BUILDING INTEGRATED SOLAR THERMAL ROOFING SYSTEMS HISTORY, CURRENT STATUS, AND FUTURE PROMISE

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ABSTRACT

The integration of solar energy collection systems into a building shell and mechanical systems can reduce the cost of solar energy systems. This paper recaps the history of building integrated solar thermal (BIST) designs using active solar collection techniques. The review begins with U.S. patents of the 1940s and concludes with a review of the current designs. Active BIST systems are categorized by form and function. Insights are offered into the advantages and disadvantages compared to other heating systems. Proposed application of one new solar thermal tile design on the roof of a single family home is reviewed. Finally, the paper offers future directions for BIST system applications and identifies critical research and public policy initiatives for BIST systems.

1. BACKGROUND

The desire to capture the sunlight falling on a building to provide space heating and hot water has motivated inventive minds for decades. A review of the methods proposed from the patents of the 1940s through the current designs show several unusual methods of solar collection. The designers offered various techniques to use the building itself as part of the solar collection system. All these designs face four key concerns that affect consumer acceptance: thermal performance, aesthetics, cost effectiveness, and building envelope performance. While many of the designs have failed in one or more of these areas, there have been exceptions. For several of these promising designs, supporting research lags behind in several fields. This research is necessary to, improve aesthetics, performance and lower costs of the systems.

2. WHAT IS BUILDING INTEGRATED SOLAR THERMAL ROOFING?

Building Integrated Solar Thermal Roofing is the application of solar collection equipment to the roof of a building such that the equipment performs the function of a roof and collects solar energy.

This simple definition is complicated by the complexity of both the solar energy systems available and the many architectural functions of a roof. Several methods exist to collect solar energy. Active, passive, glazed, unglazed, focusing and non-focusing systems exist. Many different systems can capture solar thermal energy. The thermal energy is used in space heating, hot water heating, drying and potentially cooling and other commercial and industrial processes. Many solar energy systems are created by adding elements to existing buildings while others form the very structure and shell of the building.

Even more complex is an understanding of the functions of a roof. A roof must keep precipitation out of the building. It must resist wind and, in northern climates the weight of snow, sleet and ice. It may also form a thermal and vapor boundary to keep the building beneath it warm or cold, humid or dry.

The roof also creates an impression of the building it covers. The shape, color and surface texture and the type and quality of the materials used to cover the roof all create an impression on those who see the building. Finally, the shape must conform to the building it covers in a way that supports the activities within the building.

This paper will confine itself to those BIST roofing systems that use mechanical circulation of heat transfer fluids, either liquid or air, and which form either fully or partially weather tight boundaries of buildings.

There are four different characteristics that will help distinguish the various types of BIST roofing. These include 1) roof panel size, 2) heat transfer fluid containment, 3) glazing, and 4) focusing methods.

Panel size varies by whether the individual panels; span the full height or breadth of the roof, span parts of the roof but are fabricated in large sheets, or span smaller areas formed from individual tiles, blocks, or modular collectors. The heat transfer fluid can be contained by three different methods. The fluid, either liquid or gas, can be contained in a conduit which is separate from the roof panel, or contained within conduits that are formed within the panels, or contained within conduits that are formed by the assembly of the collector against the roof of the building. There are glazed and unglazed systems. Finally, there are systems that focus the solar radiation and systems that use unfocussed solar energy.

3. HISTORY OF INNOVATION

One of the first documented BIST system designs in the 20th century was invented in the 1940s by Bjorn O. Christenson of DePere, Wisconsin. A patent application was filed on August 30, 1944 and U.S. patent No. 2,469,496 issued on May 10, 1949 for a CONDITION CONTROL SYSTEM. This patent describes a "... system adapted to control the temperature of air and water for domestic and industrial use ... whereby the condition control is accomplished by solar radiation." This early design incorporated water filled tanks attached to the roof and walls of a building and then glazed with hollow, evacuated glass blocks. The glass blocks were mortared together to form the outer skin of the building.

On November 15, 1950, U.S. Patent 2,529.621 issued to Reubin E. Mayo for a DRYING HOUSE. The invention used a fan to pull outside air from the top of a tobacco curing barn into a conduit running along the bottom side of the solar heated roof. As the air moved through the conduit it was heated by the warm roof, "... so that heat from the sun may be employed to aid in the curing or drying whereby fuel may be saved."

In June of 1950, Clyde Harris of Sorroco, New Mexico, filed a patent application for a sawtooth roof that focused winter sun through several glazed apertures to heat ceiling panels filled with phase change material. Summer sun was reflected away from the apertures.

During the period from 1958 to 1960, the last of four Massachusetts Institute of Technology solar houses was built with a BIST system. This house represented one of several pioneering examples of solar energy development. Harry Thomason's solar home was also built in the late 1950s in a suburb of Washington, D.C. and incorporated a BIST water heating system.

It was not until after the first of the modern energy crises, with the oil embargo of October 1973, that the pace of BIST roofing system development quickened. More experimenters and inventors began to develop new and sometimes useful and attractive techniques to harness the solar energy falling on the shell of the building. With this activity, more U. S. patents in BIST technology were issued. See Figure 1.

In July of 1974, nine months after the first of the modern energy crises, Melvin Quick applied for a patent on a modular solar energy collector (U.S. Pat 3,996,918). This air heating collector was designed to nest together with other identical collectors. Each collector resembled a glazed, air heating, flat plate collector with tongue and groove alignment means and air flow ports that mated with adjacent identical modules. This inventor's intent was to "... provide an easily constructable solar energy collector system ... utilizing the maximum available surface area."

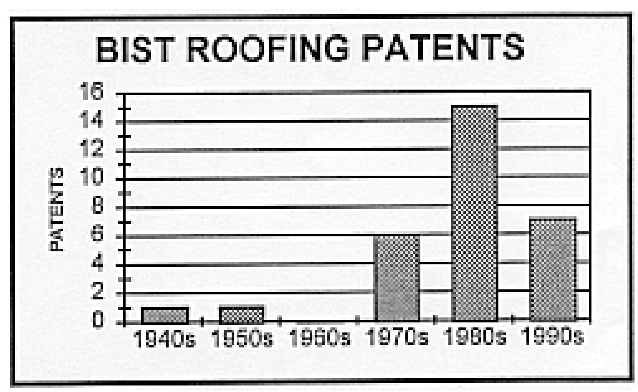

Fig 1: U.S. BIST Roofing Patents

In February 1975, Courvoisier and Meylan of Switzerland applied for a Swiss patent on a solar collection system design "... for incorporation in a dwelling, especially in a tiled roof ... " This is the first design where roofing tiles were used as the glazing for a thermal collector. An absorber plate was used to convert solar energy to heat. A pipe attached to the absorber plate was used to transfer heated fluid for space or hot water heating. Variations in tile shape, color and texture were offered as enhancements to the aesthetics of the tiles.

As interest in solar energy grew in the 1970s, many homes and test facilities were built with integrated solar thermal systems. The Colorado State University Test Houses represent a typical configuration with absorber plates and large glazing panels incorporated in the south facing roof. These houses showed a capability of delivering solar energy for 50-60% of the required winter heating load.

Many additional BIST roofing patents in the 1970s, 1980s, and 1990s followed the same trends of the previous patents with adaptations of panel size, fluid conduit configuration, partial glazing and changes in focusing methods. However, innovations in the late 1980s and 1990s appear to be the basis of a new wave of BIST roofing systems. Three particular types are currently in development: the transpired collector, a high temperature collector with focusing mirror integrated into the roof, and a solar roofing tile.

The transpired collector has been patented by John Hollick et al in different configurations. The collector is sold under the trade name SOLARWALL®. Beginning in the early 1990s, the systems were installed as walls, forming the architectural facade of the building, but recent applications of the collector have demonstrated the use in roofing. The system has been installed in more than 35 different applications.

Louis Gerics and Mike Nicklas described a design of a high temperature BIST system in the Proceedings of the 1996 ASES Annual Conference. The system uses the roof to form cylindrical mirrors to focus sunlight on a pipe carrying heat transfer fluid. The pipe is contained in an evacuated glass tube which acts both as a secondary reflector to refocus the sunlight and as a glazing over the heated pipe. The first large scale system will be constructed by Duke Solar in 1999.

The last modern system is a solar roofing tile that is designed to be installed above any absorbing surface. Patented in 1997 and under development by American Solar Roofing Company, the system is a medium temperature, air heating collector which duplicates the shape of a tile roof. Further details of this system are presented in a case study in section 5.0.

4. <u>BENEFITS OF BUILDING INTEGRATION</u>

4.1 <u>Building Envelope</u>

Over the centuries, builders and building owners have developed weather tight envelope systems that meet the needs of the occupants. These needs include preventing precipitation from entering the building; keeping out winds, dust, and odors; and controlling the temperature and humidity inside the building. Modern BIST systems take advantage of several modern technologies as well as ancient techniques to meet these needs in a manner similar to conventional building envelope systems.

Current systems use metals, glass and plastics in various forms to seal the outside of the building. The American Solar Roofing tile uses a form that is similar to centuries old roofing tiles to resist weather and add an insulating air space on the roof. The high temperature focusing collector uses insulated metal roof panels suspended between structural supports to form the weather barrier. The transpired collector resists wind and acts as the outer insulating barrier of the building. It has been installed in glazed and unglazed configurations. When installed in the unglazed configuration, the weather tight boundary of the building provides water tightness.

Metal, glass, or ceramic parts used in current BIST roofing designs can last for upwards of 50 years. Where these materials form the weather envelope of the building, they will often eliminate several replacements of materials with much shorter service lives. In the case where a BIST roofing system will provide an outer covering for an inner, weather tight roof, the inner roof is protected from the harshest weather, which further increases its service life. The extended service life of the materials reduces inspection, replacement, and repairs of the roof and adds to the convenience of owning BIST systems.

4.2 <u>Thermal Performance</u>

Different BIST roofing systems can deliver different levels of thermal energy to match the varying needs of building occupants. The roof focusing system can deliver heat to the building at up to 750°F (400°C). The transpired collector can deliver preheated air, 30-50°F (17-28°C) warmer than ambient air. At optimum air flows the system can operate at a thermal efficiency on the order of 80%. The solar roofing tile can deliver air heated to medium temperatures of 100-200°F (38-93°C) or about 100°F (56°C) above ambient and is projected to operate at an efficiency of 30-40%.

4.3 <u>Costs</u>

The most obvious benefit of building integration is the potential cost savings in construction materials and labor compared to the installation of separate systems. This savings occurs by replacing two separate systems with one system that performs both functions.

Several BIST roofing systems can be constructed at the building site, in a manner similar to existing roofing systems. This allows BIST roofing companies to draw on qualified local labor for a significant part of the construction which can lower the installed cost of the system compared to traditional solar energy systems.

Another cost benefit is due to the expansion of the BIST system to cover larger areas of the roof than traditional solar collectors can easily cover. Several BIST roofing designs use the entire height and breadth of the roof to collect solar energy. This is in contrast to traditional solar energy systems which are built in module sizes that are not always conducive to the varied shapes of existing roofs.

Longer service life also means less replacement of materials with commensurate reductions in the waste stream headed for landfills. It also reduces transportation costs related to construction by reducing the materials moved from suppliers to buildings and from buildings to landfills.

The combination of lower construction costs, extended service life, and larger collector area lowers the per square foot costs of the BIST systems compared to traditional collector systems. This lowers the cost of the delivered energy, shortens payback periods, and increases overall life cycle cost savings of the system when compared to traditional solar collector systems. It also increases the number of buildings where solar energy is cost effective.

The U.S. Department of Energy Federal Energy Management Program recently reported that the retrofit costs of a transpired collector system were about $10-12 per square foot. For new construction, the system would likely cost $5-9 per square foot. The similarity of the solar roofing tile system with existing roofing methods permits the use of routine cost estimating guides, widely available in the trades, to develop estimates of installed cost. Using this method, the solar roofing tile system is projected to cost between $7 and $12 per square foot installed. No precise cost figures are available for the roof integrated, focusing collector but Gerics and Nicklas discuss the cost implications in 1996 ASES Proceedings.

4.4 Aesthetics

A third benefit of BIST roofing systems is enhanced aesthetics, where the solar collector systems can blend into the architectural makeup of the building. For many home and commercial building buyers, aesthetics is a primary consideration in the purchasing decision. Traditional looking homes and commercial buildings continue to have broad appeal in the real estate market. So designing BIST roofing systems which mimic the existing appearance of traditional roofing systems should help their diffusion in the market.

5. SOLAR ROOFING TILE DESIGN STUDY

American Solar Roofing Company studied the potential benefits of installing its patented solar roofing tile on a typical house in a 5600 heating degree (F) day climate. Data on a typical home size and type and energy usage was developed from Energy Information Administration Housing Characteristics publications. The ‘typical’ single family home in the Boston, Mass. area would be a detached, two story, 2000 square foot home, approximately 42 feet by 24 feet. The conventional house is assumed to have a roof sloped at a 10 in 12 ratio, covered by asphalt shingles with one, 600 square foot, unshaded slope of the roof facing due south.

The roofing tile, shown, in one possible configuration, in Figure 2, is a transparent or translucent tile that is installed above any sloped roof. It is shaped to match the appearance of existing roofing tiles. However, the mating edges of adjacent tiles are formed in such a way as to make an airtight seal between the tiles. The assembled tiles then form a glazing over the underlying roof deck. Air channels are formed between the tiles and the roof deck. These air channels collect air that is warmed by heat transfer from the solar heated roof deck. Openings into these air channels at the top and bottom of the roof allow the air to flow beneath the tiles and through ducts into the house.

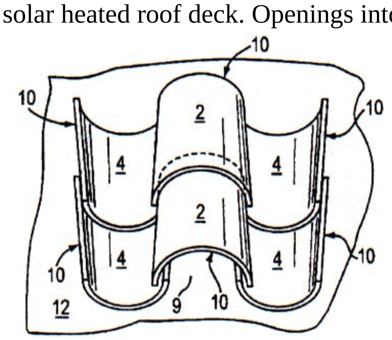

Fig. 2: American Solar Roofing Tile

Figure 3 shows the installation within the house of the ductwork to collect and distribute the solar heated air. This simple installation shows a house with an existing hot air heating system. A retrofit of the solar roofing tiles in this case would require only the installation of the roofing tiles, roof deck absorber and insulation, and the attic ductwork. This new attic ductwork would mate with the return ducts in the living space and use the existing furnace fan to circulate the air through the system. Dampers and thermostats would open and close the system as demand and roof temperatures allow. Hot water storage for space heating and domestic service are obvious extensions of this simple system.

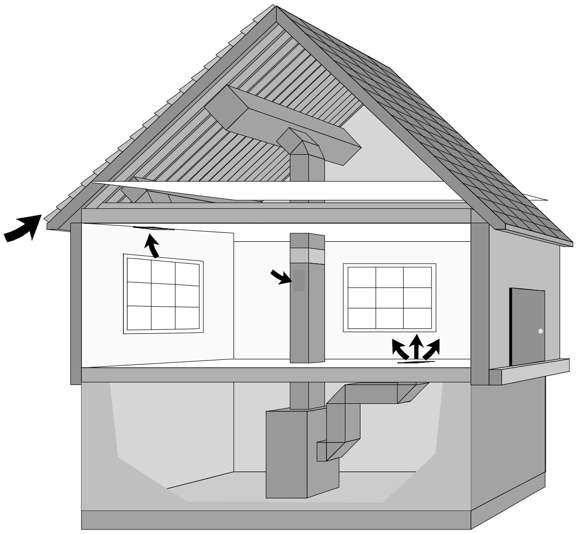

Fig. 3: Ductwork in house with ASR roofing tile

The American Solar Roofing tile has demonstrated mid-temperature performance in proof of concept tests. These tests showed stagnation temperatures of 205°F (96°C) and continuous temperature operation at 155°F (68°C) even with several inefficiencies in the materials and air flow rates used. This was 115°F (64°C) above ambient at stagnation and 60°F (33°C) above ambient with airflow. Eliminating the inefficiencies with commonly used solar collection materials and air flow management methods will improve performance.

One advantage of mid-temperature performance is that the behavior of the solar roofing tile collector system can be modeled using existing solar engineering techniques. The large amount of data available for mid-temperature, glazed, air heating collectors supports modeling for all roof configurations.

Predictable thermal performance is matched by the predictable construction costs of the system. This predictability comes from the similarity of the solar roofing tile and the installation methods with those of existing roofing tiles. Additional ductwork and thermal storage assemblies all represent routine construction operations for plumbing and heating trades. All of these similarities allow the use of construction cost estimating guides to estimate the installed costs of the solar roofing tile system.

Figure 4 shows the monthly space heating and hot water requirements for the conventional house. It also shows the available solar heat provided by the solar roofing tile system. The solar roofing tile system on the house in this study can provide 100% of the hot water heating required, 50 % of the total heating and hot water load, and, in the month of January, 25% of the peak space heating load.

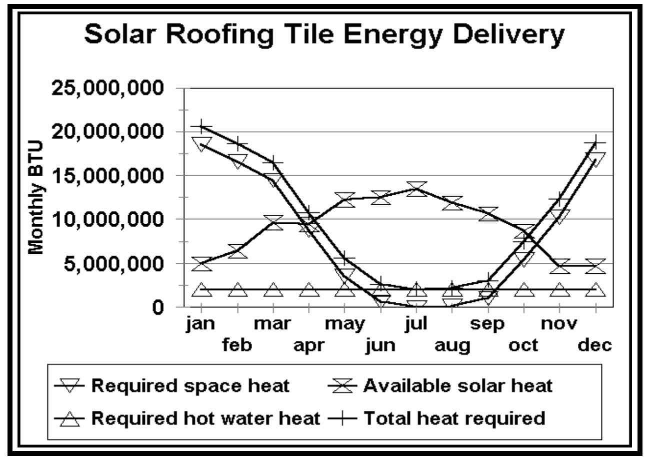

Fig. 4: Available solar energy and heating requirements

In the Boston area, this represents $615 per year in reduced heating costs compared to heating with natural gas delivered at a typical, state wide, residential rate of $9 per million Btu. In addition to the energy cost savings, the long, 50 year, life of the roof can eliminate several re-roofings and dumping fees for disposal of the old roofing. This amounts to an additional $1000 in cost savings over the life of the roof. If a $1500 tax credit is allowed for solar hot water heating, then the total annual, non-discounted savings equals $665 per year, or $1.10 per year per square foot of installed roof.

The installed cost of such a roof is projected to range from $7-12 per square foot, or $4,200 to $7,200 for 600 square feet. Using the National Institutes of Standards and Technology building life cycle costing methodology with a 6% discount rate, the roof provides thermal energy at a cost of approximately $5-6 per million Btu. This cost of delivered energy is 33-44% lower than the cost of energy from burning natural gas at a delivered price of $9 per million Btu. The net present value of the cost savings to the homeowner are on the order of $3,000 to $6,000.

The system can deliver 62 million Btu per year for space and hot water heating. An additional 47 million Btu of solar energy is available in the months from May through October. Use of this excess heat through desiccant cooling or other methods can further reduce the cost of delivered energy. Different roof configurations which take advantage of garages, carports, porches, etc. can increase the usable roof area and increase the amount of solar energy supplied by the roof. Different house configurations such as a single story house with a greater roof area-to-heated volume can substantially increase the fraction of solar energy delivered. With a large solar fraction, the size of the backup heating system can be substantially reduced. Several case studies have shown that with adequate solar energy gain and thermal storage, a backup system no larger than a water heater is required. Each of these design details creates opportunities to further reduce delivered energy costs.

6. RESEARCH, DEVELOPMENT, AND POLICY REQUIREMENTS

Accelerating the installation of these BIST systems on existing buildings will deliver benefits to the building owners and the help cut traditional energy use. With more than 66 million residential buildings, nearly 5 million commercial buildings, and approximately 2.5 million farms and manufacturing facilities, many with multiple buildings, the energy savings potential is enormous. Energy savings from BIST roofing installation on a fraction of the total building stock can contribute substantially to national energy goals of ensuring a secure and sustainable energy supply at competitive costs and reducing greenhouse gas emissions.

To capture the benefits of using BIST roofing systems in existing buildings, research is needed in the following areas:

- Develop BIST screening tools to quickly assess the economics of a building's solar potential using each system.
- Develop light weight, long life glazing materials that minimize loads on existing roof structure.
- Develop low pressure, medium temperature, air to water heat exchangers.
- Develop assessment tools and measurement devices to predict the impacts of partial roof shading from trees and other obstructions.
- Analyze thermal and economic impacts of absorber color variations and selective surface use.
- Design BIST systems to meet clothes drying and cooling thermal loads within a building.
- Design backup heating systems which operate at a fraction of the output of typical heating systems.
- Design low cost, low pressure, long life, storage tanks with integral air to water heat exchangers.
- Analyze flat roof retrofits of BIST systems.
- Evaluate business models for BIST companies.
- Evaluate regional market potential for BIST.

Policy development, with emphasis on financing BIST systems is another pressing need. Current financing mechanisms at competitive and supportive interest rates are too complex and time consuming to support the quick sales cycle of solar energy systems. Those that have a shorter cycle often have interest rates too high to support wide scale use. A method of reducing loan interest rates for solar energy systems to those comparable for home mortgages would greatly accelerate BIST deployment as well as the deployment of most other solar energy systems. Loan guarantees or secondary market development for these loans should be pursued.

7. CONCLUSIONS

There is a long history of innovation in building integrated solar thermal design. Of the most recent innovations, three are either in production or under development.

There are many advantages to using the building integrated solar thermal roofing systems currently under development. The aesthetics and building envelope performance of these BIST systems can match that of existing building products and therefore hasten their adoption by building owners. These systems can also provide substantial savings to the building or home owners from reduced heating, maintenance and repair costs. A case study for a house in a heating climate shows that BIST systems have the potential to deliver energy at lower cost per Btu than typical fuel sources and provide net savings to the homeowner.

The possibility of installing these cost and energy saving systems on millions of buildings in the U.S. suggests that the systems can aid substantially in meeting national energy goals. Research should be accelerated in those areas most critical to speeding deployment of these systems.