Final Report, Phase 2

Practical Green Greenhouse Development

A Joint Research and Development Project of

Synergistic Building Technologies

and

Cure Organic Farm

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Final Report, Phase 2

Practical Green Greenhouse Development

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 On the other hand, members of the team would be pleased to work in a professional capacity with those interested in following up on the findings and design concepts presented herein. All readers of this report are welcome to comment on its form and content. Please direct feedback to Larry Kinney, Project Director, at LarryK@SynergisticBT.com or at the address and phone below.

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Executive Summary

The Problem

Most of the food Americans eat, particularly in winter, endures trips of up to thousands of miles from the field to the table. Food destined for such journeys must be harvested well before it is eaten, packed for shipment, and jostled around in trucks (or even airplanes) on its way to distribution centers, grocery stores, and pantry shelves. The result is less-than-tasty-or-fresh 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 Colorado and many other states, this means greenhouses. Conventional commercial greenhouses must be heated with a good deal of fossil fuel energy—and many are lit with an array of grow lights. Even with this considerable energy use, when days are short, it is difficult to raise summer veggies whose not-so-fresh counterparts are trucked in from southern locales. So in one way or another, food has a large—and largely wasteful—energy/carbon footprint.

Promising Solutions

Toward seeking practical solutions to these complex problems of mediocre nutrition and profligate energy waste, Cure Organic Farm and Synergistic Building Technologies (SBT) of Boulder County, Colorado formed a team to address them with vigor. With co-funding from the Colorado Department of Agriculture for two phases of research, over the last three years, we have pioneered the design of super energy-efficient greenhouses that are both heated and illuminated by the sun. Both energy and growth performance are quite extraordinary. This document is the final report for the second phase of the research work.

Proof of Concept Success

Cure/SBT team designed, built, and instrumented a thousand square foot research greenhouse at the Cure Organic Farm. The building employs heavy perimeter, wall, and roof insulation; high solar heat gain windows; light shelves; automated insulating shutters that lower nighttime energy losses by a factor of 6; techniques for enhancing net solar flux falling on plants; large quantities of thermal mass; and three efficient air handling systems that ventilate the structure, toughen plants, and collect, store, and distribute thermal energy and moisture.

The first winter's performance both energy- and growth-wise was quite successful. The greenhouse went down to only 50F on the coldest night in Boulder in recent history, -18F—and the greenhouse temperature was up to 84F the following day. A dozen varieties of vegetables were planted from seed on Thanksgiving Day. Sprouting was immediate, growth vigorous, and many vegetables were harvested by early spring. Tomato plants are ten feet high and have been pruned several times; over a thousand tomato plants started from seed have been sold at local farmers' markets or transferred to surrounding fields.

Phase 2 Accomplishments

The first-generation farmer-friendly electronic controls SBT developed for the research greenhouse optimize energy performance, primarily by manipulating insulating/reflecting shutters and controlling a greenhouse earth thermal storage (GETS) system. The second-generation electronics substantially developed in Phase 2 of the research work control more functions (most wirelessly), perform monitoring tasks, and enable remote monitoring and control via the web. A simpler control system for smaller greenhouses was also designed.

A second generation of insulating shutters was also designed. These make use of frames fabricated using fiberglass pultrusions, stronger, quieter gear motors, enhanced reflectors, and thruster mechanisms housed in aluminum tubes that are protected from the dirt and moisture that are environmental realities in greenhouses.

These and other innovations prompted by practical wisdom flowing from findings with the research greenhouse were combined to produce designs for a new generation of greenhouses ranging from small attached and stand-alone greenhouses suitable for residential use to larger commercial units. Each design builds on strengths of research findings—and, we believe, avoids most shortcomings. Generation 2 greenhouses include better light gathering and distribution designs for high angle summer sunshine and smarter controls for air handling systems.

A good deal of attention was devoted to spreading the word about research findings and working with farmers and gardeners to assess their needs and adapt our designs to meet them—while ensuring the ability to grow wholesome food all year around while maintain a modest carbon footprint. We have been approached by parties interested in seeking our assistance in designing or supplying specialty systems for efficient greenhouses in Canada, India, New York, Kentucky—and Colorado. Such enthusiasm is gratifying.

Extensive documentation of the design, building process, and results of this research work is available both at www.Synergisticbuildingtechnologies.com under “Greenhouses” and from technical reports written by the team for the Colorado Department of Agriculture. As far as we know, there are no other greenhouse designs that have achieved the wintertime performance that the research greenhouse has demonstrated.

We can and should develop ways to improve the quality of the food we eat while minimizing the energy use associated with its growth and distribution. Feedback from all readers on the exciting and potentially paradigm-changing concept outlined in this report is welcome.

Section 1
Introduction

This is a contractually-required final report on a Colorado Department of Agriculture-supported research project funded under the Advancing Colorado's Renewable Energy (ACRE) Program. The project's overall aim is 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 fossil fuel energy.

The Phase 1 final report was delivered in February of 2011. Phase 2 of the project, which overlapped Phase 1, was launched in the Spring of 2010 and an interim report was delivered in November of 2010. Phase 2 objectives were to:

- Fully explore, extract useful information, and document the very rich data flowing from the R&D greenhouse;
- Develop electronic equipment to both *collect data* on greenhouse parameters affecting energy and growth and *automatically control* insulating shutters, energy storage, heating, ventilation, cooling, and watering;
- Enhance the design and increase the manufacturability of the moveable insulation systems;
- Develop designs of both larger and more cost-effective greenhouses that build on the most promising of the technologies pioneered in Phase I; and
- Undertake a range of technology transfer efforts to disseminate how-to-do-it information aimed at stimulating the adoption of energy-efficient greenhouses that produce quality food all year around.

Other project deliverables included a two-part interim report on Phase 1 work (the report was in both presentational and prose forms) and a videotape of the theory and construction of the research greenhouse at Cure Organic Farm and preliminary findings relevant to energy and growth performance.

This last report in the series covers:

- Work completed, preliminary findings, and key accomplishments since the Phase 2 interim report;
- Problems encountered and mitigating circumstances; and
- Next steps.

Feedback on both the form and substance of this report—or indeed the project itself—is most welcome.

Section 2
Work Completed, Preliminary Findings, and Key Accomplishments

Phase 2 Tasks

- Data collection and analysis of plant growth;
- Developing electronics for monitoring and control;
- Developing and testing enhanced shutter systems;
- Developing other scale greenhouse designs based from results; and
- Educational outreach of results.

Data collection and analysis of plant growth

Plant growth was documented extensively in the Phase I final report. This includes 12 varieties of vegetables, most summer crops. Most were harvested in February and March of 2011. Of particular consequence, approximately 1000 tomato plants were started from seed in late November, most in hanging pots throughout the greenhouse. Many were either sold at the local Farmer's Market in Boulder or planted in fields at the Cure Organic Farm. Some were retained in the research greenhouse. The entire back row is now filled with what have become perennial plants of several varieties that bear continuously. These have been trimmed back several times, but are still above the trusses over 10 feet from the ground (Figures 1 and 2).

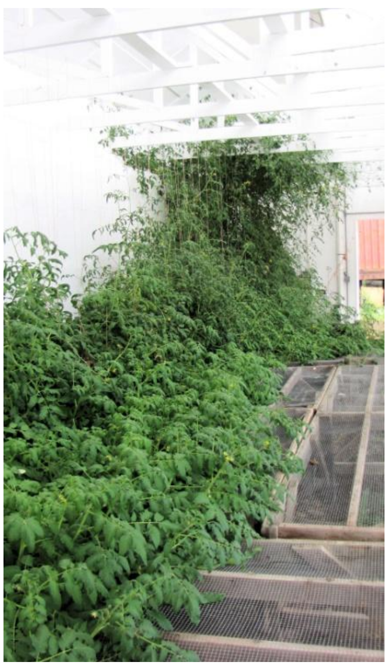

Figure 1. Tomato plants.

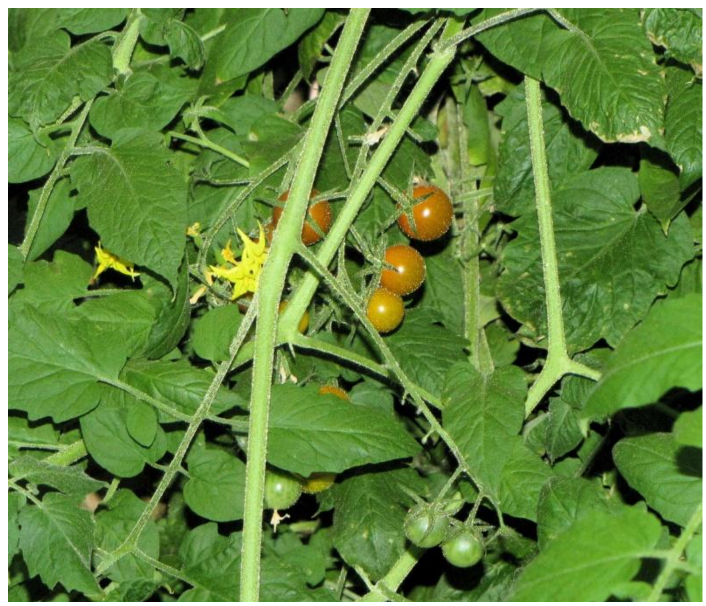

Figure 2. Small variety tomatoes at various stages of development, August 2011.

Measuring with Thermocouples

There are a number of parameters whose values change quite slowly, like temperatures deep in the earth and in other thermal mass. Thus, these may be measured infrequently, like once a week. Accordingly, we installed simple thermocouple systems inside the 2.5 feet thick concrete block wall on the north side of the building. Two sets of five sensors are placed from two inches from the inside to just outside of the 24 inch thick concrete blocks that constitute the inside of the mass wall. [The outside of the wall has two inches of Styrofoam blue board (R = 10) followed by 3 inches of polyisocyanurate (R = 18), then oriented strand board (OSB) and finally Grail Coat.] These sensors terminate in two-prong plugs that plug into a two-channel digital temperature meter.

In addition, we fabricated eight temperature-measuring stations by modifying two inch PVC pipes to contain five thermocouples for measuring soil temperatures at depths of zero to four feet below the surface at one foot intervals. The sensor ends of the thermocouples stick out of the sides of the plastic pipe while the insides of the pipes are filled with urethane foam. This prevents errors in temperature measurement that could result from convective loops inside the pipe. There is a 180 degree turn at the top of each station followed by a short length of pipe that may be screwed on or off. This arrangement protects the thermocouple plugs associated with the sensors from dirt, moisture, and rust. See Figures 3-5.

There are eight sets of these temperature measuring stations associated with the research greenhouse. Four are just inside the mid-point of the north, east, south, and west walls. Another four are on the outside of the greenhouse a few feet from the north, east, south, and west walls. All contain five sensors spaced at one foot intervals save for the temperature measuring station on the heavily-bermed north side. Instead, this station contains nine temperature sensors spaced at one-foot intervals so that the lower-most sensor on the north side of the research greenhouse has a soil depth that corresponds with the depth of the lower-most sensors in the other seven stations.

Figure 3. This set of 9 temperature sensors is installed in the soil on the outside of the north wall, which is heavily bermed.

Figure 4. This pipe is buried on the inside of the east wall of the greenhouse immediately adjacent to the Greenhouse Earth Thermal Storage (GETS) System.

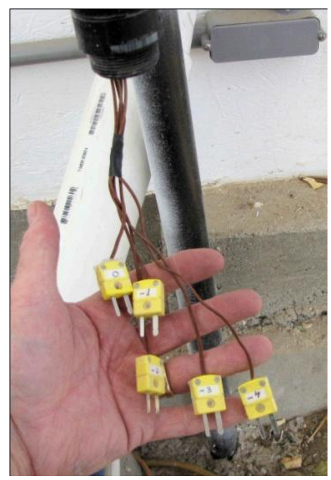

Figure 5. Plugs for the temperature sensors on east wall. On October 30, 2010, temperatures ranged from 71.6 at the surface to 63.0F; on August 10, 2011, they ranged from 82.5 to 69.9.

Table 1 shows a sample of outside temperature measurements by depth of soil taken on the north, east, south, and west from December 13, 2010 through April 6, 2011. Table 2 shows the same data taken on the inside of the greenhouse. Table 3 shows inside soil temperature data on August 10, 2011.

Table 1. Average outside temperature measurements of the soil surrounding the research greenhouse by depth and date in the winter of 2010-2011.

Date	-4 ft	-3 ft	-2 ft	-1 ft	0 ft
13-Dec-10	53	52	49	47	52
20-Dec-10	55	55	52	50	51
27-Dec-11	56	55	51	49	45
3-Jan-11	54	55	49	47	33
10-Jan-11	54	52	49	45	38
17-Jan-11	52	48	46	43	50
26-Jan-11	50	47	45	42	42
30-Jan-11	52	51	50	48	48
7-Feb-11	51	47	45	40	35
13-Feb-11	48	44	41	40	48
3-Mar-11	51	50	49	51	56
11-Mar-11	50	48	47	47	53
17-Mar-11	51	50	51	52	62
6-Apr-11	55	55	56	55	54
Average	52.3	50.6	48.6	46.9	47.6
St Deviation	2.30	3.56	3.65	4.49	8.26

Table 2. Average inside temperature measurements of the soil inside each of the four walls of the research greenhouse by depth and date in the winter of 2010-2011.

Date	-4 ft	-3 ft	-2 ft	-1 ft	0 ft
13-Dec-10	61	62	62	63	67
20-Dec-10	61	62	63	63	71
27-Dec-11	61	63	63	64	65
3-Jan-11	61	64	61	63	62
10-Jan-11	61	61	62	61	68
17-Jan-11	59	60	60	60	65
26-Jan-11	60	60	61	62	68
30-Jan-11	60	61	63	64	67
7-Feb-11	59	60	59	58	63
13-Feb-11	59	59	60	60	63
3-Mar-11	60	61	62	64	70
11-Mar-11	60	60	60	61	62
17-Mar-11	60	60	61	62	62
6-Apr-11	60	62	62	62	63
Average	60.1	61.1	61.4	61.9	65.4
St Deviation	0.77	1.38	1.28	1.77	3.08

Note in Table 1 that the outside temperatures at four feet underground vary quite moderately throughout the heart of the winter, averaging 52.3F with a standard deviation that is substantially lower than is the case with temperatures closer to the surface. Of course, temperatures descend as the surface is approached. The temperatures at 1 foot below the surface show a substantial (8F) drop between January 30 and February 7 owing to a cold snap when outside air temperature dropped to -18F on February 2. As indicated in Table 2, however, the inside of the greenhouse is much better behaved, as shown by the substantially lower standard deviations over time. Of course, fluctuations are higher as the surface is approached, just as with outside temperatures. Most important, note that the temperatures in the soil averaged above 60F throughout the winter at all levels.

Table 3. Measurements of inside temperatures in the research greenhouse on August 10, 2011

Ft below grade	North in	East in	South in	West in	Average	Std Dev
0	75.2	82.5	73.7	71.2	75.7	4.86
-1	68.8	81.1	73.2	68.3	72.9	5.92
-2	68.0	82.2	69.2	67.0	71.6	7.12
-3	66.2	73.0	68.1	65.3	68.2	3.44
-4	65.1	69.9	66.7	64.6	66.6	2.39
Average	68.7	77.7	70.2	67.3	71.0	4.75

In June, the research greenhouse doors were opened and shutters left open continuously. Note from the snapshot on August 10 that soil temperatures increased at all levels and as of the date of this report average 71F about 9F above the averages at the end of the winter; the soil at the surface is at 76F. This bodes well for the coming winter season; seeds are scheduled for planting in September. Note that the temperatures on the east of the greenhouse are a good deal warmer than are the others. This is due to the proximity of the probes to the input to the GETS system. Warm air from the top of the greenhouse is brought in close by and hasn't yet been cooled.

The first four feet of soil under the greenhouse measures about 4000 cubic feet. Let us assume that it weighs 92.6 pounds per cubic foot and has a specific heat of 0.27[1] This means that the soil represents a thermal mass of 100,000 Btu's per degree F that it is above air temperature. If it is 90 degrees colder outside than inside, the hourly heat loss of the research greenhouse with its shutters closed is only 12,630 Btu's per hour. So if it is -20F for 8 hours, the temperature of mass of the earth will diminish a degree or so F in maintaining the air inside the greenhouse at 70F. This ignores the effects of all other masses within the greenhouse, which are substantial.

It is this consideration that leads us to believe that the next generation of super efficient greenhouses will not need as much thermal mass in the north wall as does the research greenhouse. Nonetheless the mass of the north wall stayed in the mid 60F range all winter long and averaged 76F in mid August.

[1] Bulk soil density of 92.6 lb/cubic foot comes from the psu tables of construction material densities at http://www.abe.psu.edu/extension/factsheets/h/H20.pdf. The specific heat of soil of 0.27 Btu/lb °F is an average of wet and dry: http://www.engineeringtoolbox.com/specific-heat-solids-d_154.html

Shorter-term measurements

Of course, it is also useful to take shorter-term measurements of temperature distributions. A total of five four channel HOBO data loggers are used to record 15 minute data on temperature, humidity and light outside and inside the research greenhouse in both air and soil, as well at a nearby hoop-style greenhouse. Results from these measurements were shown in the Phase 1 final report.

However, in order to study faster-moving temperature changes, infrared sensing techniques are most useful.

Even simple scans using the IR temperature sensor can yield other interesting data. The mass wall on the north (which contains 58 concrete blocks weighing a total of 102 tons) serves as a giant thermal fly wheel: it heats slowly and it cools slowly. Its wall is insulated on the outside by material whose R value totals about 30. The adjacent walls on the east and west have an R value of close to 40, but far less mass. Both are painted with the same primer and high-gloss finish paint, a total of five coats all of which are white (to facilitate reflecting light onto absorptive surfaces such as earth and plants.) When patches of direct beam sunlight strike each surface, however, the concrete on the north surface is heated only a degree of two, whereas the east surface is heated by more than 10F. Of course, it cools faster as well. See Figures 6 and 7.

Figure 6. Northeast corner of greenhouse at about 5 feet above the ground. The single-axis IR sensor is looking at the patch of direct beam sunlight falling on the concrete on the north wall; it measures 83F. Indoor air temperature is 81F.

Figure 7. Same location as Figure 6, only the IR sensor is looking at the patch of sunlight falling on the OSB on the east wall. It measures 92F.

The less massive wall is like a hot rod with worn out shock absorbers on a bumpy road; it heats faster but cools faster as well. The massive wall runs like a Lincoln on autopilot on a super highway; it is blandly indifferent to the goading contingencies of the moment!

GETS System

The primary aim of the Greenhouse Earth Thermal Storage (GETS) System is to keep the greenhouse from getting too hot during the day without venting the greenhouse (and wasting heat that could be used on long winter nights) since warm moist air is cooled by the soil. In turn, the soil is both heated and moistened, thereby diminishing the effects of cold nights and ultimately lowering the amount of irrigation needed to support growth. Heat transfer is maximized when the warm moist air from the top of the greenhouse is cooled by the earth to the dew point, causing condensation. This results in transferring a good deal of energy and moisture to the soil while cooling and drying air released back into the greenhouse at plant level.

When the temperature at the top of the greenhouse goes to 80F or above, a thermostat calls for the GETS fan to come on. This pulls warm, moist air from the top of the greenhouse through a 3 inch PVC pipe via a squirrel-cage blower attached to the top of a plenum at ground level. The plenum distributes the air to eight 4-inch diameter styrene plastic drainage pipes that average 50 feet in length. The pipes have ridges that give them both rigidity (with respect to their diameter) and flexibility (with respect to their length). The pipes are laced with holes that allow moisture to drain to the surrounding soil (Figure 8.)

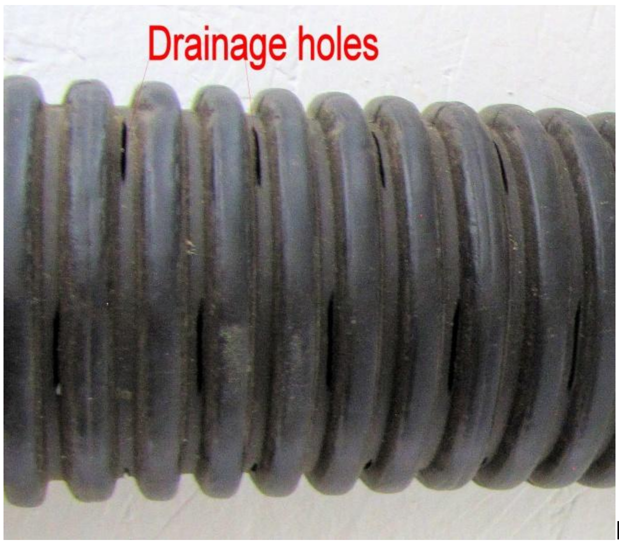

Figure 8. Styrene drainage pipe.

The pipes are covered with loose nylon “socks” that impede the flow of small creatures and dirt. Importantly, damp socks in contact with the surrounding earth, in combination with the ridges in the pipe itself (which promote turbulent air flow, a virtue in this case) result in good heat transfer from the moving air to the earth. This cools the air and warms the earth when the air at the top of the greenhouse is warmer than is the earth. At night, when the air in the greenhouse is colder that the air in the earth, actuating the GETS fan warms the air to earth temperature, thereby warming the greenhouse.

The pipes are buried from 1.5 to 3.0 feet deep on two foot centers and stretch the 50 foot length of the research greenhouse. Their total volume is 38 cubic feet, surface area 450 square feet. The input pipe is at the top of the greenhouse at the far southeastern end and the fan and distribution hub is at ground level at the center of the east end. At the far west end of the greenhouse, each set of four perforated pipes is connected together to solid 3 inch diameter PVC pipes that direct air back above ground. The two solid PVC pipes at the northwest and southwest corners terminate in elbows that direct air at plant level toward the east. Quarter inch mesh screens are installed on pipe ends.

Jerome Osentowski of the Central Rocky Mountain Permaculture Institute (CRMPI) located near Basalt, CO at 7,000 feet above sea level is a pioneer in systems that charge the earth under greenhouses with air blown in from the air above; he terms them “Subterranean Heating and Cooling Systems (SHCS). His greenhouses use two thermostats to control the fans. They are set to turn on when the temperature of the air at the input is 80F and higher (which cools air and heats the soil) and at 50F and lower (which heats air and cools the soil). See www.crmpi.org.

Since the temperature at the top of the research greenhouse at the input to the GETS system has never descended to 50F even on the coldest nights of the winter (-18F outside temperature occurred on Feb 2, 2011), we save fan power and the earth mass remains at higher temperatures. Of course, since the mass stays well above 60F, when greenhouse air temperature goes below the temperature of the mass, it is heated by radiation, conduction and natural convection by the mass of the earth. If one counts only the top four feet of the earth mass we currently measure, it stores about 100,000 Btu for each degree F it is warmer than is the air of the greenhouse.

The original monitoring system consisted of a wireless sensor that measures both temperature and humidity at the input of the GETS with temperatures being measured both at the distribution plenum and at output pipes by thermocouples and a single-axis infrared temperature sensor. This has been supplemented by a pair of four channel HOBO data loggers that collect and record data at 15 minute intervals. The one at the top of the greenhouse records temperature and humidity at the input to the GETS at the top of the southeast corner and temperature 25 feet away at the center of the top of the south wall. The second HOBO measures temperature and humidity at the exit air port near the ground at the northwest corner of the greenhouse and temperature at the exit air port near the ground at the southwest corner. A third HOBO data logger records GETS fan on and off times to the nearest second.

At present, monitoring consists of using a wireless sensor of both temperature and humidity at the input of the GETS with temperatures being measured both at the distribution plenum and at output pipes by thermocouples and a single-axis infrared temperature sensor. Indoor temperature and relative humidity is monitored by a Radio Shack weather station. Figures 9-16 illustrate.

Figure 9. Wireless temperature and humidity sensor installed adjacent to the input to the GETS System at the top of the greenhouse, 18 feet from the floor.

Figure 10. The IR sensor measures 111F in mid afternoon October 30, 2010. At the same time, the wireless sensor measures 103F at 20% relative humidity. The difference is that the IR sensor reads *surface* temperature, while the wireless sensor measure *air* temperature and relative humidity.

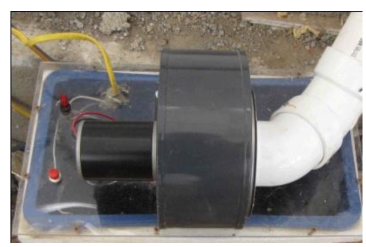

Figure 11. GETS system input pipe. Half an hour after actuating the fan, the outside of the input pipe at the fan had moved from 82F (room temperature at the floor of the greenhouse) to 96F at its surface.

Figure 12. GETS System in shop illustrates the distribution of air to eight pipes buried in greenhouse soil.

Figure 13. Inlet pipe at southwest corner, top of greenhouse with thermostat and HOBO data logger; wireless temp and humidity sensor is also used.

Figure 14. Outlet pipe at northwest corner of greenhouse. The IR sensor measure inside of the surface, 83F. The thermocouple whose sensor is at the center of the emerging air stream measures 65F.

Figure 15. HOBO at outlet pipe at northwest corner. Gray wire goes to outlet pipe at northeast corner.

Figure 16. 12 Vdc battery charger modified to run motor for squirrel cage GETS fan. Auxiliary electronic board on inside makes thermostat in Fig 13 call for "cool" instead of heat.

Measurements of GETS performance with the greenhouse open during summer months are not very useful. Nonetheless using the sensors described, a number of useful inferences can be drawn. First, the structure has over 20 to 30 degree F temperature difference between the floor and peak of the ceiling on sunny afternoons (but very little temperature stratifications when the sun is not out, a characteristic of very well insulated and air sealed buildings.) No matter what the entering temperature is, the exit temperature is within instrument error of the soil temperature. This means that the heat transfer of the air to the soil is the maximum possible for the flow of air in the research greenhouse. This is good, but suggests that a higher velocity fan could undoubtedly store more heat in the mass of the earth, as well as cool the top of the greenhouse more effectively that it presently does.

Nonetheless, a net of over 12,000 Btus per hour can be stored by the GETS system as it is presently configured in the research greenhouse even under the circumstances of quite low relative humidity. This calculation accounts for electricity use to supply fan power (Figure 17).

Figure 17. The digital electric energy meter at the research greenhouse records total kWh used for all purposes since June 1, 20ll. This photograph was taken on August 10, 2011, 71 days since the meter was installed; the reading is 37 kWh which at $0.10 per kWh cost $3.70. The temperature has not gone above 88F in the greenhouse over the summer, so there has been no need to run the 5000 cfm exhaust fan which draws 538 watts. Electricity use has been for the GETS fan and the monitoring and control electronics plus a touch of auxiliary lighting at night. Installed lighting consumes 200 watts (0.2 watts per square foot) and produces 14,000 lumens.

Developing Electronics for Monitoring and Control

The main electronic control box designed by the research team contains a ten ampere-hour 12 Vdc battery that powers the electronics and the gear motors associated with the 28 insulating shutters it controls. A large bat handle switch turns on or off main power, illuminating a green light emitting diode (LED) when on. The battery may be charged by either a small photovoltaic cell or by a 12 Vdc power supply (commonly termed a “wall wart”) that plugs into a conventional 117 Vac outlet. An analog dc ammeter near the main switch records net current flow from the battery. The battery is protected by a 40 ampere fuse and each shutter circuit by smaller slow-blow fuses.

Twelve devices controlled are “pocket” shutters on the south wall of the structure and another 12 are “swinging” shutters on the roof of the greenhouse. Each of these shutters is configured to be operated either automatically or manually via operating a switch on the control box. In the automatic mode, the pocket shutters that are switched to “auto” are all operated simultaneously to open or shut fully. They are switched in response to an algorithm whose weather-variable inputs are outside air temperature (from a sensor on the north wall underneath the gable) and solar radiation (from a radiometer mounted between shutters 6 and 7 on the south wall half way up the glazing.) In the “manual” mode, each of the pocket shutters may be operated independently from the others and be opened or closed to the extent chosen by an operator. The pair of switches associated with each shutter (auto/manual; open, off, shut) is also associated with a pair of LEDs, yellow for opening, red for closing).

The 12 swinging shutters on the roof are configured in exactly the same way, but employ a separate electronic board because of differences in solar heat gain and U factor of the fenestration.

The control box and associated work table hang on the east wall of the greenhouse. The control box is protected by a swinging Plexiglas cover which enables the user to monitor switch positions and current draw without having to open the protective cover. When not in use, the work table is allowed to hang below the control box parallel to the east wall. When needed, it hinges upward where it is held parallel by a hinged support mechanism itself stowed against the wall when not needed. Finally, when it is necessary to access the circuitry at the bottom of the control box, it can be swung down and rested on the middle of the work table (Figures 18-20.)

Figure 18. Control box with folded work table. Box measures 12 x 17 inches; the table is 4 feet long.

Figure 19. Lowering control box onto table.

Figure 20. Control box in operational mode. There are two switches and two LEDs for each shutter.

Phase 2 work included two other developments. The main work was to design a system for controlling shutter motors, fan actuators, back-up light controllers, and the like so that control and monitoring can take place from a central location such as laptop or notebook computer or dedicated controller. The system designed allows for signals from local control boxes and the central controller to be sent back and forth wirelessly. This raises reliability and lowers the cost for installation and maintenance. It also allows for flexibility in adding components, sensors, or auxiliary control systems simply, quickly, and cost effectively without the need to add hardware at the front end. Features include:

- Individual shutter control without home runs of cabling (simple-to-install 12 Vdc lines from a battery charged by a simple PV system are run from local control box to local control box);
- Inrush current limiting for each motor (to minimize starting current surges and maximize motor life);
- Inrush current staggering (to control peak demand on the battery and associated wiring when a number of motors are started at about the same time);
- Over-current protection to prevent problems from short circuits or stalled motors;
- Open load detection (from a disconnected motor or burnt out light, for example);
- Ability to easily use hall-effect or magnetic switches that are simple, reliable, and able to withstand high-humidity environments over a long life; and
- Ability to easily add distributed sensors into the network (light, temperature, humidity, CO2 inside or outside the greenhouse) without their own home runs.

The current design includes the ability to both ***record*** a number of parameters relevant to greenhouse performance (outside, inside, and soil temperatures, humidity, CO2, shutter, fan, and door configurations) and to ***act*** on the values of key parameters by changing shutter configurations, vent settings, fan flow, or auxiliary lighting. The algorithms that make decisions on configuration changes in the greenhouses when in the automatic mode can be changed in a user-friendly manner, either at the controller itself, or remotely via the web. In addition, in case of circumstances that require maintenance, the main controller has the capability of setting a flag and contacting designated people via text message or email.

Most of these functions have been designed into the hardware and software developed under Phase 2 and much of it has been tested for feasibility and debugged (Figure 21). However, developing the system to the point of being fully ready for the market place will take other resources that were not available under the current grant.

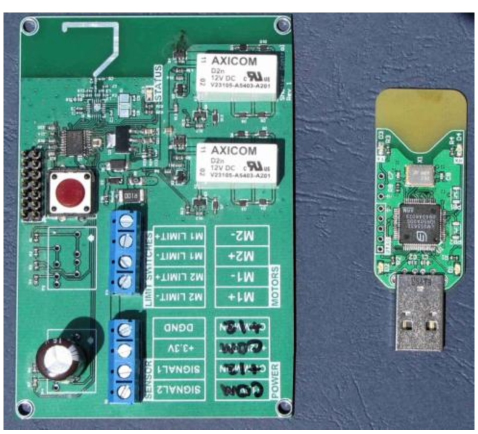

Figure 21. Prototype electronic boards developed under phase 2. The board on the left can control two gear motors. It communicates wirelessly with the board on the right which plugs into a USB port on the main controller.

We also designed a simpler system for actuating insulating shutters either manually or automatically. In the automatic mode, information from light sensors is used to feed inputs to operational amplifiers set up as comparators. These are adjusted to respond to user-determined thresholds of suitable light levels for opening and closing shutters, with adequate hysteresis to establish a dead band between the two. The outputs may control one or a set of gear motors depending on switch settings. Circuitry for ensuring soft starts for the motors is also included in the simpler controller. As with the controller built for the research greenhouse under phase 1, the simpler controller uses light emitting diodes to signal shutter status. The user can also switch between auto and manual modes for each shutter (or set of shutters) and open and close shutters to the degree desired in manual mode.

Developing Enhanced Shutter Systems

The pocket shutter design for the south wall of the greenhouse uses a pair of single glazings of high solar heat gain coefficient (SHGC) separated by several inches that allow for rigid board insulation to slide between them on cold nights or when summer or winter weather conditions indicate that extra insulation is desirable. When not in use, the rigid insulation is stowed in an insulated pocket immediately adjacent to the glazed area. The pocket may be above, below, to the right, or to the left of the glazing. In the research greenhouse, the glazing is below the pocket. Figure 22 shows an October 2010 photo of the south elevation.

Figure 22. South elevation of research greenhouse. Upper "swinging" shutters are all open; three of the pocket shutters are closed. Areas behind green colored façade are pockets. The glazed areas are R-2 when shutters are in pockets, R-12 when shutters are between glazings. The pockets have an R of 25 when the shutters are between glazings; R = 38 when shutters are in pockets.

As part of Phase 2 of this project, the design team experimented with several versions of a second generation pocket (aka sliding) shutter. The Generation 2 Automated Pocket Shutter serves two glazing areas with a pair of insulators that occupy a single pocket when solar flux through the glazings is not available or desired. One small gear motor operates the pair of shutters simultaneously thanks to ball bearing slides that minimize frictional losses when opening or closing. A fiberglass frame provides rigidity, light weight, low conductivity, long life, and modest cost (after the cost of pultrusion dies has been amortized.)

The team built and accomplished mechanical testing on a prototype that measures 3 feet high by 4 feet wide, a size chosen to be small enough to facilitate shipping on an airplane for demonstration at conferences, yet large enough to illustrate optical and mechanical properties of the design.

We anticipate that the full-scale version of 100 square feet can accommodate PV or solar thermal panels on the front of the pocket. When installed in association with a white roof or light shelf the result would both enhance solar gain through the glazing to support growth in the greenhouse and improve the system efficiency of the PV or active solar system. The Generation 2 system may be mounted on walls or roofs, where it may be tilted or vertical. The concept includes incorporating wireless electronics to enhance plug-and-play installation on new or retrofit greenhouses, both large and small.

Figures 23-25 show photos of the prototype.

Figure 23. Back of shutters in fiberglass frame before pocket complete.

Figure 24. On bench during fabrication, shutters closed, front view.

Figure 25. Controls for the demo model allow for charging the on-board battery, switching between auto and manual mode, and controlling shutters via a wireless remote or manually via the top switch.

A second version of sliding shutter was also designed under phase 2. It uses fiberglass frames, an enhanced gear motor, simpler techniques for guiding the insulating shutter, and thin metal reflectors on the inside and out to enhance reflectivity and ensure long lifetimes. This shutter can also be configured in a number of ways and will work in conjunction with different glazing types and frames (Figure 26.)

Finally, the second generation swinging shutters have been refined to also include fiberglass frames and enhanced reflectors. In addition, a “thruster” has been designed to protect key components of the drive mechanism whose motor has also been upgraded. As a result a single thruster will be able to manipulate several swinging shutters at once, thereby saving cost and improving functionality (Figure 27.)

Figure 27. This "show-and-tell" model of a second generation sliding shutter has a see-through feature to show the gear motor. It will be replaced by a simple access door in production models.

Figure 27. The new drive mechanism for swinging shutters improves reliability and lowers system costs.

Developing other Greenhouse Designs

The key design principles explored under this project include:

- Employ heavy perimeter, wall, and roof insulation;
- Integrate as much thermal mass into the conditioned envelope as practical;
- Control the flow of solar flux, both light and heat, by maximizing solar input through high solar heat gain windows, using automated insulating shutters to limit thermal losses when sunlight is unavailable or unneeded;
- Control temperature, humidity, and water using passive methods as possible and active ones when appropriate—"Build tight, ventilate right" applies to greenhouses as well as to other building types; and
- Optimize all of the systems and associated controls of the greenhouse to enhance plant growth.

From the perspective of the date of the preparation of this final report—nine months after the building was completed and first seeds were planted in November of 2010—we find that adhering to these principles is indeed quite useful in achieving efficient, successful greenhouses.

In particular, 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 using much less fenestration than conventional wisdom holds is necessary. Further, we found that technologies like insulating shutters controlled manually and automatically is likely to be broadly applicable not only in greenhouses, but also in other building types, both new and retrofit.

These findings are gratifying--but we can do better.

A great deal of practical wisdom of the kind that only flows from measuring, observing, tweaking and measuring again has been gained on this research project. 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 of parameters like CO_2, humidity, temperature all year around.

- Techniques for enhancing soil while it supports growth should be integrated into future designs—red worms are very adept at enhancing earth and pleasing plants (Figure 28).

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.

Figure 28. Only half jokingly, Jerome Osentowski of CRMPI claims that the key aim of a greenhouse should be to produce great soil—crops are just by-products! Here's a sample from one of his greenhouses.

Under the "develop new greenhouse design" task, the team examined options for attached solar greenhouses suitable for new or (especially) retrofit applications, modest size stand-alone residential and small commercial structures, as well as large stand-alone commercial greenhouses on the other.

Attached Solar Greenhouses

The Weatherization Assistance Program has been in existence since 1974, making it the longest-running federal effort in energy conservation programming in the history of our republic. It was initially sponsored by the Community Services Administration before the U.S. Department of Energy was established. It is now co-sponsored by the USDOE, the US Department of Health and Human Services, and by a host of utilities and state-and-local agencies across the nation. Recently, the Weatherization Program has been a major beneficiary of the American Recovery and Reinvestment Act of 1999 (the ARRA Program), which quintupled funding for many of the more than 900 local weatherization agencies in the US. Before ARRA, Weatherization focused on retrofit energy efficiency measures in single and multifamily housing through air sealing, insulating, enhancing heating, cooling, and hot water systems, lighting replacement, refrigerator replacement, and energy education. Presently, a number of local weatherization operations are considering adding such new arrows to weatherization's quiver as active and passive solar heat for space conditioning, enhanced fenestration systems, and both solar photovoltaic and domestic hot water solar systems.

Given this background, it comes to mind to develop attached solar greenhouses that are within the capability of local weatherization operations to install during the weatherization process. The aim would be to enhance the overall energy performance and comfort of a newly-weatherized home while providing enhanced indoor air quality and the opportunity to produce home-grown fresh food. The result should dramatically lower energy bills and carbon footprints while giving new life to older housing stock and enhancing its usefulness and livability.

The illustrations associated with Figures 29-32 represent preliminary design features of attached solar greenhouses that should perform well.

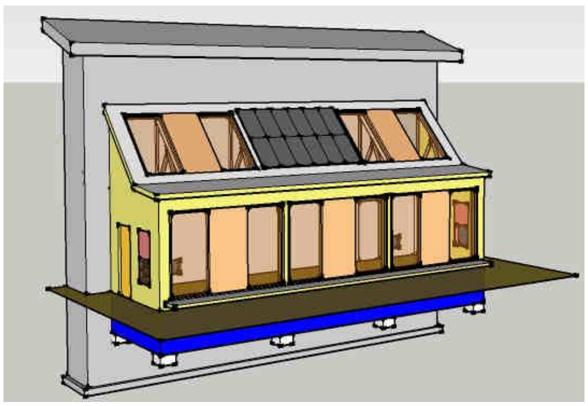

Figure 29. SSE elevation of an attached solar greenhouse, nominal dimensions of 36 feet wide by 12 feet deep. Note earth coupling with heavy perimeter insulation to supply mass, three Generation 2 Shutters on the south side; two on the roof at 45 degrees. Light shelves in front of the vertical glazing and a white roof enhance solar gain both to growing spaces on the interior and onto the PV or solar thermal array.

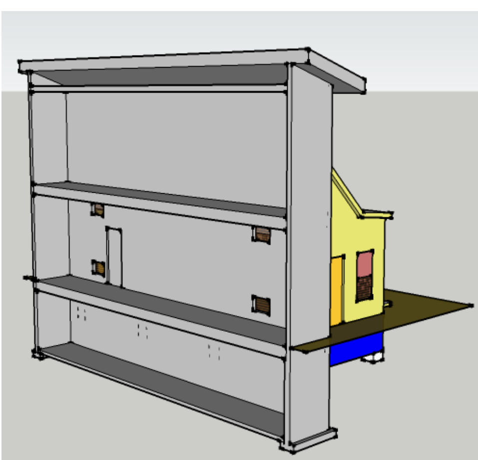

Figure 30. Existing home with greenhouse attached. Note pairs of openings to the greenhouse. These incorporate smart dampers that allow air exchange between home and greenhouse in response to the energy and air quality needs of both. Solar heat is usually adequate for both structures in much of the winter, and plants welcome carbon dioxide from residents, as residents welcome oxygen from growing plants. The earth under the greenhouse and the home itself provide thermal mass to moderate temperature swings. Fixed and moveable insulation also plays a key role in overall system efficiency, growth, and thermal control. Filters on openings discourage insect flow while improving air quality.

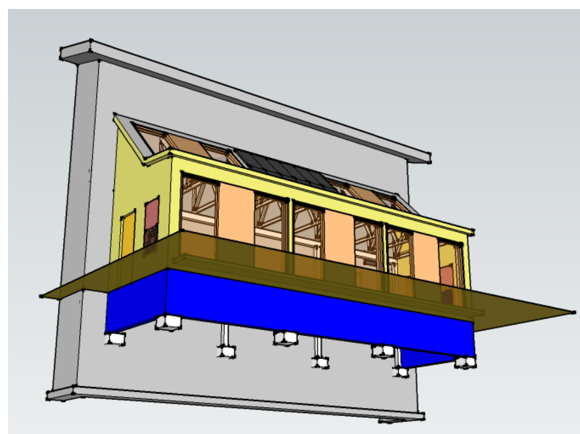

Figure 31. Perimeter insulation detail. In most climates, four feet below the surface is adequate. A thermal bubble will build up so that the second winter's energy performance is likely to be better than that of the first. Note poles on concrete pads. These constitute the main elements of the pole-barn-style framing for the greenhouse and may be of environmentally-appropriate treated wood or steel.

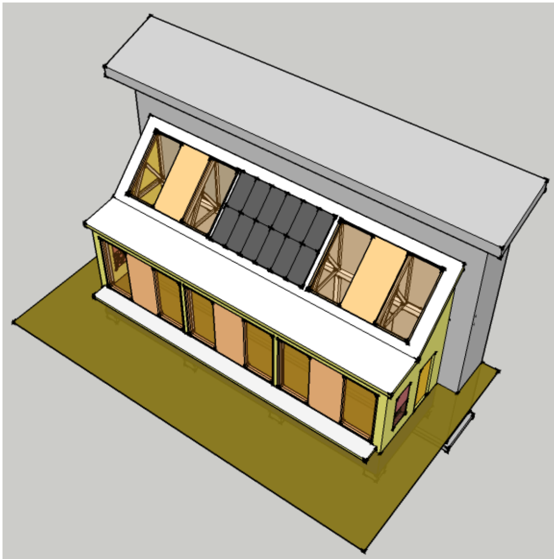

Figure 32. Aerial view illustrating the reflective properties of the roof and light shelf. The light shelf can be extended and may also be hinged. Adjustments every month or two (depending on seasons; more frequently toward the equinoxes, less frequently toward the solstices) enhance the effectiveness of solar radiation.

Of course, lots of variations on the theme are possible, both for greenhouses designed for weatherization programs and for other residential housing stock, both existing and new. Figures 33 and 34 show a conceptual design for a nominal 400 square foot stand-alone greenhouse. Designed as a zero-energy structure capable of growing food all year around via both perennial and annual plants, we envision that most components can be fabricated in an off-site factory while a shallow foundation, GETS system and associated perimeter insulation is installed on site. This would enable efficient assembly on site, erecting wall, roof, and fenestration in two days or so.

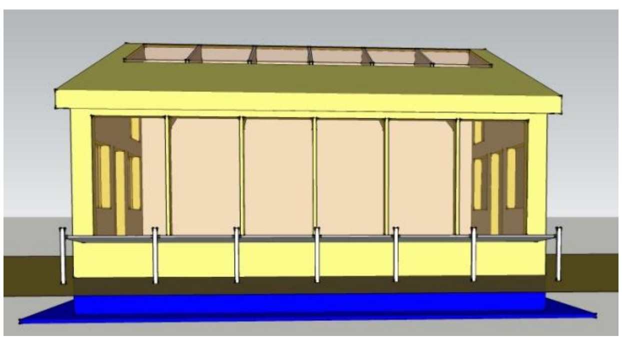

Figure 33. South elevation of 400 square foot stand-alone greenhouse. Note perimeter insulation below grade shown in blue. Four varieties of moveable insulation are under consideration for the vertical glazing on the south wall.

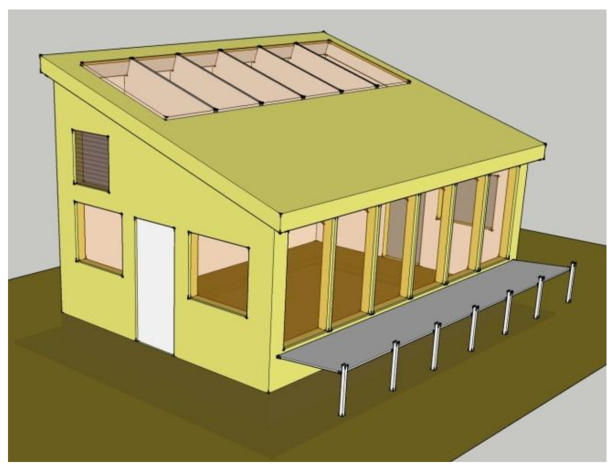

Figure 34. Southwest elevation. The space below the roof between the lower edge of the roof fenestration and the south wall houses automated sliding shutters that raise the insulating value of the window areas to R-12 + at night or other times as needed. The rooftop can also accommodate photovoltaic or solar thermal collectors.

Medium size greenhouses

Greenhouses to support the vegetable needs of community groups or are useful in getting plant starts for an organic farm, for example, are of increasing interest. Figure 35 shows a rendering of a 2200 square foot greenhouse capable of producing all year around.

Figure 35. This 2200 square foot greenhouse could be located on flat ground or on a south-facing slope. In employs three varieties of automated shutters.

Larger-Scale Commercial Greenhouses

As greenhouses get larger, the importance of solar light from the roof predominates over light from the sides. Accordingly, designers have more flexibility with the shape of the footprint of the building. On the other hand, ensuring that both fixed and moveable insulation in the roof is substantial is all the more important, particularly since temperatures at the top of the insulated envelope tend to be high, and energy losses are a direct function of indoor/outdoor temperature differences. Further, the principal element of thermal mass is most usefully the earth under the footprint of the building, whether the building uses a slab, bare earth, or a combination of the two. Accordingly, good commercial greenhouse designs include heavy perimeter insulation. Variations on the theme of GETS Systems are also cost effective even in greenhouses whose dimensions are measured in acres (where an acre is 43,560 square feet).

The sketches in Figures 36-38 illustrate a half-acre, energy-efficient commercial greenhouse.

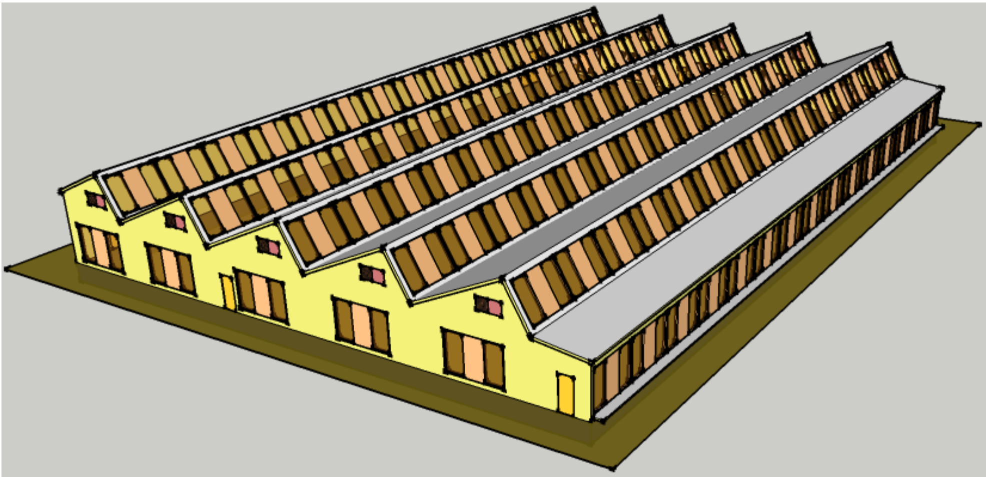

Figure 36. Five tiers of south-facing Generation 2 Shutters adorn the roof of this nominal half acre greenhouse; variations are possible. All but the front row are optimized to profit from the slope of the reflective roof in front of it; the front row has a slightly down-sloped roof to shed water. The building blocks shown can be used to expand the building as desired.

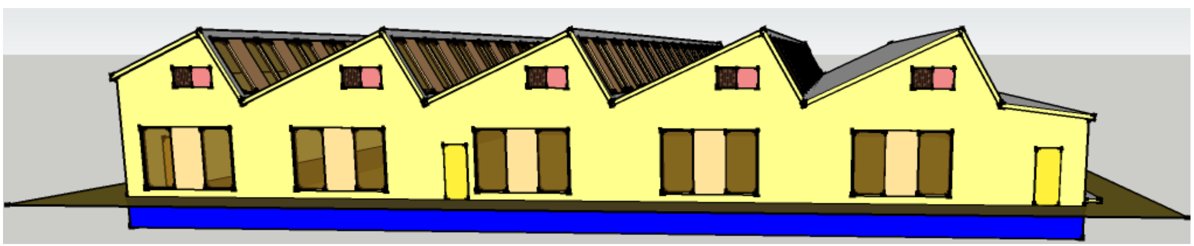

Figure 37. West elevation. A set of Generation 2 Shutters are on both the east and west facades. However, the fenestration in the roof could use swinging shutters if desired, choosing glazing to meet local climate trade offs between high solar heat gain coefficients and low heat transfer coefficients (U values) versus outside temperatures. The blue at the bottom indicates heavy perimeter insulation. The design envisions a heavily-insulated steel-framed pole barn.

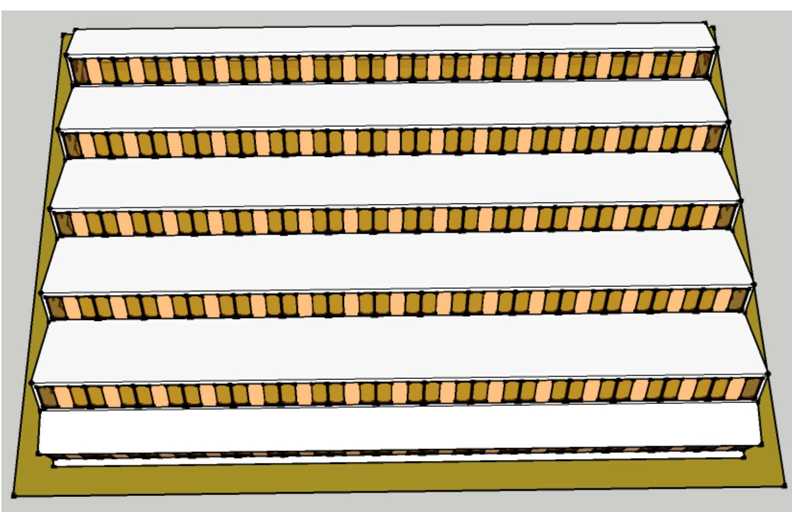

Figure 38. South elevation, aerial view. This perspective is meant to illustrate the central importance of reflective surfaces in enhancing the net SHGC of the fenestration in commercial greenhouses. There is R-30 or more of insulation under each reflective surface, which with moveable insulation of R-14 used at night is key to limiting thermal losses. Yet there is plenty of

light to support growth and solar heat to maintain desired temperatures while nonetheless using much less overall glazing than conventional wisdom holds to be necessary.

Again, many variations on the theme are possible, and controls of shuttering, the GETS System, and fans are critical design elements in matching resources to local climate circumstances.

Educational Outreach of Results

There is a great deal of interest in this project—and longer-range potential for energy-efficient greenhouses—both in the Boulder area and well beyond. In part this is due to outreach efforts by both the project team and by the Colorado Department of Agriculture. Both SBT and Agriculture Department website have information on the project, including illustrated write ups, reports, a video, and a brochure. The main brochure on the project has now been distributed to over 1100 people.

In addition to these outreach efforts, Larry Kinney gave two presentations at the National Cohousing Conference held in June 18-20, 2010; one on retrofitting for near-zero energy, the other on energy-efficient greenhouses suitable for cohousing projects.

In June 2010 Gardner Clute gave a presentation on the Research and Development Greenhouse at the Colorado Renewable Energy Society's annual conference in Montrose, CO.

In addition, Larry Weingarten and Larry Kinney presented a poster at a session of the Summer Study on Energy Efficiency in Buildings put on by the American Council for an Energy Efficient Economy near Monterey, California in mid August, 2010. The theme of the poster was insulating shutters. The SBT Team showed the Generation 2 prototype discussed above and explained its potential use in greenhouses of various sizes and in other buildings. Feedback was favorable.

A photo of the set up at the conference is shown in Figure 39.

Figure 39. Larry Weingarten and Larry Kinney with new shutter prototype at ACEEE conference.

An article entitled *Growing "Green" Food* by Anne Minard appeared in the August 2010 edition of Home and Garden Magazine, with the following introduction: "The nation's first net-zero greenhouse is being built and tested at a local organic farm by a Boulder firm, which hopes to develop it for residential applications so homeowners can grow vegetables year round—without the associated astronomical energy costs." This article prompted conversations with at least a dozen interested people, many of whom visited the greenhouse.

In October of 2010, a group of about 30 representatives of the Boulder chapter of the Association of Energy Services Professionals (AESP) had at tour of the research greenhouse and brief talk about its key features and aims.

More recently, in August 2011, Larry Kinney and Gardner Clute presented a comprehensive report on the conception, execution, findings, and future of the concepts associated with this research project in general and the greenhouse in particular at a 1.5 hour "brown bag" lunchtime workshop in Boulder. Sponsored by the Boulder Green Building Guild, it was attended by about 40 people, many of them professionals in the green building field. The following evening, the project team had a four hour open house at research greenhouse site at the Cure Organic Farm (Figures 40-41). It was also attended by about 40 people, about half of whom had not attended the brown bag gathering of the day before. Both of these sessions received warm feedback from attendees. There is clearly a strong interest in energy efficient greenhouses able to raise vegetables all year around using only solar energy for wintertime space conditioning.

The project team is continuing to spread the word, including marketing design-and-build services to potential customers that build on the strengths of project findings.

Figures 39 and 40. SW elevation of greenhouse mid August 2011. The information box near the west entrance contains brochures on project findings. The brochure may be downloaded from the "Greenhouses" page of the Synergistic Building Technologies web site, www.SynergisticBT.com

Section 3
Problems Encountered and Mitigating Circumstances; Next Steps

The construction of the greenhouse met with a number of delays, but the tasks associated with both phases of the grants from the Department of Agriculture are now complete.

It has been an exciting and very worthwhile trip.

Of course, data gathering, planting and harvesting, and a number of tweaks to various systems will continue. The research greenhouse remains a treasure trove of potential findings and a test ground for fresh ideas as well as fresh veggies. We envision continuing to learn even as attention turns primarily to producing food—and even flowers—all year around.

The SBT team is turning its attention to developing and marketing key elements of what's been learned in this research project. Our aim is to move from a primary focus on research to a primary focus on production. To be sure, we intend to continually improve the systems developed under this project aiming at increasing the production of excellent food all year around while keeping both the carbon footprint and costs as low as practical.

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