# Optimizing Energy and Process Efficiency of Radio Frequency Glass Lamination

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## ABSTRACT

Radio Frequency (RF) Lamination is a new technology that shows promise for significantly reducing the need for energy intensive autoclaving of laminated glass. RF lamination, which has been named FastFuse™, uses radio-frequency dielectric heating to directly heat the polymer interlayers that are used to laminate glass for automotive windshields, hurricane glass, safety glass, solar panels, and transparent armor. The direct heating virtually eliminates the reliance on thermal conductivity for heat transfer, which is inherent in traditional autoclave methods. RF technology has been used to laminate single-pane glass laminates in less than one minute, and multilayer transparent armor panels (up to 3 inches thick) in just five minutes. This compares to process times of 1 to 6 hours using autoclaves, and provides an energy savings of over 90%. Quality testing of RF laminated windows has confirmed that properties and performance meet or exceed the quality of autoclaved windows. Demonstrations to date have shown equivalent performance for all of the major interlayers, including thermoplastic polyurethane (TPU), polyvinyl butyral (PVB), and ethylene vinyl acetate (EVA). A cost and energy analysis was performed, comparing RF lamination to the state-of-the-art autoclave process. RF lamination can lower the cost of high value laminates such as photovoltaic panels and transparent armor, by improving product throughput, energy efficiency, and enable rapid just-in-time manufacturing for glass laminates.

## Introduction

RF technology has been successfully used in wood, paper, and packaging industries for many years, from small to very large scale. RF processing has decreased the time and energy required for many processes such as manufacture of plywood, from many days to a few hours. Energy savings greater than 90% is typical in many RF processes. The glass lamination process now applies this existing equipment supply to the glass industry.

Laminated glass currently accounts for at least 25% of all flat glass sold in the U.S., and is the fastest growing segment in the glass industry. Glass lamination is an integral component in the manufacture of major energy saving and clean energy products. Rapid growth in lamination is resulting from the rise of solar power (laminated solar panels and solar concentrator mirrors), security demands, and new energy saving and safety regulations in the automotive industry. In the automotive industry, lamination is poised to expand from just windshields today, to including all side windows in the next 10 years.

The vast majority of the energy consumed by the glass industry is used for heating. Lamination, used for fabricating a wide range of glass products, is just one of many processes that require heat. For example, with automotive windshields, heat is required to melt the raw materials, to form the molten glass into flat sheets, to bend the glass into shape, to clean and dry the glass, to de-air the vinyl used to make the laminate, and finally to produce the final clear window, typically in an autoclave (DuPont 2006; Pellegrino 2002). The heat used in each process is generally lost between steps, such as when de-aired pre-laminates await loading into an autoclave. Energy efficiency solutions for the glass industry are being sought by industry through government-industry partnerships such as the Department of Energy Industrial Grand Challenge. Radio-frequency lamination, developed by Ceralink and coined "FastFuse," is an example of an emerging efficient technology in the glass industry.

Radio-frequency (RF) heating has been used in industry for over fifty years, with significant usage in drying and gluing applications (Thermex Thermatron 2011; Tran et al. 1997). High power radiowaves cause polar molecules such as water and many organic chemicals, especially adhesives polymers, to heat via internal friction generated from the movement of dipoles in the high frequency electric field. RF energy is therefore absorbed into these materials, and converted into heat, resulting in loss of RF intensity. Meanwhile, materials that are not polar are less directly affected by RF energy, and allow RF energy to pass through them without significant loss of RF power. Some of these materials include wood pulp, paper, olefin polymers (e.g., polyethylene, polypropylene, PTFE), and glass. The properties of these materials, related to RF energy, make RF suitable for drying wood, gluing particle board, curing fiberglass and Kevlar composites, welding vinyl packaging, and now laminating glass.

## Laminated Glass

In 2001, 6.4 billion $ft^2$ of flat glass was produced in the U.S., with approximately 25% laminated (2006a). Flat glass comprises glass made in sheet form, primarily for window-type applications. Laminated glass includes products such as automotive safety glass, bullet resistance glass, hurricane glass, decorative architectural glass, transparent armor, and photovoltaic panels. The laminates are produced by bonding glass sheets together with plastic interlayers. The interlayers may be vinyl, such as polyvinyl butyral (PVB), ethylene vinyl acetate (EVA), or thermoplastic polyurethane (TPU). The type of interlayer used often depends on the application. PVB interlayers are the most common, and are used for automotive windshields, and a wide range of architectural safety and security windows. EVA interlayers are often used for photovoltaic panels and decorative applications, with some improved EVAs finding increased use in structural applications. TPU interlayers are among the toughest, and are often the interlayer of choice for transparent armor, bullet-proof glass, and lamination of acrylic and polycarbonate plastic windows.

Traditionally, laminated glass products are manufactured by assembling the glass and interlayers, de-airing the laminate with rollers or vacuum, and then heating the glass under pressure to complete the lamination (Hester 1999). The final lamination step is typically performed using a high temperature, pressurized autoclave. The autoclave process may take 90 minutes for single pane laminates such as windshields, or as long as 18 hours for very thick structures such as bullet proof transparent armor. The slow thermal conductivity of glass limits how quickly the heat can be delivered into the interlayer where it is needed. Thick windows therefore require substantially longer times to laminate. Autoclaves use significant amounts of energy to compress large volumes of air to 100 to 300 psi, and then to heat the air and laminates to 90 to 140 °C, depending on the interlayer. Most of the heating energy is used to heat the air and is lost at the end of the process or during the process through the walls of the autoclave.

Autoclaves, which are pressure vessels, are operated in batches. Glass that has been cut, washed, assembled with interlayer, and de-aired, is loaded into carts, which are then loaded into the autoclave for simultaneous lamination of large batches. The autoclave is unique in glass manufacturing, in that every other process from melting the raw materials to the final inspections after lamination is a continuous, one-piece-at-a-time process. Lamination is therefore the only process in which defects can affect a large quantity of product before detection is possible. Lamination is often considered a bottleneck in production, due to the batch nature of the autoclave. The heat energy invested into the glass during the de-airing steps, in which the heated prelaminate is passed through rollers, is completely lost as the glass is loaded into carts, awaiting the autoclave.

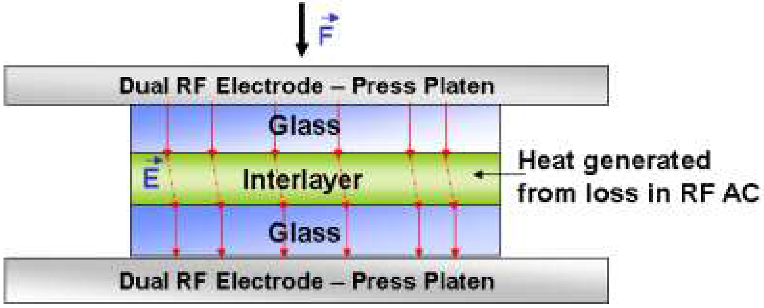
## Radio Frequency Heating

The ability of RF energy to heat materials (i.e., RF heating) is determined by the dielectric properties of the materials. Dielectric properties are a measure of the polarizability (the real permittivity or dielectric constant ($\varepsilon'$)), and the transmission loss of the RF energy (the dielectric loss factor ($\varepsilon''$)) through absorption and heating (Metaxas and Meredith 1993). These properties can be measured, and using them, the absorption of microwave power can be predicted. Polar materials generally have high dielectric loss, and are therefore good heaters. Non-polar materials have low loss and therefore allow RF energy to propagate through them without heating.

This dependence of heating on the dielectric properties results in significant advantages for RF heating over traditional radiant heating techniques. For laminated glass, the low-loss glass allows the RF energy to transmit directly to the higher-loss plastic adhesive interlayer. This interlayer heats immediately from the RF energy, and is quickly melted to complete the lamination process. RF glass lamination typically takes only 1 to 5 minutes from cold-materials to laminated, depending on the thickness of the product. In traditional heating, heat transfer must take place through the low thermal conductivity glass, and gradually into the interlayer, resulting in a slow process.

The FastFuse RF lamination process works by dielectric heating of the vinyl or polyurethane interlayers used to bond glass layers together. Dielectric heating occurs when the vinyl is placed in a RF field and the RF energy causes dipoles and weak bonds in the vinyl to vibrate and move. As a result, microfriction occurs and heat is produced. The glass surrounding the interlayer does not react significantly with the RF field, and therefore does not heat. The type of RF equipment used to perform the lamination is called an RF press. The RF press consists of a hydraulic or pneumatic press with metal platens that apply both pressure and RF energy to heat and bond products. The platens also act as electrodes, creating an RF electric field through the product. This makes the product a capacitor, therefore the heating from the RF energy is entirely due to dielectric losses. This is schematically shown in Figure 1, where a product prelaminate, made of glass-vinyl-glass layers, is placed between the press platens and pressing force (F) and the RF electric field (E) are applied.

**Figure 1. Schematic of Laminated Product in an RF Press**



Source: Ceralink, Inc.

The pressure promotes removal of air from between the interlayer and the glass, and facilitates flow of the hot molten (or softened) interlayer to conform and adhere to the glass.

## Potential for Continuous Glass Lamination Process

The rapid nature of the FastFuse RF lamination process offers an opportunity for continuous lamination processes, as opposed to the batch processes required with autoclaves. Continuous flow of laminated glass manufacturing would result in energy savings, improve quality with part-by-part inspections immediately after lamination, and greatly reduce the footprint of lamination in factories. In addition to the energy saved simply from the RF heating mechanisms, a continuous process would take advantage of heat invested in the glass during the pre-lamination steps of heating and rolling. Rather than cool down on a cart prior to autoclaving, the heated parts would travel directly into an RF press. The preheating from the rolling step would further reduce the RF process time and therefore total energy requirement, improving the efficiency of the overall process.

## Energy in the Glass Lamination Industry

The growth of the solar industry is rapidly increasing the volume of laminated glass manufacturing, as a majority of solar panels are laminated with glass. Some estimates place the growth in use of photovoltaic panels above 30% per year through 2012 (Hodge 2008; LaMonica 2008). With production doubling every 2 to 3 years, new energy burdens from glass lamination are being produced. Significant opportunities for growth within the glass, interlayer, and laminating equipment industries are being generated. FastFuse RF lamination would provide a step change in the solar industry, slashing production time and energy costs, thereby facilitating greater consumer uptake through reduced capital cost of solar power. This would provide far reaching energy and $CO_2$ benefits well beyond the already significant manufacturing reductions. FastFuse RF lamination can be a key technology to help the solar industry meet and exceed ever-shrinking cost targets for sustainable, subsidy free production.

The vinyl interlayers add UV blocking ability, which reduces greenhouse effect in cars and buildings, and subsequently, the energy and $CO_2$ burden of air conditioning. The California Air Resources Board identified that increased use of laminated glass for side windows in automobiles could decrease $CO_2$ emissions by up to 1.9 million metric tons per year nationwide by 2040 (Bekken and Lemieux 2009). That is equivalent to an annual gasoline consumption reduction of 225 million gallons or 25 trillion BTUs (calculated using EIA 2009 Official Energy Statistics). However, the cost of laminated side windows could add between $39-128 to the price of each car (Bekken and Lemieux 2009). A less energy-intensive, faster lamination process, such as FastFuse RF lamination, would reduce the cost of this transition in the auto industry, significantly reducing the energy demand and associated $CO_2$ emissions from the manufacturing process. This will facilitate the realization of even greater life-cycle benefits associated with laminated glass side windows in cars.

Changes in federal automobile safety standards are another major factor increasing the production volume of laminated glass. Laminated side windows have been found to greatly reduce the incidence of bodily ejection from a vehicle during an accident. Laminated windows add additional benefits to cars through improved security over tempered glass. These factors are driving the autoglass industry to begin a shift away from tempered glass for side windows, and move toward industry-wide lamination. This will result in dramatic growth of glass lamination over the next decade as the volume of laminated autoglass quadruples as sunroofs, side, and rear windows join windshields in the lamination process.

The potential energy efficiency improvement with RF Lamination has been determined to be 90% or greater. The methods for calculating energy usage from FastFuse RF lamination are presented below. Meanwhile, the energy consumed by autoclaves has been determined from published data and direct industry comments.

## Experimental Procedure

FastFuse RF lamination was performed using RF presses built by Thermex Thermatron (Louisville, KY). Lamination studies up to 2 $ft^2$ (16 in x 18 in) were performed using a 10 kW, 27.12 MHz fixed-frequency press with up to three tons of available pressing force. Larger panels, up to 6 $ft^2$ (2 ft x 3 ft) were laminated using a 30 kW, variable frequency press, at approximately 17 MHz, with up to 65 tons of available pressing force.

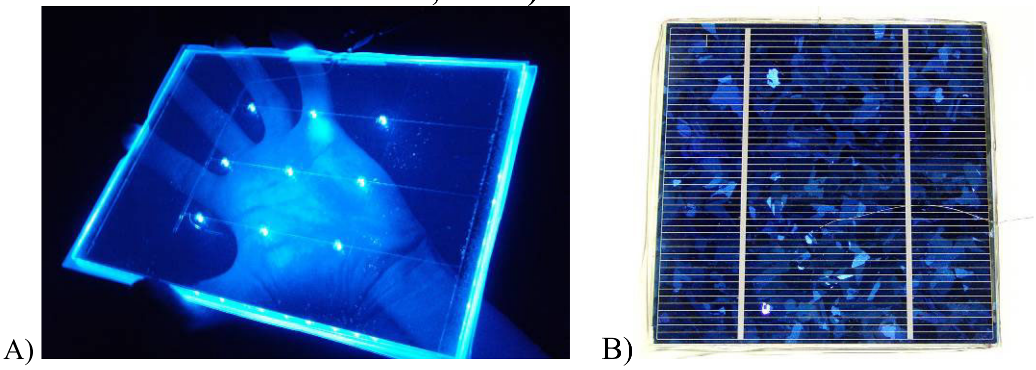
The materials used for lamination were 1/16 in. thick float glass, ranging from 4 in x 4 in squares to 2 ft x 3 ft cm sheets. Ethylene vinyl acetate (EVA) interlayers (0.38 mm thick) from Nanjing Kin Yong Fa (KYF) Plastics Mfg. Co. were used to laminate the glass in this study. Nanjing KYF EVA interlayers of several colors were used. The color of the EVA interlayer did not affect the lamination process requirements.

In the lamination experiments, RF power, the duration of RF application, and pressure were the primary adjustable variables. Panels were inspected after lamination to indentify bubbles or defects in the laminates, using ASTM C1172 procedures (2003), as well as close visual observation. The presence of small bubbles indicated that longer time or higher pressure was needed. In order to generate energy data and process scale-up estimates, only data from processes resulting in bubble-free laminates were used.

## Results and Discussion

Using the RF press, glass panels were fully laminated in one to three minutes depending on the size and power applied. No pre-lamination de-airing (i.e., heating and nip rolling or vacuum) was required for FastFuse RF lamination of the EVA interlayers. Smaller panels such as 4 in squares were laminated in approximately one minute, while larger sizes such as 2 ft x 2 ft and 2 ft x 3 ft panels were laminated in three-minute cycles. In addition to laminates with simple glass-vinyl-glass configurations, complex laminates with embedded light emitting diodes (LEDs) and silicon photovoltaics between interlayers, were produced, with examples shown in Figure 2.

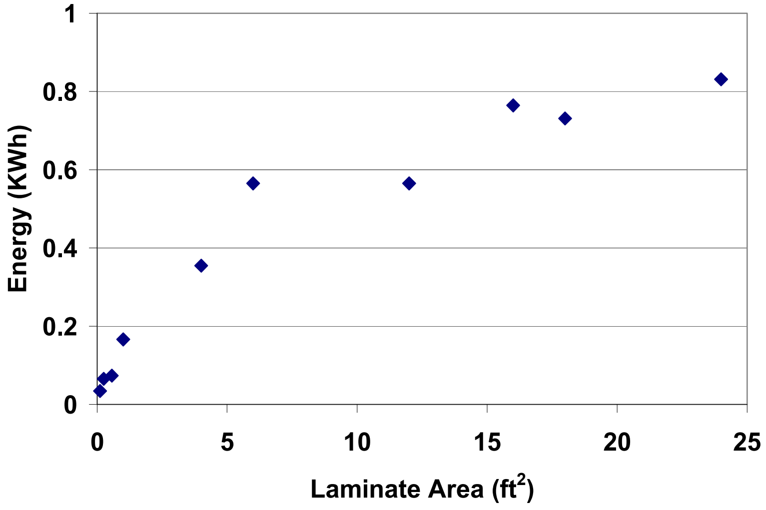
**Figure 2. Examples of FastFuse RF Laminated Glass Products with A) Blue LEDs Laminated Into Glass, and B) Silicon Photovoltaic Panel**



Source: Ceralink Inc.

Panels were visually inspected and found to be free of defects, including bubbles. The total energy consumed was calculated for each panel by multiplying the RF power by the length of time that the RF energy was applied. In general, the RF energy needed to laminate increased as the panel sizes grew larger (Figure 3).

**Figure 3. Plot of Energy Consumption for Laminating Glass with EVA, as a Function of Laminate Area. For panels Larger than 6 ft$^2$, the Panels were Stacked on Top of Each Other to Increase the Throughput of the Process**

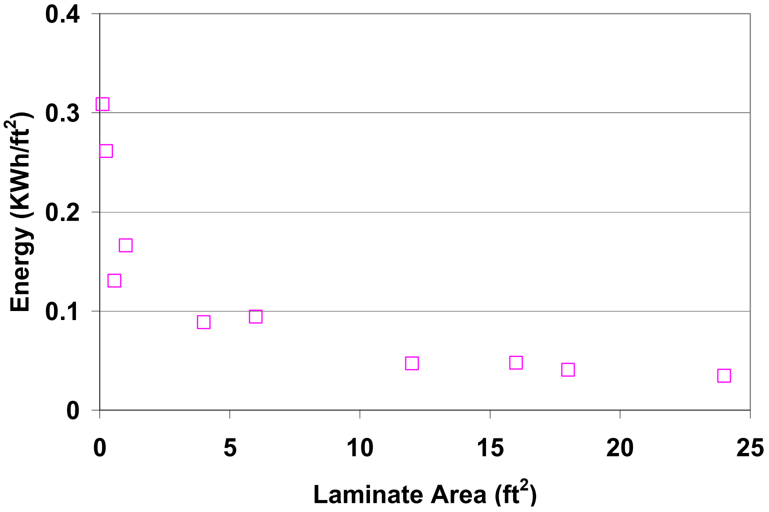


A major finding pertaining to scale-up, was that the energy required per unit of window area decreased significantly as the window area increased. From the smallest individual window (4 in x 4 in) to the largest (2 ft x 3 ft), the energy per square foot decreased by two-thirds from 0.3 kWh/ft$^2$ to 0.1 kWh/ft$^2$. Multiple windows were laminated simultaneously by stacking to achieve total cycle production of 12, 16, 18, and 24 ft$^2$. Stacking required slightly higher power input in order to achieve full lamination in the same process time needed for a single window.

Figure 3 shows that above 6 ft$^2$, the slope of energy demand rise decreased dramatically. This provided for significantly higher throughput, and even lower per unit energy requirement (Figure 4), of only 0.036 kWh/ft$^2$ for 24 ft$^2$ of RF laminated glass.

Lamination of larger panels is anticipated to bring further improvements in energy efficiency. In production, where windows may be de-aired via heating and nip rolling, less energy will be required for lamination as a result of the preheating.

**Figure 4. Plot of Energy Efficiency of the RF Lamination Process, Showing the Decrease in Per-Unit Energy Consumption as the Process Scales Up**



Using the RF energy consumption rates measured experimentally, several calculations were performed to compare scale up of an RF process to an autoclave process. Autoclave energy consumption was determined from market data on the size of the flat glass industry. In 2001, 6.4 billion ft$^2$ of flat glass was produced in the U.S., with approximately 25% laminated (2006a). The majority of laminated glass is made of two layers of glass, but laminates with multiple layers are used in some applications such as bullet resistant glass. Assuming an average of 2.5 ft$^2$ of glass for every square foot of finished laminates, approximately 640 million ft$^2$ of laminated glass was produced in 2001. The U.S. Department of Energy (DOE) showed that mid 1990s lamination energy consumption was 1.64 trillion BTUs, with an average 6.5% glass growth rate, yielding 2.11 trillion BTUs in 2001. From this data, the average energy consumption for autoclave lamination was estimated to be 0.97 kWh/ft$^2$. Bottom up estimates based on power ratings for autoclave equipment and process time also yield similar estimates, in the range of 1 to 3 kWh/ft$^2$. FastFuse RF lamination compares favorably, as discussed above with Figure 4, using 96% less energy per square foot than autoclave lamination.

Table I provides an example of the energy and throughput benefits associated with the novel RF Lamination technology. The calculations compare a hypothetical 15 ft long autoclave with 4 ft x 4 ft working cross-section, producing nearly 800 ft$^2$ per cycle, and a 5 ft x 8 ft RF press. The RF press is assumed to produce four 5’x 8’ sheets in each cycle, and to run once every 10 minutes. The 5 ft x 8 ft RF press is also assumed to use the same energy per square foot for lamination as was measured in the work with 2 ft x 3 ft panels. In this comparison, the RF press produces four times as much product, with 85% less energy than the autoclave. When the benefits were adjusted relative to the amount of glass produced, saves over 4 billion BTU per million square feet of laminated glass. Industry wide, up to 2.04 trillion BTU out of 2.11 trillion BTU consumed, could have been saved in the year 2001 if RF lamination were available.

**Table I. Table of Energy and Economic Benefits for RF Lamination**

| Metric (Unit) | Autoclave | RF Press | Net and Percentage Comparisons of FastFuse RF Lamination with Autoclave |
|---|---|---|---|
| Capital Cost Per Unit ($) | $540,000 | $850,000 | $310,000, or<br>57% higher capital cost |
| Typical Cycle Time (minutes) | 180 | 3-5 | 175 minutes, or<br>95% less time |
| Energy per $ft^2$ ($kWh/ft^2$) | 0.97 | 0.036 | 0.93 $kWh/ft^2$, or<br>96% less energy |
| Annual Production in 250, 24 hr workdays ($ft^2/yr$) | 1,400,000 | 5,760,000 | 4,360,000 $ft^2/yr$, or<br>4 times more throughput |
| Annual Energy Use in250, 24 hr days (kWh/yr) | 1,358,000 | 207,400 | 1,150,600 kWh/yr, or<br>85% less energy consumption |
| Capital Cost for Equivalent Throughput, ($) | $2,214,000 | $850,000 | $1,364,000<br>61% lower capital cost |
| Energy per million $ft^2$ (kWh) | 970,000* | 36,000 | 934,000 kWh, or<br>96% less energy |
| Energy industry wide based on 2001 statistics, 640 million $ft^2$ laminated glass (kWh) | 620,800,000 | 23,040,000 | 597,760,000 kWh, or<br>96% less energy |

*Autoclave energy estimate is for a three-hour process, seven cycles per day.

## Calculation of Autoglass Energy Projections

The U.S. Department of Energy (DOE) Office of Industrial Technologies reported in 2002 that laminated glass consumed over 1.6 trillion BTUs annually in the late 1990s (Pellegrino 2002). However this data only included glass laminated by glass manufacturers. Lamination by final product manufacturers, such as solar and transparent armor companies were excluded from that estimate. In the same time period, tempered glass accounted for 12.9 trillion BTUs annually (Pellegrino 2002). With the rapid growth of laminated glass in motor vehicles, the annual U.S. energy consumption of autoglass lamination is likely to reach 10 trillion BTUs by 2025 with autoclaving based on laminated glass growth rates reported by The Freedonia Group (2006a), a nonprofit research institution. RF Lamination has the potential to reduce that consumption to just 1 trillion BTU, based on the energy savings calculated in Table I.

The Freedonia Group, a nonprofit research institution, reported that in 2005, 32% of all flat glass was for motor vehicles. Freedonia also reported that 24.7% of all flat glass was laminated, while 31% was tempered (2006a). In most cars, only the windshield is laminated, therefore it could be assumed that 20% of all autoglass is laminated, and the remaining 80% (side, rear, and roof windows) is tempered. With this information it was possible to calculate that 26% of all laminated glass, and 81% of all tempered glass, was for the auto industry. DOE Manufacturing Energy Consumption Survey (MECS) statistics indicated the total energy used in tempering (12.9 trillion BTU) and lamination (1.64 trillion BTU) (2006b). Knowing the fraction of autoglass produced, the energy consumed for autoglass manufacturing was calculated at 10.32 trillion BTU for tempering and 0.33 trillion BTU for lamination. A glass industry growth rate of 6.5% was applied based on Freedonia (2006a). The compilation of this information, along with a conservative, demonstrated energy savings of at least 90% using RF energy, allowed for the computation of projected energy consumption by the autoglass energy.

Future-year scenarios of potential energy savings with FastFuse RF lamination are presented below in Table II. These include projected and retrospective energy consumption and potential savings for 1) autoglass with no change to the current tempering to laminating ratio (i.e., no lamination of side-windows), 2) a shift from tempered to autoclave-laminated side windows, and 3) a shift from tempered to FastFuse RF-laminated side windows. Lamination uses significantly less energy than tempering, even with autoclaving. It should be noted that this data does not include the additional energy cost of manufacturing the polymer interlayer, of manufacturing two sheets of glass rather than one, or transmission losses from switching from gas fired tempering furnaces to electric autoclaves. Therefore the benefit of switching to autoclave lamination, is expected to be less than shown here, because of capital expenditures, but still a significant improvement versus tempering.

**Table II. Energy Analysis and Projections for Autoglass Manufacturing Energy Usage and Potential Savings for RF Laminating Motor Vehicle Windows. These Calculations Assume a 6.5% Annual Increase in the Volume of Motor Vehicle Windows (Tempered or Laminated)**

| **YEAR →** | **1997** | **2005** | **2015** | **2025** |
|---|---|---|---|---|
| % change in autoglass volume over year 1997 | - | 165% | 310% | 580% |
| **Scenario 1:** No change to current side-window manufacturing | | | | |
| % Tempered | 80 | 80 | 80 | 80 |
| % Laminated | 20 | 20 | 20 | 20 |
| Energy to temper (trillion BTU) | 12.9 | 21.3 | 40.1 | 75.2 |
| Energy to laminate with autoclave (trillion BTU) | 0.33 | 0.54 | 1.0 | 1.9 |
| **Total energy with no changes (trillion BTU)** | **13.2** | **21.9** | **41.1** | **77.1** |
| **Scenario 2:** Shift from Tempering to Lamination with Autoclave | | | | |
| %Tempered | 80 | 80 | 50 | 0 |
| % Laminated | 20 | 20 | 50 | 100 |
| Energy to temper (trillion BTU) | 12.9 | 21.3 | 25.0 | 0 |
| Energy to laminate with autoclave (trillion BTU) | 0.33 | 0.54 | 2.5 | 9.6 |
| Total energy with autoclave (trillion BTU) | **13.2** | **21.9** | **27.6** | **9.6** |
| Energy savings with autoclave vs. tempering (trillion BTU) | - | - | 13.5 | 67.6 |
| **Scenario 3:** Shift from Tempering to Lamination with RF | | | | |
| %Tempered | 80 | 80 | 50 | 0 |
| % Laminated | 20 | 20 | 50 | 100 |
| Energy to temper (trillion BTU) | 12.9 | 21.3 | 25.0 | 0 |
| Energy to laminate with RF (trillion BTU) | 0.033 | 0.054 | 0.25 | 0.96 |
| Total energy with RF lamination (trillion BTU) | **12.93** | **21.35** | **25.25** | **0.96** |
| Energy savings RF lamination vs. tempering (trillion BTU) | **0.27** | **0.55** | **15.9** | **76.1** |

Sources: Glass growth rates: Freedonia Group: *Freedonia Focus on Flat Glass,* September 2006, and Energy statistics: Office of Industrial Technologies: *Glass Industry of the Future*, April 2002 DOE/GO-102002-1590.

The 90% energy savings of lamination using RF appears small when the majority of windows are tempered. As lamination overtakes tempering however, the savings become significant. If all autoglass is laminated by 2025, the annual energy savings for RF laminating would approach 10 trillion BTUs. The higher cost of laminated windows may slow the transition from tempering, however the faster, lower energy, continuous process of FastFuse RF lamination has the potential to ease the transition for side windows and sunroofs. The energy savings associated with RF laminating will be multiplied by faster transition from energy intensive tempering, reduced energy consumption in cars, and improved road safety and security.

## Conclusion

FastFuse RF lamination resulted in significant energy efficiency improvements compared to autoclaving or vacuum processing. FastFuse RF lamination has been demonstrated for a wide range of laminated glass products. Energy savings estimates were generated using ethylene vinyl acetate (EVA) interlayers in laminated glass, and evaluated based on published data for glass industry manufacturing volumes and energy consumption. In addition to resulting in decreased energy consumption for autoclaved laminated products, the continuous flow of FastFuse RF lamination could help enable the shift from tempered to laminated autoglass. The shift will produce significant manufacturing energy savings and long term efficiency and safety benefits for consumers. Projections to 2025 show potential for saving 76 trillion BTUs annually during the final steps of manufacturing autoglass alone. Ongoing studies will continue to evaluate energy efficiency for PVB interlayer lamination, which directly relates to autoglass manufacturing.

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