A Life Cycle Framework for Accounting Direct and Indirect Energies on Glazing as a Building Material

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The rapid consumption growth rate of the earth’s non renewable natural resources by an increasingly affluent and numerous human race is a global concern. This consumption growth rate concern is driving a trend towards material and energy efficiencies. Abundant, relatively cheap energy has been and continues to be the driver of the industrial revolution since the mid 1700. A framework is needed for accounting the energy inputs and outputs on materials as a basic step towards understanding the concept of an energy economy. However, not much is known about the embodied energies in construction materials in general, that is, energies used directly and indirectly in the extraction, production, processes and its life cycle, that is, cradle to grave. Glazing is a popular material used in vertical construction (such as curtain walls, and storefronts). Glazing manufacture uses high energy inputs but advancements of nano technologies show that it has the potential of becoming part of photovoltaic paneling system of increasingly higher efficiency and decreasing cost. The current popular use and future potential of glazing makes it a prime target for investigation.

This research aims at generating a life cycle energy assessment framework for calculating the embodied energy of glazing considering the direct as well as indirect energy inputs throughout its lifetime. The embodied energy associated with this building material is significant and a better understanding of an energy economy surrounding the manufacture and production of glazing throughout its life-cycle will serve as a first step towards a larger framework for understanding the complexities of an energy economy, a topic relegated for future research.

Key Words: Carbon emissions, life cycle energy analysis, embodied energy, energy efficiency, glass, glazing.

Introduction

The initial concepts of sustainability emerged in the 1990’s; lately this idea has grown its course into almost every aspect related to the environment, whether related to technologies e.g. buildings, chemicals and organizations e.g. corporations (Vos, 2006). The concept of sustainability originated from the rate at which the renewable sources of energy are being extracted, and the damage made by the pollution, if could be done without a threat to the environment and the ecosystem (Vos, 1997). From here sustainability moved to economics, and hence forth is used by policy makers like the U.S Environmental Protection Agency. Sustainability areas of interest and influence have grown into business, management, literature and lately into engineering (Dunphry, et al. 2003). The primary aim of sustainable buildings to reduce the impact of construction on the environment. This can be done by efficient and effective use of energy, with optimum utilization of materials and resources. Recently the construction industry is increasingly adapting the sustainable building concepts. Fernández-Solís, 2006, defines sustainability as the force that tames an exponential growth of resource consumption and emissions generation. This force is vectorial and multiple which encapsulates the complexity of taming harmful growth.

From the ancient times the sustainable building practices have been followed with the use of environment friendly, relatively simple, natural, minimally processed, local construction materials like stone, timber, mud etc. Modern materials which are a combination of the synthetic and largely engineered products, like steel, cement, aluminum, glass and their extensive use, have replaced local materials, as these materials are perceived to be much stronger and
more durable, for example, steel has replaced timber as a structural material, wooden windows have been replaced by glazing (Kibert, 2006). However, these modern materials require relatively large amounts of energy in their production and assembly into a building. Besides this there is high fuel consumption involved in transportation, before the material is being used.

According to Lauri Koskela, 2003, production and operations management in lean construction involves three process transformation, flow, and value. Transformation primarily is related to pre-planning of production and identification of different tasks and hence their optimization. Flow concept on the other hand focuses on minimizing waste especially in manufacturing processes where identification of efficiencies within sub processes becomes crucial. Value process as the word describes itself, is the central factor for manufacturing, where the aim is to achieve quality and variance control.

Modern manufacturing processes are based around high energy consumption. Furthermore the building life cycle is energy intensive. Estimating the energy consumed by buildings and the establishment of different combinations of materials and techniques can help make the decision process towards the reduction in the consumption of energy (Gumaste, 2006). The framework of this study is the first step towards determining the energy involved in glazing as a material throughout its entire life cycle i.e. (cradle to cradle vs. cradle to grave), the scope limits in determining the energy involved in glazing manufacturing, which will act as a reference for other materials to help cutting energy down and facilitating the efficiency of material.

The true element of sustainability can be determined by undergoing, a comprehensive life cycle energy analysis (LCEA) for the energy technologies. The main concept behind LCEA is to know the quantities of the energy and the materials used for producing it. In recent times LCEA tools have been developed for the assessment of whole buildings or building assemblies such as ATHENA and BEES.

An ideal LCEA would quantify for the materials and the energies needed at each and every progressive stage of the product. Beginning from the extraction of the raw material, manufacturing, requirements of its use, generation, storage, the final disposal or recycling and then in between each step the factor of transportation. To perform complete LCEA’s is difficult for certain materials since their fabrication technologies are under constant improvement (Pearce and Lau, 2002). Performing an LCEA for any material as a whole will involve multiple studies for each of the stages with a vast scope. This study will make an attempt to determine a correct and complete set of energies involved at the manufacturing stage of glazing.

Since the application of glazing is rather extensive on the exterior skin of the buildings, it is evident that it is responsible for the temperature within the building. There is a demand for energy saving products, and glazing gives that required edge to the industry.

**Problem**

**Statement of Problem**

The purpose of this research is to establish a life cycle framework for determining the complete set of direct and indirect (average) energy unit of one types of glazing used widely in the building construction industry for its manufacturing.

**Assumptions**

- This study will be limited to the green building practices in the United States of America and may not be applicable to other places.
- The study will not delve into the types of transportation modes, and an average fuel consumption of transportation per mile will be assumed.
- The size of the glazing considered for the study would be a panel of one square feet of ¼ inch double insulated 1 inch glazing.
The study will only keep in account the average energies and living distances of the people involved during the manufacturing stage.

The study will account for an assumption for transportation distances as 50 miles on an average.

The average family size for an employee has been assumed to be 4 persons.

Another assumption made for the study is that only the energies of the production employees, working for a flat glass manufacturing facility and their average family’s account of the people involved.

Due to the constraints of time and money, the study is being limited to the framework of manufacturing process of glazing.

Sub Problems

- To identify the manufacturing process for glazing and determine the type and amount of energies involved during glass manufacturing.
- To find out the number of people involved in the whole process of the glazing manufacturing.

Research Objectives

- Determine the indirect energies such as the people who are directly involved in glazing manufacturing and their livelihood depends on the whole process of manufacturing and their everyday transportation.
- Publish the results of the direct and the indirect energies using the unit of energy as BTU for all activities.

Significance of the Study

Today’s concern over the globe is to go green, so the efficiency of any building is under focus (Fernandez-Solis, 2006). The subject of interest is Glazing. Glazing has a great significance in the building industry and its applications are wide. The usage of glazing affects the building thermal performance to a great extent hence it makes important for us to select the right kind of glazing. The thermal performance of glazing is a concern and research has been carried out on the subject of deriving best UV coatings for achieving energy efficient glazing and this will keep continuing further. The latest technology focuses in producing photovoltaic energy through glazing where a glazing panel acts as a solar cell to produce electricity which can be used for the energy systems within the facility. But before we reach into these details there is a need for us to know about the energy footprint of the glazing that is being used on our building. This is critical for the initial energy calculation for any building in its initial planning stages.

Literature Review

Energy Consumption

A majority of environmental problems in U.S are contributed by the building community, a total of 37 % of carbon dioxide emissions, 71% of electricity and 45% of total energy use; this percentage reaches to 48% when the energy required to make building materials and construct buildings also gets added (Mazria, 2004). About 50% of raw material is being used globally every year for construction and remodeling of buildings which accounts to 3 billion tones, Figure 1&2 (Lenssen, 1995).
This 37% increase is estimated to be 34 quadrillion Btu, where 1 QBtu is equivalent to the annual energy output of 40, 1000MW power plants, Figure 3 (Mazria, 2004). There has been an increase from less than 500 million tons of construction materials from 1900s to over 3000 million tons, Figure 4.

To ensure that these growth rates there are three things those need to be addressed i.e.

**Adaptation**

The literal meaning to the word itself is that when anything is able to adjust itself to the changes made around its entire life. Materials need to adapt changes of environment to last for a longer period of time when it comes to their total life-cycle performance. Though researchers have made advances in the field of sustainability, yet there is limited work on the design of materials for extended life to have high impact on sustainability. Adaptation plays an important role, because in order to achieve advanced sustainable materials they have to adapt to the changes of global warming in order to achieve an extended life (Kasarda, et al. 2007). Adaptation refers to the initiatives and measures that are taken to reduce the susceptible impact that natural or human systems can cause against actual or expected changes that climate brings. Adaptation has various forms of existence, e.g. private and public, autonomous and planned etc. (Don and Verbruggen, 2006).
**Mitigation**

This term refers to the technological changes and substitution that could reduce the inputs of the resources and emissions per unit generated. Different policies whether social, economic or technological would also target towards emission reduction but mitigating strictly follows the implementation policy to the reduction of the green house gas emissions (Don and Verbruggen, 2006).

**Conservation**

The aim of energy conservation is to increase the efficient use of energy to achieve higher outputs with maintaining the same consumption. This may require the increase of security, financial capital, human comfort and environmental values. The direct consumer i.e. individuals and organizations, can also contribute to reduce energy costs and help in promoting environmental value.

**Life Cycle Energy Analysis**

This concept was introduced to evaluate the environmental impact of the existing products and for producing upcoming new products. A complete process starts from the procurement of material, processing, manufacture, use and services, disposal, and waste management (Kumar, et al. 2001). LCA is a method to determine and assess the product performance over its entire life cycle, a cradle to grave or cradle to cradle analysis. According to the standards, there is no single method for conducting an LCEA and is open to a wide range of environmental practices. It is very important when conducting a LCEA to follow certain goals and a defined scope and hence forth the results would be interpreted (Culaba and Purvis, 1999).

ATHENA Environmental Impact Estimator (EIE) is a tool developed to assess the LCEA and help the deciding on product selection very early on in a project. Comparisons over using different material and their energy performance can be determined. Another advanced tool is the Building for Environmental and Economic Sustainability (BEES). Additional to LCEA, BEES also combines the life-cycle costing (LCC) data. For the materials being used this can provide data related to the embodied energy, air pollutants, indoor air quality, ecological toxicity and health along with the typical performance measures of energy, GWP (global warming potential), air, water, resources. Most importantly it can provide side by side comparisons of up to five different projects, otherwise individual data is meaningless.

**Embodied Energy**

The energy requirements of the total life cycle of a building are an addition of the operational energy and its embodied energy (Bekker, 1982). Operational energy grabs much more attention into energy conservation and efficiency and includes what is used for heating, cooling, ventilation, lighting etc. The embodied energy incorporates the energy which is used throughout the processes from ground, processing, manufacturing and construction (Fay, et al. 2000). This energy comprises of direct and indirect energies, which means that the energies used for the main process are direct energies and indirect energies are used to create the inputs of products and services for the main process (Treloar, 1997).

**LCA or Embodied Energy?**

Since the aim for this study is to develop a larger framework which would act as a base for other materials, so LCEA is a better and accurate method of being closer to the value of the energy involved with the material from its inception to its demolition/ recycle or reuse.

**Glazing Functions**

The use of glazing has primarily been to enclose space for nearly two millennia and is one of the oldest manmade materials used for construction purposes. With the continuous advancement in its manufacturing and refining processes it has become the most modern material to build. It takes the shape of almost any building skin and hence is the most fascinating material that architects and designers like to use (Wurm, 2003).
The use of modern glazing began from the greenhouses in England back in the early 19th century from where the evolution of glazing construction began. In the 20th century a new construction method was recognized by the younger generation of architects to achieve transparency, openness, and abundant light in large halls. This change did result in the problems of heat losses in winter and conversely gains in summer, though a continuous effort of improving the summer gains is being done (Wurm, 2003).

Glazing construction has dominated the public environments, including airports, railway terminals, sports and leisure arenas, exhibition halls, shopping centers and atria.

**Glazing Characteristics**

“As defined glazing is a uniform material, a solidified liquid. The molecules in its composition are completely in a random order and form a crystalline lattice, hence making it transparent.” (Schittich, et al. 2007).

**Glazing Types**

- Classified on the type of resistance towards heat, there are six basic types of glazing. Soda-lime-silica which is the most common type of glazing used for door and window glazing, comprises of about 90 percent of glazing produced is soda-lime-silica. It is composed of 74 percent of silica, 15 percent soda, 10 percent lime and 1 percent alumina (Spence, 2006).
- The most commonly used glass products of the construction industry which may vary with the manufacturer are, four of the basic types of glass have been discussed below:
  - **Low-E Glass**: As the name suggests this is a low emissivity glazing that helps in reducing energy costs. Used in commercial as well as residential applications this glazing is suitable for all climates (Spence, 2006).
  - **Laminated Glass**: This glazing has its main applications in areas which are prone to higher level of breakage. It is strengthened especially while manufacture with interlayer of plasticized polyvinyl butyral (PVB) resin (Spence, 2006).
  - **Insulating Glass**: This glazing unit is composed of two layers of glazing with an airtight, dehydrated air-space between them. This is also used as a Low E glazing when tinted (Spence, 2006).
  - **Reflective Glass**: This glazing follows the principle of transmittance of the solar energy strongly. It is coated with thin layers of metallic films that help in reflection of the heat as well as reduce convection (Spence, 2006).

**Silica Mining**

The major ingredient used for the manufacturing of glazing is primarily silica. As discussed before in the paper it accounts for 74% of the glass composition. According to the USGS Mineral Industry Surveys, “A total of 1.32 billion metric tons of construction sand and gravel valued at $8.5 billion (free on board plant) was reported produced in the United States in 2006 by 3,974 companies with 6,294 active operations and 61 sales/distribution yards. A considerable quantity of the construction sand and gravel produced in 2006 came from operations with output larger than 200,000 metric tons per year; 1,949 operations, representing 31% of all operations, produced 80% of the total tonnage.” (Crawford, 2006).

According to the mineral industries survey in 2006, the 10 leading producing States were, in descending order of tonnage, California, Texas, Arizona, Michigan, Minnesota, Washington, Colorado, Ohio, Nevada, and Florida. Their combined production accounted for about 51% of the U.S. total, Figure 5 & 6.

Since 1900, use of construction materials such as crushed stone and sand and gravel has increased from about 35 percent to 60 percent of total non-food, non-fuel raw materials consumption in the United States. Figure 7. Consumption of non-food and nonfuel agricultural and forestry products has dropped from about 60 percent to 5 percent of total raw materials consumption during the same period.
Manufacturing

The most commonly used glazing i.e. soda lime glass is manufactured in four phases:

- Preparation of raw material
- Melting in a furnace
- Forming
- Finishing

Except the forming and finishing the rest of the procedure is same for glazing manufacturing for the glazing types. Flat glass manufacturing follows the step by step process of either of float, drawing, or rolling processes see Figure 8 (Reznik, 1976).

The raw materials i.e. sand, limestone and soda as reach the manufacturing facility first are crushed and then stored in separate bins that are elevated. Through the gravity feed system the raw materials are then transferred, where proper mixing is done with the help of a cullet for ensuring uniform melting. Before any of the raw materials are sent to the furnace, they are hosed separately in a batch plant, see Figure 9 (Schoor, 1976).

The most commonly used regenerative furnace is capable of producing from anywhere between 45 to 472 megagrams of glazing per day which is approximately 50-3900 tons. The material is then sent to the furnace through the feeder, it floats on the top of the molten glass which is already present in the furnace. After this the mixture is then lead to the refiner, where the molten glass is further conditioned with heat for the forming process. After the
refining process the glass is sent through fore hearths for shaping by the further processes of pressing, blowing, drawing, rolling or floating for the final product. Before the finished product decorating and coating and annealing are performed. If the glass is found to be damaged it is transferred back to the batch plant for being reused as cullet (Reznik, 1976).

Methodology

This research began with literature search on the issue of sustainability. Regular progress, delved into deeper understanding of the areas where problem lies. This review has helped greatly in defining the problem and hence for the way this research can be conducted to generate a desirable result and a base for future work, and other such materials. As the problem took shape, sub-problems also got in to further strengthen the base of the study. Since this whole process is interconnected the sub problems further defined the scope of the study by assumptions and delimitations, as previously discussed LCEA need to have its defined boundaries.

A paper by Fitch, P. E. (2004) presents a life cycle energy analysis as a tool for material selection for automotive components, where it sums up the energies used at all the stages to estimate life cycle energy. A similar approach can be followed when calculating the material energies for buildings. Selecting each material separately and breaking down the stages of material production to its final use and reuse.

This research will propose a model for glazing which is used as a construction material. And the exact unit of energy of manufacturing of glazing would be calculated with assumptions for the other steps involved during its entire process. This will act as a physical model for other similar materials for future research.

The objective of this research is to find out the complete energy set for indirect energies along with the direct energies for building materials. This will be done by a detailed study of the material itself. Knowing how a building material is extracted, transported, manufactured, stored, applied and reused/ recycled,

The following steps will be followed for the proposed methodology according to the study in three phases:

**Phase I:** The first phase will involve the data collection from the existing data, observations and specifications for the various steps and processes involved in glazing manufacturing for the considered glazing according to the LCEA pattern that will be proposed. For glass certain values of embodied energies have been derived from 9 different sources for the direct energies of glass. These values are the energies for manufacturing of the material (PER) in different units of energy. The second set of data involves in collecting the data from the glass manufacturing industry census for the number of workers involved in the production of glazing. This will determine the indirect energy data set to eventually add up to complete the entire set of energy.

**Phase II:** Data Collection and Interpretation: The second phase will delve into the conversion of the collected data into the considered unit of study and convert to a common unit for the processes involved i.e. BTU.
The estimated life cycle energy totals up as the sum of energy use at every level of the products use. Hence the life cycle energy of glazing could be estimated as:

\[ LCA(g) = E(ex) + E(mf) + E(tp) + E(ppl) + E(use) + E(mnt) + E(rec) \]

Where,

- \( LCA(g) \) = Life cycle energy of material.
- \( E(ex) \) = Energy involved for extraction of raw material/materials.
- \( E(mf) \) = Energy generated during manufacturing including packaging.
- \( E(tp) \) = Energy generated for transportation at different steps involved.
- \( E(ppl) \) = Energies of people involved at each stage*.
- \( E(use) \) = Energy involved for use of the material after it is installed.
- \( E(mnt) \) = Energy produced during maintenance.
- \( E(rec) \) = Energy used for its recycle and reuse.

Note: 1 MJ = 947.817 BTU.

These values of energy will then be divided into different cases for analysis and hence deriving conclusions.

**Phase III:** The final phase would primarily draw conclusions from the data analysis, and the use of the published results for future work. For manufacturing of glass the amount of indirect energy percentage was observed to be much lower than the direct energy. Also the transportation energies were observed to be high where large numbers of people are involved in the process.

* Energy involving people also incorporated their transport energy and energy of their homes.

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**Figure 10. Life Cycle for glazing manufacture showing different boundaries. (Culaba and Purvis, 1999)**
The Direct and Indirect Energies

The correct complete set of criteria includes the direct and indirect energies which have been further broken down and added up for taking in account the energy factors. A broader picture of these factors has been discussed previously in the paper. A precise picture is presented in detail for the manufacturing process below.

Direct Energies

In easy and straight terms direct energies account towards the direct process and production of the product. According to Bill Lawson, 1996, this is referred to PER i.e. Process Energy Requirement. The percentage of PER that accounts towards the energy of a material ranges from 50-80% of the GER (Gross Energy Requirement). GER accounts for energies of almost everything associated and required for the building.

Flat glass process involves enormous energy consuming steps beginning from, Crushing and sizing, Batching; weighing and mixing, Melting in furnace, Float fabrication, Annealing, Cooling, Finishing, Tempering, Processing.

According to the U.S. Census Bureau in the year 2002 for flat glass manufacturing, 6.3 billion square feet flat glass was produced, and 6.4 billion was shipped. A trend of the production from the years 2000-2002 in short ton and 1000 sq. ft. is shown in Figure 11 &12.

Different types of glass also carry different embodied energies which highly depend on their processing. Figure 13 shows a comparison bar chart for four types of glass mainly, laminated tinted, toughened, and float glass. Evidently toughened glass carries a larger amount of energy as its processing requires high thermal treatments in comparison to other types of glass.
From different sources nine values of the assumed approximate embodied energies are taken in Table 1 for analysis. Figure 14 shows a bar chart for all these values showing their variations.

Table 1: Embodied energy values of Glass.

<table>
<thead>
<tr>
<th>Case</th>
<th>Value</th>
<th>Unit</th>
<th>BTU/pound</th>
<th>Source</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case A</td>
<td>12.7</td>
<td>MJ/Kg</td>
<td>5462</td>
<td>Lawson, Bill</td>
<td>2006</td>
</tr>
<tr>
<td>Case B</td>
<td>6750</td>
<td>BTU/pound</td>
<td>6750</td>
<td>Allen, Edward</td>
<td>2003</td>
</tr>
<tr>
<td>Case C</td>
<td>7500</td>
<td>BTU/pound</td>
<td>7500</td>
<td>Allen, Edward</td>
<td>2003</td>
</tr>
<tr>
<td>Case D</td>
<td>15.9</td>
<td>MJ/kg</td>
<td>6838</td>
<td>Gumaste, S</td>
<td>2006</td>
</tr>
<tr>
<td>Case E</td>
<td>37550</td>
<td>MJ/m³</td>
<td>6211</td>
<td>Lawson, Bill</td>
<td>2006</td>
</tr>
<tr>
<td>Case F</td>
<td>15</td>
<td>MJ/kg</td>
<td>6451</td>
<td>American Institute of Architects, Environmental Resource Guide</td>
<td>1994</td>
</tr>
<tr>
<td>Case G</td>
<td>40060</td>
<td>MJ/m³</td>
<td>6626</td>
<td>Lawson, Bill</td>
<td>2006</td>
</tr>
<tr>
<td>Case H</td>
<td>25.8</td>
<td>MJ/Kg</td>
<td>11095</td>
<td>Suzuki, et. al.</td>
<td>1995</td>
</tr>
<tr>
<td>Case I</td>
<td>240/6mm</td>
<td>MJ/m³</td>
<td>6616</td>
<td>Lawson, Bill</td>
<td>2006</td>
</tr>
</tbody>
</table>

Table 2: Embodied energy values for the considered sample in BTU/pound.

<table>
<thead>
<tr>
<th>Case</th>
<th>BTU/pound</th>
<th>For Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case A</td>
<td>5462</td>
<td>73737</td>
</tr>
<tr>
<td>Case B</td>
<td>6750</td>
<td>91192</td>
</tr>
<tr>
<td>Case C</td>
<td>7500</td>
<td>101325</td>
</tr>
<tr>
<td>Case D</td>
<td>6838</td>
<td>92381.4</td>
</tr>
<tr>
<td>Case E</td>
<td>6211</td>
<td>83910</td>
</tr>
<tr>
<td>Case F</td>
<td>6451</td>
<td>87153</td>
</tr>
<tr>
<td>Case G</td>
<td>6626</td>
<td>89517.3</td>
</tr>
<tr>
<td>Case H</td>
<td>11095</td>
<td>149893</td>
</tr>
<tr>
<td>Case I</td>
<td>6616</td>
<td>89382</td>
</tr>
</tbody>
</table>

The considered set of embodied energies have been brought to a common unit for the study i.e. BTU/pound. These values were derived over the years by different sources.

The assumed unit of glass i.e. one square foot, one inch thick double insulated glass is equivalent to 13.51 pounds. Hence the direct embodied energy of the assumed panel i.e. 1 sq. ft. 1/4 th in thick double insulated 1” thick, total for the considered values is shown in Table 2.

**Indirect Energies**

**People**

This is one of the missing components of the GED which is usually not accounted for when considering the embodied energy of the material. But it becomes important for us to add up the energies of the manpower that is being utilized to produce the material.
According to the U.S. Census Bureau 2002, economic census for flat glass manufacturing there are about 36 establishments with 10,683 employees and 8,673 production workers on an average for a year, with over 11 establishments having 100 – 250 employees and 15 establishments having 250-599 employees. Figure 15 & 16 show variation bar charts for the flat glass establishments.

Knowing that the average energy consumed by a person in a day is 2300 calories, it can be accounted for the energy consumed by a production worker in a day.

\[
2300 \text{ calories} \times 0.0039 = 8.97 \text{ BTU}
\]

Also this amount of energy is a collective amount contributed together. Our focus is on the sample of glass considered so it is relevant to determine the amount of glazing that is being produced during a certain day on and average. According to the U.S. Census Bureau for Flat Glass – 2002 the production of flat glass in short tons was 5,266,299. Accordingly the production on an average per day was 14,428 short ton.

\[
14,428 \text{ ton} \times 2000 = 28,856,000 \text{ pounds/day}
\]

According to the U.S. Census Bureau data the number of employees involved in flat glass manufacturing is 10,683. Hence the total energy of the people involved in glass production per day would be equivalent to,

\[
10,683 \times 8.97 = 95,826.5 \text{ BTU}
\]

Hence the energy contributed by all employees per day involved in flat glass production is,

\[
\frac{95,826.5}{28,856,000} = 0.00332 \text{ BTU/pound}
\]

Additional to this we also account for the energies of the families of the employees. Considering that the average family size is 4 people. We will multiply this amount by a factor of 4.

\[
0.148 \text{ BTU/pound} \times 4 = 0.594 \text{ BTU/pound}
\]

For a size of 2325 sq. ft. single-family home in Dallas/Fort Worth the annual energy consumption for the house is 101.5 MBtu including heating and cooling (Mukhopadhyay, et. Al, 2008).

\[
101.5 \text{ BTU/ 365 days} = 0.5534 \text{ BTU/day}
\]

**Transportation**

Transportation of goods accounts directly towards a products energy. After packaging the glass is transported to either storage areas or directly to sites. What this study attempts is to account for the indirect transportation i.e. the transportation that people who come for work use for their daily commute. Apparently this energy also accounts as it is being used for the material. Table 2 shows an example of amount of energies in transportation that were used in a study conducted previously.

As assumed before their average living distances are approximately 50 miles from the manufacturing facility. The U.S. Environmental Protection Agency calculates the overall average fuel economy for passenger vehicles to be 20.3 mpg. So on an average the fuel consumed in a day is,

\[
100 \text{ miles/ 20.3 mpg} = 4.92 \text{ gallons/day}
\]
Energy for production and transportation

<table>
<thead>
<tr>
<th>Type of material</th>
<th>Production</th>
<th>50 km</th>
<th>31 miles</th>
<th>100 km</th>
<th>62 miles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand (MJ/m3)</td>
<td>0</td>
<td>87.5</td>
<td>55</td>
<td>175</td>
<td>108</td>
</tr>
<tr>
<td>Crushed aggregate (MJ/m3)</td>
<td>20.5</td>
<td>87.5</td>
<td>55</td>
<td>175</td>
<td>108</td>
</tr>
<tr>
<td>Burnt clay bricks (MJ/m3)</td>
<td>2550</td>
<td>550</td>
<td>342</td>
<td>200</td>
<td>124</td>
</tr>
<tr>
<td>Portland cement (MJ/t3)</td>
<td>5850</td>
<td>50</td>
<td>31</td>
<td>100</td>
<td>62</td>
</tr>
<tr>
<td>Steel (MJ/t3)</td>
<td>42000</td>
<td>50</td>
<td>31</td>
<td>100</td>
<td>62</td>
</tr>
</tbody>
</table>

Converting this fuel factor to our considered energy unit BTU, will help us better understand the transportation energy consumption.

4.92 gallons x 115000 BTU= 565800 BTU/day

As calculated before the amount of energy used per pound of glazing per day we need to divide this amount by the production per day,

565800/28856000 = 0.0196 BTU/pound

Results

Tables 4&5 sum up the energy calculations and give a detailed idea of these energies in comparison to the direct energy values for manufacturing of glass. Apparently all these valued indicate a very miniscule increase in the energy values which is less than 1% in all the cases. Even with the increase in size of the establishment and the number of employees the value does not vary.

Table 4: Total sum of the considered energies.

<table>
<thead>
<tr>
<th>Average Employees</th>
<th>Energy/Day</th>
<th>Assumed sample</th>
<th>Family</th>
<th>Home</th>
<th>Transportation</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>175</td>
<td>0.581</td>
<td>7.84931</td>
<td>31.3972</td>
<td>31.9506</td>
<td>46.2</td>
<td>78.1506</td>
</tr>
<tr>
<td>375</td>
<td>1.245</td>
<td>16.81995</td>
<td>67.2798</td>
<td>67.8332</td>
<td>99</td>
<td>166.833</td>
</tr>
<tr>
<td>750</td>
<td>2.49</td>
<td>33.6399</td>
<td>134.56</td>
<td>135.113</td>
<td>198</td>
<td>333.113</td>
</tr>
</tbody>
</table>

Table 5: Energy Chart for all total values Direct and Indirect.

<table>
<thead>
<tr>
<th>Case A</th>
<th>73737</th>
<th>73815</th>
<th>73982</th>
<th>74315</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case B</td>
<td>91192</td>
<td>91270</td>
<td>91437</td>
<td>91770</td>
</tr>
<tr>
<td>Case C</td>
<td>101325</td>
<td>101403</td>
<td>101570</td>
<td>101903</td>
</tr>
<tr>
<td>Case D</td>
<td>92381</td>
<td>92459</td>
<td>92626</td>
<td>92959</td>
</tr>
<tr>
<td>Case E</td>
<td>83910</td>
<td>83988</td>
<td>84155</td>
<td>84488</td>
</tr>
<tr>
<td>Case F</td>
<td>87153</td>
<td>87231</td>
<td>87398</td>
<td>87731</td>
</tr>
<tr>
<td>Case G</td>
<td>89517</td>
<td>89595</td>
<td>89762</td>
<td>90095</td>
</tr>
<tr>
<td>Case H</td>
<td>149893</td>
<td>149971</td>
<td>150138</td>
<td>150471</td>
</tr>
<tr>
<td>Case I</td>
<td>89382</td>
<td>89460.15</td>
<td>89627</td>
<td>89960.08</td>
</tr>
</tbody>
</table>
Conclusions

The energies of the people and their families considered though become very important for the manufacturing of the product. Eventually when this energy is compared to the total bulk of the glazing manufacturing and processing it is miniscule. Hence what we can infer here is that the materials which involve high processing and manufacturing energies in comparison to the total energy have a very small fraction of the energies of people involved. A recommendation is to draw a comparison with other materials that do not require high processing energies.

It then becomes highly important to understand that the materials that require high amounts of energy for their manufacture require serious attention towards on their production and processing techniques. If steps are taken to minimize the energy use for the production of materials faster and in larger amounts, the efficiency of the system and the energies of the material itself will be less.

All buildings carry operational energy along with the embodied energies of materials that have been used. Operational energy varies according to building occupancy as the number of people increases. Similar to this the material embodied energy also varies slightly depending upon the labor involved, this is critical for all materials. For a material like glass the operational energy might vary considerably depending upon its U value but the embodied energy has to be taken into account carefully. This is also referred to as initial EE which if carefully selected while deciding upon materials for a building can help in saving energy it its overall design.

The overall transportation involved whether directly or indirectly is a major factor contributing towards the energy footprint of any material. It is very evident that larger the distances involved for the transportation of the material the higher energy involved with the material. Very similar to this is the indirect energy account, larger the number of employees associated with the manufacturing facility, larger is the fuel consumption involved. The results of the study clearly indicate a high percentage of the fuel consumed by the employees only to reach to the facility for work.

This study can act as a tool for a sustainable wholistic approach for materials and the energy involved in its each step over a long term for calculating the operational energy and the total outcome along with its recycle potential.

Generating a complete set of materials and their embodied energy values in the form of a table where their quantities have been accounted for will add up to a total of the initial energies and an assumption of the operational energies will account to the materials along with their life cycle operating energies. The potential of recycling a material is very important while this energy is being considered, as it reduced the waste on one hand and on the other reduces the energy for using lesser raw material. Glass has tremendous processing energy and has a very high recycling potential because it can be reused even after its lifecycle. Hence the energy involve in the overall life cycle of glass is high but with considerable improvements in its manufacturing it can be reduced along with proper steps for utilizing its full recycling potential.

What we will gain from this research will be an idea of the approximate footprint of energy of glazing accounting the possible energies that can involved within the process. The glazing manufacturing framework can be used to complete the other processes i.e. mining & extraction, storage, on site use, recycle, for determining the exact energies involved. We can draw a comparison of this footprint with the footprints of other materials, which would help us in future in trying to achieve an efficient energy footprint.
List of References

Search engines used: LibCat, Google Scholar, Web of Science, Google, Engineering Village, Science Direct, Compendex, Ebsco, Wilson, Proquest, Scopus, Ingenta, Inspec, Web of knowledge, Worldcat, Iconda.


