Final Report

Industrial Glass Bandwidth Analysis

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Introduction

This Industrial Glass Bandwidth Analysis has been prepared as a guide to determining places in the glass-making process where energy can be saved and means by which energy can be saved. This has been accomplished by reviewing available literature, discussions with industry experts, and several rounds of questionnaires sent to industry experts. The glass industry is often reluctant to reveal detailed energy data for proprietary reasons. For this reason, public data has been used as much as possible and affiliations of industry experts have been left out of the references. The authors trust that this approach has improved the quality of the reported information without detracting from the credibility of the sources. Energy use data is often not collected directly but is embedded in the price of materials, utilities, or oxygen. Other times, energy data is available but only for the combination of several process steps. Efforts have been made to examine energy use alone in this report.

The Department of Energy Office of Industrial Technologies considers energy reduction in industrial processes to be an important national concern, and the authors have made every effort to document how the different glass industry segments use energy and means by which energy use can be effectively reduced. Ultimately, a more energy-efficient glass industry is healthier and better positioned to compete domestically with other products and globally with foreign glass producers.

A fair question to pose is whether the glass industry is best served, regarding energy use, by adopting available technologies (following best practices) or by relying on research to develop more energy efficient technologies. There is no simple answer to this question for a number of reasons. Available technologies, for example, are adopted industrially for cost reasons, not for energy savings directly. Major plant changes are made only occasionally and often this occurs in conjunction with furnace rebuilds. Some technologies entail some risk and are less attractive to some glass makers. And, ultimately, the lowest energy use attainable is almost universally achieved by making a number of process changes, a practice not always attractive to industry.

While adopting best energy use practices is desirable and encouraged, research in parallel is also strongly encouraged. Only research provides improvements in existing technologies. Only research leads to new energy saving technologies and only research leads to lower cost, lower risk, and optimal application of new technologies. Without new research, energy savings potential is limited to the best currently available technologies in their present configurations and at their current prices. Finally, only research offers the opportunity for revolutionary changes in glass industry practices.

Background

All industrial glass is made by 1) melting raw materials and then 2) forming the molten glass into desired products. Melting varies in scale, temperature, and residence time but is consistently carried out in tank melters. Forming is much more diverse considering the wide range of products from the glass industry. The industry can broadly be considered to include container glass, flat glass, fiber glass (wool insulation and textile fiber), and specialty glass (lighting, TV, leaded crystal, etc.). This diversity of products is accompanied by a diversity of forming processes.

The objective of this study is to provide a current benchmarking of glass industry energy use. When benchmarking energy use in the glass industry, each of the major glass segments must be considered separately in order to reach useful energy use profiles. Also, to provide guidance on where the largest energy savings are possible, the energy use in each glass industry segment has been presented two ways: 1) by process step, and 2) in current average, state of the art, practical minimum, and theoretical minimum. The original project approach is presented in the appendix for reference.

The glass industry considers many of their practices to be proprietary. This presents a challenge in collecting benchmarking energy use data. A multi-step approach was followed to obtain the best available and current data. First, a 'derived baseline' was determined from available sources. Then, a Delphi information gathering approach was carried out in two stages. In the Delphi approach, questionnaires were used to obtain data on an anonymous basis from glass industry professionals and to learn where these professionals believe the most energy can be saved. The strong industry aversion to releasing benchmarking data was handled on a person-by-person basis and included assurances of individual and corporate anonymity. Finally, the 'derived baseline' and Delphi data were combined for each of the glass industry segments.

The glass industry is undergoing changes, and this had an impact on the collection of benchmarking data. Melters are gradually being switched from air-gas to oxygen-gas firing, and older, less efficient processes are being replaced as they reach the end of their service lives. Specialty glass is the smallest of the four glass industry segments and is composed of diverse products including lighting, TV, optical, flatware, crystal, and others. There were insufficient resources available to acquire reliable data for the many specialty glass sub-segments during this project. A second problem in collecting specialty glass data is the changing nature of many of these businesses. TV glass making, for example, has declined to nearly zero in the last several years in the U.S.

The beginning of this report presents the rationale for the approach taken to benchmarking glass industry energy use. The results of the benchmarking process are presented in table and graphical form at the end of the report. Specific energy usage data is presented in this report where possible. Where specific data was not available, ranges of energy use data are presented.

Approach

All industrial glass is produced by melting. Melting is a highly energy-intensive process, and most efforts on glass industry energy savings have focused on improvements in the melting step. Improvements have included using regenerators for heat recovery, recycling scrap glass as cullet, and switching from air to oxygen firing. Other energy saving approaches have been proposed and explored. Batch preheating in several forms has been considered and is commercial in limited markets. High temperature recuperators, waste heat recovery, and thermo-chemical recuperation have been proposed but not yet implemented. The overriding factor controlling energy saving technologies is cost. If a technology is reliable and saves enough energy to warrant the cost, that technology will be implemented. Increases in energy cost are causing industry engineers and managers to examine energy saving technologies that have been considered too costly in the past.

While melting is clearly a large consumer of energy in the glass making process, other process steps also consume energy. There is no single answer to how energy is consumed in the several process steps because there are many types of glass melted. Also, energy is consumed generally as either natural gas or electricity. Cost differences between these energy sources have an impact on energy decisions since saving a small amount of electricity can be more cost effective to a glass manufacturer than saving a large amount of natural gas.

To benchmark the consumption of energy in the American glass industry, a framework needed to be developed. A three step approach was devised to provide this framework.

Step 1. Glass industry segments
The glass industry is commonly divided into four major segments of container, flat, fiber, and specialty (or pressed and blown) glass. This breakdown is somewhat useful because process steps other than the melter are similar in these segments and glass furnace types and sizes are somewhat similar within each segment. There are limitations to choosing only four industry segments. The most obvious limitations are the types of melters employed, the breakdown of fiber into textile and insulating fiber, and the identification of the most important sub-segments of the specialty segment. Furnaces are heated with air-gas burners, oxy-gas burners, or electricity (some oil-fired furnaces are still operated, but they represent a very small fraction of the glass industry and have been intentionally excluded from this survey). To cover the broadest possible range of glass industry practice, the four segments have been expanded slightly for the benchmarking survey. The expanded list of glass industry segments is shown below.

- **Container glass - air-gas-fired furnaces** - The largest fraction of the container industry uses these furnaces. Electric boosting is commonly used, but full electric furnaces are too expensive to operate.
- **Container glass - oxy-gas-fired furnaces** - Oxygen 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 making this option attractive.
- **Flat (float) glass - air-gas-fired furnaces** - Electric furnaces are impractical because of costs and these large furnaces have not yet begun to convert en masse to oxygen use (although several oxy-gas melters are in operation).

- **Continuous (textile) fiber glass - electric furnaces** - 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. Strong move to oxy-gas.
- **Wool fiber glass - oxy-gas-fired furnace** - Both oxy-gas and electric melters are used industrially. With a trend toward oxy-gas melters, the project team has chosen to focus on the oxy-gas melters, but both types were surveyed.
- **Specialty glass - lighting glass** - The most common lighting melter approach will be surveyed as a representative specialty glass process
- **Specialty glass - tableware** - This market segment was found to be diverse and small compared with other segments. Extensive surveys were no conducted for this industry segment because sufficient resources could not be devoted to obtain an energy profile.

The seven sub-segments of the glass industry do not cover all types of glass or all configurations of the glass making processes. The goal has been to select the most common and representative industrial processes in the glass industry.

Step 2. Process Steps

Every operation carried out in making glass could be considered a separate process step. This level of detail, however, is not needed to assess energy use and potential savings. The objective of this study is to determine parts of the glass making process where the largest amounts of energy can be saved. With that in mind, the energy use in each of the selected sub-segments of the glass industry can be examined in the following process steps.

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

This breakdown, however, only provides an overview. For example, melting and refining are combined in some glass industry segments and are separate in others. Some processes use an energy-intensive forehearth and other processes exclude this step. An example of the process steps for container glass production in both air-gas and oxy-gas melter-based processes is shown below. A similar approach is being taken for the other sub-segments of the glass industry.

- Batch handling and mixing
- Melting
- Refining
- Forehearth
- Forming
- Annealing
- Finishing
- Packaging
- Cullet quench
- Crushing
- Electricity generation

Energy use in each of the sub-segments selected will be examined relative to a similar list of process steps. Many of the steps will be the same for different sub-segments of the glass industries, but there are differences between all sub-segments.

Step 3. Energy Categories

Gathering benchmarking energy data involves chasing a moving target. Industry constantly adds new equipment, develops more efficient processes, and seeks better energy management practices. A 'snapshot' of any sub-segment of the glass industry will find a range of energy consumption for the same process from plant to plant and from company to company. With the goal of determining the best places to save energy, the project team has chosen to survey energy use in several broad categories. The process is straightforward. A sub-segment of the industry is selected (such as oxy-gas container furnaces). Next, the major process steps are identified (as shown in the list above). Finally, energy use data is collected from multiple sources for each major process step. Since no two processes are the same, energy use numbers must be taken as representative or average values. However, categories can be established that help clarify how efficiently energy is used. The categories and their definitions are given below.

- **Energy form.** Whether gas or electricity is predominantly used will help establish where both energy and costs are most likely to be saved.
- **Current Average.** From published sources, data from glass manufacturers, and experience. This is the best average value for current practice. Where possible, a range may also be provided.
- **State of the Art.** This is the lowest energy consuming option in current practice. This sets a lower boundary on what is possible today with technology that is already in industrial use, even if on a limited basis.
- **Practical Minimum.** This represents the lowest practical energy consumption assuming application of reasonable technologies such as heat recovery, batch preheating, etc.
- **Theoretical minimum.** This is a baseline value that assumes no energy loss during a process. While clearly impractical in reality, this value provides insight into how much energy is consumed in actual processes and how much energy is lost.

Results & Discussion

Survey Results

A total of 39 questionnaires (see Appendix for details) were sent to glass manufacturing representatives, glass vendors who were thought to represent a strong relationship with glass manufacturers, and a few consultants recognized for being involved with glass manufacturing. The exact make up of the group was 23 individuals associated with the field of glass making, 9 individuals associated with the field of glass suppliers and 7 individuals who are associated in the field as glass consultants.

A total of 31 replies were received. Of these replies, 27 decided to participate and sent 28 completed questionnaires. One glass manufacturer with two large glass plants sent separate responses from each of their plants since they had a few different responses. The 3 who declined included 1 vendor and 1 consultant, both of whom were supportive of the questionnaire but felt their information might not be representative. Only 1 glass maker declined participation.

Of the 28 completed questionnaires, there were 16 responses from glass manufacturers, 7 from vendor/suppliers, and 5 from consultants. A multiple answer could be given and 17 said their experience was in glass fiber, 15 in flat glass, 14 in container glass, and 14 in specialty glass.

Current Energy Consumption

Respondents were asked to pick from 7 areas or categories to give their relative energy consumption. They were asked to use a ranking of 1 being highest and 7 being lowest. Table 1 shows these results. The lower the score, the higher that category was viewed as an energy consumer in the process. Some respondents did not answer each category and if a result was left blank no score was given.

Table 1: Current Energy Consumption

	Score Average	# of Votes For Each Score						
		1	**2**	**3**	**4**	**5**	**6**	**7**
Raw Materials	4.8	0	2	2	8	4	5	4
Cullet Use	5.0	0	1	1	4	9	8	0
Preheat Batch & Cullet	5.9	0	2	1	1	1	5	12
Melt. Furnace	1.04	27	1	0	0	0	0	0
Refine / Cond.	2.7	1	16	5	4	1	0	1
Forming	3.5	1	4	14	6	1	1	0
Finishing	4.6	0	2	6	4	7	6	3

The highest ranking was clearly Melting Furnace with an average of 1.04 with 27 1st place votes and 1 vote for 2nd. The next closest was Refining/Conditioning at an average of 2.7 with 1 vote as 1st and 16 as 2nd. Other averages, in order, were Forming at 3.5, Finishing at 4.6, Raw Materials at 4.8, Cullet Utilization at 5.0 and Batch/Cullet Preheating at 5.9. Many participants commented that they felt both Cullet Utilization and Batch/Cullet Preheating were ways to save energy and any energy used to do these steps was more than off set by energy saved. Also many industry representatives commented that few, if anyone, are doing Batch/Cullet Preheating due to the fact that capital costs offset their energy cost savings. Responses also indicated that industry is anticipating lower capital cost routes for preheating of the material.

Energy Savings

The same 7 categories were used to classify the process steps in order from highest energy-saving potential to the lowest. The same respondents were asked to rate from 1 to 7, with 1 again being highest where the 7 categories ranked as to potential or opportunity to save energy in the future.

Table 2: Areas with Best Opportunity to Save Energy

	Score Average	# of Votes For Each Score						
		1	**2**	**3**	**4**	**5**	**6**	**7**
Raw Materials	5.0	1	3	2	3	5	5	8
Cullet Use	3.9	3	5	1	6	5	4	1
Preheat Batch & Cullet	3.6	3	3	10	5	2	4	1
Melt. Furnace	1.6	19	4	2	2	1	0	0
Refine / Cond.	3.6	2	6	6	5	3	1	2
Forming	4.1	1	5	5	4	6	6	1
Finishing	5.5	1	1	1	5	3	5	11

Table 2 portrays that the respondents strongly agree with some process steps for potential energy savings while also disagreeing on a few. The Melting Furnace was chosen as the best potential opportunity for energy savings with an average of 1.6. It received 19 1st place votes and 4 2nd place votes. There is a tie for the #2 potential area between Refining/Conditioning and Batch/Cullet Preheating at an average for each of 3.6 with Refining/Conditioning receiving 2 votes as 1st and 6 as 2nd in potential. Batch/Cullet Preheating received 3 votes as 1st and 3 votes as 2nd. Cullet Utilization followed with an average score of 3.9 with 2 votes as 1st and 5 as second. The remaining average scores are Forming at 4.1, Raw Materials at 5.0 and Finishing at 5.5.

In addition to the above responses, eighteen representatives volunteered a quantitative value for how much energy they believed can be saved throughout the manufacturing processes. These responses ranged from a low of 10% to a high of 50% with a grouping of both the median and the average around 20 – 25% as the potential opportunity to save in the total glass process.

Survey Summary

The questionnaire responses indicate that the glass industry believe that the melting furnace is both the highest energy consuming process step as well as the area with the most opportunity for energy savings. Second to melting, the refining and conditioning step is viewed as the next largest area to consume energy but there is some disagreement about whether this step is ranked second for energy savings potential. Refining and conditioning tied with batch and cullet preheating as the 2nd best area for energy saving opportunity. Both cullet utilization and forming were believed by industry to be a close 4th and 5th for energy savings potential. Industry representatives view some opportunity for energy savings in raw materials and finishing but the majority of respondents ranked these as lowest.

For the glass production process as a whole, respondents felt that the energy saving opportunity was around 20-25%.

Interview Results

A follow-up survey/interview was conducted by means of visits and phone conversations to help better understand the current average, state of the art, practical minimum, and theoretical minimum of energy usage within the high-energy consumption processes of the glass industry. This survey was limited to the larger glass producers and those who wished to participate. The results of this survey by Warren Wolf are shown below by glass sector. The quantitative energy usage information summarized here is also tabulated in the 'Combined Interview and Literature Results' section below. There were no interviews conducted for the Specialty Glass sector due to the broad range of product types that this sector covers.

<u>Glass Fiber</u>

The survey within the glass fiber industry involved extensive discussions with those at two companies with large operations in textile and wool. A major conclusion from these interviews revealed that energy information within this sector must be separated into sub-sectors of textile and wool. The process involved in the production of these two glass types differ significantly enough that they should not be consolidated, from an energy-use perspective.

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. Wool 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.

For textiles, current average melting/refining energy use in the melting/refining process steps show consumption to be as low as 4.5 MMBtu/ton for oxy-fuel with electric boosting. The front end piece of this sub-sector is as high as 2 MMBtu/ton but some electric and oxy-fuel front ends can have usage in the range of 0.3 – 0.6 MMBtu/ton. An overall average energy use for melting/refining for the textile sub-sector is 6.5 ± 0.5 MMBtu/ton. Wool glass melting has little need for significant refining and also is very efficiently melted electrically. Based on the interviews conducted, 4.5 ± 0.5 MMBtu/ton is an accurate current average melting/refining energy usage for the wool sub-sector.

Forming within the glass fiber sector portrays large variations of energy usage between wool and textile sub-sectors. An industry source believes that a good current average energy usage for forming textile is in the range of 1 – 2 MMBtu/ton. For wool fiber, several interviews yielded an average forming energy usage of 4.5 MMBtu/ton. Warren Wolf, however, has seen actual energy usage numbers from two different facilities that are in the range of 5.5 – 6.5 MMBtu/ton. It was therefore decided that the best current average energy usage for forming wool fiber is 5.0 ± 0.5 MMBtu/ton.

Post forming for the textile sub-sector uses about 1 – 2 MMBtu/ton, as cited by an industry member. Wool fiber post forming was found to be a bit higher with a current average of 2.0 ± 0.5 MMBtu/ton.

State of the art technology for melting/refining processes was found to vary between textile and wool fiber sub-sectors as well. For textile, it found that the current best state of the art at one company was in the range of 3.0 – 3.5 MMBtu/ton for oxy-fuel with another 1 – 2 MMBtu/ton for front end energy. It was also found that an all electric or an oxy-fuel front end could lower this to 0.3 – 0.6 MMBtu/ton. These numbers yield a state of the art energy usage for melting/refining in the textile sub-sector of 3.8 ± 0.4 MMBtu/ton. A best state of the art number for an air-gas process was found to be about 5 MMBtu/ton. In both cases it is assumed optimal when electric boost is used. The wool fiber sub-sector, assuming mainly batch production, was found to have a state of the art melting/refining energy usage in the range of 2.5 – 3.0 MMBtu/ton, with perhaps 2.8 MMBtu/ton as a best average. High cullet percentages (~40 – 80%) could lower this number.

The theoretical minimum energy usage for the whole glass fiber sector was agreed to be in the range of 2.3 – 2.5 MMBtu/ton. One source felt that textile should have a higher value, such as 3.0 MMBtu/ton, but this was not supported by others. There is a difference in melting temperature between wool and textile but unless a furnace was utilizing much higher temperatures, the higher theoretical energy usage does not appear justified for textile.

For the textile sub-sector it was decided that a practical minimum melting/refining energy usage would involve extensive preheating. This step could save about 15% of the melting/refining energy lowering the usage to just below 3 MMBtu/ton. One industry member stated that a preheating step would work for textile cullet but not for preheated batch. The reasoning was that experience has shown that preheated batch might produce enough foaming that most of the energy savings from the preheating would be lost. Wool fiber furnaces with preheating of batch could be near the 2.3 MMBtu/ton theoretical energy usage. The energy use could be taken below the theoretical value if high cullet (60 – 80%) is used. This would involve preheating of the cullet and not much batch melting.

Flat Glass

Two flat glass companies chose to participate with this follow up survey and cooperated extensively. Also included here, where applicable, is information obtained from past interviews conducted on the P-10 process development by PPG. These interviews were performed over two years ago. The responses obtained from the flat glass sector have only focused on melting and refining energy use. This is the major energy usage step for the flat glass sector and is also the area of common technology focus for all of the glass sectors that do continuous melting.

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.

The current average energy usage for melting/refining was stated by industry participants to be in the range of 5 – 7.5 MMBtu/ton. A reasonable average value is 6.5 ± 0.5 MMBtu/ton.

State of the art technology has lowered melting/refining energy usage for flat glass production to about 4.7 MMBtu/ton, as confirmed by two sources. Details about the technology used here were not provided but it involves oxy-fuel furnaces. The operation of this process does not appear to use preheating.

Flat glass industry participants agreed that an accurate theoretical melting/refining energy usage is 2.8 MMBtu/ton.

Practical minimum energy usage for flat glass melting/refining was not agreed upon universally, but the best prediction is 3.5 MMBtu/ton. Industry interviewees agreed that this value could be achieved with improvements in refining and continued evolvement in controls. It should also be noted that in the P-10 a value of 4 MMBtu/ton was achieved when it was felt that energy costs were going higher. In addition, those involved on the project agreed that a target with continuous improvement would have taken it to about 3.5 MMBtu/ton.

Container Glass

Two container glass industry experts with extensive industrial experience were interviewed for this sector. Furnaces within the container glass sector are gas-air, and electric boosting is frequently used. This industrial sector has a trend towards more use of oxy-fuel fired furnaces. Improvements in economics, glass quality, and emissions are among the factors driving this trend. Also, container glass tonnage increases are important when emissions are limited to maintain existing melter footprints.

The current average energy consumption for the melting/refining phase was found to have an average of 5.75 ± 0.25 MMBtu/ton. Interviewees believe that about 15% of this energy is commonly supplied as electric boost during the melting. These numbers assume operation at 90% or better production capacity.

Non-melting/refining energy was estimated to be 0.68 MMBtu/ton of packed product. This includes the energy necessary for the forming and post-forming stages of production. This value has increased 10-15% over the past 10-15 years. This increase is attributed to larger I.S. machines and more product inspection equipment.

State of the art technology for the melting stage of container glass production involves the use of oxy-fuel furnaces. A credible industry interviewee believes the energy required for this technology is 3.0-3.2 MMBtu/ton. Another industry member stated that a good new end port would yield about 5 MMBtu/ton while a common new oxy-fuel furnace would require about 3.8 MMBtu/ton. The state of the art technology for melting/refining in the sector therefore has an average of 3.5 MMBtu/ton.

Both of the container glass industry experts believe that the theoretical minimum energy required for the melting/refining stage is 2.2 MMBtu/ton. Here, primarily batch melting was considered.

The interviewees believe that the practical minimum amount of energy required for container glass melting/refining could be as low as 2.7 MMBtu/ton. It was stated that extensive preheating with the state of the art melting technology could save about 15% of the energy consumption. It was also noted that this preheating can be difficult since heat losses become more substantial as the theoretical minimum is approached. These additional heat losses might require capturing the lost energy for use in reheating batch or cullet in order to achieve the most efficient production method.

Combined Interview and Literature Results

Production Process Energy Usage

The primary goal of this investigation is to identify where the glass industry feels the largest energy use is occurring and what methods the industry feels are best for reducing energy consumption by closely observing energy consumption in average practice, best state of the art, practical minimum, and theoretical minimum requirements. Initially as a baseline, data from the book Energy Analysis of 108 Industrial Processes (1996)[2] was used to set values for energy use in different glass segments by process step. Further analysis showed that this data was dated and not representative of current processes. Through review of the Energetics report[1] and the surveys listed above, more accurate data was assembled.

The eight tables below summarize this data. Also shown is the theoretical minimum energy required to produce each type of glass. This data represents the thermodynamic minimum amount of energy needed for each type of glass production. In Table 7, interviews yielded one combined energy usage number for both the forming and post-forming phases. The forming and non-forming current average data shown in the table was proportioned to the data obtained from the Energetics report cited below. Also, due to the two distinct sub-sectors of the glass fiber sector, data in this sector is presented for both textiles and wool. Data used in the tables below was obtained from "Energy and Environmental Profile of the U.S. Glass Industry"[1], "Energy Analysis of 108 Industrial Processes"[2], "Integrated Pollution Prevention and Control"[3], and surveys conducted with glass industry representatives[4].

As noted in the survey section, many factors influence energy use in the glass industry. Air-gas, oxygen-gas, and electric melters use significantly different amounts of energy per ton of glass. The use of cullet can lower glass melting energy use by up to 10 percent. Consideration of all possible variations in practice was not practical. For that reason, the current average data reflects the average of currently working furnaces in each industry segment. The impacts of process modifications such as varying electric boost, using cullet, switching from air-gas to oxygen-gas, etc., are left for later parametric studies in this or other projects.

[1] "Energy and Environmental Profile of the U.S. Glass Industry", Energetics Inc., 2002.
[2] Brown, H. L. et al., "Energy Analysis of 108 Industrial Processes", 1996.
[3] "Integrated Pollution Prevention and Control, Reference Document on Best Available Techniques in the Glass Manufacturing Industry", 2001.
[4] Data obtained by Dr. Warren Wolf from surveys conducted with glass industry representatives.

Table 3: Flat Glass Production Energy Distribution[2]

	Sub-Category	Energy Distribution (Source)	Energy Distribution (% for Phase)
Mixing	Mixing	Electricity	100%
Melting / Refining	Melting	Fuel	94%
		Electricity	2%
	Refining	Fuel	4%
Forming	Fabrication Float	Electricity	100%
Post-Forming	Annealing	Fuel	16%
		Electricity	1%
	Cooling	-	0%
	Finishing	Electricity	0.3%
	Crushing	Electricity	0.3%
	Final Heat Treatment	Fuel	51%
		Electricity	2%
	Heating	Fuel	8%
	Autoclave	Fuel	4%
		Electricity	1%
	Cooling	-	0%
	Packaging	Electricity	1%

Table 4: Flat Glass Production Energy Usage

	Current Average[1,4] (MMBtu/ton)	Current Average[1,4] (%)	State of the Art[3] (MMBtu/ton)	Practical Minimum[3] (MMBtu/ton)	Theoretical Minimum[3,4] (MMBtu/ton)
Mixing[1]	0.68	6%	-	-	-
Melting / Refining[4]	6.5	60%	4.7	3.5	2.8
Forming[1]	1.5	14%	-	-	-
Post-Forming[1]	2.2	20%	-	-	-

All footnotes are on page 11.

Table 5: Glass Fiber Production Energy Distribution[2]

	Sub Category	Energy Distribution (Source)	Energy Distribution (% for Phase)
Mixing	Mixing	Electricity	100%
Melting / Refining	Melting	Fuel	ND
		Electricity	ND
Forming	Rotary Fiberizer	Electricity	3%
	Blow Chamber	Electricity	4%
	Cooler	Electricity	6%
	Compressor	Electricity	13%
	Boiler	Fuel	74%
Post-Forming	Curing Oven	Fuel	95%
	Batt Machine	Electricity	2%
	Packaging	Electricity	2%

ND: no data

Table 6: Glass Fiber Production Energy Usage

	Current Average[1,4]				State of the Art[4]		Practical Minimum[4]		Theoretical Minimum[3,4]
	Wool		Textile		Wool	Textile	Wool	Textile	
	(MMBtu/ton)	(%)	(MMBtu/ton)	(%)	(MMBtu/ton)		(MMBtu/ton)		(MMBtu/ton)
Mixing[1]	0.68	6%	0.68	7%	-	-	-	-	-
Melting / Refining[4]	4.5	37%	6.5	64%	2.8	3.8	2.3	3	2.3
Forming[4]	5.0	41%	1.5	15%	-	-	-	-	-
Post-Forming[4]	2.0	16%	1.5	15%	-	-	-	-	-

All footnotes are on page 11.

Table 7: Container Glass Production Energy Distribution[2]

	Sub Category	Energy Distribution (Source)	(% for Phase)
Mixing	Mixing	Electricity	100%
Melting / Refining	Melting Furnace	Fuel	ND
		Electricity	ND
	Refining	Fuel	ND
		Electricity	ND
	Forehearth	Fuel	ND
		Electricity	ND
Forming	Forming	Electricity	100%
Post-Forming	Annealing	Fuel	69%
		Electricity	6%
	Finishing	Electricity	3%
	Packaging	Fuel	18%
		Electricity	2%
	Cullet Quench	-	0%
	Crushing	Electricity	2%

ND: no data

Table 8: Container Glass Production Energy Usage

	Current Average[1,4] (MMBtu/ton)	(%)	State of the Art[3] (MMBtu/ton)	Practical Minimum[3] (MMBtu/ton)	Theoretical Minimum[3] (MMBtu/ton)
Mixing[1]	0.68	10%	-	-	-
Melting / Refining[4]	5.75	80%	3.4	2.7	2.2
Forming[1]	0.12	2%	-	-	-
Post-Forming[1]	0.56	8%	-	-	-

All footnotes are on page 11.

Table 9: Specialty (Pressed and Blown) Glass Production Energy Distribution[2]

	Sub Category	Energy Distribution (Source)	(% for Phase)
Mixing	Mixing	Electricity	100%
Melting / Refining	Melting	Fuel	95%
		Electricity	1%
	Refining	Fuel	4%
Forming	Forming	Electricity	ND
	Forming & Drawing	Electricity	ND
	Fire Polishing	Fuel	ND
Post-Forming	Annealing	Fuel	66%
		Electricity	2%
	Cooling	-	0%
	Finishing	Electricity	1%
	Drier	Fuel	16%
	Finishing	Electricity	1%
	Packaging	Electricity	13%
	Cullet Quench	-	0%
	Cullet Crusher	Electricity	2%

ND: no data

Table 10: Specialty (Pressed and Blown) Glass Production Energy Usage

	Current Average[1] (MMBtu/ton)	(%)	State of the Art[1] (MMBtu/ton)	Practical Minimum (MMBtu/ton)	Theoretical Minimum[3] (MMBtu/ton)
Mixing	0.68	4%	-	-	-
Melting / Refining	7.3	45%	5.6	-	2.3
Forming	5.3	33%	-	-	-
Post-Forming	3.0	18%	-	-	-

All footnotes are on page 11.

To further expound upon the current average data presented in the tables above, Table 11 shows the two fiber sectors, flat, and container glass sectors with a breakdown of the current melting/refining technologies in use. These distribution numbers were obtained from conversations with industry representatives and experts and are an average for each sector. The specific current average energy use is also shown, as presented in the above tables. Table 11 portrays the textile fiber sector to have the highest amount of oxy-fuel conversion (75%), followed by wool fiber (35%), container (30%), and flat (20%). Electric boosting is used in conjunction with burner melting/refining in both the textile fiber sector (35%) and the container glass sector (15%). Only wool fiber uses electric melting (55%) currently, where the choice between oxy-fuel and electric varies by energy costs in different regions.

Table 11: 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

A major oxygen supplier to the glass industry provided similar oxy-fuel conversions as those noted above. This oxygen supplier believes that 48% of the fiber sectors, 7.5% of flat glass, 25% of container glass, and 85% of pressed and blown glass sectors have converted to oxy-fuel melting/refining technology. Overall results at the time of this study indicate that roughly 30% of the glass industry has converted to oxy-fuel technology.

The figures below illustrate the distribution of ‘current average’ energy consumption between the four production steps as a percentage of the overall production energy for each glass type.

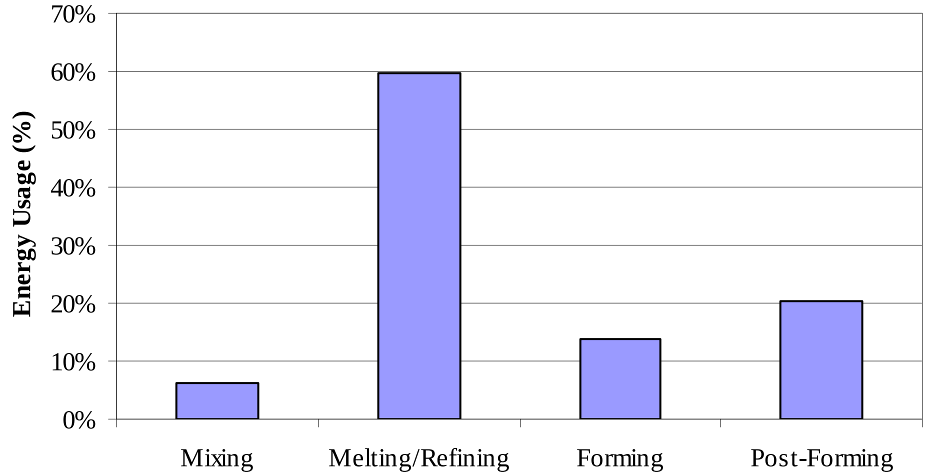

Figure 1: Flat Glass Energy Usage for Process Phases

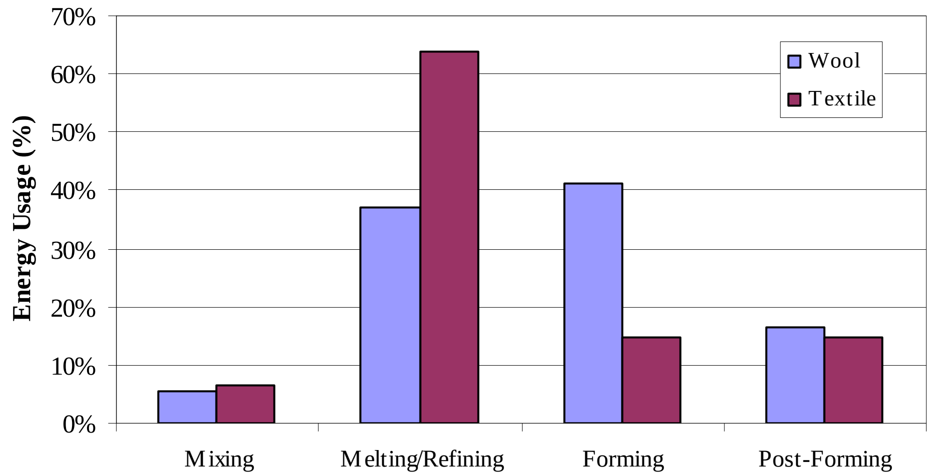

Figure 2: Glass Fiber Energy Usage for Process Phases

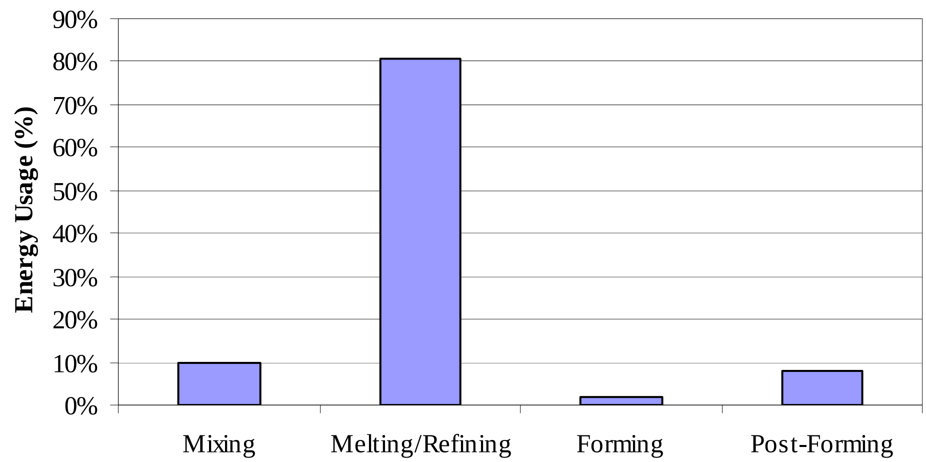

Figure 3: Container Glass Energy Usage for Process Phases

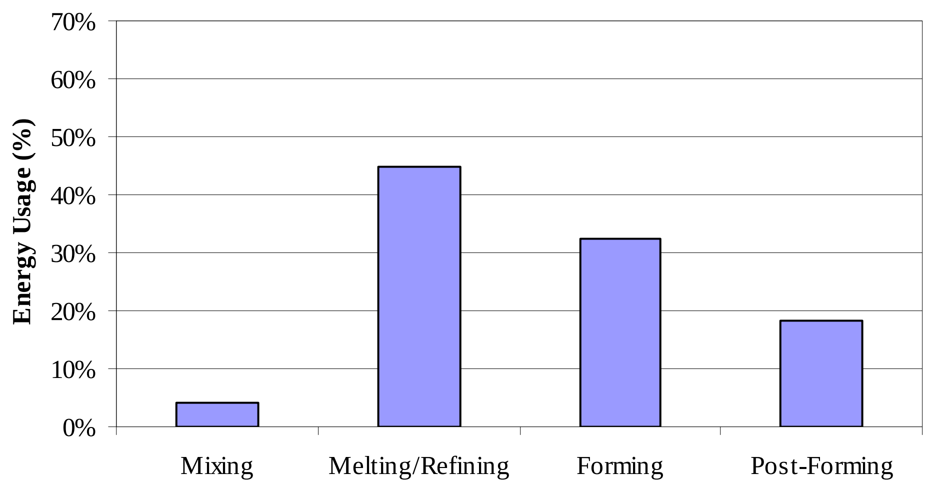

Figure 4: Pressed and Blown Glass Energy Usage for Process Phases

With the exception of wool fiber, the above figures illustrate that the melting/refining phase is the most energy-intensive. Pressed and blown glass is the only other segment with a process step (forming) coming close in energy consumption to the leading energy-consuming process step, melting/refining. For all glass-types the post-forming phase uses, on average, less than 20% of the overall production energy. Also notable is that the mixing phase consumes less than 10% of the total average energy for each glass type.

A closer look at the melting/refining phase portrays which glass sectors have the most room for improvement, as revealed by the industry interviews. The figures below show melting/refining energy consumption data plotted for each glass sector as the current average and also the predicted energy usage for state of the art, practical minimum, and theoretical, the same data tabulated above. Here, flat glass, glass fiber, and container glass are portrayed. Industrial survey data was not obtained for specialty glass primarily because of the wide process energy variations among the many glasses produced in the pressed and blown segment.

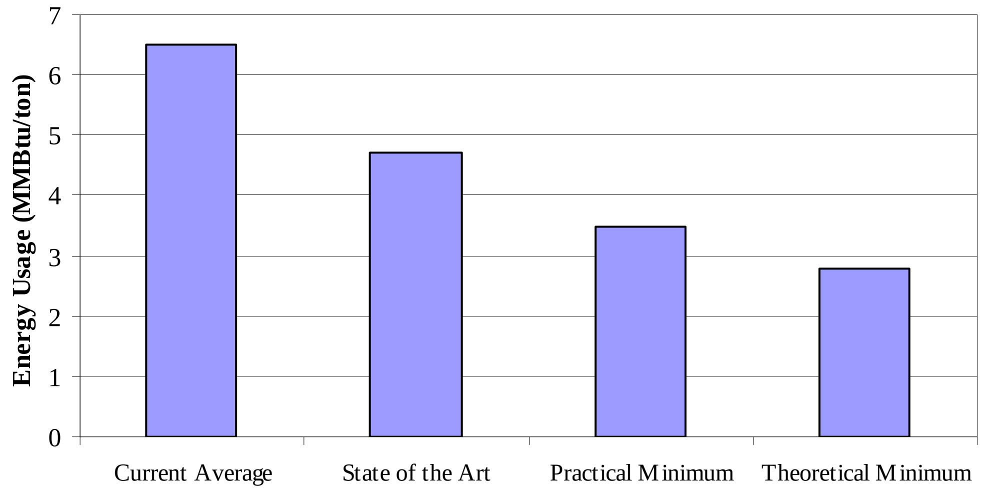

Figure 5: Flat Glass - (a) Current Average, (b) State of the Art, (c) Practical Minimum, and (d) Theoretical Minimum Energy Usage for the Melting/Refining Phase

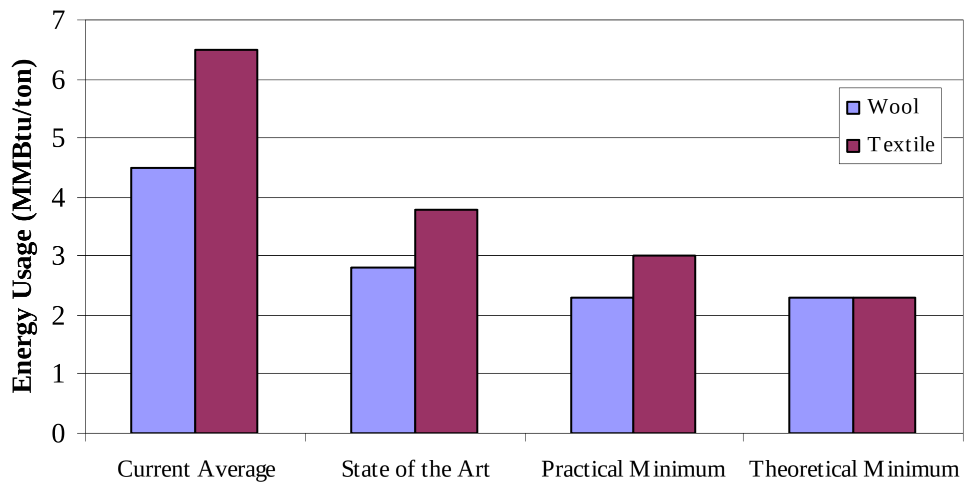

Figure 6: Glass Fiber - (a) Current Average, (b) State of the Art, (c) Practical Minimum, and (d) Theoretical Minimum Energy Usage for the Melting/Refining Phase

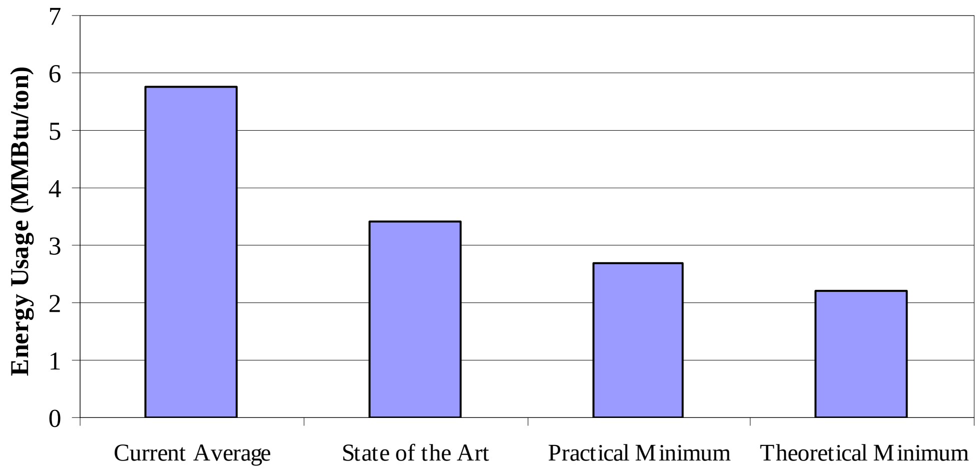

Figure 7: Container Glass – (a) Current Average, (b) State of the Art, (c) Practical Minimum, and (d) Theoretical Minimum Energy Usage for the Melting/Refining Phase

Energy for Oxygen Production

Many state of the art melting/refining furnaces are fired with oxy-gas burners instead of traditional air-gas burners. Switching to oxy-gas firing is a major technological shift, but the technology is now well understood and in common practice except in flat glass production. Oxy-gas firing is the single best available technology to reduce energy use in melting/refining. It is important, however, to recognize that energy is required to produce this oxygen. While many factors enter into the energy cost to produce oxygen, a full understanding of energy use requires presentation of the energy price to generate oxygen.

Table 12 displays the energy required to produce oxygen though three different methods. Cryogenic air separation (Cryo), Vacuum Swing Absorption (VSA), and Pressure Swing Absorption (PSA) are the three primary oxygen production methods in use with oxy-fired burners. The production energy associated with these three production types varies significantly, but the production method selection is primarily decided by the consumption volume and the price of the oxygen. Cryogenic oxygen production is the most energy efficient but is only used for large-scale production needs. For lower production levels cryogenic air separation is not economically sound and therefore VSA or PSA is used. Varying glass production operations have different glass production capacities and therefore the type of oxygen production selected by a glass producer will vary accordingly. A further factor in the selection of oxygen production method is the financial arrangements offered by the gas suppliers. These arrangements can vary depending on factors such as geography, electricity cost, and the presence of other oxygen customers nearby.

Table 12: Energy Required to Produce Oxygen for Use with Oxy-Fire Burners

Production Type	Production Energy [MMBtu/ton]	Production Volume [ton/day]	Purity [% O_2]
Cryo	0.84 – 1.36 [5,6,7]	> 50	90 – 99%
VSA	2.08 [8]	20 – 90	90 – 93%
PSA	2.60 [4]	< 20	90 – 95%

The energy savings realized by a glass melter firing oxy-gas burners is primarily from the natural gas saved. Oxy-fired melters are estimated to be up to 25% more efficient than conventional air-fired regenerative melters (although numbers between 25% and 45% have been reported)[9]. In order to estimate the savings with the use of oxy-firing, energy savings were calculated to be 25 – 45% more efficient than air-fired regenerative melters for melting/refining. The air-fired melter energy usages were deduced from the current average melting/refining energy data presented previously in this report (Table 4, Table 6, and Table 8) and the known percentage of each industry sector that uses air, oxy, and electric melters (Table 11). The oxy-firing energy data presented in the figures below represent the energy consumed from natural gas and the energy required for production of oxygen (the production of electricity used in the oxygen plant is estimated to be 35% efficient). The ranges of data presented result from estimated ranges of oxy-firing efficiency, oxygen production purity variability, and ranges of current average and state of the art melting/refining energy use.

Figure 8 - Figure 11 show the predicted melting/refining energy consumption for glass production assuming cryogenic, VSA, and PSA oxygen production plotted against the current average and state of the art melting/refining energy. Note that the current average is a 'snapshot' mix of air-fired and oxy-fired melters for each industry segment, and the ratio of air-fired to oxy-fired melters by industry segment is provided in Table 11. The three oxygen production method cases shown in each of Figures 8 through 11 assumes melters are using only oxygen.

Data for all of the glass sectors show the oxy-fire melting/refining energy averages to be between the current average and state of the art melting/refining energy averages. The ranges for each oxygen production type are slightly larger than that of the current average and state of the art melting/refining energy due to the range of savings that was assumed with a transition from air to oxy-fired melters. Examination of results presented in Figure 8 to Figure 11 confirms that even though oxygen production has an energy price, the use of oxygen provides an overall energy savings for glass melting/refining (sometimes large and sometimes small) and that oxy-gas

[5] Bolland, O. and Saether, S., "New Concepts for Natural Gas Fired Power Plants which Simplify the Recovery of Carbon Dioxide", *Energy Conversion and Management*, Vol. 33, No.5-8: 467-475, 1992.
[6] "Energy and Environmental Profile of the U.S. Glass Industry", Energetics Inc., 2002.
[7] "Carbon Dioxide Capture and Storage", Intergovernmental Panel on Climate Change, 2005
[8] Major Gas Supplier, Private Communications
[9] Congleton, K., "Process Improvement Through Oxy-Fuel Combustion – The Full Conversion of a Television Glass Melter", Proceedings from the 55th Conference on Glass Problems, 190-201, 1994.

conversion is the single largest part of the energy reduction in moving from current average furnaces to state of the art melters.

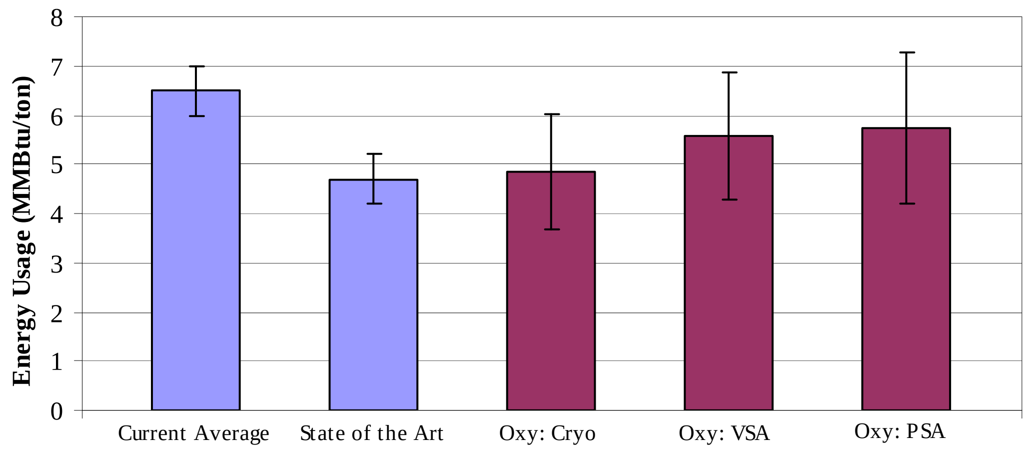

Figure 8: Flat Glass - (a) Current Average, (b) State of the Art, (c) Oxy Firing (Cryogenic Oxygen Production), (d) Oxy Firing (VSA Oxygen Production), and (e) Oxy Firing (PSA Oxygen Production) Energy Usage for the Melting/Refining Phase

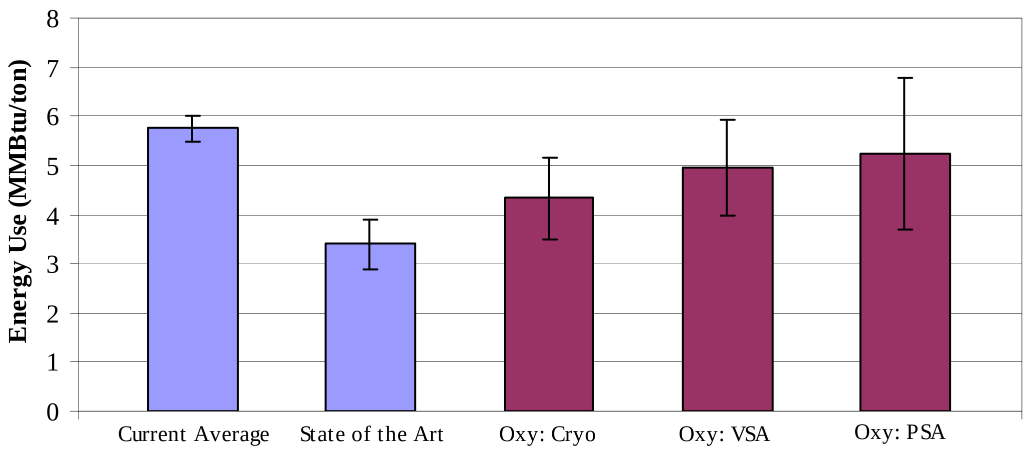

Figure 9: Container Glass - (a) Current Average, (b) State of the Art, (c) Oxy Firing (Cryogenic Oxygen Production), (d) Oxy Firing (VSA Oxygen Production), and (e) Oxy Firing (PSA Oxygen Production) Energy Usage for the Melting/Refining Phase

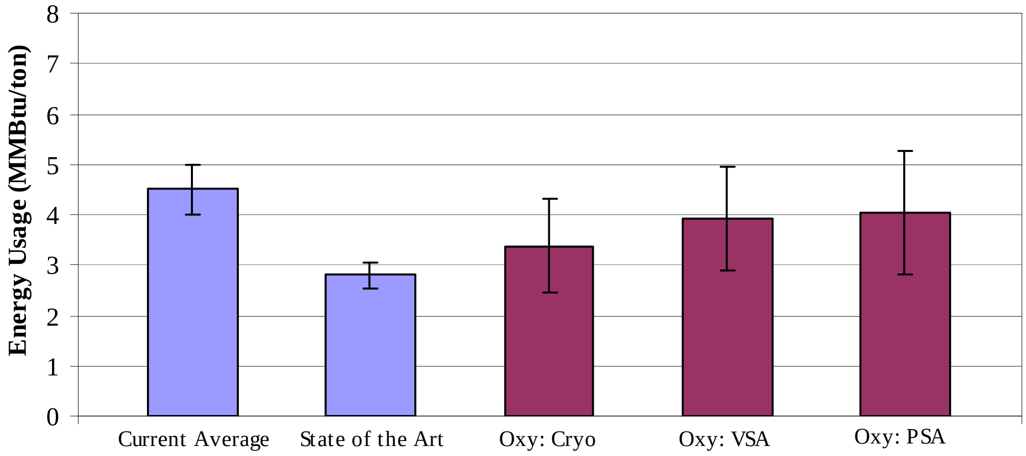

Figure 10: Wool Fiber - (a) Current Average, (b) State of the Art, (c) Oxy Firing (Cryogenic Oxygen Production), (d) Oxy Firing (VSA Oxygen Production), and (e) Oxy Firing (PSA Oxygen Production) Energy Usage for the Melting/Refining Phase

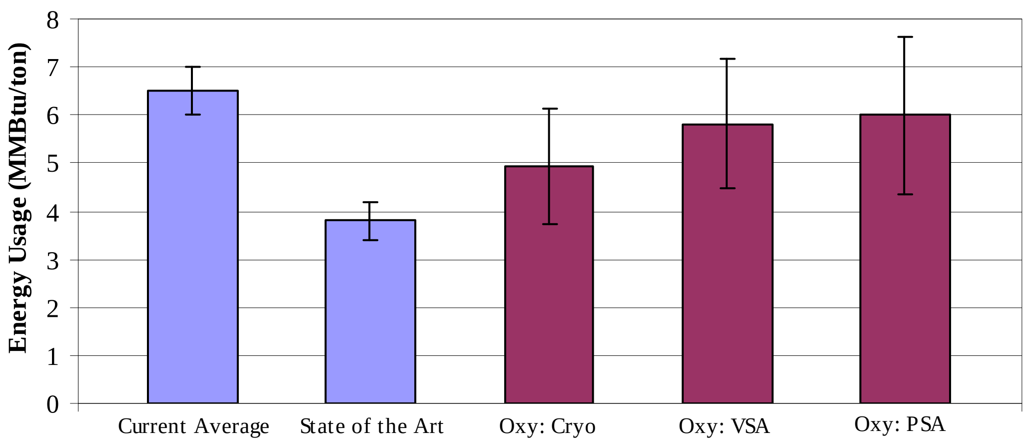

Figure 11: Textile Fiber - (a) Current Average, (b) State of the Art, (c) Oxy Firing (Cryogenic Oxygen Production), (d) Oxy Firing (VSA Oxygen Production), and (e) Oxy Firing (PSA Oxygen Production) Energy Usage for the Melting/Refining Phase

Potential Energy Savings from Melting Technology Adoption

The data presented in Figure 5 - Figure 7 was analyzed further to better understand the potential energy savings in each glass sector. Figure 12 plots the potential energy reduction for the melting/refining step of glass making. Potential energy savings for glass fiber (wool), glass fiber (textile), container glass, and flat glass are shown as a percentage of the current average energy use. Percent energy savings are shown 1) when moving from current average technology to state of the art, 2) when moving from state of the art technology to that which uses the practical minimum energy, and 3) the total of these two (moving from current average to practical minimum). This figure reflects the relative gains between changing to state of the art technology versus those gained by further moving towards the practical minimum. With the exception of flat glass, the relative potential for energy reduction when changing to state of the art melting/refining technology yields at least three times the gains portrayed for the further advancement to the practical minimum technology. This illustrates that the immediate gains for melting/refining are much more substantial than those realized when pushing towards the practical minimum after state of the art technology has been implemented. This analysis is cost-insensitive. Glass makers may choose to not adopt state of the art technology for energy use if this decision increases the overall cost of glass making.

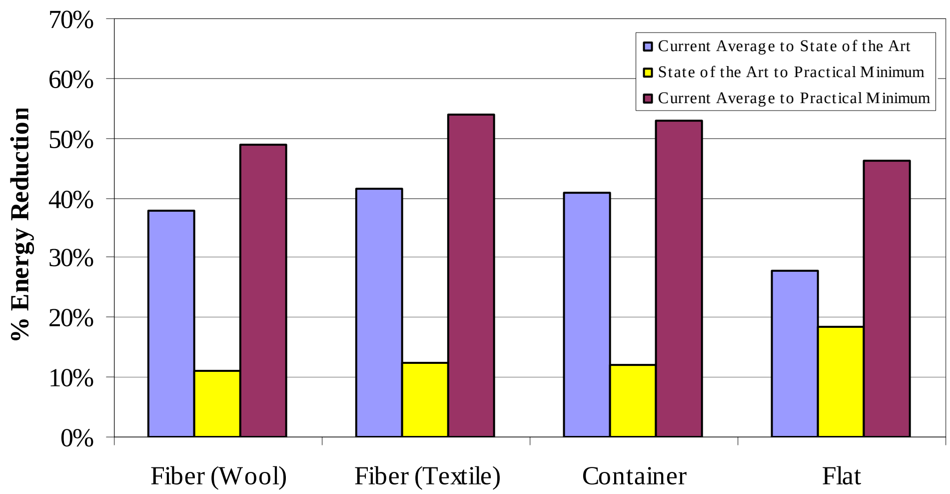

Figure 12: Potential Percent Energy Reduction For Glass Melting/Refining When Converting From (a) Current to State of the Art, (b) State of the Art to Practical Minimum, and (c) Current to Practical Minimum

Figure 13 portrays the absolute gains (per ton of glass) in energy usage that are possible for melting/refining for the glass sectors. Glass fiber (textile) is shown to have the largest potential energy savings per ton of glass production in the immediate future as the industry moves towards state of the art melting technology. Container glass, flat glass, and glass fiber (wool), in descending order, follow in energy saving potential. The figure shows flat glass with the highest potential energy savings when jumping from state of the art to the practical minimum, while glass fiber (wool) shows the least amount of energy savings for this step, only 0.5 MMBtu/ton.

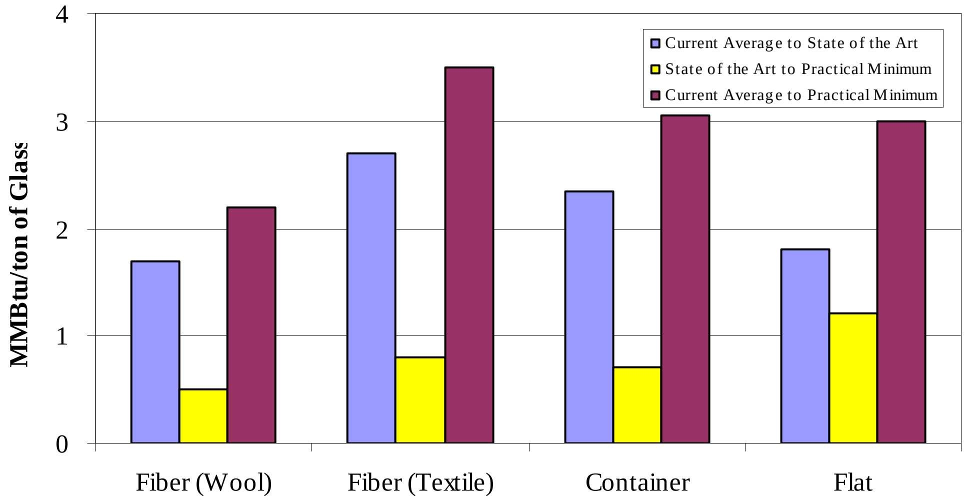

Figure 13: Total Potential Energy Reduction per Ton Produced For Glass Melting/Refining When Converting From (a) Current to State of the Art, (b) State of the Art to Practical Minimum, and (c) Current to Practical Minimum

The glass production rate, production market share, current average melting/refining energy usage per ton of glass (from above), and the current total energy usage per year for all of the glass sectors is displayed in Table 13. Most notable on this table is the dominating production rate of the container glass sector over all other sectors, more than three times that of the next highest sector. The current average energy usage for the entire glass industry is shown to be over 170 trillion Btu per year.

Table 13: Glass Production and Market Information by Sector

Sector	Production [MMton/yr]	% of Market	Current Average Energy, Melting/Refining [MMBtu/ton]	Total Energy, Melting/Refining [TBtu/yr]
Wool Fiber	3.0 [10]	15%	4.5	13.7
Textile Fiber	0.8 [1]	4%	6.5	5.3
Container	9.4 [11]	47%	5.75	54.0
Flat	5.3 [12]	26%	6.5	34.2
Specialty (Pressed & Blown)	1.7 [1]	8%	7.3	12.1
Total	20.2	100%		119.4

[10] "Energy and Environmental Profile of the U.S. Glass Industry", Energetics Inc., 2002.
[11] US Census Bureau, "Glass Containers: 2001", 2002, *http://www.census.gov/industry/1/m327g0113.pdf*.
[12] US Census Bureau, "Flat Glass: 2002", 2003, *http://www.census.gov/industry/1/ma327a02.pdf* .

The combination of the current glass production rates with the energy savings potential shown in Figure 13 yields the total potential energy reduction per year for glass melting/refining in each sector. This data is plotted in Figure 14. The large production rate of container glass yields a large energy savings advantage over all other glass sectors. Container glass melting/refining stands to reduce energy consumption by more than 20 TBtu/yr by converting to state of the art technology and an additional 6.5 TBtu/yr by conversion from state of the art to the practical minimum. All other glass sectors shown are predicted to save less than 10 TBtu/yr each for complete conversion to state of the art technology and less than 7 TBtu/yr each for the additional step to practical minimum. Over all of the glass sectors shown here (not including specialty glass), there is a total potential of energy savings of 39 TBtu/yr for the melting/refining phase for full implementation of state of the art melting/refining technology and an additional 15 TBtu/yr potential savings (based on current production rates) for the next step of changing to practical minimum technology.

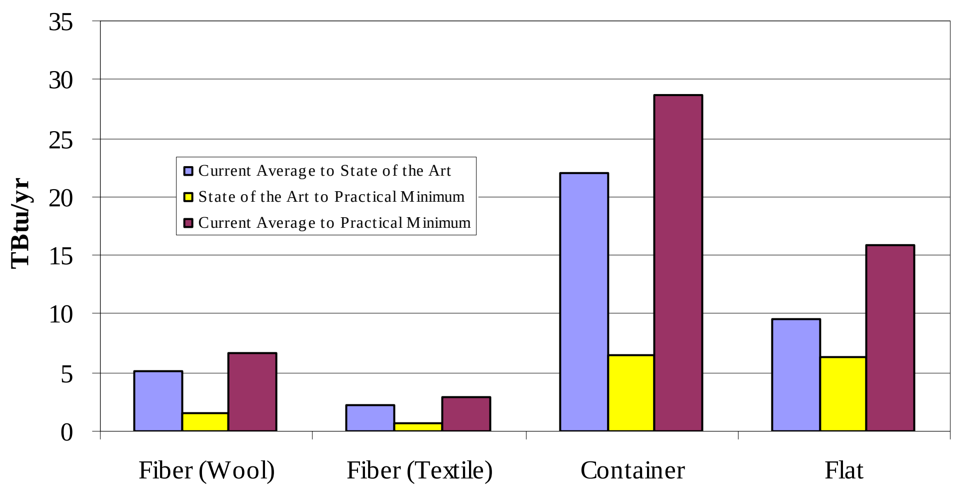

Figure 14: Total Potential Energy Reduction Per Year For Glass Melting/Refining When Converting From (a) Current to State of the Art, (b) State of the Art to Practical Minimum, and (c) Current to Practical Minimum

Glass-making is a mature industry with small profit margins in many segments. For that reason, changes occur slowly and are most commonly adopted at the end of a 5 to 15 year furnace 'campaign' when a melter is replaced. Melters are capital-intensive and management must weigh the cost savings from energy savings against the added cost of more state of the art melters. This is often a difficult decision, and choices tend toward best practice and lowest long-term cost of overall corporate operation. The question of adopting more state of the art melters (best practice) or adopting new technology that may be significantly more energy efficient, as well as less costly, is a decision that management will make on a case by case basis as technology matures. No matter what approach each glass company chooses, changes will always be slow and will follow the life cycle of the costly melters. There is clearly room for energy savings, and clearly room for large energy savings by both best practice (moving toward state of the art melters) and by adopting new types of less costly melters.

The glass industry is both capital and energy intensive. This situation compels both slow change and conservative decisions. Within this framework is a need for both best energy practices and the development of new energy saving technologies that are more cost competitive. Economic analyses are in the hands of each glass maker, and energy decisions are ultimately cost decisions. The best approach for any glass maker is to take best advantage of available, cost-effective technologies and to seek new technologies for both savings and competitive advantage. With this in mind the glass maker understands clearly that no single technology will bring a current average glass making process to state of the art, but rather a combination of technologies; some simple and inexpensive and some complex and costly.

Glass Industry Conversion to State of the Art Technology

In literature review, discussions with glass industry technologists, and review with glass processing experts, a number of means to move from current average (or current practice) to state of the art melting and refining have been examined. Some technical approaches apply to all industry segments, while others are not practical for certain segments. Also, energy savings and cost advantages can vary between different industry segments.

The results of this evaluation process are presented in Table 14. Results are ranked on a scale of Y/N or of 1 to 10, with 10 being the greatest savings or greatest benefit. The relative scale is employed rather than listing quantitative values for several reasons. Benefits are often difficult to quantify between industry segments, and even between plants in the same industry segment. Also, as technologies mature, costs and benefits will change. The goal of Table 14 is to present the most reasonable and promising means to achieve state of the art melting and refining. Review of the table allows a ranking of the most promising, cost-effective, and energy-savings technologies.

Eleven energy saving technologies have been identified. These are listed in Table 14 along with the maturity of the technologies, the applicability of the technologies as a retrofit or a rebuild-only approach, the relative cost implications, and the relative energy savings potential of the technologies.

Table 14: Glass Melting/Refining Technologies Evaluated Qualitatively for Practicality, Cost, and Benefit (1 is Lowest to 10 is Highest)

Technology	Technology Maturity [1-10]				Rebuild Required?				Cost of Implementation [1-10]				Energy Savings Benefit [1-10]			
	Textile Fiber	Wool Fiber	Flat	Container	Textile Fiber	Wool Fiber	Flat	Container	Textile Fiber	Wool Fiber	Flat	Container	Textile Fiber	Wool Fiber	Flat	Container
Cullet Percentage	2	8	8	10	N	N	N	N	3	3	3	2	2	4	2	2
Batch Preheat	2	2	2	2	Y	Y	Y	Y	8	8	10	8	8	8	8	8
Cullet Preheat	2	2	2	2	Y	Y	Y	Y	5	5	5	5	6	6	6	6
Oxy-fuel Conversion	10	10	4	7	Y	Y	Y	Y	9	9	9	9	5	5	5	5
Partial Oxy-fuel Conversion	10	10	8	10	N	N	N	N	1	1	1	1	2	2	2	2
More Efficient Air-Fuel Burners	8	8	8	8	N	N	N	N	2	2	2	2	3	3	3	3
Improve Refractory	6	6	6	6	Y	Y	Y	Y	4	4	6	5	1	1	1	1
Improve Control System	6	6	6	6	N	N	N	N	3	3	2	2	2	2	2	2
Alternate Fuel Gas	1	1	1	1	N	N	N	N	2	2	2	2	1	1	1	1
Exhaust Gas Heat Recovery	4	4	4	4	N	N	N	N	7	7	7	7	8	8	8	8
Convective Melting	3	3	3	4	N	N	N	N	3	3	3	3	3	3	3	3

<u>Cullet Percentage</u>

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. However, cullet must be collected from post-consumer use (since only small quantities of in-plant cullet are usually available). Dependence on a stream of high-quality cullet often limits the ability to use large amounts of the material. Container glass is most amenable to cullet use, with amber glass the most easily recycled and flint glass the least easily recycled. Flat glass and pressed and blown glass are more difficult to recycle because of higher quality requirements and more precise compositions of smaller melt streams. Fiberglass presently cannot be recycled because technologies are not available to cleanly remove resins and generate clean glass and because foaming is difficult to control.

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 (for raining bed preheaters, for example). A further complexity relates to the difficulty of handling heated batch material. Soda ash begins decomposing at relatively low temperatures, and the batch material will soften and stick together or to surfaces in the preheater. This limits the possible preheating temperature and adds hardware complexity and cost.

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. This conversion will only be undertaken by industry after careful economic analysis and at the end of an air-gas furnace campaign. Decreasing oxygen costs and increasing gas costs are making oxy-gas conversion more attractive. Oxy-gas conversion is discussed in more detail below.

Partial Oxy-Gas Conversion

On some melters, particularly near the end of a campaign, oxygen is substituted in one or two burners, or a /zero port/ oxy-gas burner is added. The additional heat allows pull rate to be increased and can increase melter efficiency. As a global industrial approach, this technology is a temporary measure and not as beneficial as full oxy-gas conversion. The advantage of partial conversion is the ability to enhance performance of an older melter.

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 for air-gas or oxy-gas melters if capital cost is 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. The cost of the control system is factored into the cost of the furnace and its full campaign.

Alternative Fuel Gas

Natural gas is the predominant glass industry fuel in the U.S. Rising fuel prices have encouraged the industry to consider other, less costly, fuel options. The amount of energy saved using alternative fuels is still unknown, but the savings will be lower than the savings from other techniques listed. Price would be the primary driving force in switching to alternative fuels, but the supply must be both 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 them 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 industrial ability to recover much energy from the low temperature exhaust leaving the bottom of the regenerators (under 800°F). Exhaust gas from oxy-gas furnaces is less than 30 percent of the volume of air-gas furnace exhaust, but no heat is currently recovered from oxy-gas melter exhaust. This high-level heat (2000° - 2400°F) 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. Recuperator materials concerns, fouling, and cleaning have hampered introduction of technologies for exhaust gas heat recovery, but higher fuel costs make costs more attractive.

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.

Further Discussion of Adopting Oxy-Gas Combustion

Since oxy-gas conversion has been found to be the most practical near-term technology moving toward state of the art melting and refining, a more detailed evaluation has been given of the impact of oxy-gas conversion on glass melting.

The first step towards energy savings for the glass industry is to look at the ability and willingness of the glass sectors to convert to state of the art melting/refining technologies. Some sectors have already begun this conversion as environmental standards are tightened and as new facilities are built.

The primary melting/refining state of the art technology for container glass, flat glass, and textile fiber is the implementation of oxy-fuel burners. Insulation fiber state of the art melting/refining technology is a mix of oxy-fuel burners and efficient electric melters. Here, the state of the art technology varies by region and is dependent upon the cost of fuel and electricity throughout these regions.

Transitioning from current melting/refining technology to state of the art technology involves the consideration of several factors. The conversion to state of the art technology will include the consideration of new plants being built for a glass sector, the capital costs of new melters, and the costs associated with converting the technology of an existing plant. The decision for converting to state of the art technology is often based upon environmental factors or capital costs rather than energy savings. Furnace life extension and lower maintenance costs for oxy-gas melters can also affect decisions.

The container glass sector is currently building almost no new plants. The capital costs for conversion to oxy-fuel is a barrier for any industrial member to move quickly towards this technology. If a new technology, such as submerged combustion melting (SCM), can prove to be viable then a transition may occur faster, provided that capital costs are significantly lowered with SCM. The container glass sector is currently unable to generate enough ROI to justify the conversion costs that come along with implementing a new technology. The technology conversions to oxy-fuel that have occurred in the past were primarily pushed by environmental regulations.

The flat glass sector is building new production plants which are implementing oxy-fuel technology in limited numbers. Here, as with container glass, the conversion to this state of the art technology is limited due to the capital costs required. Environmental factors are the primary driver for this glass sector to move to oxy-fuel burners. The move to a process like P-10 in flat glass is not justified based upon today's cost picture, even with current higher fuel costs. SCM is not large enough in scale to be considered for flat, presently or in the near-term.

The textile fiber glass sector has begun to move toward oxy-fuel technology implementation at a faster rate than the container and flat glass sectors. However, this sector is being prevented from further conversion due to ROI. The only new plant to supply glass to the U.S. market has been built in Mexico by Owens Corning and Saint Gobain.

At present, the insulation fiber sector is the brightest picture for state of the art technology conversion. New insulation fiber plants using state of the art melting/refining are being planned. Where ROI is justified, plants are moving towards oxy-fuel or state of the art electric melters, dependent upon energy cost by region.

It should be noted that although all glass sectors realize that preheating cullet or batch could drive down energy costs, no sector is actively pursuing preheating. This lack of preheating is due to assumed high capital costs and fear of inconsistency and unreliability in preheating operations. This technology may need to be proven by a demonstration before industry will get really interested. Preheating was widely trialed in the 70's during the U.S. energy crisis and has found favor in Europe due to legislative incentives and higher energy prices.

Table 15 shows each glass sector presented here and the primary state of the art melting/refining technology along with qualitative ratings for the potential energy savings for transition to state of the art technology, the cost of transition to state of the art technology, and the perceived willingness of the sector to implement state of the art melting/refining technology. Here, a higher score corresponds to higher energy savings, higher cost of transition, and a higher willingness to transition to state of the art technology, respectively. Oxy-fuel melting/refining technology is state of the art for all sectors while both fiber sectors also include efficient electric melters in this category, dependent upon the energy/gas costs in a given region. The potential energy savings are based upon the production rates shown in Table 13 and the energy consumption values in Table 9. Container glass stands to save the largest amount of energy by complete transition to state of the art melting/refining technology (44 TBtu/yr), while flat glass, wool fiber, and textile fiber yield scores of 2, 1, and 1, respectively (9.5, 3.4, 5.4 TBtu/yr). The cost of transition to state of the art technology, as evaluated by Dr. Warren Wolf and his interviews with industry members, show flat glass with the highest cost followed by container glass (8), textile fiber (6), and wool fiber (4). No sector is perceived to have an extreme (10) willingness to adopt state of the art melting/refining technology. The willingness of the glass sectors to adopt these new technologies is roughly opposite that of the cost of the transition, where wool fiber is viewed to be the most willing (8), followed by textile fiber (6), flat glass (4), and container glass (2).

Table 15: Transition to State of the Art (SOTA) Technology (a) Energy Savings, (b) Cost, (c) and Sector Willingness

Sector	State of the Art Melting/Refining Technology	Potential Energy Savings after Adopting SOTA [1-10]	Cost of Transition to SOTA [1-10]	Perceived Willingness of Sector to Adopt SOTA [1-10]
Wool Fiber	Oxy-fuel / Electric	1	4	8
Textile Fiber	Oxy-fuel / Electric	1	6	6
Container	Oxy-fuel	10	8	2
Flat	Oxy-fuel	2	10	4

Beyond State of the Art

Review of the current average and state-of-the-art status of energy use in the glass industry necessitates taking a 'snapshot' view of current practice and available technologies across the different industry segments and across the major process steps. A further question deserving at least some consideration is what approaches can be imagined that might move industrial practice beyond state-of-the-art toward the practical minimum energy use. A list of these technologies and their potential means of application is attempted knowing that the list is incomplete in technologies and application methods. As technology advances, scientists and engineers from inside and outside the glass industry continue to devise more energy-efficient technologies.

As mentioned earlier, technologies can not be adopted by industry until they have reached a high level of maturity and reliability, and they must provide sufficient ROI. A partial list of energy-saving concepts that may eventually meet these requirements with further development is presented below.

The authors were encouraged in a second effort to examine options for energy savings beyond state of the art in further detail. This work was carried out in a similar manor to the earlier effort by reading the literature but primarily by personal discussions with experts. Much of this communication was confidential with regards to sources, but the information disclosed in this report was considered to be non-proprietary. The authors included written and personal sources in Europe as well as the United States. While European practice is somewhat different from American operations, technological advances are ultimately shared across national borders. For that reason, the widest possible net was cast by the authors. Areas identified for energy savings in the first and second rounds of study by the authors were:

Technology	First Survey	Second Survey
Advanced melters		
Rapid refining		
Alternative raw materials		
Exhaust gas heat recuperation		
Fluxes		
Heat recovery from cooling glass		
Higher strength glass		
Glass composite or hybrid materials		
Cullet		
Batching practices		
Batch and cullet pre-heating		
Sensors and advanced controls		
Environmental practices		
Other practices		

Results of the first and second survey stages are combined in the paragraphs below. When an area was addressed in both survey stages, the second stage information augments the initial survey results.

<u>Advanced melter designs</u>

The patent and published literature from around the world, including a Technical and Economic Assessment[13] and a melting technology workshop[14], both supported by DOE, have proposed and discussed a wide range of new approaches to glass melting. Comparison of melting approaches in Europe and the U.S. was presented at the Siemens Glass Day in 2007[3]. Review of this body of literature is beyond the scope of this study, but examination of this body of work from an energy savings perspective leads to several observations. First of all, many proposed melting approaches are clearly impractical as economical industrial processes. Other approaches could

[13] U.S. Department of Energy – Industrial Technologies Program, “Glass Melting Technology: A Technical and Economic Assessment”, Glass Manufacturing Industry Council, 2004.
[14] Glass Manufacturing Industry Council, “Glass Melting Technologies of the Future”, GMIC Workshop, Washington D.C., February 22, 2001.
[3] Siemens Glass Day, Pittsburgh, PA, May, 2007.

offer insights into improved melting methods but have never been tested. Still other methodologies, most notably the P-10 process and the Advanced Glass Melter, received considerable support and development but were abandoned for various reasons. Significant process knowledge was gained from these and other projects. Several approaches to lower the energy of melting are currently at various levels of development. The Sorg LoNOx melter is now commercial for high-cullet container glass. The submerged combustion melter is being scaled to a 1 ton/h pilot-scale melter. The Plasmelt process is being scaled to 500 lb/h. Other melting approaches including microwave heating, centrifugal melters, and ultra-rapid melting are not presently being tested. Implementation of any advance melting approaches will demand rigorous testing, proof of reliability, energy savings, lower capital cost, a lowering of air-borne emissions, and overcoming a number of other operational hurdles. Industry will only adopt a new melting technology if that technology does everything current melters can do, while offering benefits in capital cost, energy savings, emissions reduction, reliability, and/or glass quality.

Every four years starting in 1999 and repeated in 2003 and now in 2007 the Netherlands has sponsored TNO to do an energy efficiency study of glass melting facilities throughout Europe. The 2007 results are still being collected and will not be officially published until 2008. Using 2003 results, numbers collected in Europe were compared with those that were obtained in the U.S. during the first Bandwidth Study. These studies have surveyed about 280 furnaces in 1999 and 2003 although there are many repeats in the surveys between the two survey years. About 230 were container furnaces, 40 were flat/float furnaces and there were about 10 others including mostly continuous glass fiber.

Results for the most energy efficient furnaces in the glass container section were almost identical with results of 3.3-3.4 MMBTU/Short Ton.

In the U.S. the most energy efficient container glass furnaces tended to be oxy-fired. In Europe there is less enthusiasm for oxy-firing reflecting concerns over the long term operational efficiency of oxy-fired furnaces and particularly the issues around furnace environments, the added H_2O, and these effects on refractory life. Some of these issues also appear in the U.S. but the trend to have concerns over oxy-firing appears stronger in Europe. In part this could be due to less experience with oxy-firing in Europe.

Some experts in Europe feel cross fired regenerative furnaces with batch and cullet preheating are more competitive in the glass container sector than oxy-firing. It appears important for oxy-fired systems to develop good processes for batch and cullet pre-heating to ensure that oxy-firing continues to be regarded as the most energy efficient process in both the container and flat glass sectors where regenerative furnaces have long experience and record of use.

One European installation has trialed successfully using burner blocks that can be used for either air-gas or oxy-gas firing. This was done so the facility could use oxy-gas firing but be able to quickly switch to air-gas if needed. The oxy-burners fit in blocks designed for air-gas burners but are made of refractory with higher temperature resistance. Spinel has been used and now zirconia is being trialed. Each zone control is modular and uses mass flow controllers for the combustion gas and oxygen. Controllers are of the same size and interchangeable. One controller cleaned for oxygen use can be held as a common spare for both gases and programmed as needed. Installations have tended to be on borosilicate glasses and only up to about 120 tonnes per day. One major innovation was to bring down the cost of dual use burners. The borosilicate glasses as well as glass fiber operations are key targets for this dual use as boron is under strong regulatory pressure and the use of oxy-fuel has been able to reduce boron emissions as well as NO_X emissions. The first installation is the U.S. may occur shortly at World Kitchen.

Global climate change discussions have created interest among glass makers in new glass melting technology. As noted there is a marked reluctance among container and float/flat glass makers to use oxy-fuel and even smaller borosilicate glass makers are trying to hedge as they are forced to move to oxy-fuel to reduce boron emissions by being able to quickly move back to gas-air if needed. But most of this known reluctance should not overstate the fact that glass makers now realize they will need to move to more energy efficient glass melting as regulations are implemented around global climate change.

There was high interest at the Strasbourg ICG meeting (June 2007) over the need for more innovation in glass melting. The Submerged Combustion Melter presentation[2] received high attention. Most notable was a paper on the status of the float glass operations in Europe where it was explicitly stated that the next needed innovation in the float industry would have to occur in the melting area. But no specific direction was discussed nor was any mention made of past innovative attempts in float melting such as P-10. The Chinese Ceramic Society presented a paper on the status of float glass operations in China. There were about 300 float lines operating globally at the end of 2006 and China has 161 of them. None of the float lines in China use oxy-fuel melting.

Rapid refining processes

Refining or conditioning of 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[15]. Most methods rely on modifying one or more variables in the Stokes equation for the bubble velocity through a liquid. Proposed mechanical refining approaches are limited, with ultrasonics and mechanical shearing serving as examples of proposed approaches. The Stokes equation states that the velocity of the rising bubble is directly proportional to gravitational constant to the square of the bubble diameter and to the difference in liquid and bubble density and is inversely proportional to liquid viscosity. The list of approaches includes:

- Sub-atmospheric refining
- Thin-film refining
- Ultrasonic refining
- Centrifugal refining
- Inert gas (helium) refining
- Steam refining
- Microwave refining
- Shearing to promote mechanical refining
- Mechanical stirring

Sub-atmospheric refining has been operated successfully at pilot scales up to 300 tons per day and has achieved limited commercial application. Inert gas refining exploits the high diffusivity

[15] Glass Manufacturing Industry Council, “Next Generation Refining / Conditioning Workshop”, GMIC Workshop, Pittsburgh, PA, May 20, 2004.

[2] "*Combustion flow patterns and discrete particles trajectories in a submerged melter"*, Grig Aronchik, Bruno Purnode, David Rue, Proc. 9th Int. Sem. on Math. Modeling of Furnace Design and Operation Velke Karlovice, Czech Republic, June 27-29, 2007.

of the inert, monotonic helium through the molten glass for removing bubbles and has reached the commercial demonstration stage. Thin film refining has been proven at pilot scales and is employed in some melters that use a shallow refining shelf. Often thin film refining is combined with other methods to shorten the refining time. The other methods proposed, and methods not listed, have not gone beyond technical proposals or small-scale testing. A summary of proposed advance refining approaches is presented in Table 16.

Table 16. Status of Proposed Advanced Refining Approaches

Rapid Refining Approach	Status	Description
Sub-atmospheric refining	Commercial	Vacuum of 0.1-0.2 atm. needed to rapidly remove bubbles. Workable but challenging to apply.
Thin-film refining	Commercial	Used to decrease distance needed for bubbles to rise to melt surface. Multiple means of implementation.
Ultrasonic refining	Lab-scale (abandoned)	Complex mechanisms enable movement of bubbles in molten glass. Scale-up is complex.
Centrifugal refining	Lab-scale (abandoned)	Successfully removes bubbles in short times (under 1 hour). Rates of up to 1000 rpm are required.
Inert gas (helium) refining	Demo-scale	Fast-rising helium bubbled through molten glass to scavenge other bubbles.
Steam refining	Conceptual	Steam bubbles introduced rise quickly and scavenge fine bubbles from molten glass.
Microwave refining	Demo-scale	Microwaves precisely heat glass to lower viscosity and increase bubble velocity.
Shearing to promote mechanical refining	Conceptual	Glass passes in thin layer between a static and a moving plate to shear bubbles.
Mechanical stirring	Commercial	Slow stirring brings bubbles close to surface. Limited utility. Can not remove all bubbles to meet quality requirements.

Another consideration regarding glass refining is the potential to combine two or more approaches. For example, combining vacuum refining with another approach could allow the use of a smaller refining chamber or lower the amount of time or amount of vacuum required.

Refining needs very significantly between industry segments. Requirements are commonly presented in two ways: maximum allowable bubble size and maximum number of allowed bubbles per unit volume or mass of glass. Requirements become increasing stringent in proceeding from wool fiber to continuous fiber to container to flat glass. Therefore, when considering rapid refining technologies, the refining requirements for a specific type of glass must be taken into consideration. Specialty glasses can have even more stringent refining requirements, but methods used for these glasses are beyond the scope of this report.

Currently many sectors in the glass industry in both the U.S. and Europe are under scrutiny to remove or reduce materials widely used in refining of glass such as arsenic, antimony and selenium. Although work is being done on new chemistries the refining times are increasing for many glass operations which in turn increases total energy used in glass making.

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.

Glass makers in the U.S. and Europe are looking at raw materials further down the reaction path than those often used in glass making. Examples include replacing limestone or dolomitic limestone with calumite, burnt dolomite, or quick lime, as well as Synsil (a calcium magnesium silicate). Because of the balance of energy savings against cost and availability, there is no large movement toward these raw materials in the U.S. or Europe. Some European and American facilities use of small amounts of lithia as a base additive but usually to get production out of an aging furnace rather than for energy savings. There is currently no real difference between American and European batching practices and no large movement to non-carbonated raw materials or lithia.

Research continues in this area with work at Alfred University under Bill Carty and others to pre-react raw materials to aid melting and presumably reduce energy of melting. In separate work, Jon Bauer recently presented a paper providing a perspective on better melting with better raw materials and the impacts on energy reduction and greenhouse gas emissions.

Exhaust gas thermo-chemical recuperation

Waste heat recovery, particularly from oxy-gas melters, offers a means to lower energy use. Several approaches, such as recuperation, steam generation, and thermo-electric production of electricity 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 lithia, offer means to lower the melting temperature (and therefore the energy) needed for melting. Lithia, however, is costly compared with other raw materials, 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 to lower energy use 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.

[1] Jon Bauer, ACerS, Glass and Op. Mat. Div., slides (unpublished), Rochester, NY, May, 2007

Higher strength glass

Radically increasing the strength of glass[16] 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.

Cullet use

Of strong significance is that European energy studies are able to estimate their use of high cullet percentages in glass container operations saves about 29% total energy in glass melting. This appears to be a significant opportunity for U.S. operations to improve energy efficiency very quickly by moving to processes that would allow better collection of cullet and its uses within the U.S.

Europe is far ahead of the U.S. is the use of recycled glass cullet, especially in the glass container field. This is due both to higher landfill costs but especially to regulations. In glass containers Europe as a whole has a 56% cullet average but this is lower than most practices because the manufacturers of perfume bottles bring this down considerably as they can only use their own reject and can not buy on the open market. Flint makers have been able to push cullet to around 70%. Beyond this point decolorizing problems occur, so this seems to be a practical limit for flint. Amber can go to possibly 80%, and green glass is pushing toward 92 % as an upper limit.

Cullet quality is a concern in both Europe and America. In Europe some companies such as Saint Gobain run their own recycling centers. St. Gobain is reported to have at least four recycling centers in operation.

An interesting story to illustrate the importance of regulation and governmental concern over land filling comes out of the U.K. In the UK there is almost no green container manufacture as the U.K. does not bottle wine where green glass is used. But the U.K. is an importer of green wine bottles. Since most U.K. container makers are flint the green cullet cannot be used. The U.K. is now forcing external wine makers to ship wine in large vats where in the future they will be filled in green bottles at U.K. plants using the green cullet as up to 90% of the batch

Batching Practices

Activity is low in development of new batching practices. Glass companies continue to look at new charging approaches, but this is aimed at improved operations rather than energy savings. Pelletization is attracting little interest due to the complexity it adds to operations. This seems to be equally true in America and Europe. On the other hand at least one small glass specialty glass maker in Germany appears to be using batch pelletization, but this technology is not attracting any interest among major glass makers.

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[16] Green, D. J., "Recent Developments in Chemically Strengthened Glasses", 64th Conference on Glass Problems, The American Ceramic Society, 2004.

Batch and Cullet Preheating

Long identified as a promising energy-saving technology, batch and cullet preheating has realized very little commercial success. Problems with preheating batch have proved more difficult to resolve than anticipated, movement of large quantities of preheated batch requires careful engineering design, volatilization and particulate carryover questions have not been put to rest, and overall cost and size of equipment can be prohibitive relative to energy savings. Cullet preheating must be considered separately. Cullet preheating systems do not have many of the concerns that plague batch preheating systems, making cullet preheating both more cost effective and more reliable.

There is a larger trend toward adopting batch and cullet preheating in Europe than is the U.S. European sources confirm that about 8 preheaters for batch and /or cullet have been put into Germany and at least one in The Netherlands. A possible tenth unit put into Italy near Milan has recently stopped operation for unknown reasons.

Specific data on current preheating operations could not be obtained, possibly because many facilities are still being evaluated. Installations appear to be on smaller tonnage pulls and not on any large container or float tanks. A reliable report from within the largest European glass manufacturer reveals that their analyses of cullet and batch preheating concludes that the use of batch and cullet preheaters would only become a wide spread practice if carbon is priced around 40-50 Euros/tonne either by a carbon tax or through a cap and trade system. The reason for the pessimism is that operational costs associated with pre-heaters are still higher than deemed desirable, and the experience to date suggests that preheaters are still too complex for large tank operations unless some of the operational issues can be solved through innovation and/or the cost associated with carbon rises as concerns over climate change increase.

Since batch and/or cullet preheating seems to be a potential future technology it would appear prudent for American glass makers to follow several paths. One recommendation is to review actual working data by working with several installers or preheater operators to present the opportunities as well as issues that have been seen in Germany through the use of preheating batch and/or cullet. Zippe and Interprojekt are the two largest installers of preheaters and both should be contacted for participation.

In the U.S. Praxair is working on combining preheating of batch and/or cullet with oxy-fuel melting and it would appear desirable to have any update on the status of that work also presented to the glass making community.

All indications are that further innovation within preheating seems needed with a focus on capital cost reduction for installation as well as easing operational costs during the use of preheating.

Sensors and Advanced Controls

There is an active Technical Committee within the ICG on Sensors and Advanced Control. It has members from the U.S., Europe and Japan. This Committee has put together a detailed Process Map where sensors would be useful in glass making processes. The focus is on sensors as there is a feeling that current advanced controls are sufficiently developed for overall process integration but that specific measurement points needing sensors are still lacking. The world-wide glass industry feels that commercial success requires sensors for process efficiency, product quality measurements and for environmental and condition monitoring. Two specific targets are further development of oxygen sensors for waste gas streams and advanced temperature sensors in the furnace crown. Both of these sensors are important in reducing energy usage. Although sensors exist today, costs are seen as too high and too much maintenance is required during operations.

For example, temperature measurement in the furnace crown is done by thermocouples in an alumina sheath. Such measurements are cheap but suffer from drift outside required tolerances. In the furnace atmosphere continuous measurement of oxygen partial pressures using zirconia solid electrolyte sensors has been available for about 25 years. But further development is required to also measure CO concentration since positive oxygen content is not always an indication of complete combustion.

New methods could better define combustion conditions. Infrared Laser Absorption Spectroscopy has the potential to become such a powerful tool and could also help in optimizing the radiant heat transfer to molten glass and to control waste gas emissions. Another future potential is an advanced spectrometer to analyze flame emissions as well as to calculate flame composition and flue-gas NO_x emissions.

There is a general conclusion that today the glass industry uses sensors for :
>Temperature (thermocouples and pyrometers)
>Furnace Pressure
>Redox Sensors
>Flue Gas Composition
>Glass Level

At the high temperatures in the furnace it is only possible to measure the surface and near the walls. Sensors and other detection tools could be the building blocks for improved process control systems.

<u>Environmental Practices</u>

Environmental regulations are generally stricter in Europe than in the U.S. The strictest American regulations are in California. To date, the California regulations have been met by either converting to oxy-gas firing or by using conventional flue gas cleaning technologies. The glass industry will adopt tighter emissions only if regulations require them and if mitigation technologies are available. Meeting environmental standards with no loss in energy efficiency can be a challenge to glass furnace operators.

The European Union has committed to specific reductions related to CO_2 and other greenhouse gases through the Kyoto treaty by 2012. The European glass industry is struggling to meet these targets by 2012. In December, 2001 the European Commission put out a report on BAT/Best Available Technology for the glass manufacturing industry with the focus on best BAT for reduction of emissions and energy within the industry. The European Commission intends to issue a 2nd report at the end of 2008 on BAT/Integrated Pollution Prevention and Control. Few specific conclusions could be drawn from the 2001 report but that may not be true of the 2008 report.

China has begun to recognize that none of its 160 or more float furnaces, comprising more than 50 % of the world's float glass furnace production, has any oxy-fuel installed. China's Chinese Ceramic Society is hosting a large glass expo in April, 2008 and is hoping to have workshops at the expo that would include sessions on oxy-fuel firing.

Conclusions

The surveys and interviews with glass industry experts and representatives proved to be an effective means to reveal the biggest areas of energy savings. The key conclusions observed in this bandwidth study are listed below.

- The glass industry believes strongly that industrial practice is proprietary. For that reason, information presented in this bandwidth report must be considered best available information with variations based on practice from company to company
- Theoretical minimum, practical minimum, and state of the art are all point data. Current average, however, is the average of all currently operating furnaces in a specific glass industry segment.
- Survey results revealed that, on average, the glass industry believes that the manufacturing step with the most room for energy savings is the melting furnace.
- The second place average score in the survey was found to be both refining/conditioning and preheat batch & cullet.
- Forming and cullet use were also believed to be steps with significant room for energy savings.
- Interviews showed that all glass sectors believe that the largest amount of energy can be saved by improving the efficiency of the melting/refining phase, except in the glass fiber (wool) sub-sector.
- There is a very large potential for energy savings by moving from current practice to state of the art melting technology for the entire glass industry.
- As the theoretical minimum amount of energy for melting/refining is approached, gains become smaller. This is portrayed in the small gains visible when changing from the state of the art technology to the practical minimum.
- Due to much larger production rates, container glass has the largest potential for energy savings per year for implementing both the state of the art technology and the practical minimum.
- The value of glass products varies significantly. No effort was made to link energy savings to value of glass products in each industry segment. This type of analysis would certainly be conducted by glass industry management when choosing best practice or new technology for melting/refining or for other process steps. A comparison of possible energy savings per value of glass products (Btu per dollar value of products) would be useful and interesting but was beyond the scope of this bandwidth analysis.
- The glass industry (not including the specialty glass sector) stands to reduce energy usage by 39 TBtu/yr by implementing state of the art melting/refining technology.
- Container glass stands to save the largest amount of energy by complete transition to state of the art melting/refining technology (22 TBtu/yr), while flat glass, wool fiber, and textile fiber follow, respectively (9.5, 5.2, 2.2 TBtu/yr).

- The cost of transition to state of the art technology show flat glass with the highest cost followed by container glass, textile fiber, and wool fiber.
- No sector is perceived to have an extreme willingness to adopt state of the art melting/refining technology. The willingness of the glass sectors to adopt these new technologies is wool fiber followed by textile fiber, flat glass, and container glass.
- The bandwidth analysis has only considered energy use for the most common glass making methods used in the four main segments. Therefore, parametric evaluations of the impact of electric boost, cullet use, switching from air to oxygen firing, are not included
- Energy costs were not directly considered in the bandwidth analysis. The energy costs of producing oxygen and for producing electricity needed for melting were not included in the analysis. Inclusion of this information could change some of the conclusions presented in the report.

Appendix

Original Project Approach

The Gas Technology Institute is taking the lead in preparing benchmarking on industrial glass energy consumption for the U.S. Department of Energy Industrial Technologies Program (ITP). The overall objective of this work is to evaluate energy consumption in the main processing steps of primary glass industry segments and to determine process steps with the largest potential for energy savings. A three year effort is planned. First year work focused on identifying energy consumption in the primary process steps for the major glass segments (container, flat, fiber, and specialty glass). Second year effort will focus on:

- examining energy use in each of the main process steps,
- providing information on current average, state of the art, best achievable, and theoretical minimum for energy use in each step,
- assessing the impact of submerged combustion melting on the energy use in glad melting and in the major process steps for each segment of the glass industry.

A summary of the original work plan is presented below. While this approach has been followed in general, several modifications have been made to acquire useful information.

Year 1
GTI will review government and commercial databases to collect energy consumption information for the four major industrial glass segments (container, flat, fiber, and specialty). Each major process step will be defined, and current energy use ranges for these process steps will be recorded.

GTI and consultant Warren Wolf will begin the process of creating three additional columns of data. These can be labeled 1) state-of-the-art, 2) Practical Minimum, and 3) Theoretical Minimum. The columns will be filled in from industry knowledge and interviews by GTI and Dr. Warren Wolf with glass industry and glass industry vendor experts. The first year report will include the breakdown of major industry sectors into major processes and will provide estimates of current average energy use (and form of energy used) in each process step..

Year 2
Analysis of best practices for industrial glass energy savings will be carried out, completing the year one efforts to complete the table of data for the major glass industry segments. This work will rely on results of the benchmarking study carried out in the first year along with interviews with glass industry and vendor experts. This activity will be led by GTI with support on interviews and technologies available by consultant Dr. Warren Wolf. Impacts of the Next Generation Glass Melting System (NGMS) based on submerged combustion melting (SCM) will be included in the year two report.

Year 3
Further analyses will be carried out in Year 3 to review specific approaches to energy savings in glass industry processes. The objective of work in this year is to make specific selections of best approaches for the largest possible energy savings. Work will be carried out by GTI. Dr. Warren Wolf will provide input into the selection and evaluation of technologies.

Industry Surveys

Consultant Warren Wolf prepared a survey and collected information from members of the glass industry. The initial survey was mailed to 39 glass industry people representing different industry segments and suppliers. The questionnaire sent out is shown below.

<u>Survey Questionnaire</u>

All information can be sent anonymously if you wish. This survey is trying to establish (in your opinion) where the optimum areas exist to save energy in the complete glass making process and also which steps in that process consume the most energy . The purpose of this survey is to provide information in a timely fashion for the next Glass Solicitation. A second survey may be conducted at a later date when specific energy numbers have been identified and assigned to each step.

<u>INFORMATION ABOUT PARTICIPANT</u>

Work for or as (Check just one):

1. Glass Manufacturer ______________
2. Vendor/Supplier ______________
3. Consultant _______________

You participate in what Glass Sectors(Check all that apply)

1. Flat Glass _______________
2. Glass Container _______________
3. Glass Fiber ________________
4. Specialty(Optical, Pressed, Blown) ________________

Please rank each of the following process steps as to where you think the most likely ENERGY savings in GLASS MAKING are possible/ Column 1 and which steps consume the most energy in total/ Column 2 :

(1 is HIGHEST POSSIBLE SAVING STEP AND 7 LOWEST and for energy consumption again 1 is highest area and 7 lowest in consumption)

	Energy Savings	Energy Consumed
1. Raw Materials	________________	_________________
2.Cullet Utilization	________________	________________
3.Batch/Cullet Preheating	_________________	________________
4.Melting Furnace	_________________	_________________
5. Refining/ Conditioning	________________	________________
6. Forming	_________________	________________
7. Finishing	_________________	________________

WHAT IS THE POSSIBLE ENERGY SAVINGS FOR THE BEST SAVINGS AREA SELECTED?

WAS THIS ALSO THE HIGHEST ENERGY CONSUMING AREA AS WELL? AND IF NOT WHY DID YOU PREFER THIS STEP?

OTHER COMMENTS THAT COULD ESPECIALLY HELP USDOE/ ITP ON SAVING ENERGY IN GLASS MAKING AS IT CONSIDERS A NEW GLASS SOLICITATION?

Additional Comments

The following are comments from participants when asked for "Other comments that could especially help USDOR/ITP on saving energy in glass making as it considers a new solicitation.":

1. Switch to electric melting using electricity generated at glass plants.
2. Research by Cooper (I assume Al) and studies by Battelle and Corning both show preheating will provide biggest energy savings.
3. Batch/cullet preheating combined with high cullet utilization offer highest current potential savings.
4. There is a great need for more quantitative information on energy usage.
5. Need cost effective equipment to implement batch preheating.
6. Batch/cullet preheating, particularly making use of waste heat from furnace exhaust continues to be a great opportunity that has positive environmental implications as well. A project that pursues an economically attractive method to recover exhaust energy and do something with it besides firing boilers would be very beneficial across the entire glass industry.
7. Focus on new technology for glass melting/conditioning and/or pre processing of materials (such as preheating that reduce melting energy requirements.
8. The biggest hitter is still closing the sensible heat loss loop with preheating. Using raw materials which require lower reaction temperature and lower off gas will also save big.
9. One factor missing from the survey is the "cost" of achieving energy savings. For example, preheating may lead to overall energy savings but the cost of using this option (both direct, which may be easy to estimate, and indirect on maintaining process control and stability) should be factored in.
10. Need new handling equipment to minimize waste after product is made. For example, better edge trimming equipment or better paper application methods. These would improve efficiency as measured in KWH/T of finished goods.
11. Oxy-fuel is a great potential energy saver (about 20%) vs. conventional firing at a glass plant. The extreme energy usage to create the O2 for firing for oxy-fuel furnaces means energy savings in the big picture is limited-fund an efficient way to produce O2 and we could see a great energy reduction in the big picture.
12. Refining is part of melting and is the cause of the peak temperature. If refining peak temperature could be reduced by 150 degrees C or even 300 C (as suggested by Asahi Vacuum refining) –the heat required to cool/condition glass can be reduced. We don't count –and we should-invested energy to cool glass. We have to cool uniformly –and that requires 3 million BTU to remove say 1 million BTU in TV glass.
13. Finishing step may be more important in some other sectors (e.g. flat). Even in Fiberglass segment, finishing on the wool side is more energy intensive than on the textile side.
14. Support/subsidize (e.g. lower taxes) glass plants that leverage technologies/control concepts/production methods that activity save energy and reduce emissions by design.
15. The following need to be examined:
    - Preheating of gas and oxygen.
    - Gasification of coal and/or biomass.
    - Use of sensors in burner control i.e. radiation wavelengths and image analysis.

- On-site electrical generation through thermo-chemical recuperators or just the synthetic gas in the furnace.
- Steam generation through the use of ambient heat.