Advancing Energy Efficiency in the U.S. Glass Industry: Perspective from the DOE Industrial Technologies Program

Elliott Levine, U.S. Department of Energy
Keith Jamison, Energetics Incorporated
David Rue, Gas Technology Institute
Warren Wolf, Warren W. Wolf Jr. Services

ABSTRACT

The U.S. Department of Energy's Industrial Technologies Program (DOE/ITP) has conducted a R&D program focusing on glass manufacturing processes for the past decade, and has great interest in seeing the glass industry develop and deploy innovative energy-saving technologies. This paper will explore some of the commonalities in the development of these technologies for use in multiple glass industry sectors, as well as unique aspects of the specific requirements for individual industry sectors. The paper will incorporate findings from a recently published energy bandwidth report, which profiled average, state-of-the-art, and minimum energy requirements for melting and refining glass in the top glass sectors.

The paper will also examine the challenges and lessons learned in promoting collaborations and commercializing technologies in this conservative industry, describe several recent technological innovations and ongoing research activities, and highlight opportunities for further investigation. Finally, the paper will briefly profile some experiences in improving glass facility energy systems via ITP's Best Practices program activities.

Background

The Industrial Technologies Program (ITP) is the key federal program addressing industrial energy consumption, and is part of the U.S. DOE's Office of Energy Efficiency and Renewable Energy. Together with industry partners, ITP develops real-world energy solutions that lift industrial energy efficiency and flexibility to new levels. ITP's funding of technological breakthroughs catalyzes changes in industrial processes, reducing demand for energy in ways the market alone can not achieve. ITP plays a critical role in our nation's efforts to:

- Save energy
- Increase fuel flexibility
- Reduce emissions and waste
- Promote economic growth and competitiveness

ITP has been engaged in reducing industrial energy consumption through the development of advanced technologies since the late 1970s. Of particular interest to the glass industry was work sponsored by ITP (then known as the Office of Industrial Programs) in oxy-fuel combustion during the 1980s, which helped the eventual commercial development of this technology which is now used extensively throughout the glass industry and reduces NO_x emissions in addition to saving energy.

In the mid-1990s, ITP (then known as the Office of Industrial Technologies) began a planning effort known as Industries of the Future (IOF). The glass industry was one of nine industries selected to participate in IOF efforts, due to the glass industry's high energy intensity and significant energy consumption – the U.S. glass industry consumes nearly 250 trillion Btu of energy annually (DOE 2002). Significant efforts were conducted in planning and analysis to ensure that Federal investments provided significant energy savings and met technical priorities for the glass industry.

Since the inception of the Glass IOF program in the mid 1990s, ITP funded about 35 glass research projects, resulting in both commercial and emerging technologies; two R&D 100 awards; and significant intellectual property in the form of patents and copyrights. The program has helped the glass industry supplement their limited research funding for process technology, especially in light of the reduction in research staffing and funding at many companies which has occurred over the past decade. Also, by sharing the risks and costs associated with developing new technology, ITP allows technologies to be investigated that otherwise may not be funded.

Glass Technology Development

The glass industry is commonly divided into four major segments of container, flat, fiber, and specialty glass. From the beginning of the IOF partnership efforts, ITP realized that there was no single organization that represented the technology needs for the glass industry. Furthermore, most glass companies only operated in one or two major sectors. And individually, each sector viewed their operations as sharing limited commonalities with other glass sectors.

To overcome these challenges and to maximize the potential for collaboration, ITP encouraged the glass industry to form an umbrella organization to represent its interests. As a result, the Glass Manufacturing Industry Council (GMIC) was formed in 1998. From the original seven founding members, GMIC has grown into a vibrant organization representing around 40 glass companies and other organizations in all major glass sectors.

In the period between 1996 and the present about 35 major research projects were conducted. These projects were focused primarily on improving the energy efficiency of furnace operations, which is common to virtually all glass sectors and usually accounts for the largest proportion of energy consumption. Efforts included furnace modeling, refractory corrosion, and alternative melting techniques – technologies that could be applied to multiple glass sectors. Additional research and development included: efforts on sensors and controls, extending oxy-fuel technology, and preheating of batch and cullet.

The glass industry cost-sharing on these projects amounted to around 35% of total project costs. The vast majority of these projects were selected through competitive solicitations, and annual review meetings were conducted to ensure that projects were on track to meet their technical objectives.

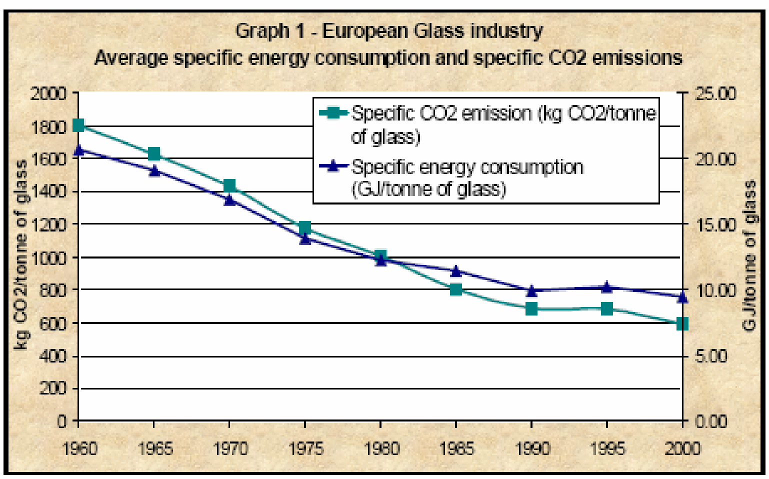
Through its interactions with the glass industry, ITP has been able to attract major industry players to participate in research and planning activities. Approximately 100 participants throughout the United States partnered with ITP over the past decade. Participation ranged from conducting research and providing specialized technical knowledge to providing cost-sharing assistance and facilities for demonstration testing. Participants include both large and niche glass manufacturers, industry vendors and technology suppliers, academic institutions, national laboratories, and other partners.

Energy Analysis and Bandwidth

The glass industry considers many of their practices to be proprietary. This presents a challenge in collecting benchmarking energy use data. To help overcome the lack of benchmarking data in the glass industry, ITP conducted several analytical studies to help identify opportunity areas and provide baseline data. The "Energy and Environmental Profile of the U.S. Glass Industry" provides an analysis of energy consumption by process, and an overview of various processes used in the industry. "Glass Melting Technology: A Technical and Economic Assessment" provides insights on previous efforts for advanced melting technologies conducted both in the United States as well as many that have been investigated overseas. And the "Industrial Glass Bandwidth Analysis" provides an assessment of potential energy savings from implementing state-of-the-art technology as well as potential technology improvements. These publications not only provide insight into glass manufacturing technology, but provide a sound basis for the pursuit of individual research topic areas.

While U.S. glass industry energy use data has been difficult to obtain, insights can be gained by looking at European data, where more extensive reporting has occurred. Figure 1 depicts information on the energy intensity of European glass operations between 1960 and 2000 (CPIV). These graphs clearly indicate a substantial reduction in energy intensity over this time period, although the rate of decrease has slowed in recent years.

Figure 1. European Glass Industry Energy and Carbon Dioxide Intensity



Energy Bandwidth

ITP contracted with the Gas Technology Institute (GTI) to conduct a bandwidth study for the glass industry. While the operations of each major glass sector differ due to differences in products, composition, and quality requirements; they generally share four primary process steps, for which the energy use in each of can be examined:

- Batch preparation and charging
- Melting and refining
- Forming
- Post-forming

However, since in most sectors the largest proportion of energy is used in the melting and refining process, this process was the primary scope for the bandwidth effort. Results from the report are shared below and include information about the technologies employed and current trends, including comments on recent changes due to high natural gas prices. Tables 1 and 2 provide summary statistics from the bandwidth analysis (GTI 2006).

Glass fiber. In the past the textile sub-sector has used recuperative fired furnaces (air-gas) but the trend in recent years has been towards oxy-fuel. Air-gas with electric boost is the predominant technology because the furnaces are smaller, control and product quality can be maintained, and industry has committed to this approach. Wool fiber operations, on the other hand, use both oxy-gas and electric melters with a recent trend towards oxy-fuel. However, the recent rise in natural gas prices has caused several companies to review their moves to oxy-fuel and there is now a movement back to electric melting. Wool glass melting has little need for significant refining and also is very efficiently melted electrically. Forming within the glass fiber sector portrays large variations of energy usage between wool and textile sub-sectors. State of the art technology for melting/refining processes was found to vary between textile and wool fiber sub-sectors as well. For textile, the current state of the art is oxy-fuel.

Flat glass. The flat glass sector is building a few new production plants. The flat glass sector uses primarily air-gas fired furnaces. Electric furnaces have been impractical because of the cost of electricity. There has been some conversion to oxy-fuel but it has been slow. Oxy-fuel melting operating costs have been historically higher than air-gas, but the rising costs of natural gas are helping to alleviate this concern since oxy-fuel melters are more energy efficient. The issue of refractory wear in oxy-fuel furnaces is still a concern when deciding to convert to this technology. State of the art technology involves oxy-fuel furnaces. Practical minimum values could be achieved with improvements in refining and continued evolvement in controls.

Container glass. The container glass sector is currently building almost no new plants. Furnaces within the container glass sector are mostly air-gas. This sector has a trend towards more use of oxy-fuel fired furnaces. Electric boosting is commonly used, but full electric furnaces are too expensive to operate. Oxy-fuel is being used in more furnaces every year because of energy savings, glass quality improvements, capital savings, and emissions reductions. Lower oxygen costs and better combustion systems are also making this option more attractive. Also, container glass tonnage increases are important when emissions are limited to maintain existing melter footprints. State of the art technology for melting involves the use of oxy-fuel furnaces.

Specialty glass. This sector includes lighting glass and tableware, among others. Due to the diversity of products and smaller nature of the sector, detailed information was not gathered for this sector.

GTI is also comparing European energy practices and consumption for the glass industry with the U.S. data. While this activity has not been completed, preliminary information indicates fairly close agreement except for some differences in priorities. These differences include a greater emphasis in Europe on glass recycling and therefore cullet use, as well as a higher propensity to utilize batch and/or cullet preheating.

Table 1. Current Average Melting/Refining Technology and Energy Use

Sector	Current Average Technology Distribution		Current Average [MMBtu/ton]
Wool Fiber	Air-fired Oxy-fuel Electric	10% 35% 55%	4.5 ± 0.5
Textile Fiber	Air-fired Oxy-fuel Electric Boost	25% 75% 35%	6.5 ± 0.5
Container	Air-fired Oxy-fuel Electric Boost	70% 30% 15%	5.75 ± 0.25
Flat	Air-fired Oxy-fuel	80% 20%	6.5 ± 0.5

Table 2. Glass Production and Melting/Refining Energy Use

	Estimated Glass Production (MMton/yr)	Energy Use			
		Current Average (MMBtu/ton)	State of the Art (MMBtu/ton)	Practical Minimum (MMBtu/ton)	Theoretical Minimum (MMBtu/ton)
Wool Fiber	3.0	4.5	2.8	2.3	2.3
Textile Fiber	0.8	6.5	3.8	3.0	2.3
Container	9.4	5.75	3.4	2.7	2.2
Flat	5.3	6.5	4.7	3.5	2.8
Specialty	1.7	6.5	4.7	3.5	2.8

Collaboration and Commercialization

ITP's Glass research partnership has worked with the Glass Manufacturing Industry Council and other industry partners to provide technology solutions that have broad applicability and high energy savings impacts. As a result, innovative technologies are boosting the energy productivity and competitiveness of the U.S. glass industry.

Additionally, an Allied Partnership agreement was signed between DOE and the GMIC in June 2003. This agreement formalized a relationship that will lead to the implementation of numerous energy improvement technologies and techniques across the glass industry. As part of these efforts, GMIC hosted or arranged several energy efficiency training workshops in subjects such as process heating and compressed air. The GMIC remains a primary conduit for ITP in providing technology solutions to the U.S. glass industry.

Technological Innovations

Glass companies, industry suppliers, research institutes, universities, and government agencies all provide technology advancements and funding for glass industry process innovations. Even though ITP provides only a small portion of glass industry technologies, some key advancements with ITP involvement are highlighted below.

Commercial Technologies

Four technologies funded by ITP are currently being used by the U.S. glass industry. A brief description of each is included below.

Oxy-fuel firing. Oxy-fuel firing uses oxygen instead of air in the high-temperature combustion process employed in glass melting furnaces. Burners specifically designed for oxy-fuel firing are employed to provide maximum efficiencies. Glass manufacturers are using this process in all major glass sectors. This technology, commercialized in 1990, is used in about one-third of U.S. glass furnaces.

Primefire 400. The PrimeFire 400 is an advanced flat flame burner designed for oxy-fuel glass furnaces which can be fitted into existing control schemes. This burner improves performance by modifying the fuel prior to combustion and then forming and burning soot in the flame. The PrimeFire 400 comes in four sizes with maximum capacities of 2, 4, 10 and 20 million Btu/hr. All models can be fired using natural gas or fuel oil. The technology was commercialized in 2004.

Advanced temperature measurement system. This temperature measurement system uses a calibration reference matrix built into the sensor and an associated remote signal processor and signal analysis software. A proprietary dielectric material used in the sensor helps avoid the normal failure mechanisms of other sensors. The sensor system performs real-time signal processing of the matrix data to provide accuracy in sensor readings. Glass manufacturers can use this sensor in their high-temperature melting furnaces. This technology has been marketed since its introduction in 2000.

Oxygen enriched air staging. This technique controls NO_x formation and improves heat transfer in air-gas glass furnaces without interrupting furnace operation or adversely affecting product quality. The system stages combustion by holding back a portion of the combustion air normally provided during the earliest stages of combustion and flame development. The resulting flame is hotter and more luminous. Glass manufacturers can employ this technique in existing endport and sideport regenerative glass furnaces.

Knowledge-Based Results

Three projects funded by ITP have contributed to the scientific understanding and improvement of glassmaking operations. A brief description of each is included below.

Modeling of refractory corrosion in oxy-fuel glass furnaces. The use of energy efficient oxy-fuel firing in glass melting furnaces requires refractories that are more resistant to corrosion than those in traditional air-gas melting. Researchers gathered experimental data, determined corrosion factors, and developed mathematical models to predict corrosion rates in several types of refractories. The results can be used to identify furnace conditions, furnace designs, and refractory compositions that lower corrosion rates.

High temperature glass melt property database. The database, published in a 290 page book in 2005, contains information on many key glass melt properties for several glass compositional families. This data can be used by the entire glass industry to improve modeling capabilities, which will ultimately improve glass melting and forming processes. Accurate, improved modeling can also eliminate the need for costly experimental melts to test for proposed process changes.

Oxy-fuel protocol. By better monitoring and characterizing oxy-fuel furnace operations through advanced measurement techniques and mass and energy balances, operational inefficiencies can be identified and energy saving changes can be recommended. The protocol was completed in 2004.

Emerging Technologies

Eight projects funded by ITP have the potential to provide significant benefits to glassmaking operations if they are adopted by the glass industry, and may become commercially available in the next two to three years. A brief description of each is included below.

Coupled combustion space modeling. A three-dimensional combustion space/melt tank/batch melting model using real-world furnace data and conditions has been developed in order to better regulate heat flux distribution on the batch and glass melt surfaces both in existing and new glass furnaces.

Submerged combustion melting. An innovative method injects the combustion flame directly into a pool of hot glass melt, yielding intense combustion, direct-contact heat transfer, and turbulent mixing. Participants are testing glass melts in a pilot-scale melter.

High intensity plasma melting. An innovative, modular glass melter utilizes electric-based plasma melting and increases torch life and process stability. Exploratory glass melting trials were conducted on a wide variety of glass compositions and efforts are continuing to improve process parameters.

Oxy-fuel fired front end system. Oxy-fuel-fired front-end technology provides significant improvements in energy consumption by replacing air-gas burner systems and optimizing heat transfer distribution. Full-scale testing of the system was completed in a fiberglass plant.

Measurement and control of glass feedstocks. A lased-induced breakdown spectroscopy (LIBS) instrument measures the chemical make-up of glass batch materials in order to detect contaminants and batch nonuniformity. A long-term plant demonstration of the commercial instrument is ongoing at a glass facility.

Model of on-line coating of float glass. A computational model of tin oxide deposition by chemical vapor deposition predicts growth rates on a float-glass line as a function of process parameters. Testing using data from laboratory experiments was conducted in a pilot-scale coating reactor. The model, together with kinetic data describing the decomposition of the tin precursor and thermodynamic information for gas-phase species present during growth, is publicly available.

Improved yield in fiber drawing. Through modeling and improved process control techniques for glass fiber drawing, reductions in break frequency for fiber drawing can be reduced by a factor of four. The pilot-scale drawing tower has successfully demonstrated only one break in a four-hour period; technology transfer to the plant floor is being pursued.

Monitoring and control of batch carryover and alkali volatilization. A high-temperature laser-induced breakdown spectroscopy (LIBS) sampling probe measures the time-dependent batch carryover and alkali concentrations in the exhaust of glass furnaces. Volatilized alkali metals contribute to refractory crown corrosion and both carryover and volatilized alkali increase particulate emissions. A conceptual design has been developed for a low-cost, low-maintenance LIBS probe sampling system.

Technology Opportunities

While the glass industry has made huge strides in improving its energy intensity, there are numerous technology opportunities available which can further improve energy efficiency and productivity. Barriers to implementation of these technologies are frequently cost and technical maturity. Several potential opportunities are highlighted below.

Increasing cullet percentage. Glass from cullet requires less energy per ton to produce than glass from batch. Since substituting cullet for batch can be relatively easy to implement, industry will willingly utilize this technology.

Batch preheating. The use of process waste heat to preheat batch is clearly a winning way to conserve energy. The heat returned to the batch immediately lowers combustion demands. A number of means to carry out batch preheating have been tested at pilot scale and been installed in limited industrial use. Batch preheating is capital-intensive in most cases, sometimes requiring equipment on the same size scale as the melter itself.

Cullet preheating. When cullet can be used, cullet preheating is much more practical than batch preheating. Cullet can be heated to a higher temperature than batch before it softens, and cullet does not undergo decomposition reactions. For these reasons, cullet preheating is a promising means to reduce energy use in situations where capital costs warrant installation.

Oxy-fuel conversion. Conversion from air-gas to oxy-gas firing is the single most promising means to reduce energy use. Conversion to oxy-gas requires furnace rebuild and installation of various support equipment. Conversion will only be undertaken after careful economic analysis and at the end of a furnace campaign. Decreasing oxygen costs and increasing gas costs are making oxy-gas conversion more attractive.

More efficient burners. Combustion system providers regularly work to develop more efficient burners with lower emissions and tighter control capabilities. New burners are always installed at a rebuild, but most companies will not pay the cost of new burners during a campaign. However, this is a reasonable retrofit option if capital costs are low enough and energy savings are large enough to warrant the cost.

Improved refractory. Refractory companies also work to produce products with superior thermal properties and longer life in the glass melter environment. Similar refractories are used throughout the industry, but variations are required based on glass chemistry. New refractories can only be employed at the time of furnace rebuild.

Improved control system. Control systems have improved dramatically over the last decade. Tighter control of the combustion and melting processes leads directly to energy savings. Control systems, however, are both costly and difficult to install on a working furnace. Although new control systems can be installed on a retrofit basis, they are almost always upgraded only at the time of furnace rebuild.

Alternatives to natural gas. Rising fuel prices have encouraged industry to consider other, less costly, fuel options. The amount of energy saved using alternative fuels is unknown, but the savings will be lower than savings from other techniques. Price would be the primary driving force in switching to alternatives, but the supply must be consistent and reliable before being seriously considered. Alternative fuels and combustion systems for them could be installed as a retrofit, but most companies would likely only consider at the time of furnace rebuild.

Exhaust gas heat recovery. Regenerators are used for exhaust gas heat recovery in air-fired furnaces. Technologies such as steam generation may be practical for air-fired melters, but cost constraints limit ability to recover much energy from the low temperature exhaust leaving the bottom of the regenerators. Oxy-gas furnaces exhaust only 30% of the volume of air-gas furnace exhaust, but no heat is currently recovered from oxy-gas melter exhaust. This high-level heat can potentially be used to generate steam, to preheat batch or cullet, to generate electricity by thermo-electrics, to generate needed oxygen, or to preheat oxygen or gas. Needed cost-effective technologies for heat recovery are not yet available, but rising fuel costs may spur development.

Convective melting. Glass is heated in a gas-fired melter predominantly by radiation and partially by convection. In convective melting, one or more burners are mounted on the crown and fired downward toward the melt surface. This combustion approach is purported to increase heat transfer and improve energy efficiency. The method has been installed on a number of furnaces on trial bases and is available as a furnace retrofit. Convective melting could also be installed at the time of rebuild.

Advanced melter designs. The patent and published literature from around the world, including a Technical and Economic Assessment and a melting technology workshop, both supported by DOE, have proposed and discussed a wide range of new approaches to glass melting.

Rapid refining processes. Refining or conditioning glass to meet product requirements can be time-consuming, capital-intensive, and energy-intensive. A number of approaches to rapid refining have been proposed, tested, and demonstrated. Approaches include:

- Centrifugal
- Inert gas (helium)
- Microwave
- Shear or mechanical
- Sub-atmospheric
- Steam
- Thin-film
- Ultrasonic

Alternative raw materials. Alternative raw materials and new melt chemistry pathways offer means to lower melting energy demands. Proposals have been made to change raw materials to achieve this goal. Other proposals involve adding a process step before the melter to generate batch that requires less energy to melt.

Exhaust gas thermo-chemical recuperation. Waste heat recovery, particularly from oxy-gas melters, offers a means to lower energy use. Several approaches have already been mentioned. Another approach is to use a partial reforming approach, operated catalytically or non-catalytically, to modify the feed natural gas and increase fuel content of the gas.

Fluxes including lithium and steam. Glass chemists have known for decades that fluxes, particularly lithium, offer means to lower the melting temperature (and therefore the energy) needed for melting. Lithium, however, is costly, and that cost has not overcome energy cost savings. Steam also is a good glass flux, but production and utilization of steam is more costly than the benefits realized. With recent and anticipated long-term energy cost increases, the use of fluxes may receive renewed attention.

Heat recovery from cooling glass. The theoretical minimum energy use in making glass assumes that no energy is recovered from the glass product. In most cases this is impractical, but the scientist can envision scenarios in which heat from the cooling product could be recovered for batch or fuel gas preheating or some other energy need.

Higher strength glass. Radically increasing the strength of glass would not directly lower glass making energy needs. However, the ability to make thinner bottles or stronger, thinner fibers would allow the glass maker to make lower weight products. This would lead directly to lower energy use for the same amount of containers or fibers.

Glass composite or hybrid materials. Demands for better materials performance are leading to concepts involving composite or hybrid materials and products. Development of these materials offers a wide range of ways to reduce materials demands and materials production (including energy) costs. A further potential is the development of classes of materials based on recycled products including post-consumer glass.

Best Practices

ITP's Best Practices program has conducted many activities devoted to using existing technology to improve energy efficiency, and developed numerous resources for industrial use including software tools and publications. The glass industry has actively participated in many of these activities and utilized these resources. For example, ITP has developed numerous software tools that can help industry identify opportunities to save energy in several areas. Furthermore, ITP developed a series of glass-specific "Cost Reduction Now" factsheets for the following areas: Combined Heat and Power, Compressed Air, Industrial Assessment Centers, Motors, Process Heating, Pumps, and System Management.

ITP's Best Practices program has also provided limited financial assistance for identifying energy saving opportunities. Smaller facilities that qualify participate in ITP's no-cost Industrial Assessment Center program. Larger plants have competed for cost-shared assessments; glass plants selected for these assessments include:

- Anchor Glass
- Corning
- Johns Manville
- Osram Sylvania
- Visteon

More recently, 10 glass companies were selected to participate in the first round of DOE's Save Energy Now Energy Saving Assessments program. Save Energy Now is part of a national campaign, "Easy Ways to Save Energy," initiated by DOE in 2005. The glass companies selected include:

- AFG Industries
- Anheuser-Busch Packaging Group
- Automotive Components Holdings
- Cardinal Glass Industries
- Corning Incorporated
- Osram Sylvania Products
- Owens Corning
- PPG Industries
- Saint-Gobain
- World Kitchen

These assessments represent a broad cross-section of the glass industry and indicate that companies are continually searching for opportunities for improving energy efficiency in their operations. While specific details for many of these assessments are not currently publicly available, the potential energy savings of the 200 assessments conducted throughout the industrial sector total over 50 trillion Btu annually.

Summary

Over the past decade, ITP has successfully partnered with the glass industry. Overall, the ITP program has made a significant difference to the glass industry by:

- Providing new technologies and knowledge for the glass industry;
- Solving technical barriers and problems through the research and development of technology;

- Providing energy savings and energy saving protocols though the application of commercial technologies and protocols in the marketplace;
- Developing new learning tools such as a distance learning class under development to share knowledge of efficiency opportunities to plant personnel in the glass industry;
- Encouraging new collaborations by providing the requisite framework and helping the GMIC establish itself as a major agent for broad collaboration within the glass industry; and
- Identifying future opportunities through the development of the technology roadmap and bandwidth documents.

To ensure the legacy of the ITP glass program, a dedicated website has been developed to archive research findings, program documents, and other results. The URL for this website is http://www.osti.gov/glass. This website will be a valuable repository of knowledge for the entire glass community.

Outlook and Conclusions

Even though there has been increased emphasis on energy efficiency given high natural gas prices and increasing electricity prices over the past several years, ITP realizes that technical success alone will not ensure market acceptance by the glass industry or other manufacturing industries. Increased efforts are required to ensure that adequate business planning is conducted, the value proposition is appropriate for end-users, and that there are champions for the technology. ITP has encountered greater success in technologies that had that project partners together from the start and where a clear development path was evident.

In retrospect, an earlier and better understanding of the glass industry and its drivers may have enhanced the potential impact of the program, as energy is often not the primary driver for technology development. Similarly, more technology demonstrations and broader collaborations may have resulted in a greater impact.

Looking forward, ITP plans to continue using the convening power of government to catalyze industrial energy efficiency improvements. ITP also encourages the glass industry to continue to collaborate in the future, in order to maximize both the extent of industrial participation as well as the value of technology throughout the various glass industry segments.

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