The case for building-integrated hydroponics

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ABSTRACT

Cultivation of crops such as tomatoes or lettuce in a modern hydroponic growing system reduces water consumption, requires no soil, doubles the growth rate, and enables year-round production. The product is healthier than field agriculture, because pesticide use is often unnecessary, and contamination from soil or airborne pathogens is nearly eliminated. On Mediterranean islands, high import costs, poor soils, and limited water supplies further favor hydroponic vegetable production.

Effective hydroponic cultivation requires intensive regulation of the greenhouse environment. Typically, a combination of evaporative cooling, fossil fuel heating, forced draft ventilation, and natural transpiration is employed in greenhouses to maintain interior temperature and relative humidity in the ranges 18-24°C and 30-70%, respectively.

By mounting a hydroponic greenhouse on the roof of a small (e.g. two-storey) building of the same plan area, considerable energy savings may be realized for the building, particularly in dry, warm climates where evaporative cooling is effective. In winter, solar heat gain in the greenhouse can be shared with the building, in some cases eliminating the need for additional heating. In summer, the building is shaded from solar gain, while an evaporative cooling system in the greenhouse serves both structures.

A simplified spreadsheet model was constructed to estimate annual energy savings. The model requires specification of ambient temperature, humidity, and insolation for a diurnal cycle in each season of the year, together with various physical properties of the building and greenhouse. The model yields the daily heating and cooling loads and the evaporative water demand.

For a climate roughly similar to that of southern Greece, the model predicts that the building cooling load would be less than 9% of the total cooling load for the combined structure. Various arrangements for meeting this load through evaporative cooling are discussed.

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.

All of these benefits are increased on islands, particularly Mediterranean islands, where dry conditions, thin soils, and remote geography

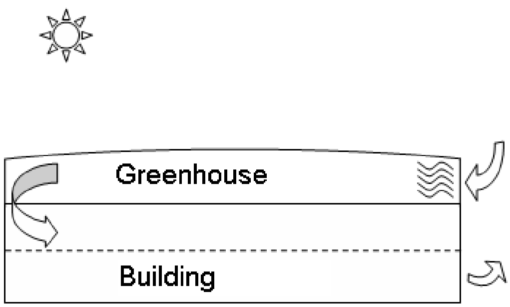

Figure 1: Schematic of greenhouse with evaporative cooling mounted on the roof of a two-story building.

further increase the value and price of vegetables, and where scarcity of land and environmental sensitivity increase the need for earth-friendly cultivation.

Greenhouse agriculture, and hydroponics in particular, requires considerable control of the indoor environment, and with regard to heating, ventilating, and air conditioning (HVAC), closely resembles operation of a modern building. In fact, the energy required to maintain a relatively constant greenhouse thermal environment at optimal growing conditions is much greater than that required to maintain the indoor environment of an office or residential building of comparable size.

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 (a common practice in hydroponics). It is anticipated that this system could readily handle the cooling load for both buildings, because the HVAC load of the building represents only an incremental increase on the HVAC load of the greenhouse. An evaporative cooling system might not otherwise 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. 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 (Mar./Sep.). The loads were calculated for the building and for the greenhouse as separated structures, and then re-calculated for the combined structure.

Table 1: Physical model parameters.

Parameter	Value	Units
plan area	357	m^2
aspect ratio	4.3	
Greenhouse:		
height	3.5	m
U, covering	4	$W\ m^{-2}\ C^{-1}$
transmissivity	60%	
Building:		
floors	2	stories
height	6	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.

The primary quantitative parameters necessary to construct the model are listed in Tables 1 and 2. The model uses an hourly timestep for a 24-hour period, and then sums the heating and cooling loads and the water demand (for evaporative cooling). Temperature is assumed to vary sinusoidally between the specified minimum (at 00:00 hours) and maximum (at 12:00 hours). Modeled solar insolation also varies sinusoidally, with a maximum at noon (12:00 hours).

The mean daily insolation is specified in the model for each season, and the mean seasonal noon maximum is then calculated to yield a daily total that matches the specification. 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 to yield a mean insolation for each hour of the day, and this insolation is then reduced by the specified transmissivity of the greenhouse covering.

The model does not account for thermal storage or dynamic effects of any kind, but instead

Table 2: Daily climatic model parameters

Parameter	Value			Units
	Dec	Mar/Sep	June	
low T	5	10	15	C
high T	15	22.5	30	C
insolation	9.8	15.8	21.9	$MJ\ m^{-2}\ day^{-1}$
RH*	72	64	48	%

*RH = mean relative humdity

treats each hour as a quasi-steady state. This treatment is acceptable because the model’s purpose is the estimation of mean total daily loads for the evaluation of energy savings, rather than the estimation of peak loads.

The plan area of the greenhouse and the building are specified to be identical (a rectangle of 357m^2 with an aspect ratio of 4.3:1) and are used directly for all calculations of solar gain and heat transmission at the building roof; i.e., a flat roof is assumed in both cases. (Real greenhouses typically 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 3.5m, and the building height is specified as 6.0m, representing two stories.

Conductive resistance through the walls and roof was assumed to be much larger than convective resistance, and heat transfer through these surfaces was modeled based on the U values listed and the hourly differential between interior and ambient temperatures. Thermal exchange with the ground was neglected.

Temperatures in the building (when occupied) and in the greenhouse were allowed to float between a minimum of 20°C and a maximum of 24°C, depending on the conditions and the season. Under cooling conditions, the temperature in the greenhouse was kept a little below the temperature in the building, because it is assumed that the cooling air passes through the greenhouse first (see Fig. 1).

The building was assumed to be an office or commercial space with occupancy hours of 08:30 to 19:30 (11 h per day). Outside these hours, the building space was not conditioned. No correction was applied for weekends or holidays. Greenhouse temperature was kept within the specified range 24 h per day.

People are assumed to occupy the building at a density of 20m^2 per person, with a mean occupancy rate of 75% over the operating hours, and a mean metabolic rate of 130W per person. For the sake of simplicity, the combined heat load for lighting and equipment is assumed to scale with occupancy and to equal double the metabolic load (McQuiston et al., 2005). The combined internal load is treated as sensible heat gain (the effect of any latent gains is ignored).

Evaporative cooling is assumed to saturate the ambient air. The initial ambient moisture content is calculated by specification of a mean relative humidity. This humidity is used, in conjunction with the mean temperature, to determine the moisture content of the air on a mass basis, which is assumed (for simplicity) to be invariant over the day (note that the relative humidity still changes with temperature). The net potential temperature reduction and water consumption at the minimum and maximum hourly temperatures was estimated using psychrometrics, assuming an adiabatic humidification process originating at ambient conditions and terminating at saturated conditions. These results were interpolated to cover the remainder of the day. The quantities of air and water needed to match the cooling load (for the greenhouse or for the combined structure) were calculated for each hour and summed over each of the three prototypical seasonal days.

Solar gain through the building roof presents a particular challenge to simplification, because the temperature of the roof will depend upon the radiation received as well as the ambient conditions. For the results presented here, the roof was assumed to reach a maximum temperature of 30°C above the ambient at noon (12:00 hours) during the summer (June) model run. Excess roof temperature (in degrees above ambient) for other hours was scaled according to the ratio of the current hourly mean insolation to the maximum June hourly 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.

3. RESULTS

Representative data for hours of 00:30, 06:30, 12:30, and 18:30 for all three seasons are presented in Table 3, and summary energy and water data are presented in Table 4.

As expected, 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). 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

Table 3: Typical hourly results.

Hour	Solar gain (kW)	Thermal load (kW)	Water demand (kg h^{-1})
December			
00:30	0	-28	0
06:30	10	-5	0
12:30	75	74	58
18:30	0	-8	0
Mar./Sep.			
00:30	0	-18	0
06:30	16	14	19
12:30	122	136	158
18:30	0	8	8
June			
00:30	0	-9	0
06:30	22	28	44
12:30	169	194	620
18:30	0	19	35

Note: Negative numbers indicate heating loads. Building plan area is 357 m^2 and total floor area for the combined structure is 1071 m^2.

Table 4: Summary results by season.

Parameter	Value			Units
	Dec	Mar/Sep	June	
Building (separated):				
Cooling load	45	113	217	kwh day^{-1}
Roof load	8	21	40	kwh day^{-1}
Combined structure:				
Cooling load	0.5	1.1	1.6	MWh day^{-1}
Heating load	0.3	0.1	0.02	MWh day^{-1}
Water demand	0.40	1.2	4.5	ton day^{-1}
Peak air changes*	18	33	85	h^{-1}
Mean air changes*	5	11	27	h^{-1}
Building load / total	7.1	8.6	8.8	%

*air changes are based on greenhouse volume.
Note: See notes at Table 3 for plan and floor areas.

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 1456 and 217 kwh per day, respectively, and heating loads are estimated to be 24 and 0 kwh per day, respectively. When the structures are combined, elimination of solar gain through the building’s roof is estimated to shave 40 kwh per day off the cooling demand. The remaining combined cooling load could be met evaporatively with approximately 4.5 metric tons of water per day. The cooling load of the building represents less than 9% of the total cooling load.

In winter (Dec.) the modeled cooling loads are estimated at 458 and 45 kwh per day for the separated greenhouse and building, respectively. These loads are approximately one-third of the summer loads. Heating loads are estimated at 256 and 0 kwh, respectively. Eliminating the building roof saves only a small amount of energy (8 kwh per day) at this time of the year. The cooling requirements of the combined load can be met with approximately 400 kg of water per day, about one-tenth of the summer requirement, despite more humid ambient air. The building represents about 7% of the combined cooling load.

In the fall/spring season, cooling loads are estimated at 965 and 113 kwh per day for the separated greenhouse and building, respectively, and heating loads are estimated at 118 and 0 kwh, respectively. Evaporative cooling requires approximately 1.2 metric tons of water per day, and, as in the summer, the building cooling load is just below 9% of the total.

From the perspective of traditional energy conservation, the potential savings are approximately equal to the entire cooling load of the building (from 45 to 217 kwh per day, depending upon the season), because this load will be covered by the low-energy evaporative cooling system in the greenhouse if the structures are integrated.

The most striking feature of the results is that, under the assumptions used, the thermal load for the office building is predominantly a cooling load in all three seasons, including winter. This result reflects the warm climate chosen for modeling (with mean winter temperatures around 10°C), as well as the assumption of a highly efficient, modern building with substantial insulation and a relatively high (but not atypical) density of people, lights, and office equipment.

The importance of a low-energy cooling system in the modeled climate is underscored by the dominance of the cooling load in the results. A residential building, with 24 h occupancy extending into the cooler night-time hours, would have a different load profile, although substantial savings would still result.

Replacement of the building roof with the hydroponic greenhouse offers some savings (as shown by the "roof load" in Table 3), but this benefit is probably not itself sufficient to motivate the project.

In all three seasons, the building load was less than 9% of the total, for both heating and cooling. This finding suggests that few (if any) physical changes would be necessary to the greenhouse HVAC systems to accommodate the building load, aside from those caused by the altered geometry.

4. DISCUSSION

The results indicate that the proposed integration of a hydroponic greenhouse with a 2-story office building has two potential advantages. Meeting the building cooling load with the greenhouse evaporative cooler adds about 10% to the water demand of this system and eliminates the need to provide about 130 kwh per day of heat transfer (67 kwh per m^2 per year) from electricity, fossil fuel, or other means. Elimination of solar gain through the building's roof is estimated to save 20 kwh per day (10 kwh per m^2 per year).

It is important to note the many limitations of the highly simplified model presented here. In addition to the obvious deficiencies of climatically averaged data, sinusoidal temperature and insolation profiles, neglect of convective dynamics, and simplified box geometry, the use of hourly bins to represent climatic means forces each hour in the prototypical seasonal days to be designated either as a cooling hour or a heating hour. In reality, the variation of climatic conditions between days within the seasons selected for analysis will produce a more complex pattern for certain hours. The particular risk is that hours which appear to have very small thermal loads (because the mean ambient conditions are close to the desired interior conditions) may in reality have both positive (cooling) and negative (heating) loads that have cancelled out in the aggregate. As a result, the total loads are probably slightly understated by the model.

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, so the structural feasibility of roof mounting is not expected to be insuperable (although it may be impractical in older buildings and therefore limited to new construction).

The suitability of greenhouse exhaust air for direct introduction into an office space is another matter. Air changes per hour for the greenhouse (and building) were calculated, and the annual mean is of the order of 10 changes per hour (5 changes per hour in the building). This rate of air replacement, while several times higher then typically required in buildings, might be suitable, but the peak air exchange rate (during mid-day, summer conditions) is estimated to be as high as 85 changes per hour in the greenhouse (about 40 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. In addition, depending upon the crop grown, the greenhouse air may contain unacceptable allergens for certain individuals at certain times of year.

One possible solution to the problem of using the greenhouse air directly is for the cooling air to flow through a small space (perhaps 50 cm) between the ceiling of the building and the greenhouse floor. This heat exchanger arrangement eliminates direct contact with the greenhouse air, while providing a very large surface area for heat transfer, located at the top of the building where cooling is most effective. Energy (and water consumption) are expected to rise slightly under this arrangement, according to the efficiency of the heat exchange process, but independent control of building air justifies this approach.

Other system configurations may also merit further consideration. For example, 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. 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 tangible and intangible benefits have been identified for the proposed combination of a building and a hydroponic greenhouse. 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). Considerable refinement is necessary of the energy analysis and of the proposed design, but the preliminary model introduced here suggests that the southern Mediterranean region should contain locations that are well suited to capture the benefits of the proposed structure.

REFERENCES

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