# Building-integrated greenhouse systems for low energy cooling

T. Caplow, J. Nelkin
*New York Sun Works, USA*

## ABSTRACT

Installation of an evaporatively cooled hydroponic greenhouse on the roof of building can yield net energy savings for the combined structure, when compared to conventional air conditioning, and can conserve space by adding productive capacity to the rooftop. The proposed system offers energy and water savings far exceeding the levels achieved by traditional green roofs, but requires circumstances that favor co-location of a technically sophisticated agricultural facility with the building. Compared with field agriculture, the hydroponic cultivation of crops in greenhouses sharply reduces water consumption, requires no pesticides, uses several times less land, and doubles the growth rate. Integration of hydroponics into the built environment also sharply reduces the distance from farm to consumer, saving transport costs, reducing waste, and increasing product quality. A 120 m$^2$ low-energy greenhouse was constructed in 2006 on a barge platform in the Hudson River Estuary, a temperate eastern North American climate. A staged cooling algorithm escalates from passive ventilation to active ventilation to evaporative cooling as a function of internal and external temperature.

In a Mediterranean climate, a temperature differential as large as 15 C can be achieved by evaporative cooling in arid summer conditions.

Placed on a building, the greenhouse could serve as a complete HVAC system, although higher air velocities will require customized design of building ventilation systems. A hypothetical 720 m$^2$ building of two stories in a Mediterranean climate is analyzed using a highly simplified spreadsheet model. Results indicate that this building adds only 9% to the summer cooling load for a rooftop greenhouse of the same planform area. Required inputs include water (550 tons per year) and power for fans (23 MWh per year), but these inputs for the combined system are lower than the energy cost to cool the building alone using conventional air conditioning. For this purpose, it is assumed that the greenhouse is independently viable as an agricultural venture.

## 1. INTRODUCTION

The economic viability of greenhouse agriculture continues to increase, particularly in temperate regions of the world, where the market price for horticultural products rises sharply in the winter as quality and yield from traditional agriculture declines. Hydroponic cultivation (where plants are grown in water or in an inert growth medium, without soil) adds additional benefits, including faster growth rates, more precise quality control, and reduced or eliminated need for pesticides.

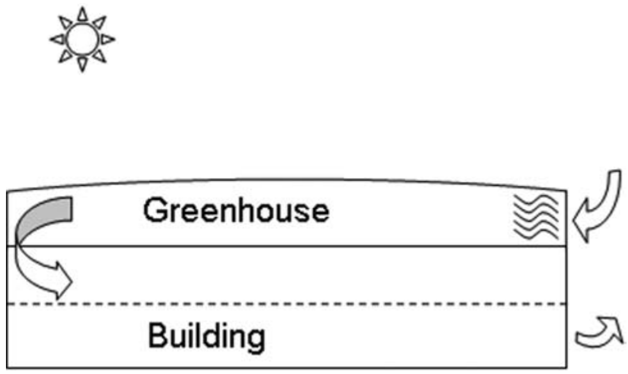


Figure 1. Schematic of greenhouse with evaporative cooling mounted on the roof of a two-story building. In typical summer operation, air: (1) enters the evaporative pad wall (top right) with high T and low RH; (2) becomes cool and saturated moving through the pad wall; (3) passes through the sunny greenhouse raising T and lowering RH to appropriate indoor levels; (4) moves into the building at a high flow rate; (5) is exhausted.

Greenhouse agriculture, and hydroponics in particular, requires considerable control of the indoor environment, and with regard to heating, ventilating, and air conditioning (HVAC), presents challenges similar to the operation of a modern building. However, the heat transfers required to maintain a productive greenhouse environment are much larger than those required to maintain an office or residential building of comparable size. For this reason, greenhouses commonly employ passive and low energy cooling methods, particularly ventilation and evaporative cooling.

This initial investigation into the energy conservation advantages of placing a hydroponic greenhouse on the roof of a two-story office building (Fig. 1) is motivated by the observation that the greenhouse provides a suitable space to implement a large evaporative cooling system for the combined structure. Without the greenhouse, it is assumed that an evaporative cooling system would not be feasible for the building due to constraints of space, humidity, and/or cost.

Energy is also saved in the combined structure by the elimination of solar gain and thermal losses through the building roof (because this surface now becomes the floor of the greenhouse, with approximately the same temperature above and below).

The potential energy savings of *integrating* the structures are the focus of this study. It is assumed that the hydroponic operation is independently viable.

## 2. COMPLETED GREENHOUSE

The Science Barge greenhouse is a 120 $m^2$ aluminum framed structure in New York City, operated as a public demonstration and research facility. Tomato, cucumber, lettuce, and other vegetable crops are grown using recirculating hydroponics. Water is supplied by rainwater and desalinated water from the estuary. Energy needs of approximately 25 kwh per day are met by a combination of onsite solar, wind, and biodiesel.

Table 1: Physical model parameters

| Parameter | Value | Units |
|---|---|---|
| plan area | 361 | $m^2$ |
| aspect ratio | 5.3 | |
| Greenhouse: | | |
| height | 4.0 | m |
| U, net total | 4 | $W\ m^{-2}\ C^{-1}$ |
| transmissivity | 70% | |
| Building: | | |
| floors | 2 | stories |
| height | 7 | m |
| U, walls, net | 0.8 | $W\ m^{-2}\ C^{-1}$ |
| U, roof | 0.4 | $W\ m^{-2}\ C^{-1}$ |
| occupancy | 20 | $m^2\ person^{-1}$ |
| occupancy rate | 75% | |
| occupancy time | 11 | $h\ day^{-1}$ |

Note: See text for additional specifications. Thermodynamic values (heat capacity, density, vapor pressure) are not listed. Standard air values were used.

Greenhouse climate is managed by a computerized controller to maintain day and night temperature at 24 and 18 C respectively. First stage cooling minimizes energy demand through the use of passive roof and side vents, and escalates to forced ventilation when required. Ventilation ceases to be effective when the outdoor temperature climbs above acceptable limits for plant growth, at which time evaporative cooling is employed.

In the evaporative cooling mode, air is drawn through a 12 $m^2$ evaporative pad wall composed of special corrugated cardboard sheets hydrated from above. Excess water is captured and re-circulated within the pad wall. Greenhouse air is exhausted by two 0.5 kW fans located 8 m away. The short air path reduces air velocity and fan power. When the greenhouse is too cold, a ductless forced air heating system is employed, combusting waste vegetable oil. The growing systems in the Science Barge greenhouse have the capability to produce vegetables at a rate between 40 and 70 kg per $m^2$ annually, using three to five times less water and five to ten times less land than a conventional farm with the same yield.

## 3. HVAC LOAD MODEL

Highly simplified thermal models of the building and the greenhouse were constructed in a computer spreadsheet (MS-Excel), and the daily heating and cooling loads were estimated on three prototypical days: one day each for winter (“Dec”), summer (“June”), and autumn/spring (“Equinox”). The loads were calculated for the building and for the greenhouse as separated structures, and then re-calculated for the combined structure.

The primary quantitative parameters necessary to construct the model are listed in Tables 1 and 2. The greenhouse in the model is exactly three times the size of the actual Science Barge greenhouse, with an expected yield between 9 and 18 tons of vegetables per year. The model assumes the air from the greenhouse exhaust fans is ducted through the building without an increase in fan power. This will require large ducts and louvers, which will also aid in the management of air velocity.

The model uses an hourly timestep for a 24-hour period, and then sums the heating and cooling loads, the water required for evaporative cooling, and the power required for fans. The model has three modes for the combined structure: heating, forced ventilation, and cooling. One of these modes is selected for each hour in each prototypical day. In the heating mode, the fans are off, as airflow requirements are much lower in this mode. In the forced ventilation mode, the fans are at half-speed. Ambient temperature (T) in the model maintains a specified minimum value from midnight (00:00) to sunrise, increases linearly to a specified maximum that is maintained from 13:00 to 15:00, then decreases linearly until midnight. Solar insolation is modeled sinusoidally, with a maximum at noon (12:00) and specified daily hours of sunlight (Table 2).

Temperatures in the building (when occupied) and in the greenhouse are allowed to float between a minimum of 20 C and a maximum of 24 C, depending on the conditions and the season.

A mean daily insolation is specified in the model for each of the four prototypical days, and the hourly solar profile was constructed to yield a daily total that matched this figure. Insolation in the model corresponds to the mean global radiation on a horizontal surface for the month modeled. Sunny days and cloudy days are thus averaged together.

The model does not account for thermal storage or dynamic effects of any kind, but instead treats each hour as a quasi-steady state. The model is suitable for the estimation of mean daily loads, but not suitable for peak loads.

The plan area of the greenhouse and the building are identical. A flat roof is modeled in both cases. (Real greenhouses feature arched roof profiles, but the degree of arch has a relatively minor effect on the net radiation received). The greenhouse height is specified as 4.0 m, and the building height is specified as 7.0 m, representing two stories.

Conductive resistance through the walls and roof was assumed to be much larger than convective resistance, allowing heat transfer through these surfaces to be modeled solely on the basis of area, U-value, and the hourly differential between interior and ambient temperatures. Thermal exchange with the ground was neglected.

Table 2: Daily climatic model parameters

| Parameter | Value | | | Units |
|---|---|---|---|---|
| | Dec | Equinox | June | |
| low T | 5 | 10 | 15 | C |
| high T | 15 | 22.5 | 30 | C |
| insolation | 9.8 | 15.8 | 21.9 | MJ $m^{-2}$ $day^{-1}$ |
| sun hours | 10 | 12 | 14 | h $day^{-1}$ |
| RH* | 72 | 64 | 48 | % |

*RH = mean relative humidity

Table 3: Typical hourly results for combined structure

| Hour | Solar gain | Thermal load | Water demand |
|---|---|---|---|
| | kW | kW | kg $h^{-1}$ |
| "December" | | | |
| 00:30 | 0 | -29 | 0 |
| 06:30 | 0 | -29 | 0 |
| 12:30 | 105 | 101 | 0 |
| 18:30 | 0 | -11 | 0 |
| "Equinox" | | | |
| 00:30 | 0 | -19 | 0 |
| 06:30 | 19 | 3 | 0 |
| 12:30 | 144 | 157 | 170 |
| 18:30 | 0 | 6 | 0 |
| "June" | | | |
| 00:30 | 0 | -10 | 0 |
| 06:30 | 54 | 51 | 58 |
| 12:30 | 174 | 200 | 522 |
| 18:30 | 18 | 37 | 61 |

Note: Negative numbers indicate heating loads. Where a positive number is seen with zero water demand, the model is in forced ventilation mode.

The building was assumed to be an office or commercial space with occupancy hours of 08:00 to 19:00, seven days per week. Outside these hours, the building space was not conditioned. Greenhouse temperature was kept within the specified range at all hours.

People are assumed to occupy the building at a density of 20 $m^2$ per person, with a mean occupancy rate of 75% over the operating hours, and a mean metabolic rate of 130 W per person. For simplicity, the combined sensible heat load for lighting and equipment is assumed to scale with occupancy and to equal double the metabolic load (McQuiston et. al 2005). Latent heat gains are ignored and air is not recirculated.

A mean relative humidity (RH) is included in the model inputs, and used in combination with mean T to determine the moisture content of the air on a mass basis, which is held invariant over the day.

Evaporative cooling is assumed to saturate the ambient air (RH = 100). The ambient RH, reduction in T as outside air crosses the pad wall, and mass flow of water were calculated at the minimum and maximum ambient temperatures using a psychrometric chart. An adiabatic humidification process was assumed. These results were interpolated to cover each hour of the day, and the total demand for water and air were summed over each of the three prototypical seasonal days.

To estimate solar gain through the building roof in the absence of the greenhouse, roof temperature was assumed to reach a maximum of 30 C above the ambient at noon on the prototypical summer ("June") model run. Elevation of roof temperature above ambient for other days and hours was scaled in proportion to mean insolation. The roof was assumed to have a conductive resistance equal to twice that specified for the building walls. Solar gain at the vertical sides of all structures was ignored for simplicity.

## 3. RESULTS

Representative data for hours of 00:30, 06:30, 12:30, and 18:30 for the combined greenhouse and building on all three prototypical days are presented in Table 3, and summary energy and water data are presented in Table 4. The cooling load of the building is sufficiently small compared to that of the greenhouse that no physical changes to the greenhouse cooling system are necessary to add the building load (although the system will use slightly more water and power). Furthermore, by passing the very humid air produced by evaporative cooling through the greenhouse first, substantial heat is added to the air, reducing the relative humidity to levels appropriate for office space.

In summer ("June"), the cooling loads for the greenhouse and for the building, as separate structures, are estimated at 1627 and 215 kwh per day, respectively, and heating loads are estimated to be 54 and 0 kwh per day, respectively. When the structures are combined, elimination of solar gain through the building's roof is estimated to shave 37 kwh per day off the cooling demand. The remaining combined cooling load could be met evaporatively with approximately 3.9 metric tons of water per day. The cooling load of the building represents 9.4% of the total cooling load.

In winter (Dec.) the modeled cooling loads are estimated at 535 and 26 kwh per day for the separated greenhouse and building, respectively. Heating loads are estimated at 366 and 7 kwh, respectively. Covering the building roof saves only a small amount of energy (6 kwh per day) at this time of the year. The cooling requirements of the combined load can be met entirely through forced ventilation (an opportunity for maintenance on the evaporative cooling pads). The building represents 13.4% of the combined cooling load.

From the perspective of traditional energy conservation, the potential annual savings are approximately equal to the entire cooling load of the building, 44 MWh, because this load will be met by the low-energy forced ventilation / evaporative cooling system in the greenhouse if the structures are integrated.

Replacement of the building roof with the hydroponic greenhouse contributes to these savings ("roof load" in Table 4), but this benefit alone is not sufficient to motivate the project.

On an annual basis, using the HVAC system of the greenhouse to cool the building increases water demand by about 55 tons, and eliminates the need to provide 44 MWh of cooling through conventional means such as fossil fuels or grid electric power. The combined system uses 552 tons of water and 23 MWh of electricity for fans to deliver 435 MWh of cooling.

In a sustainable design, it will be important to consider the source of water. If rainwater is unavailable, reverse osmosis could be used to desalinate ocean water, as one example. Modern pressure recovery technology can achieve yields of 100 L per kwh at a small scale, indicating that the water requirements could be met with four times less power than the fans consume.

## 4. DISCUSSION

On an annual basis, the building cooling load was less than 12% of the total, suggesting that few physical changes would be necessary to the greenhouse HVAC systems to accommodate the building load, aside from the necessary large ductwork between greenhouse and building. The importance of a low-energy cooling system in the modeled climate is underscored by the dominance of the cooling load in the results. This thermal asymmetry reflects a warm climate, a building with substantial insulation, and a high density of occupants and equipment. A residential building, with 24 h occupancy extending into the cooler night-time hours, would have a different load profile, and allow for solar heating if effective thermal storage were incorporated into the design.

Table 4: Summary results by season

| Parameter | Value | | | Units |
|---|---|---|---|---|
| | Dec | Equinox | June | |
| Building (separated): | | | | |
| Cooling load | 26 | 120 | 215 | kwh $day^{-1}$ |
| Roof load | 6 | 21 | 37 | kwh $day^{-1}$ |
| Combined structure: | | | | |
| Cooling load | 607 | 1189 | 1781 | kwh $day^{-1}$ |
| Heating load | 366 | 180 | 54 | kwh $day^{-1}$ |
| Water demand | 0 | 1.1 | 3.9 | ton $day^{-1}$ |
| Peak air changes* | 20 | 19 | 37 | $h^{-1}$ |
| Mean air changes* | 4 | 7 | 12 | $h^{-1}$ |
| Building load / total | 13.4 | 10.9 | 9.4 | % |

*air changes are based on building volume.

Note: See notes at Table 3 for plan and floor areas.

It is important to note the many limitations of the highly simplified model presented here, including the obvious deficiencies of climatically averaged data, simplified temperature and insolation profiles, neglect of convective dynamics, simplified box geometry, and the use of hourly bins, forcing each hour in the prototypical days to be designated either as a cooling hour or a heating hour in its entirety.

The approach presented here does not consider the details of ductwork and architecture necessary to integrate the structures and their HVAC loads. Hydroponic greenhouses are relatively lightweight (and certainly much lighter than greenhouses containing soil) and the water in them is typically well contained, and the structural feasibility of roof mounting is not expected to be insuperable. The mounting of the Science Barge greenhouse on a flat steel deck partially validates the practicality of rooftop integration of a similar system.

Direct introduction of greenhouse exhaust air into an office space is another area of potential concern. The annual mean air exchange rates in the modeled system are approximately 15 and 7 changes per hour in the greenhouse and in the building, respectively. These rates, while several times higher then typically required in buildings, might be suitable, but the peak air exchange rate (during sunny summer conditions) is estimated to be as high as 73 changes per hour in the greenhouse (about 36 changes per hour in the building). These rates are not uncommon for passively or evaporatively-cooled greenhouses (Brown 1995) but may present a significant problem for an office building unless a substantial wall area on each of two opposing facades of the building is dedicated to HVAC louvers.

One possible solution to the problem of high air flow rates in the building is for the cooling air to pass instead through a small space (perhaps 50 cm) between the ceiling of the building and the greenhouse floor. A heat exchanger in this space below the roof would eliminate direct contact with the greenhouse air, and provide a very large surface area for heat transfer, located at the top of the building where cooling is most effective. Energy (and water consumption) would rise slightly under this arrangement, according to the efficiency of the heat exchange process.

Other system configurations may also merit further consideration. Under certain conditions, including different relative sizes of the building and greenhouse, it could be advantageous to partly recirculate the air back to the evaporative cooler. Although humidity will have to be carefully controlled by the addition of outside air under this arrangement, energy (and water) demand will be reduced and excess building heat can be captured in the greenhouse. Another advantage of recirculation is the potential for a symbiotic exchange of oxygen and carbon dioxide between crops and building occupants.

## 5. CONCLUSION

A variety of benefits have been identified for the proposed combination of a building and a hydroponic greenhouse. Intensive greenhouse cultivation is fundamentally well matched with evaporative cooling for built structures, because both technologies thrive under the same climatic conditions (sunny and arid).

Energy conservation benefits will depend to a large degree on local climatic conditions, particularly the ambient temperatures, the strength of solar radiation, and the relative humidity. Benefits associated with hydroponic cultivation depend on climate as well as the local, year-round market prices of fresh vegetables (and/or flowers). The energy analysis and the proposed design require considerable refinement, but the preliminary results suggest that the southern Mediterranean region is well suited to capture the benefits of the proposed structure.

## REFERENCES

McQuiston, F. C., Parker, J. D., and Spitler, J. D. (2005). *Heating, Ventilating, and Air Conditioning: Analysis and Design.* New York: Wiley.

Brown, J. E. (1995). *Crop King Grower's Workbook.* Seville, OH, USA: Crop King, Inc.