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E-Futures

Mini-project report summary

Current state of Building-Integrated Agriculture, its energy benefits and comparison with green roofs - Summary

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Abstract
Building-integrated agriculture (BIA) is the integration of controlled-environment hydroponic greenhouses with buildings. It allows for the production of high-quality vegetables in an urban context. A review of major BIA projects is presented in this report, focusing on rooftop greenhouses. Similarly to green roofs, rooftop greenhouses add an insulating layer to the building, reducing heat losses and gains through the building roof. It is also possible to use waste heat from the building to heat the greenhouse, excess solar gains in the greenhouse to heat the building, and low-energy evaporative cooling methods to cool the building as well as the greenhouse. Using simple spreadsheet calculations, it is found that compared to conventional stand-alone greenhouses and buildings, a combined building + rooftop greenhouse structure can save up to 41% in heating. This research suggests that BIA provides a strong case for retrofitting buildings in the UK.

1. Introduction
The United Nations estimate 9 billion people living on the planet by 2050 [1]. By 2030, two thirds of the world population will be living in cities [2]. Cities will need to grow to accommodate more people. As a consequence, available land for farming will become scarce. Farming will become more intensive to meet the increasing demand, and thus more destructive, mainly due to enormous amounts of fertilisers needed, whose run-offs lead to eutrophication of lakes, rivers and coastal areas [3-5]. Moreover, food miles and the negative impacts associated with them will increase as we will import food from greater distances into the cities [6-7].

Urban agriculture (UA) can solve many of these problems by growing food directly in cities. However there is not much land to grow large amounts of food in cities. Building-integrated agriculture (BIA) offers a solution by effectively growing food on unexploited building rooftops. It uses controlled-environment hydroponic greenhouses for their extreme efficiencies at growing large amounts of quality produce with little land and no soil.

This report first reviews major BIA projects. It then investigates the energy benefits of integrating a greenhouse with the building below, reducing heating and cooling loads for the combined structure. Using published literature and simple spreadsheet calculations, these benefits are approximately quantified. This then allows for a brief comparison with green roofs.

2. Building-Integrated Agriculture
BIA refers to the use of hydroponic greenhouse methods adapted for use on top of or in buildings [8]. There are two main types of BIA: horizontal rooftop greenhouses and vertically integrated greenhouses. This report focuses on the former type, which consists in installing hydroponic greenhouses on top of unused flat roofs.

Controlled-environment agriculture (CEA) allows for the control of all variables such as temperature, humidity and pH in the greenhouse throughout the year in order to keep optimum conditions for the growing of plants. Hydroponics is a soil-less method of controlled plant growth [9]. The major BIA projects reviewed in the next section all make use of the Nutrient Film Technique (NFT), which consists in circulating a thin layer of nutrient solution past the roots of plants in water-tight channels. At the end of the channels, excess water and nutrients are collected and recirculated until exhaustion of the necessary nutrients [10-11]. These systems can double the growth rate, use 10-20 times less land and 5-10 times less water when compared with conventional field agriculture [12-13].

BIA also helps improve air quality and reduce the Urban Heat Island (UHI) effect, helps improve stormwater management by rainwater harvesting, and can use beneficial insects such as ladybugs to avoid the use of pesticides. Moreover, it creates green-collar jobs, improves public health, and provides excellent education. However the main focus of this report is the energy benefits BIA can bring by integrating a rooftop greenhouse with the building structure (section 4).

3. Review of Major BIA Projects

3.1 The Science Barge (Research)

The Science Barge was built as a prototype facility for research into the feasibility and viability of BIA, as well as for public demonstration [13], by the non-profit organisation New York Sun Works. It is not built on a building but rather on a mobile steel-deck barge [12] on the Hudson River in New York. It is by far the most documented project, and one of the earliest of its kind.

The facility includes a 121 m^2 recirculating hydroponic greenhouse made of twinwall polycarbonate and a rainwater catchment system. The electrical requirement of 25kWh/day on average is all satisfied with on-site PV arrays and wind turbines. Heating requirements are met with a 51kW vegetable oil furnace. The greenhouse produces tomatoes, cucumbers, squash, bell peppers, lettuce, strawberries and herbs [14-15] with no pesticides or fertiliser run-offs [14, 16]. It grows 40-70 kg/m^2/year using 3 to 5 times less water and 5 to 10 times less land when compared with conventional farms of similar yields [13].

3.2 The Sun Works Center for Environmental Studies (Education)

Following their success with the Science Barge, NY Sun Works built a greenhouse on top of the Manhattan School for Children. It was completed in the fall of 2010. It is a 132 m^2 twinwall polycarbonate greenhouse equipped with recirculating hydroponics, rainwater harvesting and PV panels. It is projected to grow 28 kg/m^2/year of pesticide-free vegetables [14, 17].

A classroom of 35 students within the greenhouse [17] provides education on state-of-the-art horticulture, sciences and sustainability. The food grown in the greenhouse can be used for the school cafeteria, providing healthy, nutritious and pesticide-free food for the children. Schools are ideal environments for the installation of BIA, with health benefits strongly coupled to educational benefits.

3.3 Forest House, Blue Sea Development Corporation (Residential)

Due to be completed in Spring 2011, this 1000 m^2 greenhouse is located on the roof of a green and affordable housing project built in South Bronx, NY. It is a recirculating hydroponics greenhouse integrated with the building structure so that it can make use of waste heat from the building below. It is estimated that it will capture a total of 225 MWh of waste heat annually.

Enough food will be produced for 450 people's consumption year-round [18]. The area is known as a low-income area, with 40% of the population living below the poverty line [19]; residents lack access to fresh vegetables at affordable prices (effect known as 'food deserts') [18]. The project therefore considerably improves public health and education, and creates much needed green-collar jobs.

3.4 Gotham Greens, NY (Commercial)

One of the first commercial scale urban rooftop hydroponic greenhouse is being developed by the start-up firm Gotham's Green. It is a £0.88 million, 1100 m^2 greenhouse on top of a one-storey building currently home to a church, in Queens, NY [20].

The Gotham Greens concept incorporates most of the previously described technologies: recirculating hydroponics, integration to the building to make use of waste heat, rainwater harvesting, PV arrays and beneficial insects [21]. It is expected to produce between 30 and 50 tonnes of produce a year [20-22] with a wholesale value of over £310,000 [14]. It is predicted that over a 20 year design lifetime, the greenhouse will save up to 6.8 GWh compared to a conventional greenhouse [14]. This project will determine whether or not rooftop hydroponic greenhouses are commercially viable.

4. Heating, Cooling and Insulation

A rooftop greenhouse can minimise heat gains and losses through the building roof, as the latter becomes the floor of the greenhouse. The waste heat from the building below can be used to heat the greenhouse, thereby reducing the total combined heating requirements. Rooftop greenhouses could also use potential excess heat due to solar gains in the greenhouse during cold but sunny days to heat the building below. These exchanges of hot air from the greenhouse to the building (and vice-versa) also offer the benefit of symbiotic exchange of CO_2 and O_2.

Another system proposed by Caplow & Nelkin (2007) [13] is the use of evaporative cooling to cool both the greenhouse and the building below, something which could not be done without the greenhouse due to humidity and space considerations:

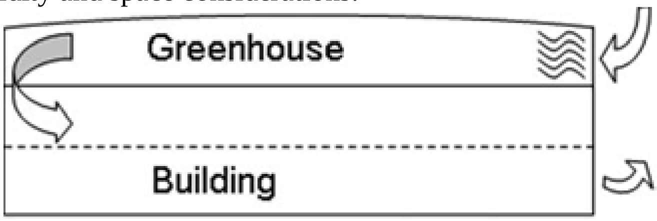


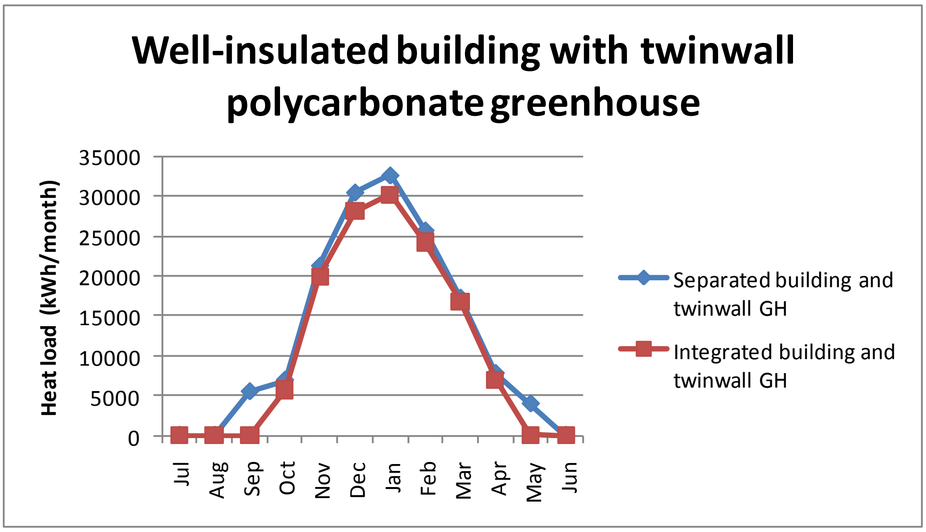
Fig1. Evaporatively cooled hydroponic greenhouse on top of a hypothetical 2-story building, from [13].

On warm days, the high temperature, low relative humidity (RH) air enters the greenhouse through an evaporative pad, lowering the temperature and raising the RH to the required conditions for the greenhouse. As the air moves through the greenhouse, it will gain some heat from solar gain, thereby raising the temperature and reducing the RH to comfortable levels for humans. This air can then be ducted to the building below for low-energy cooling [13].

It is possible to calculate the heating requirements of a building by taking the difference between the monthly heat load of a building (without gains) and the useful gains (solar and internal); this is the principle of the Method 5000 [23] used here. The temperature data is monthly-averaged data from the period 1961-1990 for Greenwich from the Met Office [24], and the solar radiation data is monthly-averaged data for London from the period 1966-1975, from the European Solar Radiation Atlas [25].

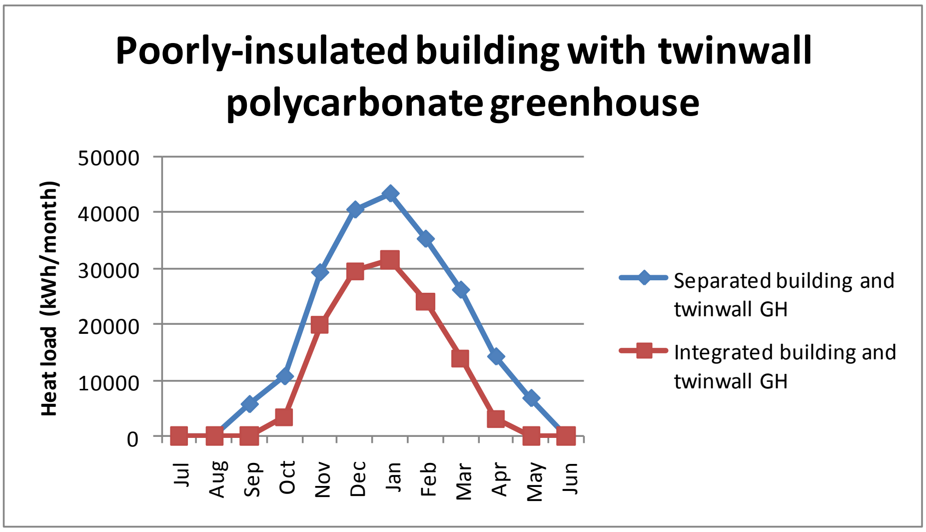
The following results assume the greenhouse is constantly kept between 18 and 24°C. The building is assumed to require 8 hours heating a day, with a thermostat temperature of 18°C. Air changes per hour are set at 0.5 for the building and 3 for the greenhouse. The dimensions of the building are the same as for those from Caplow & Nelkin (2007) [13], i.e. floor area of 361 m^2, 2-storey, with aspect ratio 5:3. The results compare the amount of energy needed to heat a greenhouse and a building when they are stand-alone structures (blue line on the graphs) with the amount of energy needed to heat the combined greenhouse + building structure (i.e. using excess gains from the greenhouse to heat the building when necessary and vice-versa, plus added insulation benefits; red line on the graphs).

1. Well insulated building (U-values: roof = 0.4 $Wm^{-2}K^{-1}$, walls = 0.8 $Wm^{-2}K^{-1}$) and 10mm twinwall polycarbonate greenhouse (U-value = 3.2, transmissivity = 72% [26]):



The integrated scenario saves a total of 19,500 kWh per year, which represents 13% of the total load for the separated building and greenhouse.

2. Poorly insulated building (U-values: roof = 8 $Wm^{-2}K^{-1}$, walls = 2 $Wm^{-2}K^{-1}$) and 10mm twinwall polycarbonate greenhouse (U-value = 3.2, transmissivity = 72%):



Here the effect is considerable; integrating the rooftop greenhouse with the building potentially saves 86,500 kWh/year, representing 41% of the original load.

5. Comparison with green roofs

Castleton *et al.* (2010) [27] extensively reviews the energy saving potential of green roofs; in general it is found that green roofs offer substantial energy savings when retrofitted onto old buildings with low insulation, whereas the savings are negligible for well-insulated roofs. As the following table shows, this is also the case for rooftop greenhouses:

	Existing U-value ($Wm^{-2}K^{-1}$)	U-value with green roof ($Wm^{-2}K^{-1}$)	U-value with greenhouse ($Wm^{-2}K^{-1}$)
Well insulated	0.26 – 0.4	0.24 – 0.34	0.25 – 0.38
Moderately insulated	0.74 – 0.80	0.55 – 0.59	0.67 – 0.71
Non insulated	7.76 – 18.18	1.73 – 1.99	3.57 – 4.85

Table1. Comparison of U-values for a building alone, with a green roof, and with a rooftop greenhouse. Data for green roofs taken from [28].

Table 1 shows that green roofs perform better than rooftop greenhouses in terms of insulation. However, as discussed earlier, one of the strong arguments for rooftop greenhouses is the possible utilisation of solar gains during the heating season to aid heating the building below, or the use of evaporative cooling during the cooling season for low-energy cooling methods. It also has to be noted that heat loss is proportional to the temperature differential between inside the building and outside – this difference will be much higher for green roofs than for heated rooftop greenhouses.

These results show that both green roofs and greenhouses perform better if retrofitted onto poorly-insulated buildings. Over half of the UK building stock was built before 1965 [29], when no minimum insulation requirements were set in building regulations. Moreover, in a survey conducted by *Seawater Greenhouse* looking at 11 random cities in the UK, it was found that approximately 30% of the buildings have flat roofs [30]. This suggests that green roofs and rooftop greenhouse both provide a strong potential for retrofitting buildings in the UK.

6. Conclusion

A brief review of current BIA projects showed that the state of development is extremely young. The Science Barge is one of the earliest examples, built on a barge as a research facility for the development of BIA. Its success in terms of producing good quality food in an urban environment with low environmental footprint, as well as for educational purposes, led notably to the construction of rooftop hydroponic greenhouses on schools (the Sun Works Center for Environmental Studies), apartment blocks (Blue Sea Development), and on commercial scales (Gotham Greens).

Integrating greenhouses to buildings has the potential of saving energy: similarly to green roofs, it provides a layer of insulation to the building, reducing heat fluxes through the roof. This effect is particularly strong when integrated on poorly-insulated surfaces. Although rooftop greenhouses are not as efficient as green roofs in terms of reducing U-values, they allow using excess heat gains in the greenhouse to heat the building below (and vice-versa), and to use low-energy evaporative cooling methods to cool the building during summer months.

An initial attempt to quantify the energy benefits of integrating a greenhouse with the building structure was undertaken. It was found that a combined building + greenhouse structure requires less energy to heat than if they are stand-alones. With a poorly-insulated building it is estimated that the integrated system can reduce the total heat load by 41%. The method used is limited and only intended as a preliminary study to investigate the potential of integrated greenhouses – more sophisticated computer simulations should be used with real-time data, and experimental measurements should be taken on completed projects to verify the models.

With over half of the UK building stock built before 1965, when there was no insulation requirements, and approximately 30% of buildings possessing a flat roof, the preliminary results shown in this report suggest a strong retrofitting potential using rooftop greenhouses, similar to the potential for green roofs. On top of the HVAC load benefits, the urban agriculture element of rooftop greenhouses advocates that a wide implementation of such technology could lead to considerable reduction of stress on external resources (fertile land and water mainly), allowing for lower-yield, more environmentally friendly methods of cultivation in rural areas.

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