THE SOLAR WINDOW PROJECT

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ABSTRACT

For Millennia, Man has known that South-facing hillsides and cave openings have stayed warmer in winter because low angle winter sun can enter the space and warm it. In response to the energy crisis of the 1970s, there was an effort to build residential structures using the same principle which was called passive solar. Though these structures certainly influenced architecture of the day, far too often they were built by experimentation, with widely varying performance results. Daytime overheating and excessive brightness, as well as nighttime heat losses plagued these structures, and cast a pall over the concept. But this concept is age old, and still does have merit.

Presented here is a passive solar solution that is the product of 10 years of research and development in this field. Supporting empirical testing demonstrates why this is an appropriate solution to the shortcomings of previous passive solar endeavors.

1. INTRODUCTION

The issues that were seen as passive solar was adopted in the 1970s are well known. Technology has improved since this time, particularly in the area of low-e glazing systems. If a well-tested, pre-engineered solution to those issues could be developed, the hoped-for supplemental heating benefits might be finally realized. The system would need to be one that the builder could specify and incorporate as a South-facing window into his structure with predictable measured performance, and most importantly, occupant comfort. Over 10 years of research, engineering, and actual building construction, a finished product, referred to here as the Solar Window, was developed, with this goal in mind. An optimized high solar gain low-e package was used, combined with light-transmitting window-integrated thermal mass storage, and window-integrated automated exterior shading. The three technologies must be used together, as when they are combined, they provide a synergistic effect. Because Hunter Douglas is first and foremost a design-driven company, with a good track record of selling high design consumer products, we knew that the resulting window system not only had to perform well, but look both attractive and conventional at the same time.

The development process that led to these solutions will be detailed here along with a discussion of the underlying technologies. This will be followed by a detailed description of the actual patent-pending window unit itself. Test data is included, designed to validate the various critical performance features of the Solar Window. The data will show that even in three very diverse and reasonably severe heating dominated climates in the USA, cutting a hole in an un-shaded South-facing well-insulated R-20 (3.5 R_{SI}) wall and installing a Solar Window in its place will result in reduced heating requirements. It will show that the Solar Window will do this while maintaining a comfortable interior environment, both night and day, with glass surface temperatures above that of the room for the majority of the time.

2. DEVELOPMENT PROCESS

One of the authors watched firsthand as builders built passive solar houses in the 1970s and 80s using rudimentary design principles, and then witnessed the failings of those principles. The logical inclination today would be to attempt to model structures via computer to predict their thermal performance, and then refine the design parameters to achieve a stable reliable performance. A different path was chosen. The modeling of some of these concepts, especially delayed gain due to thermal mass, can be quite difficult, and real-life empirical testing and iterative design could obtain faster answers. Well-insulated small-scale test buildings were built and various passive solar heating solutions were installed in them. Performance parameters were continuously monitored, recorded and analyzed. Eventually three identical test structures were built, which allowed comparative testing of solution A vs. solution B vs. control. This proved to be very useful, and allowed continued rapid refinement of product concepts.

Fig. 1: Three test buildings oriented Southward at a Boston, MA test site.

3. THE UNDERLYING TECHNOLOGIES

As a result of this research, the team defined three interdependent guiding principles that outlined the solution, listed and described below. It is crucial to understand that each of these principles is as reliant on each other as each leg is of a three-legged stool.

3.1 High Solar Gain Low-E Glazing Selection

The original developers of low-e glazing were passive solar pioneers. They emerged from the passive solar boom of the 1970s with a goal to develop a glass system that would allow the full heating power of the sun to stream through the glazing, while insulating against nighttime thermal losses. Southwall's first product, Heat Mirror 88, did just that extremely well. This is called high solar gain low-e.

However, as this invention evolved, it was discovered that the same low-e coating process could be used to cut out solar gain at the same time as it cut thermal losses. As the product was adopted by the window industry this low solar gain version was the one that went on to widespread acceptance. Ironically, this low solar gain low-e actually performs quite poorly for passive solar, as it cuts out most of the beneficial daytime solar gains. Today, it is hard to purchase a window with high solar gain low-e. When a high solar gain low-e glazing package is used by itself, it provides a very harsh and uncomfortable solar radiation into the room. However, as the goal was the evolution of a pre-engineered package with other absorption elements, it could be safely used.

3.2 Thermal Mass as the Inner Glazing Layer

Felix Trombe had it right. It is well-known that thermal mass is required for proper passive solar performance. But Trombe put the thermal mass directly behind the glazing, absorbing the excess solar gains of the day, and storing them for the night to come. This resolved the daytime overheating issue, as well as what is called the sunwashing issue. Sunwashing is where the sunspace becomes too bright, and the infrared radiation too strong, making it feel like Miami Beach in July, suitable for dark sunglasses and a bathing suit, but not for normal indoor winter activities. When properly insulated, the Trombe mass also resolves the nighttime cold glass issue, because it remains warm through the evening. Of all of the passive solar structures built in the 70s and early 80s, the ones with Trombe walls were the most thermally comfortable. Of course, low-e glass did not exist back then, so proper insulation was much harder. And because these structures put a big dark masonry wall behind South-facing glazing, they tended to be unpopular.

In more recent years, water walls have been shown to be a good Trombe solution, because they absorb the incoming solar radiation more quickly, keeping surface temperatures, and therefore thermal losses, lower. Further, water is an excellent heat storage medium. Most earlier Trombe systems had used a vented air space between the glazing and the mass, but many experiments, including our own, have proven this to be unnecessary with today's low-e glazing and water wall systems.

3.3 Control Solar Input with Exterior Shading

The Europeans have known for years that exterior shading can be very effective at controlling solar gains. Because of generally cloudy winters, and thus less intense winter thermal inputs, Europeans have adopted high solar gain low-e for residential projects much more widely than Americans. Today's low-e is so good that once solar thermal inputs get past it, it is very hard to send them back outside, making exterior shading the logical solution to solar thermal control in combination with high solar gain glazing. Therefore, exterior shading has been quite popular in Europe for a while now. This has not happened in the USA. It is our widespread adoption of low solar gain low-e that has made exterior shading less relevant here than in Europe. Further, Americans seem to have less architectural tolerance for a bulky, purely functional, exterior device than their European counterparts.

Traditional overhangs can be used to control solar thermal input to just winter months. However as performance of test structures was monitored, it was learned that though the overhang may work perfectly as designed on June 21 and December 21, the performance in between was a serious compromise. Heating and cooling needs lag behind the solstices by approximately 60 days. An exterior shade best solved the problem of controlling solar thermal inputs because of the large difference it makes in net solar gain, and would be the answer for this project.

4. THE SOLAR WINDOW

The authors, as a team, have developed a complete window package, called the Solar Window. It installs and looks as much like an ordinary window as possible. By incorporating the independent technologies into one cohesive unit, usage of them together has been ensured. In this way, it is hoped that the builder of the future can specify this window for his un-shaded South-facing facades to provide predictable, comfortable and uniform supplemental solar heating. Because of the weight of the thermal mass, a decision was made to execute the design in a fixed glass version only for the time being. This window is in pilot production. In addition to the units in various test buildings, a number of private residences have been built with these same windows featured prominently on their South facades. Patents have been applied for on the following described concepts.

High solar gain low-e glazing is used in the unit. An equation was developed to maximize the net gain of the glazing package considering average wintertime daily solar gains versus daily thermal losses for each glass selection, using Lawrence Berkeley National Laboratory's Window 6 software. At first, only Boston area climate data was used, but this process can be repeated for other climates as well. This process led to the selection of a triple-glazed glass package using Pilkington Energy Advantage on surface 5. Surprisingly, maximizing gains trumped minimizing losses, and thus the two outer layers consist of low iron clear glass. Argon gas is used as the fill, with 0.5 inch (12.7mm) thick Edgetec spacers. The u-value of this resulting glazing package is 0.2 BTU/ft^2-°F-h (1.16 W/m^2-K), and it has a SHGC of 0.72.

The window uses Trombe water wall technology to absorb and store for later the gains from this glazing. But it was desired to create a product that was as much like a window as possible. Therefore it was resolved to make a translucent or transparent water-containing thermal absorption and storage unit that could be placed directly behind, and in thermal contact with, the inner layer of glazing. The glazing used strongly transmits infrared radiation. The water in the translucent or transparent system becomes the spectrally selective layer, absorbing a high percentage of the infrared that the glazing lets through. A mask or tint is added to the system to absorb excess visible light, creating additional heat in the mass. Two versions are described here.

The Water Block system is a modular series of white translucent water-filled stacking plastic blocks. Almost four inches (101.6mm) in depth, these provide an optimized amount of thermal mass. A black absorber mask is placed on the outside surface of the blocks to absorb excess light without coloring the transmitted light, leaving a clean diffuse white light. These blocks are heavy, but because they are modular and stackable, they can be installed as a second installation step after the window frame is installed in the structure.

The Gel Glass system uses an aqueous gel to tie up the water contained between two sheets of glass. This can only be reasonably manufactured with a water gel depth of one inch (25.4mm), which is less than optimal, but still far better than no thermal absorber at all. However, this system can be made visually transparent, making a system that looks as conventional as an ordinary window. This gel package is given a dark tint to absorb excess visible light. Many have questioned this tint, but it serves a valuable purpose in absorbing the excess visible light that would cause sunwashing on sunny winter days, and turns it into thermal energy for later.

An exterior shade is used to dynamically control the solar input depending on structure needs. When a heating system is installed in a building, it is sized appropriately for the largest temperature differential that it will be required to handle, and then it is throttled as needed by a thermostat. No one would install a heating system without a thermostat. As the Solar Window is a supplemental heating system, it therefore needs an exterior shade as the valve to shut it off, controlled by a room mounted "solar thermostat". By having this control valve on the Solar Window, one can install as many Solar Window units as desired, while providing the ability to shut off the heating when it is not required. This is free heat, so the user has an incentive to keep that thermostat set as high as he can comfortably stand in winter, and then to lower it in summer to cut off solar heating.

A novel exterior shading system was developed specifically for this application. A rolling screen shade, it incorporates opaque louvers, curved to the roll-up radius, which provide directional shading. This stops all incoming direct sun from above, while allowing a view and indirect light from below. A self-contained motor is enclosed inside the roller tube. The entire motor and shade assembly can be easily removed for service or cleaning. The system is smart enough to sense obstructions and stop motion in either direction, but simple enough to be reinstalled without cumbersome setting of travel limits. This shade system is then integrated into the exterior trim of the window system, which hides the presence of the shade until needed, and has an integrated shutter-like appearance when deployed. Exterior trim is painted aluminum for durability, but connected to a wood interior frame system for thermal isolation.

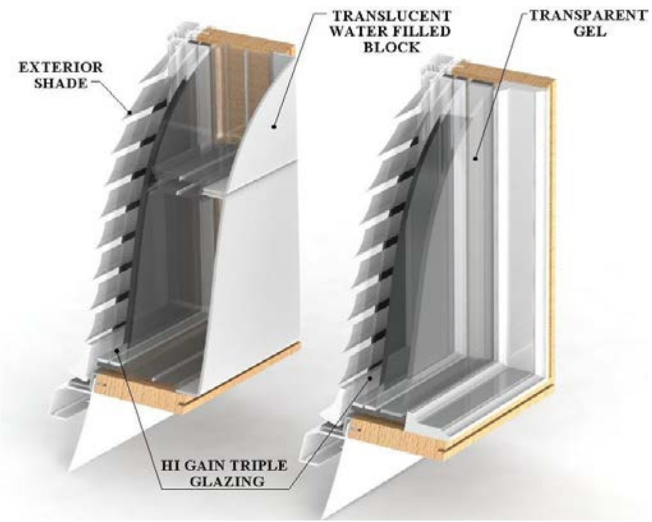

Fig. 2: A cross-section view of the two versions of the Solar Window.

5. TESTING RESULTS

The test buildings referenced earlier in fig. 1 were extensively used to test the effectiveness of the various Solar Window components and assemblies. These three buildings were constructed identically with 6.5 inch (165mm) thick expanded polystyrene structural insulated panels (EPS SIPS) for the walls and floor, and an 8.5 inch (216mm) thick EPS SIPS for the ceiling. The outsides of the buildings were sided with cedar shingles, the roofs shingled, the floors carpeted, and the interior walls plastered and painted. Additionally, electric resistance heaters were installed into each building, controlled by a thermostat. In essence, these test buildings were constructed as similarly to a well-insulated home as possible.

Each test building was outfitted with identically-sized (36ft^2 or 3.34m^2) and identically-located window openings, into which the various Solar Window assemblies were installed for testing. Each of these test buildings was also equipped with identical monitoring equipment recording the indoor temperature, interior glazing temperature, and total power drawn by the electric heater within each building. Recorded simultaneously were the outside temperature and insolation normal to the South wall.

A number of comparative experiments were performed using the test buildings in order to ascertain the effectiveness of the Solar Window. Initial experiments were performed at the Hunter Douglas facility in Natick, MA while the previously discussed Solar Window units were being developed. Following extensive testing at the Hunter Douglas facility, two of the buildings were relocated to alternate climates. One was moved to Northern Minnesota, which is a location renowned for its brutally cold weather. The other building was moved to near Denver, Colorado, where the winters are relatively mild and experience exceptionally high amounts of insolation. The third test building remained in Natick, MA as a control.

Additionally, during development, several real-world homes were equipped with the Solar Window, and data was collected from these sites as well to aid in performance evaluation. This also provided valuable feedback on occupant comfort.

5.1 Test Building Control

Prior to conducting the comparative testing of the various Solar Window systems, the test buildings were all positioned with identical Southern solar exposure, and their thermostats were set to maintain a minimum indoor temperature of 65°F (18.3°C). All three test buildings had their window apertures covered with an identical EPS SIPS panel to that used in the building wall construction, in order to simulate a solid insulated South-facing wall. This test, conducted in winter, was intended to confirm that the test buildings all had equal heating needs. Following a test period of approximately one month, an average energy usage per Fahrenheit-based degree day was determined for each of the buildings. The results are summarized in table 1.

TABLE 1: TEST BUILDING HEATING LOADS

Test Building	**Avg. Energy Usage/Degree Day (BTU/°F)**
2	516
3	502
4	519
Avg. of 3 buildings:	512

As can be seen from table 1, the three test buildings all exhibited similar behavior, with an average of 512 BTU/°F (270 W-h/°C) required to maintain temperature. This number also closely agreed with the calculated load based off of the construction data from the buildings, which was a value of 532 BTU/°F (281 W-h/°C).

5.2 <u>Effects of Proper Thermal Mass Placement vs. Code-Compliant 3030 Window in a Full Scale Home Environment.</u>

During the fall of 2010 several Solar Window installations were completed as full-scale beta tests in homes. In fig. 3, one of the homes, located in Weston, MA, was outfitted with the two different versions of the Solar Window. Each Solar Window was instrumented and the surface temperature at the center of glass was measured at 30 minute intervals for 5 months starting in January 2011.

Located on the same facade and in the same room, a code compliant window with a u-value of 0.3 BTU/ft^2-°F-h (1.704 W/m^2-K) and a SHGC of 0.30 was installed and similarly instrumented. The home, while completely finished, was left unfurnished and unoccupied during the entire test period. Finally, the home's heating system was set to maintain an indoor temperature of 60°F (15.6°C).

Fig. 3 shows the results from a typical sunny midwinter day in the Northeast United States. The center of glass temperature of the 3030 window quickly surpassed the indoor temperature while the sun rose in the sky, but then just as quickly fell below the indoor temperature, even before the sun had completely set. When this occurs, the 3030 window transitions from an energy gain element to an energy loss element. The center of glass temperature of the gel glass Solar Window rose throughout the solar day, reaching a glass surface temperature peak of 105°F (40.5°C). The water mass allows storage of heat energy at the glazing surface, and on this day, it maintained a temperature above that of the room's until the early morning hours. The center of glass temperature of the water block Solar Window rose and fell a slower rate than that of the gel unit throughout the solar day due to its greater thermal capacitance. This increase in thermal capacitance allowed the water block Solar Window to maintain a temperature above that of the room into the next solar day.

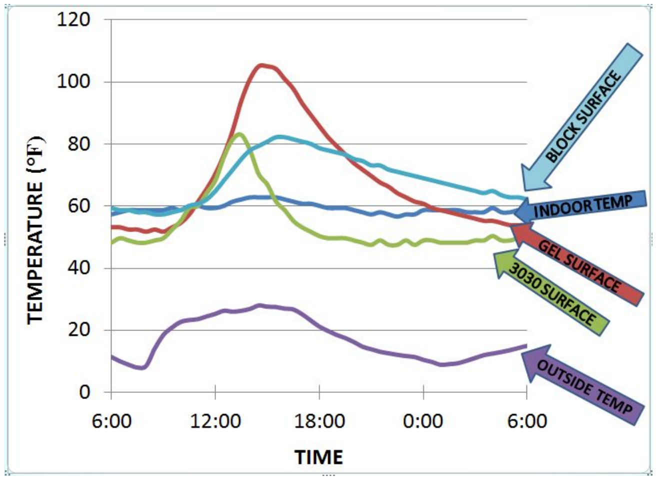

Fig. 3: Comparison of various window assemblies.

This demonstrates that window-integrated thermal mass has the ability to delay gains and store them for later use. Heat energy stored here provides a warmer inside glazing surface temperature throughout the evening hours, which translates to occupant comfort. This should also result in lower heating energy requirements.

5.3 <u>Exterior Shade as a Dynamic Solar Input</u>

Experiments conducted during the development of the Solar Window included a dynamic external integrated shading system controlled by an in-room thermostat. The results shown in fig. 4 demonstrate a comparative test of this shading system using two of the test buildings. Building 2's shading system was set to stay open and building 4's shading system was set to remain closed.

During the test it was observed that the window with a closed shade had a glass surface temperature 10-25°F (5.6-13.9°C) below the one with the shade open. This difference in magnitude is the due to the difference in solar input because the shade in building 4 was closed. This shows that external shading cuts out a significant amount of the solar gains.

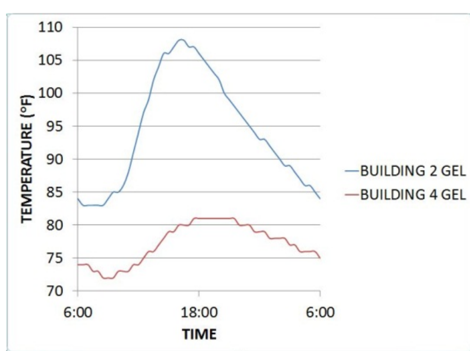

Fig. 4: Demonstration of exterior shading's effects on room temperature.

Fig. 5: Solar Window exterior with shade deployed.

5.4 Energy Consumption

For analysis of energy consumption, two of the three test buildings were relocated (to Colorado and Minnesota), and the pertinent winter-time data was collected over a period of several weeks from each to evaluate the relative performance of the Solar Window in each of these climates. The environmental data collected simultaneously at these sites enabled the calculation of the energy usage of the buildings should the Solar Window have been replaced with either the EPS SIPS panel used in the earlier control test, or with a code-compliant 3030 window. The windowless calculation was performed using the previously-determined energy usage per degree day (532 BTU/°F, or 281 W-h/°C). Conversely, the calculation for the 3030 window was performed using the 0.3 SHGC to find the gains such a window provides, while accounting for the losses from the u-value of 0.3 BTU/ft^2-°F-h (1.703 W/m^2-°C). The net sum of these values was totaled against the non-window value to yield a total energy usage for that test building.

For the Massachusetts building, shown in fig. 6, the average temperature difference from the inside to the outside was 35.9 °F (19.9°C) and the average daily solar energy that struck the window was 34,900 BTU (10.23 kWh). A 3030 window would have led to slightly less energy usage than a well-insulated wall due to the high level of solar insolation, which meant that the gains from the solar energy through the window outweighed the losses from the lower insulating value when the sun was not out. However, the Solar Window in this time frame led to a significantly lower amount of energy usage than either other solution.

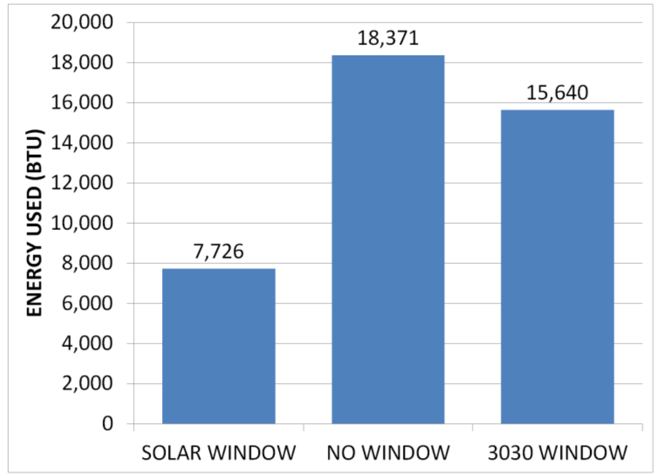

Fig. 6: Average daily energy usage for Massachusetts building.

The time period for the test in Colorado, shown in fig. 7, experienced an even higher amount of insolation, at an average of 55,800 BTU (16.35 kWh), while experiencing a slightly higher average temperature difference to the outside at 40.9°F (22.7°C). Therefore, the test building saw even larger gains from both the Solar Window and the calculated 3030 window. With the even greater average insolation, the Solar Window was once again the clear winner, using approximately one-fourth of the energy of the building with a well-insulated wall in place of the window. It should be noted that in this installation, two-thirds of the Solar Window aperture was comprised of the water block system, while the remaining area was comprised of the gel glass system (this is shown in fig. 8 below).

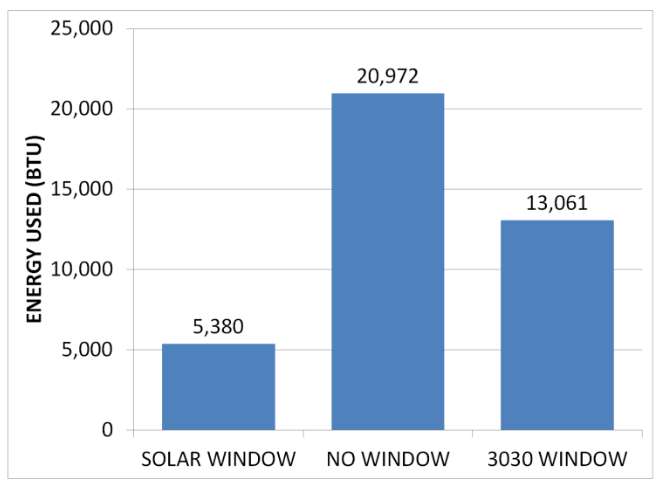

Fig. 7: Average daily energy usage for Colorado building.

Fig. 8: Solar Window installation used for Colorado test.

In the Minnesota test, there was a slightly lower amount of insolation than in the Massachusetts test (32,600 BTU or 9.55 kWh) but a much greater temperature difference at 61.4°F (34.1°C). Demonstrated in fig. 9, even this test building saw respectable improvements in energy usage versus the building with a well-insulated wall in place of the window, despite the very cold outdoor temperatures. Also, due to the greater temperature differential, a 3030 window would not perform as well as a well-insulated wall.

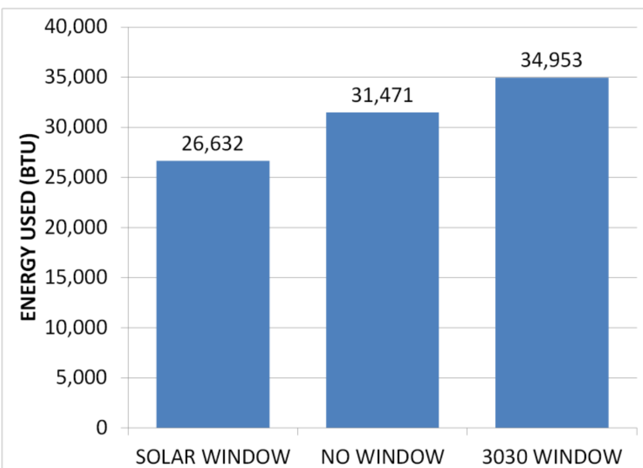

Fig. 9: Average daily energy usage for Minnesota test building.

Fig. 10: Solar Windows dominating South façade of private residence.

6. <u>CONCLUSIONS</u>

The combination of the three technologies into one pre-engineered package allows comfortable, controllable passive solar heating. The high solar gain low-e glazing harvests the largest amount of solar input with manageable thermal losses. The integrated thermal mass allows the use of this glazing with interior comfort, both day and night. The exterior shade allows control of the heating function.

The use of a transparent Trombe thermal mass, integrated with the glazing, allows this package to be defined as a window. Now, because of the technologies used, one can install as many South-facing Solar Windows as desired. This product can change the paradigm of a window from a net negative in energy calculations to a net positive. Windows can once again be good energy policy.