A Study of the Balance between Furnace Operating Parameters and Recycled Glass in Glass Melting Furnaces.

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Executive Summary

Glass manufacture is a high temperature energy intensive process. In the 12 month period to May 2003 the container sector of the industry consumed some 4.64 TWh (4.64×10^9 kWh) of delivered energy [1]. Over 70% of this energy was used by the furnaces to melt the glass. Fuel related CO_2 emissions from these furnaces amount to approximately 650,000 tonnes per year. Glass is essentially manufactured from sand, limestone and soda ash all of which are abundant natural minerals. However both limestone and soda ash are carbonates which decompose during the melting process to liberate additional CO_2. One of the many virtues of glass is that it can be endlessly remelted and recycled without any loss in quality. Producing new items from recycled glass (cullet) reduces CO_2 emissions as cullet is easier to melt than the individual raw materials, so uses less fuel, and it contains no carbonates so does not releases any CO_2 during the melting process. Furnaces melting higher proportions of recycled glass can thus operate at lower fuel inputs. However, in order to maximise this energy saving potential, the furnace operators need the tools to get the best from the furnaces.

Ideally a working furnace control algorithm able to automatically optimise fuel consumption in relation to changing cullet levels can be produced.

The work reported here has been undertaken with funding and support from the Carbon Trust and a club of leading glass container manufacturers.

This project has hopefully produced the precursor to such a control algorithm. A mathematical model has been developed which is able to predict furnace energy consumption at various production outputs and cullet levels. The model also has the facility to allow operators to apply corrections for furnace ageing and batch and cullet moisture levels. Furnace operators are thus able to calculate current (optimum) furnace efficiency at any combination of production level and cullet ratio and then compared this value with the furnace actual value. Any large and unexplained variations can then be investigated.

The model can also be used as a forecasting tool to predict furnace energy demand under a number of operating scenarios.

Current furnace control strategies do not always reproduce optimum fuel efficiency under seemingly identical conditions. Some of this scatter can be explained by the influences of parameters that fall outside the boundaries of these strategies. From the statistical analysis on which this report is based it is estimated that a improved furnace control regime which was able to automatically compensate for changes to cullet levels and moisture content could produce energy saving of 2.1% of furnace energy consumption. Such a saving would translate into a reduction of CO_2 emissions of 13,650 tonnes per year

The model has been produced in a hopefully “user-friendly” spreadsheet format which will be widely disseminated within the glass container industry. If the model gains widespread acceptance then a further collaborative project to develop a working algorithm may follow.

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[1] Energy Benchmarking Guide for the UK Glass Container industry 2004 – Action Energy Programme

Contents

1 Introduction

Glass making is high temperature, energy intensive process. Industrial manufacturers employ large furnaces which operate on a continuous basis and are typically fossil fuel fired. The UK container sector currently operates 32 furnaces each melting an average of 207 tonnes per day of glass and consuming 304 MWh of energy[1]. The annual fuel derived CO_2 emissions from these furnaces is approximately 650,000 tonnes per year. Addition CO_2 is released from the actual glass making process which essentially fuses silica sand with various minerals e.g. limestone. During the glass forming reaction these minerals, many of which are added in the form of carbonates, decompose releasing so call "process" $CO_{2.}$ For each tonne of glass produced from virgin raw materials this decomposition produces approximately 185 kg of $CO_{2.}$

The glass industry has long since realised the benefits of using recycled glass (cullet) in its processes. If more recycled glass can be reprocessed into new bottles then fewer raw materials need be quarried. Each tonne of glass returned to the melting furnaces reduces our demand on raw materials by 1.2 tonnes. The cullet is also much easier to melt than the raw materials so recycling glass significantly reduces the fuel consumption of the glass melting furnaces.

Increased glass recycling thus has the potential to deliver significant reductions in CO_2 emissions. However, in order to maximise this potential, the furnace operating systems need to have the inbuilt sophistication to enable them to reduce the fuel consumption when melting loads containing higher levels of recycled glass. The first stage in developing a control strategy is to gain a fundamental understanding of the process and quantify the potential savings. Armed with this knowledge the second stage involves the development of so-call algorithms. These algorithms are simply mathematical statements which allow process engineers to develop control routines which optimise furnace operation and ensure that the furnace is always run in the most fuel efficient manner.

The work detailed here is principally concerned with the first stage (quantification of benefits) but also is intended to identify those parameters that could be incorporated into a furnace control strategy control.

2 Glass Melting Furnaces

A large-scale glass melting furnace is basically a refractory box-like structure (Figure 1), which operates at temperatures up to 1,600°C. The furnace operates continuously providing glass 24 hours a day 7 days a week and all activities within the factory are entirely dependent upon its output. A furnace is designed to operate a "campaign" lasting typically 10 years before it is demolished and rebuilt. The cost of a furnace rebuild is obviously related to its size but a typical 300 tonne per day container furnace would cost of the order of £6 million.

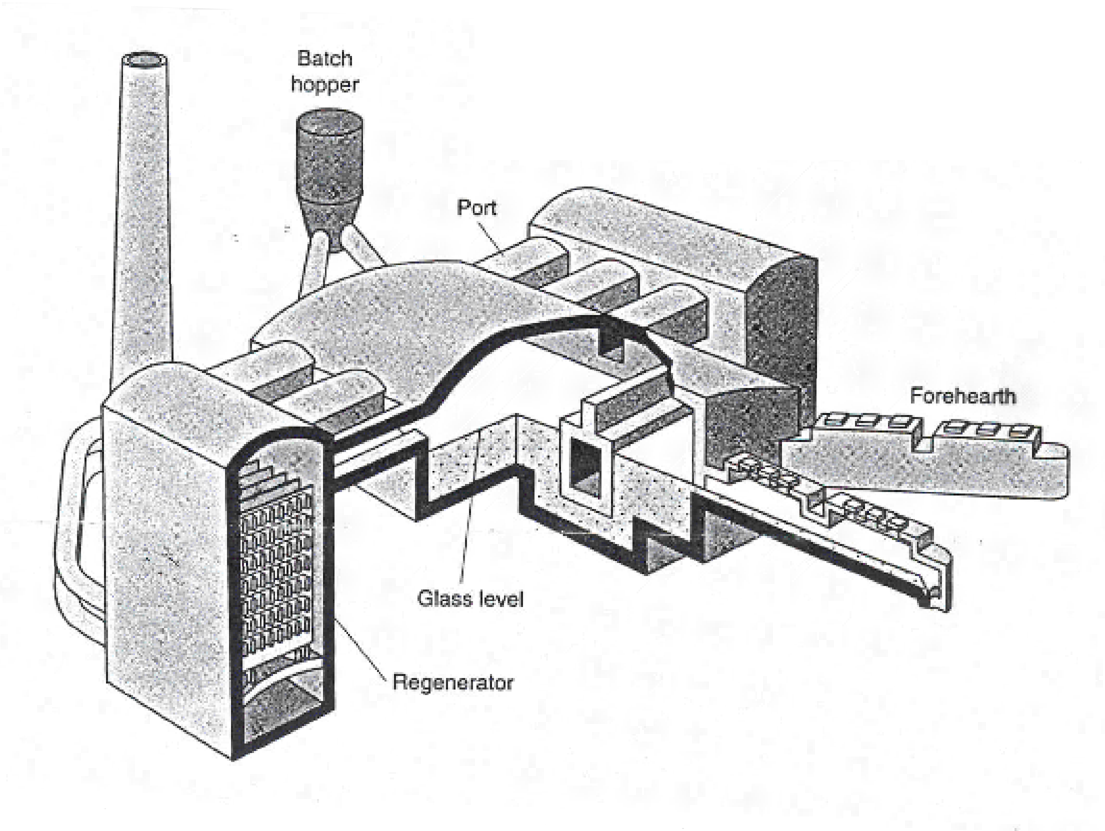

Figure 1 Typical large glass-melting furnace.

The high temperatures required to melt the glass requires a lot of fuel and consequently the furnace is the main energy centre in any glass plant, accounting for around 70% of the total plant demand. Most furnaces are fired with natural gas but can also be fired on oil as a standby fuel. An efficient large furnace will require 1100 kWh of energy for each tonne of glass melted. Thus a furnace melting 300 tonnes per day consumes around 32,000 cubic meters of natural gas each day which will release some 62 tonnes per day of CO_2.

The glass-making raw materials also release $CO_{2.}$ Glass made entirely from virgin raw materials releases approximately 185kg of CO_2 per tonne of glass produced whilst glass produced from cullet produces no (process) $CO_{2.}$ Thus if the 300 tonne per day furnace was producing clear glass at a typical cullet ratio (the relative proportion of cullet to virgin batch material) of 40% then 33 tonne of CO_2 would be released from the raw materials. However, if the furnace was producing green glass if would typically be operating at cullet levels in excess of 90% and as such would be producing just 6 tonnes of CO_2 per day. The disparity between these typical clear and green cullet levels is due to an imbalance in the UK between the amount of green glass collected and that produced. Approximately 46% of glass collected by commercial schemes is green, yet green glass production comprises just 18% of UK output.

3 Furnace Energy Requirements

3.1 Theoretical Energy Requirements

The energy requirement needed to produce glass is the sum of three components:

- The thermochemical heat required to promote the chemical reactions. For a typical (dry) container glass this would equate to 155 kWh per tonne of glass.

- The so called "sensible" heat associated with the glass produced i.e. the heat contained in the molten glass produced by the furnace. For a typical glass at 1,300°C this element would equate to a value of 440 kWh per tonne of glass produced.

- The sensible heat that will be lost by the hot furnace gases as they depart the furnace system. Waste gases leave the furnace chamber at temperatures in excess of 1,500°C however regenerative heat recovery systems recover much of this heat and typically discharge gases at a temperature of around 550°C. Most of these process gases arise from the decomposition of the carbonates in the batch material and, at 550°C, have a calculated heat content of 170 kWh per tonne of glass produced.

  Water vapour is the other source of process waste gases. For technical reasons the principal raw material (sand) is added with approximately 4% moisture adding 28kg of water to the furnace for each tonne of glass produced. Vaporising this water and heating it to an exit temperature of 550°C requires an additional 28 kWh of furnace energy.

  Cullet however is nominally added dry, although it will have some inherent moisture due to its processing and outdoor storage. Thus the net moisture content of the furnace feed is reduced as cullet increase. Replacing sand having 4% moisture with cullet with a nominal 1% moisture content would "save" 18 kg of water per tonne of glass produced. The energy saved by adding 18 kg less moisture per tonne of glass is calculated at 18 KWh, assuming that the water is converted to steam at 550°C.

The practical minimum energy requirement to produce 1 tonne of glass at a temperature of 1,300°C is thus 793 kWh. When cullet is substituted for batch no reaction energy is required [155 kWh], less water must be vaporised [18 kWh] and no process gasses would be produced [170kWh]. Thus it is calculated that an energy saving of 343 kWh would accrue for each tonne of glass produced from cullet as opposed to virgin raw materials.

3.2 Simplified Energy Requirements

For practical purposes the energy requirements of a furnace can be split into 2 elements. The first element is the fixed term and usually referred to as the "holding heat". Essentially this is a fixed quantity of energy required to hold the furnace at its working temperature at a zero level of production. The size of this element is a function of the furnace capacity, the level of furnace insulation and age of the furnace (as a furnace wears it loses more heat to its surroundings gradually increasing the holding heat).

The second element is a variable term which is the additional energy, over and above the holding heat, that the furnace requires to produce its molten product. This value is to some extent independent of furnace size but is influenced by furnace design and general efficiency of the combustion system.

In simple mathematical terms the energy consumption of a furnace would be described by the following equation:

Furnace Energy = Holding Heat + Load x Constant

A plot of furnace energy vs glass melted should produce a straight line from which the fixed and variable elements of the energy/load relationship could be derived.

A typical plot of such furnace data is shown in Figure 2.

From such a plot is possible to determine:

The furnace holding heat (zero load) = Intercept of the best fit line

The energy to melt 1 tonne of batch = Slope of the best fit line

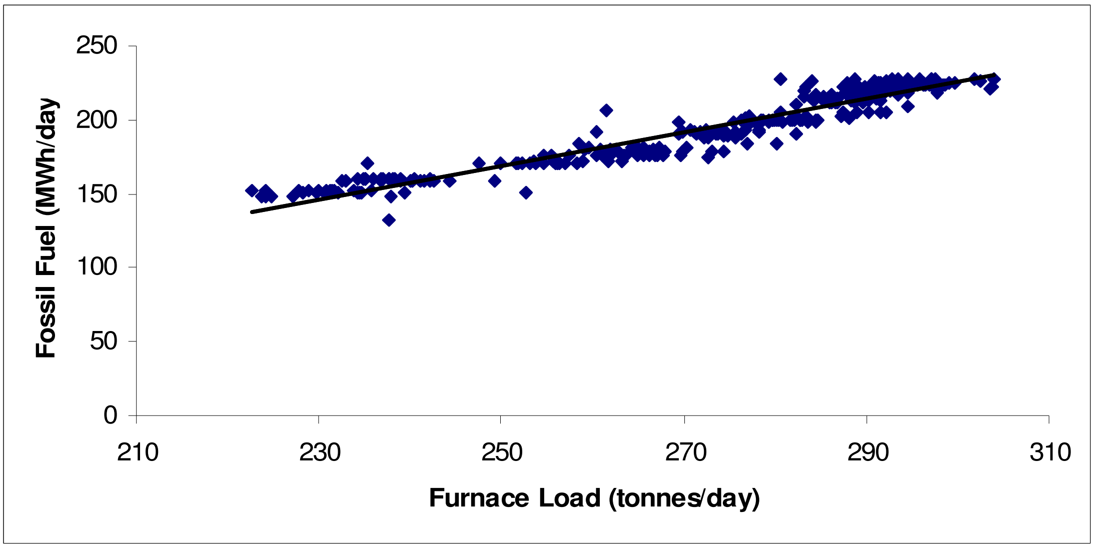

Figure 2 Typical Plot of Furnace Load vs Fossil Fuel Input.

3.3 Practical Energy Requirements

In practice the energy consumption of a furnace is influenced by several sometimes interdependent factors. The scatter of data points is an indication of the influence of these factors on furnace energy consumption. The more important factors include:

Furnace design – a well insulated and designed furnace will have inherently lower energy consumption.

Cullet levels – higher cullet levels require less energy.

Electrical input – in addition to the fossil fuels, many furnaces use a small amount of electrical heating energy to melt the glass. This electrical energy is utilised more efficiently by the furnace than that from the fossil fuels.

Furnace Age – furnaces become less efficient with time.

4 Statistical Analysis of Energy Requirements

4.1 Basic Methodology

The statistical technique of (multiple) regression analysis has been used to investigate and quantify the various factors that have an important influence on furnace energy consumption. The basic approach is to begin with a simple single variable relationship e.g.

Furnace Energy = Holding Heat + Load x Constant

It is assumed that the correlation coefficient [R squared] is indicative of the strength of an existing relationship. The relationship is then refined by modifying the base equation using secondary factors e.g. electrical input, cullet ratio and any furnace control parameters that are deemed relevant (melting temperature). A better defined relationship will then produce an improved correlation coefficient.

4.2 Cullet Additions

In order to determine the influence of cullet additions on furnace energy consumption the data from several furnaces was analysed using multiple regression. A complicating factor was the use in some of the furnaces of electrical boost. Most of the furnace energy is provided by gas flames burnt in the combustion chamber. Typically some 65% of this energy heats the glass and maintains the furnace temperature; the balance is lost in the waste gases. An electrically heated furnace produces no hot fuel-derived waste gases and the furnace can operate at lower structural temperatures. In effect around 95% of all electrical energy is used in the melting process. (It is however important to remembered that in order to generate the electricity, fossil fuel must be burnt in a power station at a conversion rate of around 40% and subsequently the energy must be conducted to the required destination incurring further transmission losses).

Two mathematical methods can be used to remove the effect of electrical boost prior to investigating the influence of cullet on melting energy. The electrical energy can be weighted to recognise the amount of fossil fuel that is required in its production. This approach is the method favoured by energy trading schemes and essentially converts the electrical energy into primary energy. The second approach, and the one that has been adopted for the purposes of this study, is to determine the quantity of glass that the electrical energy would have produced and subtract this from the total glass melted. The remaining glass is accredited to the fossil fuel input. The correlation analysis then compares the fossil fuel use with the so-called "top-fired" glass.

Having removed the influence of electrical boost the first step is to determine the basic statistical relationship between the top-fired glass and the fossil fuel input. Following this multiple regression analysis is used to refine the analysis to determine the relative energy requirements of producing glass directly from cullet as opposed to glass from virgin batch materials. This is achieved by calculating, from the known cullet ratio, how much of the "top-fired" glass was derived from the cullet. The remainder was deemed "new" glass being produced from raw materials. A relationship following the form:

Furnace Energy = Holding Heat + Cullet Glass x Constant [1] +
Virgin Glass x Constant [2]

is assumed and multiple regression used to quantify the various constants and determine the strength of the relationship. Figure 3 below illustrates the analytical procedure adopted.

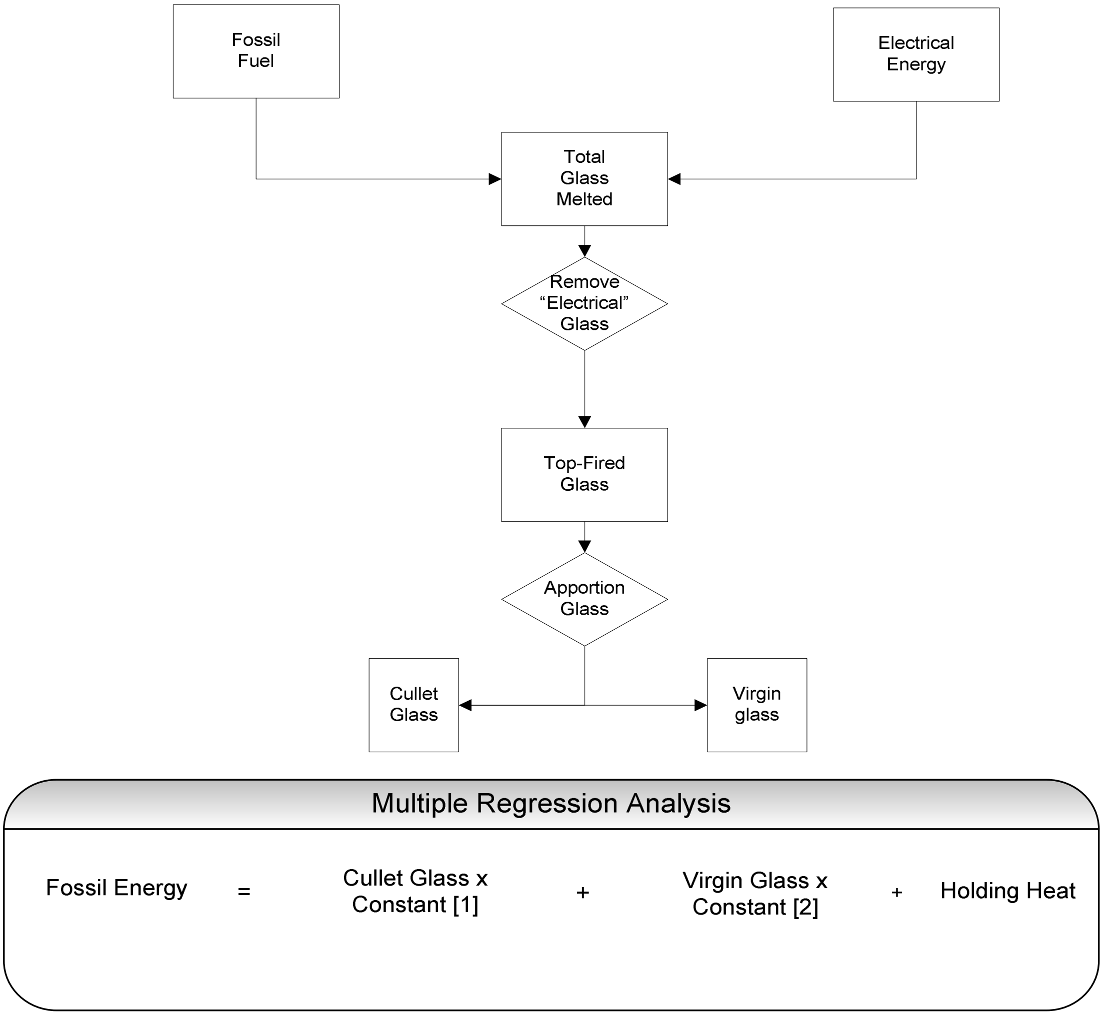

Figure 3 Schematic Representation of Analytical Procedure.

For the purposes of the project detailed daily furnace data was collected from 8 furnaces operating over 16 sample periods. Data was initially analysed in yearly periods to avoid seasonal temperature variations. The data was also analysed in quarterly periods to investigate the effect of furnace ageing, A summary of the results is given below in Table 2.

With some exceptions the analytical procedure was able to quantify the energy savings associated with the replacement of batch with cullet. The strength of the correlation varied between furnaces and with individual furnaces over time periods. In general better correlation was obtained when the furnace was operated at a wider range of cullet additions. The "cullet effect" was also found to be less pronounced at higher cullet levels suggesting a somewhat more complex relationship than a simple linear form used for the basic analysis.

Based on the general (linear) formulae:

Furnace Energy = Holding Heat + Cullet Glass x Constant [1] + Virgin Glass x Constant [2]

The average difference between the factors i.e. the lower melting energy requirement was 0.322 MWh per tonne. Thus, on average the production of 1 tonne of glass from cullet will require 322 KWh less (gas) fossil fuel than the production of the same glass from virgin raw materials. The combustion of 322 kWh of natural gas would produce 61 kg of CO_2. In addition to requiring more fuel to produce glass from raw materials an average of 185kg of CO_2 is also released from a typical container glass batch. Thus when 1 tonne of cullet is recycled a total of 246 kg of CO_2 emissions is avoided.

Item	**Average Value**	**Range**
Sample size	16	n/a
Furnace load (tonnes/day)	264	181 - 302
Cullet ratio (%)	52	28 – 95
Specific energy (MWh/tonne)	1.47	1.08 – 1.64
Batch constant (MWh/tonne)	0.88	0.41 – 1.29
Cullet constant (MWh/tonne)	0.56	0.28 – 1.00
Cullet saving (kWh/tonne)	322	184 – 475

Table 2 Influence of Cullet Additions on Melting Energy.

However, for the purposes of this work the variation in results is of interest. The large variation between furnaces and more particularly between the same furnaces operating at slightly different periods indicated that there is scope to improve the furnace control strategy with respect to cullet addition. The aim would be to "tighten" the relationship so that furnaces operate at the optimum levels of efficiency.

4.3 Optimising furnace Efficiency

Figure 4 below is a typical plot of the furnace fossil fuel input against the glass melted (corrected to remove glass melted by electric boost). The plot shows a reasonable relationship but does display significant scatter. Points above the line of best fit line coincide with less efficient operation.

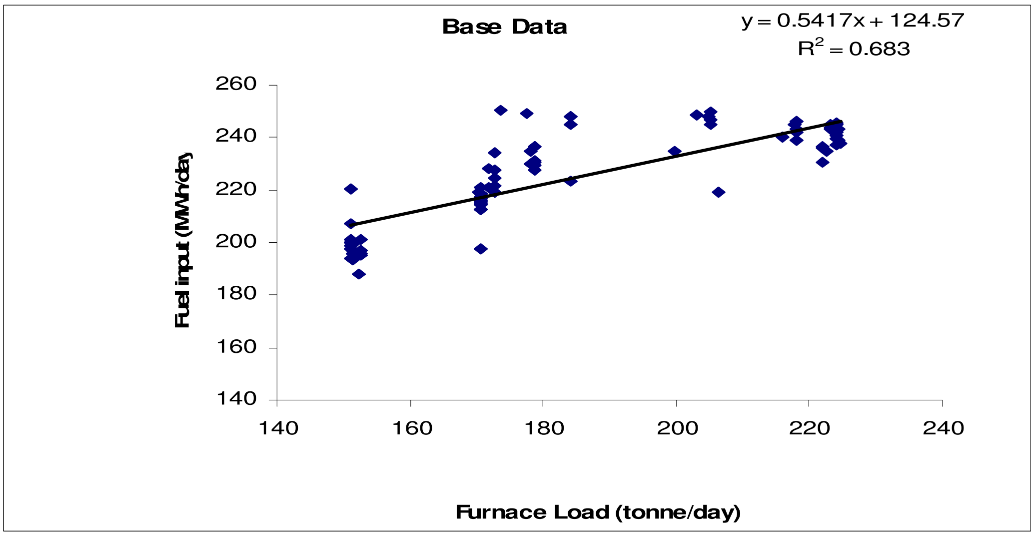

Figure 4 Furnace Load vs Fossil Fuel (base case)

Figure 5 represents the same furnace output data but the fuel input for all points has been calculated from constants derived from the regression analysis for this particular data set i.e. is of the form:

Furnace Energy = Holding Heat + Cullet Glass x Constant [1] +
Virgin Glass x Constant [2]

Had the fuel input to the furnace been at these "optimum" levels then in this instance the fuel consumption would have been reduced by a factor of 0.6%. This method applies corrections to those all points including those that are displaying better than optimum performance.

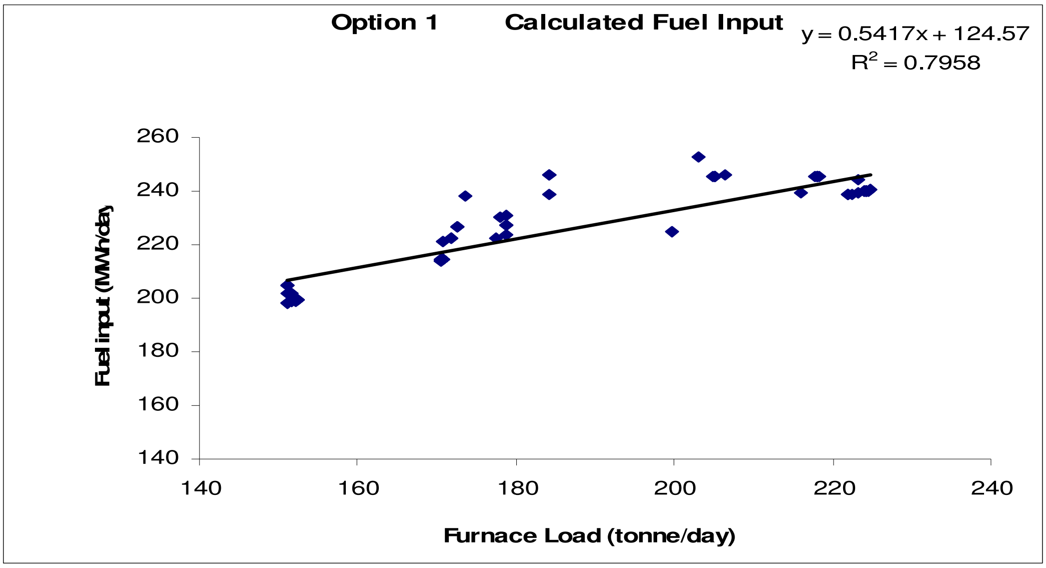

Figure 5 All fuel inputs trimmed to optimum (saving 0.6%).

The control scenario used in the above example recalculated all the data points to bring them closer to the line of best fit. In practice a control trimming strategy would only become active when the furnace was operating at efficiencies below target. Figure 6 below adopts this strategy and only adjusts those points that coincide with less than optimum efficiency. As this scenario only acts on "under performing" points it necessarily produces larger savings. Had the fuel input to the furnace been trimmed in line with this relationship then fuel savings of 1.6% would have been achieved.

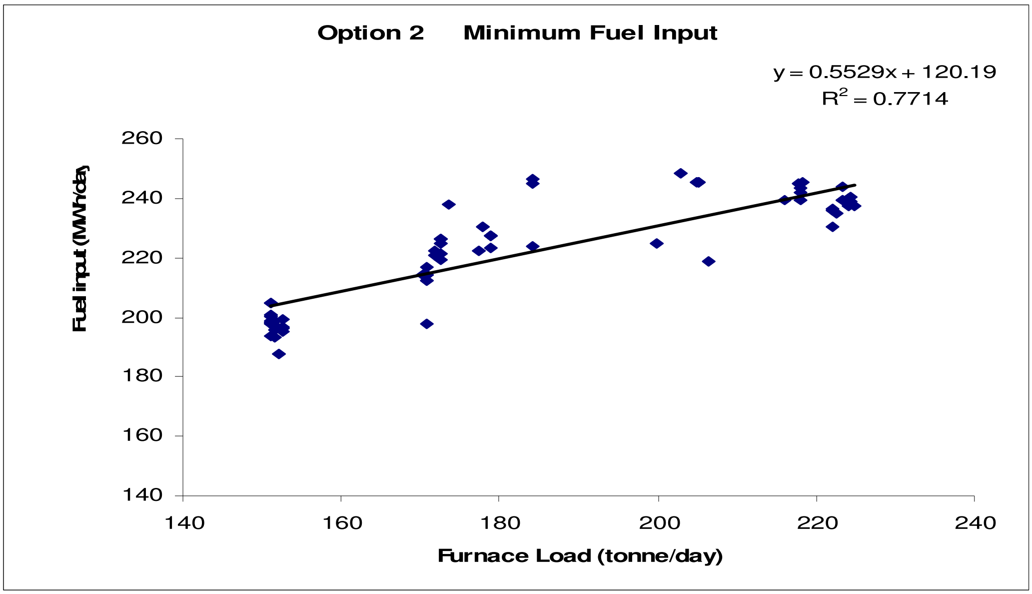

Figure 6 **High fuel only inputs trimmed to optimum (saving 1.6%)**

The fuel savings that would be achieved if such a control strategy could be adopted is a function of the scatter of the original data. An analysis of all the data sets found that savings from the option 1 scenario averaged 0.9% with a range of zero to 3.0%. Savings from the option 2 scenario averaged 2.1% with a range of 1.3 to 3.6%. Details of these results are given below in Table 3

Item	Average Value	Range
Sample size	16	n/a
Furnace load (tonnes/day)	264	181 - 302
Cullet ratio (%)	52	28 – 95
Energy Savings Option 1 (%)	0.9	0 – 3.0
Energy Savings Option 2 (%)	2.1	1.3 – 3.6

Table 3 **Theoretical Energy Savings with Enhanced Furnace Control.**

4.4 Other Parameters

In practice many factors influence furnace efficiency. Some can be changed rapidly at the operator's discretion e.g. top fired fuel and electrical boost input. Other important parameters which influence furnace energy consumption can be changed but the thermal inertia of the furnace limits their response times e.g. glass and furnace temperatures.

Batch (including cullet) moisture has a direct influence on energy consumption. Whilst the moisture content of the sand is generally well controlled that of the cullet is more variable. As cullet level increase so does the difficulty in maintaining a known batch moisture content.

Finally the furnace ages; the continuous process of drawing molten glass though the furnace erodes the internal lining which results in increased heat losses. The regenerative heat recovery system is particularly prone to ageing. The regenerators essentially comprise 2 large structures which are sited either side of the furnace and contain a honeycomb of brickwork. The regenerators operate a cyclic process of 20 to 30 minute duration. At any one time one of regenerators is being heated by the hot furnace gases (1,500°C) as they leave the combustion chamber whilst the other regenerator is returning heat to the combustion air (input temperature 60°C). Every 20-30 minutes their roles reverse. The regenerator brickwork is thus constantly being cycled between very hot and relatively cold gas inputs. Unsurprisingly the heat recovery system deteriorates with time.

4.4.1 Furnace Temperatures.

Temperature measurement and control is critical to good furnace operation. Higher furnace production requires higher operating temperatures. Most furnace monitoring systems record several temperatures; usually at various positions in the furnace crown (roof) and in the body of the molten glass. Other commonly recorded temperatures include the regenerators and the working end. However most of these temperatures are measured by thermocouples which are not capable of producing a true reading as they are usually embedded into the brickwork close to the surface at which the measurement is required. Consequently when these temperature measurements are used in as a control parameter it is the trend in the number rather than its absolute value that is used.

The relationship between energy consumption and various temperatures was investigated and whilst some loose correlations were evident no universal relationship was found. Thus whilst "set-point" temperature measurements are an integral element of furnace control strategies no useful predictive temperature/energy input relationship was evident.

4.4.2 Batch and Cullet Moisture

The introduction of water into the furnace will reduce its thermal efficiency. Online moisture monitors have been developed which can be used with the sand but are not suitable for cullet measurements. The moisture content of the furnace feed is thus a parameter which is difficult to control and perhaps impossible to incorporate into a dynamic furnace control strategy. If, as is likely, no correction is made for any excess moisture content of the cullet when the material is weighed to the furnace then furnace efficiency will be reduced by 2 factors. Firstly additional water is being added to the furnace which must be vaporised. Secondly, on a dry basis, proportionally more glass will be produced from batch material which requires more energy to melt than cullet. If for example a furnace melting 200 tonnes per day with a nominal 50% cullet ration is adding (wet) cullet with 1% more moisture than anticipated then 1 tonne of water is replacing 1 tonne of glass making cullet. In addition to the energy required to drive off this water (1 MWh) more furnace feed is required to make up the "lost" tonne. 50% of this glass will be produced from harder-to-melt batch material thereby adding a further 172 kWh to the furnace energy requirement.

4.4.3 Furnace Age

Once commissioned a modern container furnaces should run continuously for perhaps 8 years before it will undergo a hot repair that should extend its life by a further 3-4 years. The arduous duty that these furnaces perform results in a slow but inexorable deterioration in the integrity of the refractory materials. The result is a reduction in furnace efficiency as the furnace ages. The thermal efficiency of a furnace may deteriorate by 25% over a typical 8 year campaign. The aging effect has not been widely studied and, whilst most furnace operators agree that the effect is not a linear trend, in the absence of detailed data a simple linear relationship is adequate for most purposes.

5 Mathematical Model

5.1 Simple predictive model

Based on the data supplied by the club members a spreadsheet based mathematical model has been developed to predict furnace energy consumption at various production outputs and cullet levels. The model has been refined to allow the operator to apply corrections for furnace ageing and batch and cullet moisture levels (or more precisely deviations from the normal operating values of these parameters). The predictive model allows individual furnace operators to calculate the current (optimum) furnace efficiency at any combination of production level and cullet ratio. The predicted result can then be compared with the actual value and any large and unexplained variations investigated. The model also allows the operator to see the effects of changing some input parameters. As an example the operator may suspect that a higher than predicted fuel consumption is the result of the cullet moisture being higher than specification. The operator could use the model to determine if higher than specified levels of cullet moisture could reasonably explain the high fuel consumption.

Complete details of the spreadsheet programme are given in Appendix 1.

Tables 4, 5 and 6 below show a typical input into the model and its output prediction for a 300 tonne per day furnace.

Input Data	**Value**	**Units**
Furnace load	300	tpd
Electric boost	0	MWh
Nominal cullet addition	50	%
Sand moisture	6	%
Cullet moisture	5	%
Age	36	months

Table 4 Query data input.

Calculated Data		**Value**	**Units**
Glass	Electrical boosted glass	0	
	Virgin glass produced	153	tpd
	Cullet used	148	tpd
Energy	Holding heat	237	MWh
	Batch glass	132	MWh
	Cullet glass	98	MWh
Moisture	Sand	2.1	MWh
	Cullet	5.9	MWh
Age	Furnace	9	MWh

Table 5 Model output (calculation routines).

The model predicts a furnace holding heat of 237 MWh, that the 50% of glass produced from batch and cullet will require 132 and 98 MWh respectively, the correction due to additional sand and cullet moisture (compared with base values of 4 and 1% respectively) will add 2.1 and 5.9 MWh and the age of the furnace will add a further 9 MWh to furnace consumption.

Input Data	Value	Units
Fossil energy input (daily input)	485	MWh
Specific energy consumption	1.62	MWh/t

Table 6 Model output (predicted energy consumption)

Table 6 merely sums all the predicted energy components to give the daily (fossil) fuel requirement (485 MWh) and also presents this value in terms of specific energy consumption (1.62 MWh per tonne of glass melted).

5.2 Forecasting Model

In addition to using the model to estimate anticipated daily fuel consumption it can also be used to generate various the scenarios that are required for production forecasting. Other practical uses include building the model into the algorithms that can be used under the current climate change agreement to vary milestone targets in order to mitigate the effects of reduced production.

An example of a potential use is shown below in figure 7.

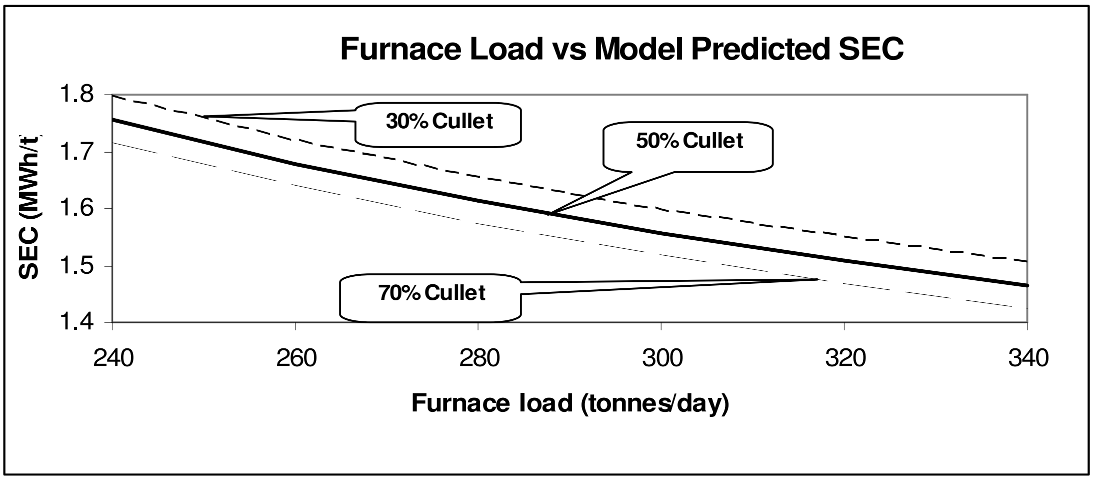

Figure 7 The predicted energy consumption of the furnace over a range of outputs and cullet levels.

Similarly the model could be used as the basis for price adjustments between cullet suppliers and the glass plants. The basic contact could stipulate a nominal moisture content of say 1%. Cullet supplied at higher moisture levels could obviously have a simple factor to account for the fact that water is being delivered in place of the purchased material. However with the aid of the model it would be possible to cost the energy penalty associated with wet cullet. As an example, assume that a plant that purchased 3000 tonnes of cullet at a nominal moisture level of 1% for use in a 300 tonne per day furnace. If the furnace were operating at a 50% cullet level then the purchase would be sufficient for a 20 day period during which some 9340 MWh of gas would be consumed. If however the cullet actually had a moisture level of 5% then the model would predict a fuel consumption of 9480 MWh. Thus, in addition to being "short-changed" by virtue of being supplied with 120 tonnes of water in place of cullet, the fuel consumption of the furnace has been increased by 140MWh. At a typical unit cost of £12/MWh (August 2004) for natural gas the additional fuel requirement is valued at £1,680.

Similarly the model could be used as justification for related capital spend. As cullet is usually stored outdoors in open bays the energy penalty of wet cullet could determine the payback period of a simple roof.

6 Conclusions

Multiple regression techniques have been used to analyse the relationship between the glass furnace energy requirements and the relative proportions of recycled glass (cullet) and virgin raw materials melted by the furnace. The study found that on average the production of 1 tonne of glass from cullet requires 322 KWh less (gas) fossil fuel than the production of the same glass from virgin raw materials.

The results from the study have been used to develop a methodology to predict the optimum furnace fuel consumption based on the recent history of the furnace. If these predictive algorithms could be incorporated into a simple control strategy for the furnace then saving of a least 0.9% of furnace fuel consumption would accrue. With current industry-wide annual fuel derived CO_2 emissions of 650,000 tonnes this 0.9% saving would equate to an annual reduction of 5,850 tonnes of CO_2. The potential savings arising from a more sophisticated control strategy are estimated at 2.1% or 13,650 tonnes of CO_2.

A spreadsheet-based mathematical model has been produced which will allow glassworks managers to predict furnace energy consumption at various production outputs and cullet levels. The model also has the facility to allow operators to apply corrections for furnace ageing and batch and cullet moisture levels. Furnace operators are thus able to calculate current (optimum) furnace efficiency at any combination of production level and cullet ratio and also use the model as a forecasting tool.

The energy penalty associated with variations in cullet moisture has long since been recognised by the industry but little work had been done to quantify these effects. The model incorporates a specific cullet moisture routine which will enable users to accurately quantify this element of furnace energy consumption.

7 Model Development

The model has been developed thus far with funding and support from the Carbon Trust and a club of leading glass container manufacturers. The model will be released to all club members and, whilst it has been designed to be "user friendly" in its current format, it is anticipated that some local assistance will be required to customise the model to individual sites and furnaces. This assistance will be provided (gratis) by British Glass as part of its normal commitments to member companies.

The model will initially be provided as a predictive tool but, dependant on a favourable reception, there may a demand from the industry for a further collaborative project specifically aimed at developing the tool into a more sophisticated furnace control algorithm.

Cullet Furnace Energy Model

This spreadsheet programme is designed to predict furnace enegy consumption based on historical data

The programme allows changes the operator to invesigate the infulence on furnace energy consumption of the following variables:

Furnace load

Cullet level

Sand moisture

Cullet moisture

Furnace age

Instructions

1 Use the "Input Sheet" to enter daily values of >>>

Furnace Load (tpd)	Cullet (%)	Gas (MWh)	Boost (MWh)

2 Use the "Input Sheet" to ammend **<u>(if required)</u>** default values of sand moisture, cullet moisture, furnace ageing factor and furnace age

3 The programme will automatically calculate the relationships between furnace energy and the various parameters

4 Input the furnace conditions for which en energy prediction is required

Appendix 1 **Data Input Sheet** **Page 2**

Insert daily furnace data below

The following data will be used as default **but may be overwriten**

Sand moisture	4	%
Cullet Moisture	1	%
Furnace aging factor	2	% deterioration per year
Furnace age	24	months

Input default values - can be varied

Input data:- Load, Cullet, Fossil Fuel and Boost

	Furnace Load (tpd)	Cullet (%)	Gas (MWh)	Boost (MWh)
Average	304	24	479	0
1	279.6	40	434.5	0.0
2	300.3	40	465.9	0.0
3	300.3	40	455.3	0.0
4	300.3	40	470.4	0.0
5	310.5	40	479.0	0.0
6	310.5	40	474.0	0.0
7	310.5	40	472.6	0.0
8	298.5	40	459.7	0.0
9	310.4	40	460.8	0.0
10	310.3	40	450.2	0.0
11	299	40	430.1	0.0
12	297.7	40	438.3	0.0
13	297.7	40	439.1	0.0
14	297.7	40	451.0	0.0

Data below is automatically calculated from the input data

Programme calculates:- Holding Heat, Batch and Cullet constants

1) furnace holding heat and cullet constants

0.067	0.665	237
0.0756	0.0823	22.90
0.4813	14.6047	#N/A

Programme calculates age factor

2) age factor

-0.234	0.90556	0.1588

	Load (less boost) (tpd)	Cullet (less boost) (tpd)	Virgin (less boost) (tpd)
	0.686		
	304	72	232
1	280	112	168
2	300	120	180
3	300	120	180
4	300	120	180
5	311	124	186
6	311	124	186
7	311	124	186
8	299	119	179
9	310	124	186
10	310	124	186
11	299	120	179
12	298	119	179
13	298	119	179
14	298	119	179

Cullet Furnace Energy Model

Methodolgy

Tabel 1 ***Calculated data from historical records***

Regression Analysis		
Item	*Value*	*Units*
Holding Heat	237	MWh
Batch Constant	0.867	MWh/tonne
Cullet Constant	0.665	MWh/tonne

Table 2 ***Default values (can be overwritten)***

Base Data		
Item	*Value*	*Units*
Sand moisture	4	%
Cullet moisture	1	%
Age	24	months
Age Factor	4	% hh/year
Cullet base	45	%

Table 3 ***Input data to obtain predicted fuel consumption***

Input Data		
Item	*Value*	*Units*
Furnace Load	300	tpd
Electric Boost	0	MWh
Nominal Cullet	50	%
Sand moisture	6	%
Cullet moisture	5	%
Age	36	months

Table 4 ***Calculation Routine***

Calculated Data	*Item*	*Value*	*Units*
Glass	Boosted glass	0	
Glass	Virgin Glass produced	153	tpd
	Cullet used	148	tpd
Energy	Holding Heat	237	MWh
	Batch Glass	132	MWh
	Cullet Glass	98	MWh
Moisture	Sand	2.1	MWh
	Cullet	5.9	MWh
Age		9	MWh

Table 5 ***Predicted Energy and SEC values***

	Item	*Value*	*Units*
Total	Fossil Energy Input - daily input	485	MWh
	Specific Energy consumption (SEC)	1.617	MWH/t