Modeling and Control of a Solar-heated Greenhouse with Auxiliary Heat Pump

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We investigate the energy utilization strategy of an experimental solar-heated greenhouse that equips with 70 flat-panel solar thermal collectors. The greenhouse is designed to operate with an auxiliary heat pump system, which uses electricity to back up the solar input insufficiency during the night or through low-solar-radiant weather. Our work focusses on developing a control mechanism that can minimize the usage of electricity or other fossil-fuel energy based on optimization methods. The main contribution of this control system is that the control mechanism can adapt to future changes of heat loss, solar energy supply, and coefficient of performance (COP) of the heat pump using weather forecast information, such as ambient temperature and solar radiation. The numerical results show that our optimal dynamic control mechanism can reduce 15~20% of the cost to operate an auxiliary heat pump while providing adequate energy supply to support greenhouse production.

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I. INTRODUCTION

Population growth needs increasing agricultural product production in all climates. As a result, greenhouses are commonly used to achieve this goal. However, to control the growth micro-climate within, greenhouses are also one of the most energy demanding sectors in the agricultural industry. Commercial greenhouses are used to grow higher-quality plants and to protect them against natural elements such as wind or rain. Another benefit of utilizing a greenhouse is that it allows for out-of-season growing. As a result, greenhouse agriculture is one of the most profitable sectors, with controllable production timing and a higher yield output than that of outdoor horticulture (Vadiee and Martin, 2012, 2013). Greenhouses need a consistent supply of energy, in the form of electricity or fossil fuels for heating, to provide and maintain the environment that will result in optimal crop production with maximum profit. Most greenhouses deal with high operating costs due to the high energy needs. Increasing energy usage in the greenhouse has resulted in non-environmentally sustainable production (Sethi, Sumathy, Lee, and Pal, 2013). The energy needed for heating greenhouses is so significant that it reaches 65-85% of the total energy demand in greenhouse operations. Therefore, a good understanding of the energy utilization in the commercial greenhouse sector and moving towards the use of solar thermal collectors in greenhouses is essential (Taki, Abdi, Akbarpour, and Mobtaker, 2013). The dynamic behavior of a greenhouse climate is a combination of physical processes involving energy (radiation and heat) and heat transfer (heat transfer fluid or water vapor fluxes) taking place in the greenhouse, and goes to the outside environment. These processes depend on the outside weather, greenhouse structure, crop type, state of growth, and the overall control of the system (Taki, Ajabshirchi, Ranjbar, Rohani, and Matloobi, 2016).

This study investigates an experimental solar-heated greenhouse located in Shandong China. As shown in Fig. 1 and Fig. 2, the total area of this greenhouse is about 770 m^2 (11m x 70m) and the planting area is about 620 m^2. Constructed in the summer of 2019, the greenhouse is equipped with 70 flat-panel solar thermal collectors, and each collector has 1.85 m^2 of surface area (or total of 130m^2 solar collecting area). The greenhouse is also equipped with a thermal energy system that uses an underground water tank to store and distribute heat captured by solar radiation or produced by an auxiliary heat pump through underground U-tube heat exchangers. During planting seasons, thermal energy is delivered via the heat exchange tubes placed on the plants shelves and in the soil. The greenhouse has a south-facing tilted roof covered with 2 mm of polyester (PE) plastic film. The south facing roof is covered with an R6 thermal blanket on top of the PE film during the night. The under-floor system consists of buried pipes placed 12 inches deep in the soil. Considerable soil depth is required to avoid damage from tillage equipment. The control system consists of a sensor, a signal receiver, a processor, and an actuator to control the energy supply. Besides the energy control mentioned above, a greenhouse also needs to monitor and control conditions such as air humidity, CO_2 levels, soil moisture, pH levels, etc. in a timely manner.

To maintain the energy balance in a greenhouse, the total heat loss must equal the total heat demand provided by an energy supply system connected to solar thermal collectors and heat pumps that produce hot water that is distributed through heat exchangers, piping, or radiators. The greenhouse is designed to operate with an auxiliary heat pump system, which uses electricity to back up the solar input insufficiency during the night or through low-solar-radiant weather.

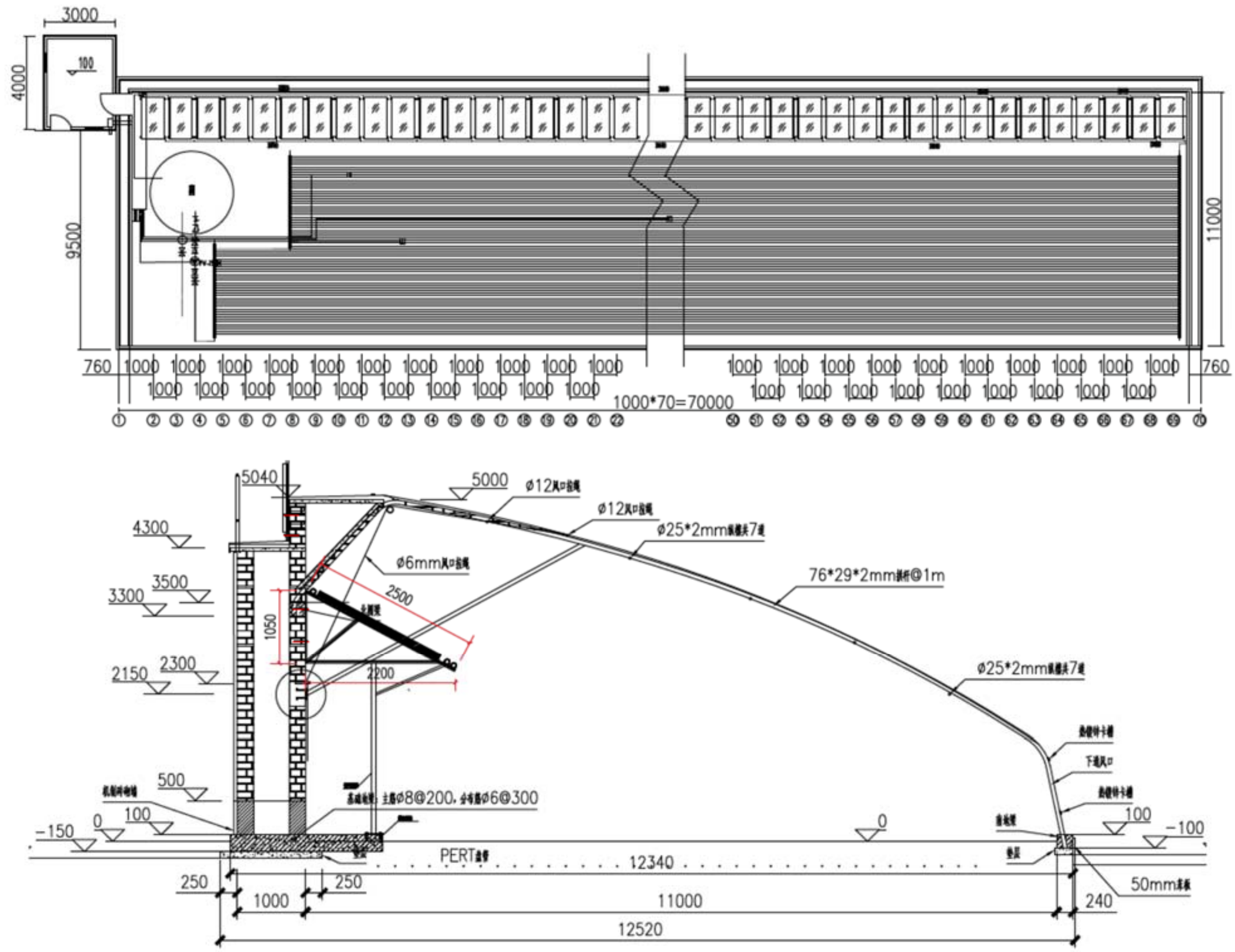

FIGURE 1. GREENHOUSE ACHITECHAL DESIGN.

In current greenhouse engineering or system simulation research, the control mechanisms are still based on some rule-based approaches. For example, the control policy is mostly determined by fixed time schedules or plans. The aim of this work is to develop a dynamic control policy based on real-time forecasts, such as temperature, solar radiation, and energy demand, using an optimization model to minimize the cost of consuming supplement fossil fuel energy such as electricity or natural gas. In order to keep the temperature at the required level, the greenhouse can be described as an energy balanced system in which the combined energy supply from solar and electricity should match the total heat loss in the forms of radiation, conduction, or convection. The main limit of solar energy supply is that solar is only available when the sun is shining. Even there are some energy storage technologies to help match the solar energy supply with demand, supplement fossil fuel energy supply is needed when solar energy is not sufficient. However, the usage of fossil fuel is costly and not environmental friendly. The goal of our model is to optimize the usage of supplement fossil fuel so that the total cost of consuming fossil fuel can be minimized.

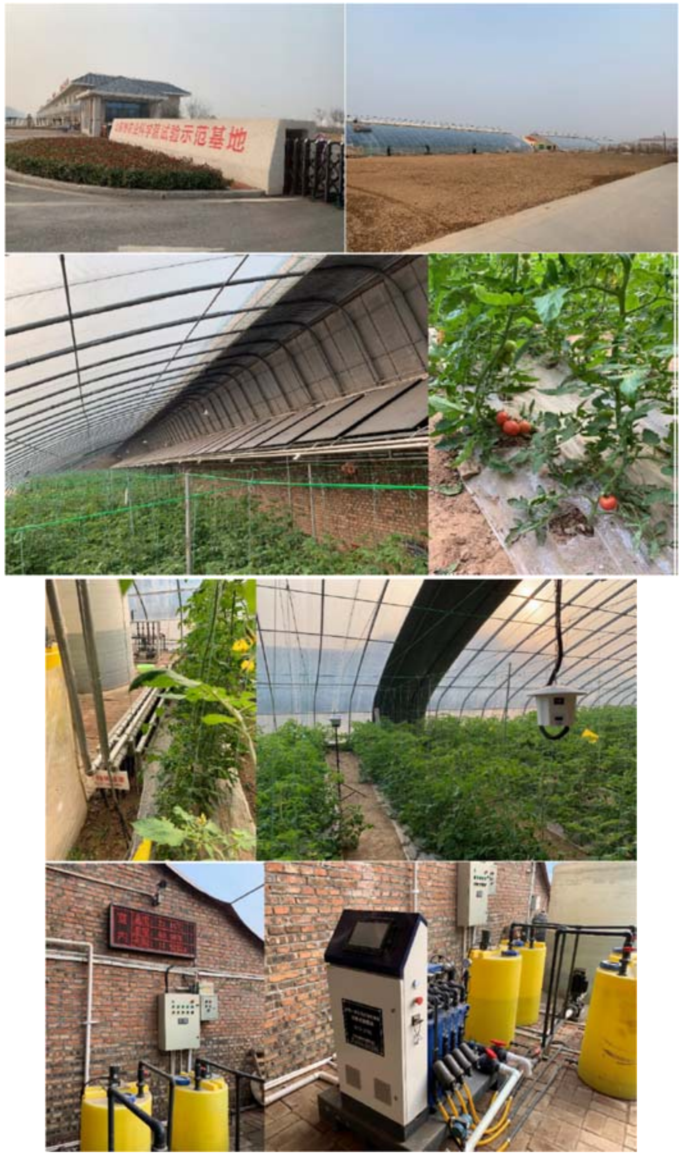

FIGURE 2. GREENHOUSE INTERIAL AND EXTERIAL PICTURES.

The main contribution of this control system is that the control mechanism can adapt to future values of heat loss, solar energy supply, and coefficient of performance (COP) of the heat pump using weather forecast information, such as ambient temperature and solar radiation. Our model provides an optimal dynamic control mechanism that can minimize the cost of operating an auxiliary heat pump while providing adequate energy supply to sustain a greenhouse production. The optimization of the dynamic control mechanism is based on real-time forecasts of ongoing weather conditions within a rolling window of finite future, such as a 24-hour or 48-hour period. The iterative feature of our model uses the prediction of demand, solar energy supply, and the prediction of COP values within this rolling time window, and relies on the forecasted temperature and solar radiation to create a control mechanism that optimizes energy usage. Since the forecast is most accurate for the immediate future and the actual values of these parameters can be observed at the end of each period, fossil fuel usage can be managed and minimized through iterative optimization of our planning model. Specifically, at time period *t*, the parameters are forecasted and an optimal policy is calculated by minimizing the cost over the entire predictive horizon, while only the first period of the policy is applied. At the next period *t*+1, the parameters period *t* is updated with observed values and the optimization is redone to get a new strategy based on updated set of predictive set of parameters.

II. LITERATURE REVIEW

In general, a greenhouse can be described as an energy balance system in which the main parameters involved are a solar efficiency factor and an overall energy loss coefficient. In recent years, most of the models in renewable energy or in building engineering use simulation-based methods to determine the desirable combination of thermal collector area and greenhouse design. Specifically, systems are modeled in a variety of simulation software packages, such as TRNSYS, DYMOLA, POLYSUN, and DeST (Guo, Zhang, Shan, and Yang, 2018). In these simulation-based models, a large variety of design parameters, such as thermal collector type, circulation flow rate, tank water temperature, heat exchanger area, as well as the optimum size of solar collectors and storage tanks could be optimized by evaluating system performance parametrically (Hobbi and Siddiqui, 2009; Hang, Du, Qu, and Peeta, 2013; Zainine, Mezni, Dakhlaoui, and Guizani, 2017). Among those simulation models, Xu, Li, Wang, and Liu (2014) reported the performance analysis of a demonstrated solar-heated greenhouse equipped with a seasonal thermal energy storage system in Shanghai, China. Cossu et al. (2014) assessed the climate conditions inside a greenhouse in which 50% of the roof area was replaced with solar modules, describing the solar radiation distribution and the variability of temperature and humidity. Wang et al., (2017) presented research for reviewing the changing volumetric thermal capacity and thermal conductivity of a hollow block wall by filling soil and perlite into the cavities to improve wall thermal performance. Zhou, Yu, Yi, and Liu (2017) proposed an approach that stores solar energy during the daytime, provides heat using earth-tubes at night, and then applies the heat to a plastic greenhouse to elevate the inside air temperature. Zhang et al. (2017) analyzed a design of solar energy storage and heating system as well as the thermal performance analysis of greenhouses. A comprehensive review can be found in (Taki, Rohani, and Rahmati-Joneidabad, 2018) focusing on key strategies of energy saving technologies based on simulation of heat and mass transfer and using artificial intelligence for climate control. A great number of comparative studies are involved in this method, however, simulating all the cases with possible combinations of system parameters one-by-one can be very time-consuming because it may be difficult for designers to determine all of these parameters before determining the greenhouse design and the size of the solar collectors (Yan, Wang, Ma, and Shi, 2015).

Many advanced control techniques have attracted the attention of many researchers in solar power systems (Camacho, Eduardo, Rubio, and Berenguel, 2007). Most of these techniques control the outlet temperature by changing the heat transfer fluid flow rate (Silva, Rato, Lemos, and Coito, 1996). In order to align solar energy production and consumer demand, energy storage technologies are developed with several applications (Dincer and Rosen, 2002). The usage of thermal energy storage creates another manipulated variable: the flow rate from the storage tank to the load heat exchanger. Powell and Edgar (2012) develop a two-tank-direct method for the thermal energy storage and study the interaction between the storage component and other component of the system.

Model-based predictive control has become a popular control scheme in many research areas (Steinboeck, Graichen, Wild, Kiefer, and Kugi, 2010; Karer et al., 2008; Linder and Kennel, 2005). In our study, we develop the optimal usage policy for supplemental electricity energy using an optimization model based on predictive information. Since most of the information needed to develop the control scheme is based on predictive data, predictive control offers a better chance of achieving energy efficient control for buildings (Ferhatbegović, Tarik, Zucker, and Palensky, 2011). For instance, Oldewurtel et al. (2010) developed and analyzed a Stochastic Model Predictive Control strategy for building climate control that considers weather predictions in order to increase energy efficiency. In our study, the predictive feature of the model is mainly based on the future values of heat loss, solar energy supply, and the coefficient of performance (COP) of the heat pump because the values of these parameters are mainly based on predictive information about weather changes, such as ambient temperature and solar radiation.

Using electricity energy to backup the solar energy shares similarity on a dual-sourcing model studies under numerous supply chain management literature. In this application, the solar energy supply can be viewed as a cheap but unreliable supplier, while the electricity supply can be viewed as an expensive but reliable supplier. The unreliability of solar energy mainly shows on two factors. First is on random capacity (Yang, Jian, Qi, and Xia, 2005; Feng and Shi 2012; Li, Tao, Sethi, and Zhang, 2013). Second is on random yield (Tomlin, 2009; Li and Zheng 2006). Random yield is a major issue for solar energy supply as under different weather conditions, the solar energy could be collected by the greenhouse fluctuate a lot. Various strategies have been used to mitigate the supply risk. For example, Kouvelis and Li (2012) study an offshore outsourcing arrangement for a buyer of a produced good in the presence of supply yield uncertainty. Wang, Yimin, Gilland, and Tomlin (2010) investigate when should a firm exert effort on improving supplier reliability. In our study, electricity energy is selected as a supplemental energy source when solar energy is unavailable. However, as an unrenewable fuel, electricity is more expensive than solar energy. When the demand considered in our study is continuous, multiple research papers already prove that it is optimal to select the cheaper supplier before the more expensive one (Dada, Maqbool, Petruzzi, and Schwarz, 2007; Burke, Gerard, Carrillo, and Vakharia, 2007; Federgruen and Yang, 2009). Among these papers, Dada, Maqbool, Petruzzi, and Schwarz (2007) consider the problem under a newsvendor setting, while Federgruen and Yang (2009) analyze a planning model for a firm or public organization that needs to cover uncertain demand for a given item by procuring supplies from multiple sources. In our study, as the solar energy supply is considered as the cheap but unreliable supplier, so the electricity is considered as the supplement energy to fill the gap between energy demand and solar energy supply.

III. MODELING

In this section we develop a mathematical model which provides an optimal dynamic control mechanism that can minimize the cost of operating an auxiliary heat pump while providing adequate energy supply to sustain a greenhouse production.

3.1. System Structure

Fig. 3 represents the structure of the energy system in the greenhouse. The goal of keeping the output temperature close to the desired temperature during period t is to supply enough greenhouse energy demand D_t that is needed to keep the temperature at the desired level. To meet the energy demand, the greenhouse needs an energy supply from a passive source of solar radiation (S_t) and an active source of energy (x_t) generated by auxiliary heat pumps using electricity.

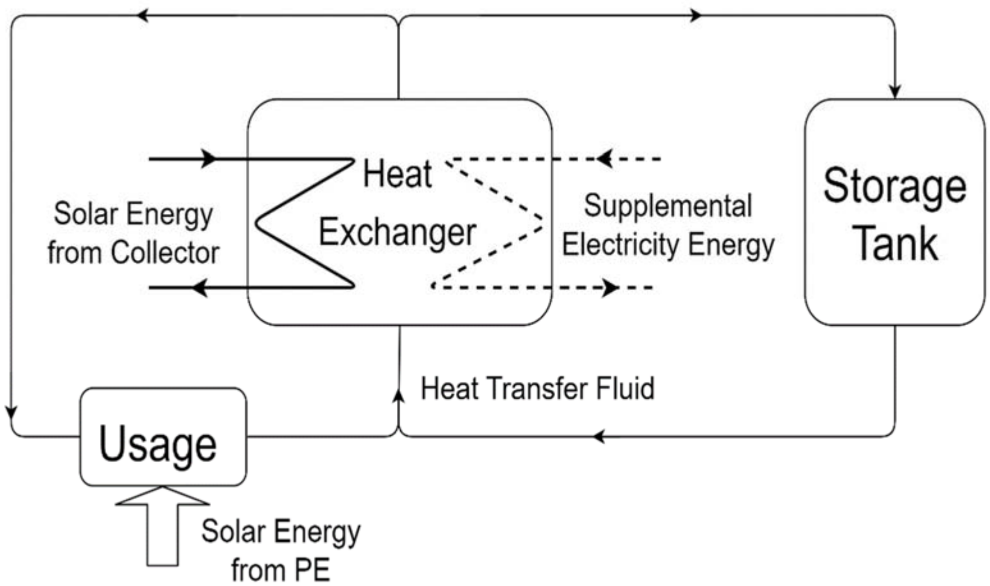

FIGURE 3. THE GREENHOUSE THERMAL SYSTEM STURCTURE.

The solar energy supply is a combination of the solar energy supply coming through the PE film S_t^{pe} and the solar energy supply collected by solar thermal panels S_t^c. Although S_t^{pe} and S_t^c are both energy supplied by the radiation from the same sun, the effects of S_t^{pe} and S_t^c are quite different. This greenhouse has a south-facing tilted roof covered with 2 mm of polyester (PE) plastic film. S_t^{pe} represents the solar energy supply coming through the PE film that directly reaches the surface of the crop, soil, or wall. This S_t^{pe} is the driving force of the photosynthesis process and the main source of energy used to maintain the air temperature inside of the greenhouse during the day. In contrast, S_t^c represents the solar energy collected through the solar thermal panels and absorbed by heat transfer fluid. The heat transfer fluid then circulates through underground pipes buried 12 inches below the surface to maintain the underground soil temperature. The heat transfer fluid can also be used to exchange excessive heat into a heat storage tank. In other words, S_t^c can be used as energy storage for the next period while S_t^{pe} cannot.

A major limitation of solar energy is that it is not always available when needed. In some situations, S_t alone is not enough to satisfy the energy demand D_t. Another limit of solar energy is that its supply is unreliable, as it is affected by many uncontrollable factors such as cloud covers. The energy gap between energy demand and solar energy supply can be fulfilled using a supplemental source of energy (A_t) generated by auxiliary heat pumps using electricity and the energy storage (I_t) in the heat storage tank. Based on the energy balance equation, we have

$$min(S_t^{pe}, D_t) + S_t^c + A_t + I_{t-1} = D_t + I_t. \quad (1)$$

When demand is continuous, it has been repeatedly shown in the literature that, regardless of the suppliers' reliability, it is optimal to select the cheaper supplier instead of a more expensive supplier. Compared to solar energy, the usage of fossil fuels is costly and not environmentally friendly. Thus, we assume that the greenhouse will utilize as much solar energy as possible. The goal of our model is to optimize the usage of supplement fossil fuels so that the total cost of consuming fossil fuels can be minimized. Before we discuss the optimization model, we will first describe three key parameters: *Dt, St,* and *COP*. The values of these three parameters are decided by the dynamic behavior of a greenhouse climate, which is affected by outside weather and greenhouse structure.

3.2. Parameters D_t, S_t and COP for Production Planning

This section describes two key parameters applied in our production-planning model. The first parameter, D_t, represents the greenhouse heat demand at time t and the second parameter, S_t, is the solar energy supply at time t.

To keep the energy balance in a greenhouse (i.e., to maintain required air or soil temperature in a greenhouse), the heat demand or heat load, D_t, must be equal to the total heat loss of the greenhouse. The heat loss calculation summarizes all of the heat transfer mechanisms that include radiant heat loss, conduction heat loss, and convection heat loss (i.e., air infiltration) through the greenhouse PE film, wall and ground, perimeter, as well as the gaps causing air infiltration. Specifically,

$$D_t = \textit{total heat loss} = h_{\mathrm{Lpe}}(t) + h_{\mathrm{Lwg}}(t) + h_{\mathrm{Lpm}}(t) + h_{\mathrm{Lcv}}(t) \quad (2)$$

Where,

$h_{\mathrm{Lpe}}(t) = A_{\mathrm{pe}}U_{\mathrm{pe}}\,[T_{\mathrm{i}}(t) - T_{\mathrm{o}}(t)]$

$h_{\mathrm{Lwl}}(t) = A_{\mathrm{wl}}U_{\mathrm{wg}}\,[T_{\mathrm{i}}(t) - T_{\mathrm{o}}(t)]$

$h_{\mathrm{Lpm}}(t) = P\,U_{\mathrm{pm}}\,[T_{\mathrm{i}}(t) - T_{\mathrm{o}}(t)]$

$h_{\mathrm{Lcv}}(t) = 0.02\,M\,[T_{\mathrm{i}}(t) - T_{\mathrm{o}}(t)]$

$T_{\mathrm{o}}(t)$ = Forecasted temperature outside of greenhouse at time t

$T_{\mathrm{i}}(t)$ = Required temperature inside of greenhouse at time t

$h_{\mathrm{Lpe}}(t)$ = heat loss rate (kW) through PE film at time t

$h_{\mathrm{Lwg}}(t)$ = heat loss (kW) through wall and ground at time t

$h_{\mathrm{Lpm}}(t)$ = heat loss (kW) through the greenhouse perimeter at time t

$h_{\mathrm{Lcv}}(t)$ = heat loss (kW) through air convection or infiltration at time t

A_{pe} = polyester (PE) film area, m^2

U_{pe} = heat transfer coefficient through polyester, kW-°C-m^2

A_{wg} = wall and ground area, m^2

U_{wg} = heat transfer coefficient through wall and ground, kW-°C-m^2

P = perimeter, m

U_{pm} = heat transfer coefficient through the perimeter, kW-°C-m

M = air exchange/infiltration rate, m^3/hr

Other than the constant energy transfer coefficients and geometric dimensions, the estimated heat demand D_t (or the total heat loss) of a greenhouse at time t is dynamically affected by $T_o(t)$ (the forecasted temperature outside of greenhouse at time t) and $T_i(t)$ (the required temperature inside of greenhouse at time t). Depending on the type of crop and its growth stage, $T_i(t)$ is set to maintain an optimal average growth temperature for both air and soil, and to keep the greenhouse temperature within the maximum and minimum temperature shocks at any time in order to avoid irreversible negative impacts on crop growth. Besides the energy control mentioned above, a greenhouse also needs to monitor and control conditions such as air humidity, CO_2 levels, soil moisture, pH levels, etc. in a timely manner.

The calculation of S_t^{pe} is shown in (3). The light transmission of this 2 mm PE film is about 90% when it is new, but the light transmission will decrease to 80% by the end of its 4-year expected lifetime. As a result, we estimate the average light transmission of the greenhouse roof to be 85%. The solar energy supply, S_{pe}, through the PE film area is used mainly for maintaining the air temperature inside of the greenhouse.

$$S_t^{pe} = 0.85\, R(t)\, (A_{pe} - A_c)\, (1 - E_m) \quad (3)$$

Where,
$R(t)$ = forecasted solar radiation at time t, kW/m2
A_c = solar thermal collector area, m^2
E_m = overall emissivity of greenhouse outer surface

The emissivity E_m is defined here as the ratio of the energy radiated from a subject's surface to that radiated from a perfect emitter or blackbody. The measurements of the overall greenhouse are as follows: $E_m = 0.35$, $A_{pe} = 805$ m^2, $A_c = 130$ m^2, and $R(t)$ is about 0.85 kW/m^2 when it is sunny and about 0.35 kW/m^2 when it is cloudy.

Obtaining a detailed thermal analysis of the solar energy collected through the solar thermal panels is a complicated process. A common numerical model known as the Hottel-Whillier-Bliss equation (Dović, Damir, and Mladen, 2012) provides a simplified but useful calculation of the solar energy supply, S_t^c, collected through solar thermal panels. Equation (4) shows a modified Hottel-Whillier-Bliss equation, in which the solar energy is collected by the solar thermal panels and then transferred to the heat transfer fluid. Part of the solar energy is lost, and this loss is defined as the heat transfer from the solar panel surface to the ambient air in the greenhouse. Specifically, the solar energy supply, S_t^c, is expressed as a function of the inlet temperature of fluid, components and geometry of solar thermal panels, and the ambient conditions. When applying the Hottel-Whillier-Bliss equation, it is common to assume F_R as a constant for a given collector temperature and heat transfer fluid flow rate. In practice, F_R can be experimentally evaluated based on collector design parameters and collector performance in the field.

$$S_t^c = F_R\, A_c\, \{R(t)\, f_c - U_c\, [T_c(t) - T_i(t)]\} \quad (4)$$

Where,
F_R = collector heat removal factor (assumed as a constant, verified in a field test)
A_c = collector area, m^2

U_c = heat transfer coefficient through collector surface, kW-°C-m^2
f_c = (transmission coefficient of collector glazing) x (absorbing coefficient of collector surface)
$T_c(t)$ = collector operation (inlet fluid) temperature at time t

The estimated solar energy supply S_t (sum of S_t^{pe} and Stc) of a greenhouse at time t is dynamically affected by R(t) (forecasted solar radiation), Ti(t) (the required temperature inside of greenhouse at time t), and Tc(t) (collector operation temperature) at time t. It is estimated that in each operation year, an average of 93.9 GJ (or 26.3 MWh) of solar energy is harvested by the greenhouse, while about 45 GJ (or 12.6 MWh) is produced by a heat pump system for greenhouse heating. The greenhouse measures boundary conditions every minute to monitor the solar radiation, outside ambient temperatures, and soil temperature 1 m below the soil surface. We estimated that this system was capable of maintaining an average interior air temperature of 17 °C and an average soil temperature of 18 °C when the outside ambient temperature is at its lowest, at about −12 °C (which is generally taken as 5°C below the average minimum temperature during the winter). The overall ECOP (electrical coefficient of performance) of an entire operation year is expected to be 7.8, indicating a better performance than the common heat pump heating system.The selection of heating equipment depends on the size and type of greenhouse operation, structures, and availability and cost of fuel system components. A system is made up of an array of solar thermal collectors, electric heat pump units, heat exchanger, distribution, and controls that are powered by electricity. The greenhouse equips with an auxiliary heat pump system with average COP 4.5 at 10C and COP 2.5 at -5C. The electric heat pump units is located outside of the greenhouse. The air-source heat pump is coupled with solar thermal panel system that connect to a ground heat exchanger (GHE) with pipe loops buried at 1 foot of depth. The heat from solar thermal panels and/or heat pumps are delivered to the crops by convection and radiation.

If the influence of ambient temperature on the energy consumption is ignored, COP of the heat pump can be expressed as function of the inlet water temperature (at the condenser side) and the ambient temperature (at the evaporator side). It is assumed that the condenser inlet water temperature is 45℃, and the atmosphere temperature is Ta, the the COP of heat pump is as follows:

$$COP = f(T_a) = aT_a^2 + bT_a + c$$

Fitting data in Fig.4 by Polyfit in MATLAB, we got a=-0.0007，b=0.0913，c=3.0133, with the square of deviance of 0.0573.

$$COP = -0.0007Ta^2 + 0.0913Ta + 3.0133$$

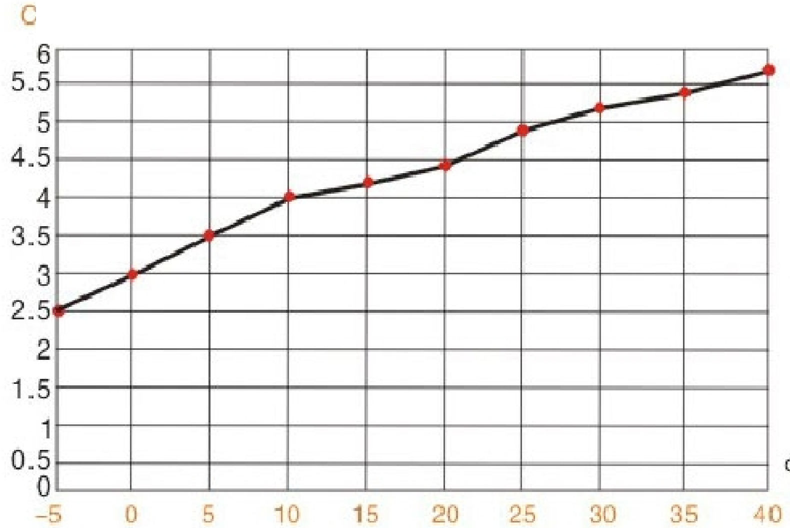

FIGURE 4. COP OF HEAT PUMP UNDER DIFFERENT AMBIENT TEMPERATURE.

3.3. Production Planning Model

The heat pump uses electricity as its energy source to generate additional heat to compensate for the heat loss. Electricity is a non-renewable energy resource. We assume that there is a unit cost u_t and a fixed cost f_t for using a heat pump in period t. Each time the heat pump is started, there will also be a start-up cost F_t charged to setup and reheat the system. We want to minimize the total cost associated with using fossil fuel energy by deciding when to use the heat pump to generate additional heat and how much energy should be used. We use binary variable y_t to model whether or not to use heat pump in period t. When heat pump is turned on, $y_t = 1$; otherwise, $y_t = 0$. We use variable x_t to represent how much electricity will be used by the heat pump in period t. Based on the predictive COP value, we know that $x_t = \frac{A_t}{COP}$.

The values of D_t, S_t and COP are all determined by predictive values of related temperature and solar radiation. The optimization of the dynamic control mechanism for the usage of electricity energy of the heat pump should be based on real-time forecasts of ongoing weather conditions within a rolling window of the next T periods. Based on the predictive values of D_t, S_t, and COP on a T period time horizon (based on equations from section 3.2), the optimization problem for x_t and y_t can be formulated as

$$J_t(I_0, y_0) := \min_{x,y} \sum_{i=t}^{t+T-1} (F_i(y_i - y_{i-1})^+ + y_i f_i + u_i x_i) \quad (5)$$

$$s.t. \quad I_i = \alpha_i\left(min(S_i^{pe}, D_i) + S_i^c + A_i + I_{i-1} - D_i\right) \quad i = t, \dots, t+T-1 \quad (6)$$

$$A_i \le C_i y_i \quad i = t, \dots, t+T-1 \quad (7)$$

$$x_i = \frac{A_i}{COP_i} \quad i = t, \dots, t+T-1 \quad (8)$$

$$I_{t-1} = I_0, y_{t-1} = y_0 \quad (9)$$

$$x_i \ge 0, y_i \in \{0,1\} \quad i = t, \dots, t+T-1 \quad (10)$$

In this formulation, we use $J_t(I_0, y_0)$ to represent the T period planning problem with an initial inventory level at I_0 and the on-and-off state of the heat pump is y_0 ($y_0 = 0$ means the heat pump is off at the start of the planning horizon and $y_0 = 1$ means the heat pump is on at the start of the planning horizon). Equation (5) defines the objective value, which is to minimize the total cost of utilizing the heat pump. As shown in equation (5), the total cost includes three parts: start-up cost, fixed cost, and unit cost. Equation (6) is the energy balance equation. As the heat storage tank is not fully insulted, so there is a heat loss for the energy stored in the tank. We use a discount factor α_t between 0 to 1 to model the heat loss of stored energy in the tank. Equation (7) is the capacity constraints for the heat pump in each period. Equations (8) defines the relationship between the needed electricity and the generated heat energy using the heat pump. Equation (9) defines the initial state of the system at the start of the planning horizon, and equation (10) defines the decision variables.

Since the forecast is most accurate for the immediate future and the actual values of these parameters can be observed at the end of each period, fossil fuel usage can be managed and minimized through iterative optimization of our planning model. Let $V_t(I_{t-1}, x_{t-1})$ be the optimal cost function in period t while planning the control scheme for the next (t+T-1) periods. Then, the dynamic programming equation is given by

$$V_t(I_{t-1}, y_{t-1}) = \min_{x_t, y_t}\{F_t(y_t - y_{t-1})^+ + y_t f_t + u_t x_t + J_{t+1}[\alpha_t(min(S_t^{pe}, D_t) + S_t^c + A_t + I_{t-1} - D_t), y_t]\},$$

where function $J_{t+1}[\alpha_t(min(S_t^{pe}, D_t) + S_t^c + A_t + I_{t-1} - D_t), y_t]$ is the optimization problem defined at equation (5) and starts at period $t+1$ with initial energy storage level at $\alpha_t(min(S_t^{pe}, D_t) + S_t^c + A_t + I_{t-1} - D_t)$ and initial on and off state of the heat pump at y_t. The dynamics of this programming equation can be explained as that at time period t, the parameters are forecasted, and an optimal policy is calculated by minimizing the cost over the entire predictive horizon, while only the first period of the policy is applied. At the next period t+1, the parameter period t is updated with observed values and the optimization is redone to get a new strategy based on updated set of predictive set of parameters.

IV. NUMERICAL EXAMPLES

The optimization model, $J_t(I_0, y_0)$, is a mixed-integer nonlinear problem. Large-scale mixed-integer nonlinear programming models take a long time to solve. In this section, we implement our model into a 24-hour planning horizon with a 12-hour prediction horizon to test how the optimal usage strategy of the heat pump performs compared to the current default strategy used by the greenhouse. Since the greenhouse is newly installed, some parameters are still unavailable for testing, so we simulated the predictive information, including temperature parameters and solar radiation, under each period. Then energy demand, solar energy supply, and COP values were calculated using equations provided in section 3.2 with estimated parameter values. The start-up cost is estimated to be 100 Chinese Yuan as the heat pump needs extra energy for the pre-heat process and turning on the heat pump needs extra setup work from the working staff. We assume that the cost to run the heat pump involves two types of cost, a 20 Chinese Yuan hourly fixed cost and a unit cost of 0.05 Chinese Yuan per kw heat generated. These costs are our current best estimation. However, since the greenhouse is newly installed, the cost parameters might be updated in the future based on new estimations. For example, the start-up cost could decrease as the worker will get more experienced on set-up the heat pump. The fixed cost and unit cost may also be updated if we have a better estimation of the real cost incurs when running the heat pump.

In current practice, the working staff at the greenhouse is scheduled to turn on the heat pump when the solar energy is not enough to keep the greenhouse at the desired temperature level. Due to high estimated start-up cost, the greenhouse worker will keep the heat pump operating over the nigh until the heat storage together with the solar energy is estimated to be sufficient to keep the greenhouse around the desired temperature level. The turn on and turn off time for the heat pump is scheduled based on rule of thumb. Basically, on a sunny winter day, the heat pump will be turn on at 5:30 pm and keep running until 8 am on the next morning. However, on a cloudy winter day, when there is not enough solar energy available, the heat pump will be up from 4:30 pm to the 1:30 pm on the next afternoon. The output quantity from the heat pump is not optimized during the run as currently the worker only set up the heat-pump at a fixed level and leave it keep running until the scheduled turn-off time.

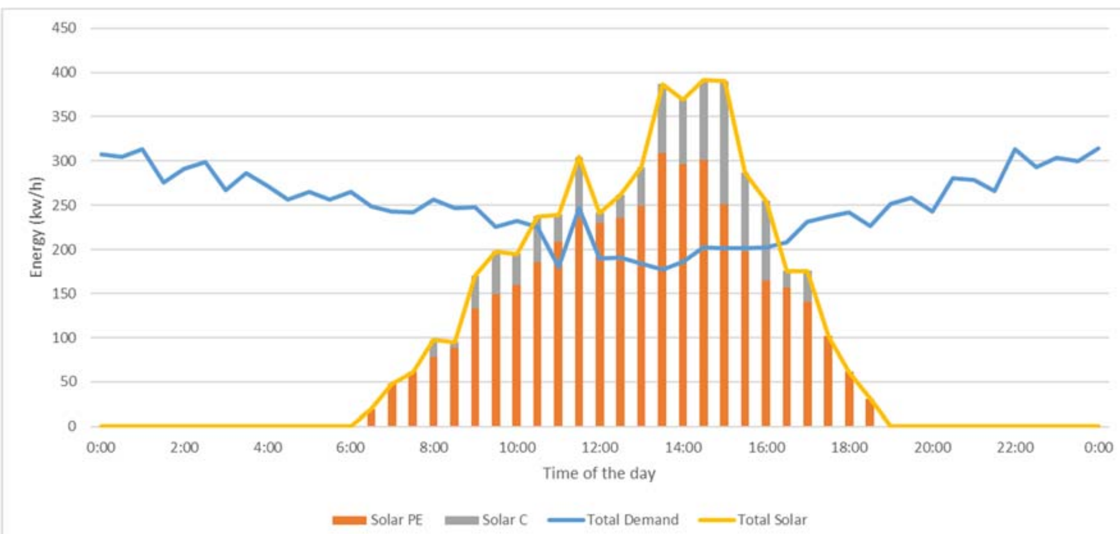

FIGURE 5. TOTAL DEMAND AND SOLAR ENERGY SUPPLY ON A WINTER SUNNY DAY.

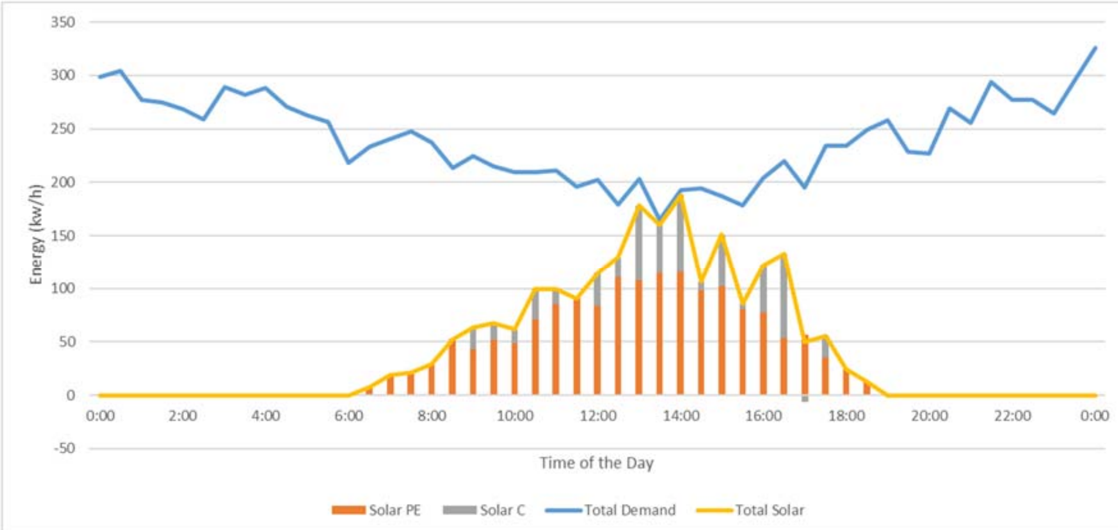

FIGURE 6. TOTAL DEMAND AND SOLAR ENERGY SUPPLY ON A WINTER CLOUDY DAY.

Weather condition has the highest effect on solar energy supply. Solar radiation is greatly affected by the cloud coverage. It is estimated that on a sunny day the solar radiation can be as high as 0.85 kW/m2, while on a cloudy day it may go as low as 0.35 kW/m2. Figures 5 and 6 above show the estimated total energy demand and solar supply for the whole greenhouse on a typical sunny and cloudy winter day respectively. In this section, the optimal usage policy of the heat pump is calculated under both weather conditions.

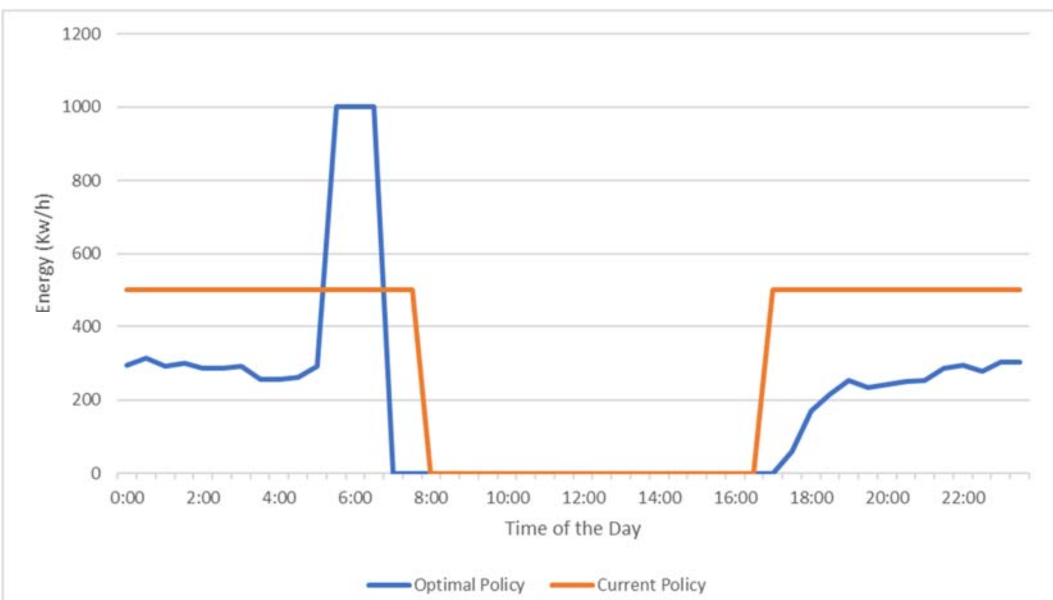

FIGURE 7. OPTIMAL USAGE POLICY AND CURRENT POLICY UNDER SUNNY WINTER DAY

The total cost per day for using the optimal policy is 1332.807 Chinese Yuan comparing with 1450 Chinese Yuan of using the current policy under the current policy. Comparing with the current policy, the optimal policy saves on two main parts. First, by adjusting the output energy level during the night, the optimal policy save on total unit cost. Second, by let the heat pump run at full capacity to store energy in the morning so that the heat pump could be turned off early, the optimal policy also save on fixed cost.

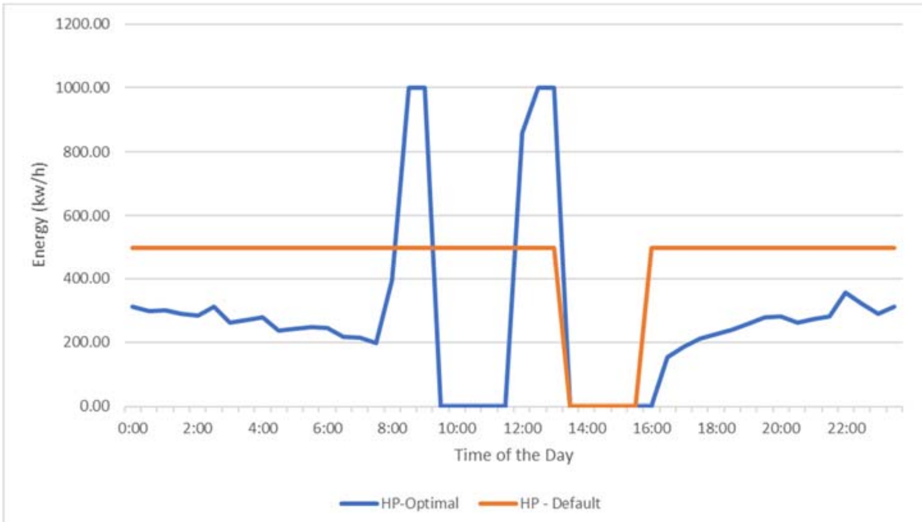

FIGURE 8. OPTIMAL USAGE POLICY AND CURRENT POLICY UNDER CLOUDY WINTER DAY

The total cost per day for using the optimal policy is 1609.68 Chinese Yuan comparing with 2035 Chinese Yuan of using the current policy under the current policy. During a cloudy winter day, as shown in figure 6, the solar energy supply is not enough to support the greenhouse. Comparing to the current usage policy, which is keeping the heat pump running most of the day, the optimal policy only turn on the heat pump and let it run at full capacity for around two hours. In this case, even the optimal policy has to pay more startup cost for turn on and turn off the heat pump during the day time, but the saving on fixed cost and the unit cost is higher than the increased startup cost.

As the cost estimation is due to change in the future, we also tested our model under different cost structure. Overall, the optimal policy can save 10% to 15% of the total cost comparing to the current policy.

V. CONCLUSION

Greenhouses are commonly used to grow higher-quality plants and to protect them against uncertain natural elements such as temperature or solar radiation. However, greenhouses are also one of the most energy demanding sectors in the agricultural industry as they need a consistent supply of energy to provide and maintain an environment for optimal crop production with maximum profit. In this study, we investigate the energy utilization strategy of an experimental solar-heated greenhouse that equips with 70 flat-panel solar thermal collectors. The greenhouse is designed to operate with an auxiliary heat pump system, which uses electricity to back up the solar input insufficiency during the night or through low-solar-radiant weather.

The main contribution of this control system is that the control mechanism can adapt to future changes of heat loss, solar energy supply, and coefficient of performance (COP) of the heat pump based on updated weather forecast, such as ambient temperature and solar radiation. By using weather forecast information, our model is able to adjust energy control policy accordingly to provide continuous optimization on greenhouse operations.

The numerical study shows that our model is able to provide an optimal dynamic control mechanism that can minimize the cost of operating an auxiliary heat pump while providing adequate energy supply to sustain a greenhouse production. Based on four different cases, our optimal dynamic control mechanism can reduce 15~20% of the cost to operate an auxiliary heat pump while providing adequate energy supply to support a greenhouse production. Specifically, the optimal strategy performs better on cloudy days when the demand of supplement energy is high.

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