Energy-Efficient Greenhouse Breakthrough

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ABSTRACT

Most of the food Americans eat, particularly in winter, endures long trips from the field to the table. The result is less-than-tasty-or-fresh food whose embodied energy for transportation alone can be substantial. Growing locally in cold months requires greenhouses. Conventional commercial greenhouses are routinely heated with more fossil fuel energy than are other similar-sized commercial buildings—and lit with an array of grow lights. So in one way or another, food has a large energy/carbon footprint.

Toward seeking practical solutions, the authors' team designed, built, and instrumented a 1000 square foot research greenhouse in Boulder, Colorado that uses only sunlight for heat and illumination. The building employs high R-value foundation perimeter, wall, and roof insulation; high solar heat gain coefficient (SHGC) windows; light shelves; automated insulating shutters that lower nighttime losses through fenestration six fold; large quantities of thermal mass; and efficient air handling systems that ventilate the structure and collect, store, and distribute thermal energy and moisture.

Monitored performance of both energy and growth demonstrates concept feasibility. The greenhouse went down to only 50 ^{o}F on a night that went to -18 ^{o}F—and the greenhouse temperature was up to 84 ^{o}F the following day. A dozen varieties of vegetables were planted from seed on Thanksgiving Day, 2010. Sprouting was immediate, growth was vigorous, and many vegetables were harvested by early spring.

Work on commercial and residential greenhouses built on these principles is underway. Substantially lowering energy use in this large sector shows great potential world wide.

Background

Every sector contributes to profligate energy use, but the production, transportation, distribution, and preparation of food results in particularly large energy consumption. As an approximation, each unit of energy ingested by Americans consumes ten times as much fossil fuel energy to plant, fertilize, harvest, transport, and prepare (www.theoildrum.com/node/9145).

Most of the food Americans eat is grown a long way from the dinner table. In 2005, 15% of U.S food by volume was imported, 32% of fruit and nuts. Food destined for such journeys must be harvested well before it is eaten, packed for shipment, and jostled around in trucks or trans-ocean cargo ships (and even airplanes) on its way to distribution centers, grocery stores, and pantry shelves. The result is food whose embodied energy for transportation alone can be substantial.

Growing locally can solve many of these problems, but for upwards of six months of the year in many climate zones this requires greenhouses. For conventional greenhouses, fossil fuel use rises quickly with descending temperatures, reflecting both low insulation around the thermal envelope and little thermal mass within it. Even with considerable energy consumption, when days are short, it is difficult to raise summer vegetables whose counterparts are trucked in from warmer locales.

Saving follows waste. This generalization is virtually without exception and certainly applies to the dilemma of food production and associated transportation. Indeed, opportunities for limiting waste are multifold. In the present paper, we concentrate on strategies for designing and operating more efficient greenhouses whose use of non-renewable sources of energy approaches zero, but whose capabilities for supporting plant growth year around are robust. Success in this endeavor shortens the distance between field and table, enhances food quality, increases local jobs, and saves transportation energy.

Conventional Greenhouse Construction and Performance

Greenhouses have been employed to extend growing seasons or to raise exotic plants in otherwise inhospitable climate zones since Roman times. The Dutch have constructed cold frames and glass greenhouses since the 16th century (Butti and Perlin, 1980). Figure 1 shows a Victorian style greenhouse in England.

Figure 1. Victorian Greenhouse

Presently in the US, greenhouses are predominated by glazing composed of glass or any of several varieties of plastic. Framing is designed to support the glazing, shed snow loads, and to withstand winds. Many conventional greenhouses are heated in shoulder and winter seasons by forced air furnaces or boilers fired by natural gas, propane, or fuel oil and lit by “grow” lights, which also contribute to heating.

“Hoop houses” are quite prevalent throughout the United States. The 3000 square foot commercial hoop houses shown in Figures 2 and 3 are in Lyons, CO, heating degree days of 6020 and percentage of possible sunshine of 69 (CLR Search.com). They employ hoops of steel pipe that support two layers of plastic that form sides and roof. These are aligned north and south, although orientation has less effect on insolation received by fully-glazed structures like hoop houses than on structures not dominated by glazing.

Controlled by modern electronic sensors and digital controllers, they are heated by 300,000 Btu/hr gas-fired overhead furnaces that run close to continuously on nights when temperatures are in the teens are below. They are ventilated by two 8000 cfm fans on their south ends. Louvers on their north ends allow air to flow through fine screens (to keep out pollen) then through evaporative cooler media which when sprayed with water cools and humidifies the air that then flows across the plants. On sunny days like the one pictured in late November, cooling is employed sporadically to keep from overheating the greenhouses, whereas heating is employed through much of cold nights. In consequence, wintertime gas consumption is on the order of 1200 million Btu (as calculated from data logger and long-term weather statistics) and annual energy bills are $15,000 (at about $0.10 per kWh for electricity and $1.00 per therm for natural gas) for each of these 3000 square foot greenhouses.

Figure 2. 3000 ft2 Greenhouses, Lyons, CO

Figure 3. Inside of Lyons Greenhouse

Energy consumption is high primarily because conventional greenhouses suffer from very poor insulation (overall R value) and very little thermal mass (C). The product of the two (RC) is called thermal time constant, an index useful in characterizing the energy performance of a variety of building types.

Well-insulated and air-sealed buildings with substantial thermal mass have long time constants so in the absence of heating drift in temperature slowly even on cold winter nights. Poorly-insulated structures with modest thermal mass have short time constants, so drift rapidly in the absence of heating. Examples of structures of short time constants include older mobile homes and conventional greenhouses, which in the absence of heating energy drift to 38% of the difference between their inside temperature at sunset and outside air temperature in four hours or so. Since conventional greenhouses (both hoop houses and most others) also have a large solar aperture, the lack of thermal mass allows them to overheat very quickly on sunny days. This can be as deleterious to plant growth as overcooling.

Toward a Solution

With co-funding from the Colorado Department of Agriculture, in March of 2008 a research team headed by the principal author of this paper launched a project to investigate promising strategies and practical techniques for designing, building, operating, and controlling a new class of greenhouses capable of producing food all year around with minimal use of non-solar energy. The project included demonstrating promising design principles through the construction, instrumentation, and analysis of a 1000 square foot greenhouse built on the Cure Organic Farm in Boulder County, Colorado.

Principles of the developing field of building science applied to greenhouse designs include:

- Keep the time constant of the building long through insulation and thermal mass;
- Control the flow of solar flux, both light and heat;
- Control the temperature and flow of air; and
- Integrate the systems of the greenhouse to optimize plant growth.

Figure 4 shows key features and Figure 5 a photograph of the greenhouse.

Figure 4. Key Energy-Related Features of the Research Greenhouse

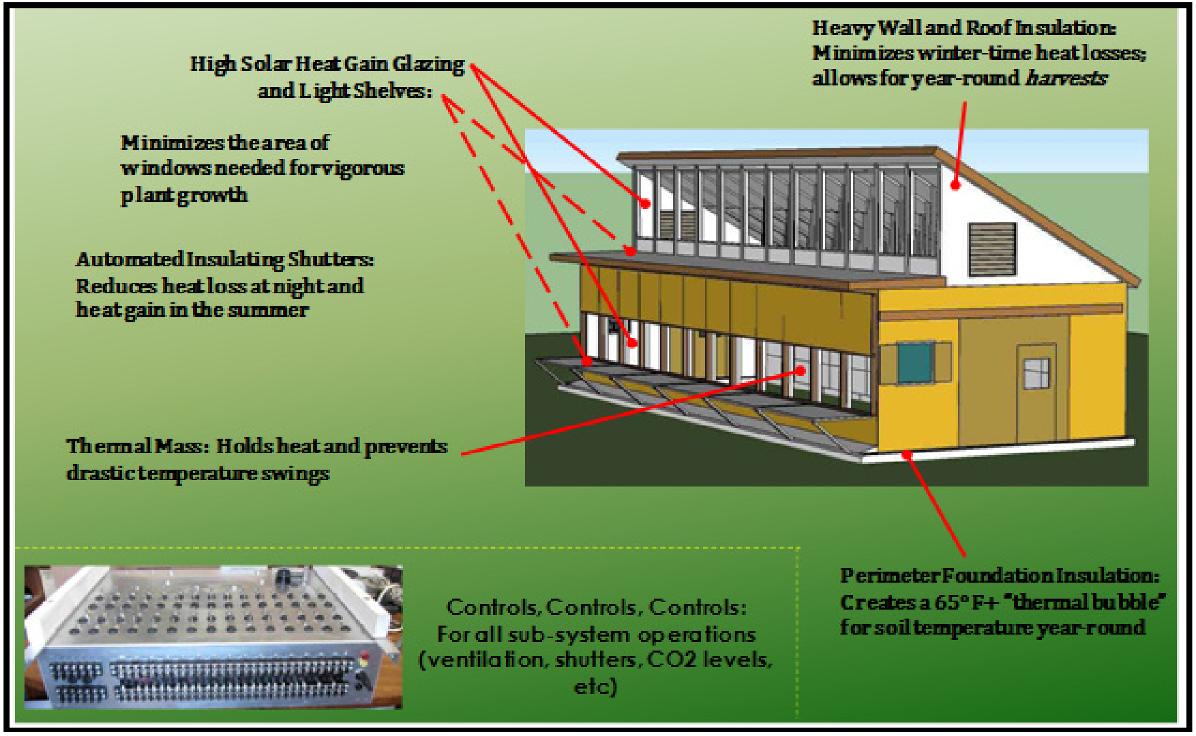


Figure 5. Nearing End of Construction

Insulation

R-20 extruded polystyrene insulation surrounds the perimeter down four feet; the inside floor is soil to support plant growth. The lower shutters live in insulated pockets during the day and occupy the space between glazings at night. The upper shutters are inside of the single glazing and swing on hinges on the upper frame. Electronic controls allow for manual or automatic control of each insulating shutter.

Glass is a poor thermal insulator, as is clear plastic. Yet both allow radiant heat transfer of solar flux, in the form of both light and heat. Consequently, conventional greenhouse designs use a lot of glass or plastic in both walls and ceilings to support photosynthesis. However, in the middle of winter when days are at the most 10 hours long and nights 14, these un-insulated surfaces allow a great deal radiant heat transfer to clear cold skies. Accordingly, auxiliary heat must be used to keep plants from freezing (yet it too is rapidly lost through radiation to the sky.)

Toward dealing with this problem, the window industry has developed a number of techniques for lowering window heat loss. Examples include using multiple layers of glazing to provide more dead air spaces, employing thin coatings or films that diminish radiant emissions in the mid to far infrared (low E and other selective coatings), and replacing air between glazings with inert gases. Each of these techniques helps to lower the heat transfer of glazing (its U factor, measured as Btu/hr sq ft deg F of indoor/outdoor temperature difference.) However, each also diminishes both the visual transmittance (Vt, the portion of available light that is transmitted rather than reflected or absorbed) and the solar heat gain coefficient (SHGC, the net portion of solar radiation—UV, visible, and IR—that is transmitted rather than reflected or absorbed). Further, insulated glazing units with U factors of 0.25 and below routinely cost four to ten times a much as do simpler glazing systems.

Since it is critically important to get sunlight on plants, this trade-off of U value versus Vt and SHGC is usually settled on the side of Vt and SHGC. (Many plants require light at both ends of the visible spectrum and also favor radiation in the near IR.) Thus U-values are high (and R-values are low) and nighttime energy losses are substantial. The greater the glazing area—the circumstances of most greenhouses—the greater the losses.

In the light of these problems, the strategy our team has developed is as follows:

- Keep the glazing area as small as possible consistent with ensuring that plants have plenty of light falling on them and the surrounding growing medium to ensure proper growth and to provide adequate solar energy to meet the thermal needs of the facility.
- Use inexpensive glazing that has high Vt and SHGC. (The research greenhouse used both single and double-glazed clear glass to evaluate economic and performance trade offs. Subsequent designs employ double-glazed clear insulating glass units at $4 per square foot).
- Thoroughly insulate all non-glazed surfaces of the greenhouse thermal envelope to R-20 or greater. (The walls and ceilings of the research greenhouse average R-35.)

Other strategies are discussed under “Controlling Solar Heat and Light” below.

The Enclosed Soil Volume and Thermal Mass

Deep earth temperatures tend to be the average of annual temperatures while the surface temperature tracks within a few degrees of the ambient temperature. Unless the soil at a building site is exceptionally conductive (usually due to high moisture content), at only four feet underground, annual fluctuations in temperature are usually less than 8° F from the annual mean. The deep earth temperature is about 51° F to the east of the front-range mountains in Boulder County. Installing insulation around the perimeter of a building between wall insulation and four feet below grade effectively ***couples*** the structure to deep earth beneath the footprint of the structure. Equally important, it ***decouples*** the structure from the surface of the earth immediately surrounding the structure, thereby isolating the building from soil whose temperatures vary substantially from season to season. The net result is that a thermal bubble builds up under the structure that contributes importantly to the thermal mass of the building, smoothing out the extreme effects of both cold nights and hot days and extending the thermal time constant.

The research greenhouse instrumentation includes temperature sensors in the earth at one foot intervals (from 0 to 4 feet) on the north, east, south, and west close to its perimeter on the inside and outside of the structure, a total of 44 probes. In the winter and spring of 2011, the temperature at 4 feet under the soil of the research greenhouse averaged 60° F, by August of 2011 it was over 65° F. The soil outside of the greenhouse at a depth of 4 feet averages 51° F.

Concrete is energy intensive in its manufacture, but it has structural and thermal properties that make it attractive for use as thermal mass. It weighs 144 pounds per cubic foot, has a specific heat of 0.2 Btu/lb/F and can carry enormous loads in compression. In our case, the sting of energy intensity is mitigated to a significant degree because companies that provide concrete in mixers to construction sites have a need to dump any residue from the day's work in order to leave their machines clean for the following day. Thus, they fill up forms that make blocks designed for fabricating walls and barriers. A ready-mix supply company close to the construction site of the R&D Greenhouse sold us 2 x 2 x 6 foot blocks for $10 apiece (346 pounds per dollar!) Accordingly, a total of 84 of these blocks were integrated into the foundation and the north wall. R-20 extruded Styrofoam four feet deep was used below grade around the perimeter. A combination of Styrofoam and polyisocyanurate (R-28 total) was used between the blocks on the north wall and the Grailcoat stucco-like covering on the exterior wall.

Controlling Air Temperature and Flow

We employ a variation on a Chinese technique for cooling warm air that gathers at the top of a greenhouse on sunny days (Hobbit, 2007). The team devised what we dub a "Greenhouse Earth Thermal Storage" (GETS) system that pulls warm air from the top of the greenhouse through drainage pipes in the earth underneath. This transfers moisture and heat into the ground and cools the air. After exiting the earth, the air blows across plants, thereby cooling them and giving them some useful exercise. This strategy avoids having to vent the greenhouse on bright solar days in the winter and stores both moisture and heat in the earth mass for later use. It also retains moisture in the greenhouse so that net water use per unit of plant production is lower than with conventional greenhouses. (Further, according to old farmer's wisdom, greenhouse growing is ten times less water intensive than open field growing.)

Just as with all buildings designed for energy efficiency, the research greenhouse was carefully sealed so that air infiltration/exfiltration is low when ventilation is not desired. Blower door measurements indicate 710 cfm of air flow at 50 pascals inside-outside pressure difference, quite tight for a 1000 square foot greenhouse whose average height is 13.5 feet. We estimate the average natural air exchange rate in wintertime to be 0.16 air changes per hour.

Vents that are shuttered when not needed are located both toward the bottom and top of the greenhouse to take advantage of the buoyancy of warm air. Opening doors and vents at the bottom and top of the greenhouse and at each end promotes natural ventilation from wind and from stack-effect forces between the bottom and top of the envelope.

Although a key aim of the greenhouse is to use as little non-solar energy as reasonable, some fan use is essential, especially for brief periods during the winter to lower humidity and bring in CO2 to enhance growth. We use a 5200 cubic per minute (cfm) fan whose motor draws 538 watts. This produces an air exchange every 2.6 minutes, which is useful in lowering relative humidity quickly. Stainless steel blades and frame impede rust. Average monthly greenhouse **total** energy use, which included ventilation, lighting, and instrumentation, is 12 kWh; only solar is used for heating and growth.

Controlling Solar Light and Heat

In general, greenhouses may be allowed to have temperature excursions of 50^{o} F or so, circumstances most people tolerated in their homes and work places until about a century ago. In contrast, the research greenhouse has much lower thermal excursions (winter low of 50^{o} F when outside air temperature went to -18^{o} F; summer high of 90^{o} F) and soil temperatures stay within a few degrees of 65^{o} F throughout the winter.

We employ a variety of strategies to control solar flux in the R&D Greenhouse to optimize the environment for photosynthesis and healthy plant growth while controlling thermal losses and gains:

- Use moveable insulation that automatically insulates all glazed areas when solar light availability is low and energy losses exceed gains. Shutters automated to thermally seal the greenhouse envelope on cold nights enable the use of low-cost glazing that has both high Vt and SHGC. The R-13 shutter systems are equipped with outer surfaces that are over 90% reflective in the visible and highly reflective in the infrared spectrum. When fully open, the swinging shutters in the upper windows direct light downward to the earth and plants below. In addition, the shutter systems can be manipulated to reflect solar flux back outside to the degree desired. This helps to control for potential overheating in summer. (A small solar electric panel can charge batteries to operate the shutters without the capital and operating expense of purchased utility electricity and can be designed to provide sufficient charge for energy-efficient night-time lights for intermittent use when needed. Somewhat larger solar panels can be used to power intermittent fans.)
- Maximize light and heat gathered by windows with highly-reflective light shelves or roofing materials in front of south-facing glazing. (This also enhances light gathered from the sun in earlier and later portions of the day while reducing the glazed area required to meet plant growth and thermal needs.)
- Ensure that interior surfaces (other than growing media and plants) are reflective so that as much solar light as possible ends up being absorbed by plants themselves or areas that promote growth. (The glazed area of the research greenhouse is 474 square feet, 47% of the nominal footprint of the 1000 square foot structure, 20% of its insulated wall and

ceiling area. These numbers are substantially lower than conventional wisdom holds are minimums, yet the research greenhouse produces extraordinary growth rates of summer vegetables in mid winter.)

Performance Results and Key findings from the Research Greenhouse

Performance

Arugula, radishes, cucumbers, summer squash, basil, eggplant, sweet peppers, melons, carrots, rainbow chard, salad mix, and two varieties of tomatoes grew well in the first winter of operation. Figure 6 shows growth 54 days after seeding on Thanksgiving day in the first year of operation.

Figure 6. Growth in Research Greenhouse 54 Days after Planting from Seed

The team monitored soil temperatures at one foot intervals down to 4 feet at eight locations inside and outside of the greenhouse and at 9 places within the mass wall on the north. We also measured humidity, light, and soil and air temperatures from 24 other sensors in both the research greenhouse and a nearby hoop house of similar footprint, recording data at 15 minute intervals. Figures 7 and 8 show soil and air temperatures in both the research and hoop greenhouses versus outside air temperature.

Figure 7. 24 hour Period with Sunny day, Snow on Ground, Low 5° F, High 35° F

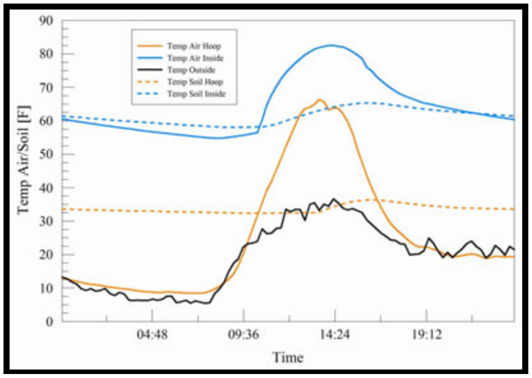
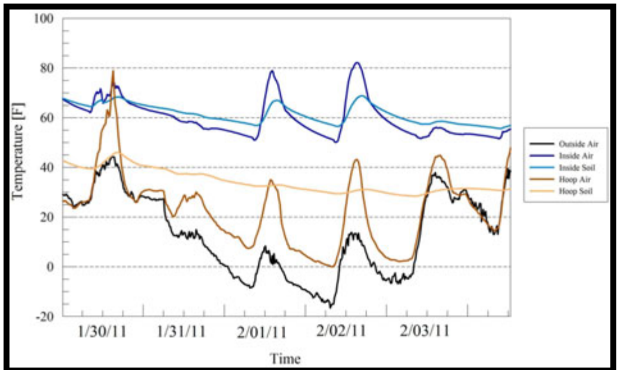


Figure 8. Five Cold Days, High 44° F, Low -18° F



The first shows a 24 hour period in mid winter; the second several cold days in which the outside air temperature dipped to -18° F. Note the relatively moderate temperature swings in the research greenhouse versus the substantially larger swings in the unheated hoop house. This reflects differences in thermal time constants.

Key Findings

The concept of well-insulated, tight structures, coupled to deep earth to achieve plenty of controlled mass, a greenhouse earth thermal storage (GETS) system, high SHGC fenestration, reflectors inside and out, and automated moveable insulation—is sound. It enables excellent wintertime growth performance with no back up for solar energy while using much less fenestration than conventional wisdom holds is necessary. Further, technologies like insulating shutters controlled manually and automatically appear likely to be broadly applicable not only to greenhouses but also to other building types, both new and retrofit.

These findings are gratifying—but we can do better. In particular:

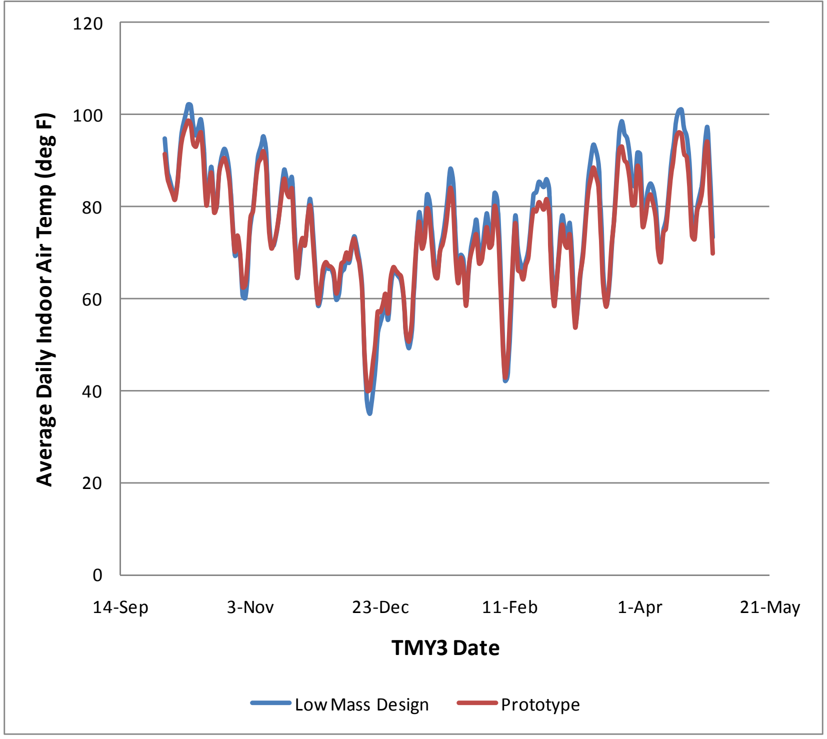
- Future designs should allow more sunlight, mostly diffuse, into the greenhouse during warm months;
- The next generation of shutters should employ fiberglass frames and better means to actuate them;
- Toward optimizing growth, future designs should continuously measure and automatically control parameters like CO2, humidity, temperature all year around; and
- Techniques for enhancing soil while it supports growth should be integrated into future designs—for instance, red worms are very adept at enhancing earth and pleasing plants!

Model for Future Designs

Co-author Michael Stiles constructed a mathematical model to simulate the effect of varying the mass in the north wall on the thermal behavior of a second generation greenhouse design (Stiles, 2012). The low-mass design alternative excluded the concrete blocks that the existing prototype incorporated into its northern wall.

The results of thermal mass simulations germane to second generation designs are plotted as simulated average daily interior temperature in Figure 9.

Figure 9. Simulated Average Daily Indoor Temperature for the Research Greenhouse



The low-mass design alternative excluded the concrete blocks that the prototype incorporated into its northern wall. Note that:

- Both use Denver, CO weather data; the two temperature trends are almost identical.
- Deviations are most notable at the peaks of both the warmer and colder months; the low-mass design is less damped at the peaks (as expected).
- The prototype as built reaches its lowest simulated average daily temperature of 40.0 ^{o}F while the low-mass version's minimum was found to be 34.8 ^{o}F

The results indicate modest temperature performance degradation without the extra mass. In both cases, the thermal time constant of the greenhouse is an order of magnitude longer than that of glazing-dominated hoop houses and similar greenhouses. Accordingly, the second generation greenhouses are being designed without north-wall concrete block thermal mass.

Projects Underway

Given these findings, we believe that the next generation of greenhouses should both work better and be as economically efficient as they are energy efficient. As of the present writing, five second-generation, super-efficient greenhouses are in various stages of design and development, ranging in size from a 250 square foot residential attached greenhouse to a 3000 square foot stand-alone commercial structure (Figures 10-12).

Figures 10 and 11. Rendering of SE Elevation (left); Nearing Completion, April 2012

Figure 12. South Elevation of 3000 ft2 Greenhouse, April 2012

Note that the roof windows are tilted 30 degrees, a feature that enhances direct gain throughout the year. White metal roofs contribute to solar gain as well, as do the extended light shelves outside the south windows. The second-generation greenhouses use three newly-designed insulating shutter types: sliders that can be on the inside or outside of the envelope and cover both fenestration and venting systems, "insider" swinging shutters (those within the envelope) for the upper windows that can span over 10 feet, and insider Bifold Lighting and Insulating Shutter Systems (BLISS) that reflect light from the window and light shelf onto plants below when open, and provide insulation when shut. All of the shutter systems add an extra R-13 to the R value of the fixed fenestration.

The light shelves, surfaces of the shutters, and inside walls and ceilings all employ thin white aluminum sheet stock whose total reflectivity in the visible is 92%. In addition to providing a well-sealed vapor barrier that is easy to clean, these surfaces reflect solar light and heat onto earth and plants. A new generation of electronic controls senses indoor and outdoor temperatures and light levels at the center of each bank of windows to control shutter operations. The aim is to optimize both plant growth and energy performance (Kinney *et al*, 2012).

Upcoming

We have demonstrated that it is possible to raise summer vegetables throughout the year in a somewhat severe climate using only the sun as a source of light and heat along with quite small energy requirements for control electronics, fan power, and motors to manipulate shutters. This modest demand may be met by a small stand-alone PV array. Furnaces and boilers are not needed, fans are small and have low duty cycles, and thus energy bills are tiny.

To be sure, there remains much to be mastered in optimizing plant growth and optimizing building details and driving down component costs while maintaining quality and elegance.

There appear to be ample opportunities for applying such technologies as earth coupling, insulating shutters and controls, daylighting, and novel ventilation schemes to residential, commercial, and industrial buildings. In addition, we envision applying the principles researched to the very broad sector of greenhouses, from cold frames (perhaps redubbed "tepid frames") to residential-size units to commercial greenhouses whose sizes are measured in acres.

Figure 12 shows an attached solar greenhouse that is coupled to the earth, has insulating shutters, and employs a small PV array. It uses the attached dwelling as thermal mass, supplying oxygen and winter heat while harvesting CO2. Figure 13 shows a half-acre commercial greenhouse that employs reflective roofs to enhance solar gain so fenestration areas can be relatively small. It employs excellent insulation, both moveable and fixed, and is earth coupled.

Figure 12. Attached Greenhouse

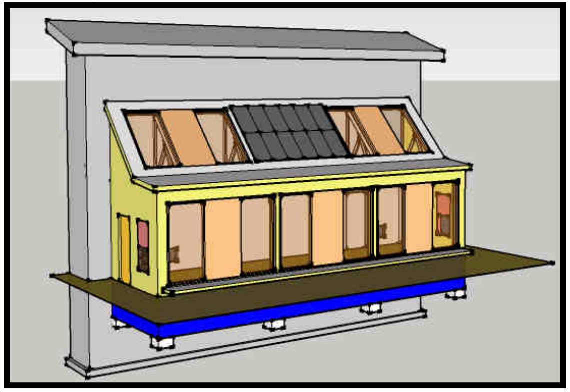
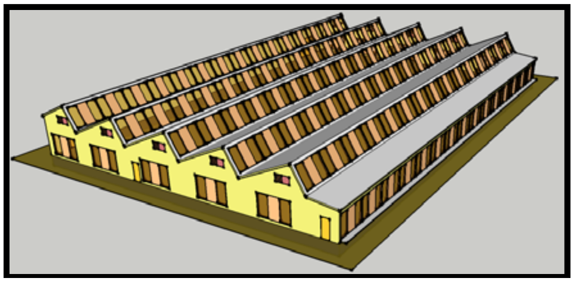


Figure 13. Conceptual Design of Commercial Greenhouse



These designs can benefit from economies of scale. Large greenhouses intended for commercial farms exhibit lower per-square-foot capital and operating costs than smaller ones, especially if designs are further simplified and additional cost-saving measures are implemented. An informal comparison of first costs, energy costs, and maintenance costs of existing 3000 square foot commercial greenhouses that use (1) energy-efficient designs described herein versus (2) conventional hoop-style house designs shows payback periods of less than ten years. This is quite conservative since it ignores the production of higher-quality produce throughout the winter, transportation energy savings, and the expectation of much longer lifetimes of the permanent energy-efficient structures.

We welcome collaborators to build on the strengths of our findings—and to help avoid shortcomings.

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