# HIERARCHICAL MODEL PREDICTIVE CONTROL OF A VENLO-TYPE GREENHOUSE

by

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# SUMMARY

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Greenhouse cultivation can increase crop yield and alleviate the food shortage caused by population growth and reduction of arable land. However, the greenhouse production process consumes lots of energy and water. The energy consumed mainly comes from the combustion of fossil fuels, which will produce lots of greenhouse gases. In addition, the operating efficiency of some greenhouses is low, resulting in energy and water waste and increasing production costs. Therefore, the greenhouse system needs to be optimized to improve the operating efficiency. In this thesis, different methods of greenhouse operation efficiency optimization to improve energy efficiency and water efficiency are studied.

In Chapter 3, three strategies for greenhouse operation optimization are studied. Strategy 1 focuses on the optimization of the greenhouse heating system to save energy. The optimization of the heating system can effectively reduce energy consumption. However, people often pay more attention to reducing energy costs than reducing energy consumption in the production process to obtain more profits. Strategy 2 is to reduce the energy cost. It should be noted that Strategy 2 only considers the

cost of heating and cooling, while the cost of ventilation and carbon dioxide ($CO_2$) is not considered. Strategy 3 reduces the cost of greenhouse heating, cooling, ventilation and $CO_2$ consumption. In addition, greenhouse environmental factors must be kept within the required ranges. In Chapter 3, a dynamic greenhouse climate model is proposed. In the modeling process, the influence of crop growth and the interaction between different variables are considered to improve model accuracy. The proposed optimization problems are solved by ‘fmincon’ function with sequential quadratic programming (SQP) algorithm in MATLAB. Compared with Strategy 1, Strategy 2 has higher energy consumption but lower energy cost. Because Strategy 2 can shift some loads from high electricity price period to low electricity price period. Moreover, among the three strategies proposed, Strategy 3 has the lowest cost.

It should be pointed out that the strategies studied in Chapter 3 only consider the impact of the greenhouse climate, but ignore the irrigation, which is also important for greenhouse production. In Chapter 4, four optimization methods are proposed. These optimization methods consider climate control and irrigation control. Therefore, strategies proposed in this chapter can not only improve energy efficiency, but also increase water efficiency. Method 1 reduces the energy consumption. Method 2 reduces the water consumption. Method 3 reduces the $CO_2$ consumption. Method 4 reduces the total cost of greenhouse heating, cooling, ventilation, irrigation and $CO_2$ supply. In addition, greenhouse environmental factors and crop water demand need to be met. The dynamic model of greenhouse environmental factors presented in Chapter 3 is used for greenhouse climate control. A modified crop evapotranspiration model is proposed to predict crop water demand. Moreover, a sensitivity analysis method is introduced. The influence of prices and system constraints on optimization results is studied. The cost of Method 4 can be reduced compared with other methods. In addition, changes of prices and system constraints have a great impact on optimization results.

In Chapters 3 and 4, open loop optimization strategies for a greenhouse system operation are studied. However, these strategies have low control accuracy under system disturbances. Therefore, it is necessary to adopt some control methods to improve the control accuracy. In Chapter 5, a hierarchical model predictive control method is presented. The upper layer generates the optimal reference trajectories by solving greenhouse operation optimization problems. The lower layer designs controllers to follow obtained reference trajectories. Two model predictive controllers (MPC) are designed. Two performance indicators, namely relative average deviation (RAD) and maximum relative deviation (MRD), are used to compare designed controllers. The simulation results show that the proposed

MPC can deal with greenhouse system disturbances and the problem of model plant mismatch better than the open loop control method.

In Chapter 6, the findings of this thesis are summarized. Moreover, some topics for future research are proposed.

# ACKNOWLEDGMENT

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| $CO_2$ | Carbon dioxide |
| °C | Degrees Celsius |
| HPS | High pressure sodium |
| h | hour |
| ha | hectare |
| kg | kilogram |
| kW | kilowatt |
| L | Liter |
| LED | Light-emitting diodes |
| m | meter |
| MAE | Mean absolute error |
| MIMO | Multi-input-multi-output |
| MPC | Model predictive control |
| MRD | Maximum relative deviation |
| MSE | Mean squared error |
| PID | Proportional-Integral-Differential |
| R | South African currency rand |
| SD | Standard deviation |
| RAD | Relative average deviation |
| RMSE | Root mean squared error |
| s | second |
| SQP | Sequential quadratic programming |
| TOU | Time-of-use |
| W | Watt |
| Wh | Watt hour |

# LIST OF SYMBOLS

| | |
|---|---|
| $\alpha_1$ | transmission coefficient |
| $\alpha_2$ | heat transfer coefficient, $\mathrm{Wm^{-2}{}^{\circ}C^{-1}}$ |
| $\varepsilon$ | ratio of latent to sensible heat content |
| $\gamma$ | crop specific parameter |
| $\eta$ | lighting thermal conversion coefficient |
| $\rho_{air}$ | density of air, $\mathrm{kg/m^3}$ |
| $\omega_o$ | off-peak electricity price, R/kWh |
| $\omega_s$ | standard electricity price, R/kWh |
| $\omega_p$ | peak electricity price, R/kWh |
| $\lambda$ | conversion coefficient from $g_v$ to $Q_v$, $\mathrm{W/m^3}$ |
| $\Delta$ | slope of vapor pressure curve |
| $C_{air}$ | $CO_2$ concentration in greenhouse, ppm |
| $C_{out}$ | $CO_2$ concentration outside greenhouse, ppm |
| $C_{inj}$ | $CO_2$ injection rate, $\mathrm{g/m^2s}$ |
| $C_{inj,min}$ | minimal $CO_2$ injection rate, $\mathrm{g/m^2s}$ |
| $C_{inj,max}$ | maximal $CO_2$ injection rate, $\mathrm{g/m^2s}$ |
| $C_{ass}$ | $CO_2$ assimilation by the crop, $\mathrm{g/m^2s}$ |
| $C_{vent}$ | effect of ventilation on $CO_2$ concentration, $\mathrm{g/m^2s}$ |
| $C_{cap}$ | heat capacity of greenhouse, $\mathrm{J/{}^{\circ}C\,m^2}$ |
| $C_{p,air}$ | heat capacity of air, $\mathrm{J/kg^{\circ}C}$ |
| $D$ | deep percolation, mm |
| $e_s$ | saturation vapour pressure, kPa |
| $e_a$ | average daily actual vapour pressure, kPa |
| $ET$ | crop evapotranspiration, mm |
| $ET_o$ | reference evapotranspiration, mm |
| $H_{air}$ | humidity in the greenhouse, $\mathrm{g/m^2s}$ |
| $H_{cov}$ | vapour condensation to the cover, $\mathrm{g/m^2s}$ |
| $H_{crop}$ | vapour concentration at crop level, $\mathrm{g/m^2s}$ |
| $H_{out}$ | humidity outside the greenhouse, $\mathrm{g/m^2s}$ |
| $H_{trans}$ | vapour evaporated by the crop, $\mathrm{g/m^2s}$ |
| $H_{vent}$ | vapour flux due to ventilation, $\mathrm{g/m^2s}$ |

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|---|---|
| $I$ | irrigation flow, mm |
| $I_{rad}$ | solar radiation power, W/m$^2$ |
| $I_{rad,min}$ | lower limit of solar radiation power, W/m$^2$ |
| $g_e$ | transpiration conductance, m/s |
| $g_v$ | ventilation rate, m/s |
| $g_{v,min}$ | minimal ventilation rate, m/s |
| $g_{v,max}$ | maximal ventilation rate, m/s |
| $K_c$ | crop coefficient |
| $k_1$ | change rate limit of heating or cooling power, W/m$^2$s |
| $k_2$ | change rate limit of ventilation rate, m/s$^2$ |
| $k_3$ | change rate limit of $CO_2$ injection, g/m$^2$s$^2$ |
| $L$ | energy needed to evaporate, J/g |
| $LAI$ | leaf area index |
| $N$ | sampling times |
| $N_o$ | sampling times of open loop control |
| $N_m$ | sampling times of model predictive control |
| $N_c$ | control horizon |
| $N_p$ | prediction horizon |
| $p_c$ | price of organic $CO_2$, R/ton |
| $P$ | precipitation, mm |
| $P_E$ | artificial lighting power, W/m$^2$ |
| $Q$ | weighting matrix of reference trajectory tracking |
| $Q_{sun}$ | incoming radiation power, W/m$^2$ |
| $Q_{lamp}$ | lamp heating power, W/m$^2$ |
| $Q_{cov}$ | heat transfer through the cover, W/m$^2$ |
| $Q_{trans}$ | transpiration endothermic power, W/m$^2$ |
| $Q_{vent}$ | heat loss through ventilation power, W/m$^2$ |
| $Q_c$ | controlled heating or cooling power, W/m$^2$ |
| $Q_{c,min}$ | maximal cooling capacity, W/m$^2$ |
| $Q_{c,max}$ | maximal heating capacity, W/m$^2$ |
| $Q_p$ | pumping power, kW |
| $r_b$ | boundary layer resistance parameter, s/m |
| $r_s$ | stomatal resistance, s/m |

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| $R$ | weighting matrix of control effort |
| $R_n$ | net radiation at crop level, $\mathrm{W/m^2}$ |
| $R_o$ | surface runoff, mm |
| $RH_{air}$ | relative humidity in the greenhouse, % |
| $s_a$ | greenhouse area, $\mathrm{m^2}$ |
| $s_r$ | shading rate |
| $T$ | total optimization time, min |
| $T_{air}$ | temperature in the greenhouse, °C |
| $T_m$ | sampling interval of model predictive control, min |
| $T_{max}$ | maximum greenhouse temperature, °C |
| $T_{mean}$ | greenhouse average temperature, °C |
| $T_{min}$ | minimum greenhouse temperature, °C |
| $T_o$ | sampling period of open loop control, min |
| $T_{out}$ | temperature outside the greenhouse, °C |
| $v_2$ | wind speed at 2 meter height, m/s |
| $W$ | water from the water table, mm |

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# CHAPTER 1 INTRODUCTION

## 1.1 PROBLEM STATEMENT

### 1.1.1 Context of the problem

The global population is increasing, but the arable land is limited [1]. For example, in South Africa, only about 11% of the land is arable [2]. Moreover, arable land is gradually decreasing [3]. The food insecurity problem is very serious [4, 5]. Greenhouse cultivation is an effective method to solve this problem and has been used worldwide [6]. A greenhouse can provide the environment for crops to grow and protect them from bad weather, such as severe cold, heavy rain and heavy. Therefore, crops planted in the greenhouse can obtain higher yields than those planted outdoors [7]. According to the research in [8], there are about 5.4 million hectares of greenhouses worldwide, which produce 60 % of the global consumption of vegetables.

However, greenhouse operation consumes large quantities of energy [9, 10]. The energy price has been rising in recent years. Moreover, the energy consumed by modern greenhouses mainly derived from the combustion of fossil fuels. Therefore, the high energy consumption of greenhouses will not only reduce production profits, but will also produce a great deal of greenhouse gases. For instance, the energy consumed by greenhouses comprises about 16% of total agricultural energy consumption [11]. The energy cost accounts for more than half of the total greenhouse operating costs [12]. In addition, due to the low operating efficiency, some greenhouse systems have too much energy waste during the operating process [13]. Therefore, the operation of the greenhouse system needs to be optimized.

An effective method is to use renewable energy to power greenhouses. Renewable energy is widely used for greenhouse heating. The use of renewable energy does not only reduce the consumption of traditional energy, but can also reduce the emission of greenhouse gases. In addition, energy consumption can be reduced through energy efficiency optimization. Greenhouse energy efficiency can be improved by the following methods: (1) use high-efficiency devices; (2) reduce greenhouse energy consumption through greenhouse optimization control; (3) increase crop yields per unit of energy consumption; and (4) energy substitution [14].

Many studies focused on improving greenhouse energy efficiency. Most of these studies consider the temperature, relative humidity, $CO_2$ concentration, lighting and irrigation [15]. Temperature is one important environmental factor [16]. To increase crop yield and improve crop quality, greenhouse temperature must be kept within suitable ranges. During winter, the outdoor temperature is low. To maintain the temperature, the greenhouse needs to be heated. Lack of heating in the greenhouse will have adverse effects on cultivation time, crop yield and quality [17]. Heating energy sources include electric energy, the combustion of fossil fuels and renewable energy, such as solar energy. Greenhouse heating can be carried out by adjusting the heating pump, air conditioning and other equipment. The heat sources of a heat pump system include geothermal energy, groundwater heat energy, solar assisted air heat and seawater thermal energy [18].

Relative humidity is also an important environmental factor. When the relative humidity exceeds 95%, the growth of crops will be adversely affected. High humidity will accelerate the spread of diseases and reduce the respiration of plants [19]. Relative humidity control can be achieved by controlling the ventilation or dehumidity of the greenhouse. The exchange of humid air and outdoor dry air through ventilation can effectively reduce the relative humidity. Ventilation methods include natural ventilation and forced ventilation [20]. The research on greenhouse humidity control can be found in [21].

Carbon dioxide ($CO_2$) concentration affects crop photosynthesis. Increasing the $CO_2$ concentration in the greenhouse within a reasonable range will increase the yield of crops [22]. The control of greenhouse $CO_2$ concentration can be achieved by greenhouse ventilation or $CO_2$ supplement. $CO_2$ enrichment can effectively increase the greenhouse $CO_2$ concentration. The sources of $CO_2$ enrichment include fossil fuel emissions, natural ventilation and forced ventilation. However, the supply of $CO_2$ will increase production costs. When the $CO_2$ concentration is low, air exchange with the outside through ventilation can increase the $CO_2$ concentration.

Lighting is important for the greenhouse system. Crops need light throughout their life cycle. Light affects the photosynthesis of crops, thereby affecting their yield and quality [23]. According to [24], the intensity, quality and duration of light will affect the growth of crops. Light intensity affects photosynthesis, which can convert $CO_2$ into carbohydrates. Light quality is related to the spectral distribution of radiation. Spectral distribution affects crop shape, development and flowering. Red light and blue light have a huge influence on crop photosynthesis. Light duration mainly affects flowering. High pressure sodium (HPS) lamps and light-emitting diodes (LEDs) can be used to supplement light in greenhouses. The conversion efficiency of LED is higher, but the price of the HPS lamp is lower [25].

Greenhouse irrigation is important for crop growth. The amount of irrigation affects the yield and quality of crops. The use of drip irrigation method can effectively improve the utilization rate of water. With drip irrigation, water and nutrients can be applied directly to the roots of crops [26]. Moreover, optimizing the operation of the irrigation system can improve water use efficiency [27]. Compared with outdoor planting mode, greenhouse cultivation can reduce water consumption, mainly for the following four reasons: 1. Low wind speed in the greenhouse and high relative humidity, which reduces water loss through plant evapotranspiration; 2. The drip irrigation system used inside the greenhouse to improve the water efficiency; 3. The distance between the crops inside the greenhouse is closer than that in the outdoor planting mode, thereby reducing water waste; 4. The growth cycle of the crops inside the greenhouse is usually shorter than that of outdoor planting. The short growth cycle reduces water consumption throughout the growth season.

Some research about greenhouse climate control focuses on greenhouse system modeling. The greenhouse system is complex [28, 29]. Greenhouse climate is affected by the surrounding environment and indoor crops [30, 31]. For instance, crop transpiration affects greenhouse temperature and relative humidity [32, 33].

Some research focuses on the control methods of the greenhouse system. A nonlinear model predictive control (MPC) method is studied in [34]. This method is compared with the commonly used PID control method. To reduce the computational complexity, model linearization is performed. The results show that the MPC has better tracking performance than PID control. However, the study in [34] only considers the control of temperature and did not consider the control of other environmental factors. Moreover, the reference value of temperature is set, not obtained by optimization. Therefore, the energy consumption under this strategy is high. A fuzzy logic control approach for greenhouse temperature control is studied in [35]. The proposed method is verified by simulation. A double closed loop control method is considered in [36]. In [37], the parameter tuning of a PID controller for a greenhouse system is investigated. Aiming at the efficiency optimization of the classic heating system in greenhouse temperature control, the comparison between commercial predictive control and MPC strategy is studied in [20].

In [38], a fuzzy logic control method for greenhouse operation is explored. In [39], a robust control based on H2 method is proposed and compared with an on-off control method. The simulation results show that although there are interactions between greenhouse environmental factors and external weather, the proposed method has still performed well. The focus of the research in [40] is to develop control algorithms to maintain the greenhouse environment. The water and energy consumption is largely reduced. Moreover, the cost is reduced and the installation performance is improved. In [41], a hierarchical control strategy is proposed. On the upper layer, a multi-objective optimization approach is used to generate set-points for temperature and electrical conductivity. On the lower layer, controllers are designed to track the set-points. In [42], a hierarchical control method to save energy and increase production is studied. In [43], an optimal control method for energy saving is introduced. The results show that heating energy consumption and cooling energy consumption have been reduced by 47% and 15%, respectively.

**Figure 1.1.** Traditional plastic greenhouse and modern glass greenhouse

Figure 1.1 shows two commonly used greenhouses. The one on the left is a traditional plastic greenhouse, and the one on the right is a modern glass greenhouse. The plastic greenhouse is widely used worldwide because of its ability to prolong the growth period of crops and improve crop yield, and has made great achievements in agriculture and horticulture [44]. However, most of these greenhouses are manually controlled by people based on their experience. The control accuracy is low. Modern smart glass greenhouses are mostly equipped with shading systems, ventilation systems, heating systems, supplementary light systems, $CO_2$ generators and other related devices. Therefore, compared with traditional greenhouses, modern smart greenhouses provide a more suitable environment for crop growth, and obtain higher crop yields and better crop quality. The research in this thesis is based on a modern smart greenhouse.

### 1.1.2 Research gap

The research gap can be described as follows:

Firstly, greenhouse cultivation can effectively alleviate the food shortage crisis and is widely used worldwide. However, a large amount of energy is consumed. Energy is mainly derived from the burning of fossil fuels, which will produce a large amount of greenhouse gases and adversely affect the environment. Moreover, some greenhouse systems have low operating efficiency, causing lots of energy waste. Therefore, greenhouse systems need to be optimized. In addition, most of the current research on greenhouse efficiency optimization focuses on saving energy or reducing energy costs, while few studies consider reducing the total operating costs of heating, ventilation and $CO_2$ supply. This research tries to analyze and compare different greenhouse optimization strategies to help greenhouse managers make optimal decisions.

Secondly, most of the traditional optimization strategies only consider greenhouse climate control, but not greenhouse irrigation control, which is also important for crop growth. Moreover, greenhouse irrigation consumes lots of water, which aggravates the shortage of water resources in some countries and regions, such as in South Africa [45]. Therefore, the greenhouse irrigation process needs to be optimized. However, many related studies only consider one goal, such as reducing energy consumption, or water consumption or $CO_2$ consumption. Only a few studies have considered multi-objective optimization including energy, water and $CO_2$ consumption. In this thesis, optimization strategies considering greenhouse climate control and greenhouse irrigation control are proposed to reduce the consumption of energy, water and $CO_2$.

Thirdly, the greenhouse system modeling is complex. The growth of crops in the greenhouse affects greenhouse climate. Moreover, greenhouse environmental factors (such as temperature and relative humidity) affect each other. However, most of the traditional greenhouse climate modeling and greenhouse optimization ignore the impact of crop growth on greenhouse climate and the interaction between variables, so the accuracy is low and the optimization effect is not good. In the outdoor environment, the evapotranspiration model is generally adopted to predict the water demand of crops and perform related irrigation control. Due to the greenhouse environment is relatively closed, the wind speed is low. If the evapotranspiration model is directly used to predict the water demand of crops, there will be large errors. Therefore, the evapotranspiration model must be modified accordingly to adapt to the prediction of crops water demand in the greenhouse environment. In this thesis, a greenhouse model based on energy and mass balance is used for greenhouse control. The impact of crops on the greenhouse environment and the interaction between different environmental factors are considered in the modeling process. Moreover, a modified evapotranspiration model is used for irrigation control.

Finally, the traditional greenhouse control methods mainly include PID control, fuzzy logic control and open loop control. These control methods do not optimize the operation of the greenhouse system. Therefore, the greenhouse energy efficiency is low. In addition, these methods are mostly used for the control of single-input and single-output greenhouse systems, but cannot be used for the control of multiple-input and multiple-output systems. The control effect is not good under model plant mismatch and system disturbances such as outdoor solar radiation power and wind speed. Therefore, research on greenhouse control methods is of great significance.

## 1.2 RESEARCH OBJECTIVE AND QUESTIONS

The objectives of this research are:

- To reduce the energy consumption by improving the energy efficiency of the greenhouse system, thereby reducing production costs and reducing greenhouse gas emissions.
- To reduce the water consumption by improving the water efficiency of the greenhouse system and reducing the water demand of the crops, thereby reducing the production cost and alleviating the water shortage crisis.
- To reduce the total costs of greenhouse energy, water and carbon dioxide to obtain higher profits.
- To improve the control accuracy of the greenhouse system under system disturbances and model plant mismatch.

The research questions include:

- How to build an accurate model for the greenhouse system?
- How to build a water demand model of crops in the greenhouse environment?
- How to achieve the goal of reducing energy consumption, water consumption and total cost through different optimization methods?
- How to solve the proposed optimization problems?
- How to design a suitable controller for the greenhouse system?

## 1.3 APPROACH

First, a greenhouse model is established based on energy balance and mass balance. The model considers the interaction between greenhouse environmental factors and the impact of crops on the greenhouse environment. Then some optimization methods are proposed to reduce energy consumption, water consumption and total production cost, respectively. These optimization problems are solved by ‘fmincon function with sequential quadratic programming algorithm in MATLAB environment. Finally, a hierarchical model predictive control method is proposed to deal with system disturbances.

## 1.4 RESEARCH GOALS

The research goals are to reduce energy, water and carbon dioxide consumption by optimizing the operation of the greenhouse system, thereby reducing production costs and greenhouse gas emissions, to achieve sustainable development.

## 1.5 RESEARCH CONTRIBUTION

A summary of the research contribution is as follows:

- Traditional greenhouse optimization methods mainly focus on how to reduce the greenhouse energy consumption of heating and cooling, while maintaining greenhouse temperature within the required range. However, to provide a good growth environment for crops, relative humidity and $CO_2$ concentration also need to be maintained within a proper range. For greenhouse optimization, the energy consumption of the greenhouse ventilation system and the $CO_2$ consumption of the $CO_2$ supply system should also be considered. In Chapter 3, three greenhouse optimization strategies are studied to reduce the energy consumption, energy costs and total costs of heating and cooling, ventilation and $CO_2$ supply, while ensuring that environmental factors are within appropriate ranges.

- Most of the research on greenhouse water saving focuses on improving water use efficiency by changing crop planting or irrigation methods. However, these strategies cannot reduce greenhouse irrigation water demand. In Chapter 4, four greenhouse optimization methods considering greenhouse climate control and greenhouse irrigation control are studied. The proposed methods improve water use efficiency and reduce water demand as well. A modified crop evapotranspiration model is introduced to calculate irrigation water demand. The influence of the changes of prices and system constraints on the optimization results is studied by sensitivity analysis.
- Most previous studies only considered the optimization of the heating system, ventilation system and $CO_2$ supply system. However, few studies considered the optimization of the shading system. In Chapter 4, the optimization of the shading system is also considered.
- Most previous studies on hierarchical control of greenhouse systems only considered a single environmental factor, while the research in this thesis considered multiple environmental factors. Moreover, MPC controllers are designed and compared with open loop controllers.

## 1.6 RESEARCH OUTPUTS

The research outputs include two journal papers and two conference papers.

**Journal Papers:**

[J1] D. Lin, L. Zhang, and X. Xia, “Model predictive control of a Venlo-type greenhouse system considering electrical energy, water and carbon dioxide consumption,” Applied Energy, vol. 298, p. 117163, 2021.

[J2] D. Lin, L. Zhang, and X. Xia, “Hierarchical model predictive control of Venlo-type greenhouse climate for improving energy efficiency and reducing operating cost,” Journal of Cleaner Production, vol. 264, p. 121513, 2020.

**Conference Papers:**

[C1] D. Lin, L. Zhang, and X. Xia, “Hierarchical model predictive control of greenhouse climate to reduce energy cost,” in *2nd International Conference on Industrial Artificial Intelligence (IAI)*, Shenyang, China, October 2020.

[C2] D. Lin, L. Zhang, and X. Xia, “Greenhouse climate model predictive control for energy cost saving,” in *Applied Energy Symposium 2019: Low carbon cities and urban energy systems*, Xiamen, China, October 2019.

## 1.7 OVERVIEW OF STUDY

In this study, some optimization strategies and control methods of the greenhouse system are studied.

In Chapter 2, some literature on the use of renewable energy, greenhouse system modeling, climate control, irrigation control, hierarchical control and model predictive control is reviewed.

In Chapter 3, three optimization strategies are studied. The objectives are to minimize the energy consumption, energy cost and total cost while ensuring greenhouse environmental factors are within appropriate ranges. The feasibility of the proposed strategy is proved through the analysis of energy consumption and cost.

In Chapter 4, four optimization methods, considering greenhouse climate and irrigation, are studied. A dynamic irrigation model is proposed according to the soil water balance. For the closed environment of the greenhouse, a modified evapotranspiration model is introduced to predict crop water demand. A sensitivity analysis is conducted to study the impact of prices and system constraints on the performance of the optimization results.

In Chapter 5, a two-layer hierarchical control method is studied. On the upper layer, reference trajectories of greenhouse environmental factors are obtained by solving the greenhouse optimization problem. On the lower layer, MPC controllers are designed to track the obtained reference trajectories. The proposed MPC method can effectively address system disturbances.

Finally, in Chapter 6, conclusions are drawn and future research topics are given.

# CHAPTER 2 LITERATURE STUDY

## 2.1 CHAPTER OVERVIEW

In this section, some literature on the operation of the greenhouse system is reviewed. In Section 2.2, some literature on the use of renewable energy is presented. In Section 2.3, different greenhouse modeling methods are given. Some research on greenhouse climate control and irrigation control are presented in Section 2.4 and 2.5, respectively. The introduction of hierarchical control and model predictive control can be found in Section 2.6 and 2.7, respectively. In Section 2.8, a conclusion of this chapter is drawn.

## 2.2 USE OF RENEWABLE ENERGY

Some studies use renewable energy instead of fossil fuels to provide energy for greenhouses, which can not only reduce costs, but can also reduce greenhouse gas emissions. For instance, a soil heat storage system is studied in [46]. The proposed method uses the energy stored in the greenhouse soil to reduce energy demand for extreme cold and continuous cloudy days. The system designed was used in two pilot projects in Shanghai. The results of using this system in blueberry greenhouses show that the yield has increased by 120% and the price has increased by 50-100%. The theoretical dynamic investment payback periods are 5.45 years and 6.15 years respectively. The use of biogas and ground energy for greenhouse heating is evaluated in [47]. In [48], the use of energy storage solar air heaters to improve the greenhouse climate is studied. In [49], the ground thermal energy is used for heating a greenhouse. The system can increase the night air temperature, which makes the greenhouse climate suitable for pepper planting. To reduce energy cost, the use of a solar air heater system is studied in [50]. In [51], an analytical method is proposed for the design of a geothermal solar greenhouse, which can minimize the consumption of fossil fuels and replace it with geothermal energy. In [52], the use of low-enthalpy geothermal sources to heat a greenhouse in northern Greece is studied.

## 2.3 GREENHOUSE SYSTEM MODELING

Greenhouse system modeling methods include: first-principles modeling, data-driven modeling and hybrid modeling [53]. The first-principles modeling uses the physical model to describe the system. Therefore, the parameters of these models have physical meanings. First-principles modeling requires a comprehensive understanding of the greenhouse system and a lot of calibration work. These details are not required for data-driven modeling. Compared with data-driven models, physics-based models have stronger generalization capabilities but lower accuracy. The data-driven model has high accuracy within the range of training data, but its generalization ability is poor. The hybrid modeling is between the two characteristics of using physical models and data-driven models for better results. The hybrid model provides a feasible choice when there is no data or the physical knowledge of the model is incomplete [54].

### 2.3.1 First principles modeling

Some modeling methods are based on first principles. For instance, a greenhouse model based on first principles is established in [55]. In [56], a model of a greenhouse powered by a photovoltaic system is established and verified. In [57], a dynamic greenhouse climate model is proposed and good prediction results are obtained. In [58], the modeling and simulation of a greenhouse system is studied. The proposed model can predict temperature and radiation well. In [59], a greenhouse yield model is presented and validated.

### 2.3.2 Data-driven modeling

Some research studied data-driven greenhouse modeling methods. In [60] and [61], the black box model of a greenhouse system is built. In [62], a greenhouse model based on the neural network is designed and verified. The performance index, mean squared error (MSE) is introduced. The designed model has good performance. However, this modeling method requires a lot of data. In addition, the model can only be used for the analysis of the current greenhouse, and cannot be used for the research of other greenhouses [63, 64]. A temperature adaptive model is presented in [65]. In [66], the artificial neural network is adopted to model a greenhouse system. The advantages and limitations of two greenhouse modeling methods (data modeling and physical modeling) are discussed in [67].

### 2.3.3 Hybrid modeling

Some studies focus on hybrid modeling methods. In [40], a greenhouse model based on energy and water balance is proposed. Fifteen parameters are selected for model tuning. The genetic algorithm is used to identify model parameters. In [68], a physical model is presented. Based on the actual measurement data of the greenhouse, an adaptive particle swarm optimization and genetic algorithm is used to correct the uncertain parameters of the model. The results show that the model has a prediction accuracy of 95.6%.

### 2.3.4 Simulation software

In addition, simulation tools are used for modeling. Some research studied the use of TRNSYS software for greenhouse modeling and energy analysis. TRNSYS software is developed at the University of Wisconsin. It is used in renewable energy engineering and building simulation [69]. In [70], a study is conducted using TRNSYS 16 to obtain the best system performance. The results show that the error does not exceed 6%. Therefore, the TRNSYS 16 simulation program can be an effective method to evaluate the true system performance. A simulation project is created using TRNSYS 17 software to analyze the optical and thermal behavior of soil-less tomato crops in [71]. In [72], the performance of a heating system is evaluated by TRNSYS simulation according to the climate conditions in Tunisia. In [73], a greenhouse model is built in the TRNSYS environment and verified by the measured data. Then, based on the model, methods to improve performance, reduce basic design costs and adapt to the local climate are discussed. Other similar studies can be found in [74, 75]. Some research studied greenhouse modeling methods in an EnergyPlus environment. EnergyPlus can be used for parameter studies to determine the size of the greenhouse using waste heat and quantifying its energy saving [53].

For greenhouse control, black box models and first principles models have their own advantages. However, biologists and agronomist engineers prefer first principles models [40]. The reason is that first principles models offer a closer interpretation of phenomena. Moreover, the first principles model is suitable for different types of greenhouses planted with different types of crops. In this thesis, a first principles model is used for greenhouse operation optimization and control.

## 2.4 GREENHOUSE CLIMATE CONTROL

Greenhouse climate depends on external weather conditions, greenhouse structure, types and status of crops, and execution control signals [76]. Most of the research on greenhouse climate control focuses on how to keep greenhouse environmental factors within the required ranges while reducing energy consumption or production costs, and so forth.

For example, a method of greenhouse energy saving is studied in [77]. In [78], an adaptive fuzzy approach for temperature control is studied. The results of greenhouse tomato cultivation show the method is effective. Although energy consumption is reduced, energy costs are still high.

In [79], an adaptive fuzzy control scheme is proposed. An improved genetic algorithm for the greenhouse economic optimal control is proposed in [80]. In [81], an MPC method for greenhouse ventilation system is studied. In [82], a nonlinear MPC approach for greenhouse temperature control is proposed. A parameter self-tuning PID control method for greenhouse climate control is studied in [83]. Deep reinforcement learning for greenhouse climate control is studied in [84]. The application of neural network for greenhouse climate prediction is introduced in [85].

## 2.5 GREENHOUSE IRRIGATION CONTROL

Different methods for greenhouse irrigation control had been studied. For example, a fuzzy-logic control strategy for greenhouse irrigation is studied in [86]. In [87], the use of solar multi-effect distillation equipment to produce water for irrigation is studied. An MPC controller is designed for the operation control of a desalination plant to meet the water demand of crops. To improve the efficiency of greenhouse irrigation, some strategies are proposed. Some research studied different irrigation method for saving water. In [88], the impact of drip irrigation on tomato growth in greenhouse is studied. The research in [89] shows that drip irrigation can effectively reduce water consumption in greenhouse pepper production. Based on historical weather data, the irrigation scheduling problem of a plastic greenhouse is studied in [90].

Some studies focus on the modeling of greenhouse irrigation. Accurate prediction of crop water demand in the greenhouse is important for the design of the irrigation system. In [91], modeling of irrigation water demand for greenhouse spinach is studied. A water balance model is designed and applied to simulate the daily irrigation demand of greenhouse crops. Two experiments are conducted. The results show that it has good model performance during verification and calibration. In [92], four main models of greenhouses water saving are introduced and quantified, and a simplified model is proposed to calculate the long-term water saving potential of greenhouses using easy-to-measure data.

## 2.6 HIERARCHICAL CONTROL STRATEGY

A two-layer structure hierarchical control structure is shown in Figure 2.1. On different layers, different models are used to design corresponding regulators. The regulator operating at lower frequencies calculates the "slow" control variables, and the "fast" control variables, state and output reference values.

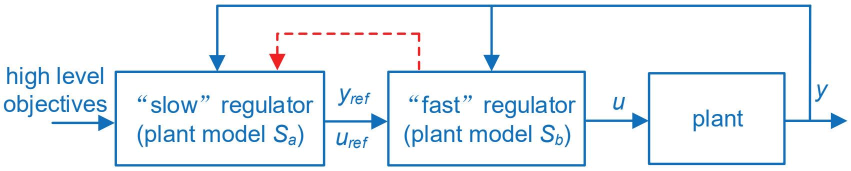

**Figure 2.1.** Hierarchical control structure

Hierarchical control can decompose a complex problem into several simple subproblems to reduce the computational complexity [93, 94]. Therefore, the hierarchical control method is widely used in complex system control. For instance, a hierarchical distributed control strategy for an air conditioning system is proposed in [95]. In [96], the hierarchical control method is used for the irrigation canal planning.

Traditional greenhouse control methods, such as PID control and fuzzy logic control, are adopted in greenhouse control due to their flexibility and simplicity. These methods do not require accurate models. However, these strategies have some disadvantages, such as unable to deal with system constraints, low control accuracy due to the interaction of control variables, and high energy consumption due to the lack of optimization [97]. Moreover, the adjustment of the controller is also a time-consuming process. MPC can effectively solve the problems mentioned above. MPC has high performance when the model is accurate. In addition, MPC can deal with the optimization problem of MIMO system with constraints.

## 2.7 MODEL PREDICTIVE CONTROL

Figure 2.2 shows the principle of model predictive control [98, 99]. MPC minimizes certain cost functions over the prediction horizon to obtain a control vector. The first value of the obtained control vector is used and the other values are ignored. The whole process is repeated at the next sampling interval [100, 101].

According to the research in [102], some advantages of the MPC method can be summarized as follows:

- The disturbance model is integrated for disturbance rejection;

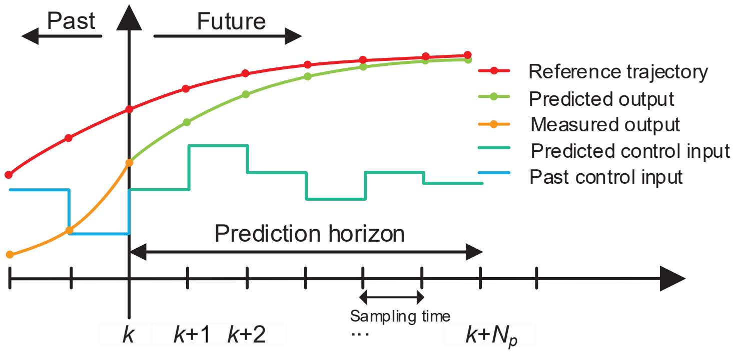

**Figure 2.2.** Principle of model predictive control

- It can deal with time-varying system dynamics;
- Ability to deal with constraints and uncertainties;
- Be able to deal with the process with slow time delay;
- The cost function is used to achieve multiple objectives;

The MPC strategy is widely used in process control[103]. For instance, the model predictive control strategy for pumping station operation is proposed in [104]. In [105] an MPC method of an air conditioning system is studied. In [106], a robust model predictive strategy for hot water devices control is proposed. In [107], the MPC method is introduced to solve the optimal maintenance planning problem of a lighting retrofit project. MPC strategy for urban household energy-water management is presented in [108]. The MPC of a heavy haul train is studied in [109].

MPC strategy is also widely used in greenhouse control. For example, the MPC strategy for greenhouse temperature control is studied in [110]. In [111], an MPC controller is introduced to adjust the indoor temperature. A robust MPC strategy for greenhouse system is studied [112]. The proposed controller has stronger robustness than the traditional MPC.

## 2.8 CONCLUSION

In this chapter, some literature on the operation of the greenhouse system is reviewed. First, some studies on the use of renewable energy are presented. Using renewable energy instead of traditional energy can reduce greenhouse gas emissions and energy costs. Then, some research on modeling methods is analyzed. The use of accurate models can improve the control accuracy of the greenhouse system. In addition, some studies on greenhouse climate control and irrigation control methods are discussed. Greenhouse climate control and irrigation control can not only provide a suitable growth environment for crops, but also reduce energy and water consumption. Finally, some research on hierarchical control and model predictive control are studied. The hierarchical control can reduce complex calculations. The model predictive control method can improve the control accuracy under model plant mismatch and system disturbances.

# CHAPTER 3 OPTIMIZATION OF GREENHOUSE ENERGY EFFICIENCY

## 3.1 INTRODUCTION

In recent years, the world's population is increasing while arable land is decreasing. In some countries and regions, the food shortage problem is serious [113]. For example, in Africa, about 250 million people are suffering from hunger, which accounts for nearly 20% of the total population. Greenhouse planting can effectively solve this problem. Greenhouses can protect crops from outside bad weather, such as severe cold, heavy rain, heavy snow, etc. Crops planted in greenhouses can get higher yields and better quality than crops planted outdoors. However, greenhouse cultivation consumes a lot of energy for heating. The energy consumed by greenhouse systems is mainly derived from the combustion of fossil fuels. Therefore, improving greenhouse energy efficiency is of great significance for sustainable development.

According to the research in [114], greenhouse energy saving can be achieved through the following methods:

- Improving the energy efficiency of greenhouse systems.
- Using renewable energy for greenhouse heating;
- Using a heating system with high efficiency;
- Using precise control systems;

In this chapter, the methods of reducing energy consumption by improving greenhouse energy efficiency are studied.

## 3.2 CHAPTER OVERVIEW

This study is based on the research in our published paper [115]. In this chapter, three strategies for a Venlo-type greenhouse operation are proposed. The optimization goals are to minimize the greenhouse energy consumption, energy costs and total operating costs while maintaining greenhouse environmental factors within their appropriate ranges. The greenhouse model presented in [43] and [55] is adopted. Weather data for Pretoria, South Africa is adopted. MATLAB software is used for simulation. The sequential quadratic programming (SQP) method is adopted.

The configuration of this chapter is arranged as follows: In Section 3.3, the system modeling is conducted. In Section 3.4, three optimization problems are formulated. In Section 3.5, simulations are presented. In Section 3.6, conclusions are drawn.

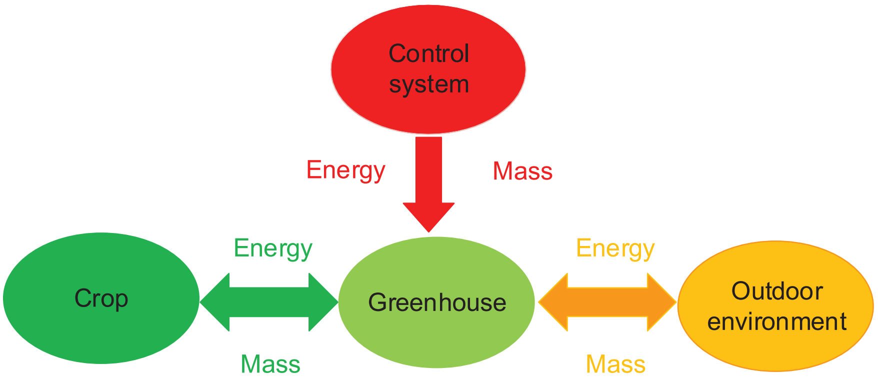

**Figure 3.1.** Exchange of mass and energy

A greenhouse is an agricultural building covered by plastic or glass. The greenhouse system can obtain energy from solar radiation through the transparent cover. The cover can also prevent the energy loss. Crops exchange mass and energy with greenhouse through photosynthesis and transpiration. However, the greenhouse cannot provide the greenhouse environment needed only by exchanging with the surrounding environment. Therefore, additional energy and mass supplies are needed to achieve a higher yield and better quality. The energy and mass exchange for a greenhouse system is shown in Figure 3.1.

## 3.3 SYSTEM MODELING

Greenhouse systems can be controlled by experts based on experience, or can automatically adjust and control the internal climate according to changes of surrounding environment. Figure 3.2 shows how a greenhouse system operates.

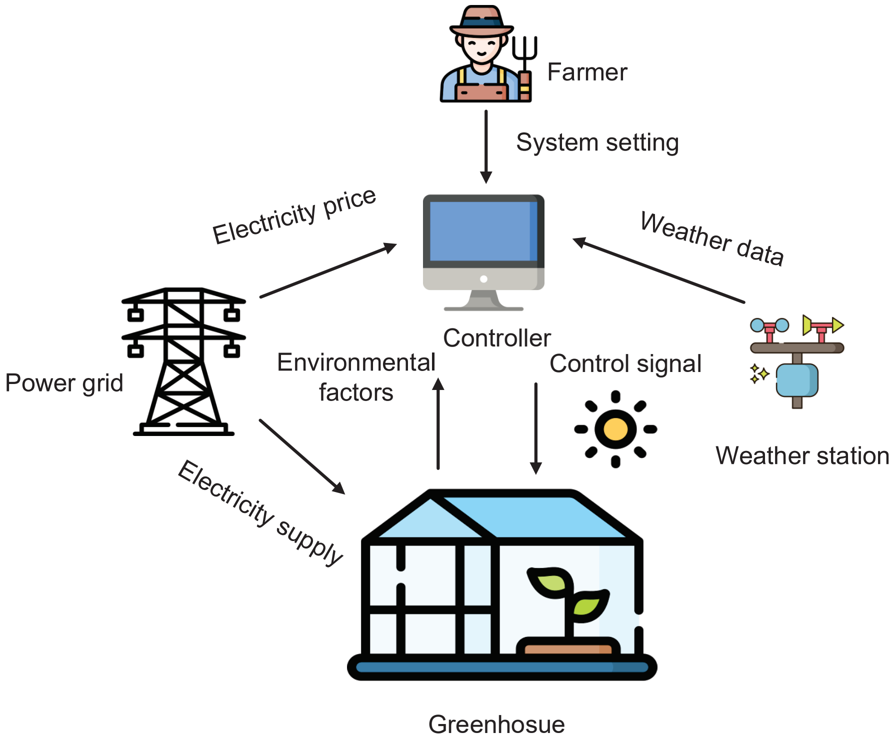

**Figure 3.2.** Greenhouse climate control process

First, growers set goals and system constraints. Then, the controller solves the corresponding optimization problem according to the collected information (electricity price, greenhouse climate data and external meteorological data). Finally, adjust the system based on the control signal obtained from the control center.

Figure 3.3 shows a greenhouse control system. Temperature control is usually achieved by heating or cooling, whereas humidity control is achieved by ventilation or dehumidification, $CO_2$ concentration control is by artificial $CO_2$ supply, and lighting control is by supplemental lighting.

In this chapter, the influence of crop growth and the interaction between different variables are considered in the modeling process to improve model accuracy. The dynamic model presented in [43] and [55], is used. It should be noted that the model used is built based on the energy and mass balance of the greenhouse system. This modeling method is suitable for greenhouses with different specifications and layouts.

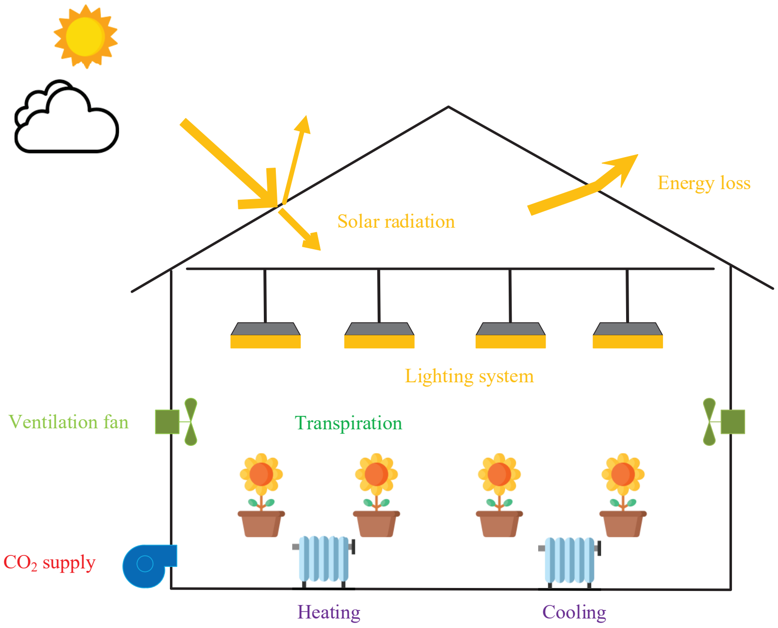

**Figure 3.3.** Greenhouse climate control system

### 3.3.1 Temperature

The energy of the greenhouse system mainly comes from solar radiation and heating. Energy lose through greenhouse ventilation, heat exchange with outdoor air, crop transpiration and greenhouse cooling. Therefore, the temperature model can be given by:

$$\frac{dT_{air}}{dt} = \frac{1}{C_{cap}}(Q_{sun} + Q_{lamp} - Q_{cov} - Q_{trans} - Q_{vent} + Q_c), \tag{3.1}$$

where $T_{air}$ is the temperature in the greenhouse, $C_{cap}$ is the heat capacity of air, $Q_{sun}$ is the incoming radiation, and $Q_{lamp}$ is the lamp heating power. $Q_{cov}$ is the heat loss through the cover, $Q_{trans}$ is the energy absorbed by crop transpiration. $Q_{vent}$ represents the energy loss through ventilation. $Q_c$ is the controlled heating or cooling power. When the value of $Q_c$ is positive, the greenhouse is being heated, and the heating power is $Q_c$. When the value of $Q_c$ is negative, the greenhouse is being cooled, and the value of cooling power is the absolute value of $Q_c$. The temperature in the greenhouse can be controlled by adjusting the value of $Q_c$.

$Q_{sun}$ is calculated by:

$$Q_{sun} = \alpha_1 I_{rad}, \tag{3.2}$$

where $\alpha_1$ represents the transmission coefficient, and $I_{rad}$ represents the solar radiation power.

$Q_{cov}$ can be described by:

$$Q_{cov} = \alpha_2 (T_{air} - T_{out}), \tag{3.3}$$

where $\alpha_2$ is the heat transfer coefficient, and $T_{out}$ is the outside temperature.

$Q_{trans}$ can be obtained by:

$$Q_{trans} = g_e L (H_{crop} - H_{air}), \tag{3.4}$$

where $g_e$ is the transpiration conductance, and $L$ is the energy consumed to evaporate water from a leaf. $H_{crop}$ is the absolute water vapour concentration at crop level. $H_{air}$ is the absolute water vapour concentration.

$H_{crop}$ can be obtained by:

$$H_{crop} = H_{air,sat} + \varepsilon \frac{r_b}{2LAI} \frac{R_n}{L}, \tag{3.5}$$

where $H_{air,sat}$ is the saturated vapour concentration. According to [116], $H_{air,sat}$ is calculated by:

$$H_{air,sat} = 5.5638 e^{0.0572 T_{air}}. \tag{3.6}$$

$g_e$ is obtained by:

$$g_e = \frac{2LAI}{(1+\varepsilon) r_b + r_s}, \tag{3.7}$$

where $LAI$ is the leaf area index, $\varepsilon$ is the ratio of latent to sensible heat content of saturated air, $r_b$ is the boundary layer resistance and $r_s$ is the stomatal resistance.

$\varepsilon$ and $r_s$ can be calculated by:

$$\varepsilon = 0.7584 e^{0.0518 T_{air}}, \tag{3.8}$$

$$r_s = (82 + 570 e^{-\gamma \frac{R_n}{LAI}})(1 + 0.023 (T_{air} - 20)^2), \tag{3.9}$$

where $\gamma$ is a crop specific parameter, and $R_n$ is the net radiation at crop level.

$$R_n = 0.86 (1 - e^{-0.7 LAI})(Q_{sun} + P_E), \tag{3.10}$$

where $P_E$ is the lighting power.

$$Q_{lamp} = \eta P_E, \tag{3.11}$$

where $\eta$ is the coefficient of energy conversion to heat.

$$Q_{vent} = g_v \rho_{air} C_{p,air} (T_{air} - T_{out}), \tag{3.12}$$

where $g_v$ is the ventilation rate, $\rho_{air}$ is the density of the air, and $C_{p,air}$ is the specific heat capacity of the air.

### 3.3.2 Relative humidity

$RH_{air}$ can be obtained by:

$$RH_{air} = H_{air}/H_{air,sat}, \tag{3.13}$$

where $H_{air}$ is the vapour concentration. $H_{air}$ can be calculated by:

$$\frac{dH_{air}}{dt} = \frac{1}{h}(H_{trans} - H_{cov} - H_{vent}), \tag{3.14}$$

where $H_{trans}$ is the vapour produced by plant transpiration, $H_{cov}$ is the vapour condensation to the cover and $H_{vent}$ is the vapour flux due to ventilation. $h$ is the greenhouse height.

$H_{trans}$ is influenced by $H_{crop}$ and $H_{air}$, and it can be described by:

$$H_{trans} = g_e(H_{crop} - H_{air}). \tag{3.15}$$

$H_{cov}$ can be obtained by:

$$H_{cov} = g_c\left[0.2522e^{0.0485T_{air}}(T_{air} - T_{out}) - (H_{air,sat} - H_{air})\right], \tag{3.16}$$

where $g_c$ is the condensation conductance and can be obtained by:

$$g_c = \begin{cases} 0 & \text{if} \quad T_{air} \le T_{out}, \\ p_{gc}(T_{air} - T_{cov})^{1/3} & \text{if} \quad T_{air} > T_{out} \end{cases} \tag{3.17}$$

where $p_{gc}$ is related to the properties of the condensation surface.

$H_{vent}$ can be obtained by:

$$H_{vent} = g_v(H_{air} - H_{out}), \tag{3.18}$$

where $g_v$ is the ventilation rate.

### 3.3.3 Carbon dioxide concentration

$CO_2$ is derived form greenhouse ventilation and $CO_2$ supply. $CO_2$ loss is due to assimilation of crops. The $CO_2$ concentration model is as follows:

$$\frac{dC_{air}}{dt} = \frac{1}{h}(C_{inj} - C_{ass} - C_{vent}), \tag{3.19}$$

where $C_{air}$ is the $CO_2$ concentration, $C_{inj}$ is the $CO_2$ injection rate, $C_{ass}$ is the $CO_2$ assimilation and $C_{vent}$ is the changes in $CO_2$ concentration caused by ventilation.

$C_{ass}$ and $C_{vent}$ can be obtained by:

$$C_{ass} = 2.2 \times 10^{-3} \frac{1}{1 + \frac{0.42}{C_{air}}}(1 - e^{-0.003(Q_{sun}+P_E)}), \tag{3.20}$$

$$C_{vent} = g_v(C_{air} - C_{out}). \tag{3.21}$$

It should be noted that the models presented in this section (from Equation (3.1) to Equation (3.21)) are derived from [43] and [55].

### 3.3.4 Model performance analysis

The validation of the greenhouse temperature, relative humidity and $CO_2$ concentration model presented in Section 3.3.1, 3.3.2 and 3.3.3 can be found in [43] and [55]. In this section, the results of model verification are briefly introduced. There are eight measurement boxes in the greenhouse for greenhouse climate data measurement. The mean absolute error (MAE), standard deviation (SD) and correlation coefficient ($r_1$) between the measured value and the average value are calculated to assess the uniformity and consistency of the different measurements. The root mean square error (RMSE) and correlation coefficient ($r_2$) between the measured value and the predicted value are calculated to evaluate the model performance.

The RMSE can be obtained by:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Y_{m,i} - Y_{p,i})^2}{n}}, \tag{3.22}$$

where $Y_{m,i}$ and $Y_{p,i}$ are the measured value and the predicted value, respectively. $n$ is the number of data measurements.

The results of greenhouse climate measurement in [43] and [55] show that the temperature difference between each measurement box is less than 2.0 °C. The MAE of temperature, relative humidity and $CO_2$ concentration are 0.31 °C, 1.3 % and 88.4 ppm, respectively. The standard deviation (SD) of temperature is 0.31 °C. It is smaller than the value (between 1.0 °C and 1.5 °C) obtained in [117]. The correlation coefficient ($r_1$) of temperature, relative humidity and $CO_2$ concentration are 0.98, 0.94 and 0.86, respectively. The results show that the environmental factors in the greenhouse are uniform.

The correlation coefficient ($r_2$) of temperature, relative humidity and $CO_2$ concentration are 0.89, 0.54 and 0.75, respectively. The RMSE of temperature, relative humidity and $CO_2$ concentration are 1.26 °C, 7.7 % and 194 ppm, respectively. In most cases, the predicted value can very well follow the actual value, but when the outdoor temperature is low, the prediction error is large. Model verification results similar to the research in [43] and [55] can be found in [118]. It should be pointed out that the temperature in Pretoria is relatively high. Therefore, this model can be used for the research in this thesis. For more details about the model validation, please refer to [43] and [55].

## 3.4 OPTIMIZATION

In this chapter, three strategies to optimize the greenhouse system operation are proposed. The objectives of these optimization strategies are to reduce energy consumption, energy cost and total production costs while maintaining greenhouse environmental factors between grower defined bounds. The following sections describe the proposed optimization problems.

### 3.4.1 Decision variables

The greenhouse system studied in this chapter is a MIMO system. The decision variables include $Q_c$, $g_v$ and $C_{inj}$. The outputs (controlled variables) include $T_{air}$, $RH_{air}$ and $C_{air}$.

### 3.4.2 Objectives

Energy consumed by the greenhouse is mainly for heating or cooling. The optimization of the heating system can effectively reduce energy consumption. Strategy 1 focuses on energy saving. The objective function of Strategy 1 can be given by:

$$J_1 = \int_{t_i}^{t_f} |Q_c(t)|\, dt, \tag{3.23}$$

where $t_i$ and $t_f$ represent the initial and final time, respectively. It should be pointed out that when the value of $Q_c$ is positive, the system is in the heating state, and the heating power value is $Q_c$. When the value of $Q_c$ is negative, it does not mean that the power value is negative, but that the system is in the cooling state and the cooling power value is the absolute value of $Q_c$.

In the actual production process, farmers generally pay more attention to energy cost than energy consumption. That is because focusing on energy costs can obtain more profit than focusing on energy consumption. Strategy 2 minimizes the energy cost under the time-of-use (TOU) tariff. For the TOU tariff, people are encouraged to use electricity during off-peak time to reduce the pressure of power supply [119]. The objective function of Strategy 2 is expressed as:

$$J_2 = \int_{t_i}^{t_f} |Q_c(t)w(t)|\,dt, \tag{3.24}$$

where $w(t)$ is the electricity price at the time $t$. In this chapter, the TOU tariff in South Africa is used and given by:

$$w(t) = \begin{cases} w_o & t \in [0,6] \cup [22,24] \\ w_s & t \in [9,17] \cup [19,22], \\ w_p & t \in [6,9] \cup [17,19] \end{cases} \tag{3.25}$$

where $w_o$, $w_s$, $w_p$ are the off-peak, standard, peak electricity price in R/kWh. R is the South Africa Currency, Rand. $w_o$, $w_s$, $w_p$ are 0.5157, 0.9446, 3.1047 respectively.

It should be noted that Strategy 2 considered greenhouse heating and cooling, but ignored greenhouse ventilation and $CO_2$ supply. Strategy 3 minimizes the total cost of energy, ventilation and $CO_2$ supply. The objective function is expressed as:

$$J_3 = \int_{t_i}^{t_f} (Q_c(t)w(t) + g_v(t)\lambda w(t) + C_{inj}(t)p_c)dt, \tag{3.26}$$

where $p_c$ is the price of organic $CO_2$. $p_c = \text{R}1000/\text{ton}$. $\lambda$ is the conversion coefficient from $g_v$ to $Q_v$. $\lambda = 0.06\,\text{W/m}^3$.

### 3.4.3 Constraints

Optimization of a greenhouse system operation is subject to some constraints, which can be found in the following sections. The constraints include state constraints and input constraints. For greenhouse cultivation, the greenhouse environmental factors (state variables) should be maintained within appropriate ranges. If the greenhouse environmental factors are not within suitable ranges, the yield of crops will decrease [120]. For example, too high temperature will cause crop wilting or even death, and too low $CO_2$ concentration will reduce the rate of photosynthesis of crops. It should be pointed out that the ranges of greenhouse environmental factors for different types of crops are different. The ranges of greenhouse environmental factors for different growth stages of the same crop should also be different. The constraints of these state variables can be set by growers according to their own experience, and can also be obtained through the optimization of greenhouse crop yields or profits. The state constraints are given below:

$$T_{air,min} \leq T_{air} \leq T_{air,max}, \tag{3.27}$$

$$RH_{air,min} \leq RH_{air} \leq RH_{air,max}, \tag{3.28}$$

$$C_{air,min} \leq C_{air} \leq C_{air,max}, \tag{3.29}$$

where $T_{air,min}$ is the lower temperature bound, $T_{air,max}$ is the upper temperature bound, $RH_{air,min}$ is the lower relative humidity bound, $RH_{air,max}$ is the upper relative humidity bound, $C_{air,min}$ is the lower $CO_2$ concentration bound, and $C_{air,max}$ is the upper $CO_2$ concentration bound.

The input constraints can be given by:

$$Q_{c,min} \leq Q_c \leq Q_{c,max}, \tag{3.30}$$

$$g_{v,min} \leq g_v \leq g_{v,max}, \tag{3.31}$$

$$C_{inj,min} \leq C_{inj} \leq C_{inj,max}, \tag{3.32}$$

where $Q_{c,min}$ is the maximal cooling power, $Q_{c,max}$ is the maximal heating power, $g_{v,min}$ is the minimal ventilation rate, $g_{v,max}$ is the maximal ventilation rate, $C_{inj,min}$ is the minimal $CO_2$ injection rate, and $C_{inj,max}$ is the maximal $CO_2$ injection rate.

To reduce the actuator wear caused by frequent changes, the rate of change constraints must be considered [121]. Therefore, the following constraints are considered:

$$\left|\frac{dQ_c}{dt}\right| \leq k_1, \tag{3.33}$$

$$\left|\frac{dg_v}{dt}\right| \leq k_2, \tag{3.34}$$

$$\left|\frac{dC_{inj}}{dt}\right| \leq k_3, \tag{3.35}$$

where $k_1$, $k_2$ and $k_3$ are the change rate limits of $Q_c$, $g_v$ and $C_{inj}$, respectively.

## 3.5 SIMULATION

The optimization problems proposed are solved by ‘fmincon’ function in MATLAB environment. The sequential quadratic programming algorithm is used, which can solve nonlinear optimization problems with nonlinear constraints. Therefore, it can be used to solve the optimization problem proposed in this Chapter. The simulation data and the simulation results can be found in the following sections.

### 3.5.1 Simulation data

Greenhouse parameters are from [55] and [43] and shown in Table 3.1. System constraints are shown in Table 3.2. The ventilation fan power is 300 W. The air flow is 5000 $m^3$/hour. The price of the $CO_2$ supplied is R 1000 per ton.

**Table 3.1.** Greenhouse parameters

| Variable | Value | Unit |
|---|---|---|
| $\alpha_1$ | 0.7 | – |
| $\alpha_2$ | 10 | – |
| $\gamma$ | 0.008 | – |
| $LAI$ | 2.6 | – |
| $C_{cap}$ | 30000 | $\mathrm{J/m^2\,^{\circ}C}$ |
| $h$ | 7 | m |
| $s_a$ | 40709 | $\mathrm{m^2}$ |
| $L$ | 2450 | $\mathrm{J/g}$ |
| $r_b$ | 150 | $\mathrm{s/m}$ |
| $\rho_{air}$ | 1.225 | $\mathrm{kg/m^3}$ |
| $C_{p,air}$ | 1003 | $\mathrm{J/kg^{\circ}C}$ |
| $p_{gc}$ | $1.8 \times 10^{-3}$ | $\mathrm{m^{\circ}C^{-1/3}s^{-1}}$ |

**Table 3.2.** System constraints

| Variable | Value | Unit |
|---|---|---|
| $T_{air,min}$ | 14 | °C |
| $T_{air,max}$ | 26 | °C |
| $RH_{air,min}$ | 0 | % |
| $RH_{air,max}$ | 90 | % |
| $C_{air,min}$ | 400 | ppm |
| $C_{air,max}$ | 2000 | ppm |
| $Q_{c,min}$ | -200 | $\mathrm{W/m^2}$ |
| $Q_{c,max}$ | 200 | $\mathrm{W/m^2}$ |
| $g_{v,min}$ | 0 | $\mathrm{m/s}$ |
| $g_{v,max}$ | 0.05 | $\mathrm{m/s}$ |
| $C_{inj,min}$ | 0 | $\mathrm{g/m^2s}$ |
| $C_{inj,max}$ | 0.05 | $\mathrm{g/m^2s}$ |
| $k_1$ | 0.51 | $\mathrm{W/m^2s}$ |
| $k_2$ | $5.1 \times 10^{-5}$ | $\mathrm{m/s^2}$ |
| $k_3$ | $5.1 \times 10^{-5}$ | $\mathrm{g/m^2s^2}$ |

For the study in this chapter, the data comes from a weather station at the University of Pretoria. The data for July 13, 2016 is used and shown in Figure 3.4 and Figure 3.5. The lighting power is zero in the daytime (between 07:00 and 18:00) and 110 $\mathrm{W/m^2}$ in the night (between 19:00 and 06:00). The outdoor $CO_2$ concentration is 407 ppm. The initial values of $T_{air}$, $RH_{air}$, and $C_{air}$ are set to 20 °C, 74%, and 500 ppm, respectively.

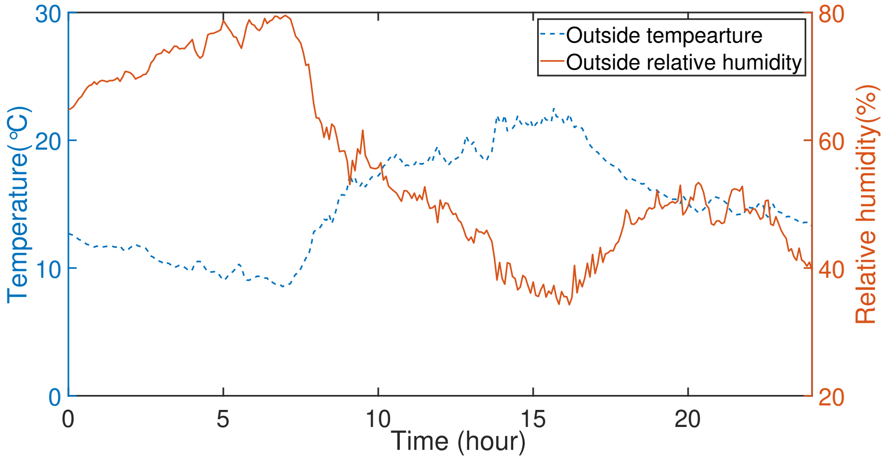

**Figure 3.4.** Outside meteorological data

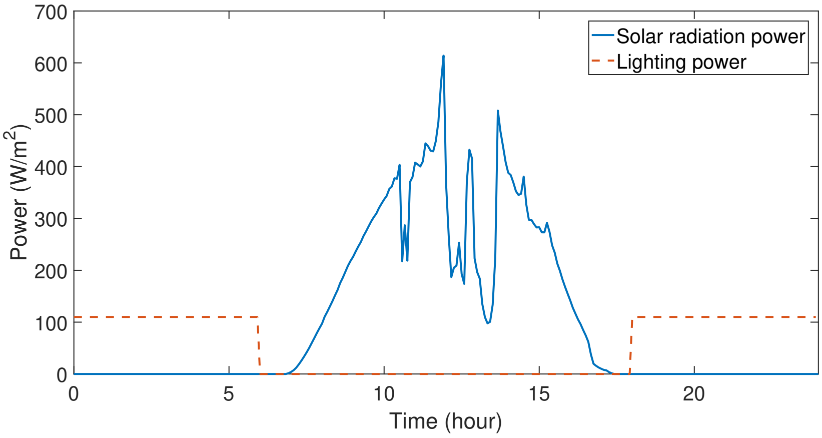

**Figure 3.5.** Solar radiation power and greenhouse lighting power

### 3.5.2 Results of energy consumption optimization

Figure 3.6 shows the results of Strategy 1. From Sub-figure 1, it can be seen that the value of $Q_c$ is zero during most of the day. $Q_c$ is a positive value between 7:00 and 8:00. This means that the greenhouse is heated during this time. The reason is that the temperature gradually drops to the lower limit of temperature in the early morning (as it can be seen from Sub-figure 4). The greenhouse needs to be heated to keep the required temperature. Moreover, the value of $Q_c$ is a negative value at noon. This means that the cooling system of the greenhouse is running during this time. This is because the temperature in the greenhouse has reached the upper limit of the temperature, and the cooling system is needed to reduce the temperature. From Sub-figure 2, it can be noticed that ventilation is mainly during noon time (from 10:00 to 15:00). That is because the outdoor temperature is high during this period, and ventilation can reduce indoor humidity without causing too much energy loss. Moreover, it can be observed that, under this strategy, greenhouse environmental factors are within the required ranges.

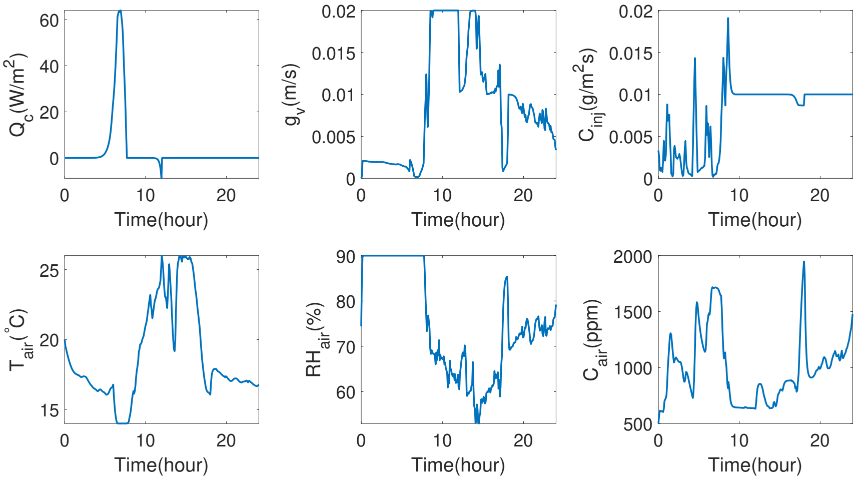

**Figure 3.6.** Optimization results of Strategy 1

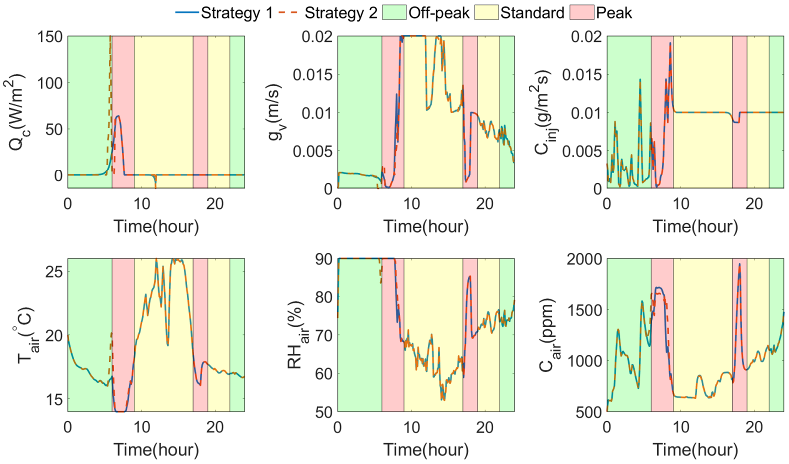

**Figure 3.7.** Comparison of Strategy 1 and Strategy 2

### 3.5.3 Results of energy cost optimization

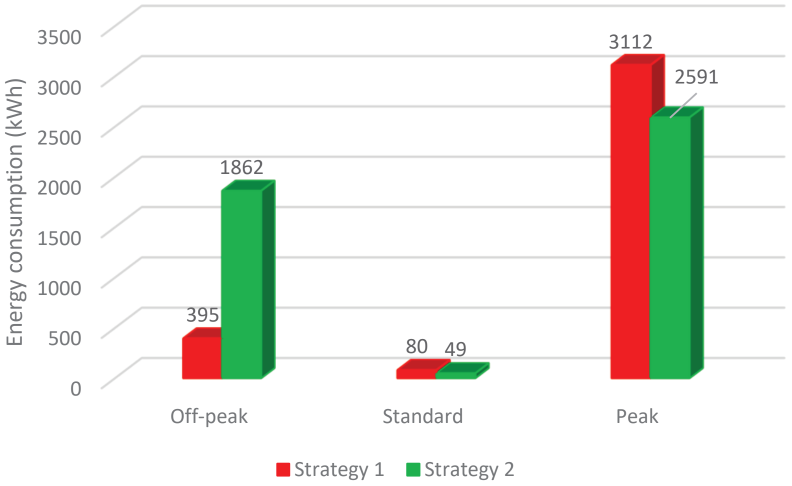

**Figure 3.8.** Energy consumption during different periods

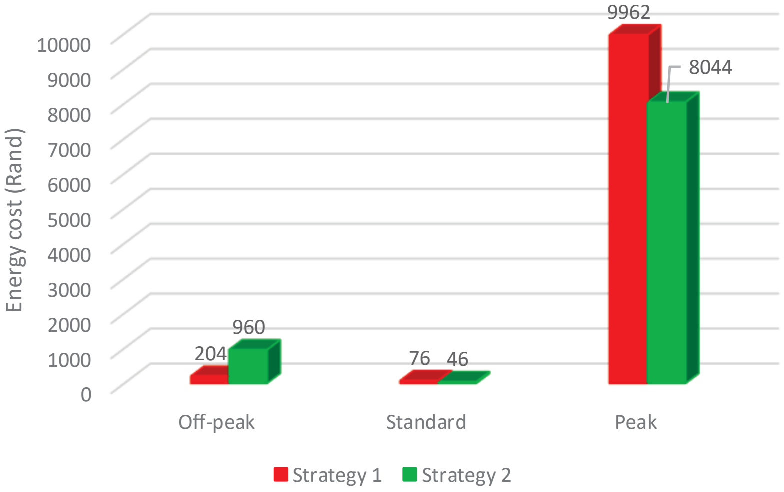

**Figure 3.9.** Energy cost during different periods

The comparison of Strategy 1 and Strategy 2 is shown in Figure 3.7. Sub-figure 1 shows the comparison of the control power under the two strategies. Sub-figure 2 shows the comparison of the ventilation rate under the two strategies. Sub-figure 3 shows the comparison of the $CO_2$ supply rate under the two strategies. From Sub-figure 1, it can be found that the $Q_c$ of Strategy 1 is mainly during the peak-period, while the $Q_c$ of Strategy 2 is mainly during the off-peak period. From Sub-figure 2, it can be noticed that the $g_v$ (ventilation) of two strategies is mainly at noon. From Sub-figure 3, it can be observed there is no big difference between the $g_v$ ($CO_2$ supply) of two strategies.

Figure 3.8 shows the energy consumption. The energy consumption of Strategy 1 is 395 kWh, 803 kWh and 112 kWh during the off-peak, standard and peak period, respectively. The energy consumption of Strategy 2 is 1862 kWh, 49 kWh and 2591 kWh during the off-peak period, standard period and peak period, respectively. Figure 3.9 shows the cost. The energy cost of Strategy 1 is R204, R776 and R9962 during the off-peak, standard and peak period, respectively. The energy cost of Strategy 2 is R960, R46 and R8044 during the off-peak, standard and peak period, respectively. The total energy consumption of Strategy 2 (4502 kWh) is higher than that of Strategy 1 (3587 kWh). However, the total cost of Strategy 2 (R9050) is lower than that of Strategy 1 (R10242). The reason is that the energy consumption of Strategy 2 is mainly in the off-peak time, while the energy consumption of Strategy 1 is mainly in the peak time.

### 3.5.4 Results of total cost optimization

Figure 3.10 shows the optimization result of Strategy 3. As can be seen in Sub-figure 3, the $C_{inj}$ which affects the $CO_2$ consumption of Strategy 3 is small. From Sub-figure 6, it can be found that the $CO_2$ concentration is low. For a long time, the greenhouse $CO_2$ concentration is the lower limit.

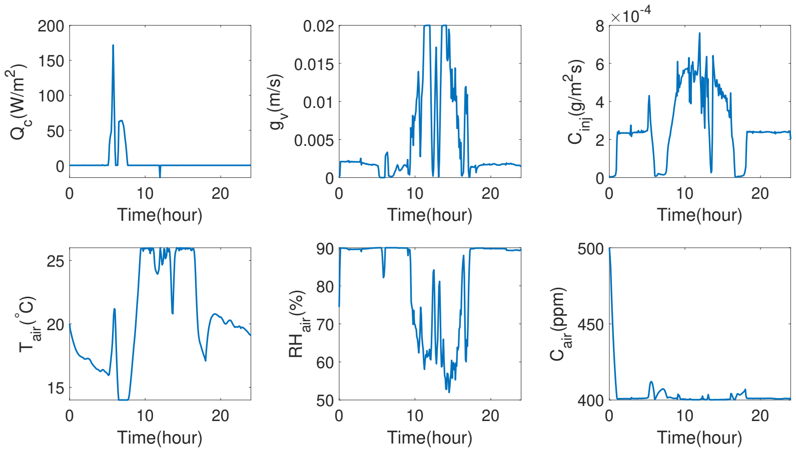

**Figure 3.10.** Optimization results of Strategy 3

Figure 3.11 compares the energy consumption and $CO_2$ consumption of the proposed three strategies. Among these three strategies, Strategy 1 has the lowest heating and cooling energy consumption

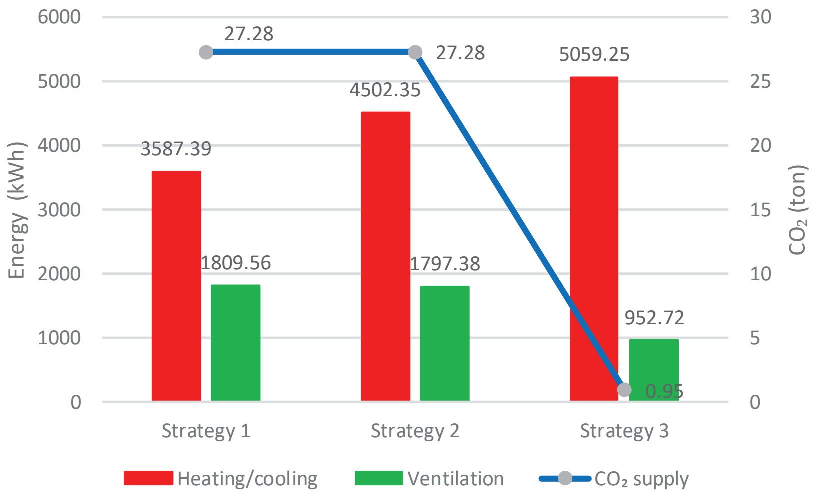

**Figure 3.11.** Energy and $CO_2$ consumption

(3587.39 kWh), while Strategy 3 has the lowest ventilation energy consumption (952.72 kWh) and $CO_2$ consumption (0.95 ton).

Figure 3.12 compares the costs of heating or cooling, ventilation and $CO_2$ supply for the three proposed strategies.

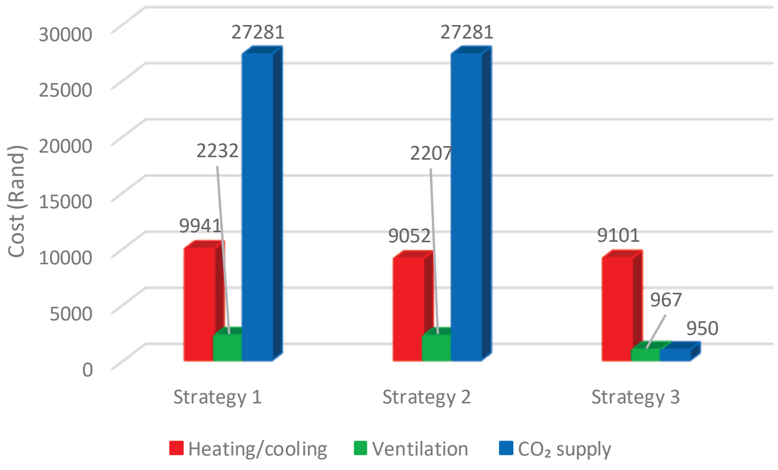

**Figure 3.12.** Costs of three different strategies

It can be seen that the energy costs of the three strategies are close, but the cost of $CO_2$ supply is quite different. The reason is that Strategy 3 consumes little $CO_2$. The total cost of Strategy 3 (R11018) is much lower than that of Strategy 1 (R39454) and Strategy 2 (R38540). It should be noted that Strategy 3 can only keep the $CO_2$ concentration in the greenhouse at a low level. The crop yield of Strategy 3 may be low.

### 3.5.5 Optimization with different weather data

The previous research is based on the weather data of July 13, 2016. To make the conclusions more convincing, the proposed strategies are also analyzed based on the meteorological data of another two winter days (June 5, 2016 and August 3, 2016). The weather data used is shown in Figure 3.13 and Figure 3.14.

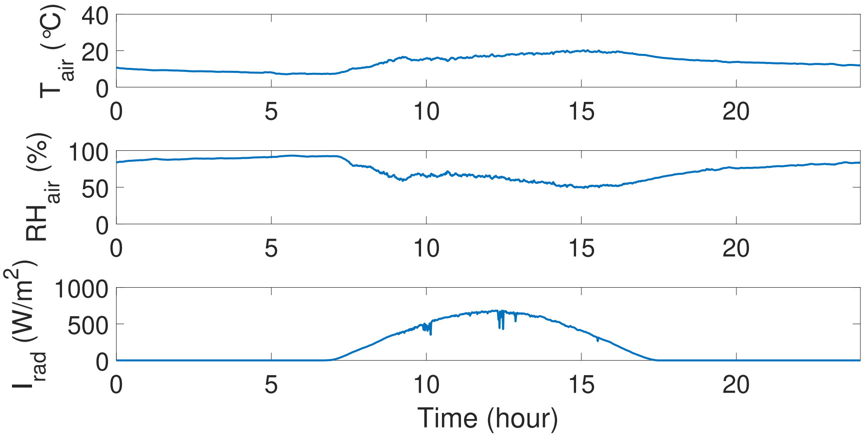

**Figure 3.13.** Meteorological data of June 05, 2016

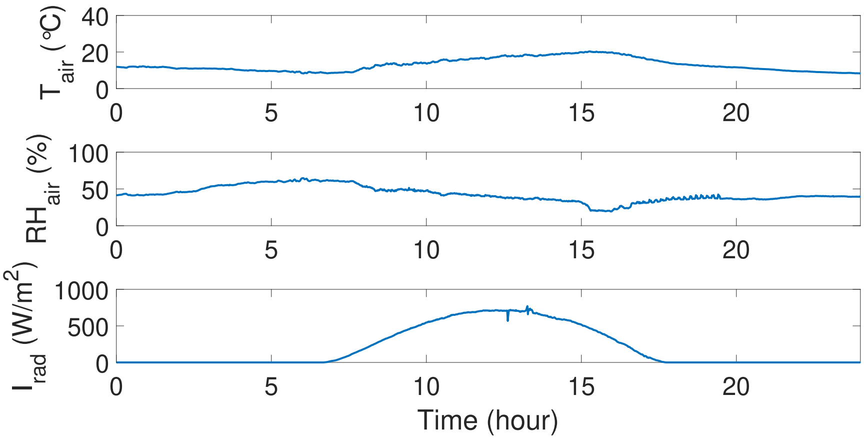

**Figure 3.14.** Meteorological data of August 03, 2016

The optimization results based on the data of June 5, 2016 show that compared with Strategy 1 and Strategy 2, the operation cost of Strategy 3 is reduced by 67.58% (from R41076 to R13317) and 67.18% (from R40576 to R13317), respectively. The optimization results based on the data of August 3, 2016 show that, compared with Strategy 1 and Strategy 2, the operation cost of Strategy 3 is reduced by 73.73% (from R37935 to R9966) and 72.84% (from R36687 to R9966), respectively. It can be seen that similar optimization results can be obtained based on weather data of different dates. Strategy 3 has the lowest cost among the three strategies proposed.

## 3.6 CONCLUSION

In this chapter, three strategies for the optimization of a greenhouse system operation are studied. Strategy 1 minimizes the energy consumption. Strategy 2 minimizes the energy cost. Strategy 3 minimizes the total cost of greenhouse heating, cooling, ventilation and $CO_2$ supply. In addition, greenhouse temperature, relative humidity, and $CO_2$ concentration are required to be maintained within suitable ranges. A greenhouse model based on energy and mass balance is introduced. The proposed optimization problems are solved by ‘fmincon’ function with sequential quadratic programming (SQP) algorithm in MATLAB.

Compared with Strategy 1, Strategy 2 consumes more energy, but costs less. Strategy 3 has the lowest cost among the three strategies proposed. Moreover, all system constraints are satisfied. Greenhouse environmental factors are kept within the required ranges. The optimization based on different meteorological data can obtain similar results.

# CHAPTER 4 OPTIMIZATION OF GREENHOUSE WATER USE EFFICIENCY

## 4.1 INTRODUCTION

In Chapter 3, different strategies for improving greenhouse energy efficiency are studied. The objectives of these strategies are to minimize the energy consumption, energy cost and total operation cost, respectively. However, these strategies only consider the impact of greenhouse climate and ignore the impact of greenhouse irrigation. Greenhouse irrigation is also an important part of greenhouse production [122]. Moreover, the greenhouse irrigation process consumes lots of water. Therefore, using reasonable greenhouse irrigation methods will not only help the growth of crops, but will also reduce water consumption and alleviate the crisis of water shortage.

In this chapter, four methods of greenhouse operation efficiency optimization to improve energy efficiency and water efficiency are studied. It should be pointed out that the research is based on our published paper [123]. The objectives of proposed methods are to minimize the energy consumption, water consumption, $CO_2$ consumption and operating costs, respectively. Temperature, relative humidity and $CO_2$ concentration should be kept within suitable ranges. Water demand for greenhouse irrigation needs to be met. A four-input three-output greenhouse climate model is introduced for greenhouse climate control. A modified crop evapotranspiration model is proposed to predict crop water demand. Moreover, a sensitivity analysis is conducted to analyze the influence of model parameter uncertainties on the optimization results.

## 4.2 CHAPTER OVERVIEW

This chapter presents four optimization methods. In Section 4.3, the modeling of greenhouse irrigation system is conducted. In Section 4.4, four optimization problems are formulated. In Section 4.5, simulations are presented. In Section 4.6, conclusions are given.

## 4.3 SYSTEM MODELING

In this chapter, a greenhouse model and a irrigation model are presented. The influence of crop growth and the interaction between different variables are considered. Moreover, the model performance is analyzed.

### 4.3.1 Greenhouse climate model

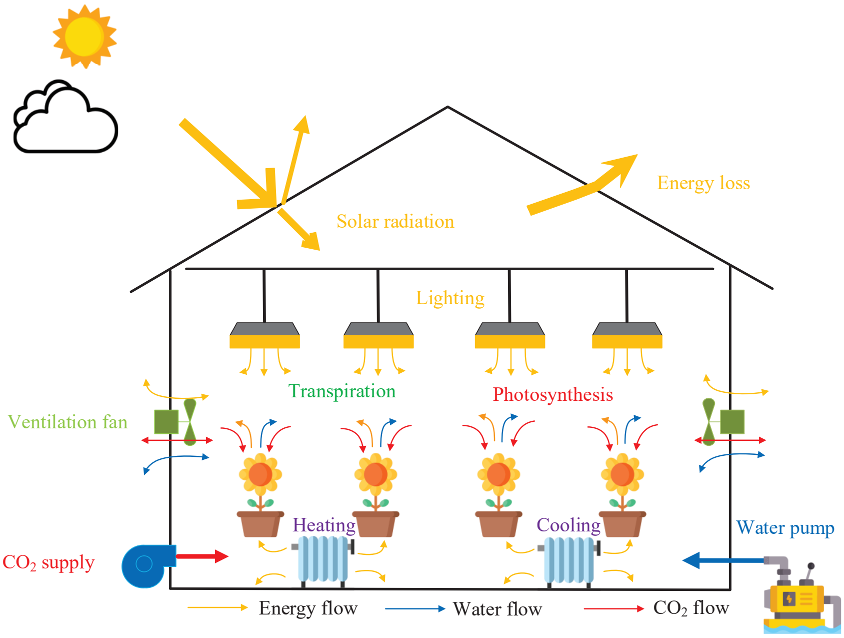

**Figure 4.1.** Energy, water and $CO_2$ flow

Figure 4.1 shows the energy, water and $CO_2$ flow. It should be pointed out that the model proposed in Chapter 3 has three inputs ($Q_c$, $g_v$, $C_{inj}$), while the model used in this chapter has four inputs ($Q_c$, $g_v$, $C_{inj}$, $s_r$). The greenhouse climate model used in this chapter is given below.

The temperature $T_{air}$ can be obtained by:

$$\frac{dT_{air}}{dt} = \frac{1}{C_{cap}}(Q_{sun}(1-s_r) + Q_{lamp} - Q_{cov} - Q_{trans} - Q_{vent} + Q_c). \tag{4.1}$$

The humidity $H_{air}$ can be calculated by:

$$\frac{dH_{air}}{dt} = \frac{1}{h}(H_{trans} - H_{cov} - H_{vent}). \tag{4.2}$$

The $CO_2$ concentration $C_{air}$ can be given by:

$$\frac{dC_{air}}{dt} = \frac{1}{h}(C_{inj} - C_{ass} - C_{vent}). \tag{4.3}$$

### 4.3.2 Irrigation model

An accurate irrigation model is important for greenhouse irrigation control. A greenhouse irrigation model can be obtained based on soil water balance. Figure 4.2 shows the outdoor soil water balance.

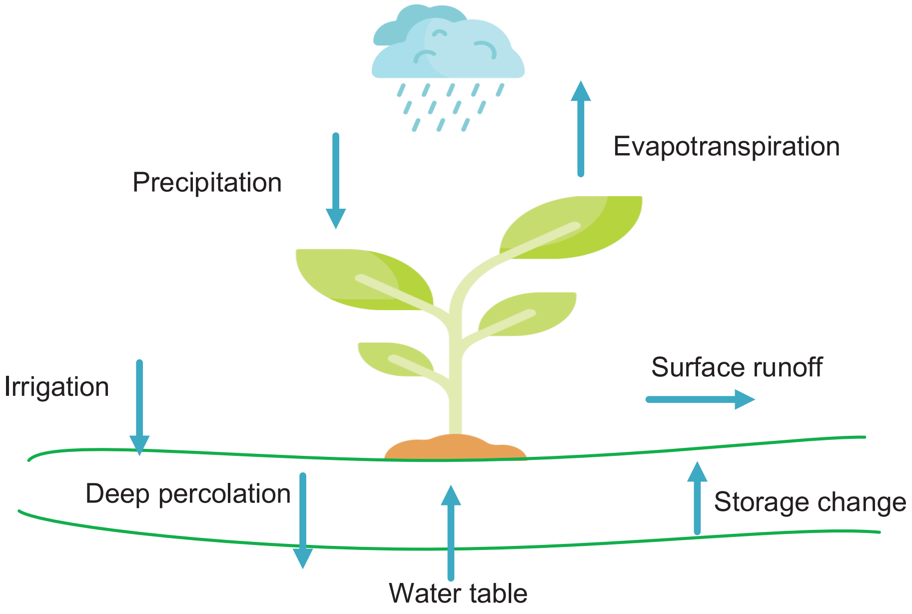

**Figure 4.2.** Outdoor soil water balance

The soil water balance is given by:

$$P + I + W = ET + R_o + D + \Delta S, \tag{4.4}$$

where $P$ represents the precipitation, $I$ represents the irrigation, $W$ represents the water from the water table, $ET$ is the evapotranspiration, $R_o$ represents the surface runoff, and $D$ represents the deep percolation. For the greenhouse environment, $P = 0$. Moreover, $W$, $R_o$ and $D$ can also be ignored [91]. The soil water balance in the greenhouse environment is expressed as:

$$I = ET + \Delta S. \tag{4.5}$$

To obtain an accurate value of soil water content, the soil should be in the oven at 105°C for six to eight hours to obtain the difference between the moist soil and the dried soil. Therefore, many irrigation control methods set $\Delta S = 0$ [124], [125]. The irrigation model can be expressed as:

$$I = ET. \tag{4.6}$$

$ET$ can be calculated by:

$$ET = ET_o \times K_c, \tag{4.7}$$

where $ET_o$ is the reference evapotranspiration and $K_c$ is the crop coefficient.

For the calculation of $ET_o$, many methods have been proposed, including the FAO Penman, the FAO Radiation, FAO Pan methods, the Hargreaves equation, the Almeria radiation method, and the Penman-Monteith method [126, 90].

The Penman-Monteith equation is recommended to predict the evapotranspiration $ET_o$ [127].

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T_{air}+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34v_2)}, \tag{4.8}$$

where $\Delta$ is the slope of the vapor pressure curve, $G$ is the soil heat density, $\gamma$ is the psychometric constant, $e_s$ is the saturation vapour pressure, $e_a$ is the average vapour pressure and $v_2$ is the wind speed.

$$e_s = 0.6108 \times \exp(\frac{17.27 \times T_{air}}{T_{air} + 237.3}), \tag{4.9}$$

$$e_a = e_s \times RH_{air}, \tag{4.10}$$

$$\Delta = \frac{4098 \times e_s}{(T_{air} + 237.3)^2}. \tag{4.11}$$

The FAO24 Penman equation can be expressed by:

$$ET_o = c\left[\left(\frac{\Delta}{\Delta + \gamma}\right)0.408R_n + \left(\frac{\Delta}{\Delta + \gamma}\right)2.7\left(1 + 0.01u_2\right)\left(e_s - e_a\right)\right], \tag{4.12}$$

where $c$ is an adjustment factor.

The FAO 24 Pan evaporation equation is given by:

$$ET_o = K_p \times E_o, \tag{4.13}$$

where $K_p$ is the pan coefficient and $E_o$ is the pan evaporation.

The FAO24 Radiation equation is given by:

$$ET_o = b \times \left(\frac{\Delta}{\Delta+\gamma}\right) R_s - 0.3, \tag{4.14}$$

where $b$ is an adjustment factor and $R_s$ is the daily solar radiation.

The Hargreaves equation is recommended by FAO to estimate evapotranspiration in the absence of climate data on relative humidity and wind speed. The Hargreaves equation is as follows:

$$ET_o = 0.0023 R_a \tau (T_{mean} + 17.8)(T_{max} - T_{min})^{0.5}, \tag{4.15}$$

where $R_a$ is extraterrestrial radiation. $\tau$ is the transmittance of the greenhouse. $T_{mean}$, $T_{max}$ and $T_{min}$ are the average, maximum and minimum values of the greenhouse temperature, respectively. According to [128], $R_a$ is assumed to be 1 on the open air farm and 0.88 in the greenhouse. This equation makes several important assumptions about weather conditions. Therefore, the evapotranspiration calculated by this equation is an approximate value.

Finally, the locally-calibrated radiation method is as follows:

$$\text{Juliandays(JD)} \leq 220;\ ET_o = (0.288 + 0.0019JD) R_o \tau, \tag{4.16}$$

$$\text{Juliandays(JD)} > 220;\ ET_o = (1.139 - 0.00288JD) R_o \tau, \tag{4.17}$$

where $R_o$ represents outside solar radiation.

Although there are many methods to calculate $ET_o$, Equation (4.8) is the most recommended [129], [130]. However, this method is only suitable for the calculation of outdoor $ET_o$, and not suitable for the calculation of $ET_o$ in the greenhouse. This is because the wind speed inside is low, and the use of this model will produce large errors [131]. The daily wind speed measured in greenhouse fluctuates between 0.01 and 0.2 $\text{m/s}$, so the corresponding $r_a$ fluctuates between 20800 and 2080 $\text{s/m}$. The calculated value is much larger than the actual observed value [131]. Therefore, the model needs to be modified to predict the evapotranspiration more accurately [132].

A modified $ET_o$ model can be give by:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{1713}{T_{air}+273}(e_s - e_a)}{\Delta + 1.64\gamma}. \tag{4.18}$$

Please note that compared with $R_n$, $G$ is very small. In this chapter, $G$ is set to $G = 0$.

### 4.3.3 Model analysis

The analysis of the reference evapotranspiration model can be found in [89]. This section analyzes the impact of environmental factors on evapotranspiration based on the proposed modified evapotranspiration model, and then adopts corresponding methods to reduce evapotranspiration.

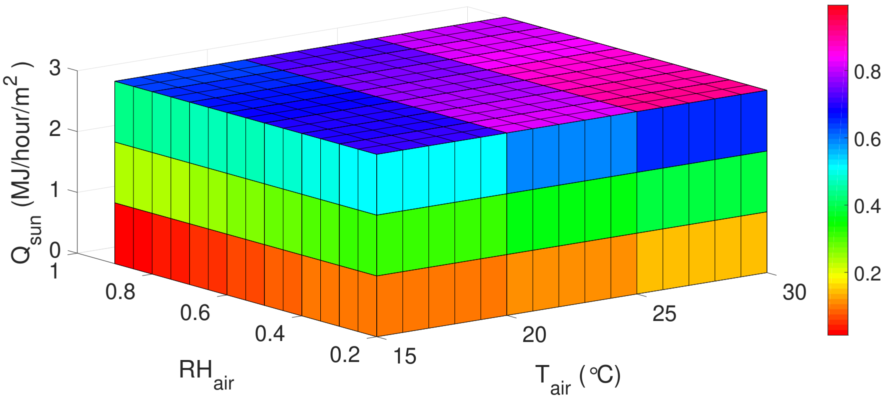

**Figure 4.3.** Crop reference evapotranspiration

According to (4.18), $ET_o$ is related to $T_{air}$, $RH_{air}$ and $Q_{sun}$. Figure 4.3 shows how these greenhouse environmental factors affect crop evapotranspiration. As shown in Figure 4.3, while keeping other variables unchanged, $ET_o$ increases with the increase of $T_{air}$, decreases with the increase of $RH_{air}$, and increases with the increase of $Q_{sun}$. Therefore, the greenhouse water consumption can be reduced by the following methods: (1) Reduce the value of $T_{air}$; (2) Increase the value of $RH_{air}$; (3) Reduce the value of $Q_{sun}$.

## 4.4 OPTIMIZATION

The optimization problems studied in this chapter are described in three parts: decision variables, objectives and constraints.

### 4.4.1 Decision variables

For the study in this chapter, the decision variables include $Q_c$, $g_v$, $C_{inj}$ and $s_r$, while the controlled variables include $T_{air}$, $RH_{air}$ and $C_{air}$.

### 4.4.2 Objectives

Four operational optimization methods considering climate control and irrigation control are studied and given below. Method 1 focuses on energy saving. The objective function can be expressed as:

$$J_1 = E_1 + E_2 + E_3, \tag{4.19}$$

where $E_1$ represents the energy consumed by heating, $E_2$ represents the energy consumed by ventilation, $E_3$ represents the energy consumed by irrigation.

$$E_1 = \int_{t_i}^{t_f} |Q_c(t)|\, dt, \tag{4.20}$$

$$E_2 = \int_{t_i}^{t_f} Q_v(t) dt, \tag{4.21}$$

$$Q_v = \lambda g_v, \tag{4.22}$$

where $\lambda$ represents the conversion factor from $g_v$ to $Q_v$.

$$E_3 = \int_{t_i}^{t_f} Q_p dt, \tag{4.23}$$

$$Q_p = \frac{1}{\eta} \rho_w p_f g h_w, \tag{4.24}$$

where $Q_p$ represents the pumping power, $\eta$ represents the pumping efficiency, $\rho_w$ represents water density, $p_f$ represents the pumping flow, $g$ represents the acceleration of gravity and $h_w$ represents the pumping height.

Method 2 focuses on reducing water consumption. Only irrigation water consumption is considered in this chapter. The modified evapotranspiration model (Equation 4.18) is adopted for the calculation of greenhouse water consumption. The objective function is as follows:

$$J_2 = \int_{t_i}^{t_f} I(t) dt. \tag{4.25}$$

Method 3 focuses on reducing $CO_2$ consumption. The objective function can be expressed as:

$$J_3 = \int_{t_i}^{t_f} C_{inj}(t) dt. \tag{4.26}$$

Method 4 focuses on reducing the cost of energy, water and $CO_2$. The objective function can be expressed as:

$$J_4 = \omega_1 J_1 + \omega_2 J_2 + \omega_3 J_3, \tag{4.27}$$

where $\omega_1$, $\omega_2$ and $\omega_3$ are the prices of energy, water and $CO_2$, respectively. Electricity prices shown in Equation (3.25) is adopted for energy cost calculation. The groundwater is used for irrigation, $\omega_2 = 0$. It should be pointed out that, in some studies, the water used for irrigation is derived from water plants, and $\omega_2$ will not be zero. In this thesis, the price of supplied $CO_2$ is constant. $\omega_3 = \text{R}1000/\text{ton}$.

### 4.4.3 Constraints

The input constraints can be given by:

$$Q_{c,min} \leq Q_c \leq Q_{c,max}, \tag{4.28}$$

$$g_{v,min} \leq g_v \leq g_{v,max}, \tag{4.29}$$

$$C_{inj,min} \leq C_{inj} \leq C_{inj,max}, \tag{4.30}$$

$$\begin{cases} 0 \leq s_r \leq 1, \ if \ I_{rad} \geq I_{rad,min} \\ s_r = 0, \qquad if \ I_{rad} < I_{rad,min}, \end{cases} \tag{4.31}$$

where $Q_{c,min}$ and $Q_{c,max}$ are the maximum cooling power and heating power. $g_{v,min}$ and $g_{v,max}$ are the maximum and minimum ventilation rate. $C_{inj,min}$ and $C_{inj,max}$ are maximum and minimum $CO_2$ injection rate.

The input rate of change constraints are given by:

$$\left|\frac{dQ_c}{dt}\right| \leq k_1, \tag{4.32}$$

$$\left|\frac{dg_v}{dt}\right| \leq k_2, \tag{4.33}$$

$$\left|\frac{dC_{inj}}{dt}\right| \leq k_3. \tag{4.34}$$

Due to $s_r$ can vary abruptly, the corresponding rate of change constraint is not considered.

Greenhouse environmental factors should be within suitable ranges [133, 134]. The corresponding constraints are as follows:

$$T_{air,min} \leq T_{air} \leq T_{air,min}, \tag{4.35}$$

$$RH_{air,min} \leq RH_{air} \leq RH_{air,max}, \tag{4.36}$$

$$C_{air,min} \leq C_{air} \leq C_{air,max}, \tag{4.37}$$

where $T_{air,min}$ and $T_{air,max}$ are the minimum and maximum temperature. $RH_{air,min}$ and $RH_{air,max}$ are the minimum and maximum relative humidity. $C_{air,min}$ and $C_{air,max}$ are the minimum and maximum $CO_2$ concentration.

The constraints of radiation power after shading can be given by:

$$I_{rad,min} \leq Q_{sun}(1 - s_r). \tag{4.38}$$

## 4.5 SIMULATION

These optimization problems are solved by MATLAB software with sequential quadratic programming algorithm. The data used and the simulation results are given below.

### 4.5.1 Simulation data

The weather data used is shown in Figure 4.4. The model parameters are shown in Table 4.1. The constraints are given in Table 4.2.

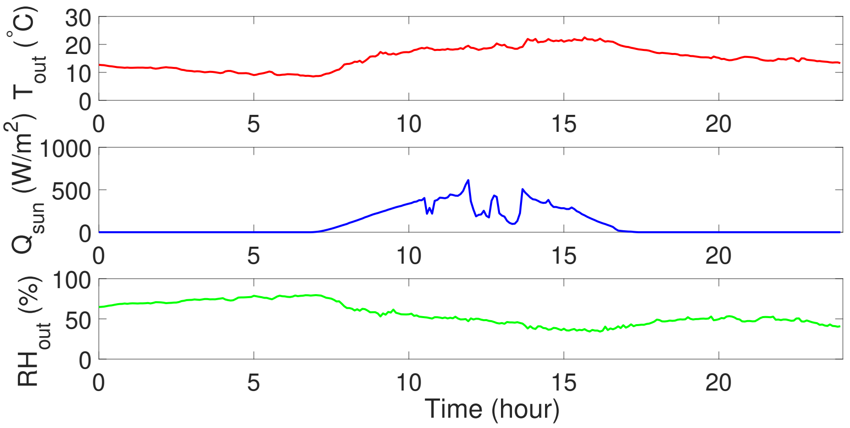

**Figure 4.4.** Meteorological data for July 1, 2016

**Table 4.1.** Greenhouse model parameters

| Parameter | Value | Unit | Parameter | Value | Unit |
|---|---|---|---|---|---|
| $\alpha_1$ | 0.7 | – | $p_{gc}$ | $1.8\times10^{-3}$ | $\mathrm{m}^\circ\mathrm{C}^{-1/3}\mathrm{s}^{-1}$ |
| $\alpha_2$ | 10 | $\mathrm{Wm}^{-2\circ}\mathrm{C}^{-1}$ | $\omega_o$ | 0.5157 | R/kWh |
| $\gamma$ | 0.008 | – | $\omega_s$ | 0.9446 | R/kWh |
| $LAI$ | 2.6 | – | $\omega_p$ | 3.1047 | R/kWh |
| $C_{cap}$ | 30000 | $\mathrm{J/m^2\,^\circ C}$ | $\lambda$ | 0.06 | $\mathrm{W/m^3}$ |
| $h$ | 7 | m | $\eta$ | 0.75 | – |
| $s_a$ | 40709 | $\mathrm{m^2}$ | $g$ | 9.8 | $\mathrm{m/s^2}$ |
| $L$ | 2450 | J/g | $h_w$ | 7 | m |
| $r_b$ | 150 | s/m | $\omega_3$ | 1000 | R/ton |
| $\rho_{air}$ | 1.225 | $\mathrm{kg/m^3}$ | $K_c$ | 0.7 | – |
| $C_{p,air}$ | 1003 | $\mathrm{J/kg^\circ C}$ | $\rho_w$ | 1000 | $\mathrm{kg/m^3}$ |

### 4.5.2 Results of energy consumption optimization

Figure 4.5 shows the results of Method 1. From Sub-figure 1, it can be seen that most energy is used for heating and a small amount of the energy consumed is used for cooling. That is because the temperature drops to the lower limit, and the solar radiation power is low in the morning. Therefore,

**Table 4.2.** System constraints

| Variable | Value | Unit |
|---|---|---|
| $T_{air,min}$ | 14 | °C |
| $T_{air,max}$ | 26 | °C |
| $RH_{air,min}$ | 0 | % |
| $RH_{air,max}$ | 90 | % |
| $C_{air,min}$ | 400 | ppm |
| $C_{air,max}$ | 2000 | ppm |
| $Q_{c,min}$ | -200 | $\mathrm{W/m^2}$ |
| $Q_{c,max}$ | 200 | $\mathrm{W/m^2}$ |
| $g_{v,min}$ | 0 | $\mathrm{m/s}$ |
| $g_{v,max}$ | 0.02 | $\mathrm{m/s}$ |
| $C_{inj,min}$ | 0 | $\mathrm{g/m^2s}$ |
| $C_{inj,max}$ | 0.02 | $\mathrm{g/m^2s}$ |

the greenhouse must be heated to maintain the required temperature. The temperature at noon is high, so cooling is needed to lower the temperature.

From Sub-figure 2, it can be seen that ventilation occurs mainly around noontime. That is because the outdoor temperature is high, and ventilation will not cause energy loss. The value of the shading rate is small, ranging from 0 to 0.3. The small shading rate enables more light radiation in the greenhouse and reduces heating energy consumption. Finally, the greenhouse environmental factors are kept within the required ranges.

### 4.5.3 Results of water consumption optimization

Figure 4.6 shows the optimization results of Method 2. From sub-figure 5, it can be found that the temperature is low. From Sub-figure 6, it can be observed that the relative humidity is high. Most relative humidity values are on the upper bound. As shown in Sub-figure 8, the solar radiation power is low. The reason is that $s_r$ is large, which can be found in Sub-figure 4. Low temperature, high relative humidity, and low solar radiation power can reduce water consumption. Related explanations can be found in Section 4.3.3. However, the energy consumption is high. Therefore, it is better to choose a method that considers water consumption and other indicators, such as energy consumption and cost, in the actual production process.

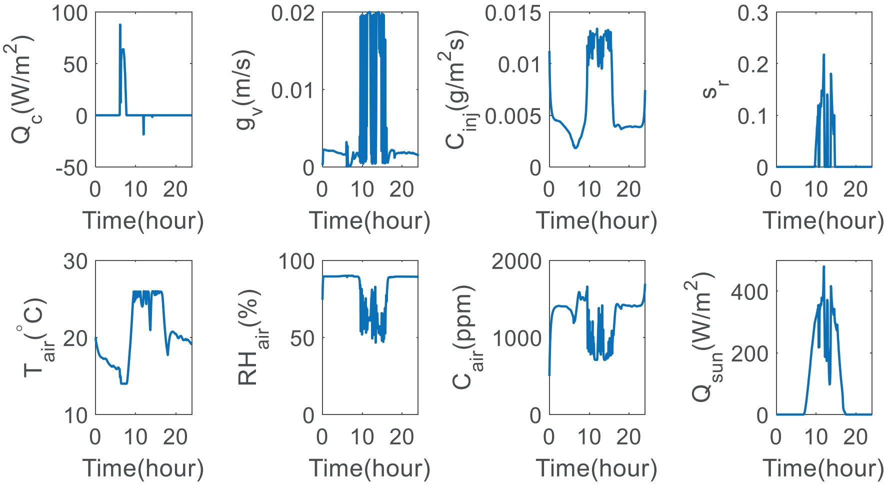

**Figure 4.5.** Optimization results of Method 1

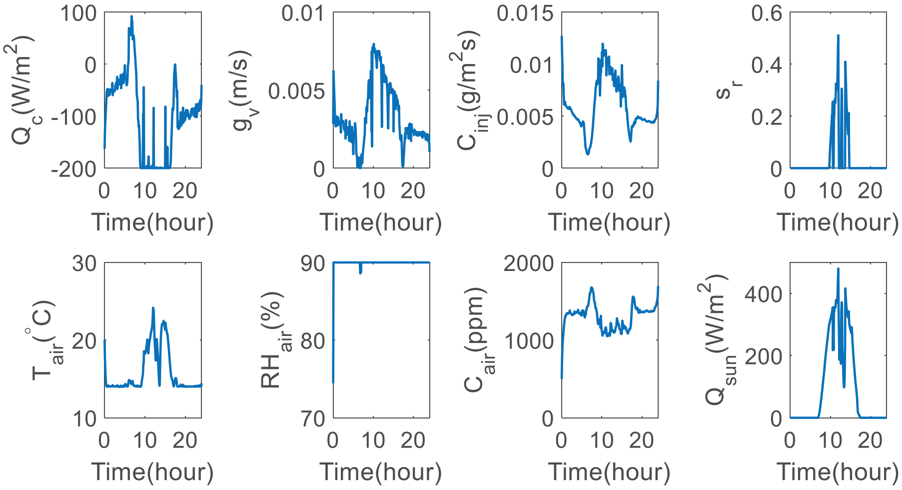

**Figure 4.6.** Optimization results of Method 2

### 4.5.4 Results of carbon dioxide consumption optimization

Figure 4.7 shows the optimization results of Method 3. From Sub-figure 7, it can be seen that the $CO_2$ concentration is low. This is because very little $CO_2$ is injected into the greenhouse, which can be found in Sub-figure 3. In addition, the ventilation rate is high. Ventilation can bring $CO_2$ from the external environment into the greenhouse. It should be pointed out that ventilation can only keep the $CO_2$ concentration in the greenhouse at a low level. To increase crop yield, the greenhouse $CO_2$ concentration should be higher in some stages of crop production, which cannot be achieved by ventilation.

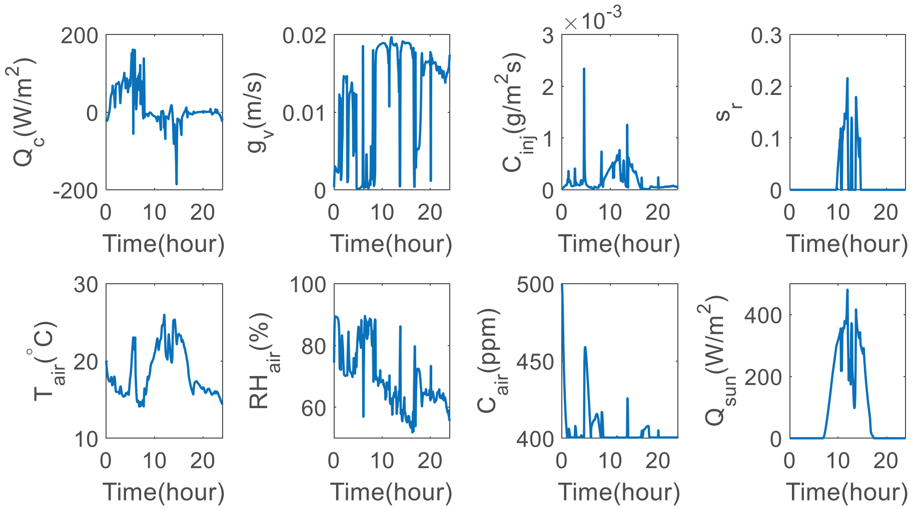

**Figure 4.7.** Optimization results of Method 3

### 4.5.5 Results of total cost optimization

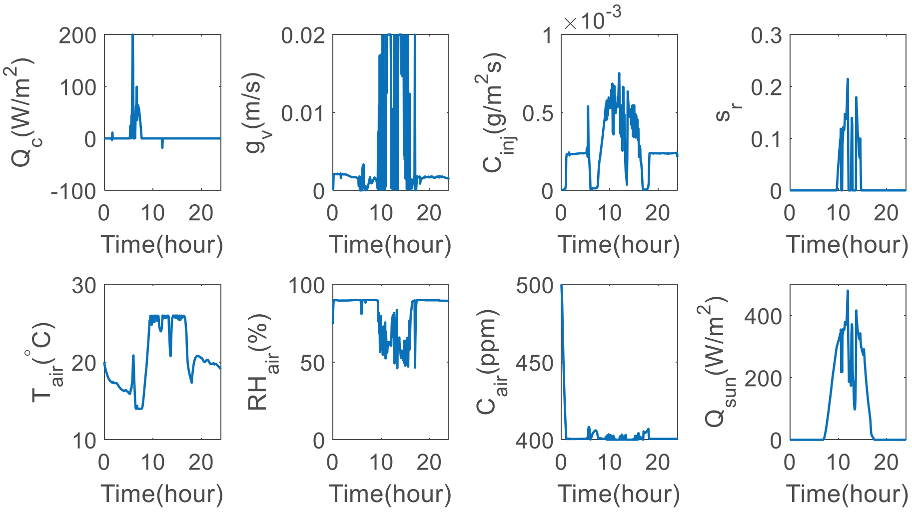

**Figure 4.8.** Optimization results of Method 4

Figure 4.8 shows the optimization results of Method 4. From Sub-figure 1 and Sub-figure 3, it can be found that the energy consumption and $CO_2$ consumption are not much, which can reduce the total cost. In addition, similar to Method 1, $s_r$ of Method 4 is low, which can reduce the energy consumption and cost.

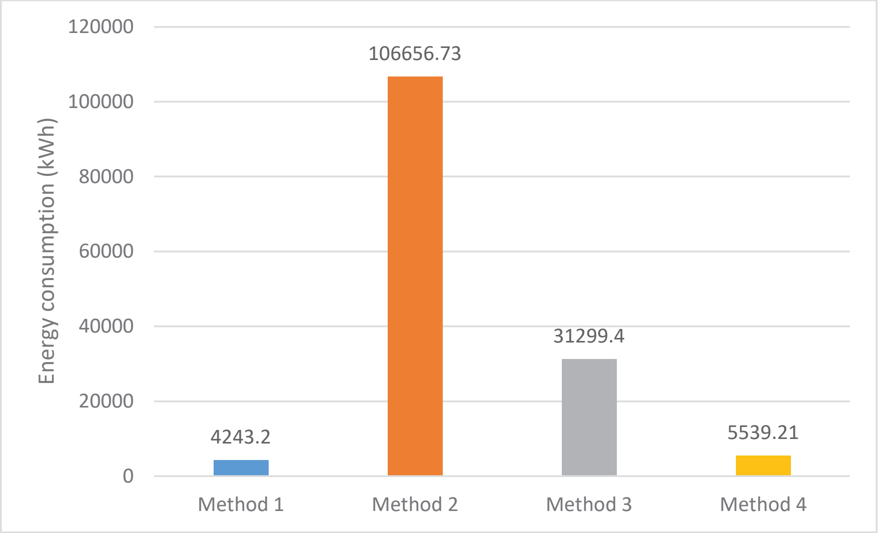

**Figure 4.9.** Energy consumption of four methods

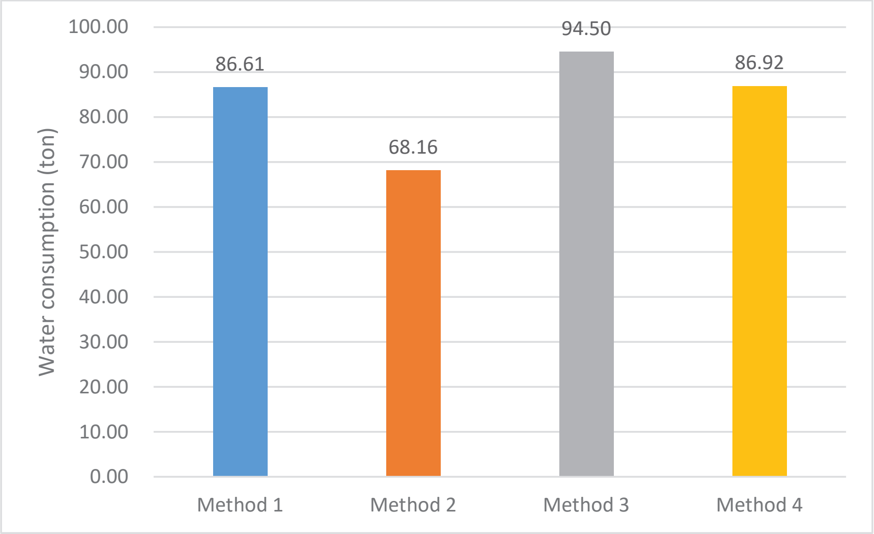

**Figure 4.10.** Water consumption of four methods

The energy consumption comparison is shown in Figure 4.9. The water consumption comparison can be found in Figure 4.10. The $CO_2$ consumption comparison of four methods is shown in Figure 4.11. The total cost comparison is shown in Figure 4.12.

From Figure 4.9, it can be seen that the energy consumption of Method 1, Method 2, Method 3 and

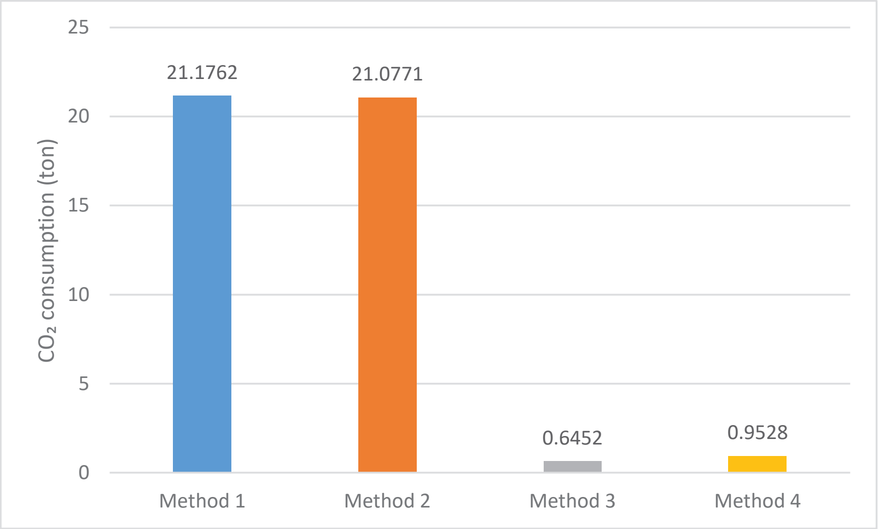

**Figure 4.11.** $CO_2$ consumption of four methods

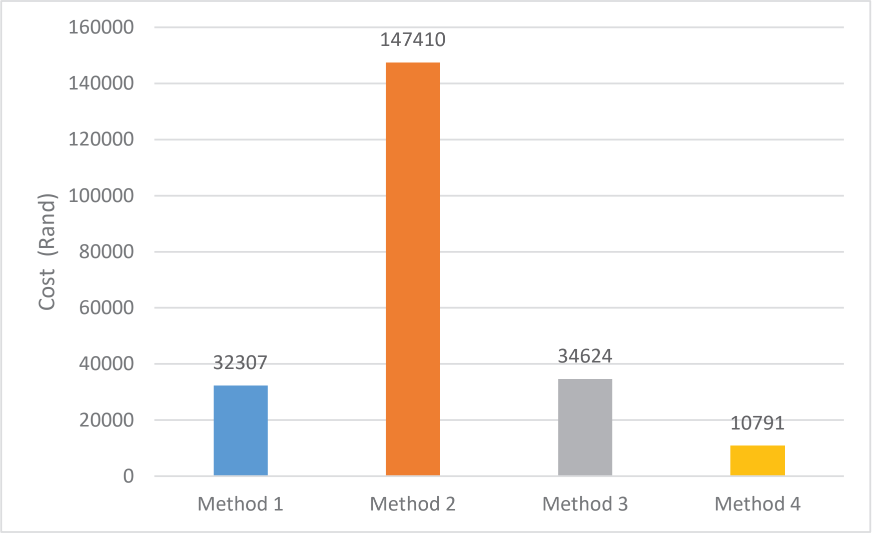

**Figure 4.12.** Cost of four methods

Method 4 are 4243.2 kWh, 106656.73 kWh, 31299.4 kWh and 5539.21 kWh, respectively. Compared with Method 2, Method 3 and Method 4, Method 1 can reduce energy consumption by 96%, 86% and 23%, respectively.

From Figure 4.10, it can be seen that the water consumption of the four proposed Methods is 86.61

ton, 68.16 ton, 94.50 ton and 86.92 ton, respectively. Compared with Method 1, Method 3 and Method 4, Method 2 reduces water consumption by 21%, 28% and 22%, respectively.

From Figure 4.11, it can be found that the $CO_2$ consumption of the four proposed methods are 21.1762 ton, 21.0771 ton, 0.6452 ton and 0.9528 ton, respectively. Compared with Method 1, Method 2 and Method 4, Method 3 reduces $CO_2$ consumption by 96.95%, 96.94% and 32.28%, respectively.

From Figure 4.12, it can be observed that the cost of the four proposed methods are R32307, R147410, R34624, and R10791, respectively. Compared with Method 1, Method 2 and Method 3, Method 4 can reduce the total cost by 66%, 93% and 69%, respectively.

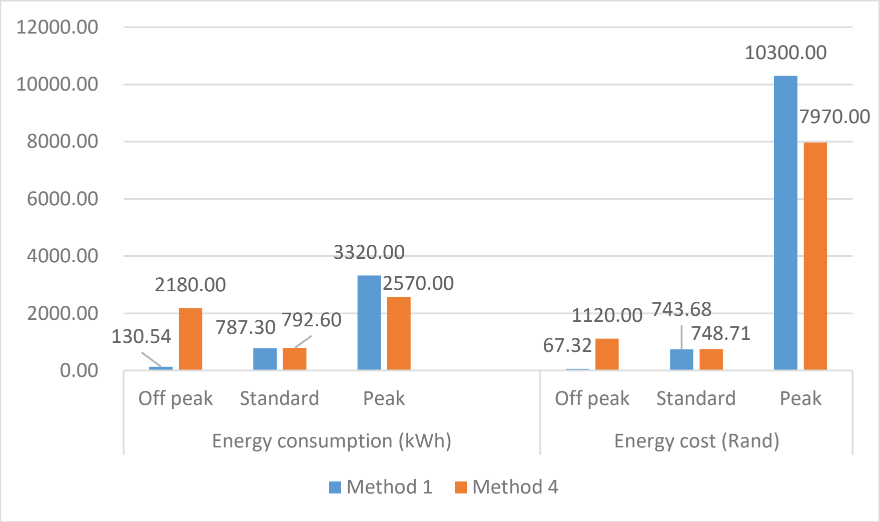

**Figure 4.13.** Comparison of Method 1 with Method 4

Figure 4.13 compares Method 1 with Method 4. The reason why Method 1 and Method 4 are chosen for comparison is that these two methods are commonly used methods in the production process. Method 4 consumes more energy but costs less. This is because Method 4 can shift the load from a period of high electricity prices to a period of low electricity prices.

Figure 4.14 shows the $s_r$ of proposed methods. It can be seen that the $s_r$ of Method 2 is larger than that of other methods. This is because shading can reduce the radiation power in the greenhouse, thereby reducing water consumption. However, when $s_r$ is too large, the photosynthesis of plants will be adversely affected.

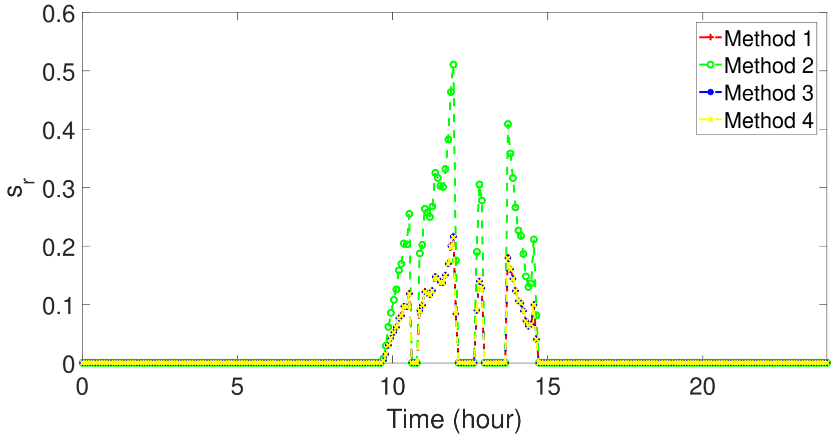

**Figure 4.14.** Greenhouse shading rate $s_r$

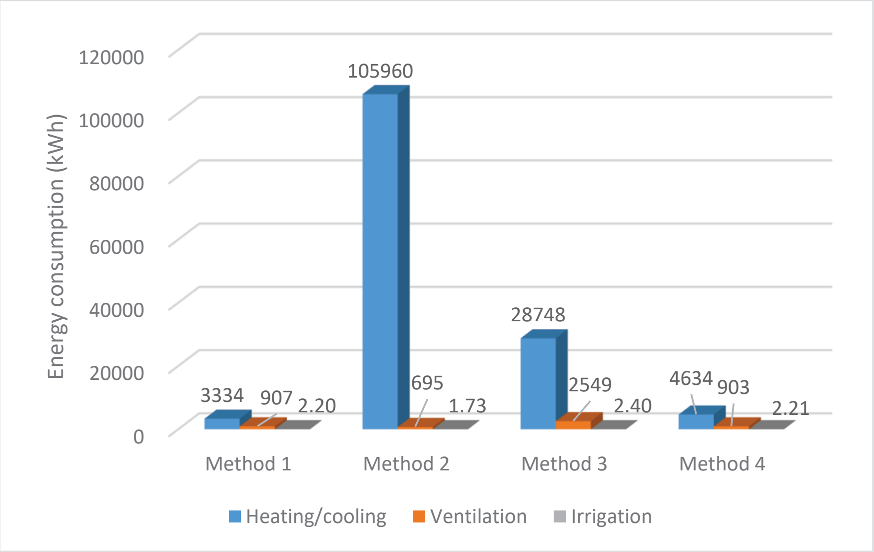

**Figure 4.15.** Energy consumption composition of four methods

Figure 4.15 shows the energy consumption composition. By comparing the use of energy, it can be found that the heating energy consumption is the highest, the ventilation energy consumption is second, and the irrigation energy consumption is the least. Figure 4.16 shows the cost composition. For Method 1, the cost of energy and $CO_2$ accounts for most of the total cost. The three other methods have a similar cost composition. Please note that the total cost of Method 2 is higher than that of other methods. That is because Method 2 consumed more energy than other methods to reduce water consumption. If only water consumption is considered, the production cost will be high. Therefore, in the actual production process, other objectives such as reducing energy consumption and $CO_2$

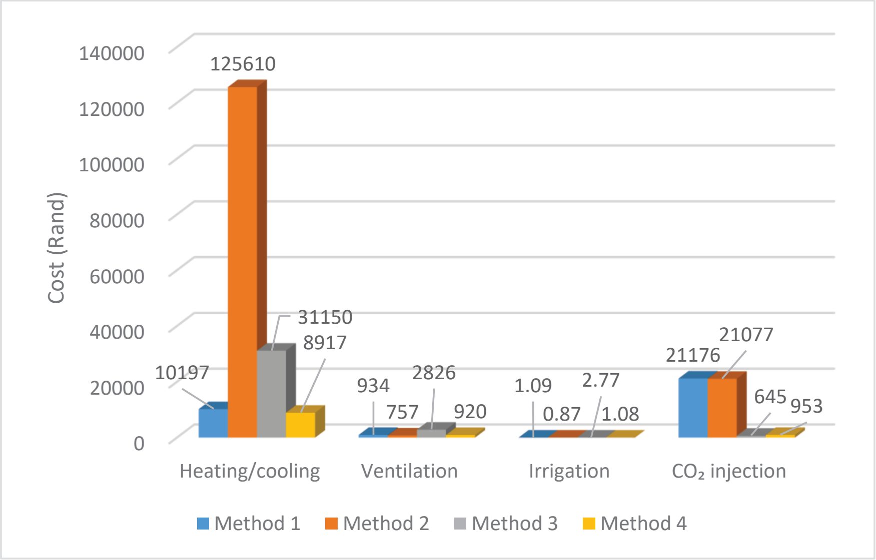

**Figure 4.16.** Cost composition of four methods

consumption also should be considered.

### 4.5.6 Sensitivity analysis

Through sensitivity analysis, the influence of model parameter uncertainty on optimal controller performance can be understood [135, 13]. In this chapter, the influence of parameter changes on the optimization results are studied. It should be pointed out that the change is in increments by 5%.

#### 4.5.6.1 Influence of prices change

The sensitivity analysis of different prices is shown in Figure 4.17. It can be found that the cost increases with prices. Compared with the water price and $CO_2$ price, the electricity price has a greater impact on the cost. When the electricity price increases by 5%, the cost increases by 4.56%. However, when the price of water and $CO_2$ increased by 5%, the cost only increased by 0.38% and 0.44% respectively.

#### 4.5.6.2 Influence of constraints change

Figure 4.18 shows the influence of constraint changes on the greenhouse operation cost. It can be found that increasing the upper limit of the temperature constraint or lowering the lower limit of the temperature constraint will reduce the cost. Increasing the lower limit or lowering the upper limit of the temperature constraint will increase the cost. It should be pointed out that when the upper temperature limit is increased to a certain value, the cost will no longer decrease with the increase in

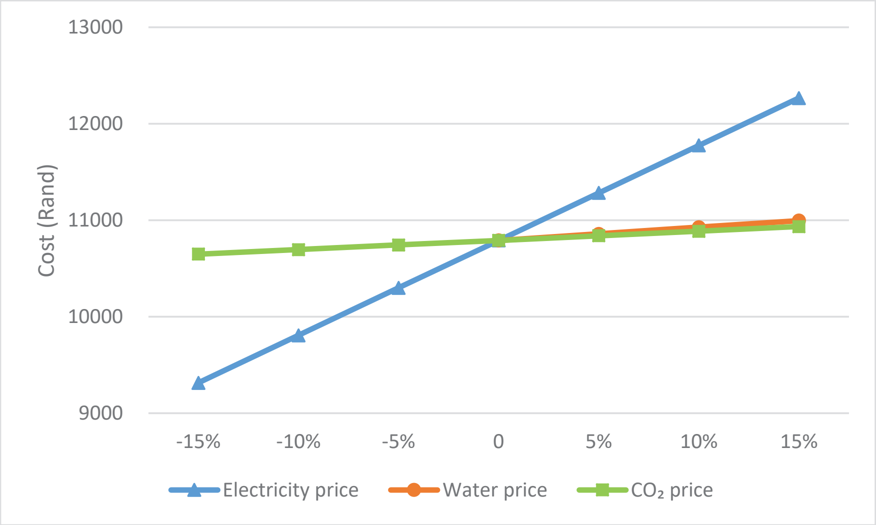

**Figure 4.17.** Sensitivity analysis of prices

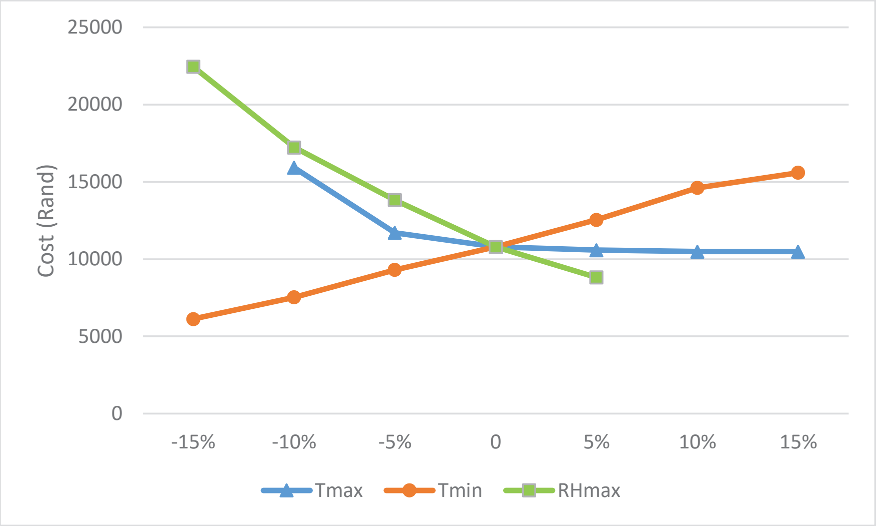

**Figure 4.18.** Cost under the constraints of different percentage changes

the upper limit.

In addition, it can be found that the cost decreases with the increase of the upper limit of relative humidity. The constraints of temperature and relative humidity have great influence on the optimization results.

## 4.6 CONCLUSION

In this chapter, four optimization methods are studied. Method 1 minimizes greenhouse energy consumption. Method 2 minimizes greenhouse water consumption. Method 3 minimizes greenhouse $CO_2$ consumption. Method 4 minimizes the total cost. In addition, some environmental factors are required to be within suitable ranges. These methods are based on a dynamic climate model and a modified irrigation model. Moreover, a sensitivity analysis is studied.

The results show that the proposed methods can achieve their respective goals. From an economic perspective, Method 4 is more suitable than the other three methods for optimization of a greenhouse system operation. The total costs of Method 1, Method 2, Method 3 and Method 4 are R32308, R147440, R34624 and R10791, respectively. Compared with Method 1, Method 2 and Method 3, Method 4 reduces the total cost by 66.60%, 92.68% and 68.83%, respectively. Moreover, changes in prices and constraints have a great impact on the optimization results.

# CHAPTER 5 HIERARCHICAL MODEL PREDICTIVE CONTROL

## 5.1 INTRODUCTION

In Chapter 3 and Chapter 4, different open loop optimization strategies are studied. However, these strategies have low control accuracy under system disturbances. Therefore, closed-loop control methods should be used to improve the control accuracy. In this chapter, a greenhouse hierarchical control approach is presented. The hierarchical control method can decompose a complex problem into multiple simple sub-problems. Therefore, the computational complexity can be reduced [94, 136]. The proposed hierarchical control method has two layers. On the upper layer, two open loop controllers are designed to find the reference trajectories of greenhouse environmental factors. On the lower layer, two MPC controllers are designed to follow the obtained reference trajectories.

## 5.2 CHAPTER OVERVIEW

In Section 5.3, the hierarchical control scheme is introduced. In Section 5.4, controllers are designed. Simulations are shown in Section 5.5. Conclusions are drawn in Section 5.6.

## 5.3 HIERARCHICAL CONTROL SCHEME

Figure 5.1 shows a two-layer hierarchical structure. On the upper layer, the optimization objective is to obtain the reference trajectory over a horizon $T$. The sampling interval is $T_o$. The optimization solution at each sample time $kT_o$ is used as the reference trajectory for the lower layer during the interval time $[kT_o,(k+1)T_o]$. On the lower layer, controllers are designed to track the obtained trajectories. The sampling interval is $T_m$.

In this chapter, a two-layer hierarchical structure for greenhouse climate control is proposed. The proposed hierarchical control scheme is shown in Figure 5.2. On the upper layer, open loop optimization

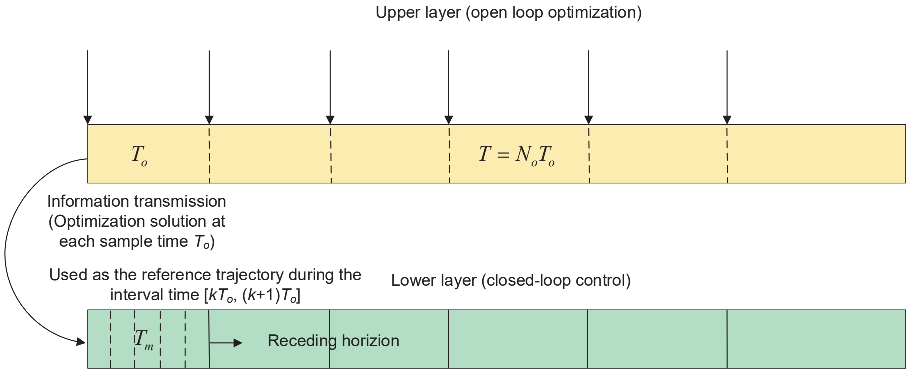

Figure 5.1. Two-layer hierarchical structure

controllers are designed to find the reference trajectories of greenhouse environmental factors. On the lower layer, closed-loop MPC controllers are designed to track the reference trajectories obtained from the upper layer.

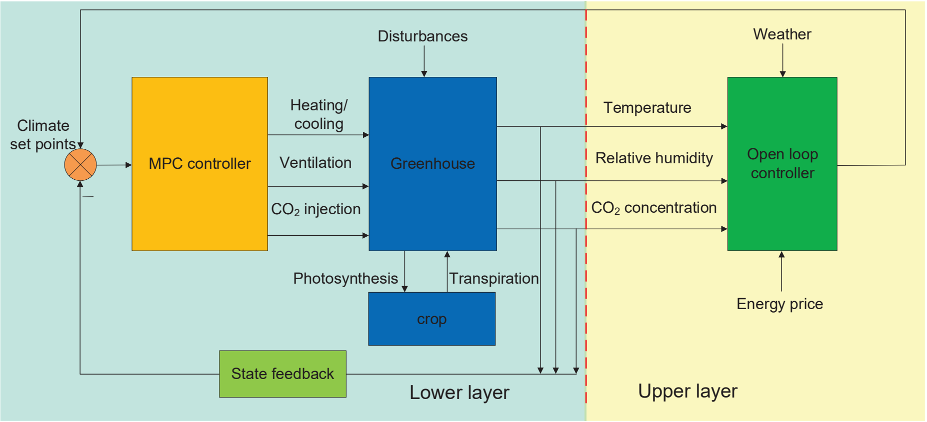

Figure 5.2. Greenhouse hierarchical control

## 5.4 CONTROLLER DESIGN

In this section, two open loop controllers are designed for Strategy 3 in Chapter 3 and Method 4 in Chapter 4. Open loop controllers are required to optimize the greenhouse environmental factors with respect to external information including the outdoor temperature and electricity price. This was done in Chapter 3 and 4 from an operation research perspective. Here in this chapter, however, optimization problems presented in Chapter 3 and 4 are re-structured and presented in control system language to facilitate the subsequent closed-loop MPC design on the lower layer to tackle modeling uncertainties and external disturbances. In particular, the optimization Strategy 3 in Chapter 3 and optimization Method 4 in Chapter 4 are both replicated in the controller design. They both consider the overall cost minimization of the greenhouse, which is most important for farmers.

### 5.4.1 Open loop controller design

For Strategy 3 in Chapter 3, the state-space model can be expressed as:

$$x_1(k+1) = f_1(x_1(k), u_1(k)), \tag{5.1}$$

where $x_1$ is the state variable, $u_1$ the input variable, $k$ is the time $kT_o$, $T_o$ is the sampling period, $N_o$ is the number of samples. $u_1(k) = [Q_c(k), g_v(k), C_{inj}(k)]^T$, $x_1(k) = [T_{air}(k), RH_{air}(k), C_{air}(k)]^T$. $f_1(\cdot)$ is the nonlinear functions that represent the discrete greenhouse model obtained from Equation (3.1) to Equation (3.21). The objective function $J_{3a}$ is derived from Equation (3.26) and can be expressed as:

$$J_{3a} = \sum_{k=1}^{N_o} Q_c(k)\omega(k) + \lambda g_v(k)\omega(k) + C_{inj}(k)p_c(k). \tag{5.2}$$

The constraints are derived from the inequality (3.27) to (3.35) and given by:

$$T_{air,min} \le T_{air}(k) \le T_{air,max}, \tag{5.3}$$

$$RH_{air,min} \le RH_{air}(k) \le RH_{air,max}, \tag{5.4}$$

$$C_{air,min} \le C_{air}(k) \le C_{air,max}, \tag{5.5}$$

$$Q_{c,min} \le Q_c(k) \le Q_{c,max}, \tag{5.6}$$

$$g_{v,min} \le g_v(k) \le g_{v,max}, \tag{5.7}$$

$$C_{inj,min} \le C_{inj}(k) \le C_{inj,max}, \tag{5.8}$$

$$|Q_c(k+1) - Q_c(k)| \leqslant k_1 T_o, \tag{5.9}$$

$$|g_v(k+1) - g_v(k)| \leqslant k_2 T_o, \tag{5.10}$$

$$\left|C_{inj}(k+1) - C_{inj}(k)\right| \leqslant k_3 T_o. \tag{5.11}$$

The open loop controller resulted from Strategy 3 in Chapter 3 solves the optimization problem:

$$u_1^* = \arg\min_{u_1} J_{3a}, \tag{5.12}$$

subject to the constraints (5.1), (5.3) to (5.11). The corresponding state $x_1^*$ can be calculated according to the input $u_1^*$ and the model (5.1). The obtained $x_1^*$ will be taken as the reference trajectory ($x_{1,ref}$) for the lower layer closed-loop MPC.

For Method 4 in Chapter 4, the state-space model is given by:

$$x_2(k+1) = f_2(x_2(k), u_2(k)), \tag{5.13}$$

where $u_2(k) = [Q_c(k), g_v(k), C_{inj}(k), s_r(k)]^T$, $x_2(k) = [T_{air}(k), RH_{air}(k), C_{air}(k)]^T$. $f_2(\cdot)$ is the nonlinear functions that represent the discrete greenhouse model obtained from Equation (4.1) to (4.11). The objective function $J_{4a}$ is derived from Equation (4.27) and can be expressed as:

$$J_{4a} = \sum_{k=1}^{N_o} \omega_1(|Q_c(k)| + \lambda g_v(k) + \frac{1}{\eta}\rho_w g h_w I(k) + \omega_2 I(k) + \omega_3 C_{inj}(k), \tag{5.14}$$

It should be pointed out that how $I$ is affected by $s_r$ can be found in Equation (4.1), (4.6), (4.7) and (4.18).

The constraints of $s_r$ is derived from inequality (4.31) and can be expressed as:

$$\begin{cases} 0 \le s_r(k) \le 1, \; if\ I_{rad}(k) \ge I_{rad,min} \\ s_r(k) = 0, \qquad if\ I_{rad}(k) < I_{rad,min}, \end{cases} \tag{5.15}$$

$$I_{rad,min} \le Q_{sun}(k)(1 - s_r(k)). \tag{5.16}$$

The open loop controller resulted from Method 4 in Chapter 4 solves the following optimization problem:

$$u_2^* = \arg\min_{u_2} J_{4a}, \tag{5.17}$$

subject to the constraints (5.3) to (5.11), ( 5.13) and (5.15) to (5.16) . The corresponding state $x_2^*$ can be obtained according to the input $u_2^*$ and the model (5.13). The obtained $x_2^*$ will be taken as the reference trajectory ($x_{2,ref}$) for the closed-loop MPC.

### 5.4.2 MPC controller design

The objectives of the designed MPC controllers are to track the reference trajectories under modeling uncertainties and external disturbances. $T_m$ represents the sampling interval of MPC. $T_m = T_o/N_m$, where $N_m$ is a positive integer. For time $t_m \in [m_1T_o + m_2T_m, m_1T_o + (m_2+1)T_m]$, $m_1 = 0, 1, 2, \cdots, N_o - 1$, $m_2 = 0, 1, 2, \cdots, N_m - 1$, the MPC is to track the reference trajectories $x_{ref}(m_1 + 1)$.

The objective function can be expressed as:

$$J_m = \sum_{i=1}^{N_p} (\Delta x(k+i|k))^T Q(\Delta x(k+i|k)) + \sum_{i=0}^{N_c-1} (\Delta u(k+i|k))^T R(\Delta u(k+i|k)), \tag{5.18}$$

where $N_p$ and $N_c$ are the prediction horizon and control horizon, respectively. $|k$ means that the predicted value is based on the information up to time $k$. $\Delta x$ is the tracking error. $\Delta u$ is the control effort. $Q$ and $R$ are the weighting matrices that penalize the future tracking and control efforts, respectively

[110].$\Delta x(k+i|k)$ and $\Delta u(k+i|k)$ are given by:

$$\Delta x(k+i|k) = x(k+i|k) - x_{ref}(k+i), \tag{5.19}$$

where $x_{ref}$ represents the reference trajectories.

$$\Delta u(k+i|k) = \begin{cases} u(k+i|k) - u(k-1), i = 0 \\ u(k+i|k) - u(k+i-1|k), i = 1,2,\cdots,N_c - 1. \end{cases} \tag{5.20}$$

For Strategy 3 in Chapter 3, the model shown in Equation (5.1) is used. $x_{1,ref}$ is taken as the reference trajectories.

The rate of change constraints can be given by:

$$|\Delta Q_c(k+i|k)| \leqslant k_1 T_m, \tag{5.21}$$

$$|\Delta g_v(k+i|k)| \leqslant k_2 T_m, \tag{5.22}$$

$$\left|\Delta C_{inj}(k+i|k)\right| \leqslant k_3 T_m. \tag{5.23}$$

Denote $\Delta U = [\Delta u(k|k), \Delta u(k+1|k), \Delta u(k+2|k), \Delta u(k+N_c-1|k)]^T$; thus, the MPC controller solves the following optimization problem:

$$\Delta U^* = \arg\min_{\Delta U} J_m, \tag{5.24}$$

subject to the constraints (5.1), (5.3) to (5.8) and (5.21) to (5.23).

After the optimal control sequence $\Delta U^*$ has been obtained, the MPC works according to the receding horizon scheme as shown follows:

(1) Given initial value $x_1(0)$, $u_1(0)$ and set $k = 0$;

(2) Calculate $\Delta U^*$ formulated in (5.24);

(3) Implement the first value of the solution $\Delta U^*$ and discard the rest of the solution;

(4) Calculate the state of the next interval $x_1^*(k+1)$;

(5) Let $k = k+1$ and repeat step (2) to (4).

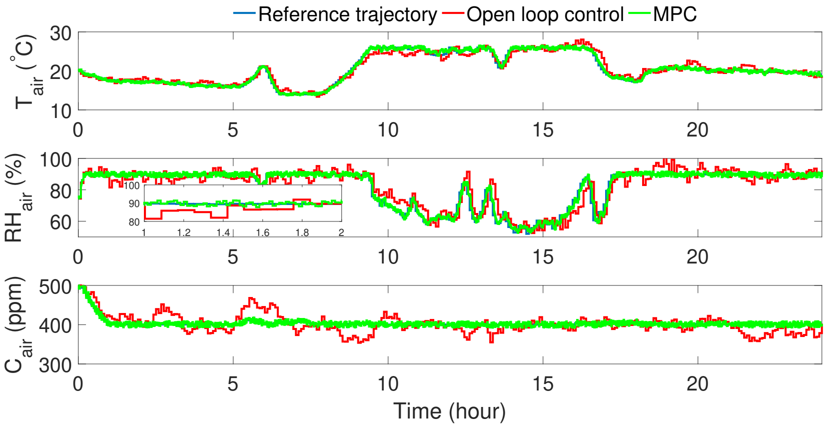

**Figure 5.3.** Open loop control and MPC under 2% system disturbances

Please note that $x_1(0)$ and $u_1(0)$ in step (1) should be within their bounds.

For Method 4 in Chapter 4, the model shown in Equation (5.13) is used. $x_{2,ref}$ is taken as the reference trajectories. The constraints for $s_r$ is derived from inequality (4.31) and can be expressed as:

$$\begin{cases} 0 \leq s_r(k+i|k) \leq 1, \ if \ I_{rad} \geq I_{rad,min} \\ s_r(k+i|k) = 0, \qquad if \ I_{rad} < I_{rad,min}, \end{cases} \tag{5.25}$$

$$I_{rad,min} \leq Q_{sun}(k+i)(1-s_r(k+i|k)). \tag{5.26}$$

MPC controller solves the following problem:

$$\Delta U^* = \arg\min_{\Delta U} J_m, \tag{5.27}$$

subject to the constraints (5.3) to (5.8), ( 5.13), (5.21) to (5.23) and (5.25) to (5.26). The receding horizon scheme for MPC has been explained above and will not be repeated.

## 5.5 SIMULATION RESULTS

The simulation parameters are set as follows: $N_p = 10$, $N_c = N_p$, $T_s = 60$ s, $T = 24$ h, $Q = \text{diag}(100,100,100)$, $R = \text{diag}(1,1,1)$.

Figure 5.3 shows the reference trajectory tracking results under 2% system disturbances. The MPC (green line) can follow the reference trajectory (blue line) well, while the open loop control (red line) has a large reference trajectory tracking error.

To quantitatively compare the control performance of the controllers designed, two tracking performance indicators are introduced. The relative average deviation (RAD) is proposed to evaluate the

**Table 5.1.** Tracking performance indicators

| | Open loop control | | MPC | |
|---|---|---|---|---|
| | RAD (%) | MRD (%) | RAD (%) | MRD (%) |
| $T_2$ | 3.38 | 13.80 | 1.35 | 6.31 |
| $RH_2$ | 3.63 | 18.18 | 1.07 | 6.13 |
| $C_2$ | 4.57 | 19.27 | 1.00 | 2.06 |
| $T_5$ | 8.37 | 37.51 | 3.23 | 12.39 |
| $RH_5$ | 8.61 | 39.62 | 3.05 | 29.70 |
| $C_5$ | 11.48 | 50.40 | 2.49 | 6.38 |
| $T_{10}$ | 16.62 | 90.09 | 7.95 | 44.96 |
| $RH_{10}$ | 17.33 | 78.77 | 5.99 | 80.30 |
| $C_{10}$ | 23.07 | 124.92 | 4.97 | 11.15 |

overall tracking performance. The maximum relative deviation (MRD) is used to reflect the worst tracking point.

Denote the measurement value as $x_{meas}$, the relative deviation (RD) of $x$ can be calculated:

$$\text{RD}(i) = \left| \frac{x_{meas}(i) - x_{ref}(i)}{x_{ref}(i)} \right|. \tag{5.28}$$

RAD is calculated by:

$$\text{RAD} = \frac{1}{N} \sum_{i=1}^{N} \text{RD}(i), \tag{5.29}$$

where $N$ is the sampling times. For the open loop control, $N = 288$. For the MPC, $N = 1440$.

MRD is obtained by:

$$\text{MRD} = \max(\text{RD}) \tag{5.30}$$

Table 5.1 shows the tracking performance indicators under different levels of system disturbances. The subscripts 2, 5 and 10 represent the results under 2%, 5% and 10% system disturbances. It can be seen that when the system disturbance is 2%, compared with the open loop control, the MPC reduced the temperature RAD by 60.06% (from 3.38% to 1.35%), the relative humidity RAD by 76.19% (from 3.36% to 1.07%), and the $CO_2$ concentration RAD by 78.12% (from 4.57% to 1.00%). MPC reduced 54.28% of temperature MRD (from 13.80% to 6.31%), 66.28% of relative humidity MRD (from 18.18% to 6.13%) and 89.31% of $CO_2$ concentration MRD (from 19.27% to 2.06%).

The proposed MPC has better tracking performance than the open loop control under system disturbances.

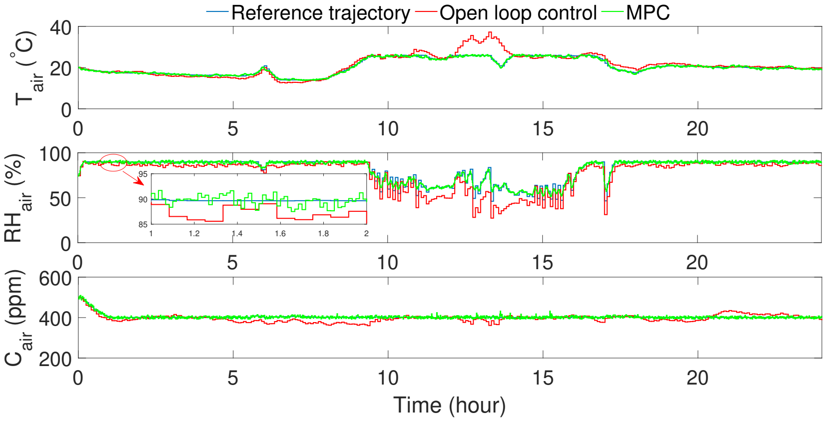

**Figure 5.4.** Results of tracking reference trajectory under 2% system disturbances

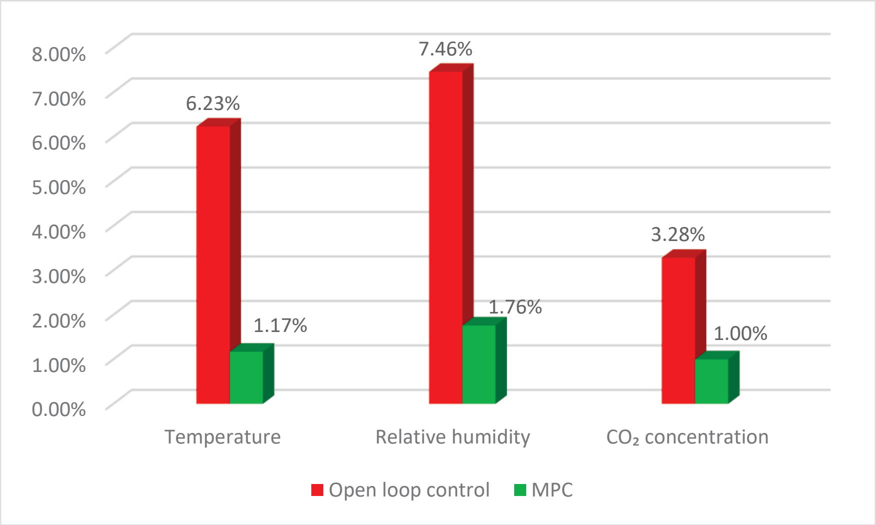

**Figure 5.5.** RAD of open loop control and MPC

For Method 4 in Chapter 4, the reference trajectory tracking results of the designed MPC controllers and open loop controller under 2% system disturbances is shown in Figure 5.4. The RAD comparison can be found in Figure 5.5. Compared with open loop control, MPC can reduce 81.22% temperature RAD (from 6.23% to 1.17%), 76.41% relative humidity RAD (from 7.46% to 1.76%), and 69.51% $CO_2$ concentration RAD (from 3.28% to 1%).

## 5.6 CONCLUSION

A hierarchical control method is proposed. This method can decompose a complex problem into multiple simple sub-problems to reduce the computational complexity. In this chapter, the proposed hierarchical control structure has two layers. On the upper layer, different optimization problems are solved to generate setpoints for the lower layer. The results of Strategy 3 in Chapter 3 and Method 4 in Chapter 4 are taken as reference trajectories. On the lower layer, two MPC controllers are designed to track the reference trajectories. The RAD and MRD under system disturbances are calculated to evaluate the tracking performance.

For Strategy 3 in Chapter 3, when the system disturbance is 2%, compared with the open loop control, the MPC reduced the temperature RAD by 60.06%, the relative humidity RAD by 76.19%, and the $CO_2$ concentration RAD by 78.12%. MPC reduced 54.28% of temperature MRD, 66.28% of relative humidity MRD and 89.31% of $CO_2$ concentration MRD. When the system disturbance is 5% and 10%, similar results are obtained. The MPC has better tracking performance than the open loop control. For Method 4 in Chapter 4, similar results can be obtained. The proposed model predictive control method can effectively deal with system disturbances and model plant mismatch.

# CHAPTER 6 CONCLUSION AND FUTURE WORK

This thesis focuses on optimization strategies and control methods of a greenhouse system. Firstly, optimization strategies are presented to reduce energy consumption, energy cost and operating cost. while keeping environmental factors within suitable ranges and meeting irrigation demand. Then, a hierarchical control method for the control of greenhouse systems is studied. An MPC method is proposed to deal with greenhouse system disturbances and the problem of model plant mismatch. In this chapter, the contributions are summarized, and then the potential future works are briefly introduced.

## 6.1 CONCLUSION

Optimization strategies of a greenhouse system are studied in Chapter 3 and Chapter 4. The hierarchical model predictive control method is presented in Chapter 5. The following paragraphs summarize the main contributions of these chapters individually.

In Chapter 3, three strategies for improving greenhouse energy efficiency are proposed. The objectives are to minimize the energy consumption, energy cost and total cost while keeping some environmental factors that are important for crop growth within the required ranges. It is found that the energy consumption of Strategy 1 and Strategy 2 are 3587 kWh and 4502 kWh, respectively. The energy cost of Strategy 1 and Strategy 2 are R 10242 and R 9050, respectively. Compared with Strategy 1, Strategy 2 consumes more energy, but costs less. The reason is that the energy consumption of Strategy 2 is mainly in the off-peak period with a low electricity price, while the energy consumption of Strategy 1 is mainly in the peak period with a high electricity price. The total cost of the greenhouse as a result of Strategy 1, Strategy 2 and Strategy 3 are R 39454, R 38540 and R 11018, respectively. Strategy 3 has the lowest total cost.

In Chapter 4, four optimization methods are proposed to improve not only energy efficiency, but also water use efficiency. These optimization models consider greenhouse climate control and greenhouse irrigation control simultaneously. A sensitivity analysis is conducted to study the impact of prices and system constraints on the optimization results. Simulation results show that the four proposed strategies can achieve their respective objectives, namely, reducing energy consumption, water consumption, $CO_2$ consumption and total cost while maintaining greenhouse environmental factors within the required ranges and meeting crop water demand. Method 4 can effectively reduce the production cost compared with the other three strategies. From the economic perspective, Method 4 is more suitable than the other three strategies for the optimization of a greenhouse system. Sensitivity analysis shows that both prices and system constraints have a great impact on the results. People should pay more attention to the price prediction and the setting of system constraints. More energy can be saved, more profits can be made.

In Chapter 5, a hierarchical control strategy is presented to facilitate the practical implementation of the optimization of modeling uncertainties and external disturbances, which are inevitable in a real-world situation. The proposed hierarchical control approach has two layers. On the upper layer, reference trajectories of greenhouse environmental factors are obtained by solving open loop controllers. On the lower layer, MPC controllers are designed to track the reference trajectories. Two controller performance indicators ( RAD and MRD) are introduced to compare the control performance of the open loop controller and the closed-loop MPC controller under different levels of system disturbances. It is found that both the RAD and MRD of the MPC are smaller than that of the open loop control under 2%, 5% and 10% system disturbances. The proposed MPC has better tracking performance than the open loop control.

## 6.2 FUTURE WORK

In future, the research will be further improved from the following aspects:

1. Optimization of system constraints settings. In this thesis, the constraint range of the greenhouse system optimization is constant. However, the weather conditions outside the greenhouse are changing. Therefore, the constraints setting should also change over time. For example, the light intensity is high during the daytime. To improve the photosynthesis of crops, the greenhouse temperature should be maintained at a high value. The light intensity in the greenhouse is low at night. To reduce the consumption of nutrients caused by the respiration of crops, the

temperature in the greenhouse should be maintained at a low level.

2. Research on optimization strategies that take into account long-term objectives. The optimization strategies studied in this thesis are based on short-term objectives such as energy consumption, energy cost and total cost. In future works, the greenhouse optimization process will consider some long-term objectives including crop yields and sales price to maximize greenhouse production profits.
3. Land-energy-water-food nexus. Greenhouse operation decisions involve land use efficiency, energy consumption, water consumption and food production. How to use less energy and water resources to get more food in limited land is of great significance to alleviate the energy crisis and achieve sustainable development.
4. Distributed control method. In this thesis, a centralized control method is used for greenhouse system control. When a greenhouse is large, due to the complexity of greenhouse system and the limitation of communication bandwidth, it may be difficult to control the greenhouse system with the centralized control method. A distributed control approach can be adopted to solve the above problems.
5. Use a hybrid energy system to power the greenhouse. In this study, the power grid provides the energy needed for a greenhouse operation. However, most of the electricity comes from the burning of coal or oil, which generates lots of greenhouse gases. In future, the use of a hybrid system, composed of clean energy and energy storage devices, to power the greenhouse will be studied. The use of a hybrid energy system can not only reduce the emission of greenhouse gases, but can also improve the reliability of power supply for the greenhouse system.
6. Optimal control of a photovoltaic greenhouse. Photovoltaic greenhouses can not only grow crops, but can also generate electricity through photovoltaic panels on the roof, which improves land use efficiency. In recent years, photovoltaic greenhouses have been rapidly developed worldwide. However, there are few studies on the optimization of photovoltaic greenhouse systems. One branch of future studies will be dedicated to investigate how to control the operation of photovoltaic greenhouses efficiently and effectively.
7. The use of artificial intelligence techniques to manage greenhouses. Data-driven methods, including artificial neural networks and support vector regression, can be used for complex greenhouse systems modeling. Intelligent optimization algorithms, such as the genetic algorithm, particle swarm algorithm, can be used to solve greenhouse optimization problems with multiple constraints and complex objective functions.

8. The use of other advanced control strategies such as fuzzy control, adaptive control, robust control and neural network-based control for greenhouse management will be studied.
9. Verify the effectiveness of the proposed strategies through case studies. To make the conclusions of this research more convincing, the models used and the strategies proposed in this thesis will be tested in an actual commercial greenhouse.

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