Practical Innovations for Low-Energy Community Housing

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ABSTRACT

This paper describes ideas for designing buildings suitable for communities whose members share concerns for living as lightly on the land as possible. Design concepts include Permaculture; tight, well-insulated envelopes using recycled (or at least recyclable) material; radiant heating and cooling supplied by a district loop largely fueled by solar; ventilation and better bathrooms; fenestration strategies; daylighting systems; cooking; and solar greenhouses. The ultimate aim is to develop sound strategies to influence groups of people to live lives that are less energy intensive—while being creative and fulfilling.

Introduction

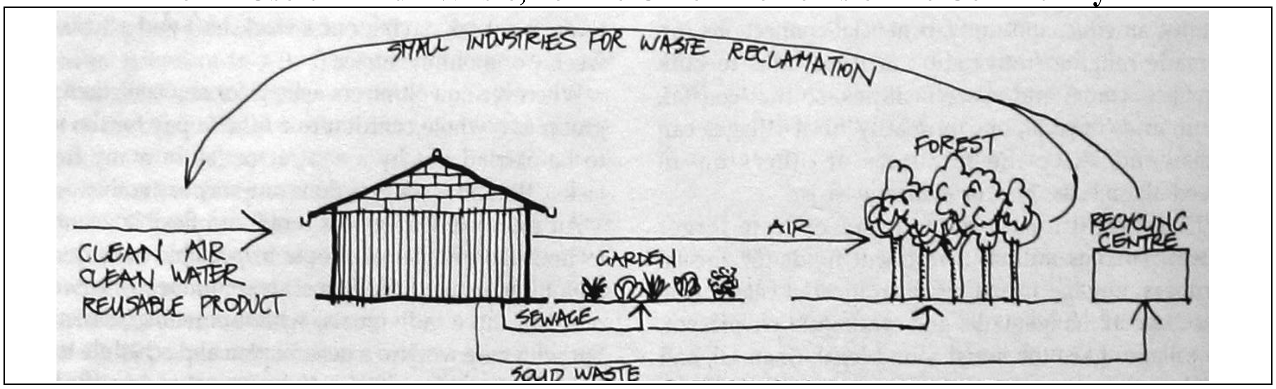
The overwhelming messages of the phenomena of global warming and peak oil are manifestations of a fundamental issue: the un-sustainability of the exponential growth of population, non-renewable energy, and related resources. Waste in all sectors is enormous, growing—and unsustainable. Although inroads have been made into raising the efficiency of buildings, waste in the building sector is still very substantial and it too is growing.

Happily, this growth in waste is accompanied by the growth in interest on the part of many people in trying to do better, to live less wasteful lives in shelters which reflect such values as the need to husband resources, to be kind to one another and to Mother Earth, and generally to contribute as best we can to solutions instead of problems. One recalls Eldridge Cleaver's observation, "if you are not part of the solution, you are part of the problem."

Design Concepts

Whole systems thinking and permaculture. Recognizing the interrelations between and within each community and building system is a good place to start. Known for the application of systems analysis to sustainable food production, water and waste management within a specific ecosystem, Permaculturalists exemplify a level of intention and attention to design that is communal in ways both large and small (Figure 1). Consider what resources are needed to develop and operate each element of the design (be it home, garden, farm, chicken house, cottage industry, or the whole community) to achieve the desired output (comfortable shelter, healthful food from vegetables to chicken dinner, energy-efficient technologies for local and global transformation—even sustainable social structure). Consider also the excess products of each design element (waste heat, less than pristine water and air, left over flora, chicken manure, CO_2 and more). The challenge is to use the extra outputs in a productive, healthy fashion whose environmental consequences are positive. The goal is a complete cycle in which waste is eliminated because all output is usable and used. This vision can take design a step beyond zero net energy consumption and into the realm of productive, sustainable community life (Mollison 1997).

Figure 1. The Needs of Each Element in the Community Are Sought from the Products, Both "Useful" and "Waste," of the Other Elements of the Community



Source: Mollison 1997

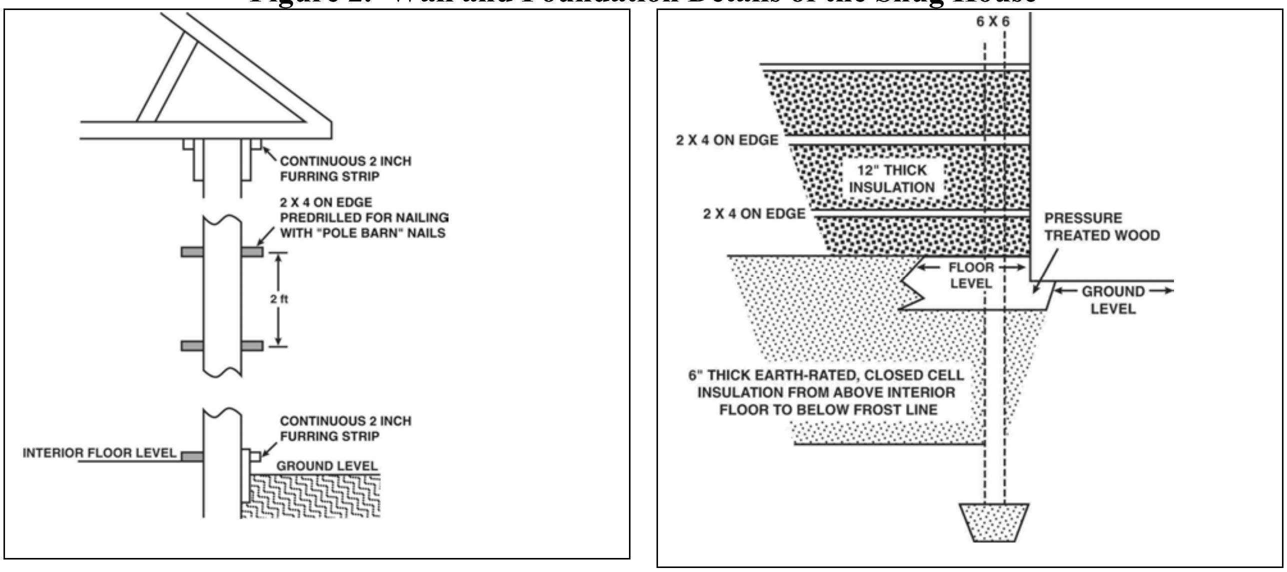
Permaculture addresses water conservation and controls, sustainable landscaping, community gardening and food storage from community kitchen for joint food processing to root cellars and wine making (and joyous consumption). For energy use, a systems analysis approach suggests mindful, conscientious use of embedded fossil fuel energy and zero ongoing fossil fuel consumption.

Tight, well-insulated envelopes using recycled (or at least recyclable) material. The first step is to minimize heat gain and loss across the building envelope, to achieve the building equivalent of a thermos bottle that is coupled to the earth (and decoupled from the earth outside of the perimeter of the conditioned envelope.) Then indoor air quality can be maintained by both active and passive means depending on user needs and instantaneous weather circumstances. Where topography and local conditions allow, slab-on-grade construction is recommended where the slab is connected to deep earth and is constructed of a concrete that integrates fly ash—a byproduct of coal-fired power stations—in the mix to the degree practical. This saves cement and strengthens the resulting concrete (see www.flyash.com).

One option, dubbed the "Snug Home," is a super-insulated version of a pole barn (or "timber column") technique (Kinney 2004). Instead of poured-concrete foundations, these structures are supported by environmentally-benign, sodium silicate treated (www.TimberSIL.com) wood poles placed on 8-ft centers in 5-ft-deep holes with a concrete plug in the bottom—in much the same way as pole barns are supported. Trenches 4 ft deep are dug between the poles to accommodate 4-inch to 6-inch-thick closed-cell insulation. The perimeter insulation is used to define the edges of a concrete slab and mate with wall insulation without thermal breaks. Twelve inch plus walls are insulated with fiberglass or (preferably) blown in cellulose (produced from recycled newspaper) behind an interior vapor barrier (for cold and moderate climates). The attic floor (or ceiling) is insulated to R-50 depending on the climate zone. Plumbing, wiring, and ventilation ducts run on the inside of the thermal shell. Double- or triple-glazed windows with specularly-selective coatings are used to ensure solar gain in the winter, and both overhangs and exterior shading are used to limit summertime heating.

Buildings constructed in similar ways in Upstate New York and the mountains of Colorado have very low heating and cooling bills, will never go below freezing even with no energy input save for the energy from the deep earth, and cost as little as $50/ft^2.

Figure 2. Wall and Foundation Details of the Snug House



Source: Synertech Systems Corporation

A second construction option uses Rastra,™ a building material composed of 85 percent recycled Styrofoam and 15 percent Portland cement laced with fly ash. It serves as structural wall, supplies both thermal mass and insulation, and functions as a base for stucco, plaster, or other finishing materials. The material is delivered in 10 foot long blocks that are 15 inches high and 10, 12, or 14 inches thick, where thicker blocks are preferred for severe climates, both hot and cold. The sections may be handled easily by two workers, who seal the joints with urethane foam and carve out spaces for wiring and plumbing using routers and electric chain saws. The blocks contain hollow cores that run through their centers horizontally and vertically. These are filled with rebar as the walls are laid up, after which cement is pumped into the top. The resulting web provides strength for the walls as well as thermal mass. Rastra construction passes stringent building codes and has been adopted in many areas (Holik 2003). First costs of homes built with Rastra are about equal to conventional building costs, but lifetime costs are substantially lower, owing to excellent energy performance, low maintenance, and high resistance to fire.

The insulating value of walls made of Rastra (with a rebar-laced concrete web) has been measured by several laboratories in Europe and the US. Steady state thermal resistance is R-11 for the 10 inch thick wall, R 16.3 for the 12 inch wall and R 22.7 for the 14 inch wall. However, since mass is within the insulated space in the case of Rastra, it is useful to ask what would be the equivalent insulating value of a conventional wood frame dwelling to achieve identical heating and sensible cooling loads as a home whose walls are constructed of Rastra. A team at the Building Technology Center of the Oak Ridge National Laboratory (ORNL) undertook an analysis of this question (Kosny *et al*., 1999). The answer is a complex function of climate zone and the dynamic response of homes to changing conditions. In order to achieve the same thermal performance as a Rastra dwelling, the R-value of the walls of a wood frame building would have to be approximately double that of Rastra walls in most climate areas; "Dynamic Benefit for Massive Systems" (DBMS) values range from 1.79 in Miami, FL through 2.05 in Minneapolis, MN, to 2.17 in Phoenix, AZ.

Radiant heating and cooling supplied by a district loop. Radiant heating is routine in many building in the US, but radiant cooling is not (Feustel and Kinney 2002). Yet the same radiant surface can be used for both. Possible strategies include polyethylene loops buried in the concrete floor, and, in such spaces as upper floors, products such as Warmboard® (Figure 3.) Warmboard is a 1-1/8 inch thick plywood sheet with channels for the tubing routed in one surface. This surface is then covered with a thin aluminium sheet that fits into the channels and holds the tubing in place. Since aluminum is a good thermal conductor, this approach provides a near-uniform floor temperature. A well-insulated and air-tight building envelope, coupled with the large cross section of the radiant heated area, means that the difference in temperature between the water in the loops and desired temperature is the space may be quite small. This design is an advantage in both summer and winter, and improves the system efficiency of the space conditioning system to near optimal levels. Individual dwellings can now avoid fan-driven HVAC equipment and except for strategic ventilation (see below), ducts, noise, and drafts are avoided as well.

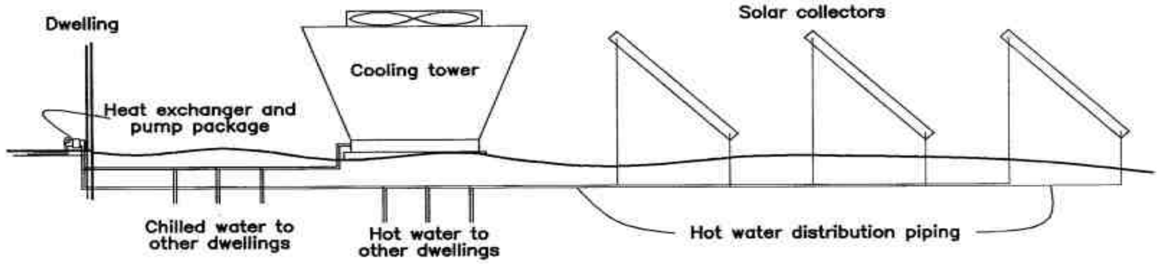
Figure 3. Light-Weight Concrete (left) and Warmboard (right)

Sources: Slant/fin® Warmboard®

Each of these characteristics lends itself to using a district heating and cooling system whereby hot water and chilled water are delivered from a front end that is primarily a solar thermal system for heating needs and an evaporatively cooled chilled water system. District heating, cooling, and DHW keeps mechanical equipment in buildings to a bare minimum; a heat exchanger, circulation pump, and thermostat and likely a small domestic hot water (DHW) storage tank using supplied heat are the key elements necessary in buildings.

The "front end" of this system includes hot water solar collectors with storage matched to local climate and a cooling tower to evaporatively cool the chilled water (Figure 4). The cooling tower and pumps would employ variable-speed, premium-efficiency motors and the cooling tower would have high-efficiency fans. Two storage tanks, one larger and another smaller, would be installed. During the winter, both would store hot water. During the summer only the smaller tank would hold hot water for domestic uses. The larger tank would be used to hold chilled water produced at night when cooling loads are reduced and the cooling tower can produce excess chilled water.

Figure 4. Schematic of Solar Heating and Evaporative Cooling System (Storage Tank not Shown)



Source: Gary Cler

There is a small energy "overhead" with such a system, since the hot and chilled water are generated remote from the point of use. However, with properly-sized and well-insulated distribution pipes, the benefits of the central plant concept outweigh the pumping energy that is small owing to good pipe design, layout, and the fact that it is closed loop. Additionally, there might be a premium in the installation cost as a result of the hot and chilled water distribution system. This added cost is partially offset by the installation of a single heating and cooling system rather than multiple systems, one per building. Being larger than the units that would have been installed in the community buildings, it is less costly on a per-unit-of-energy basis.

This design would need to be a 4-pipe system since during the summer months domestic hot water is needed in parallel with cooling. Within the buildings, two heat exchangers, one for space conditioning and another for DHW, will be required along with a pair of circulation pumps and associated controls. It is expected that these heat exchanger/pump modules would be standardized items, built in the shop, and installed in the field, thus reducing labor and the likelihood of leaks and other problems. Having the DHW heat exchanger receive the incoming hot water first will provide the hottest DHW. The slightly cooler water will still be adequate for space heating, due to the large heat exchange area–the entire floor.

In many climates, proper sizing of the solar collectors and storage tank can eliminate the need for a back-up heating system. Climates with long periods of cloudy weather would necessitate a very large collector array and storage tank volume if no back-up system were installed. When backup is desired, a low-mass, high-efficiency condensing hot water boiler with large turn-down ratio would be included in the central plant. Such units can be fueled with natural gas, LPN, or renewable fuels such as biomass or even waste cooking oil.

Owing to the large heat-exchange area, the chilled water temperature can be quite modest by vapor compression standards. This arrangement helps avoid chilled water below the dew point temperature within the conditioned space and resultant condensation on the cool floors. Due to the tight construction, careful attention to detail in sealing the structure, and proper ventilation only when and where needed, indoor humidity issues are expected to be minimal.

When they are significant, such as in very humid climates, several alternatives exist:

- Desiccant-based dehumidification systems dry and warm the air. These systems would be regenerated using heat from the underutilized (during the summer) solar system.

- Small electric vapor compression dehumidifiers can be used. These could substantially increase the electric load of the dwellings, increasing the number of PV panels required and thus adding significantly to the overall system cost.

Even though desiccant systems have higher first costs than vapor compression dehumidifiers, the system cost as well as energy costs will be lower. In both of these cases a small amount of ducting may be needed to ensure adequate circulation of air through the conditioned space to the dehumidification system. This ducting would all be within the conditioned space, so no insulation would be required. Finally, the front end may include a photovoltaic (PV) system or a solar Stirling combined heat and power (CHP) system, community wind, etc. Modest loads will help keep such systems small.

Ventilation and better bathrooms. Using passive means for ventilation when possible are always desirable, but when conditions do not permit this to be done effectively, we favor air-to-air heat exchange with careful attention to the location of intake and supply ducting, as well as to the design of the controls. It is important to modulate the fans to maintain pressure balances as well as to adjust for the extent of ventilation needed. The use of electronically-commutated motors and efficient fans is critical in achieving adequate ventilation at modest energy use. CO_2 sensors are useful in automating ventilation rates to ensure good indoor air quality (IAQ.)

The case of bathrooms is special. Instead of a substantial fan designed to control for both odors and moisture, we favor a small (15 cfm) fan drawing from a plenum around the bottom of the toilet seat which is actuated by occupancy. Thus, instead of objectionable odors passing through the air to a bathroom fan in the ceiling, they are removed close to their source. Both Jon-Air (www.jon-air.com) and Sun Frost (www.Sunfrost.com) have developed such specialized fans (Figure 5).

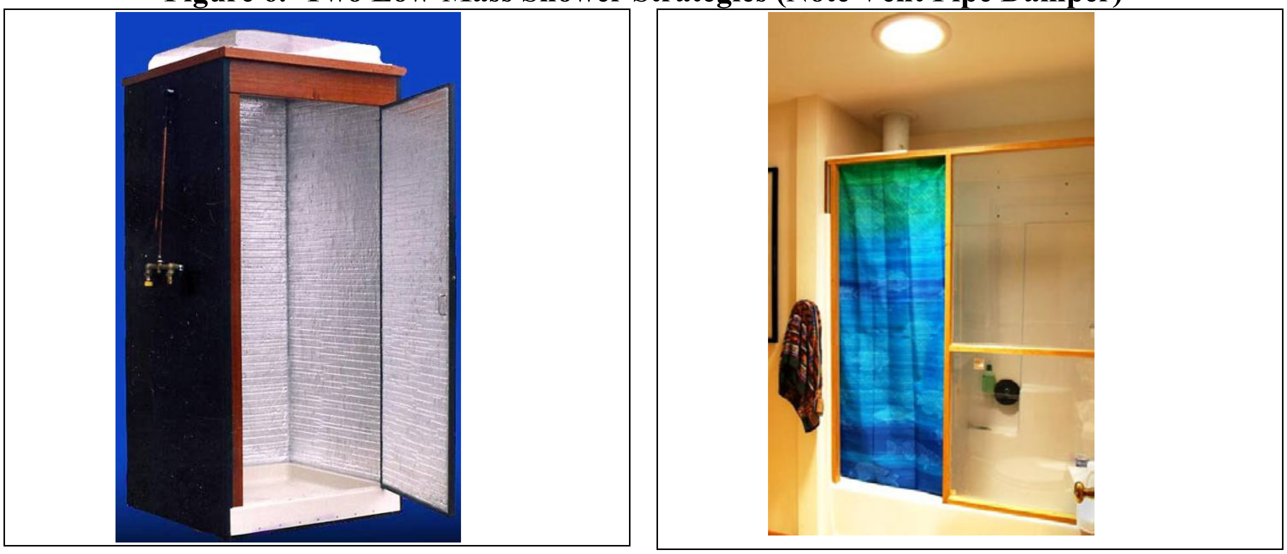
Figure 5. Sun Frost (left) and Jon Air (right) Approaches to Spot Ventilation

Sources: Sun Frost and Jon-Air

A well-designed shower is much more comfortable than a conventional shower, while saving more water, wasting less heat, and avoiding moisture problems that can result in mold and mildew. Most showers are subject to a remarkable drop in temperature from the shower head to the body and in turn to the floor of the shower, from 10 to 20 degrees F. This loss is due to evaporative cooling of the water, particularly when the droplets are quite small, as is the case for many low-flow models. If the shower stall is of low mass and able to be closed quite tightly while showering, the walls are quickly heated by the shower itself, thereby virtually eliminating radiant heat loss from the bather to the shower walls. Further, since the closed environment quickly approaches 100 percent humidity, evaporative cooling of shower water is eliminated.

Thus, a very comfortable shower can be enjoyed at lower water delivery temperatures, even in shower stalls located in bathrooms that may be quite chilly. At the end of the shower, a damper may be opened above the shower stall and the shower door opened. This allows warm, moist air to be thermo-siphoned through a vent pipe to the outside with no need for a fan. This design quickly lowers the humidity of the shower stall area to well below levels that risk the formation of mold and mildew (Figure 6).

Figure 6. Two Low-Mass Shower Strategies (Note Vent Pipe Damper)



Source: Sun Frost

Fenestration strategies. Recent advances in window technology have resulted in better energy performance, but even super windows have properties which represent trade-offs that make their performance less than optimal for all circumstances of weather and occupant needs and desires. Windows with high R-values (low U) are available that boast numbers like R-14 (Clarke 2004). These may be wonderful for a cold winter night, but their comparatively low solar heat gain coefficient (SHCG) makes them less fit for a sunny winter day on a building's south façade. In areas such as the southwest which have large diurnal temperature swings in both summer and winter, high R-value windows are outperformed by single glazing on summer evenings the moment outside air temperatures drop below indoor air temperatures. Finally, in almost all climate areas, it is desirable to block direct beam sunlight from entering the conditioned envelope of a building during the heat of the summer, unless it is carefully controlled to supply measured levels of daylighting.

Even very fancy (and expensive) windows cannot achieve these goals. What's really needed are variable solar heat gain coefficient (SHGC) *and* variable heat transfer coefficient (U value) fenestration systems. An elegantly simply way to achieve this is through exterior insulating shutters. Suitably-designed exterior insulating shutters save energy used for space conditioning, substantially reduce peak demand for electricity used for cooling, enhance comfort, provide security, and lessen the likelihood of catastrophic damage due to hurricanes or fire (Figure 7).

Figure 7. Photo of External Insulating Shutters Made in the US Superimposed Electronically onto a Home in France

Source: Larry Kinney

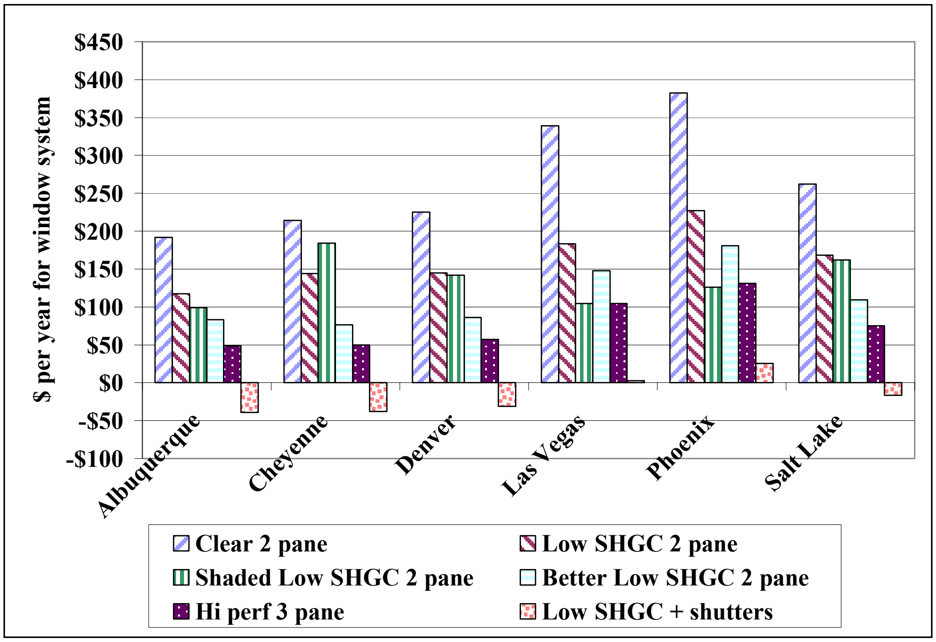
These shutters open and close automatically via wireless controls that may be overridden at the push of a button. The automatic mode optimizes energy performance and comfort summer and winter. The shutters are air tight when closed and well insulated, but facades may be chosen to optimize resistance to hurricanes, bullets, or fire—or to accommodate a variety of aesthetic desires, including the provision of daylighting. Each shutter system is powered by an integrated PV cell and energy storage device. This design facilitates installation in new and retrofit applications and avoids the need for adding power wiring and piercing exterior walls.

In many climates, such shutters work quite well with conventional double glazing with high SHGCs; in colder climates, a low-e coat enhances performance. In practice, during the winter, the shutters remain open as long as solar gain outstrips conductive and convective losses, but are closed when losses exceed gains except when users desire to override them. In summer, shutters are actuated to block direct solar gain, leaving windows on other facades open for view and daylighting. In addition, one version of an insulating shutter includes a fibrous material that transmits diffuse light ($V_t = 0.4$), while still providing good insulation. Other shutter insulation used does not transmit light but has an insulating value of R-13.

A number of simulation runs on homes in Southwestern cities were made using an hourly simulation program derived from DOE 2 (RESFEN version 3.1) to quantify the performance of windows of various characteristics (Kinney 2004). In all cases, we assumed single-story, frame, 2,000 square foot homes with 300 square feet of fenestration systems (about 15% of wall area) distributed evenly on the four facades of the homes.

Results of the analysis expressed in annual cost of electricity and gas to make up for losses (while considering gains) through the 300 square feet of evenly-distributed windows showed that shuttered low SHGC windows reduced the annual energy cost of windows to $25 or less, actually reducing overall energy costs to less than zero in climate zones modeled except where cooling energy dwarfs heating energy. (Kinney 2004, 2005; Cler and Kinney 2005).

Figure 8. Annual Energy Cost Comparisons of Six Fenestration Systems in Southwestern Cities



Source: Larry Kinney

Even better performance in most climate zones would be achieved by using high SHGC glazing, or even clear glazing, because of enhanced solar gain in the winter that nonetheless causes few problems in the summer because the shutters shield the building from direct beam sunlight. This approach allows for adequate glazing to ensure good passive solar heating without paying a penalty on cold winter nights or hot summer days.

Daylighting systems. Figure 9 is a generic representation of a number of classes of daylighting schemes several of which may be practical for the community building project envisioned.

In order to adequately daylight large open spaces such as assembly areas and the like, it is important to intercept large amounts of lighting flux, which usually entails significant openings in the conditioned envelope. Conventional skylights achieve daylighting, but at the cost of glare, bright spots in the ceiling area, substantial thermal losses through the ceiling when there are large temperature differences between inside and outside of the building—or all three. It is possible to design daylighting systems that largely overcome each of these shortcomings.

As illustrated in Figures 9 and 10, specular reflectors on architectural surfaces direct beam sunshine across a white ceiling. Provisions are made for cleaning the mirrors using a burst of compressed air. The geometry of the reflectors is selected to keep beam sunshine from falling on the surface below while distributing it as evenly as possible across the ceiling for all sun angles. This design controls for glare and allows the ceiling itself to function as a diffuse source of natural light. Back-up lighting (high efficiency T5 or T8 fluorescent bulbs controlled by dimmable electronic ballasts) is integrated into the architectural elements and the reflectors ensure that light from them is uniformly spread across the ceiling. Sensors modulate electric lighting as a function of instantaneous daylight availability. Glazing properties are matched to climate zone, but in climates that experience a cooling load, specularly-selective glazing with a high visual transmittance but relative low solar heat gain coefficient is used to ensure that the daylighting system has a relatively high luminous efficacy, on the order of 150 lumens per watt. As a consequence, cooling loads are substantially lower than would be the case with conventional lighting, and both energy and peak demand is lower as well. Thermal loads are also diminished because either insider or outsider insulating shutters are employed to limit thermal losses through the glazing at night, or to limit daylighting if users desire (e.g., for audio/visual presentations). Under normal circumstances, these shutters are actuated automatically to optimize energy performance, but they may be manually over ridden if desired.

Figure 9. Generic Solar Lighting Schemes

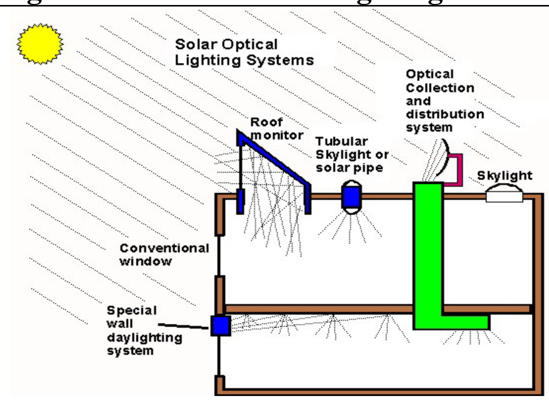
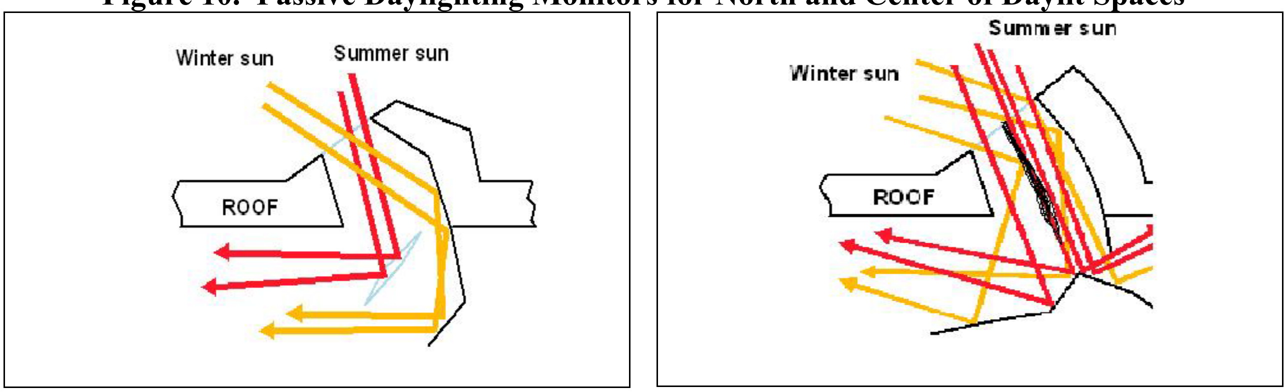


Figure 10. Passive Daylighting Monitors for North and Center of Daylit Spaces



Source: Synertech Systems Corporation

Figure 10 also shows a variation on the theme that may be employed toward the center of the roof of a building, as it distributes light in both directions. Exterior insulating shutters are employed for cold winter nights, or to enhance or modulate incoming light during the day.

Two other insulating shutter options may also be employed: interior shutters that slide over the light well; or interior shutters integrated with the center mirror. This latter option is consistent with being able to optimize light distribution during the day.

Another approach to elegant passive solar and daylighting whose key features may be worthy of emulation is illustrated by Sunhawk, a 2900 ft^2 passively-solar-heated home recently built near Hopland, California on a mountain about 30 miles east of the Pacific Ocean and 100 miles north of San Francisco (Research by Larry Kinney. See also Lawrence, 2004). Summertime temperatures are frequently 110 ^oF in the afternoon; wintertime temperatures fall well below freezing. A grid-free home with both micro-hydro and photovoltaic systems for electricity, Sunhawk is made of Rastra. It also includes an interesting daylighting system. As shown in Figure 11, the design was inspired by a red-tailed hawk, where the tail feathers point from southeast to southwest. There is a shading device between the lower tier of fixed glazing and the upper tier. The lower tier of glazing is used for solar heat gain during the winter, so has a relatively high solar heat gain coefficient. The upper glazing functions primarily to supply daylighting, so has a high visual transmittance with relatively low SHGC. The fixed horizontal element between glazings functions as a shade for the lower glazing during shoulder months and the summer. Since its top surface is diffusely reflective, it also enhances the transmission of daylight through the upper glazing onto the ceiling of the great room at the south of the home. Insulating shutters would result in improved performance (Kinney 2003).

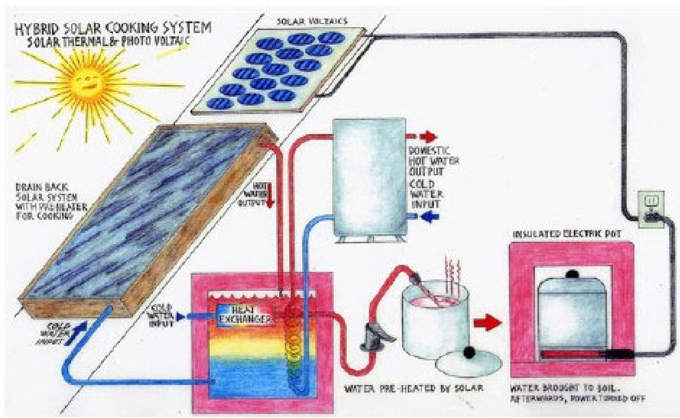
Figure 11. Sunhawk Under Construction, South Elevation

Source: Larry Kinney

Cooking. Cooking energy is often ignored, with the consequence that only a small portion of energy used in the process actually cooks food, the rest being lost. Second, attention is rarely given to using solar systems to supply cooking energy. It is nonetheless possible to do much better—and do it simply. Larry Schlussler uses 180 ºF water from the top of the solar collectors on his home to supply a special tap at the kitchen sink (Figure 12). He uses this water directly to prepare tea, and also uses it to start the cooking process of such food as rice and stews. Electric elements are built into the pots he uses, which are also fitted with excellent insulation—and electricity comes indirectly from his PV cells. Cooking energy is thus very modest and food is prepared without heating the kitchen. Variations of solar hybrid cooking are possible where the principles include deriving heat from renewable sources, applying heat directly to food, and making good use of insulation around containers (Schlussler 2005).

Solar greenhouse. Greenhouses are usually quite energy intensive structures owing to the intrinsic low R-value of many of the surfaces which let in solar energy (and have substantial conductive and radiative losses as well.) Toward making them more energy efficient, many of the same features of other buildings discussed above should be employed, including earth-coupling by heavy perimeter insulation four to six feet underground surrounding the slab and moveable insulation that fits in pockets around the foundation or between panels of glazing in sidewalls and roof. Employing compost and animals strategically to enhance soil and provide heat and CO_2 may add useful energy and growing strategies. We envision very simple inside-the-greenhouse active solar systems that thermosiphon warm water into insulated containers such as 55 gallon drums during the day and into the beds to maintain warmer temperatures as needed. Simple sensor and control strategies that rely on thermally-operated valves and check valves should be employed to ensure stable temperature control. Similarly, shuttered green houses can keep plants cool and moist in extreme hot, dry climates, optimizing growing conditions.

Figure 12. Hybrid Solar Cooking System Schematic



Source: Sun Frost

Concluding Thoughts

Details are important in achieving good communities and associated buildings, as are shared principles, shared visions, and shared work. The structures used by members of a community must be more than the sum of a number of design ideas, even if they are good ones. The goal of achieving a kind of organic unity that is reflective of the spirit of the community and the functional needs of its members is a lofty one. Indeed, undertaking to influence groups of people to live less energy intensive lives that are nonetheless creative and fulfilling is a daunting task. It is, however, a critical one for the survival of our species on this fragile planet whose ecosystems much of humankind continues to desecrate.

We find hope envisioning the integration of permaculture-style cottage industry into the imagined communities as they move from vision to reality. The production of insulating shutters, daylighting devices, cookware, and related energy-efficient products may bring to fruition some of the design ideas discussed while serving as a model for that special variety of creativity of which fulfillment is its most easily recognizable characteristic.

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