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NEXUS: integrated sustainable energy for enhancing farm productivity

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Abstract. The NEXUS at Appalachian State University, NC, USA is a multidisciplinary team of faculty and students housed in the Department of Sustainable Technology and the Built Environment whose research lies at the intersection of agriculture, energy, and natural resources. NEXUS is developing inexpensive and efficient sustainable energy greenhouse heating technologies that provide affordable and sustainable means to improve the food-growing capacities and the standard of living for farmer communities in rural Appalachia while reducing the use of fossil fuels. This is done by using on-farm biomass resources/wastes such as agricultural waste and wood chips to produce energy. Growing season extension with heated greenhouses increases the availability of local food throughout the year, expands available markets and increases farmers' profits. The 7 m by 10 m greenhouse (conventional hoop) includes an above ground 5,700-liter water storage tank and an aquaculture pond. It is supported by a small-scale pyrolysis system, an anaerobic digestion system, solar thermal, and compost heating. The heat from various heating methods is delivered and stored in the water storage tank inside the greenhouse. An Arduino module controls the flow rate of water from the tank to various heat exchangers based on temperature differentials. A closed loop heat exchanger circulates heated water from the tank to the aquaculture pond to maintain an optimal temperature for tilapia growth. The pond also acts as a thermal storage, and holds/distributes heat to the greenhouse. The main purpose of this study is to test the integrated sustainable energy heating system for growing season extension with less energy cost. Our preliminary result shows that compared to a conventional space heating system, about 30% of energy was saved to keep the greenhouse temperature available for growing by radiation from the water storage tank.

1. Introduction

There has been high demand for local food in western North Carolina. Food surveys in the mountain region of North Carolina and Tennessee conducted by the Appalachian Sustainable Agriculture Project (ASAP) discovered that demand for local food exceeds potential supply. They conducted 20 separate food surveys of buyers in western North Carolina in 2003 and found that while current spending on locally grown produce was $14 million, there was a demand for nearly $37 million [1]. In addition, as a result of ASAP's successful local food movement, there has been a significant increase in local food demand in this region, a 69% increase in direct sales of agricultural products to consumers from 2007 to 2012 [2]. The purchase of local foods supports local farmers and local economies, provides improved health benefits, and has a positive environmental impact. However, the limited availability of locally grown food along with consistency and access hinders these benefits [3].

There are several reasons for limited availability of locally grown food with consistency in this region. The rough mountainous terrain and frigid winter weather limit agricultural opportunities such as the size of farms, shorter growing season, and limited large-scale mechanized farming operations. In addition, dramatic weather change in mountain region increases risks in agriculture such as spring frost damage. These result in Appalachian rural farmers' low income and high rates of off-farm workers [4]. Therefore, most Appalachian farms are small-scale family owned and struggle to maintain profitability with limited resources [5]. The United States Department of Agriculture (USDA)'s Census of agriculture (2012) states that most Appalachian counties in northwestern North Carolina are reported to have less than 100 acres average farm size and less than $10,000 average net cash income per farm [6].

Some Appalachia farmers dedicate a portion of their limited acreage to greenhouse production to maintain their profitability. Greenhouse production can extend growing season and prevent damages from dramatic weather change, but the requisite heating and energy costs exclude many producers from being able to afford a heated greenhouse. Pena reported about 40% of production costs are spent on fuel costs for greenhouse tomato production [7].

The purpose of this study is to build and test various inexpensive and efficient biomass heat delivery systems for a greenhouse in order to demonstrate how to improve local crop productivity for farmers in Appalachia or other cold mountainous regions. Biomass energy, generated from all available feedstock from farm such as livestock manure, agricultural waste, wood waste and food waste, can be an affordable greenhouse-heating energy source for those seeking lower energy costs to extend growing season.

2. Method

The greenhouse (called Nexus site) built for this study includes an above ground 5700-liter heat storage tank (thermal battery, TB) and an aquaculture pond supported by small-scale pyrolysis (biochar kiln), solar thermal, compost-heating, and anaerobic digestion (AD).

Thermal battery (figure 1): The 5700-liter water tank acts as our heat storage for the entire greenhouse. Modular lids, 10 cm × 10 cm, were constructed with 5 cm foam insulation (R-10) and treated plywood tops. Metal bands tying the long sides of the tank were also added for structural reinforcement since the lids were made to be removable to access the hot water piping. The lid of the thermal battery is at working height and will serve as an area to start and grow plants.

Figure 1. Inside the greenhouse, thermal battery (left) and raised aquaponics grow beds (right).

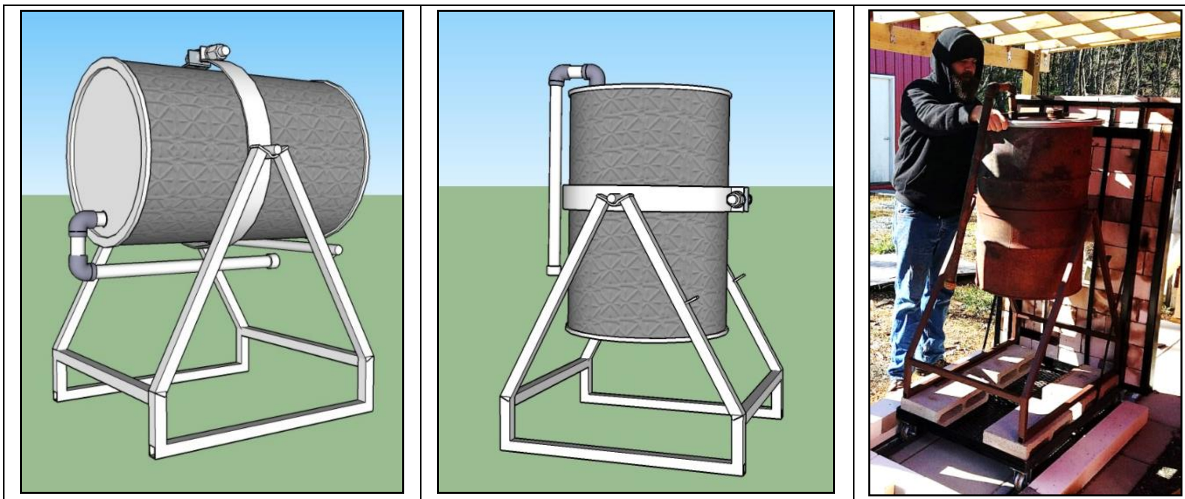
Aquaponics: In order to maximize the utilization of limited greenhouse space, increase farmers' income, and diversify available local foods, we designed and built an aquaponics system inside of our greenhouse (figures 1 and 2). Heated water from the water tank is circulated to the pond to keep the right temperature range for fish. The pond also acts as a thermal storage, and holds/distributes heat to the greenhouse. There are three tables for hydroponics over the pond. Air start syphon circulates the water between the pond and the hydroponics. The water with excretions from the pond is cleaned by feeding it to the plants in the hydroponics.

Figure 2. Plant growing test conducted in the aquaponics system.

Solar thermal system (figure 3): An evacuated tube solar thermal collector (30 tubes at 1.8 m length) was previously installed on the east head house as a drainback style system. The solar thermal system is direct, meaning that is uses water directly from the thermal battery. This solar system alone is capable of adding over 10.551 MJ/day to the greenhouse envelope.

Figure 3. Photovoltaic (left) and Solar thermal (right) installed at Nexus.

Wood stove/ biochar kiln: Initially, a wood stove with firebox heat exchanger and flu wrap-around heat exchanger, was up-fitted and piped to the thermal battery. Initial observations (15.1-liter per minute flow rate and temperature delta of 16.7°C) show a heating capacity exceeding 52.753 MJ/hr. In addition, a propane water (37.982 MJ/hr) heater with 454-liter propane fuel tank was added and the water heater was plumbed into the thermal battery for periods of cold cloudy weather when personnel are not available to maintain a wood fire. Later, we designed and built a small scale pyrolysis system (i.e., biochar kiln) at Nexus to replace the wood stove. The kiln is composed of three walls and a roof, with a cart that would provide the floor and the fourth wall. This meant that the cart could be pulled out, providing plenty of space to insert or remove the biochar vessel, a 125-liter steel barrel and build a fire. We built a temporary rolling cart-door with angle irons to check its convenience and any possible issues. We inserted a pane of high temperature glass so we could see the reaction without opening the door. After plenty of operations, we confirmed that our new rolling cart-door design for biochar kiln would be applicable to local farms. Just one concern raised by local farmers after on-site demonstration was heavy weight, however. Since most heavy components on the rolling cart are concrete blocks on the floor and the old cradle. After consulting with a local welding expert, we resolved this issue by reducing cart dimension and improving cradle design. With smaller cart dimension (96.5 cm × 263.5 cm), we used only four concrete blocks (figures 4 and 5). It is made of lighter metal square bars and has rounded barrel holders, so a barrel with a center belt that has a short bar on each side could swing and be positioned vertical or horizontal. It would help users load and unload biochar feedstocks very easily. Both new cart-door and new cradle was fabricated with welding work. From a user's standpoint, its improvement on easiness of rolling and loading/unloading is incredible.



New cradle design | New cart door and cradle

Figure 4. New biochar kiln design.

The heat generated from various biomass technologies (e.g., biochar kiln, compost, anaerobic digester) and collected from solar collector is delivered to TB and stored in thermal mass (water). A heat exchanger at the aquaponics pond distributes the heat from TB to the pond, so the fish has adequate temperature for their living and the pond can radiate some heat to atmosphere. In addition, the warm pond water with excretion from fish is circulated to a hydroponics system, which provides heat and nutrients to plants' roots.

We wanted to investigate how efficient our heat delivery system is compared to conventional heating. To do so, we needed to know:

- What is the adequate temperature setting for TB to keep temperatures of the pond and the hydroponics safe for living components?
- How much energy is consumed to keep a desired temperature for TB during wintertime?
- How much energy is required to heat whole space inside the greenhouse (conventional

heating)?

- What is wintertime temperature distribution over days and nights on each component (e.g., TB, pond, and hydroponics)?

Figure 5. New biochar kiln built at Nexus.

In order to investigate accurate energy usage during winter time, we disconnected all heat delivery pipes from heating sources to TB except propane water heater and solar thermal collector from December 2015 through Feb 2016. Then, we collected temperature data from five different locations: 1) inside TB, 2) pond, 3) hydroponics, 4) inside greenhouse ambient, and 5) outside greenhouse ambient as shown in figure 6.

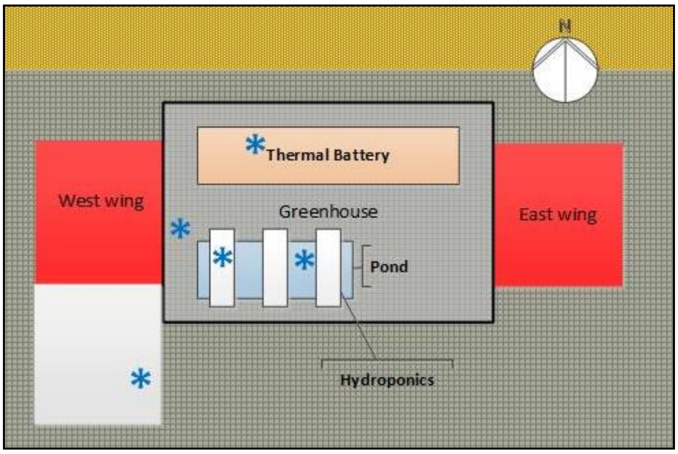


Figure 6. Temperature monitoring locations at Nexus.

3. Result and discussion

Since the minimum pond temperature of 12.8°C is suggested for tilapia to survive, our target temperature for pond was above 18.3°C. We began with temperature setting at 26.7°C for thermal battery (TB), and monitored the pond temperature distribution in the last one week (12/24 to 12/31) of 2015. We figured out that the pond temperature kept above 21.1°C all the time during our monitoring period as shown in figure 7. With 26.7°C TB temperature, the pond kept above 15.6°C during January 2016 except for one outlier of January 26th – 27th period, when the power running pumps was out. In the same manner, hydroponics beds kept above 12.8°C. Inside temperature of the greenhouse kept above -1.0°C even with outside temperature recorded below -15.5°C (1/19). Table 1 shows a summary of average and minimum temperature data for each component.

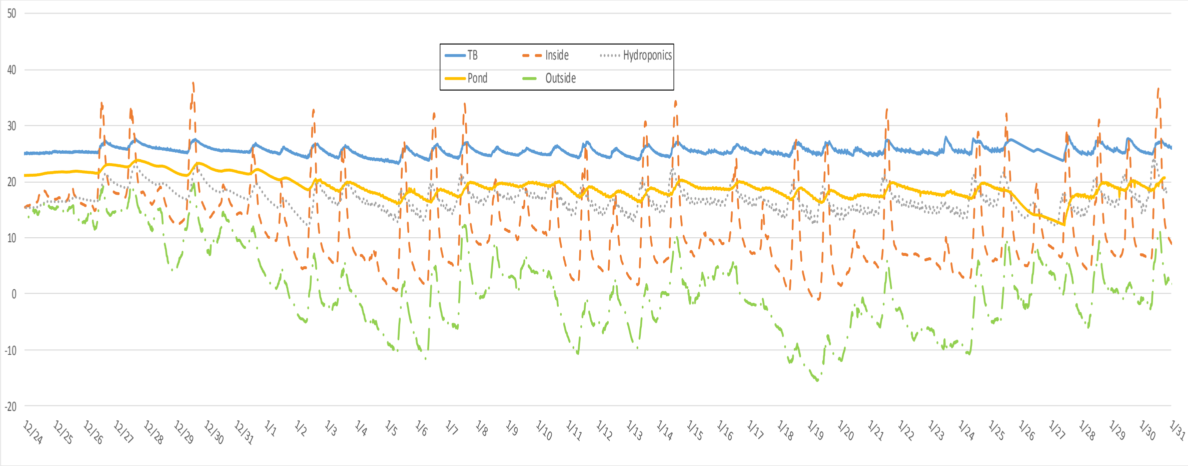


Figure 7. Temperature data during the monitoring period (°C).

Table 1. Average temperature data for each monitoring location.

	Average (°C)	Lowest (°C)	Time
GH inside	6.1	-1.0	1/19/2016
GH outside	-3.3	-15.5	1/19/2016
Pond	18.5	16.1	1/5/2016
Bed	15.6	12.3	1/19/2016

The propane tank was refilled four times during this winter time, and the last refill (336.5-liter) was made on 2/19/2016. Since a propane tank is usually filled up to the same point (i.e., 85% of the tank capacity), the amount of propane refilled indicates that how much propane was consumed since the previous refill date. Therefore, we assumed that 336.5-liter of propane was consumed from 1/15/16 (the third refill date) to 2/19/16. Converting propane liter to MJ (25 MJ/liter of propane), we figured out 8,413 MJ was consumed to keep the thermal battery at 26.7°C.

In order to estimate the energy required to keep the inside of a greenhouse above 10°C, we developed a heat loss & gain modelling tool. It is noted that 10°C was suggested by a local farmer as an inside temperature of a greenhouse during wintertime. We considered: 1) conduction heat loss through roof and wall, 2) perimeter and ground heat loss, and 3) infiltration heat loss for heat loss calculation according to the University of California Cooperative Extension [8]. We also considered: 1) direct solar heat gain and 2) solar collector for heat gain since the heat from the collector was stored at the thermal battery. We used the equation expressed in USDA Virtual Grower 3 manual [9] to calculate solar radiation heat gain.

Using our modeling tool, we estimated 12,371 MJ to heat the greenhouse with a conventional heating method (i.e., space heating) during 1/15/16 to 2/19/16. It indicates that we could save 32% of energy with our thermal battery (TB) plus aquaponics heat distribution as shown in table 2.

Table 2. Potential savings.

	TB + Aquaponics	Space Heating	Potential Savings
Energy Consumption (1/15 ~ 2/19)	8,413 MJ	12,371 MJ	32%

Since the aquaponics bed temperature (i.e., root zone temperature) affects directly on plant growth, this data indicates that our system, storing heat at the thermal battery and distributing the heat via aquaponics, is more efficient to grow crops and save energy in cold season.

4. Conclusion

Our main goals in this study are to build various affordable greenhouse heating technologies and to integrate them into a system for growing season extension with less energy cost. Our result shows that over 30% of energy was saved compared to a conventional space heating system to keep the greenhouse temperature available for growing by radiation from the water storage tank, which suggests the practical feasibility of these technologies at a test scale.

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