

# Case Study: Promoting Sustainable Energy Greenhouse Heating Systems to Small-Scale Local Farms

Jeremy Ferrell<sup>1</sup>, Ok-Youn Yu<sup>1</sup> and Heiyoung Kim<sup>2</sup>

1. Department of Sustainable Technology and the Built Environment, Faculty, Appalachian State University, Boone, NC 28608, USA

2. Appalachian Energy Center, Boone, NC 28608, USA

**Abstract:** Biomass energy generated from livestock manure, other agricultural by-products and food waste can be an affordable greenhouse-heating energy source for those seeking lower energy costs. Appalachian State University, North Carolina (NC), USA, has built a 6.1 m × 9.1 m greenhouse, called the “Nexus” to test the integrated sustainable energy heating system for growing season extension with less energy cost. This is done by using on-farm biomass resources/wastes such as agricultural waste and wood chips to produce energy coupled with solar water heating to store and supplement required thermal inputs. Growing season extension with heated greenhouses increases the availability of local food throughout the year, expands available markets and increases farmers’ profits. Nexus includes an above ground 5,680-L 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 preliminary result showed 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. The main purpose of this study was to test the proposed greenhouse heating systems developed at Nexus by implementing pilot systems on two local farms. Pyrolysis and solar thermal system in conjunction with heat storage and delivery system for each farm were built and tested in order to demonstrate how to reduce greenhouse energy use. This paper describes the results of the case study, which showed significant energy savings that can promote the resource-limited farmers’ interest.

**Key words:** Greenhouse, sustainable energy, farms, heating system, small-scale.

## 1. Introduction

There has been high demand for local food in Western North Carolina (NC), USA. Food surveys in the mountain region of NC 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 NC 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, demonstrated by a 69% increase in direct

sales of agricultural products to consumers from 2007 to 2012 [2]. The purchase of local food 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 limits farm size and opportunities for mechanization, while frigid blasts of winter weather shorten the growing season and increase risk of spring frost damage. This results in Appalachian rural farmers’ low income and high rates of off-farm workers [4]. The majority of Appalachia farms are small-scale, family owned and struggle to maintain profitability [5]. The 2012 Census of Agriculture indicates that there are 609 farms (average

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**Corresponding author:** Ok-Youn Yu, Ph.D., associate professor, research fields: practical agriculture, sustainable energy and farm operation.

size 37 ha) and negative net cash income of operation (average -\$191 per farm) in Watauga County, NC, USA [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 [7] reported about 40% of production costs are spent on fuel costs for greenhouse tomato production.

Appalachian State University's greenhouse site, called the "Nexus", looks to reinvent the heated greenhouse (6.1 m  $\times$  9.1 m) by using on-farm biomass resources and solar energy to extend growing season with less energy cost. Nexus includes an above ground 5,680-L 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. Smart utilization through energy and material management produce high-quality soil amendments and process energy. This holistic design results in the cycle of healthy soil, significant reduction of fossil fuel inputs, and increased viability of the region's farms. According to the preliminary result, the Nexus greenhouse saved about 30% of heating energy compared to a conventional space heating system to keep the greenhouse temperature available for growing by radiation from the water storage tank [8].

In this paper, a real-world application of the proposed greenhouse heating systems is described by conducting a case study on two local farms. The research team has begun collaboration with two working farms in Watauga County, NC, USA. Springhouse Farm in Vilas and Against the Grain (ATG) Farm in Zionville can be characterized as small farms that intensively manage less than 8 ha. These two farms are diversified and practice primarily organic production methods. They both rely on considerable amounts of human labor for management and harvest, while mechanization is reserved for

cultivation and land clearing. The opportunities and limitations of the case study are discussed in this paper.

## **2. System Design, Installation and Performance**

### *2.1 Springhouse Farm*

Springhouse Farm has a 6.1 m  $\times$  9.1 m high-tunnel propagation greenhouse and there are four growing benches and one germination bench inside. They start using the greenhouse as early as late January or mid-February. Before the proposed heating system was installed, they used a propane forced-air unit heater to keep the temperature inside the greenhouse at 12.8 °C, and electric heat mats for germination. Conventional forced air heating system that tries to maintain the soil temperature through warm air is very inefficient in both economic and energy-saving aspects. The research team designed and installed the greenhouse heating system to reduce the propane consumption through sustainable energy and efficient heat distribution. The system includes a solar collector, a biochar kiln, a food dehydrator, a heat storage and a root zone heating (RZH) system.

#### *2.1.1 System Design*

Fig. 1 shows schematic of the system at Springhouse Farm. The pilot system consists of three components: collection, storage, and distribution. Heat transfer fluid flows throughout the system to collect heat (thermal energy) and deliver it to the plants' root zone inside the greenhouse. The collected heat from sustainable energy sources such as the solar collector and the biochar kiln, is stored in a heat storage (i.e., 151-L propane water heater) inside the greenhouse: heat collection to storage phase. When heat is needed for greenhouse plants at night, the stored heat is supplied first. After the stored heat is all used, propane gas is burned to heat the transfer fluid. The heat stored or produced in the water heater is distributed to the plants through the RZH system: storage to distribution phase. These two phases (collection-to-storage and

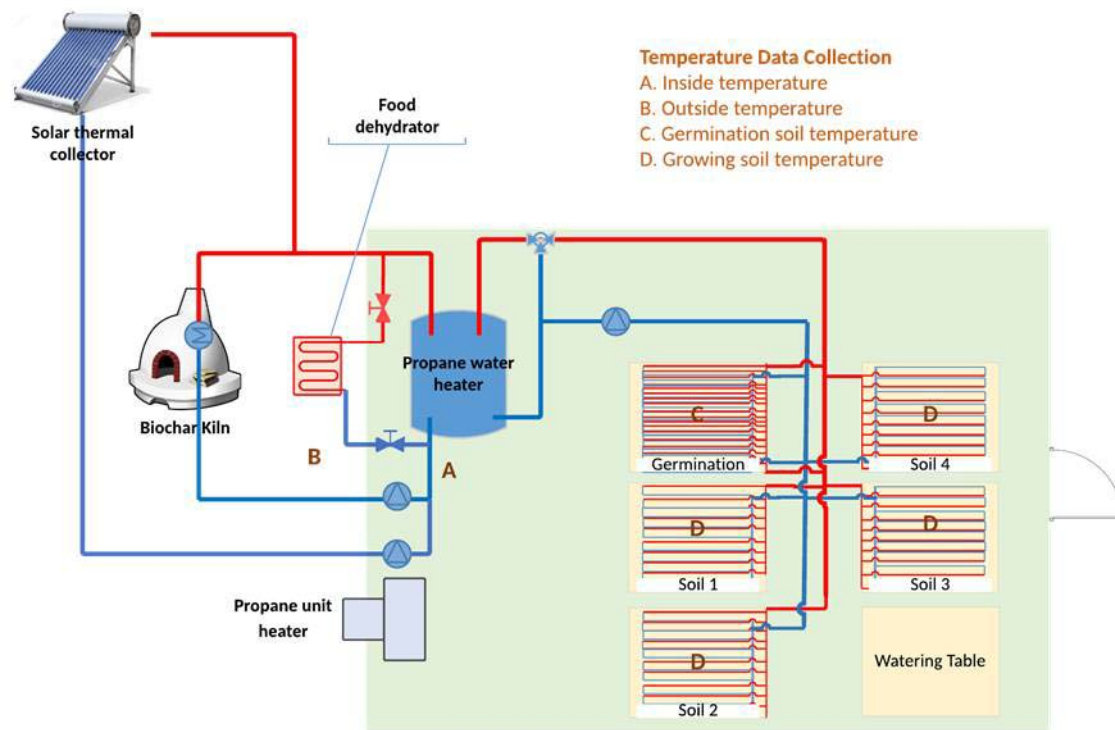


Fig. 1 Schematic of the heating system at Springhouse Farm.

storage-to-distribution) are separate and regulated by different controllers. A differential controller is used to collect thermal energy from solar collector and biochar kiln and deliver it to the water heater. A thermostat that senses germination soil temperature controls a circulation pump to distribute heat. In the warm season when heat is not needed in the greenhouse, the system manifold can be manually adjusted to have the collected heat bypass the storage and send it to the food dehydrator.

#### 2.1.2 System Installation

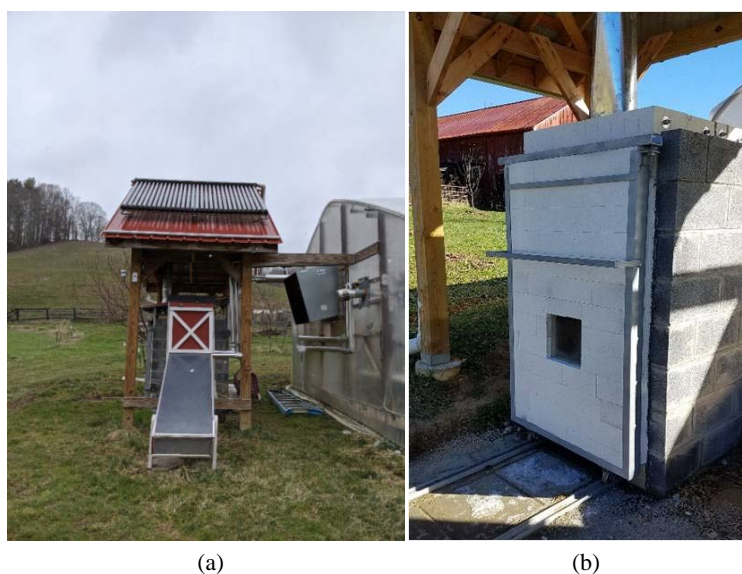
A shed for the solar collector, biochar kiln and food dehydrator was installed first. A  $3.7 \text{ m} \times 2.4 \text{ m}$  shed is located on the west side of the greenhouse. A solar collector with 30 evacuated tubes was installed on the roof of the south facing shed as shown in Fig. 2. Under the shed, a biochar kiln and a food dehydrator were installed. The design details of the biochar kiln will be presented in a future paper. The biochar kiln contains a heat exchanger (18.3 m long with 13 mm K-type copper tubing) which collects heat from the

exhaust gas produced during biochar production into the heat transfer fluid (50:50 propylene glycol/water-based solution). It is a closed loop system and is pressurized to maintain around 103 kPa.

A differential controller is used to control the “collection-to-storage” system based on the temperature difference between the water heater and the solar collector or the heat exchanger in the biochar kiln. It turns on and off a circulation pump installed in each pipeline of the solar collector and the biochar kiln depending on the set temperature differences and delivers the collected heat to the 151-L water heater inside the greenhouse through 1.9 cm copper tubing. Fig. 3 shows the system manifold and the water heater.

Depending on the season, the collected heat is distributed to  $1.2 \text{ m} \times 2.4 \text{ m}$  plant growing benches inside the greenhouse or a food dehydrator located outside the greenhouse. This can be manually regulated by opening and closing valves on the system manifold. In the cold season, the water heater is turned on and

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**Fig. 2** Heating system at Springhouse Farm: (a) shed, including solar thermal and food dehydrator; (b) biochar kiln.



**Fig. 3** The system manifold and the water heater at Springhouse Farm.

set to the “low” setting, which starts the propane burner at 26.7 °C and stops at 32.2 °C. Once the heat collected from the solar collector and biochar kiln is consumed (i.e., the water heater’s temperature drops below 80 °C), the heat transfer fluid is heated by the propane burner and ready to be supplied to the plants. The hot fluid from the water heater is mixed with the returning cold fluid by a mixing valve for proper temperature and then supplied to each bench. As can be seen in Fig. 4, the main pipe (2.5 cm polyvinyl

chloride (PVC)) from the system manifold to each bench was wrapped with foam pipe insulation and flashing tape and buried in the ground to make it easier for farmers to work inside the greenhouse. The header pipe (13 mm PVC) on each bench is connected in parallel to the main pipe. The heat delivered from the water heater to the bench is radiated to the soil through 0.64 cm ethylene propylene diene monomer (EPDM) tubing installed on top of the benches. The EPDM tubing is connected to the perforated header





**Fig. 4 Heat distribution with root zone heating (RZH) system: (a) header pipes and ethylene propylene diene monomer (EPDM) tubing on benches; (b) polyvinyl chloride (PVC) painted with latex for ultraviolet (UV) protection; (c) temperature sensor in the germination table; (d) plants on heated bench.**

pipes using barbs. While each growing bench table includes nine parallel loops of EPDM tubing, the germination bench includes 18 loops of EPDM tubing for higher soil temperature. Each supply and return header pipe has a ball valve to isolate each bench if not used.

In the warm season, the heat is dumped to the food dehydrator. Farmers can use the food dehydrator for food preservation. Fig. 5 shows the seasonal valve position that directs the heat transfer fluid to where heat is needed. The passive solar food dehydrator contains a water to air heat exchanger with finned area  $45\text{ cm} \times 50\text{ cm}$  (commonly used in a plenum of a forced air system for heating from solar or wood boiler) in the bottom of the box where active heat transfer and passive heat convection occur concurrently (Fig. 6).

### 2.1.3 System Performance

The system was used to heat the greenhouse plants from February 15, 2018 through June 12, 2018. Each growing bench was covered with 0.152 mm polyethylene greenhouse film at night and during cold cloudy days until the end of March. The unit heater (i.e., propane forced air heater) was set to turn on at  $4.4\text{ }^{\circ}\text{C}$  on March 8 and raised the set temperature to  $8.9\text{ }^{\circ}\text{C}$  on March 12 because some plants were placed outside the RZH benches. It was normally set at  $12.8\text{ }^{\circ}\text{C}$  before the system was installed. The supply fluid temperature of the system ranged from  $26.7\text{ }^{\circ}\text{C}$  to  $48.9\text{ }^{\circ}\text{C}$ , which resulted in soil temperature of  $18.3\text{ }^{\circ}\text{C}$  to  $23.9\text{ }^{\circ}\text{C}$  on the germination bench at night and  $12.8\text{ }^{\circ}\text{C}$  to  $18.3\text{ }^{\circ}\text{C}$  on the growing benches at night. Fig. 7 shows daily temperature distribution of



(a)



(b)

**Fig. 5 Seasonal valve positions of the system manifold: (a) winter mode; (b) summer mode.**



(a)



(b)



(c)

**Fig. 6 The Appalachian food dehydrator with heat exchanger: (a) complete passive dehydrator; (b) finned heat exchanger; (c) drying trays [9].**

germination soil and average daily temperature of soil in growing benches in March 2018. For the growing benches, different insulation was applied under the RZH tubing to check its effect. The tubing on growing bench 1 was placed over both blue board and reflective bubble insulation, while bench 3 and bench 4 contained only reflective bubble insulation and blue board, respectively. Bench 2 had no insulation. Fig. 8 presents average daily temperature of soil in growing benches in March 2018. Notice that the average soil temperature for bench 2 (no insulation) is 1.7 °C to 2.8 °C lower than for bench 1 and bench 3. The average soil temperature for bench 1 and bench 3 is similar except during the daytime. The owner of Springhouse Farm occasionally used bench 4 differently from other benches as needed, so its results are not included in Fig. 8.

Propane usage was reduced by 43% in 2018 compared to the previous year when the propane unit heater was the only heat source (450-L in 2018 and 787-L in 2017). Heating degree days (HDD) during the greenhouse operating period (i.e., February through May) of 2017 and 2018 with a base temperature of 12.8 °C were calculated as 856 HDD and 792.4 HDD, respectively. Considering that

the heat demand in 2017 was only 7% higher than in 2018, a 43% reduction in propane use is a meaningful result while maintaining productive growing conditions.

## 2.2 ATG Farm

ATG Farm has a 4.9 m × 9.1 m passive greenhouse built in 2016 as shown in Fig. 9. This greenhouse has insulated east, west and north walls. The south wall has 5 mm twin-wall Solexx glazing. There is no thermal mass in the greenhouse other than the gravel floor and the building itself, therefore additional heating is essential to prevent freezing.

### 2.2.1 System Design

Fig. 10 shows schematic of the system at ATG Farm. The heating system installed includes a solar collector (50 evacuated tubes), a biochar kiln, a food dehydrator, a water storage tank and an RZH system. Unlike Springhouse Farm, heat storage at ATG Farm is not a propane water heater, but a 1,136-L water storage tank, called thermal battery made of wood, waterproof liner, and blue board insulation. Therefore, there are no supplemental heat sources (e.g., fossil fuels) other than the solar collector and biochar kiln.

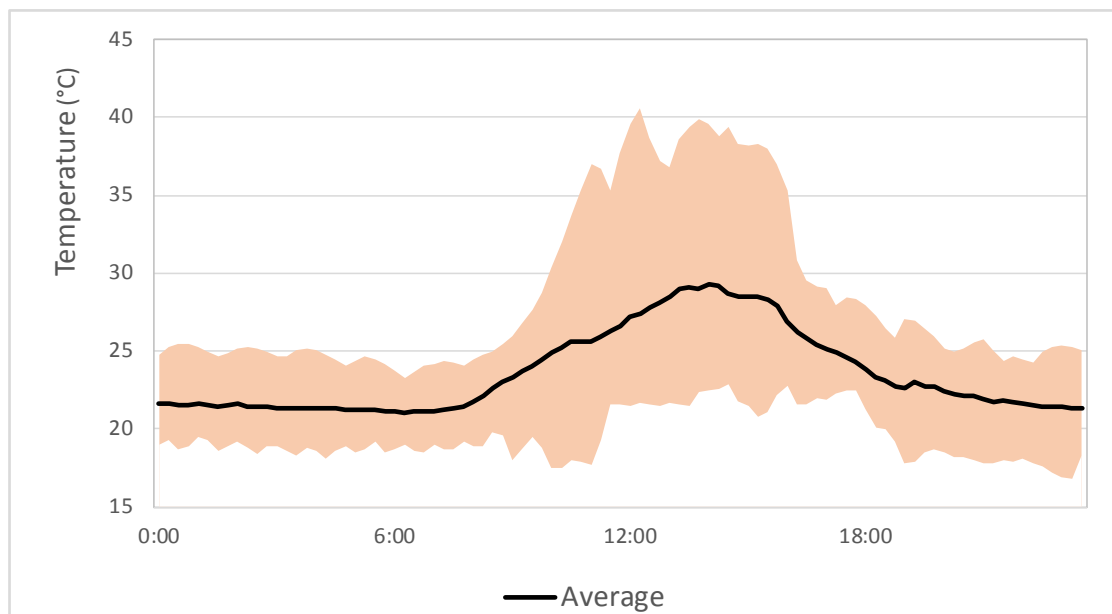
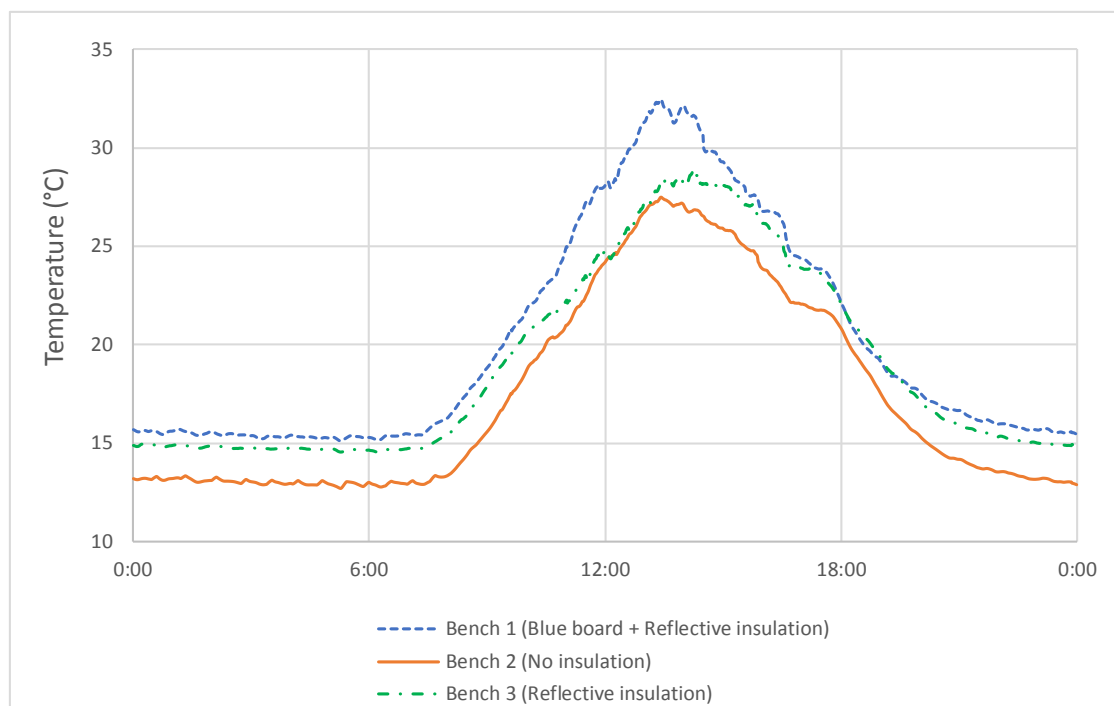


Fig. 7 Daily temperature distribution of soil in the germination table in March 2018.



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**Fig. 8** Average soil temperature on growing benches in March 2018.



**Fig. 9** Passive solar greenhouse at Against the Grain (ATG) Farm.

#### 2.2.2 System Installation

The thermal battery has an internal heat exchanger (30.5 m long with 13 mm copper tubing) to make a pressurized closed-loop piping system. The heat exchanger transfers heat from the solar collector and biochar kiln as shown in Fig. 11. The pump is controlled by a differential controller with temperature

sensors on heat exchanger outlet at the kiln and inside the thermal battery. The pump will circulate if a temperature difference of 6.5 °C or greater exists between the heat exchanger and thermal battery. The heated water is radiated to the passive greenhouse and to the germination pots sitting on vertical racks over the thermal battery at night.



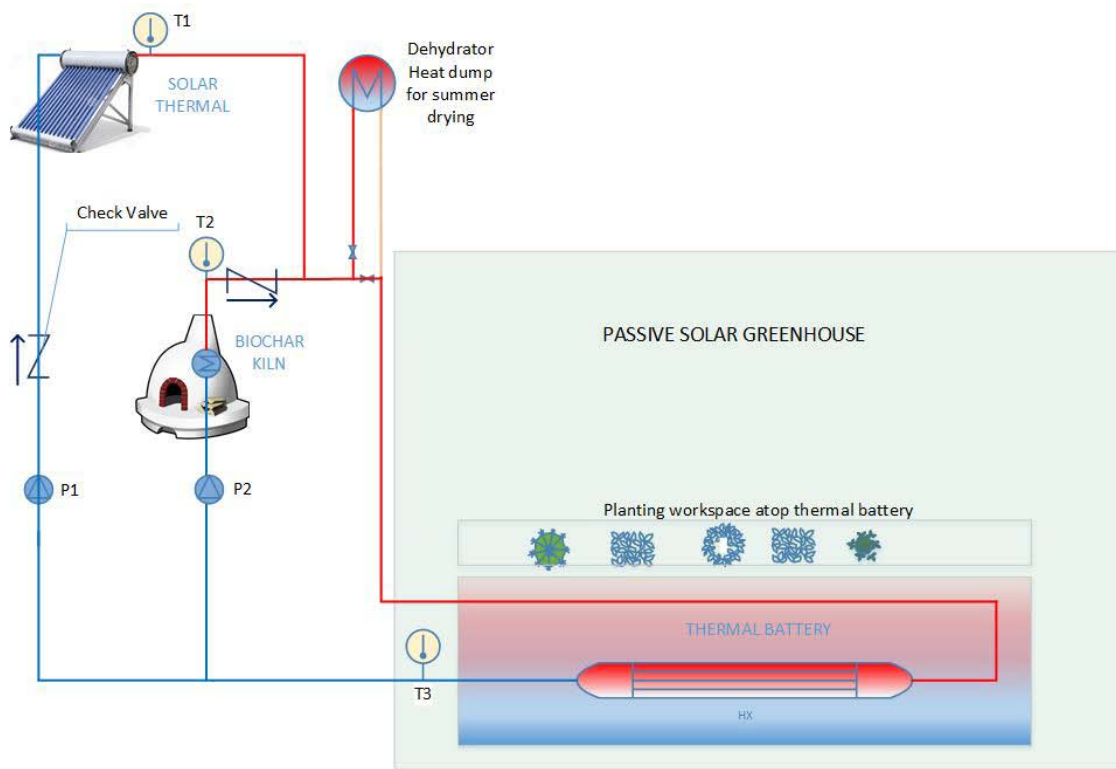


Fig. 10 Schematic of the heating system at ATG Farm.



Fig. 11 Thermal battery, heat exchanger and the system manifold.

Fig. 12 shows the biochar kiln and food dehydrator installed at ATG Farm. The biochar kiln is designed to collect waste heat from combustion. During kiln operation, the heat transfer fluid (50:50 propylene glycol/water-based solution) is pumped at a rate of 11

L/min through the heat exchanger (18.3 m long with 13 mm copper tubing) in the top room (heat exchange room) to capture heat from the flue gas and is returned to the thermal battery. During the warm season when heating is not needed, the collected heat is used to dry

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**Fig. 12** Heating system components: (a) biochar kiln; (b) food dehydrator.



**Fig. 13** RZH system installed at ATG Farm.

food in the food dehydrator. The food dehydrator has a heat exchanger equipped with two fans at the bottom of the box for fast heat transfer. The farm has dried apples, tomatoes, squash and herbs, representing another source of income for farmers.

The RZH system at ATG Farm has four racks over the thermal battery and there is 0.64 cm EPDM tubing installed under each rack. Each rack has 10 loops of tubing and a ball valve installed to isolate the rack if not used as shown in Fig. 13. While the “collection-to-storage” loop is a pressurized closed loop with 50:50 propylene glycol/water-based

solution, the “storage-distribution” transfers heat with pure water in an open and unpressurized loop.

#### 2.2.3 System Performance

Preliminary test results showed that 16 kg of firewood and 7.7 kg of feedstock (0.5 of woodchip to firewood ratio (WFR)) produced stable pyrolysis and complete biochar in the kiln. Additional tests were conducted with the pilot system at ATG Farm to observe the effect of changing this ratio on the pyrolysis process. In order to monitor the process, two thermocouples were inserted into the kiln: one at the combustion room and the other at the top room. Table 1

shows data from the kiln at ATG Farm, from the 2017-2018 period. Since Test (1) ended up with incomplete biochar, a shorter secondary wall that stands about 1 cm away from the back wall was built. It was anticipated that making a downdraft with a secondary wall in the combustion room would increase heat retention time and overall efficiency. Additionally, the secondary wall prevents flames of the burning firewood from directly exiting via the kiln exhaust, thus improving heat transfer to the retort.

Installation of the secondary wall proved helpful and the completed biochar was reliably produced.

Table 2 shows retention time in minutes in the combustion room and heat exchange room for each test at ATG Farm. The heat recovery system has two positions to dump heat via a piping manifold, summer and winter. The summer position is valved to food dehydrator built on the side of the greenhouse, while the winter position is valved to a 1,136-L storage tank called thermal battery. Figs. 14 and 15 depict retention

**Table 1 Inputs and outputs of test-runs.**

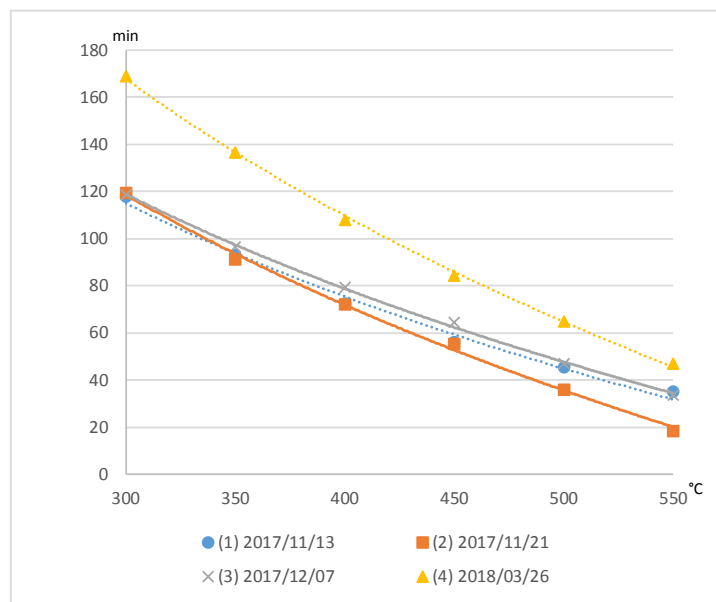
| Tests        | Woodchip used (kg) | Firewood used (kg) | Total biomass (kg) | Woodchip to firewood ratio (WFR) | Biochar produced (kg) | The highest temperature (°C) |
|--------------|--------------------|--------------------|--------------------|----------------------------------|-----------------------|------------------------------|
| (1) 20171113 | 6.7                | 13.6               | 20.3               | 0.49                             | 3.58 (53%)*           | 682.3                        |
| (2) 20171121 | 4.0                | 13.8               | 17.9               | 0.29                             | 1.77 (44%)            | 598.1                        |
| (3) 20171207 | 7.0                | 14.0               | 21.0               | 0.50                             | 2.81 (40%)            | 622.5                        |
| (4) 20180326 | 5.9                | 17.7               | 23.6               | 0.33                             | 2.28 (39%)            | 629.6                        |

\* incomplete biochar.

**Table 2 Retention time in minutes.**

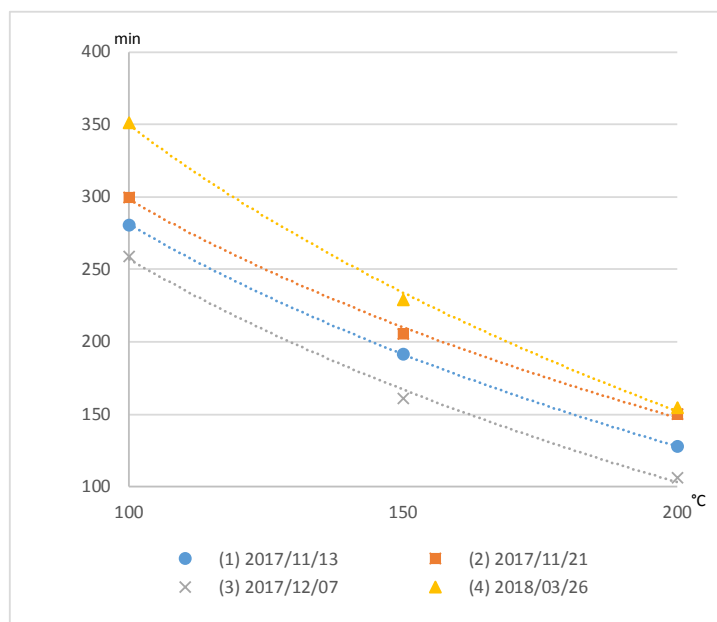
| Tests        | Combustion room (°C) |     |     |     |     |     | Heat exchange room (°C) |     |     | Heat dumping to |
|--------------|----------------------|-----|-----|-----|-----|-----|-------------------------|-----|-----|-----------------|
|              | 300                  | 350 | 400 | 450 | 500 | 550 | 100                     | 150 | 200 |                 |
| (1) 20171113 | 118                  | 93  | 73  | 56  | 46  | 35  | 281                     | 192 | 128 | FD*             |
| (2) 20171121 | 120                  | 91  | 72  | 56  | 36  | 19  | 300                     | 206 | 151 | FD*             |
| (3) 20171207 | 119                  | 97  | 80  | 65  | 47  | 34  | 260                     | 162 | 107 | TB**            |
| (4) 20180326 | 169                  | 137 | 108 | 85  | 65  | 47  | 352                     | 229 | 155 | TB**            |

\* food dehydrator; \*\* thermal battery.

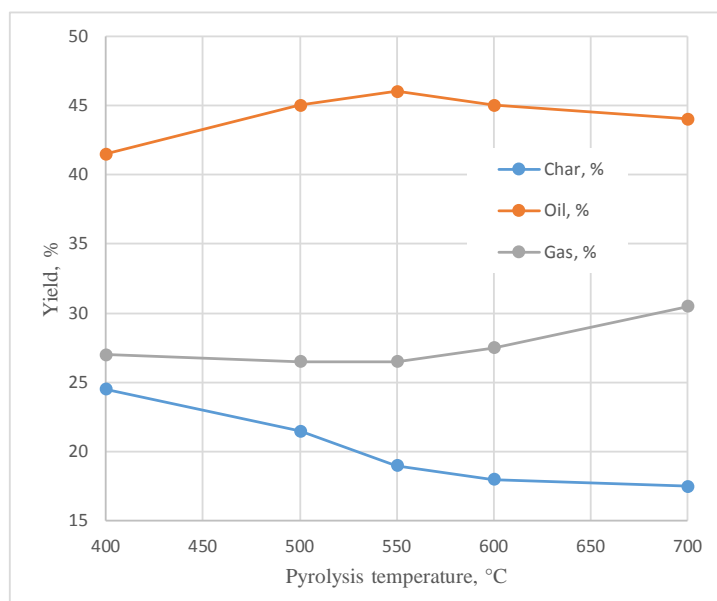


**Fig. 14 Retention time at combustion room.**

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**Fig. 15** Retention time at heat exchange room.



**Fig. 16** Proportional yields of end products in slow pyrolysis of rapeseed [10].

time in the combustion room and heat exchange room for each test. Tests (1) and (3) which had nearly the same amount of firewood and feedstock, show very close retention time values at each temperature range. However, Test (3) with secondary wall produced complete biochar while Test (1) without secondary wall ended up with incomplete biochar. Tests (2) and (4) with a WFR of 0.3 present a greater change in retention time from lower to

higher temperature range compared to Tests (1) and (3) with a WFR of 0.5. Test (4) used the most amount of firewood, and presents the highest retention time among four tests. However, firewood effect is clearer at the lower temperature range than the higher temperature range. Test (4) has 50 min longer retention time at 300 °C than other tests, but its retention time value gets closer to those of Tests (1) and (3) at 550 °C.



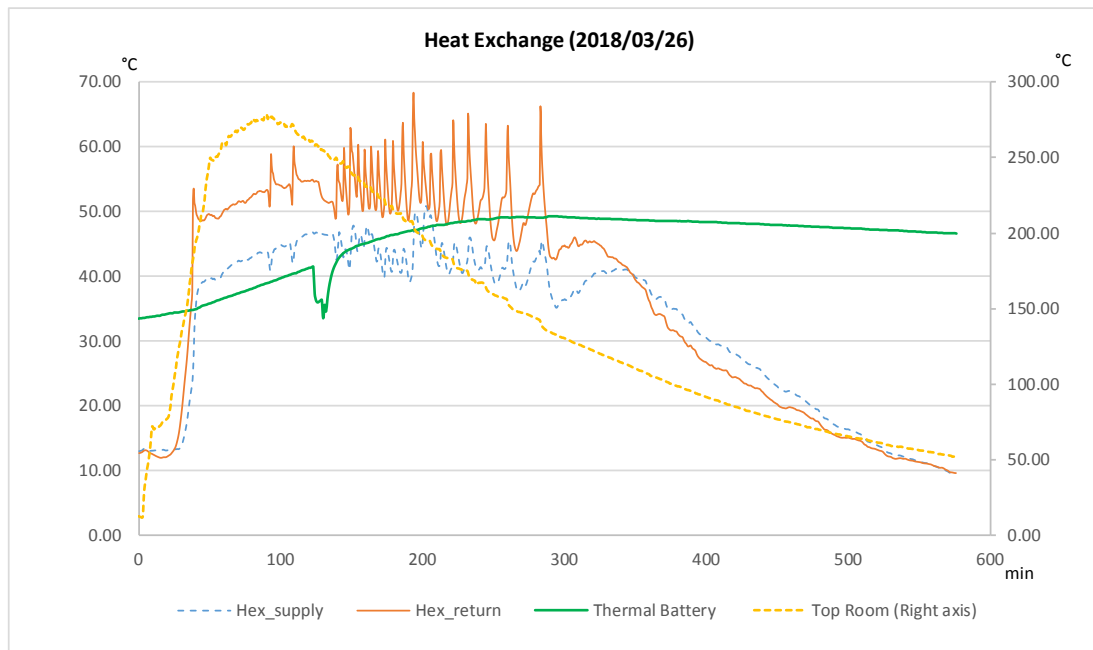


Fig. 17 Temperature data of heat exchange during the kiln operation at ATG Farm.

Table 3 Thermal data of thermal battery during the kiln operation on March 26, 2018.

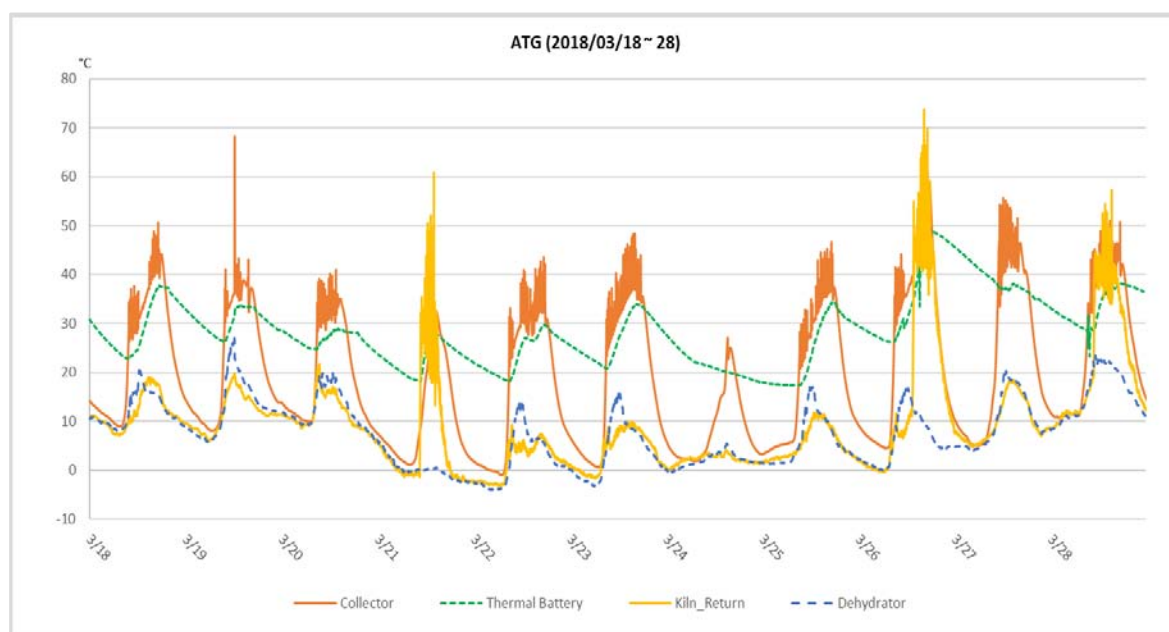
|   |                                     |           |
|---|-------------------------------------|-----------|
| Thermal battery                                       |                                     |           |
| Thermal battery temperature during the kiln operation | T1 (41 min)                         | 34.9 °C   |
|   | T2 (290 min)                        | 49.2 °C   |
|   | $\Delta T$ (temperature difference) | 14.3 °C   |
| Low thermal battery temperature of the day            |                                     | 26.3 °C   |
| Water volume  |                                     | 802 L     |
| Water mass  |                                     | 802 kg    |
| Total BTU gained during the operation                 |                                     | 47.812 MJ |

Fig. 16 shows relative proportions of the end products after slow pyrolysis (30 °C/min of heating rate) of rapeseed with temperature [10]. The yield of bio-oil tends to increase up to 550 °C, and the yield of syngas increases at higher temperature ranges. Bio-oil has a heating value of 16-17 MJ/kg [11]. Syngas has a heating content of 4.5 MJ/m<sup>3</sup> [12]. Retaining longer retention time at around 550 °C can increase yields of gaseous bio-oil and syngas. It would help efficient pyrolysis process in the system, since the kiln utilizes produced syngas and gaseous bio-oil as fuel simultaneously.

Based on those test-runs, it was found that amount of firewood affects retention time on lower temperature range while amount of feedstock affects retention time on higher temperature range. It means using minimal amount of firewood to maximize WFR

as possible can improve fuel efficiency of the system. In order to determine the optimal amount of firewood required for the kiln size, more tests are need to be done by increasing the amount of woodchip or reducing the amount of firewood (i.e., increasing WFR).

Fig. 17 shows four temperature data during the kiln operation on March 26, 2018: (1) top room where heat exchange occurs between flue gas and heat exchange fluid; (2) thermal battery where heat exchange occurs between heat exchange fluid and water; (3) supply temperature toward the top room; (4) return temperature from the top room. As shown in Table 1, 17.7 kg of firewood and 5.9 kg of woodchip were used for the kiln operation on March 26. Two heat exchangers captured about 48 MJ of heat during the



**Fig. 18** Temperature data of each component of the pilot system at ATG Farm.

**Table 4** Heat gain in thermal battery at ATG Farm from March 18 to 28, 2018.

|                       | Mar. 18 | Mar. 19 | Mar. 20 | Mar. 21 | Mar. 22 | Mar. 23 | Mar. 24 | Mar. 25 | Mar. 26      | Mar. 27 | Mar. 28 |
|-----------------------|---------|---------|---------|---------|---------|---------|---------|---------|--------------|---------|---------|
| $\Delta T$ in TB (°C) | 15.0    | 7.3     | 4.2     | 9.9     | 11.8    | 13.3    |         | 16.4    | 22.6         | 1.1     | 9.4     |
| Low TB temp. (°C)     | 22.8    | 26.2    | 24.8    | 18.1    | 18.1    | 20.8    |         | 17.3    | 26.3         | 36.7    | 28.6    |
| Heat gain in TB (MJ)  | 50.4    | 24.7    | 14.2    | 33.4    | 39.8    | 44.8    | -       | 55.3    | 76.0         | 3.5     | 31.8    |
| Pump 1 (collector)    | on      | on      | on      | off     | on      | on      | off     | on      | partially on | on      | on      |
| Pump 2 (kiln)         | off     | off     | off     | on      | off     | off     | off     | off     | on           | off     | on      |
| Low temp. (°C)*       | 5.2     | 5.2     | 4.4     | -4.4    | -4.8    | -4.1    | -1.2    | 0.1     | -2.2         | 1.9     | 10.4    |
| High temp. (°C)*      | 15.0    | 18.4    | 15.8    | 4.2     | 3.3     | 6.6     | 2.7     | 6.2     | 6.2          | 17.9    | 21.0    |
| Heating degree days*  | 8.8     | 7.9     | 8.5     | 20.6    | 19.8    | 17.4    | 18.1    | 16.4    | 16.3         | 10.8    | 3.7     |

$\Delta T$ : temperature difference; TB: thermal battery; \* retrieved from local weather stations (raysweather.com).

burn (Table 3). Total heat captured from the solar collector and the kiln on March 26, 2018 was about 77 MJ.

Overall temperature data of the pilot system (i.e., solar collector, thermal battery, kiln and food dehydrator) at ATG Farm from March 18 to 28, 2018 are shown in Fig. 18. Since the food dehydrator was turned off and sitting outside, the temperature data of food dehydrator can be considered as outside ambient temperature. Table 4 shows heat gains, calculated based on thermal battery temperature as well as weather data obtained from local weather stations (raysweather.com). Notice that since it was cloudy

and cold on March 21, no heat was gained from the solar collector but the biochar kiln was run and 33.4 MJ of heat was collected from it. It was sunny (but cold at night) on March 22 and 23, so 39.8 MJ and 44.8 MJ of heat were gained from the solar collector, respectively. March 24 was also cloudy and cold, so there was no heat gained from the solar collector and the kiln was not run either, so the temperature of the thermal battery dropped to 17.3 °C the next morning. The system collected 55.3 MJ of heat on March 25 from the collector (Table 4).

Even though the solar collector temperature was lower on March 25 than on March 23 (Fig. 18), more

heat was gained on March 25 because the early morning thermal battery temperature was lower on that day as shown in Table 4 (17.3 °C vs. 20.8 °C). In addition, there was only 3.5 MJ of heat gained on March 27 despite relatively high collector temperature (Fig. 18). This is because the high heat (76 MJ) gained from the solar collector and the kiln on March 26 was not radiated much at night (i.e., the ambient temperature in the greenhouse was not cold enough). Due to the remaining heat in the thermal battery, the temperature of the thermal battery kept over 36.7 °C in the early morning on March 27. As a result, the system did not collect heat from the solar collector until its temperature exceeded 43.5 °C due to the setting of the differential controller. This is not a very efficient way of collecting heat, so it is important to lower the temperature of the thermal battery by dumping/radiating heat from the thermal battery at night. In this way, the system can efficiently collect heat from both the solar collector and the kiln.

### 3. Conclusions

The research team has begun collaboration with two local farms in Watauga County, NC, USA to transfer the technology developed at the Nexus greenhouse facility to extend the growing season. Agricultural economic growth should be derived from technology transfer. Two local partner farms (Springhouse Farm and ATG Farm) participated in this study. After assessing their resources, a unique greenhouse heating system for each farm was designed and built. The heating system includes a solar collector, a biochar kiln, a heat storage (water heater/thermal battery), a food dehydrator and RZH tables. According to the first year (2018) data collected from Springhouse Farm, propane consumption was 43% lower than in 2017. Since ATG Farm did not have any greenhouse heating system until 2017, there are no data available to compare the energy consumption before/after the system installation. However, the first year (2018) data show that the thermal battery installed in ATG

Farm has consistently collected heat from the solar collector and biochar kiln and radiated it inside the greenhouse. The next step is to upgrade the RZH tables by replacing the table cover material (more air tight). Additionally, the overall system cost will be estimated and ultimately a list of actions that will benefit the most, based on cost/benefit will be developed. It is believed that on-farm field demonstration will promote farmers' interest in an affordable and efficient sustainable energy greenhouse heating systems.

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### Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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