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Design of a vegetable greenhouse system for subtropical conditions in Taiwan

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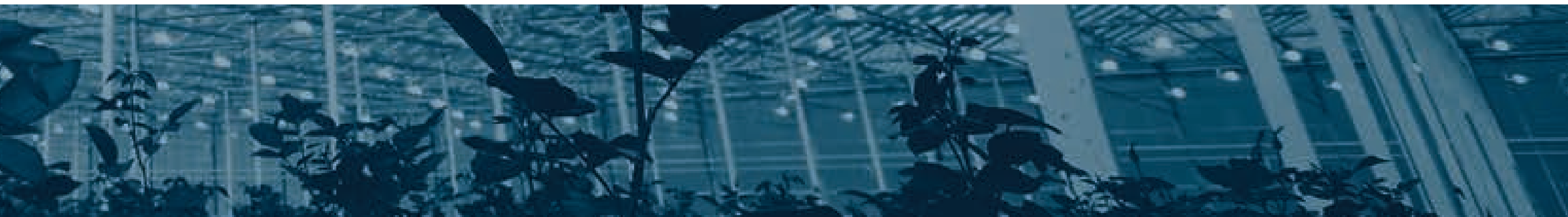

Referaat

Doel van deze studie was om antwoord te vinden op de vraag “wat is het optimale kasontwerp voor het telen van glasgroenten in Taiwan?”. Hiertoe hebben we een systematische ontwerp procedure gevolgd, warin alle sub-functies van het kassysteem zijn geïdentificeerd. Voor iedere sub-functie is een aantal mogelijke oplossingen bepaald, welke zijn gewogen door middel van computer simulaties met het kasmodel KASPRO. Dit model simuleert het klimaat in de kas en de groei van het gewas. Deze uitkomsten zijn gebruikt in een economisch model, waarmee de economische prestatie van de verschillende ontwerpen is vergeleken.

Het resulterende kasontwerp functioneert goed in het Taiwanese klimaat, dat wordt gekenmerkt door hoge zoninstraling (jaarlijkse stralingssom ligt rond de 6 GJ/m^2, en hoge temperatuur en luchtvochtigheid. De belangrijkste eigenschappen uit het voorgestelde ontwerp zijn een natuurlijk geventileerde kas met een groot raamoppervlak van 0.5m^2 per m^2 kas, waarbij de ramen zijn afgedicht voor witte vlieg door middel van netten. Het kasdek bestaat uit hoog transparante plastic folie, met hoge haze factor en welke doorlatend is voor IRstraling. Verder is de kas uitgerust met een mistinstallatie en een verwarmingssysteem.

Abstract

The question raised in this study is: *What is the optimum greenhouse design for vegetable growing in Taiwan?* To answer this question, we have used a systematic design procedure to come to the design of the greenhouse. In this approach, all sub-functions within the greenhouse system are mapped and for each sub-function many possible solutions are identified. The differences between the possible solutions are studied with the use of our greenhouse simulation model KASPRO. The climate and crop growth inside a greenhouse are simulated. This data served as input to the economic model, which was used to come to the economic optimal greenhouse design.

The resulting greenhouse design functions well in the Taiwanese climate (which is characterized by a solar radiation sum of around 6 GJ/m^2 and high temperatures and humidity levels. The main elements of the proposed design are a naturally ventilated greenhouse with large windows (0.5 m^2 window area per m^2 greenhouse ground surface) and insect nets to repel white fly. The greenhouse should be covered with a highly transparent plastic film cover that has high haze and is transparent for infra red radiation. Furthermore, the greenhouse should be equipped with a fogging installation and a heating system.

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1 Summary

The question raised in this study is: What is the optimum greenhouse design for vegetable growing in Taiwan? Our goal is to realise an environmentally friendly production system with low energy input and a high water use efficiency. The possibility of solar energy is examined. The ideal greenhouse should have a high crop yield and at the same time provide a high product quality and food safety. Moreover, the proposed greenhouse should be economically viable.
Many factors influence the design of a greenhouse. In this study focusses on the local climate conditions, energy sources, water, local costs and prices, as well as on prices of equipment. The study aims to design a good greenhouse for mid-sized growers with limited room for investment.

We have used a systematic design procedure to make the design of the greenhouse. In this approach, all sub-functions within the greenhouse system are mapped and possible solutions are identified. To study the effect of these different solutions for the sub-functions of the greenhouse, we have employed our greenhouse simulation model KASPRO. This is a dynamic model that accurately mimics the behavior of a greenhouse, resulting in hourly data on –amongst others-temperature, relative humidity, crop growth and CO_2 concentration. The model is based on the computation of relevant heat and mass balances.
An economic model is used to study the economic performance of the proposed solutions. Benefits and cost are calculated on a yearly base. Crop yield data is taken from the KASPRO simulations. The calculation of the investment cost are based on both data from literature as well as data supplied by the horticultural industry. To be able to quickly compare different greenhouse types, the simple payback time is calculated.

Weather data for three locations in Taiwan were supplied by Tainan Dares. The yearly solar radiation sum in Tainan is around 6 GJ (compared to 3.9 GJ in The Netherlands). As plant growth is largely determined by solar radiation, the potential crop yield for vegetable production in Taiwan is higher than in the Netherlands. However, due to the higher radiation intensities in Taiwan, the temperature in the greenhouse will be higher, which will reduce crop growth. The relative humidity of the air is very high and often exceeds 95%. Another important consideration in the design of the greenhouse is the existence of typhoons in Taiwan. The greenhouse structure should not be permanently damaged by these typhoons.

As said before, a dynamic greenhouse model was used to simulate the effects of different types of equipment in the greenhouse. In an iterative process with the economic mode, the following technologies were examined:

- **Ventilation and insect nets**
  A greenhouse for sub-tropical climate in Taiwan should be equipped with a well designed ventilation system to avoid excessive temperatures inside the greenhouse. The power consumption of mechanical ventilation is high, so we advise to use natural ventilation. The vents should be equipped with insect net to keep whitefly out. To provide sufficient ventilation capacity, even with insect nets, the surface of the vents should be at least 0.5 m2 per m2 greenhouse ground surface. In that case, the temperature inside the greenhouse is close the outside temperature. Natural ventilation is not able to decrease the temperature below the outside temperature level.

- **Greenhouse cover material and shading screens**
  We advise to use a plastic film that is diffuse and has a high transmission of light (>75%). It should also have a high transmission of infra red radiation, which helps to reduce high greenhouse temperatures. Shading screens are useful to decrease crop temperature during periods with high irradiation. Due to the lower light transmission, the potential crop production is lower than without the application of a screen. As Taiwan has many cloudy days, the effect of shading is limited. However, a screen does provide an additional way of reducing crop stress, so we advise to install an external screen with a shading percentage of 30%. This type of screen does not limit the ventilation too much and reduces the risk of crop damage by too much light.

- **Adiabatic cooling**

  We advise to install a fogging system with a net capacity of at least 300 g/m2/h. This system will decrease the temperature inside the greenhouse during the hottest hours of the day and will contribute to a less stressed crop. We do not advise a pad and fan system, because of the higher energy cost and inhomogeneous temperature distribution inside the greenhouse.

- **Heating system and CO_2 dosing**

  A heating system is recommended to avoid cold hours that have negative impact on the crop growth. Without heating system in the greenhouse, plants will survive. However, crop production is higher with a heating system. The greenhouse may be heated either with fossil fuels or by solar energy (or a combination of both). Heating the greenhouse by means of solar energy is more sustainable and has low running cost. However, it is not the most economical option (which may change in future, as energy prices keep raising). If the greenhouse is only heated with solar energy, we advise to install a solar collector of 0.7 m2 collector/m2 greenhouse ground surface. In this case, the buffer size should be in the order of 200 m3/ ha greenhouse ground surface. The capacity of a boiler (if it is the only heat source) should be around 100W/m2 to keep the greenhouse warmer than 12°C. With a buffer, the boiler capacity may be substantially reduced. Unless CO_2 is free/cheaply available, it is not economically viable to supply CO_2 to a ventilated greenhouse in Taiwanese weather conditions. If, in future projects, a connection can be made to industrial (waste) CO_2, it is worth investigating the possibilities again.

- **Closed greenhouse**

  A closed greenhouse provides optimal growing conditions for the crop, resulting in very high crop yields. Unfortunately, investment costs of these greenhouses are high (expensive greenhouse and cooling equipment is needed). Also the skills of the grower to fully exploit the benefits of the technology must be very well developed. For an average Taiwanese vegetable grower, the transition from the currently used greenhouses to a closed greenhouse is (probably too) large. The concept of closed greenhouses is more suitable as a demonstration and research project in the near future than to be used for commercial vegetable production.

2 Introduction

Protected cultivation systems are used throughout the world for crop production. Areas with protected cultivation are still growing. Driving forces range from improved food production with higher production levels, extended growing seasons, decreased water use compared to open field production and/or diminished risks of crop failure by for instance storm, rain or hail and pests and diseases, to better quality and safer food products and a growing demand for convenience products like specialties, flowers and potted plants.
A scan of the systems used throughout the world reveals that a wide range of protected cultivation systems has evolved that fit local circumstances. These solutions rangefrom low-tech, low-cost plastic tunnels to high-tech expensive glasshouses used in Western-Europe and North-America. Greenhouses differ in size, shape and materials used, ranging from single span structures covered with plastic to multi-span greenhouses with glass covers. Instrumentation ranges from unheated greenhouses with natural ventilation to production systems with computer controlled heating, cooling, humidification and dehumidification, CO_2-supply and artificial light. Even fully closed greenhouses with mechanical cooling are build in for example The Netherlands and the Middle East. Crops are grown in soil, but also in artificial substrates with water and nutrient supply using drip irrigation and closed water circuits with drain water recycling. Manual labour is commonly used throughout the world, but in high-tech greenhouses the first robots have recently been introduced to replace human labour.

With these observations in mind, this study addresses the design of a protected cultivation system that satisfies the local conditions in Taiwan. Definitely, this question is not raised for the first time. An abundance of literature exists in which various design issues have been tackled, related to greenhouse structure and greenhouse covering materials (*e.g.* Von Elsner *et al.* 2000a,b), to optimize the greenhouse design to one specific location or to one single construction parameter (*e.g.* Hemming *et al.* 2004; Impron *et al.* 2007; Zaragoza *et al.* 2007), to optimize climate conditioning (*e.g.* Garcia *et al.* 1998), greenhouse climate control (*e.g.* Bakker *et al.* 1995) or substrates and nutrition control (*e.g.* Gieling, 2001), to mention just a few examples. In most of these studies greenhouse design is approached as a single factorial problem, which means that only one issue is being considered which may lead to a sub-optimal design. However, the design of protected cultivation systems is a multi-factorial design and optimization problem (van Henten *et al.* 2006, Hemming *et al.* 2008), thus multiple factors have to be addressed to find the optimum design.

The question raised in this study is: *What is the optimum greenhouse design for vegetable growing in Taiwan?* Our goal is to realise an environmentally friendly production system with low energy input, use of sustainable energy where possible, high water use efficiency, high production and predictability of production, high product quality, high food safety and good ratio of benefit and costs of the production system.

One of the most important factors influencing the optimum greenhouse design is the climate of a location. The weather strongly influences the greenhouse inside climate and therefore crop production inside the greenhouse to a large extend. Hanan (1998) and Van Heurn and Van der Post (2004) have identified some other factors that determine the particular choice of the protected cultivation system used. A combination and extension of their lists of factors:

1. Market size and regional physical and social infrastructure which determines the opportunity to sell products as well as the costs associated with transportation
2. Local climate, which determines crop production and thus the need for climate conditioning and associated costs for equipment and energy. It also determines the greenhouse construction dependent of, for example, wind forces, snow and hail
3. Availability, type and costs of fuels and electric power to be used for operating and climate conditioning of the greenhouse
4. Availability and quality of water
5. Soil quality in terms of drainage, the level of the water table, risk of flooding and topography
6. Availability and cost of land, present and future urbanisation of the area, the presence of (polluting) industries and zoning restrictions
7. Availability of capital
8. The availability and cost of labour as well as the level of education
9. The availability of materials, equipment and service level that determines the structures and instrumentation of the protected cultivation systems
10. Legislation in terms of food safety, residuals of chemicals, the use and emission of chemicals to soil, water and air

The main focus in this study will be on the local climatic conditions, special attention will be given to the availability of electric power, energy sources, water, local costs and prices, as well as to prices of equipment. The design aims to be a good greenhouse for mid-sized growers with limited room for investment.

3 Methodology

3.1 Design methodology

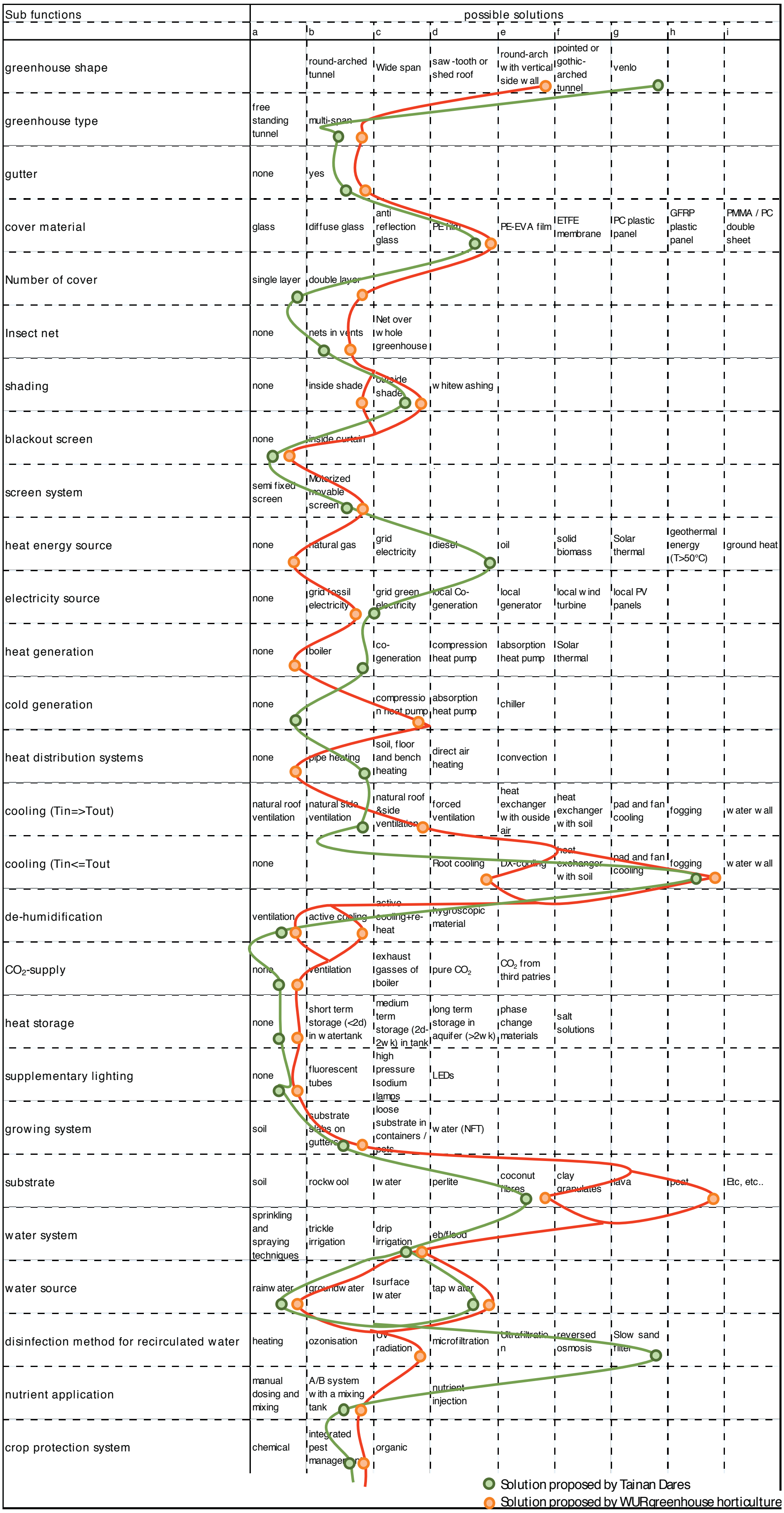
Designing protected cultivation systems is a multi-factorial optimization problem as described above. During the design process, choices have to be made with respect to construction, cladding material, climate conditioning equipment, energy sources, energy management, light management, growing substrates, water and nutrient supply, internal logistics and labour, to mention a few. All of these choices mutually influence each other and are influenced by local boundary conditions like climate, market, legislation and availability of resources, the degree of technology chosen. The choices made also strongly influence the economic result.

To push the multi-factorial design of protected cultivations systems, a general design method is suggested here. It is based on systematic design procedures that have been described by for instance Van den Kroonenberg and Siers (1999) and Cross (2001). The design procedure roughly contains the following steps:

0. Definition of the design objective, (here: design of a vegetable greenhouse for Taiwan)
1. In a brief of requirements the specifications and design objectives are stipulated (here: low energy input, use of sustainable energy, high water use efficiency, high production and product quality and predictability of production, high food safety by low pesticide use, high ratio of benefit and costs of the production system)
2. A systems analysis will reveal the functions needed
3. Derivation of alternative working principles for each function which yields a so-called morphological diagram. For example, in case of cooling we may consider natural ventilation, recirculation fans, fogging systems, pad-and-fan cooling or even air-conditioning systems with heat exchanger as design alternatives. Similar alternative working principles have to be described during this phase for the other functions
4. Concept development stage. During this stage, the different functions, or more specifically working principles in the morphological diagram, are combined into a conceptual design that should at least satisfy the functional requirements stated in the design specifications. Several different concepts are designed at this stage. The Figure below shows two concepts for the greenhouse.
5. Design evaluation and bottle-neck assessment. During this stage the various conceptual designs are evaluated in view of the design requirements stated above. Design evaluation is based on expert assessment and on quantitative simulation using mathematical models (here: dynamic greenhouse climate models and an economic models)
6. For the conceptual design(s) chosen, each working principle has to be worked out in more detail, For example greenhouse climate setpoints and cropping strategies; not part of this study.
7. The design prototype is built and tested in view of the design requirements

The advantages of such a design procedure can be summarized as follows. It prevents jumping too quickly to a solution while not having looked into the overall design problem seriously. It offers the opportunity for a multi-disciplinary approach to systems design. It prevents trial and error. It produces a good overview of the design requirements and reduces the chance of overlooking some essential design requirements. Bottle-necks and design contradictions are identified at an early stage. It offers insight into design alternatives and economical perspectives. It offers a basis for sound and objective decisions during the design procedure. By producing insight, stake-holders and decision makers can contribute to the process and are more easily convinced of the correctness of the design. Clearly, such a design method guides the engineer in the design process, but it does not guarantee success. In depth assessment of promising concepts with adequate models (here greenhouse climate, crop and economic models) and decision support systems helps to increase the success rate.

3.2 Morphological diagram



Sub functions	possible solutions								
	a	b	c	d	e	f	g	h	i
greenhouse shape		round-arched tunnel	Wide span	saw-tooth or shed roof	round-arch with vertical side wall	pointed or gothic-arched tunnel	venlo		
greenhouse type	free standing tunnel	multi-span							
gutter	none	yes							
cover material	glass	diffuse glass	anti reflection glass	PE film	PE-EVA film	ETFE membrane	PC plastic panel	GFRP plastic panel	PMMA / PC double sheet
Number of cover	single layer	double layer							
Insect net	none	nets in vents	Net over whole greenhouse						
shading	none	inside shade	outside shade	whitewashing					
blackout screen	none	inside curtain							
screen system	semi fixed screen	Motorized movable screen							
heat energy source	none	natural gas	grid electricity	diesel	oil	solid biomass	Solar thermal	geothermal energy (T>50°C)	ground heat
electricity source	none	grid fossil electricity	grid green electricity	local Co-generation	local generator	local wind turbine	local PV panels		
heat generation	none	boiler	co-generation	compression heat pump	absorption heat pump	Solar thermal			
cold generation	none		compression heat pump	absorption heat pump	chiller				
heat distribution systems	none	pipe heating	soil, floor and bench heating	direct air heating	convection				
cooling (Tin=>Tout)	natural roof ventilation	natural side ventilation	natural roof &side ventilation	forced ventilation	heat exchanger with ouside air	heat exchanger with soil	pad and fan cooling	fogging	water wall
cooling (Tin<=Tout	none			Root cooling	DX-cooling	heat exchanger with soil	pad and fan cooling	fogging	water wall
de-humidification	ventilation	active cooling	active cooling+re-heat	hygroscopic material					
CO_2-supply	none	ventilation	exhaust gasses of boiler	pure CO_2	CO_2 from third patries				
heat storage	none	short term storage (<2d) in watertank	medium term storage (2d-2wk) in tank	long term storage in aquifer (>2wk)	phase change materials	salt solutions			
supplementary lighting	none	fluorescent tubes	high pressure sodium lamps	LEDs					
growing system	soil	substrate slabs on gutters	loose substrate in containers / pots	water (NFT)					
substrate	soil	rockwool	water	perlite	coconut fibres	clay granulates	lava	peat	Etc, etc..
water system	sprinkling and spraying techniques	trickle irrigation	drip irrigation	eb/flood					
water source	rainwater	groundwater	surface water	tap water					
disinfection method for recirculated water	heating	ozonisation	UV radiation	microfiltration	Ultrafiltration	reversed osmosis	Slow sand filter		
nutrient application	manual dosing and mixing	A/B system with a mixing tank		nutrient injection					
crop protection system	chemical	integrated pest management	organic						

🟢 Solution proposed by Tainan Dares
🟠 Solution proposed by WURgreenhouse horticulture

The use of a morphological diagram is useful in a design process. The diagram below shows all sub functions that a greenhouse can fulfill (left most column). For every sub function, various possible solutions are listed. By making choices for every sub function, we can define the design of a new greenhouse system.

3.3 Description dynamic climate model Kaspro and input data

For the evaluation of various designs of greenhouse systems, several decision support systems have been developed such as KASPRO (de Zwart, 1996), SERRISTE in France (Tchamitchian *et al.* 2006) or HORTEX (Rath, 1992) or GTa-Tools (Van 't Ooster, 2006). These systems support either designers or growers with reliable and quick assessment of energetic effects and crop responses of both the strategic and the operational choices.
In this study the KASPRO model is used. This extensive dynamic simulation model simulates a full-scale virtual greenhouse based on the greenhouse construction elements, ventilation openings, greenhouse equipment, different covering materials and their properties (transmission, reflection, and emission), set points for inside climate and the outside climate of a given location. Any computed physical quantity can be listed as output, but for the current project the observed output comprises the realised greenhouse climate at every hour of the year, the energy consumption, the amount of water evaporated by the crop, the amount of CO_2 applied and the dry matter production of the crop.

The model is based on the computation of relevant heat and mass balances (Bot, 1983). The heat balances describe both the convective and radiative processes. The mass balances are constituted from exchange processes through leakage and ventilation (de Jong, 1990). They include canopy transpiration (Stanghellini, 1987) and condensation at cold surfaces. The mass balances around the CO_2-concentration are based on losses of CO_2 by ventilation and photosynthesis, and gains of CO_2 by dosing and respiration.
Basically, the model describes the entrance of solar radiation into a greenhouse structure and computes the heat and moisture fluxes induced from this radiation. The heat and moisture is released predominantly by the canopy, but the heat fluxes originate from other opaque elements in the envelope as well. Also, reflection of solar radiation, typically by the covering structure and by reflecting shading screens, is taken into account. The heat and moisture fluxes affect the air conditions around the canopy, which are in dynamic interaction with the greenhouse construction and the environment. To a certain extent, the interaction between the microclimate around the canopy and the environment can be controlled by means of heating, ventilation, humidification and dehumidification, CO_2 application, shading and optionally even by means of cooling.
Greenhouse climate is controlled by a replica of commercially available climate controllers. The total set of differential equations is solved numerically (de Zwart, 1996).

For this project, the KASPRO simulation model was used to analyze the effect of local outside climate conditions on inside greenhouse climate and crop response with an assumed greenhouse configuration. The effect of cooling by natural ventilation or evaporative cooling by fogging was analysed. The effect of CO_2-dosing was computed and light control by means of a shading screen or artificial lighting was studied.
Cooling by natural ventilation might not be enough in a subtropical climate with high temperatures and high irradiations. Providing low outside humidity conditions, evaporative cooling by fogging helps then to improve the greenhouse indoor climate conditions on these days. The fogging capacity that has to be installed is dependent on the typical local outside climate conditions.
CO_2-dosing can increase the biomass production, but when the ventilation rates are high, large dosing capacities are required and do not contribute to sustainability since CO_2 is then released into the outside air.
In regions with radiation intensities as high as in Taiwan , the contribution of the highest intensities to the production can be much less than the contribution of the moderate intensities. Therefore, it has to be investigated if the application of a shading screen could be favourable in order to avoid too high temperatures in the greenhouse, whereas the decrement of photosynthetic potential remains limited.
The following data was used as input on an hourly base: outside temperature, humidity, global radiation, windspeed and sky temperatures.

KasPRO uses a photosynthesis model to estimate the growth and evapotranspiration of the crop. This approach works well to simulate the greenhouse climate, but is less suitable for an accurate prediction of the total yield in (sub)tropical climates. Therefore we have used an additional model to predict the yearly yield of a tomato crop. The model is developed by Vanthoor (Vanthoor, 2011) and uses a more detailed crop model that takes into account the adverse effects of extreme temperatures on the crop.

The effect of artificial lighting was studied in simulation. To this end, we combined greenhouse model KasPRO with crop growth model IntKAM (Elings *et al.* 2010) to simulate the crop growth without artificial light and with 2 levels of lighting (85 μmol /m^2 and 195mmol/m^2). These three cases were repeated for a greenhouse with and without CO_2 fertigation. Moreover, for comparison the same cases are simulated for a Dutch greenhouse in Dutch climate.

The result of all KASPRO simulations were the realised greenhouse climate at every hour of the year, the energy consumption, the amount of water transpired by the crop, the amount of CO_2 applied and the dry matter production of the crop for different scenario's. These results were then used to feed the economical model.

3.4 Description of economic model and data collection

In an economic model several scenarios concerning different degrees of technology are analyzed to find the optimum greenhouse design for vegetable production in the sub-tropical climate of Taiwan.

The economic model is made based on the systematic calculation method given by KWIN (2010). Benefits and cost are calculated on a yearly base. On one side the yield and product price are calculated as benefits, on the other side costs of heat, electricity and CO_2 consumption, plant material, labor costs, costs for crop protection, crop nutrition, water, substrate, plastic films, wires, clips and packaging with related cost prices are calculated as variable costs. Next to that the initial investments for installations like greenhouse construction, covering material, screening, insect netting, heating and cropping system, irrigation system, CO_2 dosing, fogging, artificial lighting, climate control and general costs for supervision, transport, packaging area and machinery are calculated per scenario. Initial investments are calculated back to annual costs by taking into account depreciation, maintenance and interest. The simple payback period is calculated by the total investment sum divided by the annual crop benefit - annual variable costs - annual maintenance costs.

Several input data for the economic quick scan are given by the model calculations. The virtual greenhouse model KASPRO gives data for the tomato yield in terms of dry matter production, heat, electricity, CO_2 and water consumption, which are used as input data for the economic model. The amount of plant material is assumed to be 2.5 plants per m^2. The costs for crop protection, crop nutrition, substrate, plastic film, wires and clips are taken from KWIN (2010) and are assumed to be comparable for Dutch and Taiwanese production. For all scenarios the labor costs are assumed to vary in proportion to the yield. It is not considered that the labor costs are higher in the traditional Taiwanese situation due more manual work instead of the use of machinery. An open irrigation system is assumed to consume 40% more water than a closed irrigation system. The costs for packaging are assumed to vary with yield. Prices for energy, electricity, CO_2 and labor are given by TN Dares. Depreciation is assumed to be 3 years for plastic film covering material, insect netting, screening and CO_2 system. For most other installations it is assumed to be 15 years. Maintenance costs are between 2% and 8%, depending on the equipment (KWIN, 2010). Actual interest rates in Tainan are 6.5% (source: Trading Economics). The tomato price is given by TN Dares, around 120 TND per kg (€3/kg). Since no information was available for seasonal changes in product prices for greenhouse tomato in Taiwan , we used this price year-round. For all economic calculations a company size of minimum 2 ha is assumed. The total investment of the company is taken into account incl. general facilities and packaging area. An overview of assumptions of prices, costs and benefits are given in Table 3.3, assumptions considering investments, depreciation, maintenance and interest rates and the resulting annual costs of investments are given in Table 3.4.

Table 3.3. Assumptions of prices, costs and benefits for the economic model.

	Price [TND]	*Source of information*
Price for cherry tomatoes [TND/kg]	120.00	Tainan Dares
Diesel [TND/liter]	29.50	Tainan Dares
Electricity [TND/kWh]	3.00	Tainan Dares
CO_2 (pure [TND/kg]	27.50	Tainan Dares
Ground water [TND/m^3] (plant feed water)	10.00	Tainan Dares
Plant material [TND/plant]	11.75	Tainan Dares
Labor costs crop [TND/h]	170.00	Tainan Dares
Crop protection [TND/m^2]	21.50	KWIN, 2010
Crop nutrition closed cycle [TND/m^2]	18.90	Estimate based on KWIN, 2010
Crop nutrition open system [TND/m^2]	48.26	Estimate based on KWIN, 2010
Substrate [TND/m^2]	49.40	KWIN, 2010
Plastic film, wires, clips [TND/m^2]	19.00	KWIN, 2010
Packaging [TND/m^2]	0.38	KWIN, 2010

Table 3.4. Assumptions of investments, depreciation, maintenance and interest for economic model. Investment cost are taken from quotes given by industrial partners.

all investments are per m^2 greenhouse ground area	investment [TND/m_2]	depreciation [%/year]	maintenance [%/year]	interest rate [%/year]	annual costs investments [TND/m^2/ year]
glass covering	152.00	7	0.5	6.5	16.34
plastic film covering	68.40	30	2	6.5	24.11
modern glass greenhouse incl. covering	1,330.00	7	0.5	6.5	142.98
modern plastic film greenhouse	1,140.00	7	2	6.5	139.65
simple plastic film greenhouse	684.00	7	2	6.5	83.79
heating system	475.00	7	2	6.5	58.19
heating system simple greenhouse	425.60	7	2	6.5	52.14
pad and fan system	456.00	25	2	6.5	137.94
active cooling system with heat pump and chiller	2,470.00	7	2	6.5	302.58
Cropping system	209.00	7	2	6.5	25.60
screening system	131.10	25	5	6.5	43.59
insect netting	190.00	20	5	6.5	53.68
CO_2 dosing	26.60	25	5	6.5	8.84
fogging system	171.00	10	5	6.5	31.21
irrigation system open	209.00	15	5	6.5	48.59
irrigation system with re-circulation and disinfection	266.00	15	5	6.5	61.85
electra installation	133.00	7	2	6.5	16.29
climate computer simple	114.00	20	8	6.5	35.63
climate computer advanced	148.20	20	8	6.5	46.31
Other: transport, packaging area, trolleys and machinery	262.20	7	2	6.5	32.12
Other: transport, packaging area, trolleys and machinery; high tech greenhouse	555.18	7	2	6.5	68.01
rainwater storage [TND/m^3]	380.00	10	5	6.5	69.35

4 Results of greenhouse climate simulations

Designing protected cultivation systems is a multi-factorial optimization problem as described in the introduction. During the design process, choices have to be made with respect to construction, cladding material, climate conditioning equipment, energy sources, energy management, growing substrates, water and nutrient supply, internal logistics and labor, to mention a few. All of these choices mutually influence each other and are influenced by local boundary conditions like local outside climate, market, legislation and availability of resources.
Simulations with a computer greenhouse model have been done to study the effects of different technologies on the climate inside the greenhouse and the potential crop growth. These results are used as input for the economic model, which is described in the next chapter.

4.1 Climate data

The optimum design for a greenhouse design is strongly influenced by the local climatic conditions. The day length of Taiwan is quite constant throughout the year compared to the Netherlands. The shortest day in winter is just less than 11 hours; the longest day is just over 13 hours (Figure 3.1.).

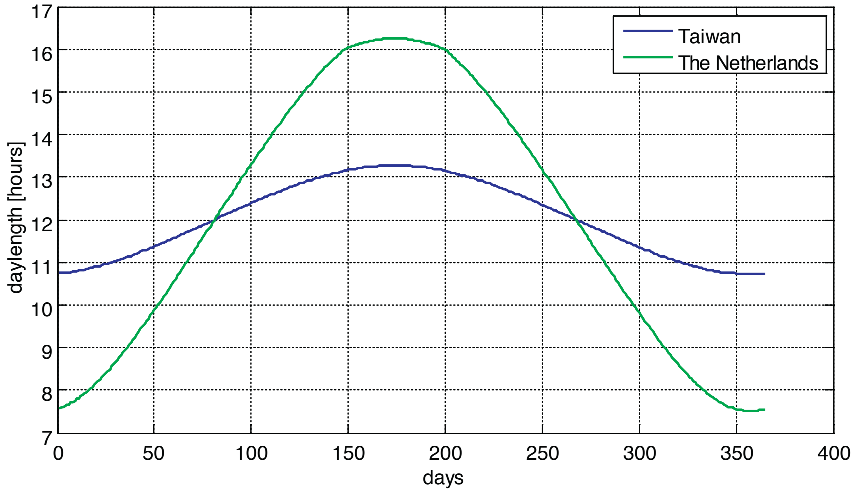


Figure 3.1. The course of day length in Taiwan and in the Netherlands.

4.1.1 Radiation

Weather data for three places in Taiwan are available on an hourly basis; Tainan, Yuanlin and Yichu. The global radiation is measured, however there are no separate data for direct and diffuse radiation. By using the data for cloudiness it is possible to construct the radiation data reasonably accurately. Based on the latitude of Taiwan (21°N), the course of the intensity of radiation on any clear day can be computed and is combined with the observed cloudiness to compute global, diffuse and direct radiation profiles.

The total yearly radiation is quite variable over the years. The plots below show the radiation data for 2009 and 2010. Data for The Netherlands are also included (gray line) as a reference. Radiation sums are different for the three locations. Tainan receives up to 40% more light than Yuanlin. As plant growth is mainly depending on the total light sum, there will be a distinctive difference in potential plant production levels between the two locations.

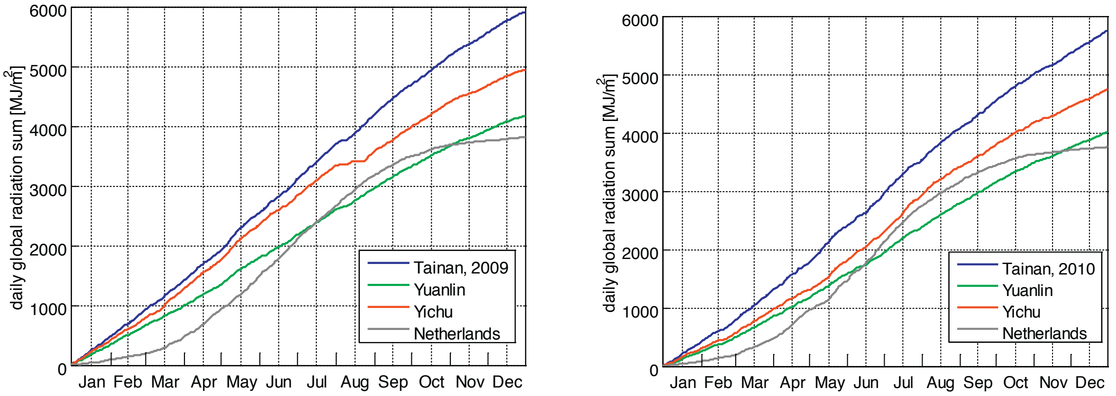


Figure 3.2. Cumulative radiation sums for global radiation in Tainan, Yuanlin, Yichu in 2009 (left) and 2010 (right).

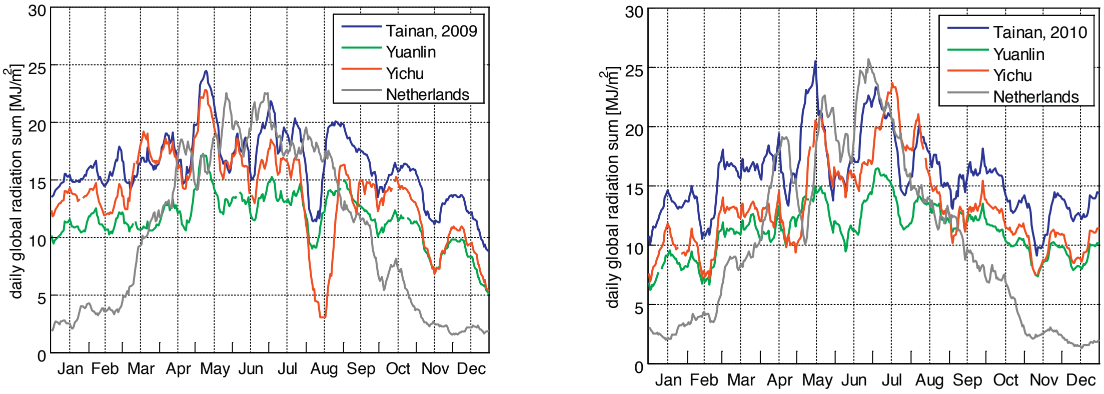


Figure 3.3. Daily radiation in Tainan, Yuanlin, Yichu and the Netherlands in 2009 (left) and 2010 (right). The data were smoothed by a 14 days moving average filter.

The yearly global radiation varies from year to year. On average, the yearly sum in Tainan is around 6 GJ compared to 3.9 GJ in The Netherlands (Figure 3.2.). Figure 3.3. shows the daily sum of radiation in three locations in Taiwan and in The Netherlands for 2009 and 2010. Taiwan has a higher total solar radiation, than the Netherlands. Moreover, the radiation levels are more constant over the year. Because of these two facts, potential yield for vegetable production in Taiwan is higher than in the Netherlands.

However, due to the higher radiation intensities in Taiwan, higher greenhouse temperatures are to be expected, especially because the mean outside temperatures are higher as well. These outside temperatures are shown in the following figures.

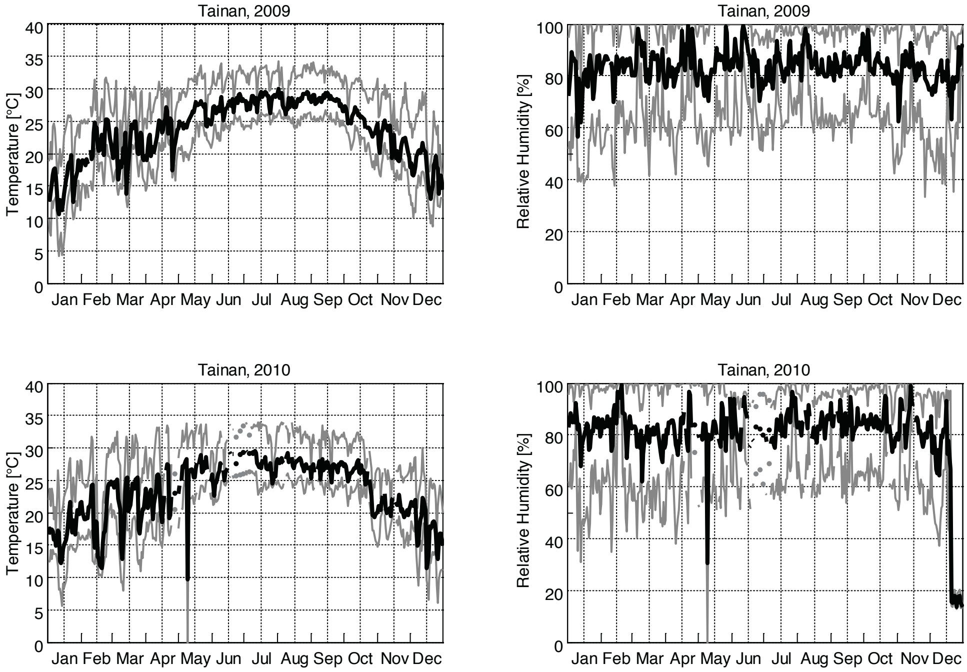


Figure 3.4. Daily mean (black line) outside temperature (left) and relative humidity (right) in Tainan in 2009 and 2010. The two gray lines give the daily minimum and maximum temperature and relative humidity.

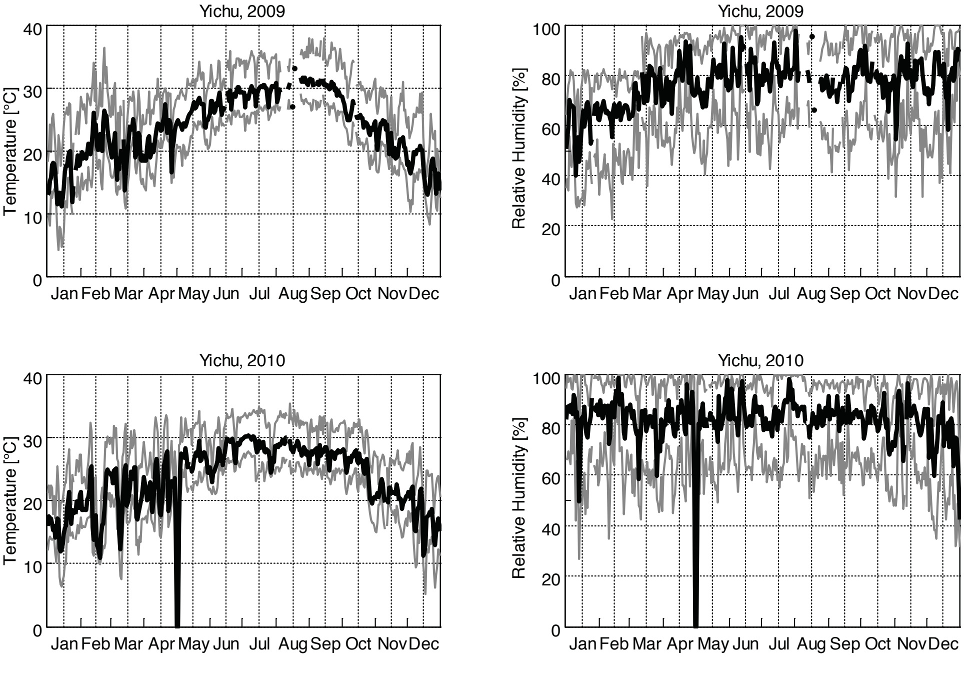


Figure 3.5. Daily mean (black line) outside temperature (left) and relative humidity (right) in Yichu in 2009 and 2010. The two gray lines give the daily minimum and maximum temperature and relative humidity.

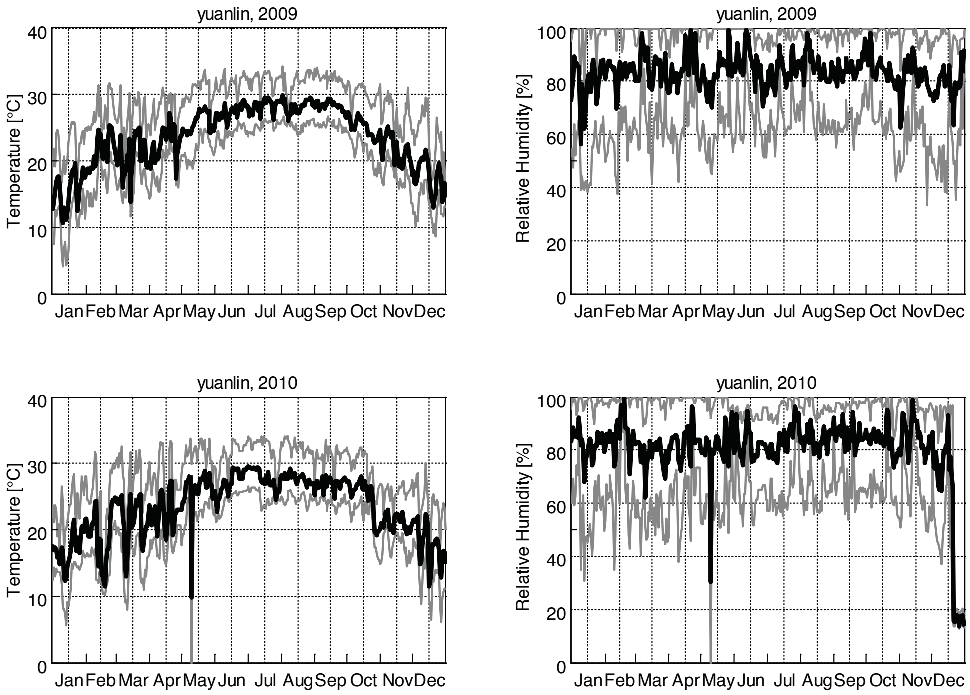


Figure 3.6. Daily mean (black line) outside temperature (left) and relative humidity (right) in Yuanlin in 2009 and 2010. The two gray lines give the daily minimum and maximum temperature and relative humidity. (due to missing data, the line 'jumps' to the x-axis at certain times).

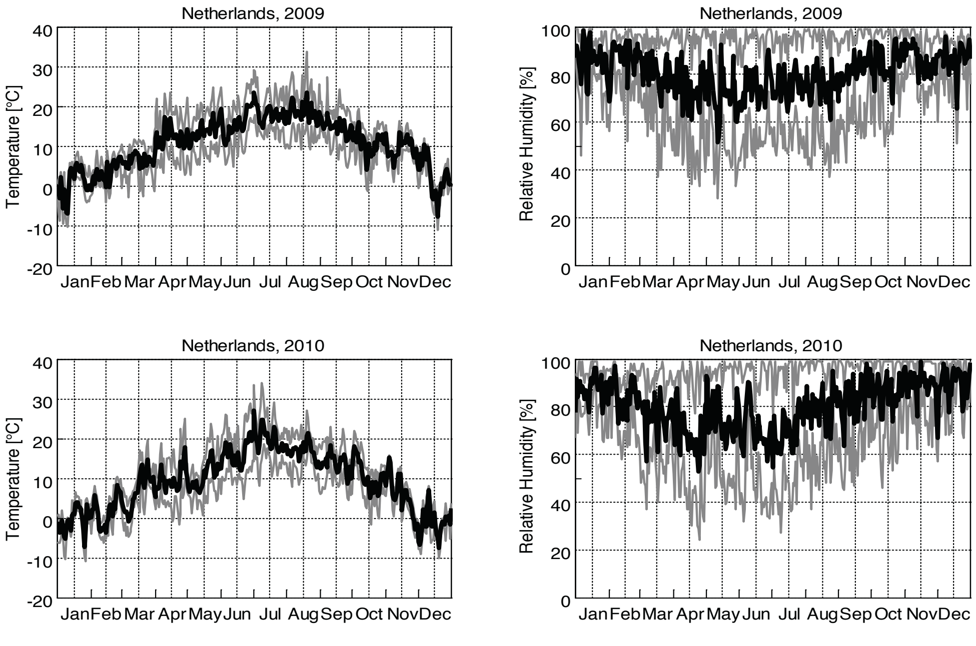


Figure 3.7. Daily mean (black line) outside temperature (left) and relative humidity (right) in The Netherlands in 2009 and 2010. The two gray lines give the daily minimum and maximum temperature and relative humidity.

4.1.2 Wind

The Figure below shows the daily average wind velocity in Tainan in 2009. The maximum and minimum speed are given by the thin gray lines. Note that the measurements do not show the typhoons very well.

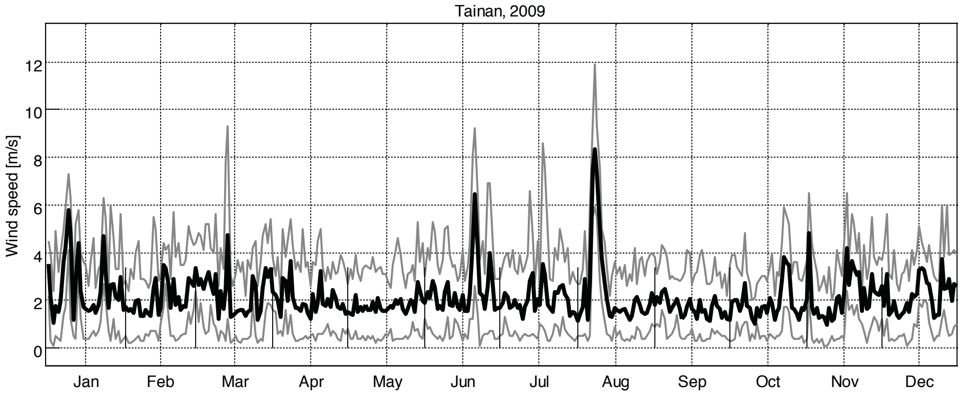


Figure 3.8. Wind velocity in Tainan, 2009. (black line is average, grey lines are the minimum and maximum values for each day).

Typhoons

Typhoons occur in Taiwan and the greenhouse design should be able to cope with the extreme weather conditions during these events. In August 2009, an extremely large typhoon hit Taiwan (*Morakot*). During this storm, wind velocities peaked at 150km/h (40m/s) and the rainfall was extremely high (http://en.wikipedia.org/wiki/Typhoon_Morakot).

The data for the Tainan weather shows over 700mm of precipitation in one day. Other sources give a precipitation of 2777mm over the course of the storm (72 hours). The high wind speed does not really show in the measured wind date; the daily average peaks at 8 m/s (30km/h), which is too low. The measurement may be wrong during these extreme events.

4.2 Ventilation capacity

Most greenhouses use natural ventilation to remove hot air out of the greenhouse, as natural ventilation is a very efficient mechanism for air exchange in case of wind outside In warm climates with low wind speeds, mechanical ventilation may be favorable despite the high energy costs for the ventilators. However, the climate data of Tainan show that at almost all times there is a mild breeze and that no extended periods without wind occur. This means that the climate is suitable to use natural ventilation for air exchange in the greenhouse.

To mix the air inside the greenhouse in order to achieve a homogeneous climate throughout the whole area, horizontal mixing fans are advisable to be applied.

4.2.1 Natural ventilation

We have studied the effect of increasing the ventilation capacity in the greenhouse by applying more roof ventilation windows. The effect on the ventilation rate and indoor temperatures was simulated. The results are listed in Table 3.1. and depicted in Figure 3.9.

The number of hours in which the temperature inside the greenhouse exceeds a threshold (30 °C and 35 °C) are given. This information is used to decide how large the windows in the greenhouse need to be. For example, a window fraction of 0.07 (0.07 m^2 window opening per 1m^2 greenhouse floor surface) results in 1507 hours during which the temperature of the crop is higher than 30 °C. When the window fraction is increased to 0.4, the number of hours is reduced to 891.

Table 3.1. Effect of increasing window fraction on the climate inside the greenhouse and the yearly evapo-transpiration by a tomato crop (Tainan 2009 climate data).

Window fraction [m^2 window / m^2 greenhouse]	Number of hours warmer than 30 °C [h]		Number of hours warmer than 35 °C [h]		Number of hours with relative humidity higher than 95 or 90%		Evapo-transp. [$kg/m^2/yr$]	Crop production [%]
	T air	T crop	T air	T crop	RH>95%	RH>90%		
0.07	1526	1507	374	365	2197	5086	985	100
0.14	1231	1173	157	191	2471	4906	1018	113
0.27	1057	964	41	117	2570	4676	1052	121
0.41	1004	891	18	91	2552	4522	1073	124
0.54	977	860	9	80	2520	4400	1087	126
1.1	943	814	1	65	2405	4176	1117	129

The Figure below is a so-called ‘duration load curve’. This type of graph is used to study the time during which a certain situation occurs during one year.

The Figure is constructed as follows: a value (*e.g.* temperature) is calculated for every hour of the year (8760 hours). After the simulation, all values are sorted resulting in 8760 values running from large to low. These values are plotted, so that the Figure gives the amount of hours that a value occurs per year. For example, in our case we are most interested in the indoor temperature and humidity. Thus, these are depicted in almost all sections of this report.

To read the graphs, do the following: first, choose a threshold (on the y-axis); for example the number of hours during which the temperature inside the greenhouse is higher than 35 °C. The number of hours during which this occurs can be read from the x-axis; *e.g.* the orange dotted line end at 500 hours. Thus, we conclude that during 500 hours in the year, the temperature in the greenhouse is higher than 35 °C.

The main conclusion for the window size is that by increasing the ventilation capacity, the temperature in the greenhouse decreases. The effect on the crop production is positive. Production increases by 10 to 15% while increasing the window opening from 0.07 to 1.1 m^2/m^2.

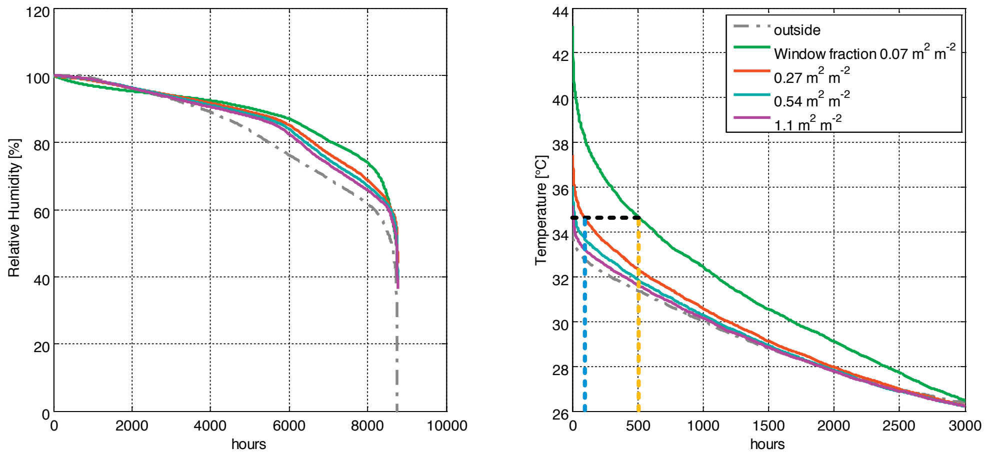


Figure 3.9. Load duration curve for greenhouse air temperature and relative humidity for various window fractions (Tainan 2009 climate data).

4.2.2 Mechanical ventilation

If we would choose to use mechanical ventilation to supply all fresh air to the greenhouse, we would need 800 to 1100 thousand m^3 of air per m^2/year. The energy need is approximately:
Flow * eff * dP = 800 * 100 /0.8 = 100 MJ m^2/year (=28kWh/m^2/year). (where eff = ventilator efficiency [0-1], dP the pressure difference over the ventilator [Pa] and Flow the volumetric airflow [m^3]).
At a cost of 3 TN$ per kWh, this adds up to 84 TN$ per m^2 greenhouse per year. Using natural ventilation is for free, therefore it is advised not to use mechanical ventilation, but use natural ventilation instead.

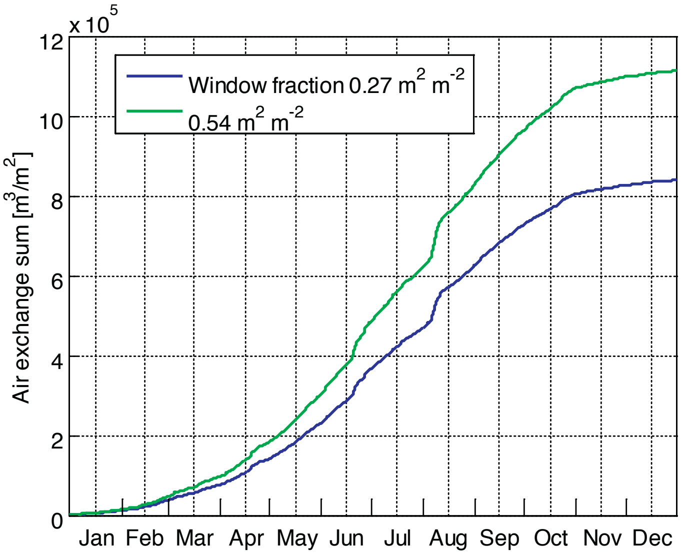


Figure 3.10. Total air exchange sum [m3 air /m2 greenhouse ground floor area] for a greenhouse in Tainan region (2009) for two different window fractions.

4.2.3 Insect nets

Insects, especially white fly, do cause diseases in Taiwanese horticulture. Therefore insect nets should be used to keep white flies out of the greenhouse. The advised hole size of reject whitefly should be at maximum 0.24x0.24mm and a porosity of 38% (see table below).
The application of insect nets has one disadvantage; the ventilation rate is reduced because the window openings are partly blocked by the nets. Perez Parra (2004) suggest the following equation to calculate the effect of insect net porosity on the ventilation rate:
ventilation = η_{screen} * potential ventilation
and $\eta_{screen} = \zeta_{screen}(2-\zeta_{screen})$
Where η_{screen} is the reduction factor on the ventilation rate and ζ_{screen} is the porosity (m^2 holes/m^2 screen). The table below shows the required porosity and the ventilation reduction cased by the nets for several insect species.

An alternative way of mounting the insect nets is to cover the whole greenhouse with it. This enlarges the net surface, which has a positive effect on the ventilation. However, light is blocked by the nets and the construction; we estimate that solar radiation inside the greenhouse is reduced by 15% in this case.

Table 3.2. Screen properties depending on the species of insects that must be rejected. (Bailey, 2003).

Insect to be rejected	hole size [mm]	porosity [-]	ventilation reduction factor [-]
serpentine leaf miner	0.61	0.64	0.13
sweet potato whitefly	0.46	0.57	0.19
melon aphid	0.34	0.48	0.27
greenhouse whitefly	0.29	0.43	0.32
silverleaf whitefly	0.24	0.38	0.39
western flower thrips	0.19	0.31	0.47

The simulation results of a greenhouse with insect nets in the window openings and a fogging system for cooling are displayed in Table 3.3. From the data in this table, we can conclude that ventilation openings of 50% in combination with insect nets give an almost similar greenhouse climate as ventilation openings of 40% without insect nets. An external insect net blocks approximately 15% of the yearly light, resulting in a yield decrease of 23%. Therefore, an external insect net is not advisable in the Taiwan light regime for vegetable production.

Thus, we advise to equip the greenhouse with vents of at least 0.5 m^2 ventilation area /m^2 greenhouse ground floor area in combination with insect nets with a hole size of 0.24mm.

Table 3.3. Effect of insect nets on indoor greenhouse climate, for Tainan 2009 climate data. The greenhouse is equipped with a fogging system in these simulations.

net porosity [%]	Ventilation area [m^2/m^2]	Number of hours warmer than 30 °C [h]		Number of hours warmer than 35 °C [h]		Number of hours with relative humidity higher than 95 or 90%		Evapo-transp. [$kg/m^2/yr$]	Crop production [%]
		T air	T crop	T air	T crop	>95%	>90%		
No net	0.4	842	1139	0	366	2388	4080	850	100
38	0.3	1015	1325	8	453	2390	4262	784	88
38	0.4	930	1233	3	397	2391	4181	806	93
38	0.5	880	1178	2	367	2386	4125	824	96
38[1]	0.5[1]	1006	1329	0	414	2406	4284	783	77

[1] Assumptions: 12% light reflection by external insect net, outside wind speed is reduced to 30% by the nets

Figure 3.11. Insect nets in the window opening, combined with an external shading screen.

Conclusion ventilation and insect nets

A greenhouse for sub-tropical climate in Taiwan should be equipped with a well designed ventilation system. A large ventilation capacity avoids excessive temperatures inside the greenhouse at daytime. The power consumption of mechanical ventilation is high, so we advise to use *natural ventilation*. The vents should be equipped with insect net to keep whitefly out.

To provide sufficient ventilation capacity, even with insect nets, the surface of the vents should be at least *0.5 m^2 per m^2 greenhouse ground surface*. In that case, the temperature inside the greenhouse is close the outside temperature. Natural ventilation is not able to decrease the temperature below the outside temperature level.

4.3 Cover: plastic film or glass

In vegetable production, a rule of thumb states that *1% more light = 1% more potential production.* Of course this rule is only valid if all other growth factors (T, RH, CO_2, etc) are not limiting and within the optimal ranges. However it is save to state that a greenhouse covering should allow the sunlight to enter the greenhouse as much as possible for a maximum potential production rate.

A glass cover has in general a higher transparency than a plastic greenhouse cover over the years as the light transmission of plastics decreases due to ageing. Also, a glass cover can be cleaned easily as opposed to plastics. However, glass is expensive and nowadays cheap, reasonably good plastics are available. Moreover, plastic covers can be made of modified plastics that give the cover special thermal properties. For example, plastic films exist that reflect or absorb the near infra red (NIR) radiation. In this way, less heat radiation enters the greenhouse, which could result in lower indoor temperatures (unfortunately this principle only works if a large fraction of the NIR is rejected, so materials need to be improved further before practical applications are possible).

Also, plastic films are available with a high IR transmission, which allows heat radiation to leave the greenhouse and therefore lead to lower air and crop temperatures. This is called a *non-thermic film*, as heat is not trapped inside the greenhouse, which is favorable in tropical areas (Hemming *et al.* 2006).

The table below gives some properties of four covering materials that are simulated. Three different types of plastic films were simulated with increasing infra red transmission.

Table 3.4. Properties of the plastic cover.

material	EVA	EVA	PE	PE	glass
Thermic	yes	yes	no	no	Yes
diffuse	diffuse	clear	diffuse	clear	Clear
ID code	*PT02A*	*PT02C*	*PH03A*	*PK02E*	*Glass*
PAR transmission (perpendicular)	0.825	0.9064	0.893	0.89	0.90
diffuse transmission	0.7099	0.8092	0.765	0.8	0.83
Infra red transmission	*0.20*	*0.3905*	*0.37*	*0.54*	0
Infra red emission up	0.77	0.58	0.60	0.43	0.80
haze	High	low	high	low	Low

NOTE that italic data is derived and not given by manufactures.

The different cover materials result in different climates inside the greenhouse, expecially at high and low temperatures. Also, the amount of PAR radiation inside the greenhouse differs, which has an impact on potential crop production. The results of our simulations with the different cover materials is shown in Table 3.5. and Figure 3.12. Please note that the effect of haze is not simulated. In practice, a cover with high haze gives a higher crop production, especially in climates with high direct solar radiation, due to two main reasons:

1. Crop temperatures are lower in comparison to a non-haze cover because no direct light falls on the leaves
2. Scattered light is favorable for crop production because more lights reaches the lower leaves of the crop (Dueck *et al.* 2009).

The air and crop temperature is lowest in a greenhouse covered by a non-thermic plastic film (Figure 3.12.). In a greenhouse covered with clear glass, the temperatures of the crop gets very high, which is not favorable for the production.

Table 3.5. Potential crop production [%] for several types of greenhouses, with either glass or plastic cover.

Greenhouse type	Cover material	
	Overall greenhouse transmissivity [%]	Potential plant production, relative to glass cover [%]
EVA, thermic, diffuse	65	98
EVA, thermic, not diffuse	71	105
PE, non thermic, diffuse	70	104
PE, non thermic, not diffuse	70	107
Glass, thermic, not diffuse	72	100

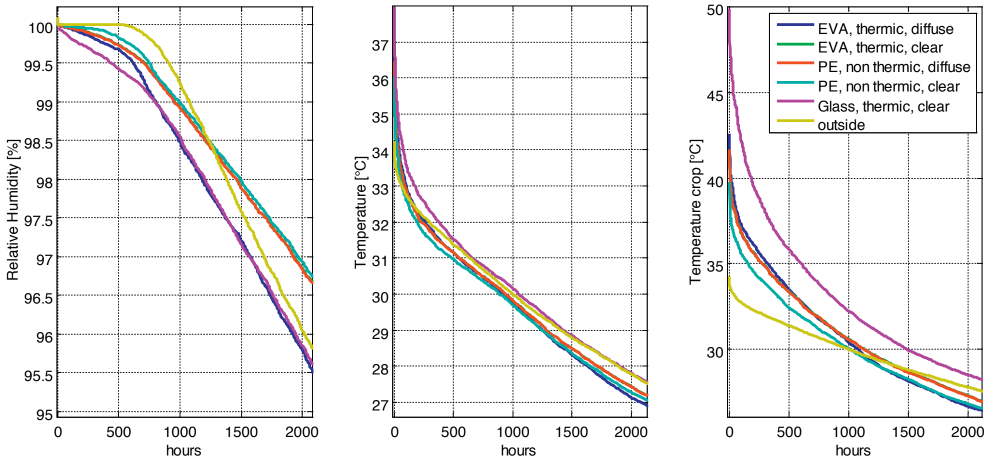


Figure 3.12. Effect of different types of greenhouse cover on the indoor climate and crop temperature.

Conclusion greenhouse cover material
We advise to use a plastic film that is diffuse and has a high transmission of light. It should also have a high transmission of infra red radiation. This helps to reduce the extreme greenhouse temperatures.

4.4 Adiabatic cooling

The simplest method of cooling a greenhouse is by means of natural ventilation with large roof ventilation. Additionally cooling by means of fogging is useful to be considered as it has (limited) ability to cool the greenhouse air under outside air temperatures. Application of fogging (also often referred to as misting) is getting more and more attention in horticulture worldwide. Especially in areas with high radiation intensities and low outside humidities (like regions Arizona and California in the United States and areas in the highlands of Andes-countries), fogging can contribute to more favorable greenhouse climate.

The objective of fogging is in the first place to increase the humidity of the greenhouse during periods with high radiation in order to increase the enthalpy of the greenhouse air. The higher the enthalpy, the more energy can be carried off per m^3 air exchange between inner and outer greenhouse air. As the ventilation capacity of a greenhouse is limited (to around 50 m^3 per m^2 floor per hour), increasing the amount of energy that can be carried off to the outside means that greenhouse air temperatures become lower.

4.4.1 Fogging

Fogging works along the same principle as the well known pad and fan systems; dry air is cooled by evaporating water. The major difference between pad and fans systems and fogging is the fact that fogging is distributed more evenly through the greenhouse. Also, the electricity consumption of fogging installations is less than the electricity consumption of ventilators that move large quantities of air through the greenhouse.

Table 3.6. Effect of fogging on the amount of hot hours and the yearly amount of water sprayed by the fogging system. The fogging system is active for approximately 1880 hours per year, in all cases. (window fraction of 0.5; insect nets; Tainan 2009 climate).

Fogging capacity [g/m^2/h]	# hours on	Number of hours warmer than 30 °C [h]		Number of hours warmer than 35 °C [h]		Number of hours with relative humidity higher than 95 or 90%		Evapo-transp [kg/m^2/ year]	Yearly fogging [kg/m^2/ year]
		T air	T crop	T air	T crop	90%	95%		
0	0	1174	1161	97	384	4263	2894	868	0
75	2328	1060	1139	35	344	4155	2839	841	137
150	2339	971	1124	16	316	4117	2801	824	242
225	2343	903	1112	3	289	4095	2802	811	318
300	2343	840	1096	0	259	4099	2800	800	374
375	2345	799	1091	0	241	4101	2801	794	410
450	2347	784	1086	0	230	4101	2804	790	432
525	2347	764	1085	0	225	4100	2804	788	445
600	2347	757	1085	0	217	4100	2804	787	452

Table 3.6. shows the effect of fogging in terms of the number of hours with unfavorable high temperatures, defined as greenhouse temperatures above 30 °C and hours above 35 °C. In the reference situation, no fogging is applied. The other cases use the fogging installation until the relative humidity of the air is 80%.

The table shows that especially the number of very hot hours diminishes when a greenhouse is equipped with a fogging system that sprays 300-375 gram of moisture per m^2 per hour. The canopy temperature does not decrease as much as the air temperature as the plant is able to cool itself by evaporating water. However, doing so does cost the plant energy and thus biomass production. Increasing the fogging dose decreases plant evapo-transpiration, which reduces plant stress.

Please note that the stated capacity is the net total fogging capacity. In practice, the nozzles of a fogging installation are never running continuously, but apply the fog by pulses of water. For example when a capacity of 300 g/m^2/h nozzle gives water for 45 seconds per minute, followed by a 15 seconds of rest, the gross fogging capacity is 400 gram per m^2 per hour.

The duration load curves of both air temperature and relative humidity are shown in Figure 3.13. The blue lines give the reference situation, the green lines the situation with 300gr/m^2 fogging capacity.

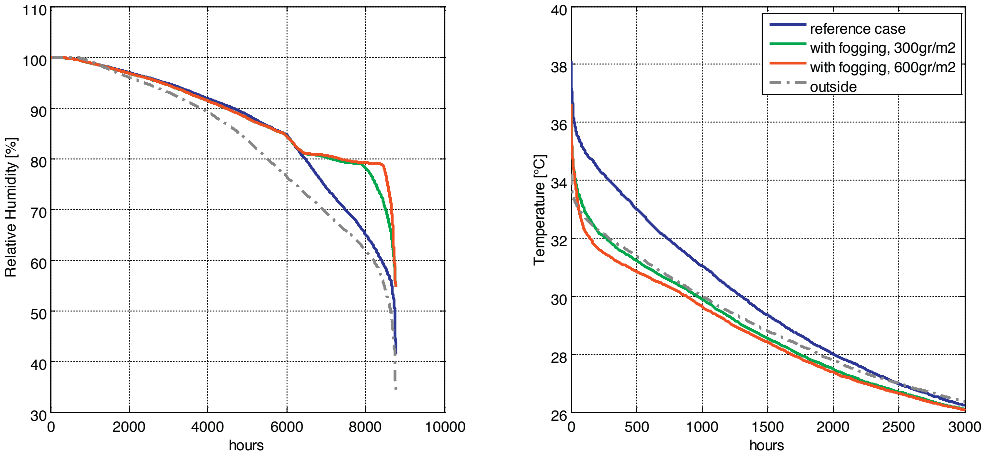


Figure 3.13. Load duration curve for greenhouse air temperature and relative humidity, both with and without fogging (300 and 600 g/m2/year) applied. Fogging effects the air temperature and it raises the relative humidity. Interestingly, the relative humidity is raised only at times when the reference case has a low relative humidity. Thus, the effect of fogging on diseases will probably remain limited.

Interestingly enough, the daily maximum humidity is the same for both cases (Figure *3.15.*). This indicates that the use of fogging will probably not increase the risk for humidity-related diseases.

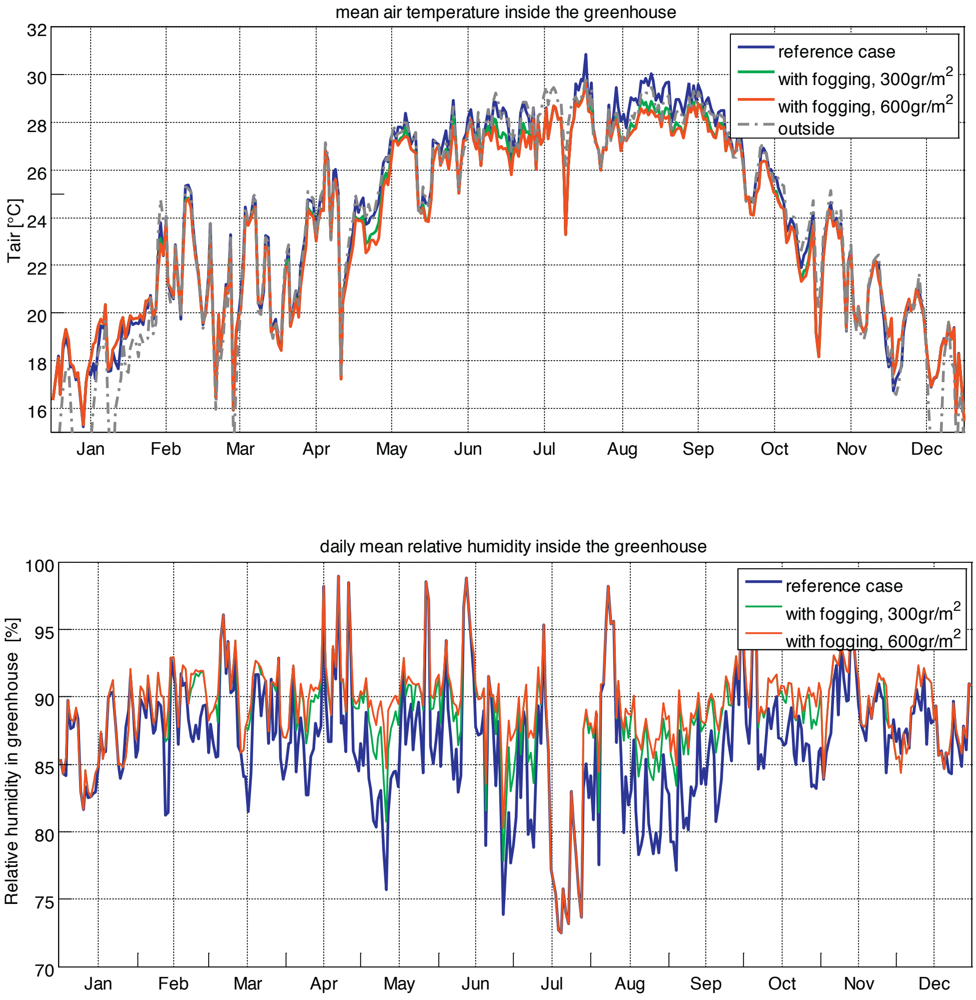
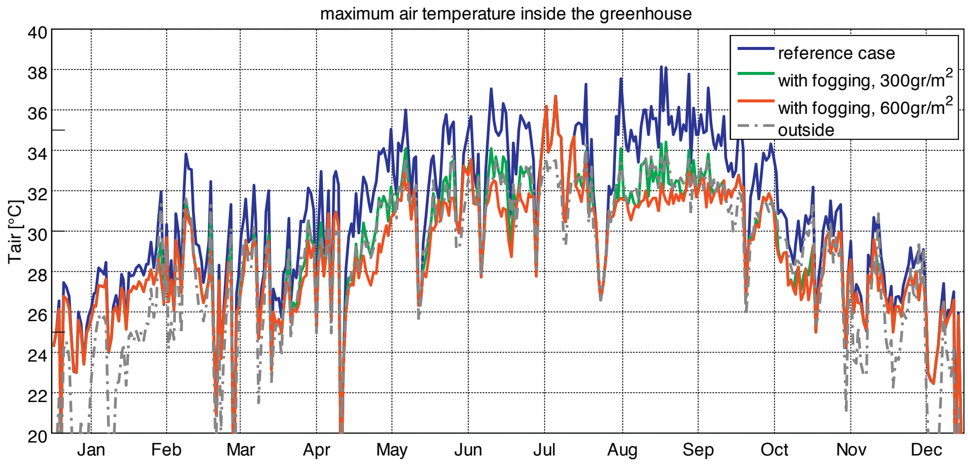


Figure 3.14. Daily mean temperature (top) and humidity (bottom) in the greenhouse without the application of fogging (the blue line) and when using fogging with a capacity of 300 (green) and 600 (red) gram per m^2 per hour.



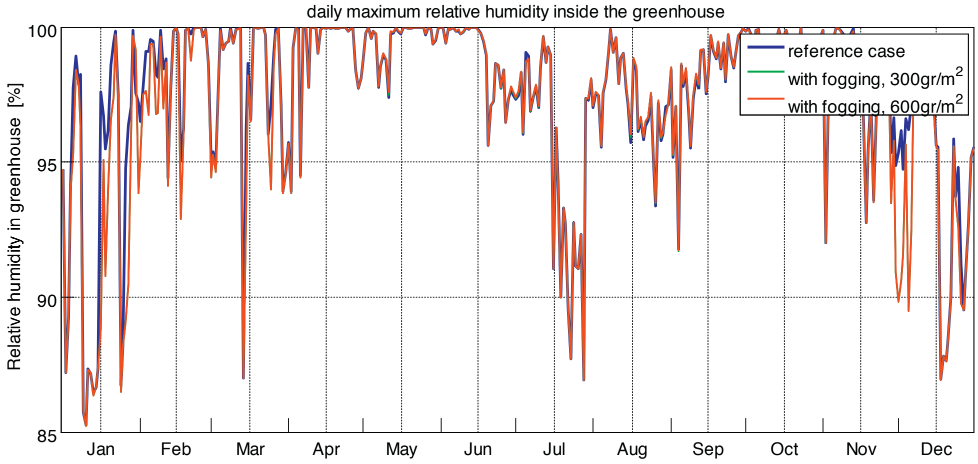


Figure 3.15. Daily maximum temperature (top) and humidity (bottom) in the greenhouse without the application of fogging (the blue line) and when using fogging with a capacity of 300 (green) and 600 (red) gram per m2 per hour. The daily maximum relative humidity is equal for both cases.

4.4.2 Pad and fan

As the operational principle of a pad-and-fan-system is the same as fogging, the operation hours are similar (~1880 per year). The main difference is that the required ventilation during these hours ($1880*80m^3/m^2/h = 150*10^3 m^3$) is realised by means of fans instead of natural ventilation. The energy demand of these fans is in the order of 47 $MJ/m^2/year$ (13 kWh $m^2/year$).

The high energy use is the main drawback of a pad and fan cooling system. Moreover, the climate inside the greenhouse becomes very inhomogeneous when a pad and fan system is used. To illustrate this, a Figure from a cfd study is included below. Right behind the pad, the air is cool and humid. As the air travels through the greenhouse, towards the fan, it is heated by the sun. At the fan-side of the greenhouse the air is much warmer, meaning that the local climate is not favorable for the plants.

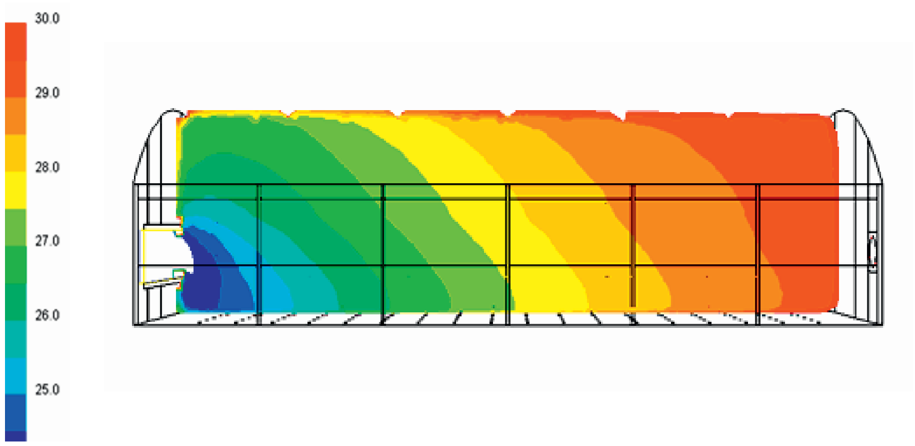


Figure 3.16. Effect of a pad and fan cooling on the temperature profile in a greenhouse. Source: Sapounas, 2010.

4.4.3 Energy use of fogging versus pad and fan

The energy use of a misting system is smaller than that of a pad and fan system. To operate the (high pressure) pump of the misting installation, around 2 W/m^2 is needed. The fans of a pad and fan system will use approximately 7 W/m^2. This means that a pad and fan system uses around 3.4 times more energy than a fogging system. However, in case ground water is used (with bad quality), a reverse osmosis system should be used, which adds another 0.7 W/m^2 of energy use to the fogging system.

Estimation of the energy use of fogging and pad-and-fan systems

1. 350 g fogging/m^2/h	2.1	W/m^2
Power rating of high pressure pump is 50kW/4ha		
Energy consumption of reverse osmosis is 2kWh/m^3 water produced	0.7	W/m^2
2. 80 m^3/m^2/h pad&fan system	7.1	W/m^2
The energy use of the fans is [1]:	6.9	W/m^2
The energy use of the pump is:	0.16	W/m^3

[1] *At 50m^3/m^2/h, 250Pa pressure difference, fan efficiency of 80%*

Conclusion adiabatic cooling

We advise to install a fogging system with a net capacity of around 300 g/m^2/h. This system will decrease the temperature inside the greenhouse and will contribute to a less stressed crop. We do not advise a pad and fan system, because of the higher energy cost and inhomogeneous temperature distribution inside the greenhouse.

4.5 CO_2 dosing

Plant photosynthesis is mainly dependent on the amount of light, temperature, humidity, CO_2, water and nutrients available at every moment. During summer time in Taiwan temperatures and light levels are high. Assuming water and nutrients can be applied to the extend needed, the amount of naturally available CO_2 limits production.

If CO_2 is added to the greenhouse air, the crop production will increase. However, because a greenhouse in Taiwanese climate condition needs a lot of ventilation to avoid excessive temperatures, most of the added CO_2 disappears quickly to the outside. This effect is illustrated with the following figures.

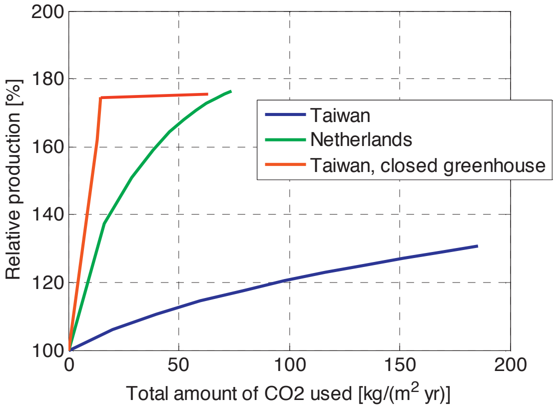


Figure 3.17. Comparison of the effect of CO_2 dosing in Taiwan and the Netherlands.

When looking at figure, we see that the production in a Taiwanese greenhouse raises with an increased CO_2 dosing. Compared to the reference situation, without CO_2 dosing, 8% production increase can be realized with a dosing capacity of 50 kg CO_2/ha/h (resulting in a total CO_2 use of 18 kg CO_2 per m^2 per year). Doubling the dosing capacity to 100 kg/(ha h) gives an increase of 20%, for which in total 45 kg of CO_2 must be supplied. Larger dosing systems do increase the production further, however also the cost increase.

The benefits of additional CO_2 supply to the greenhouse are present, however they are not as high as in colder climates. The reason behind this is the large amount of ventilation that is needed to keep the air temperatures acceptable. By opening the windows, CO_2 is lost to the ambient air, which diminishes the effect of CO_2 dosing. To illustrate this, the Figure below shows the window opening in the greenhouse over a whole year.

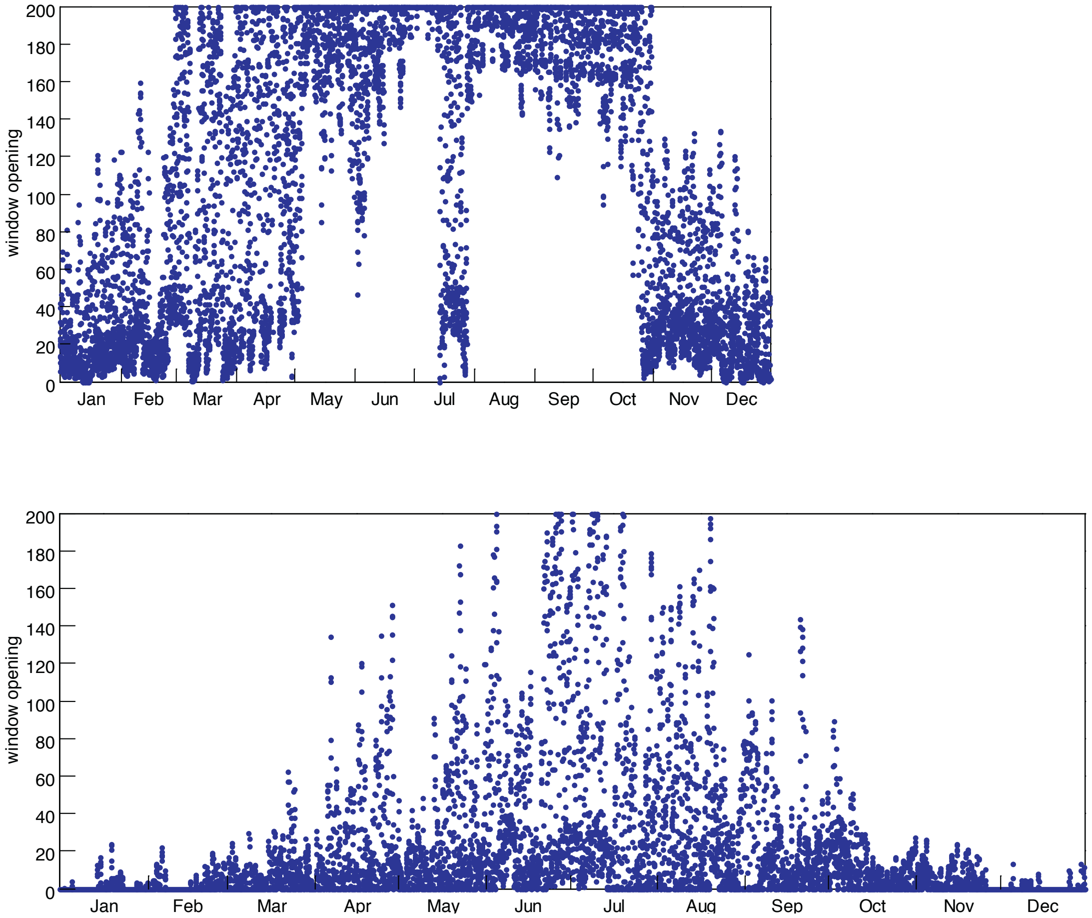


Figure 3.18. Window opening during one year in Taiwan (top) and The Netherlands (bottom). The value on the y-axis is the sum of the window opening at the windward and leeward site of the greenhouse (both 0-100%).

Figure 3.19. shows the effect of a limited CO_2 dosing system. This system supplies CO_2 to the greenhouse to levels that match the outdoor concentration (400ppm). This results in a production increase of 8%, for which approximately 18kg is needed per year.

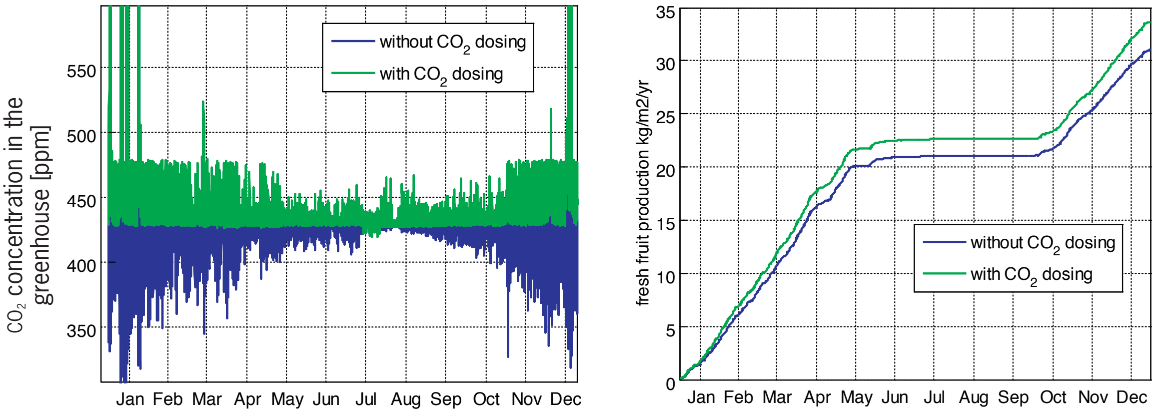


Figure 3.19. The effect of CO_2 dosing in an open greenhouse under Taiwanese climate conditions; The CO_2 concentration increases when CO_2 is dosed to 400ppm, the crop production increases up to 8%

Conclusion CO_2

CO_2 is an essential growth factor for crop production. Although CO_2 is available is the outside air, the dosing of additional CO_2 should be considered during times that the windows are (almost) closed. Unless this CO_2 is free/cheaply available, it is not worth to supply CO_2 to an *open* greenhouse under Taiwanese conditions. If, in future projects, a connection can be made to industrial (waste) CO_2, it is worth investigating the possibilities again.
In closed or semi-closed greenhouses, supplying CO_2 is very beneficial and increases potential production by more than 150%.

4.6 Screens for light control and energy saving

Screens are applied in greenhouses for various reasons: shading and reduction of sun radiation energy input during summer, energy saving by reduction of heat energy losses during winter or both in combination. This section describes considerations that should be taken into account when choosing a screen.

Shading screen

As radiation intensities in the Tainan area are quite high in summer some shading could be beneficial for the crop. Of course, limiting light levels will slightly decrease the potential production, however shading does increase crop quality and decrease risks for crop damage. Two types of screens are commonly used in greenhouses; internal screens and external screes. Internal screens are cheaper and can be used both for shading as well as for insulation at night. Their main disadvantage is the limiting effect on ventilation, as they block the air exchange between the greenhouse and the windows in the roof. External screens also limit ventilation, however to a lower extend.

Table 3.7. shows the effect of different types of shading screens on the greenhouse and crop temperature, the energy use and the crop production. In all cases the internal screen is closed when the outside radiation exceeds 500 W/m². Screens with more shading do reduce the greenhouse and crop temperature, however also the potential crop production decreases.
The table also gives the water consumption by the crop, which is an indication of the heat load on the crop; less water use means less evapo-transpiration and thus less water stress.

Table 3.7. Effect of different types of shading screens, Tainan 2009 climate (incl. fogging (300 g/m2/h) and 0.5 window fraction).

Screen type	# hours closed	Number of hours warmer than 30 °C [h]		Number of hours warmer than 35 °C [h]		Number of hours RH above [h]		Biomass . [%]
		T air	T crop	T air	T crop	91%	95%	
reference	0	864	1202	1	394	4250	2378	100
inside screen:								
500W, 30% screen	1504	1011	1199	2	314	4249	2463	80
600W, 30% screen	1042	976	1201	3	329	4241	2441	86
700W, 30% screen	538	933	1190	4	335	4232	2414	91
Exterior screen:								
500W, 20% screen	1504	985	1268	2	427	4304	2414	86
600W, 20% screen	1042	937	1232	1	404	4301	2409	92
700W, 20% screen	538	891	1213	0	388	4293	2394	97
500W, 30% screen	1504	923	1170	0	330	4324	2442	89
600W, 30% screen	1042	888	1167	0	334	4313	2426	94
700W, 30% screen	538	868	1173	0	351	4305	2410	97
500W, 40% screen	1504	867	1101	0	270	4327	2465	90
600W, 40% screen	1042	859	1123	0	302	4316	2442	94
700W, 40% screen	538	853	1146	0	322	4307	2419	97

Energy screen

In general, energy screens are used at night to increase the insulation of the greenhouse roof. This prevents heat loss, resulting in a smaller energy demand of the greenhouse. Although the nights in Taiwan are not very cold, installing an energy screen does reduce the heating demand. In one particular case, the reference greenhouse, equipped with a boiler of 40W/m^2, the number of hours lower than 15 °C goes down from 150 to 100 hours per year. However, if the greenhouse is heated with (cheap) solar energy, the savings are not high.

Conclusion screen

Screens are useful to decrease crop temperature during periods with high irradiation. Due to the lower light transmission potential crop production is influenced. Moreover, screens limit the air exchange such that the greenhouse temperature will not be substantially lower than without screens in the case of fogging. This is because cooling a greenhouse with fogging only works well at high ventilation rates. We advise to install an external screen with 30% shading. This type of screen does not limit the ventilation too much and decreases the risk of crop damage.

4.7 Crop production

KasPRO uses a photosynthesis model to estimate the growth and evapotranspiration of the crop. This approach works well to simulate the greenhouse climate and the *potential* crop production. The potential crop production is the production level that can be reached under the given climate (temperatures and solar radiation), if all other factors are optimal. This includes the absence of diseases, optimal plant management and highly skilled workers. In reality, the calculated potential production levels are only reached if the people involved (workers, growers, etc) have deep knowledge and extensive experience with all available technology.

The section below describes influence of the most important growth factors on the plants and how managing these factors contributes to reaching a high crop production level.

4.7.1 How to reach the high potential crop production

This section explains the reasons behind the high predicted potential production levels. These yield levels are quite high, comparable to the current levels in The Netherlands (33kg/m^2/yr), and very much higher compared to those traditionally reached in Taiwan (8 and 10 kg m^{-2} on a yearly basis)

There are a range of factors which are suboptimal in the traditional Taiwanese greenhouses. Optimizing these conditions will increase the production level. Furthermore the available light level in Taiwan is much higher (especially in winter) compared to The Netherlands, giving a higher production potential.

1. Light

The yearly global radiation is Tainan is around 5 to 5.5 GJ compared to 3.6 GJ in The Netherlands. When all parameters in the greenhouse are optimal (temperature, relative humidity, CO_2 level), the amount of light determines the production. So based on this the production in greenhouse in Taiwan could be up to 50% higher than for the Netherlands. In Arizona, with light levels 30% higher than in Taiwan, a production level of 100 kg tomato m^2 is reached. As the light level of Tainan is almost in between the level of The Netherlands and Arizona (USA) the potential production will be also in between. This indicates a level of 60-80 kg/m^2 of fresh tomatoes should be possible to reach.

2. Substrate instead of soil

Traditionally in Taiwan the crops are grown in soil. Using substrates has several advantages:

Less soil diseases and a much more efficient irrigation and nutrition. Comparison of these two systems over the last decades has shown at least a 15-20% production increase as a result of substrate growing. At low production levels (*e.g.* around 15 kg/m^2, sometimes even a higher production increase is found; up to 50% increase).

However, an average production increase of 20% could be expected. (Factor 1.2)

3. Temperature control

Taiwanese greenhouses usually do not have additional heating or (evaporation) cooling systems. This has several effects: (1) The humidity in the greenhouse cannot be controlled properly, leading to additional outbreaks of fungal diseases which have negative effects on the production level. Furthermore, (2) lower average temperatures (at wintertime) lead to reduced growth of the crop and fruits. And, (3) reducing summer peak temperatures by cooling and/or shading improves crop growth. The optimal average growth temperature for tomato lays around 18-22 °C but also depends on the light level and variety. At higher light levels, higher temperatures are required to convert the dry matter production into harvestable tomatoes. Too high temperatures give raise to problems in fruit setting and also increase the stress on the plants. It is estimated from temperature research that better temperature control will lead to production increases of 30%. (Factor 1.3)

4. Production period

Because of the too high temperatures in the summer, the total growth period for tomato in Taiwan in greenhouses is limited to about 5 months (often, melons are grown in summer). The first two months are used for growing the crop until the productive stage is reached. This means that the actual production period (period in which fruits are harvested) is limited to 3 months. Using modern greenhouses with the required climate control systems and substrate growing, enables an almost year round production. In total the period in which the greenhouse is “empty” is limited to 4-8 weeks only. Taking into account a two month period for growing the crop from planting until productive stage, this means the actual production period is at least 8 months, being around 2.6 times more compared to the traditional Taiwanese production period. (Factor 2.6).

5. Construction/ light transmission of the greenhouse

The traditional Taiwanese greenhouses have a low light transmission, due to the construction parts used, the covering material and the cropping system. Modern greenhouses have optimized / minimized construction parts, sometimes white coated to increase the light transmission as high as possible (left). The higher light transmission (30% estimate) increases the production. As a rule of thumb 1% more light means 1% more production, if all other factors are managed optimally (Factor 1.3)

6. **Combining all the above mentioned factors leads to the following rough calculation:**

Growth factor	*Production increase*
Light	1.5
Substrate	1.2
Temperature control	1.3
Production period	2.6
Light transmission construction	1.3
Total:	7.9

If we take the current production of 4 kg of cherry tomato per m^2 as a base level, a modern greenhouse will produce around 7.9 * 4 = approximately 30 kg/m^2

However, it cannot be stressed enough: the technology itself will enable to reach the potential high production levels. However, to actually reach these levels the growing skills are of course a key success factor. These growing skills include deep knowledge on for example:

Pruning and leave picking, finding the balance between vegetative and generative growth, choosing the best variety, etc.

4.8 Heating demand

The heating demand of a greenhouse in a sub-tropical climate is fairly limited. The graphs and table below show the number of hours that heating is needed.

Without any heating system, the temperature inside a greenhouse with (non thermic) plastic film cover will be lower than 12 °C for 200 hours per year (blue line). A heating system with a capacity of 100W/m^2; (light-blue line in figure) is able to avoid these unfavorably cold hours. Moreover, a heating system helps to reduce the hours with extremely high (over 98%) relative humidity inside the greenhouse.

The loss in potential production for an unheated greenhouse compared to a heated greenhouse is around 6% for a year-round crop. For a crop that is grown from December till May, the losses due to low temperatures are around 8%.

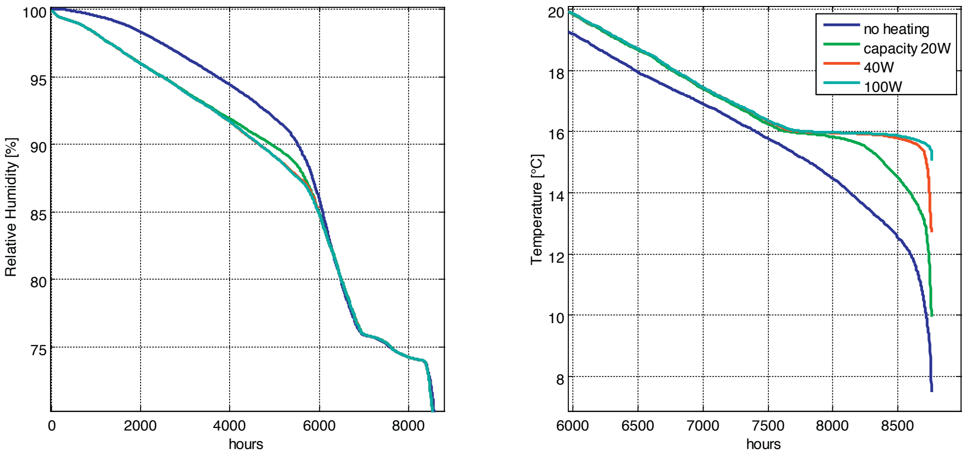


Figure 3.20. Effect of increasing the capacity of the heating system on the indoor temperature (right) and humidity (left).

Table 3.8. Capacity of the heating system for the Tainan weather data in 2009 and 2010

Heating power [W/m^2]		# hours heating system is on	Yearly energy consumption [MJ/m^2]	Number of hours colder than [h]		
				10 °C	12 °C	15 °C
0	2009	0	0	107	231	756
20		1568	109	39	108	488
40		1281	156	12	44	218
60		1189	173	0	10	85
80		1167	179	0	5	45
100		1160	183	0	1	32
40	2010	1548	186	112	182	475
60		1464	221	76	143	274
80		1446	242	48	127	216
100		1424	256	4	70	180

Conclusion heating

A heating system is recommended to avoid cold hours that have negative impact on the crop growth. The capacity of the heating system depends on the type of system that is chosen and the required safety margin on the capacity. Without a heat buffer, a boiler with a capacity of 100W/m^2 is needed to keep the greenhouse warmer than 12 °C during most of the times.

4.9 Artificial lighting

The effect of artificial lighting was studied in simulation. To this end, we combined greenhouse model KasPRO with crop growth model IntKAM (Elings *et al.* 2010) to simulate the crop growth without artificial light and with 2 levels of lighting (85 µmol /m^2 and 195mmol/m^2). These three cases were repeated for a greenhouse with and without CO$_2$ fertigation. Moreover, for comparison the same cases are simulated for a Dutch greenhouse in Dutch climate.

The results of these simulation show a limited effect of artificial lighting on tomato production in Taiwan (
Table 3.9; even with very high lights intensity (195 µmol), the production increase is limited to only 5%. In The Netherlands, the production increase is much higher (around 30%). This can be explained by the low outside light intensity in winter. In these low-light conditions the use of artificial light does increase the crop production.

Cost

A 600W lighting equipment produces around 1050 µmol of PAR light and costs (including cables and control) are between 265 and 350 euro (kwin, 2010). The cost per m^2 depend on the lighting intensity; at 85 µmol the investment cost are between 21 and 28 euro/m^2. At 195 µmol, investment cost are between 49 and 65 euro/m^2.
The simple payback time for artificial lighting of 85 µmol/m^2 is calculated from the cost and the increased crop production. If we assume a product price of 1.5€/kg, the benefits of producing 2kg/year extra is 3€/year. This brings the payback time at 7 to 9 years (without considering maintenance).

Table 3.9. Effect of artificial lighting for various cases in Tainan and The Netherlands.

	Tainan			The Netherlands		
With CO_2 dosing	E-use [kWh/yr]	Yield [kg fresh/yr]	Yield [% to ref]	E-use [kWh/yr]	Yield [kg fresh/yr]	Yield [% to ref]
Reference	0	71	100%	0	69	100%
85 µmol /m²	26	73	103%	115	78	114%
195 µmol /m²	46	74	105%	242	89	130%
Without CO_2 dosing						
Reference	0	54	100%	0	51	100%
85 µmol /m²	26	56	103%	115	59	115%
195 µmol /m²	26	56	103%	242	65	126%

Conclusion artificial light

The potential additional crop yield with the use of artificial lighting is fairly limited; at maximum 5% yield increase (approximately 3 kg/m^2/year). As the investment cost are rather high (20 to 65 €/m^2), the payback period will be long (7-9 years). For these reasons we advise not to use artificial lighting in Taiwan vegetable production.

4.10 Solar energy

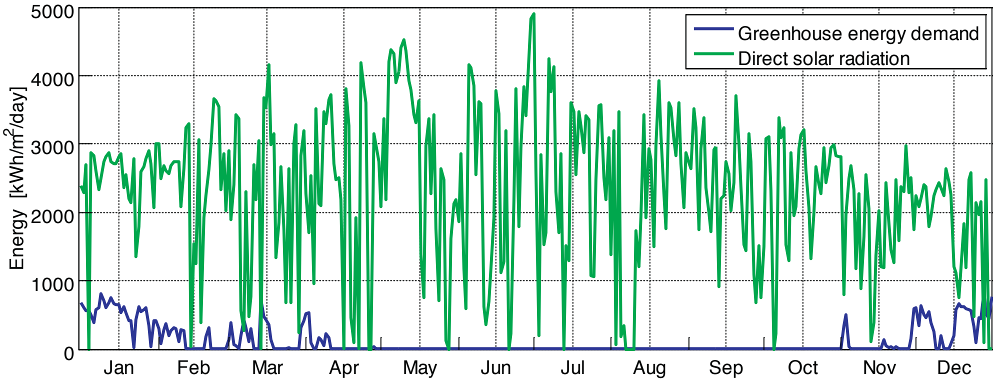
An alternative way to provide energy to the greenhouse is to use solar energy. The most simple system that is capable of collecting and utilizing solar energy consists of a solar collector, a buffer tank and a heating system inside the greenhouse (Figure 3.23.).

This section explores options for solar energy. Several collector and buffer sizes are studied in detail.

4.10.1 Available solar radiation

Obviously, in a (sub) tropical climate the yearly available solar radiation is much higher than the heating demand of the greenhouse. So, if we can (economically) install a buffer to store captured solar heat the greenhouse can easily be heated. However, long term storage of thermal energy requires large, well insulated buffers, which are expensive and require a large ground surface.

In this study we focus on relatively cheap collection and storage systems that use short term (maximum 2 days) storage of solar heat and a simple solar collector. Figure 3.21. shows the energy demand of a greenhouse with a boiler of 40W/m^2 heating capacity in one graph with the direct solar radiation. From this graph we learn that at almost every day the solar radiation is enough to cover the heating demand. At some points in time, the total direct solar radiation is lower than the total heating demand (the green line is lower than the blue line). Increasing the storage capacity, to 2 days, eliminates these days (lower part of Figure 3.21.).



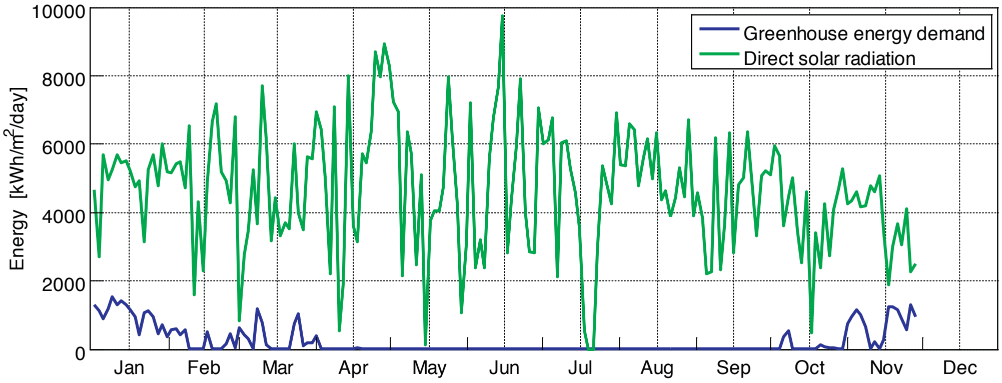


Figure 3.21. Sum of the heating demand of the greenhouse (blue line) and incoming direct solar radiation, for one day (top) and two days (bottom) (Tainan 2009 climate data).

Figure 3.22. a solar collector for greenhouse heating (left; www.certhon.com) and a heat storage tank (right).

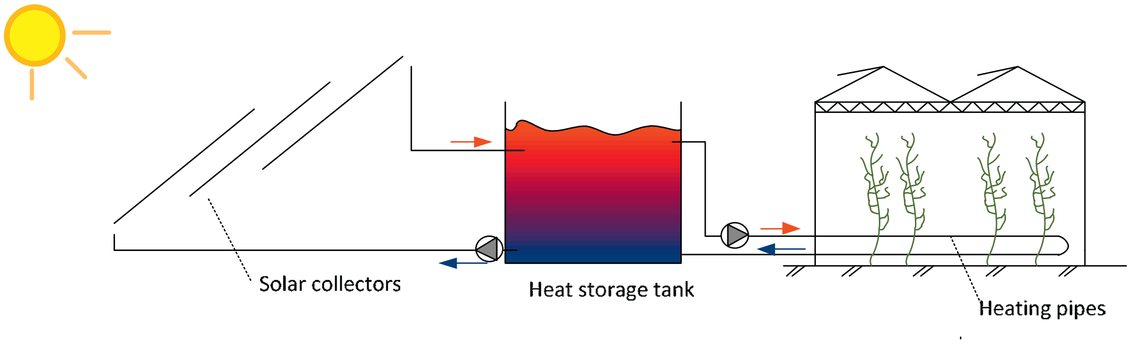


Figure 3.23. Layout of a solar thermal energy collection system.

Size of the buffer and the solar collector

The solar collector is connected to a buffer tank in which hot water (produced with solar heat during daytime) is stored and used at nighttime. The size of the buffer must be chosen such that it fits the solar collector and the heating demand. Varying the size of the solar collector changes the amount of solar heat that can be captured and used to heat the greenhouse, this effect in shown in Figure 3.24. This Figure shows the effect of increasing buffer size (left) and increasing solar collector size (right part of the figure).

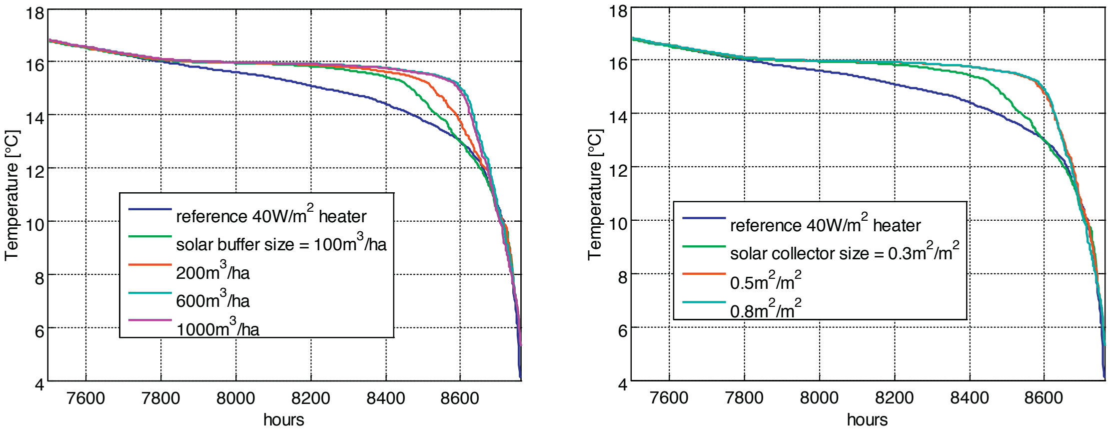


Figure 3.24. duration load curve for the temperature inside the greenhouse, depending on buffer size (left) and solar collector size (right).

Obviously, the collector and buffer must have a size that fits together. The large table below shows the results of many simulations. The data in the table is sorted on 'number of hours colder than 10 °C' (third column). From this table, we can conclude that we need a solar collector of 70% of the greenhouse surface in combination with a 200m^3/ha buffer tank to have sufficient capacity to keep the greenhouse warm at almost any moment in the year.

Conclusions solar collector

The greenhouse may be heated either with fossil fuels or by solar energy (or a combination of both). Heating the greenhouse by means of solar energy is sustainable and has low running cost. The collection system consists of a heat storage and a collector; to a certain extend the sizes of both systems are interchangeable. This means that when the buffer size is increased, the collector may be chosen smaller (and vice versa).

If the choice is made to use solar energy to heat the greenhouse, we advise to install a solar collector of 0.7 m^2 collector/ m^2 greenhouse ground surface. In this case, the buffer size should be in the order of 200 m^3/ m^2 greenhouse ground surface. This buffer needs to be insulated such that the temperature inside does not decrease more than 3 °C over 48 hours. The investment cost are considerable: we estimate them to be around 40€/m^2 (1500 TND/m^2) greenhouse ground surface. The payback period is slightly over 10 years.

Purely economically, heating the greenhouse with solar heat is not the best option.

Table 3.10. Influence of the size of the buffer and the solar collector on the temperatures and potential crop yield inside the greenhouse. The table is sorted on the number of hours during which the greenhouse temperature is lower than 10 °C.

Buffer size [m^3/ha]	Collector size [m^2/m^2 greenhouse]	Hours with T<10 °C	Hours with T<12 °C	Hours with T<15 °C	Crop yield [%]	Approx. investment [euro/m^2][1]	Payback period [years]
0	0; no heating	131	258	760	100		
0	0; 40W boiler	46	102	524	104	3.5	
0	0; 100W boiler	0	1	32	106	4	
200	0.7	1	19	72	107	39	11
400	0.7	4	20	51	107	43	12
600	0.7	6	23	55	107	47	13
200	0.6	12	31	101	107	34	10
200	0.6	12	31	101	107	34	10
400	0.6	14	34	80	107	38	11
600	0.6	17	38	83	106	42	12
100	0.7	22	60	217	106	37	11
100	0.6	23	63	230	105	32	9
200	0.5	28	56	153	106	29	9
400	0.5	31	54	115	106	33	10
600	0.5	33	57	121	106	37	11
200	0.4	49	95	233	105	24	7
100	0.4	51	108	292	104	22	7
100	0.3	80	145	361	103	17	5
200	0.3	80	138	315	104	19	6
50	0.4	83	155	436	103	21	6
50	0.3	85	160	449	103	16	5
50	0.2	95	175	489	102	11	4
100	0.2	95	169	449	102	12	4
200	0.2	96	165	413	103	14	5

Note: price based on: large, low tech solar collector 50 euro/m^2, storage tank: 200 euro/m^3 (for a large tank, source: kwin 2010).

[1] approximate investment cost (€/m^2) for the boiler or the solar collector for a 2ha size greenhouse. The installation cost and equipment inside the greenhouse is not included in these numbers.

4.11 Closed and semi-closed greenhouse

To reduce the daily mean temperatures inside the greenhouse, three basically different options are possible:

- A totally closed greenhouse in which the windows are closed during the whole year and the climate is totally controlled with air conditioning equipment. To increase crop production, CO_2 is added to the air.
- Semi-closed greenhouse, cooled during the day. By cooling the greenhouse only at daytime, the total energy demand for cooling can be reduced. Yields are high, as during daytime CO_2 is added to the greenhouse.
- Semi closed greenhouse, cooled during the night. As daily mean temperature is important for the physiological processes in plants, one could argue that cooling at night is a cheap way to reduce the 24hour mean temperature. This options uses natural ventilation (and fogging) during the day and mechanical cooling during the night. The benefits of CO_2 dosing are marginal, like in a non-closed greenhouse.

The climate and crop yield of these three options are discussed in more detail in the sections below, here the results are summarized.

Conclusions closed greenhouse

A closed greenhouse provides optimal growing conditions for the crop, resulting in very high crop yields. Semi-closed greenhouses that only use the cooling equipment during the day do not use less energy than a totally closed greenhouse. Only cooling during the night does reduce daily average temperatures (compared to an open greenhouse), but the concept has not been proved in studies or practice yet. Therefore, if a fully controlled greenhouse is to be build, a totally closed greenhouse seems the best choice for Taiwanese climate conditions.

The investment costs of these greenhouses are high (expensive greenhouse and cooling equipment is needed). Also the skills of the grower to fully exploit the benefits of the technology must be very well developed. For an average Taiwanese vegetable grower, the transition from the current greenhouse to a closed greenhouse is (probably too) large. The concept of closed greenhouses is more suitable as a demonstration and research project in the near future.

Table 3.11. Summary of the characteristics of three different types of closed greenhouses under Taiwanese climate conditions.

	Potential crop yield [kg /m^2]	Potential crop yield [%]	Heating demand[1] [kWh]	Cooling demand[2] [kWh]	CO_2 demand [kg/m^2]	Hours with temperature higher than 30 °C	Hours with relative humidity higher than 98%
Open greenhouse	29	100	44	0	0	943	1457
Closed greenhouse	93	321	122	642	18	30	597
Day cooling	73	255	124	742	20	39	1779
Night cooling	39	134	99	35	41	1634	333

[1] *The value for heating demand is the amount of heat that should be supplied to the greenhouse. It is not the electricity consumption. If a heat pump is used, the electricity consumption may be calculated by dividing the given value by 4 (at a COP of 4)*

[2] *The value for cooling demand is the amount of cold that should be supplied to the greenhouse. It is not the electricity consumption. If a heat pump is used, the electricity consumption may be calculated by dividing the given value by 3 (at a COP of 3)*

4.11.1 Closed greenhouse

A closed greenhouse uses mechanical cooling to control the temperature and the humidity inside the greenhouse. This makes the climate inside the greenhouse completely independent from the climate outside, which means that the plants grow in the best possible conditions. In this way, the plant production is only dependent on the available (solar) radiation, which is quite high in Taiwan. Of course, a closed greenhouse does not only have advantages; it requires high investment cost and high running cost (the greenhouse needs a high energy input to provide the cooling).

To study the economic feasibility of a closed greenhouse, we have made simulations with the KasPro model. In these simulations we use a greenhouse in which the following settings are used:

- The crop is planted in December and grown year-round
- During the whole year, the greenhouse climate is controlled to create favorable growing conditions; the heating set point (temperature at which the heating system start working) is set to 20 °C during the day and 17 °C at night.
- When the sunshine increases the temperature in greenhouse temperature more than 4 °C above the heating set point, the cooling equipment is started to carry off the heat excess. The windows are never opened.
- Apart from temperature control, the cooling equipment is also used to control the relative humidity. When the greenhouse air humidity exceeds 85% (during day) or 90% (at night), the coolers are used to dehumidify the air inside. The simulated greenhouse is covered with a single layer of plastic foil. No shading screen is installed, to take full advantage of all solar radiation. Pure CO_2 is supplied to a set point of 1000ppm during the day.

Results

The energy demand for the coolers is 2800kWh/m^2 per year. At a COP of 3, approximately 930kWh/m^2 of electricity is needed to keep the greenhouse cool. The heating systems is mainly used at night for humidity control. In total 1100kWh per m^2 of heating is needed, as the air is often cooled too deep for humidity control.

The irrigation water use is moderate (1000 l/m^2) and almost all water may be recycled as it condensates inside the coolers. CO_2 levels inside the greenhouse are constantly high (1000ppm), however this does not require a large CO_2 input because the windows are never opened. A yearly CO_2 input of 20 kg/m^2 is sufficient.

The simulated potential plant production in a closed greenhouse is very high; 110 kg of cherry tomatoes per year (at a harvest index of 60% and a dry matter content of 8%). In practice, production of cherry tomatoes over 100kg/m^2/year have never been realized (for normal tomatoes, this production is possible). Therefore we will use a yield of 80kg/m^2/year in the economic analysis.

The figures below show the function of the equipment in the closed greenhouse in more detail. The first Figure shows graphs for the whole year (8760 hours). The second and third figures show graphs for two representative days in July. Some observations that can be made from the figures are:

- The windows are always closed (top left figure)
- The temperature inside the greenhouse stays normally below 30 °C (during the day) and 20 (during the night). (middle left)
- The CO_2 concentration fluctuates around 1000ppm
- During the day, the maximum cooling capacity is 450W/m^2. At night, the greenhouse is dehumidified by first cooling the air (moisture condensates), followed by heating (to ensure high enough temperatures inside the greenhouse)

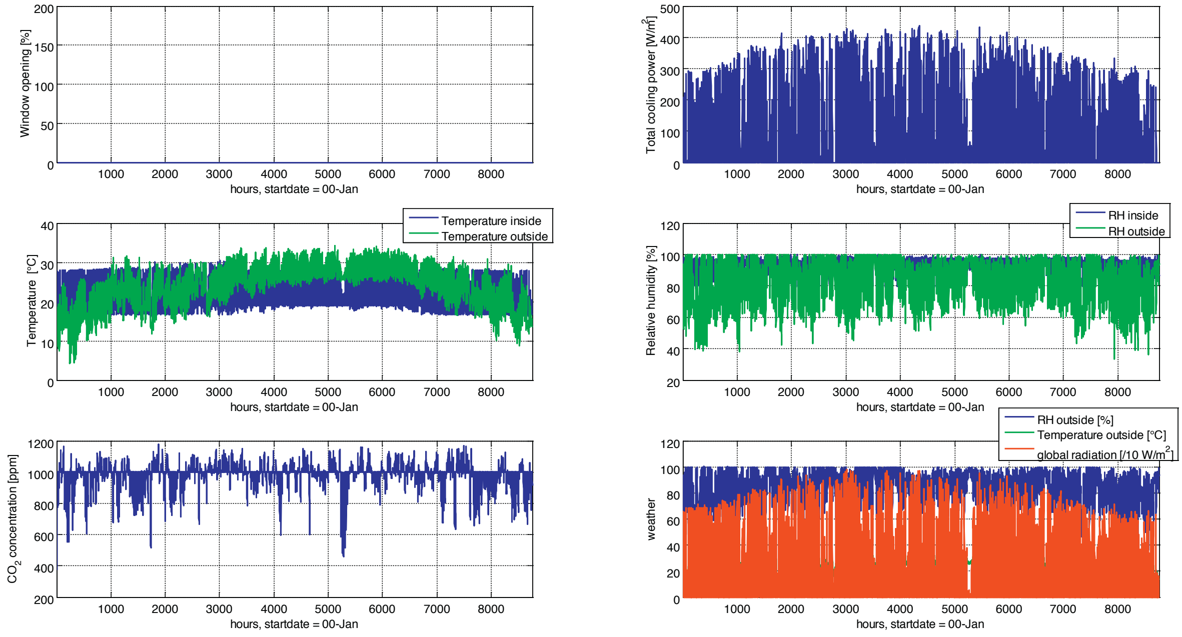


Figure 3.25. Operation of the totally closed greenhouse; year round data.

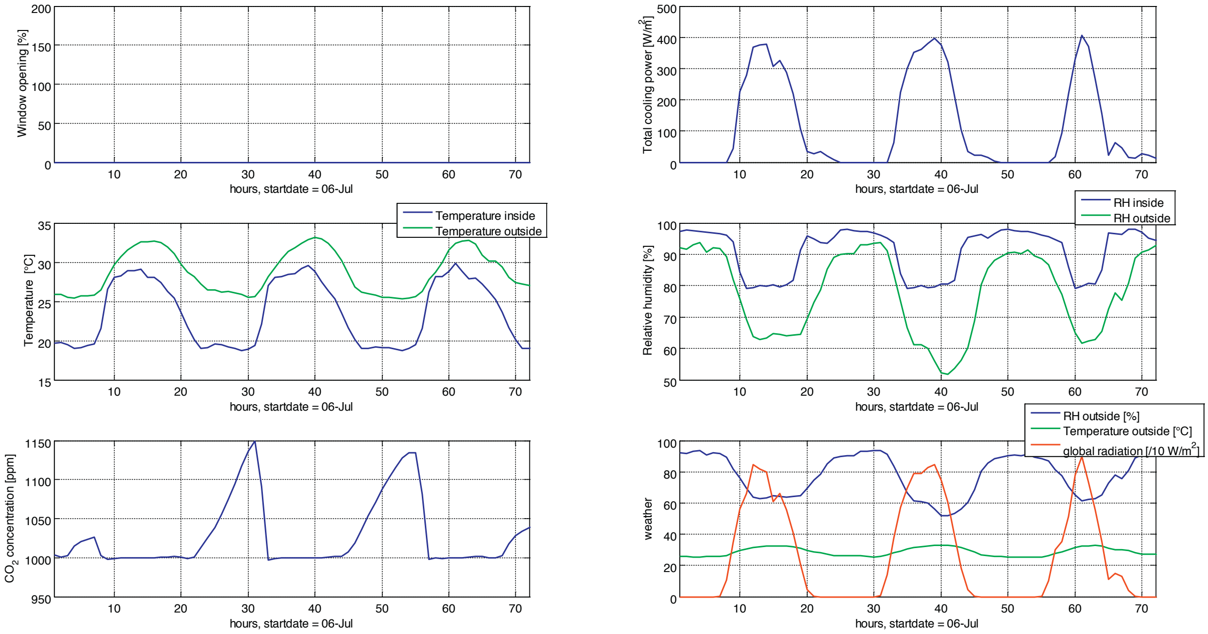


Figure 3.26. Operation of the totally closed greenhouse; data for three days in July.

Open greenhouse reference

As a reference, the same figures are given for an open greenhouse. Here, the windows are open during most parts of the year, and the mechanical cooling is zero (as it is not installed). Temperature and relative humidity inside the greenhouse are fluctuating much more than in the closed greenhouse, with maximum humidity touching 100% quite often.

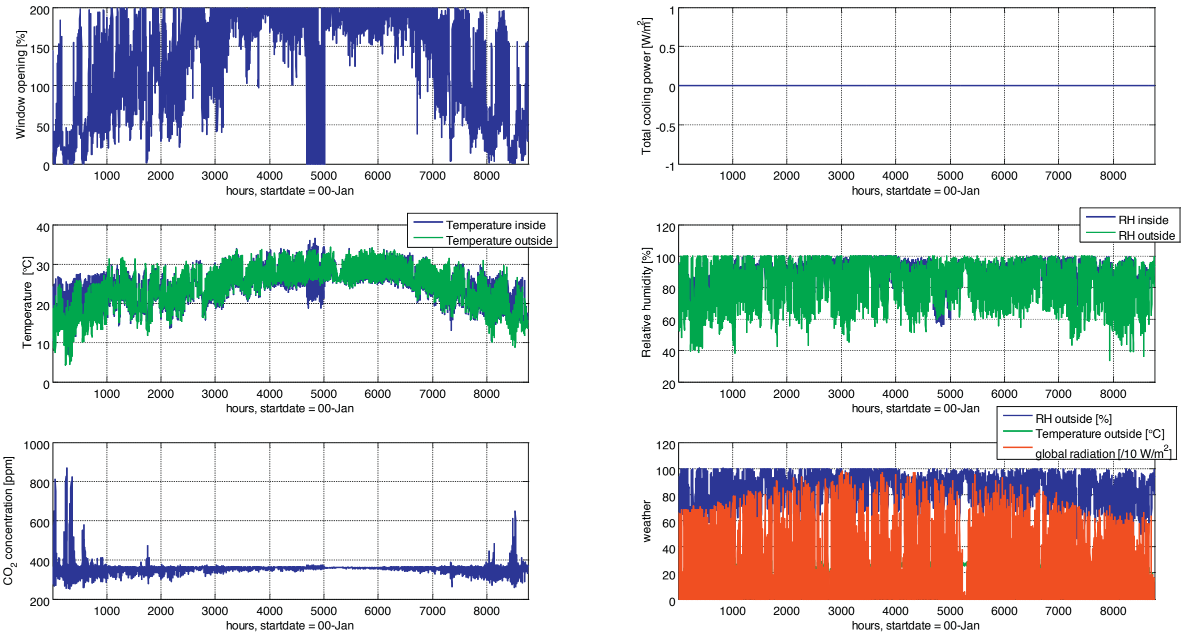


Figure 3.27. Operation of an open greenhouse.

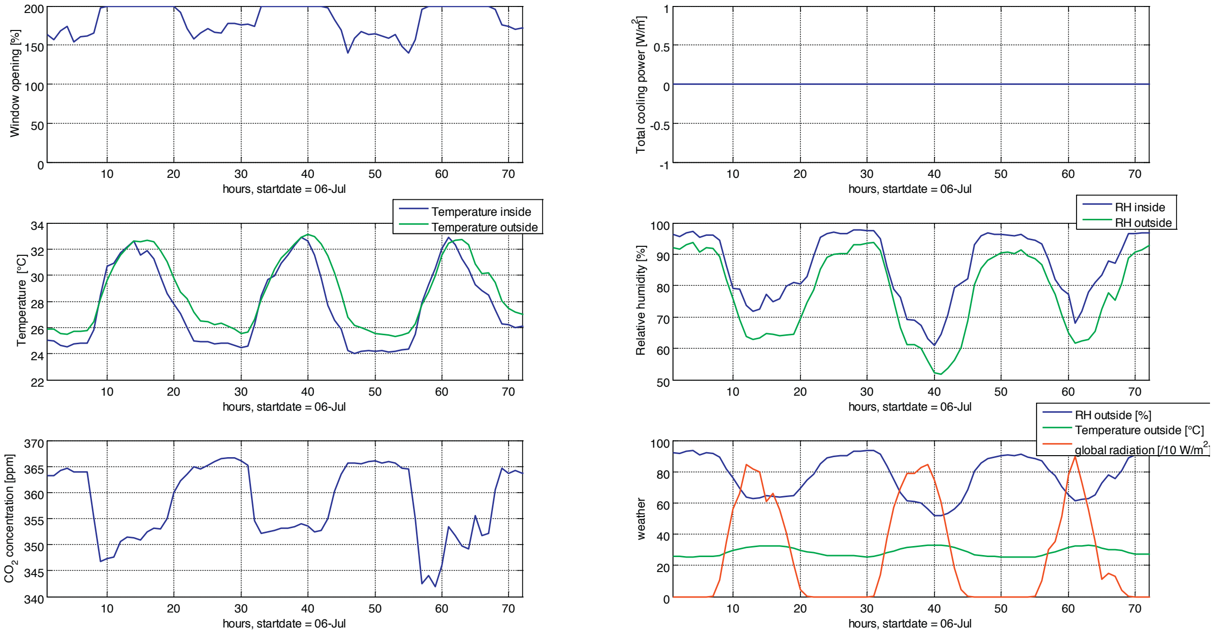


Figure 3.28. Operation of an open greenhouse.

4.11.2 Day cooling

Potential crop yield is high, because CO_2 levels at daytime are high. The cooling demand is not less than in the fully closed greenhouse, probably because the humid air that enters the greenhouse at night has to be dried again during daytime. Moreover, the relative humidity increases in the evening (when the cooling equipment is turned off) and often touches 100%. The humid climate increases the risks for fungi and diseases, which is unacceptable in a very high tech greenhouse. Therefore we advice not to use this control strategy in the Taiwan climate conditions.

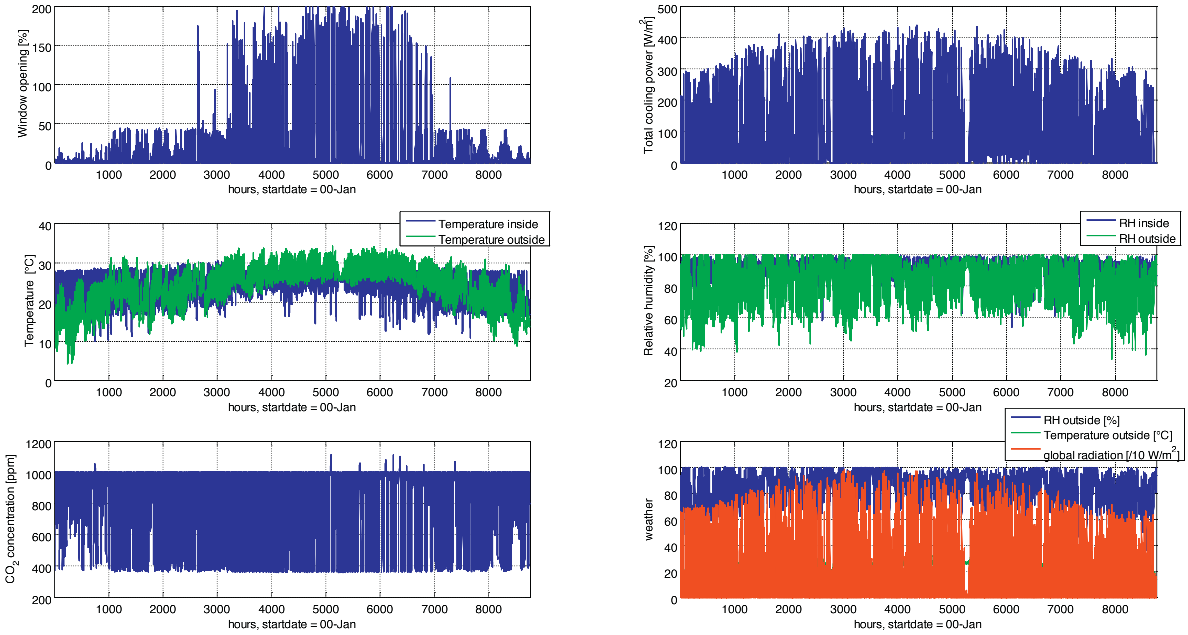


Figure 3.29. Operation of the semi-closed greenhouse in which the greenhouse is cooled during the day; year round data.

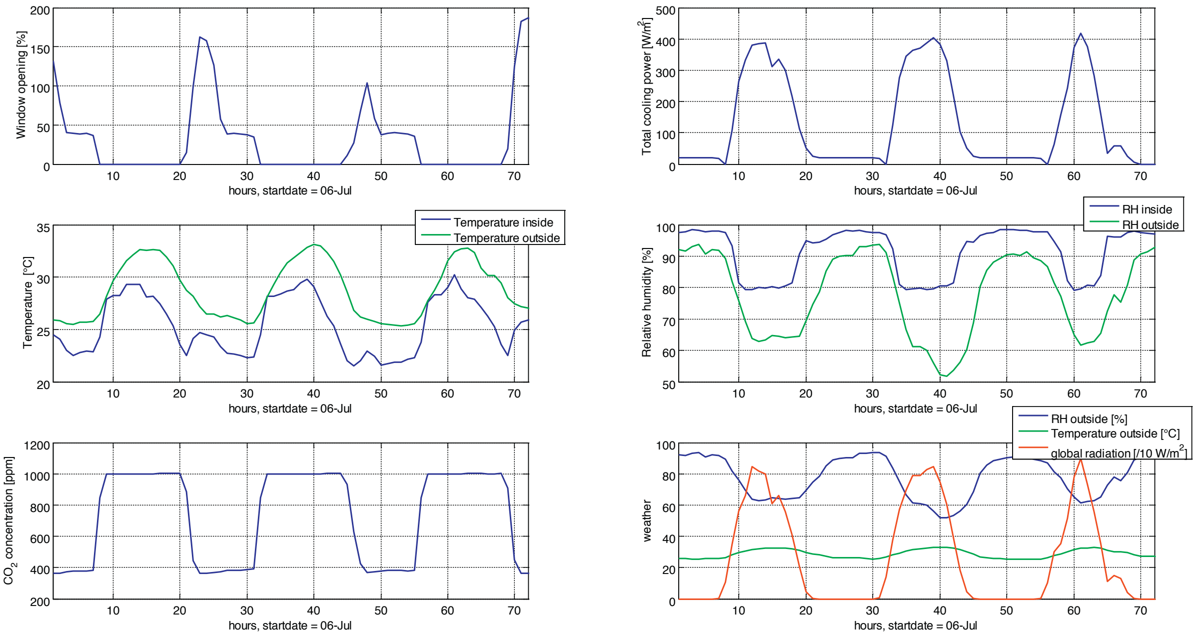


Figure 3.30. Operation of the semi-closed greenhouse in which the greenhouse is cooled during the day; data for three days in July (12-14th of July 2009).

4.11.3 Night cooling

The idea behind night cooling is to reduce the daily mean temperature, which has a positive effect on fruit setting. Unfortunately, the benefits of such a control strategy have not been shown in studies known to us. Therefore we advice not to use this way of greenhouse control in a commercial greenhouse at the moment. It could be interesting to test this regime in a research project.

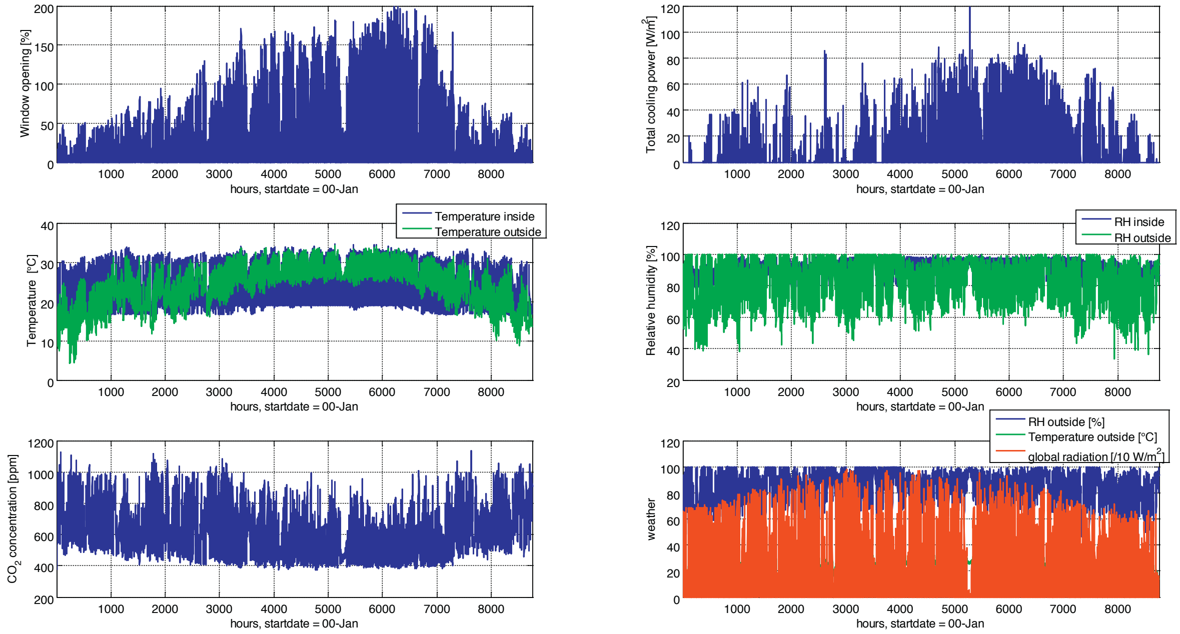


Figure 3.31. Operation of the semi-closed greenhouse in which the greenhouse is cooled during the night; year round data.

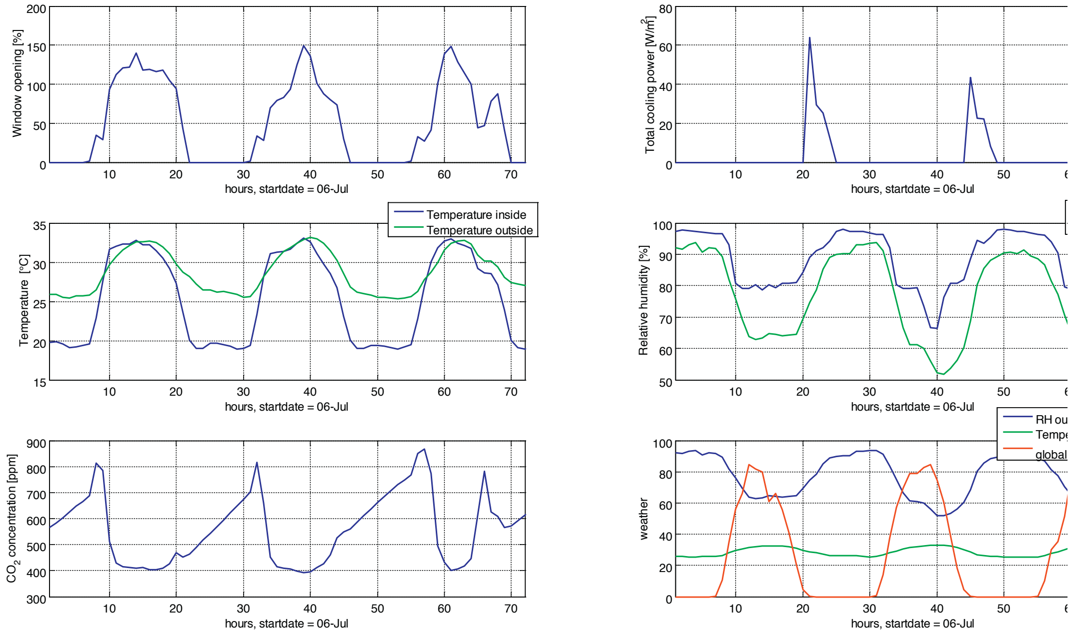


Figure 3.32. Operation of the semi-closed greenhouse in which the greenhouse is cooled during the night; data for three days in July (12-14th of July 2009).

4.12 Rainwater storage

In Taiwan the yearly rainfall is sufficient to be used as water supply to a greenhouse produced crop. Therefor rainwater collection can be recommended. Rainwater in general has a good quality to be used for crop irrigation, whereas other water sources often have a worse quality so additional treatments are necessary. Moreover, rainwater can be used in the fogging system without treatment (only filtering).

The rainwater storage should be designed such that is has a capacity large enough to supply the greenhouse with water during the whole year. The Figure below shows the cumulative precipitation pattern for Tainan in two years (2009 and 2010). Most of the rain falls in summer, winter is much dryer. During typhoons the precipitation is extremely high (*e.g.* the typhoon of august 2009 clearly shows in the Figure below). Rainwater collection systems should be made such that at least a part of the precipitation that falls during typhoons can be collected and stored.

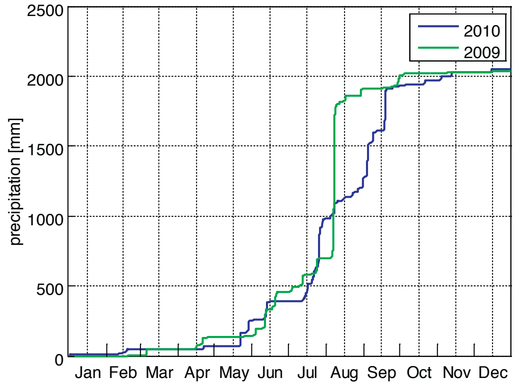


Figure 3.33. Precipitation in Tainan in 2009 and 2010.

Figure 3.34. shows the results of a two year simulation of a greenhouse with a water storage of 800 liters per m^2 greenhouse surface. This volume is enough to supply the greenhouse with rainwater both for irrigation as well as the fogging system.

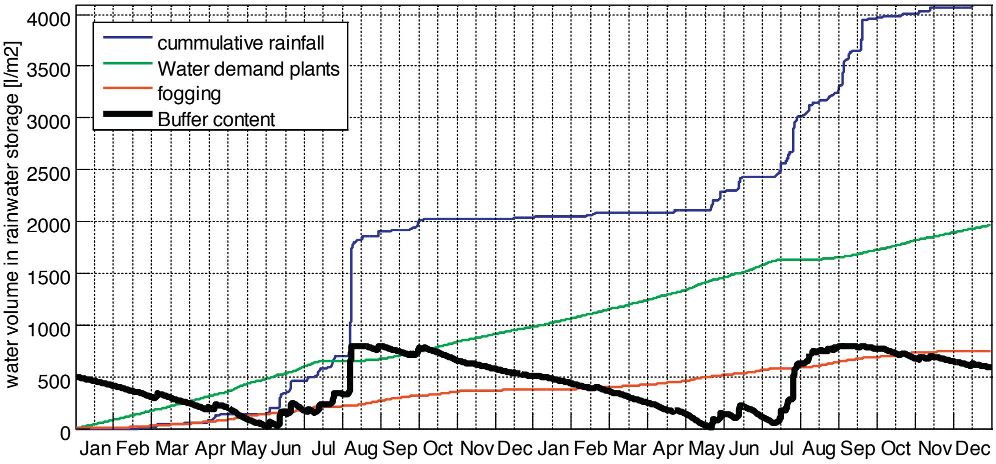


Figure 3.34. volume of water in the rain water storage over two years, given a start volume of 500 l/m2 and the yearly precipitation patterns of 2009 and 2010 in Tainan. The capacity of the storage is set to 800 l/m2 greenhouse ground surface.

Conclusion rain water storage

A rain water storage of 800l/m^2 is sufficient to supply water to the greenhouse during the whole year. Care must be taken in the start-up period of a newly build greenhouse, to avoid water shortage.

4.13 Economics of three greenhouse types compared

The previous chapter shows the effect of selecting different levels of technology for the greenhouse. The results from these simulations are used to select a 'technology package' for the new greenhouse design. In this chapter we study the economics of a few new greenhouse designs and compare them against the currently used greenhouses in Taiwan.

Three greenhouse types were identified that are technically feasible for the Taiwan weather. These types are:

1. Mid tech plastic greenhouse, without CO_2 dosing
2. Mid tech plastic greenhouse, with CO_2 dosing
3. High tech, closed greenhouse

For reference purposes, we have included simulations that describe a typical, currently used (low technology) greenhouse.

Table 3.12. Characteristics of the four greenhouse types that are compared in the economic analysis.

Main characteristics	Low tech	Mid tech	Mid tech, CO_2 dosing	Closed greenhouse
Ventilation capacity	low	high	None	
cooling	none	Fogging and natural ventilation	Mechanical cooling	
CO_2 dosing	no	no	Up to 400 ppm	Always 1000 ppm
cover	Plain plastic film	Non-thermic, UV blocking, diffuse plastic film	Diffuse glass	
heating	no	yes	yes	

Plant production

The crop yield in the mid-tech greenhouse is approximately 3.5 times higher than in the currently used low-tech greenhouse type (8 vs 29 kg/m^2; Table 3.13.). The production in the mid-tech greenhouse with CO^2 dosing is even higher (33kg/m^2). The cost of pure CO_2 is quite high in Taiwan, which causes the variable cost to double compared to no CO_2 dosing. The closed greenhouse gives the best crop yield (~80 kg/m^2), and has the highest variable cost because the energy demand for cooling is high.

Please note that our greenhouse model is used to simulate the *potential* plant production for the different greenhouse types. These potential levels can only be reached if all circumstances are optimally managed. Thus, a state of the art cropping system, crop management and perfect use of the technology the greenhouse installation offers. In the economic calculations, we have assumed that tomatoes are grown year-round. This choice is made to compare the different option sin a uniform way. We are aware that in practice year-round tomato production is not possible in the currently used, low-tech, greenhouses. Research must show to what extend the growing season can be extended in the mid-tech greenhouse.

Investment and payback period

The more technology is installed in a greenhouse, the higher the investment cost. The closed greenhouse has a five times higher investment demand than the low-tech greenhouse. Interestingly though, the payback period for the closed greenhouse is the shortest. Because of the high yield, the investment is earned back in one year. The mid-tech greenhouse is economically the second best options with a theoretical payback period of one year. The low-tech greenhouse has the longest payback period, despite its low investment. This is caused by the low crop yield.

CO_2 dosing

At the given crop and CO_2 prices, CO_2 dosing does not increase, nor decrease the benefits. The additional cost and additional crop yield balance each other out. Because of this, and to keep the new greenhouse system as simple as possible, we advise not to use CO_2 dosing at this point in time. (moreover,

Table 3.13. Economics of three greenhouse types compared. This table is a summary of the economic model.

Economic results				
	Low tech	Mid tech	Mid tech, with CO_2 dosing	Closed greenhouse
production cherry tomato [kg/m^2/year]	8	29	33	80
price tomato [TND/kg]	120	120	120	120
Total value crop [TND/m^2/year] {1}	960	3480	3960	9600
Variable cost				
energy (& CO_2)	0	162	712	1467
labour	58	140	159	193
water & nutrients (& recirculation)	56	60	60	53
others (plants, chemicals, substrate, packaging etc.)	87	136	136	136
Total variable costs [TND/m^2/year] {2}	201	498	1068	1848
Investments				
greenhouse construction & covering	684	1140	1140	1140
other installation costs (heating, CO_2, screening, climate control etc.)	279	1005	1032	3633
Irrigation system and rain water storage	125	209	209	570
additional installation costs (transport, packaging area, maschinery etc.)	79	131	131	262
ground (interest)	600	600	600	600
Total investment cost (excl. ground) [TND/m^2]	1167	2485	2512	5605
Yearly total cost for production means (incl. depreciation and ground) {3}	223	450	459	813
net result ({1} - {2} - {3}) [TND/m^2]	536	2531	2433	6938
Simple payback time [year]	2.2	1.0	1.0	0.8

4.14 Sensitivity analysis

A sensitivity analysis on the most important parameters shows what happens if a parameter value changes. This gives insight in the robustness of the proposed solutions.
We have varied the value of four parameters; yield, energy cost (electricity and diesel), crop price and CO_2 price. All parameters are varied between 60% and 140% of the nominal value (Table 3.14.)

Table 3.14. Parameter values for the sensitivity analysis.

Parameter		Nominal value	Minimum value	Maximum value
Yield [kg]				
	Low-tech	8	4.8	11.2
	Mid-tech	29	17.4	40.6
	Mid-tech & CO_2	33	19.8	46.2
	High tech	80	48	112
Energy cost (diesel [TND/l])		29.5	17.7	41.3
Energy cost (electricity [TND/kWh])		3	1.8	4.2
Crop price [TND/kg]		120	72	168
CO_2 price [TND/kg]		16.5	27.5	38.5

Figure 3.35. shows the results of the sensitivity analysis for each greenhouse type. The effect of changing the energy cost on the payback period is very limited for all solutions. The same is true for labor cost (not shown in the figure). Both factors have a limited impact on the total cost, thus an increase in these factors does not influence the payback period much.

Crop yield and crop price do have a significant influence on the payback time. If the yield or price drops to 60% of the nominal value, the payback time of a mid-tech greenhouse without CO_2 dosing increases from one to two years. With CO_2 dosing, the payback time increases from one to three years (another reason not to use CO_2 dosing in Taiwanese conditions). In the low tech greenhouse, a decrease in yield or price has an even more dramatic effect; the payback time raises from 2 to almost 7 years.

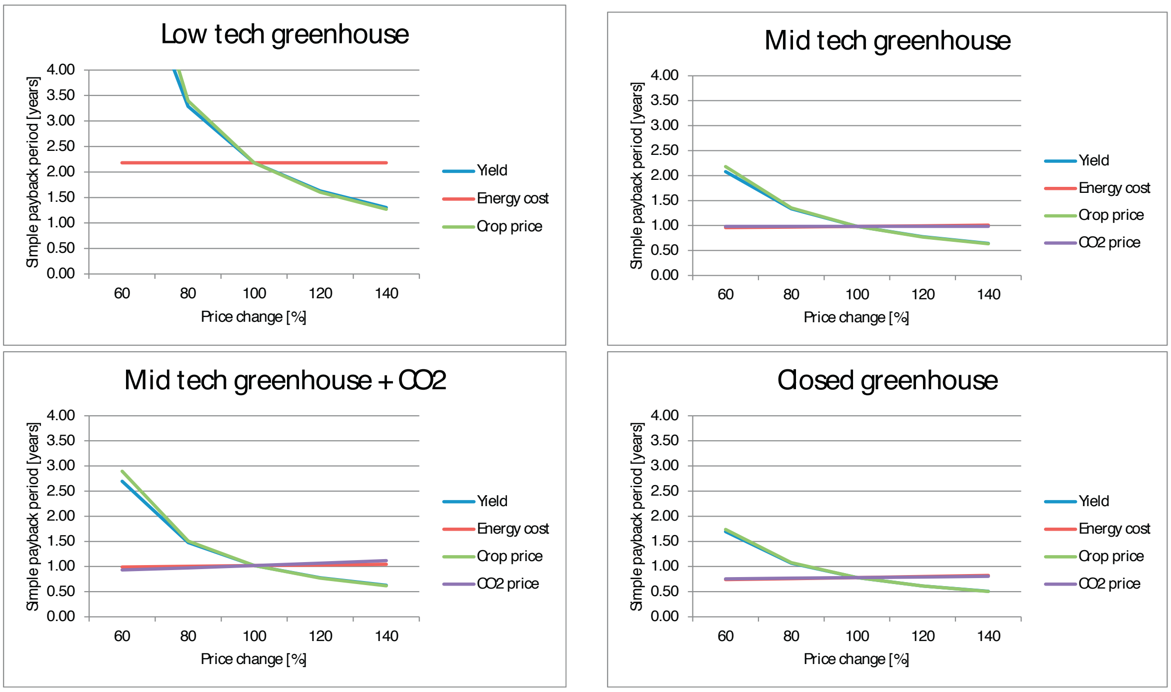


Figure 3.35. sensitivity analysis to study the effect of the most important parameters on the simple payback time.

Conclusions Economic analysis

The economic analysis shows that a mid-tech greenhouse (cooled by fogging and natural ventilation) is the best choice for Taiwanese circumstances. This greenhouse performs better than the currently used low-tech greenhouses. Even when the crop production is less than expected, the payback time is better than the low-tech type (for instance, if the crop production is only 60% of the possible yield, the payback time is around two years). Application of CO_2 enrichment is not advisable at this point in time, as it does not add to better economics.

The investment cost for a closed greenhouse are high, which will hamper the application in Taiwan. Although the payback period is very short (in optimal growing conditions), we do not advice to build this type of greenhouse.

current situation

Desired situation

No/limited window openings

Large windows for natural ventilation

Plants grown in soil, very dense crop

Substrate irrigation system combined with high wire cropping system for an open, healty crop

Nutrient mixing tank

Modern irrigation unit to give perfect mix of nutrients to the plants

Figure 3.36. Examples of improvements that new technologies will make to the current Taiwanese horticultural practice.

5 Conclusions

As said before, a dynamic greenhouse model was used to simulate the effects of different types of equipment in the greenhouse. In an iterative process with the economic mode, the following technologies were examined:

- **Ventilation and insect nets**

A greenhouse for sub-tropical climate in Taiwan should be equipped with a well designed ventilation system to avoid excessive temperatures inside the greenhouse. The power consumption of mechanical ventilation is high, so we advise to use *natural ventilation*. The vents should be equipped with insect net to keep whitefly out. To provide sufficient ventilation capacity, even with insect nets, the surface of the vents should be at least *0.5 m^2 per m^2 greenhouse ground surface*. In that case, the temperature inside the greenhouse is close the outside temperature. Natural ventilation is not able to decrease the temperature below the outside temperature level.

- **Greenhouse cover material**

We advise to use a plastic film that is diffuse and has a high transmission of light (>75%). It should also have a high transmission of infra red radiation to helps reduce extreme greenhouse temperatures.

- **Adiabatic cooling**

We advise to install a fogging system with a net capacity of around 300 g/m^2/h. This system will decrease the temperature inside the greenhouse and will contribute to a less stressed crop. We do not advise a pad and fan system, because of the higher energy cost and inhomogeneous temperature distribution inside the greenhouse.

- **CO_2 dosing**

Unless CO_2 is free/cheaply available, it is not economically viable to supply CO_2 to a ventilated greenhouse in Taiwanese weather conditions. If, in future projects, a connection can be made to industrial (waste) CO_2, it is worth investigating the possibilities again.

- **Shading Screen**

Shading screens are useful to decrease crop temperature during periods with high irradiation. Due to the lower light transmission potential crop production is lower than without the application of a screen. Moreover, screens limit the air exchange (ventilation capacity) such that the greenhouse temperature will not be substantially lower than without screens in the case of fogging. This is because cooling a greenhouse with fogging only works well at high ventilation rates. We advise to install an external screen with 30% shading and 70% open. This type of screen does not limit the ventilation too much and decreases the risk of crop damage.

- **Heating system**

A heating system is recommended to avoid cold hours that have negative impact on the crop growth. Without heating system in the greenhouse, plants will survive. However, crop productions is higher with a heating system. The capacity of the heating system depends on the type of system that is chosen and the required safety margin on the capacity. Without a heat buffer, a boiler with a capacity of 100W/m^2 is needed to keep the greenhouse warmer than 12 °C during most of the times. With a buffer, the boiler capacity may be substantially reduced.

- **Artificial light**

The potential additional crop yield with the use of artificial lighting is fairly limited; at maximum 5% yield increase (approximately 3 kg/m^2/year). As the investment cost are rather high (20 to 65€/m^2; 800 - 2500TND), the payback period will be long. For these reasons we advise not to use artificial lighting in Taiwan vegetable production.

- **Solar collector**

The greenhouse may be heated either with fossil fuels or by solar energy (or a combination of both).Heating the greenhouse by means of solar energy is sustainable and has low running cost. Purely economically, heating the greenhouse with solar heat is not the best option. However, fuel prices raise and solar collectors become cheaper every year, so in the near future the economics might look differently. If the choice is made to use solar energy to heat the greenhouse, we advise to install a solar collector of 0.7 m^2 collector/m^2 greenhouse ground surface. In this case, the buffer size should be in the order of 200 m^3/ ha greenhouse ground surface.

- **Closed greenhouse**

A closed greenhouse provides optimal growing conditions for the crop, resulting in very high crop yields. Unfortunately, investment costs of these greenhouses are high (expensive greenhouse and cooling equipment is needed). Also the skills of the grower to fully exploit the benefits of the technology must be very well developed. For an average Taiwanese vegetable grower, the transition from the currently used greenhouses to a closed greenhouse is (probably too) large. The concept of closed greenhouses is more suitable as a demonstration and research project in the near future than to be used for commercial vegetable production.

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