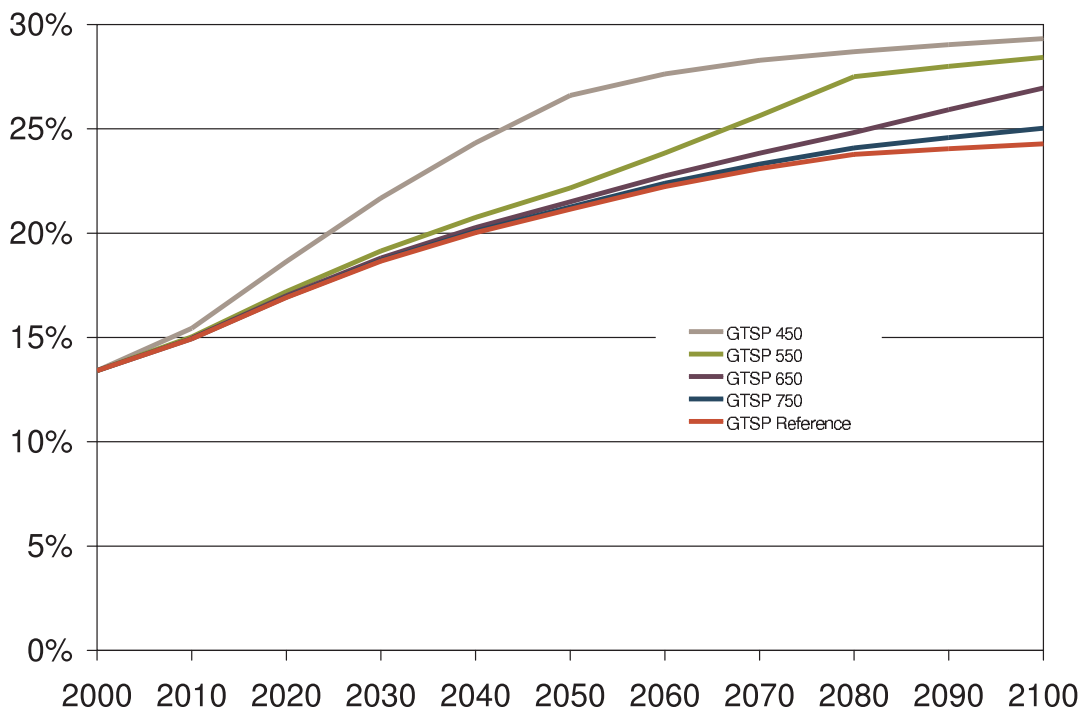
ACROSS ALL SECTORS: THE ROLE OF ELECTRIFICATION, EFFICIENCY GAINS, AND THE COSTS OF MITIGATION

A robust finding of our GTSP modeling analysis on end-use technologies is the importance of the ability to use electricity (or another carbon-free energy carrier) to provide energy services under a CO_2 emissions constraint. The more emissions have to be reduced, the more important this becomes (Figure 10). Put simply, at some point it becomes more costly and more difficult to reduce emissions further in some services by only increasing efficiency, and it becomes more economical to switch to a carbon-free source of energy to provide that service. Electricity generated by low-carbon resources and technologies fits that need and can provide services for several applications, although, as we have discussed, some more easily than others.

Electrification will be more of a challenge in transportation and certain industrial processes. There, the spread of low-carbon energy sources would require improvements in batteries for electrification or advances in other energy carriers and sources such as hydrogen technology and biofuels.

But the other aspect of end-use technology—increasing energy efficiency—remains vitally important. Energy efficiency has the potential to substantially reduce the economic burden of emissions mitigation. Improved end-use technologies provide benefits by lowering the demands for energy—benefits that accrue irrespective of climate concerns—and by decreasing the economic costs of stabilization by reducing the requirements for lower-carbon energy sources.

The potential economic benefits of end-use technologies are substantial. Increasing the rate of energy intensity improvement by only 0.25 percent annually could reduce the costs of stabilization by trillions of dollars over the course of this century (Figure 11).



▲ **Figure 10.** Electricity relative to total primary energy. GTSP analysis shows that electricity as a share of global energy use increases under tighter CO_2 emissions policies. Therefore, the ability of end-use technologies to use carbon-free energy sources such as electricity becomes critical to managing the cost of meeting tighter policy targets.

THE VALUE OF CONTINUED RESEARCH AND DEVELOPMENT

If the potential for end-use energy technologies to contribute to CO_2 emission reductions is to be realized, R&D should focus on the following:

Buildings Sector

- Optimize building shell design to reduce the need for active heating, space conditioning and lighting; and make use of advanced materials.
- Realize further cost reductions and efficiency gains in specific end-uses, such as solid state lighting and heat-pump-based technologies for space conditioning.
- Develop smart appliances that could participate in grid regulation, increasing reliability and perhaps increasing the potential of non-dispatchable renewable energy.

Transportation Sector

- Increase the efficiency of light-duty vehicles using hybrid technology with gasoline, diesel, or biofuels.
- Pursue advances in battery technologies, which would benefit all electric-based vehicles—hybrid, plug-in hybrid, or fuel cell.
- Reduce the need for light-duty vehicles by community planning, mass transportation, and information systems.

Industrial Sector

- Re-engineer industrial processes to reduce the need for energy services, such as using membrane technologies for chemical separation processes that would use much less heat and steam.
- Where processes still require high temperatures for steam or heat, make burning commercial biomass an available technology option.
- In generating heat and steam from biomass, exploit opportunities for cogenerating electricity.
- Reduce the cost of capturing or substituting material to reduce the process CO_2 emissions from cement production.

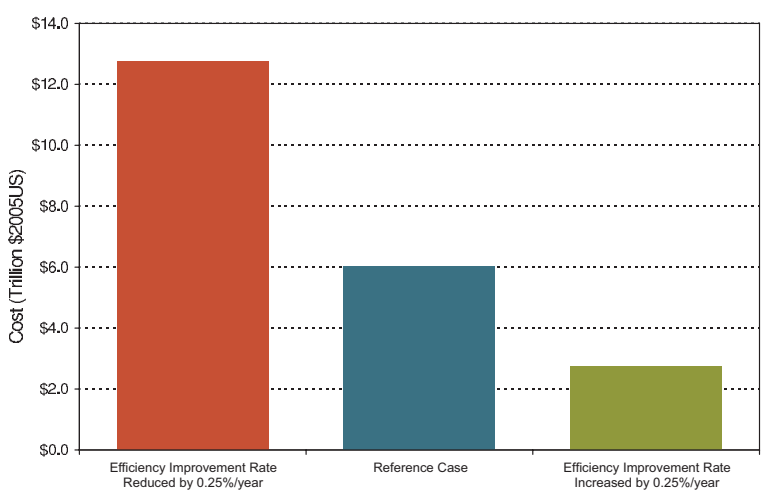


Figure 11. The effect of energy efficiency on costs for a 550 ppm CO_2 stabilization level (measured as discounted global costs incurred over the century in reducing emissions to the target). Energy intensity growth improvements of only one-quarter of one percent can have enormous economic benefits for addressing climate change.

APPENDIX Notes and References

Most of the CO_2 emissions in this study are stated in units of million or billions of tons of carbon (MtC or GtC, respectively). This differs from the conventions of the CCS technical community, which expresses values in millions or billions of tons of CO_2 ($MtCO_2$ or $GtCO_2$, respectively). Cost data can be converted to dollars per ton of ($/$tCO_2$) by dividing by 3.667, and mass data can be converted to CO_2-based units of the climate change technical community by multiplying the mass expressed in carbon-based units by 3.667.

This report makes frequent use of a very large measure of mass known as a "gigaton." A gigaton of CO_2 ($GtCO_2$) is a standard measure for scientists and policy makers familiar with carbon management, yet for most other audiences the magnitude of this unit is sometimes hard to comprehend. A gigaton is approximately equal to 77 Empire State Buildings if they were made completely of lead, 10,718 aircraft carriers the size of the USS Enterprise, or all of the iron ore annually mined in the world. For more examples of how massive a gigaton is please consult C.L. Davidson and J.J. Dooley, "A Gigaton Is…" PNWD-3299, Joint Global Change Research Institute, Battelle Pacific Northwest Division (July 2003).

Unless otherwise indicated, all scenarios and analyses result from the GTSP research, using several well-established modeling tools.

The estimates of energy uses by light-duty vehicles, freight trucks, and airplanes are from U.S. Energy Information Administration, *Annual Energy Outlook 2005 with Projections to 2025*, U.S. Energy Information Agency, Washington, DC (2005).

Advanced battery technologies are discussed in the *MIT Technology Review*, February 2006.

Data for Figures 5, 6, 7, and 8 come from the Manufacturing Energy Consumption Survey (MECS), U.S. Energy Information Administration (EIA) (2002). http://www.eia.doe.gov/emeu/mecs/mecs2002/data02/shelltables.html; 2002.

Figure 9 credit: Andrew L. Malone.

References of interest for further exploration of this topic include the following:

J.A. Edmonds, J.F. Clarke, J.J. Dooley, S.H. Kim, and S.J. Smith, "Stabilization of CO_2 in a B2 World: Insights on the Roles of Carbon Capture and Disposal, Hydrogen, and Transportation Technologies," *Energy Economics* 26, 4 (2004): 517-537.

F. Rong, L.E. Clarke, and S.J. Smith, "Climate Change and the Long-Term Evolution of the U.S. Buildings Sector," PNNL-SA-48620, Pacific Northwest National Laboratory, Richland, WA (2006).

M.A. Wise, P. Sinha, S.J. Smith, and J.P. Lurz, *Long-Term U.S. Industrial Energy Use and Carbon Dioxide Emissions*. Pacific Northwest National Laboratory, Richland, WA (2007).

THE **GLOBAL ENERGY TECHNOLOGY STRATEGY PROGRAM**

The Global Energy Technology Strategy Program (GTSP) began in 1998 with the goal of better understanding the role that energy technologies might play in addressing the problem of global climate change. The GTSP is unique, a global, public and private sector sponsored research program, whose sponsors and research collaborators are drawn from around the world.

The completion of the first phase of the GTSP in 2001 was marked by the release of a seminal report during a special session of the Sixth Conference of the Parties to the United Nations Framework Convention on Climate Change. This report, *A Global Energy Technology Strategy Project Addressing Climate Change: Initial Findings from an International Public-Private Collaboration,* demonstrated the importance of technology development and deployment as key cornerstones of a broader set of activities designed to address climate change. A central conclusion was that a robust technology strategy required the development of a *technology portfolio*. It found no evidence for a single technology whose development promised to "solve" the climate problem. That is, *a priori*, there is no technological "silver bullet." Rather, the GTSP concluded that various technologies and technology systems show promise for making a substantially expanded contribution to the global energy system in a climate-constrained world. These included biotechnology, hydrogen energy and other advanced transportation technology systems, nuclear power, renewable energy technologies, end-use energy technologies, and carbon dioxide capture and storage. The first phase of the GTSP produced groundbreaking research, including many results that have made their way into the frequently cited literature. This phase of the GTSP successfully added to the dialogue about responses to climate change a new, previously missing, element—technology. But building productive, long-term, real-world technology strategies to address climate change requires a deeper understanding of technologies and their potential. Thus, the GTSP launched its second phase in 2002. GTSP Phase 2 pushed the frontiers of our knowledge to gain a much deeper understanding of how these key carbon management and advanced energy technologies will deploy in practice, and the means for launching and sustaining a meaningful global energy technology strategy.

GTSP Phase 3 will delve into the regional diversity and institutional dimensions of developing and deploying technologies to address climate change.

GTSP PHASE 2 SPONSORS In alphabetical order

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