The perfectly smart greenhouse cover: a simulation study

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Confidential
Report WPR-776

Referaat

De huidige studie onderzoekt de mogelijkheden van slimme kasbedekkingsmaterialen met schakelbare optische eigenschappen. In de studie zijn kas-gewas simulatiemodellen gebruikt om het potentiële effect op het microklimaat, het gebruik van hulpbronnen en de groei en ontwikkeling van gewassen te onderzoeken. Drie hoofdgroepen van eigenschappen werden geïdentificeerd om ruwe simulatiestudies uit te voeren: a. filters die zowel PAR- als NIR-straling reflecteren, b. filters die selectief alleen het NIR-gedeelte reflecteren en c. filters die reflecteren in de FIR. Verschillende klimaatregio's en type kassen werden geanalyseerd om rekening te houden met een grote variabiliteit van mogelijke scenario's, waarbij ook rekening werd gehouden met andere gelijktijdige technologische verbeteringen of bestaande concurrerende technieken. De resultaten geven aan dat er een belangrijke potentiële verbetering is in het microklimaat en de opbrengst die samenhangt met het gebruik van schakelbare filters, met name in de "mediterrane/subtropische" klimaatzones, zelfs als de optische eigenschappen niet volledig optimaal zijn. Daarnaast laten we zien dat er behoefte is aan verbetering van de optische eigenschappen van kasdek materialen toegepast in de tropen, zonder behoefte dat ze schakelbaar zijn. Verder onderzoek is nodig om de technische en economische haalbaarheid van deze theoretische filters in meer scenario's te analyseren, ook door nieuwe gewassen in de analyse te betrekken en een optimalisatiestudie van de set-points en schaduwfactoren.

Abstract

The present study explores the opportunities of smart greenhouse covering materials with switchable optical properties. Greenhouse-crop simulation models have been used in the study to explore the potential effect on microclimate, use of resources and crop growth and development. Three main groups of properties were identified to perform first simulation studies: a. filters reflecting both PAR and NIR radiation, b. filters reflecting selectively only the NIR part and c. filters reflecting in the FIR. Different climate regions and greenhouse types were analysed to account for a large variability of possible scenarios, also accounting for other concurrent technological improvements or existing competing techniques. Results indicate that there is an important potential improvement in microclimate and yield associated to the use of switchable filters, particularly in the "Mediterranean/Sub tropical" climate zones, even if optical properties are not completely optimum. In addition, we show that there is a need to improve the radiative properties of cover materials applied in the tropics, without a need of making them switchable. Further research is needed to analyse the technical and economic feasibility of these theoretical filters in more scenario's; also introducing new crops in the analysis as well as an optimization study of the activation set points and shading factors.

Reportinfo

Confidential Report WPR-776
Projectnumber: 3742233900
DOI number: 10.18174/451812

Disclaimer

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Executive Summary

Background

Greenhouses are solar collectors, where a trade-off is made between the loss of sunlight to drive photosynthesis and the benefit of harnessing it to warm up the crop environment. Other benefits may also be there, such as protection against rain or wind and/or deterrence of birds and pests. The temperature within the confined environment of a greenhouse results from the balance of all energy fluxes entering and leaving it. As most fluxes (by far) are through the greenhouse cover, its properties are essential in determining inside climate and the amount of external resources (such as heating) required to maintain it within the boundaries required for crop production.

So, the overall transmittance, τ_{sun}, of the cover for solar radiation determines the amount of energy entering the greenhouse, whereas the ratio of transmittance in the photosynthetic active range (τ_{PAR}) to the transmittance in the near infrared (τ_{NIR}) determines how much of this energy is also useful for photosynthesis. On the other hand, the transmissivity of the cover for thermal/far infrared radiation (τ_{FIR}); its porosity (the openings, that is the ventilation capacity); and its thermal conductance (insulation) all affect the energy fluxes leaving the greenhouse. There is not an "ideal" greenhouse cover: properties that are useful in Holland may not be it in Mexico. The one property of which one would confidently state that is useful everywhere is τ_{PAR}, although the energy that goes with it may have drawbacks. As the amount of sunlight changes in time and among places, the properties of the greenhouse cover needed to fruitfully exploit sunlight may be variable both in time and space. The table below gives an overview of the problems faced by greenhouse growers in the main climatic regions of the world, what are the mitigating actions usually undertaken and what are the consequences. We also list which properties would be useful in the cover, and the techniques presently applied. Although three major climate zones are sufficient for this purpose, there is obviously a gradient in "severity" within any climate zone.

	Sub-arctic Temperate	Mediterranean Sub-tropic		Tropic Equatorial
Challenging season	*Winter*	*Winter*	*Summer*	*All year*
Limiting factor	Low temperature Low light	Marginal light & temperature	High temperature	High temperature
Corrective measures applied	Heating Artificial light		Whitewash	Elevation Evaporative cooling Permanent shading
Consequence	Poor/no winter production High energy requirement	Poor production	No production	Water use Poor production
Useful mitigating property of the cover	High FIR reflection, ρ_{FIR} Insulation High PAR transmission τ_{PAR}		High FIR transmission, τ_{FIR} Reduced sunlight transmission: τ_{NIR} τ_{sun}	
Competing existing technologies	[Multiple] movable screens	Thermic foil Double skin	Good ventilation Whitewash	Permanent [external] shading net

Regarding the properties of the cover, the present technology accounts somehow for the local requirement, although none of the materials presently applied is the "ideal" one for the place. On the other hand, there is very little that accounts for the required variation of properties in time: whitewash or shading nets are applied for half of the year and are there also when not needed (morning, afternoon, cloudy days,…). Movable screens have drawbacks as well: price; interference with ventilation, fixed properties, etc.

Therefore, the development of new “smart” covering materials that would allow for the instantaneous modification of the optical properties of the cover, could potentially have a large market worldwide. Some of these filters already exist in the market, such as the electrochromic glass, but they have not been optimized for their use as greenhouse covers. So, companies operating in this sector have a need to identify which properties are useful in various conditions and to quantify the advantage of [some of] them being switchable. This report quantifies the benefit (in terms of production and reduced resource requirement) of improving the properties of the cover and the added value of making some of them switchable, for the greenhouses typical of various climatic zones of the world.

Given the complexity of the greenhouse-crop system, and the many interactions among variables, this has been done by running scenario’s through a complete greenhouse climate-crop model, developed and owned by the Unit Greenhouse Horticulture of Wageningen University & Research. For the sake of simplicity we have limited this study to the spectral properties (that is, τ_{sun}; τ_{PAR}; τ_{NIR} and τ_{FIR}). In particular, we have assumed that a reduced transmission was achieved by a symmetric increase in reflection in the same waveband, in order to avoid interference with the increase in cover temperature (and thermal radiation) that would result from absorption. In addition, only when the ventilation capacity of the typical greenhouse (in the Mediterranean region) was deemed to be an important factor limiting productivity, we have also looked for any synergy between the spectral properties and the porosity of the cover.

Summary of the scenario’s and their results

For each region we have simulated only the properties that were a priori deemed relevant, assuming that the properties of the cover material could thus be modified, without affecting other properties such as heat conductance or ventilation capacity. In most cases the crop has been tomato, and the performance of the filter has been evaluated in terms of kg tomato per square meter greenhouse per year. In the summary tables below, we describe what is considered each time as the reference scenario, which filter properties have been simulated and at which temperature of the inside air the switchable filter was activated. The leftmost column gives the corresponding yield in combination with other technical improvements, such as improved ventilation capacity or evaporative cooling. In the latter case corresponding water use is given.

Mediterranean/Subtropic		Properties (%)	Activation	Yield (Kg m^{-2} y^{-1}) well ventilated	
Reference	whitewash	τ_{sun} 50	Seasonal	22.9	29.5
PAR+NIR	switchable	τ_{sun} 70	30°C	26.4	33
NIR	permanent	ρ_{NIR} 100		26.2	30.5
	switchable	ρ_{NIR} 100 τ_{PAR} 100 ρ_{NIR} 100 τ_{PAR} 90 ρ_{NIR} 50 τ_{PAR} 100	28°C	28 27.8 27.5	33.1 33 33.1
FIR	permanent	ρ_{FIR} 100			32
	switchable	ρ_{FIR} 100 ρ_{FIR} 50	16°C		31.2 30.4

Tropic/ Equatorial		Properties (%)	Activation	Yield (Kg m^{-2} y^{-1})		water use
					evapor. cooled	
Reference	Shade net	τ_{sun} 40	Permanent	23.4	56.5	1215
PAR+NIR	switchable	τ_{sun} 40	30°C	23.8		
NIR	permanent	ρ_{NIR} 100		20	61	765
	switchable	ρ_{NIR} 100 τ_{PAR} 100 ρ_{NIR} 100 τ_{PAR} 90 ρ_{NIR} 50 τ_{PAR} 100	28°C	17.5 19.4 12.5	61	811

Regarding the temperate region, it is known that light is limiting for most vegetable crops. Movable shading screens are applied on quite a few ornamental crops, so a sun radiation filter would need to be switchable to compete. A waveband selectivity $\rho_{NIR} > \rho_{PAR}$ would be a significant improvement on current technology. On the other hand, there is a need is to decrease energy use for heating, so that a high ρ_{FIR} would be ideal. If that was coupled to a high τ_{PAR} the filter could best be permanent.

Conclusions

Non-switchable filters

- A filter with high NIR reflection and very high FIR transmission would be ideal for the tropical equatorial region, even with some PAR interference.
- A filter with very high FIR reflection with no/very little PAR interference would be ideal from the sub-arctic to the sub-tropic regions of the world.

Switchable filters

- A non-selective switchable filter (PAR + NIR) would be very useful in the Mediterranean-Subtropical region and there would be even synergy with improved greenhouse design (ventilation capacity).
- Such a filter could also usefully be applied on ornamentals that are usually shaded in the temperate region.
- The value of the filter would be increased by spectral selectivity (more reflection in the NIR than in the PAR), in both above mentioned cases.
- A switchable filter with very high FIR reflection would be ideal from the sub-arctic to the sub-tropic regions of the world, even with significant PAR interference.
- The competing technology for such a filter (aluminised screen) is widespread in The Netherlands.

Context

The project Smart Materials for Greenhouses addresses the potential application in greenhouse covers of spectral-selective filters that may be switched whenever necessary. By modulating the amount of light and energy that the greenhouse environment exchanges with the ambient, such filters may both increase productivity and decrease the need for heating or cooling. This obviously means that the impact of the filter is related to the ambient conditions.

As developing such filters for greenhouse application requires quite some investment on the part of the companies willing to explore the market, the project foresees an analysis “a priori” of the potential, in order to pinpoint the most promising applications. This has been done by running scenario’s through a model of greenhouse climate and production, the model KASPRO (De Zwart, 1996; Vanthoor 2011) developed and owned by the Unit Greenhouse Horticulture of Wageningen University & Research.

As there are a huge number of possible combinations of spectral bands, switching rules and climate conditions, there was a need to limit the number of scenario simulations. In addition, not all combinations may reasonably be expected to yield promising results, nor are all possible filters within reach, therefore, during the first workshop of the project (Bleiswijk, May 10th, 2017) it was decided to concentrate on exploring the potential of:

a. Switchable filters, non-selective in the solar spectrum.
b. Switchable filters for Near InfraRed radiation (NIR).
c. Switchable filters for Thermal (or Far) InfraRed radiation (FIR).
d. Maximum thermal insulation through non switchable innovative, multi-layer covers.

The latest topic is somewhat different from the others, and it is dealt in a dedicated report.
The present document presents the results of the simulations that have been performed within Work Package 1 of the project “Smart Materials for Greenhouses” to estimate the effect on resource use (energy, water, electricity, etc.) and on potential yield (tomato) of the “smart” cover materials described above, for greenhouse regions which differ in their climate and standard greenhouse technological level. Where relevant, the scenarios have been calculated both with tomato and anthurium, two crops hugely different in their need for light.

1 Introduction

Greenhouses are solar collectors, where a trade-off is made between the loss of sunlight to drive photosynthesis and the benefit of harnessing it to warm up the crop environment. Other benefits may also be there, such as protection against rain or wind and/or deterrence of birds and pests.
The usefulness of covers, and the terms of the trade-off, have been appreciated since quite some time: the Romans, for instance, did grow exotic plants in shelters covered with the mica they used for windows, transparent enough "to let in the light of cloudy days" (Martialis 93AD, Epigrammata, VIII, 14). Things became easier when glass-making technology allowed for large enough plates of clear glass to be produced, for the south-facing, generous windows of the Renaissance orangeries. It is a fact, however, that only very special and exotic plants were deemed worth of such "care", up to the first half of the 20th century. By then, grapes were grown in stove-heated, glass-roofed buildings in Holland, the very first attempt at commercial protected horticulture. That grape was not the crop "of the future" is attested by the fact that of the 9500 Ha glasshouses operating now in The Netherlands, there is hardly one growing grapes. Later, the plastic "revolution" allowed for much cheaper crop shelters, so that protected horticulture in the world has grown to an estimated area of approximately 500 000 Ha commercial vegetable production in permanent structures (greenhouses), of which only some 40 000 are glass-covered (glasshouses) (Hickman, 2017; Rabobank, World Vegetables Map, 2018).

1.1 What is a greenhouse?

Whenever a physical shelter is used to modify somehow the aerial environment around a crop, we speak of protected cultivation, that is "cultivations carried out under any kind of permanent or temporary shelter covering the entire crop, with the aim of enhancing its productivity" (Capri *et al.* 2010: EFSA journal pages 13-18). A brief overview of the various types of protected cultivation is in Table 1.1.

Table 1.1
Various types of crop protection and their main use/s purpose.

Low tunnel	Passive increase of temperature, removed well before harvest
High, partial shelter	Protection against rain and birds, passive increase of temperature
Shade/net house	Used in high-radiation, arid environments. Prevention of leaf burn, higher humidity in the shoot environment
Walk-in tunnel	Passive increase of temperature
Low-tech greenhouse/multi-tunnel	Passive increase of temperature, very limited control of temperature through manual management of ventilation and seasonal whitewash
High-tech green/glasshouse	Computer-driven control of temperature through ventilation and heating; control of humidity through ventilation ,fogging and de-humidification; control of carbon dioxide concentration through artificial supply and ventilation; control of light level possible through shading and supplemental light.
Plant factory/vertical farm	Fully decoupled from external disturbances, full control of all production factors.

Greenhouse denotes a protection structure with a semi-transparent cover which is usually fully surrounding the crop, and has some means for control of the environment, such as manageable (even by hand) ventilation openings. We speak of high-tech greenhouse when there are more advanced, computer-controlled actuators for environmental control, such as (but not necessarily all): ventilation (either through computer-controlled openings or fans); heating; carbon dioxide supply; misting; cooling and de-humidification; movable screens for shading and energy saving; artificial light. Often the word glasshouse is used for high-tech greenhouses, as usually it is glasshouses that are equipped with high-tech actuators. However, as the amount of technology that is installed has nothing to do with the cover material, here we will consistently reserve the term glasshouse only for glass-covered greenhouses.
Plant factories (or vertical farms), are systems totally decoupled from the external climate, where production can be fully controlled. The downside of the coin is, obviously, that artificial light is used to make up for the disposal of sunlight. Graamans *et al.* 2018 have shown that this can be an economical proposition only when/where a significant marketing gain is possible or when the value of other [scarce] resources (ground, water) offsets the electricity cost required for lighting.

1.2 Different conditions, different greenhouses

It must be clear by now that there are several factors behind the variety of greenhouse systems we have seen. The most obvious is climate: somewhere a grower may need to shadow against leaf burn, somewhere else there is little that would grow without heating. To some extent the crop one wants to grow also plays a role: sweet pepper, for instance, has very different temperature requirements from blueberries. However, with the right amount of technology, one could grow everything everywhere, the real issue would be then to make a profit. So, the final factor to determine the “best” greenhouse system in a place is always the market value of what the greenhouse produces, which puts a limit to the production costs that may be allowed, which in turn puts a limit to the amount of technology and resources a grower can afford. It is a fact that the amount of technology typically installed in greenhouses increases with latitude, which is both the consequence of climate and of the affluence of the local market (with few exceptions).

So, in the equatorial/tropic region they have greenhouses in the (relatively) cool highlands (such as the 5500 Ha of flower greenhouses in the “Sávana” of Bogotà at 2800 m.a.s.l) (Soto Agudelo *et al.* 2011) and net/shadow houses elsewhere, except the monsoons tropical lowland, where impermeable covers are needed against the rain. Wherever elevation does not suffice to lower temperature enough, and external humidity allows for it, evaporative cooling is applied.
As the climate there is more friendly, the typical greenhouse in the sub-tropic/Mediterranean region is low technology, relying on solar radiation capture for passive increase of temperature in winter, and whitewash to limit it in spring/early autumn. This type of greenhouse has usually (too) small openings, controlled manually and typically no summer production.
In the temperate/sub-arctic region, production is in high-technology green/glasshouses, where supply of energy makes up for the shortcomings of climate. No production would be possible without heating and winter production is not possible without supply of additional light.
A summary is given in Figure 1.1 of the challenges faced (and typical remedies applied) by growers operating greenhouses in the three main climatic regions of the world, and a gallery of greenhouses around the world in Figure 1.2.

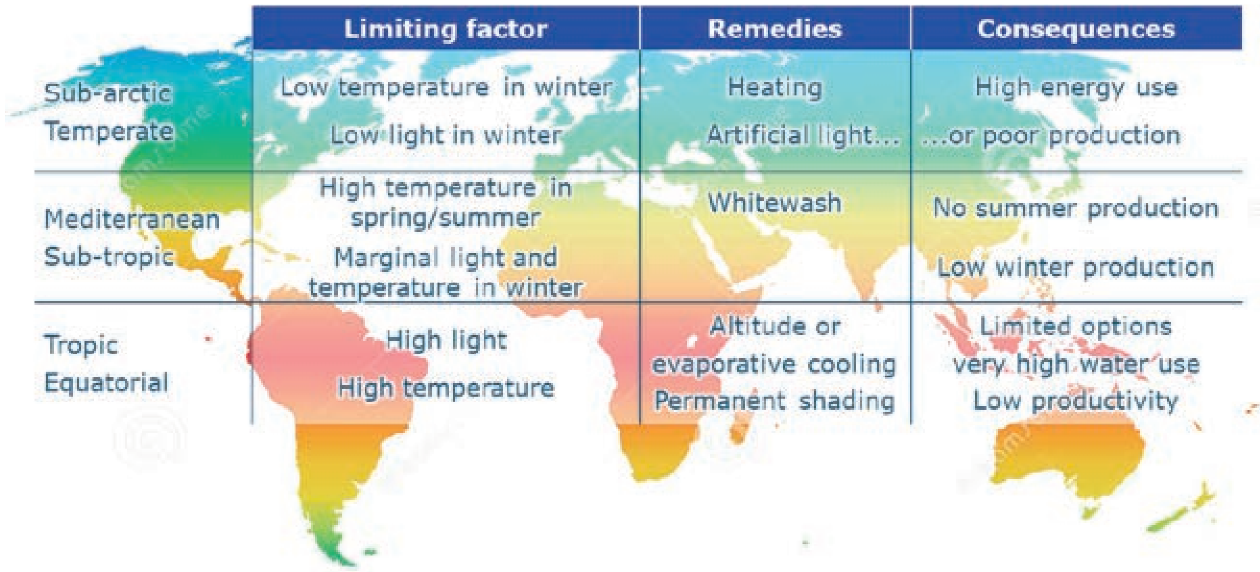

Figure 1.1 *Main factors limiting productivity of local greenhouses in the major climatic regions of the world; what can be done (remedies) to mitigate climate within a greenhouse there, and what are the consequences. The main limiting factors are common to a given climate zone, although there is obviously a gradient in "severity" within each zone.*

Figure 1.2 *Clockwise from top left: Melon in a typical "canarian" greenhouse in Morocco; lettuce in a multi-tunnel in Southern Italy; greenhouse for roses on the banks of Lake Victoria, Uganda, at 1200 m.a.s.l.; year-round tomatoes in a high-tech greenhouse in Holland; a rose crop in a Dutch greenhouse with artificial light and partially closed shadow screen; carnation under a shading net, in a greenhouse in Holambra, Brasil.*

However, there are some trends that may cause relatively rapid changes in the greenhouse outlook worldwide. In the "cold regions" the way greenhouses are managed will have to change, as heating through burning of fossil fuels will soon become unacceptable. On the other hand, increasing disposable income and awareness about food security in the "temperate-to-warm" regions will cause a shift to demand-driven production, which will need to be achieved through a better control of the production process than now is the case.

1.3 The greenhouse cover: the place of the trade-off. Can it be improved?

The temperature within the confined environment of a greenhouse results from the balance of all energy fluxes entering and leaving it. As most fluxes (by far) are through the greenhouse cover (Figure 1.3), its properties are essential in determining inside climate and the amount of external resources (such as heating) required to maintain it within the boundaries required for crop production.

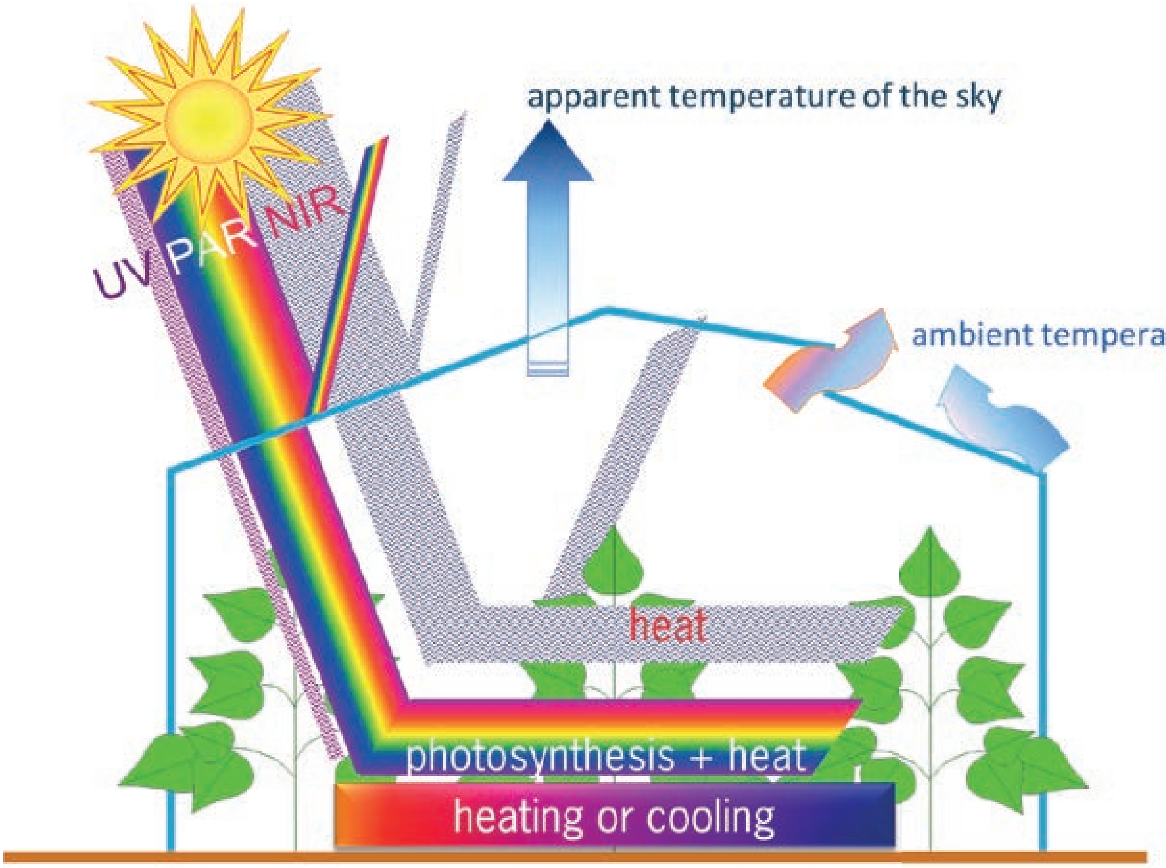

Figure 1.3 *Schematic representation of the energy fluxes entering and leaving a greenhouse. The main source of energy is solar radiation, roughly half of which is also driving photosynthesis (PAR). The other half is near infrared radiation (NIR), for which leaves have a high reflectivity. The energetic contribution of the ultraviolet fraction of sunlight can be neglected, although its presence may be relevant for some crop processes (e.g. colour in some crops) and it may affect pollinators, pests and their predators. Energy leaves the greenhouse as thermal radiation, as sensible and latent heat through air exchange with the exterior and as sensible heat conducted through the cover. Heating or cooling are required when all this results in a too low or high temperature. The energy exchange with the greenhouse soil (which is a minor flux) is neglected in the figure for clarity.*

So, the overall transmittance, τ_{sun}, of the cover for solar radiation determines the amount of energy entering the greenhouse, whereas the ratio of transmittance in the photosynthetic active range (τ_{PAR}) to the transmittance in the near infrared (τ_{NIR}) determines how much of this energy is also useful for photosynthesis. On the other hand, the transmissivity of the cover for thermal (far infrared) radiation (τ_{FIR}); its porosity (the openings, that is the ventilation capacity); and its thermal conductance (insulation) all affect the energy fluxes leaving the greenhouse.

One obvious observation is that there is not an "ideal" greenhouse cover: properties that are useful in Holland may not be it in Mexico. The one property of which one would confidently state that is useful everywhere is τ_{PAR}, although the tropical net houses suggest there may be limits to that as well. In addition, properties that are useful in winter may not be it in the summer, as all growers applying whitewash implicitly know, and what is good in a cold day may not be in a warm one.

Indeed, the most advanced glasshouse growers have three movable (computer controlled) screens: a very low-τ_{FIR} one, to be used in cold nights (it is not transparent); a highly transparent film to decrease thermal conductance during cold days; and a shadow screen to limit τ_{sun} whenever required. This may be the result of an "evolution", whereby glass (very high τ_{PAR} and relatively low τ_{FIR}) became the greenhouse cover of choice for the temperate zone, and increasing energy costs (and environmental awareness) required the installation of screens to make up for its high thermal conductance.
However, there has been an unprecedented evolution in the plastic technology and the chemical industry of additives, so that now "design" plastics, with preselected properties, are a reality (Fleischer & Dinar, 2014). Even (high-end) applications whereby some properties are variable on demand are becoming common(Casini, 2018), so that greenhouse covers with preselected properties, some of which could be switched on/off, are conceivable for the near future.

1.4 Scope of this report

Therefore, companies operating in this sector have a need to identify which properties are useful in various conditions and to quantify the advantage of [some of] them being switchable. For this to be possible, one has to first to evaluate the effect of a given, switchable property on climate inside the house, which in turns affect production. The effect on resource requirement (for instance: reduced heating/cooling need) has also to be evaluated for the picture to be complete. Given the complexity of the greenhouse-crop system, and the many interactions among variables, this is possible only running scenario's through a complete greenhouse climate-crop model, such as developed and owned by the Unit Greenhouse Horticulture of Wageningen University and Research.

The purpose of this report is to quantify the benefit (in terms of production and reduced resource requirement) of improving the properties of the cover and the added value of making some of them switchable, for the greenhouses typical of various climatic zones of the world. For the sake of simplicity we have limited this study to the spectral properties (that is, τ_{sun}; τ_{PAR}; τ_{NIR} and τ_{FIR}). Only when the ventilation capacity of the typical greenhouse (in the Mediterranean region) was deemed to be an important factor limiting productivity, we have also looked for any synergy between the spectral properties and the porosity of the cover.

For this, the greenhouse simulations model Kaspro (de Zwart, 1996) and a good tomato crop growth model (Vanthoor, 2011) have been coupled to analyse the potential of three types of filters, which include filters which reflect both PAR and NIR solar radiation when activated (non-selective filters), filters which reflect selectively only the NIR region and filters which reflect the thermal/far infrared (TIR/FIR) radiation. For each group of filters different representative climate regions have been analysed: a mild winter climate region, represented by Agadir (Morocco); a tropical lowland region, represented by Kuala Lumpur (Malaysia), a desert region represented by Riyadh (Saudi Arabia) and a cold region represented by de Bilt (The Netherlands). Different types of greenhouses and covers have been also analysed, such as traditional poorly ventilated greenhouses and more optimized structures such as the Venlo type greenhouse, with plastic film and/or glass. In addition to tomato (a high solar radiation requirement crop), one with much lower requirements, anthurium has also been studied for cold climate regions. Only the most promising combinations of filter, climate and greenhouse have been simulated.

2 Materials and methods

2.1 Greenhouse simulation model

For the greenhouse climate simulations a slightly modified KASPRO model version has been used. This model is built from modules describing the physics of mass and energy transport in the greenhouse enclosure, coupled with a large number of modules that simulate various greenhouse climate control equipment. The model can also mimic the different climate control strategies that a grower may use, making the simulations very realistic. More details of the model can be found in De Zwart (1996) and Luo *et al.* (2005a,b). For this specific study, the code was modified to include the possibility of instantaneously modifying the optical and/or thermal properties of the cover.

For the present study three ranges of the wavelength radiation with major effect on greenhouse microclimate and plant dry matter production have been considered: photosynthetically active radiation (PAR-400 to 700 nm), near infrared radiation (NIR-700 to 2500 nm) and thermal infrared radiation (TIR->5000 nm). The sum of both the PAR and NIR account for the large majority of the solar radiation. The TIR is that emitted by all objects in virtue of the their temperature.

We have considered three types of filters in the present study:

1. Non selective shortwave (solar) radiation filter: this filter affects equally both the PAR and NIR bands. The transmission coefficient in these two wavelengths(τ_{sun}) is decreased (-%) by the introduced reduction factor (β_{sun}). For this study we have assumed that the factor of non-transmitted radiation is fully reflected by the cover (in addition to the fraction normally reflected by the simulated covering material) ($\tau_{sun-tot}=\tau_{sun+}\ \beta_{sun}$) where $\tau_{sun-tot}$ is the total fraction of solar radiation reflected by the cover when the filter is activated. In addition, it is assumed that the filter does not change the properties of the cover in the TIR/FIR region, nor its heat transfer coefficient.
2. Selective solar radiation filter: this filter affects mainly the transmitted NIR radiation(t_{NIR}). PAR radiation transmission (τ_{PAR}) is considered to be both, or unaffected or slightly decreased, in different simulated scenarios. Just as previously, the NIR is assumed to be reflected by the introduced factor (β_{NIR}) in addition to the fraction of NIR normally reflected (τ_{NIR})by the simulated covering material ($\tau_{NIR-tot}=\tau_{NIR\ +}\ \beta_{NIR}$), where $\tau_{NIR-tot}$ is the total fraction of NIR reflected by the cover when the filter is activated. Also, it is assumed that this filter does not change the properties of the cover in the TIR/FIR region, nor its heat transfer coefficient.
3. Non selective thermal radiation filter: this filter acts reflecting thermal infrared radiation by the introduced factor(β_{TIR}), in addition to the fraction normally reflected (τ_{TIR}) by the simulated covering material ($\tau_{FIR-tot}=\tau_{FIR}+\ \beta_{FIR}$), where $\tau_{FIR-tot}$ is the total fraction of FIR reflected by the cover when the filter is activated. It is assumed that this filter does not change the solar radiation properties of the cover, nor its heat exchange coefficient.

These filters can be permanent, thus, they modify the optical properties of each simulated covering material during the whole simulated cycle, or can be switchable, that is, activated and deactivated instantaneously. For the present study we have chosen internal greenhouse air temperature values as the parameter that triggers the switchable filters. With this decision, we are trying to mimic the behaviour of a grower, which could potentially choose this climate parameter to establish the trigger to modify the optical properties of its cover (e.g. by applying a voltage to the cover, such as in electrochromic glasses).

2.2 Tomato crop growth model

The estimation of the potential tomato dry matter production has been done by coupling the microclimate simulated by KASPRO (temperature, light, and CO_2-concentration) with the tomato yield model of Vanthoor *et al.* (2011),which is based on the photosynthesis model of Goudriaan and van Laar (1994). The advantage of this model in relation to others is that it also accounts for the effect supra and infra optimal temperatures on photosynthesis. This is achieved by simulating the ability of organs to store and release assimilates from the leaves to the growing organs, like the fruits. For that, the model uses some tomato growth inhibition functions which account for the instantaneous and 24 h average non-optimal temperatures. The optimal range (where no growth inhibition occurs) is wider for instantaneous temperature values than for 24 h mean temperature values. For the present study, we have used the values proposed by Vanthoor *et al.* (2011), which were based on an extensive literature search. Thus, the upper boundary for unhampered instantaneous growth was 28°C and for the 24 h mean, it was 22°C. Equally, the lower boundary for unhampered instantaneous growth was 14°C and for the 24 h mean, it was 18°C.

3 Non-selective filter

(decreasing transmission in the whole solar spectrum)

3.1 Introduction and methodology

A non-selective switchable filter, which reduces transmissivity equally for both PAR (Photosynthetically Active Radiation) and NIR, has been simulated. Such a filter limits the input of solar energy in the greenhouse, thus its temperature. As it limits input of PAR at the same time, for vegetable crops it could be possibly be beneficial only in places where too high temperatures within a greenhouse may limit productivity and quality even more than the loss of PAR would do. That is warm, sub-tropical/tropical regions, where usually a permanent whitewash or shading screens are applied (for the same purpose) for several months a year.

However, for crops like anthurium, with much lower light requirements, solar radiation in the greenhouse is many days through the year simply too high to obtain a successful crop and therefore, even in northern latitudes such as The Netherlands, growers use internal mobile shading screens to protect the crop from supra-optimal radiation levels.

As a matter of fact, before performing the simulations with the optical switchable filters, simulations with increasing levels of shadingby whitewash in Agadir have been done for these two locations, and an analysis has been performed to analyze the effect of decreasing PAR levels on tomato productivity predicted by the model. However, we know in practice that the model underestimates the negative effect that combined levels of high radiation and high temperatures has on tomato crop due to the incidence of physiological problems (such as BER or cracking), often caused by non-optimum management of the growers. Therefore, the values predicted by the model have been lowered, using the good number of literature studies based on experimental trials performed in regions with a mild winter climate, as the basis to obtain the correcting factors to express yield in marketable terms.

Therefore, scenarios for tomato have been calculated for the region of Agadir (Morocco, subtropical desert climate) and Kuala Lumpur (Indonesia, sub-tropical humid low-land), with local greenhouse structures and cover materials as reference, and for anthurium in The Netherlands. However, in order to quantify what could be gained by simply increasing the technology level (which may be cheaper than a "smart" cover), for Morocco we have calculated also a "reference" scenario with good greenhouses, similar in technology as the Dutch greenhouses, although with a plastic cover.

In the tomato simulations the filter is activated when greenhouse air temperature reaches a certain threshold value, whereas for the anthurium simulations the switchable filter is activated when external solar radiation reaches a certain threshold (Table 3.1). The fraction of radiation that is not transmitted is assumed to be reflected. In addition, it is assumed that the filter does not change the properties of the cover in the TIR/FIR region, nor its heat transfer coefficient.

Crop parameters

- Tomato growing cycle:
  - Agadir (Morocco): planting date 15-08 and end of cycle 15-06
  - Kuala Lumpur (Malaysia): planting date 01-01 and end of cycle 15-12
- Anthurium:
  - De Bilt (The Netherlands): year round production

Table 3.1

Summary of scenarios simulated for the analysis of the non-selective solar radiation switchable filter.

	Regions	Year	Crops	Greenhouse type	Shading/filter activation set point	CO_2 enrich. simulation
Reference	Agadir (Marocco)	2010	Tomato	Canarian; Venlo(PE cover)	Whitewash	Only in Venlo scenario
Switchable filter 30% reduction					30°C	
Switchable filter 60% reduction					28°C/30°C	
Reference	Kuala Lumpur (Malaysia)	2010	Tomato	Venlo (PE cover)	Fixed external screen	No
Switchable filter 30% reduction					28°C	
Switchable filter 60% reduction						
Reference	De Bilt(The Netherlands)	SEL2000**	Anthurium	Venlo glass	Internal shading screen (aluminized)/ 300 W m^{-2}	Yes
Switchable filter 65% reduction					300 W/m^2	

* To decide on date of application of whitewash, a simulation has been made in which no shading is used, then weekly cyclic mean of greenhouse air temperature has been calculated to identify the moments when greenhouse temperature is above 30°C more than 5 hours per day. That moment is taken as the activation day of whitewash, which is removed when greenhouse temperature values above 30°C happens for less than 5 hours per day.

** SEL2000 is a typical meteorological year dataset, available for De Bilt (close to Amsterdam), The Netherlands (SELyear as defined by Breuer and van de Braak, 1989).

3.1.1 Greenhouse parameters and relevant set points.

Figure 3.1 *A "Canarian" greenhouse, typical of Agadir. It consists of pillars, supporting a double-layer iron net, which encloses the polyethylene cover. The space between two adjoining films is kept open for ventilation, fitted with insect nets (right).*

The reference scenario for Agadir is the "Canarian" greenhouse, of which there are there some 5000 Ha (Figure 3.1). The cover is almost flat, with a relatively small inclination, created by a difference in pillar height, to allow for discharge of rain.

Table 3.2
Summary of geometrical characteristics of the Canarian type greenhouse simulated.

Area:	10000	m²
Ridge orientation:	0 (North-South)	deg
Central path width:	3	m
Gutter height:	5	m
Roof slope:	6	deg
Span width:	10	m
Distance between pillars:	5	m
frSunAir*:	1.5%	
Leakage:	$5E^{-04}$	$m^3 m^{-2} s^{-1}$ per $m s^{-1}$ wind speed
Window length**:	2	m
Window height:***	0.27	m
fr_Window****:	2	%

* It is the percentage of incoming solar radiation intercepted by structural elements of the greenhouse.

** An insect screen with a porosity of 25%, causing a reduction of ventilation air exchange (≈ventilation area) of 60% (Perez-Parra *et al.* 2004) has been simulated.

*** Since Kaspro does not allow for the simulation of a simple opening in the roof without a "flap", we have applied a correction factor to the area of roof vents, obtained from the same study of Perez-Parra *et al.* (2004). In this study, for a "parral" type greenhouse (essentially very similar to a Canarian type greenhouse), roof rolling vents (equivalent to an opening on the roof, just as in the Canarian greenhouse) provided 72% and 39% less airflow per square meter of vent, than flap roof vents with windward and leeward wind, respectively. Then, we can assume that on average, a rolling vent provides 55% less airflow than a flap vent. Thus, in Kaspro, dimensions of the simulated flap vent have been reduced by 55%.

**** Fr_Window represents the ratio (%) of total ventilator area to greenhouse floor area.

As Canarian type greenhouses lack any kind of automation or control of the opening and closing of the vents, the scenarios have been calculated with the roof vents (as described in Table 3.2) permanently open.

For all the simulations, a polyethylene plastic film cover has been simulated with the following properties (Table 3.3):

Table 3.3
Summary of some relevant optical properties of the polyethylene film cover (hemispherical transmission is the fraction of incident light uniformly distributed that is transmitted below the cover.

Hemispherical transmission	0.7
Shortwave absorption	0.08
TIR/FIR transmission	0.35
Emissivity	0.6

These properties have been used to calculate the transmission for beam (direct) radiation, in function of solar elevation and azimuth (Table 3.4).

Table 3.4

Summary of direct solar radiation transmission values of the cover (including greenhouse structural elements) for different sun elevation and azimuths calculated using the equations proposed by Bot (1983).

directe	transmissie															
azimut	\elevation															
0.000	0.000	2.000	4.000	6.000	8.000	10.000	15.000	20.000	25.000	30.000	40.000	50.000	60.000	70.000	80.000	90.000
0.000	0.000	0.000	0.055	0.123	0.189	0.253	0.389	0.492	0.565	0.617	0.679	0.711	0.729	0.740	0.749	0.756
5.000	0.000	0.019	0.076	0.138	0.197	0.256	0.388	0.488	0.562	0.613	0.676	0.709	0.728	0.740	0.748	0.756
10.000	0.000	0.025	0.119	0.184	0.247	0.294	0.395	0.487	0.558	0.611	0.674	0.708	0.726	0.739	0.748	0.756
15.000	0.000	0.029	0.133	0.228	0.284	0.340	0.428	0.493	0.557	0.607	0.671	0.706	0.725	0.739	0.748	0.756
20.000	0.000	0.028	0.144	0.243	0.325	0.370	0.468	0.515	0.560	0.605	0.668	0.704	0.724	0.738	0.748	0.756
25.000	0.000	0.034	0.149	0.256	0.335	0.400	0.492	0.548	0.572	0.606	0.666	0.702	0.724	0.737	0.748	0.756
30.000	0.000	0.029	0.162	0.265	0.348	0.411	0.508	0.569	0.596	0.612	0.665	0.700	0.723	0.737	0.748	0.756
35.000	0.000	0.036	0.155	0.270	0.357	0.421	0.524	0.580	0.616	0.627	0.664	0.700	0.722	0.736	0.748	0.756
40.000	0.000	0.026	0.158	0.274	0.364	0.430	0.544	0.589	0.627	0.644	0.664	0.699	0.721	0.736	0.748	0.756
45.000	0.000	0.036	0.161	0.295	0.370	0.437	0.548	0.596	0.633	0.656	0.666	0.698	0.721	0.736	0.748	0.756
50.000	0.000	0.036	0.171	0.300	0.375	0.444	0.548	0.604	0.638	0.664	0.670	0.698	0.721	0.736	0.748	0.756
55.000	0.000	0.015	0.189	0.296	0.380	0.450	0.556	0.624	0.644	0.668	0.677	0.699	0.721	0.737	0.748	0.756
60.000	0.000	0.034	0.196	0.293	0.386	0.456	0.562	0.631	0.649	0.672	0.687	0.699	0.722	0.737	0.748	0.756
65.000	0.000	0.032	0.184	0.300	0.393	0.462	0.568	0.638	0.654	0.676	0.696	0.700	0.722	0.737	0.748	0.756
70.000	0.000	0.029	0.179	0.308	0.427	0.470	0.575	0.644	0.660	0.681	0.702	0.701	0.723	0.738	0.748	0.756
75.000	0.000	0.028	0.186	0.318	0.437	0.479	0.582	0.641	0.665	0.685	0.708	0.703	0.724	0.739	0.748	0.756
80.000	0.000	0.005	0.194	0.329	0.449	0.489	0.590	0.643	0.670	0.690	0.712	0.706	0.725	0.740	0.749	0.756
85.000	0.000	0.000	0.196	0.335	0.457	0.497	0.599	0.650	0.681	0.694	0.716	0.708	0.727	0.740	0.749	0.756
90.000	0.000	0.000	0.199	0.339	0.460	0.500	0.604	0.656	0.689	0.700	0.720	0.710	0.729	0.741	0.750	0.756

When the filter is activated, the transmission values of Tables 3 and 4 have been decreased by the factor given in Table 3.1 for each scenario.

A cover with exactly the same optical properties has been used for the reference simulations with a high-tech Venlo greenhouse, both in Agadir, Morocco and Kuala Lumpur, Malaysia. The greenhouse type is shown in Figure 3.2. The greenhouse has continuous roof vents, fitted with 25% porosity insect nets, molded in “concertina” shape to limit loss of ventilation capacity. The geometrical properties are given in Table 3.5.

Figure 3.2 *The Venlo greenhouse simulated.*

In the simulations with a Venlo greenhouse, opening and closing of the vents has been considered automated, and set points shown for both a tomato crop are shown in Table 3.6.

As shading reduces the ventilation requirement, it may increase the effect of CO_2 enrichment. Thus, for the Venlo scenario in Agadir (Morocco) simulations with pure CO_2 enrichment have been done, with the aim of maintaining a CO_2 concentration set point of 800 ppm with a dosing capacity of 100 kg/ha hour. For the Canarian type greenhouse and for the tropical region, simulating CO_2 enrichment would not make sense given the fact that the vents are almost always open.

Table 3.5
Summary of the geometrical characteristics of the Venlo greenhouse simulated.

Area:	10000	m²
Ridge orientation:	0 (North-South)	Deg
Central path width:	3	m
Gutter height:	6	M
Roof slope:	22	Deg
Span width:	4.8	M
Distance between pillars:	5	M
frSunAir:	4%	
Leakage:	8e-05	$m^3 m^{-2} s^{-1}$ per m s^{-1} wind speed
Window length*:	Continuous	M
Windowheight:	1.1	M
fr_Window:	23	%

* A concertina-type insect screen with a porosity of 25%, causing a reduction of ventilation air exchange (ventilation area) of 52% (Perez-Parra *et al.* 2004) has been simulated.

Table 3.6
Summary of relevant ventilation set points.

	Date	Setpoint
Ventilation set points (°C):	15-12	23
"	26-12	25 21 21.5
"	16-1	27 27 20 23
"	16-2	25 25 18 21
"	20-4	23.5 23.5 17 19.5
"	26-6	21.8 21.8 17.5
"	10-9	22 16 19 19
"	13-11	22
Hours of set point activation:	15-12	0
"	26-12	13 19 op-8*
"	16-1	14 18 21 1
"	16-2	13 19 21 4
"	20-4	13 20 22 5
"	26-6	14 on-3* on+1 op-2
"	10-9	15 on 4 11
"	13-11	0
Relative humidity (%):		90
CO2(ppm):		800
CO_2 dosing rate (kg/ha h):		120

* Op refers to sunrise time and on to sunset time.

For the simulations of anthurium in a cold climate (de Bilt, The Netherland) a Venlo glasshouse has been used. Table 3.7 summarizes the most important parameters of the Venlo glasshouse.

Table 3.7
Summary of geometrical characteristics of Venlo glasshouse simulated for Anthurium in The Netherlands

Area:	10000	m^2
Ridge orientation:	0 (North-South)	deg
Central path width:	3	m
Gutter height:	6	m
Roof slope:	22	deg
Span width:	4.8	m
Distance between pillars:	5	m
frSunAir:	4%	
Leakage:	8.00E-05	$m^3 m^{-2} s^{-1}$ per m s^{-1} wind speed
Window length:	2.25	m
Window height:	1	m
fr_Window:	11	%

For the reference simulations of a Venlo glasshouse, a transparent standard glass cover has been simulated with the following properties (Tables 8 and 9):

Table 3.8
Summary of some relevant optical properties of the glass cover.

Hemispherical transmission	0.755
TIR/FIR transmission	0
Emissivity	0.83

Table 3.9

Summary of direct solar radiation transmission values of the combination of the cover and the structure for different sun elevation and azimuths.

directe	ransmissie															
azimut	elevation															
0	0	2	4	6	8	10	15	20	25	30	40	50	60	70	80	90
0	0	0	0.06	0.136	0.212	0.284	0.437	0.553	0.635	0.694	0.763	0.799	0.819	0.832	0.842	0.85
5	0	0.02	0.082	0.153	0.22	0.288	0.438	0.551	0.634	0.692	0.76	0.797	0.818	0.831	0.841	0.85
10	0	0.026	0.131	0.204	0.275	0.327	0.445	0.551	0.632	0.69	0.76	0.798	0.817	0.831	0.841	0.85
15	0	0.03	0.149	0.241	0.318	0.381	0.477	0.556	0.63	0.687	0.759	0.796	0.818	0.83	0.841	0.85
20	0	0.032	0.162	0.273	0.351	0.415	0.525	0.577	0.632	0.685	0.756	0.796	0.817	0.829	0.84	0.85
25	0	0.033	0.169	0.289	0.381	0.44	0.553	0.614	0.643	0.685	0.754	0.794	0.816	0.832	0.84	0.85
30	0	0.041	0.172	0.3	0.394	0.476	0.573	0.641	0.67	0.69	0.752	0.793	0.817	0.831	0.84	0.85
35	0	0.033	0.192	0.307	0.405	0.477	0.588	0.655	0.694	0.704	0.751	0.792	0.816	0.831	0.84	0.85
40	0	0.045	0.182	0.313	0.414	0.488	0.601	0.666	0.709	0.724	0.751	0.791	0.816	0.831	0.84	0.85
45	0	0.03	0.186	0.317	0.421	0.497	0.629	0.675	0.716	0.74	0.752	0.79	0.816	0.831	0.84	0.85
50	0	0.026	0.19	0.322	0.428	0.505	0.639	0.683	0.723	0.75	0.756	0.79	0.816	0.833	0.843	0.85
55	0	0.048	0.194	0.356	0.435	0.513	0.63	0.691	0.729	0.756	0.763	0.791	0.816	0.833	0.844	0.85
60	0	0.017	0.213	0.368	0.443	0.521	0.638	0.699	0.735	0.761	0.773	0.791	0.817	0.833	0.844	0.85
65	0	0.011	0.242	0.379	0.451	0.529	0.646	0.721	0.741	0.766	0.783	0.793	0.817	0.834	0.844	0.85
70	0	0.005	0.254	0.362	0.461	0.539	0.655	0.732	0.748	0.771	0.791	0.794	0.818	0.835	0.845	0.85
75	0	0.044	0.267	0.37	0.471	0.549	0.664	0.741	0.754	0.777	0.798	0.797	0.82	0.836	0.845	0.85
80	0	0.055	0.282	0.383	0.484	0.561	0.673	0.749	0.761	0.782	0.804	0.799	0.821	0.837	0.846	0.85
85	0	0.054	0.287	0.39	0.492	0.571	0.684	0.758	0.768	0.788	0.809	0.802	0.823	0.838	0.846	0.85
90	0	0.055	0.291	0.393	0.495	0.574	0.688	0.766	0.775	0.794	0.814	0.805	0.825	0.839	0.847	0.85

For the simulations with a non-selective filter, the value of hemispherical transmission (Table 3.8) , and the transmission values on Table 3.9 have been decreased by a factor of 65%, being this new optical properties activated when outside global radiation reaches 300 W m^{-2}, Table 3.1.

For the reference anthurium crop simulation the following relevant climate set points and screens were used in the simulations (Table 3.10):

Table 3.10
Relevant climate set points used for the simulation of an anthurium crop.

Parameter	From	To	Setpoint
Heating temperature	1 Jan	1 Feb	19
	1 Feb	1 March	20
	1 Mar	1 Apr	19
	1 Apr	1 Aug	18
	1 Aug	1 Jan	19
Dead zone ventilation	1 Jan	1 Feb	8
	1 Feb	1 March	6
	1 Mar	1 Apr	3
	1 Apr	1 Aug	5
	1 Aug	1 Jan	6
Relative humidity set point			85
CO_2 setpoint			850 ppm
CO_2 dosing flux			50 kg ha^{-1} $hour^{-1}$
Energy saving screen			
Type			Semi-transparent
Used when radiation is below	1 Oct	1 Mar	40 W/m^2
Screen is not used when external temperature is above			12ºC
Shading screen			
Type			Aluminized(65%)/ Open (35%)
Screen is used when radiation is above			300 W/m^{-2}
When external temperature is above 10ºC screen is not used for energy saving			10ºC

3.2 Climate Data Analysis

3.2.1 Mild winter climate region: Agadir (Morocco)

For Agadir (Morocco), several complete yearly climate data sets were available. The first step was to choose the warmest year of the available sets. Table 3.11 shows the mean yearly temperature for the available complete weather data sets (years 2009, 2010, 2011,2012 and 2013). In it we can see, that year 2010 was on average the warmest of the series, and therefore, the more extreme year to explore the potential of a non-selective switchable filter for shortwave radiation, aimed at shading the greenhouse on critical moments of high temperature.

Table 3.11
Mean yearly temperatures of the available yearly weather datasets for Agadir (Morocco).

Year	Mean yearly temperature (°C)
2009	19.8
2010	20.1
2011	19.2
2012	19.3
2013	18.9

Figures 3.3, 3.4, 3.5 show the daily mean values of temperature(°C), relative humidity(%), and wind(m/s) for the chosen year, 2010, in Agadir and Figure 3.6 shows the daily sum of solar radiation (MJ/m²).

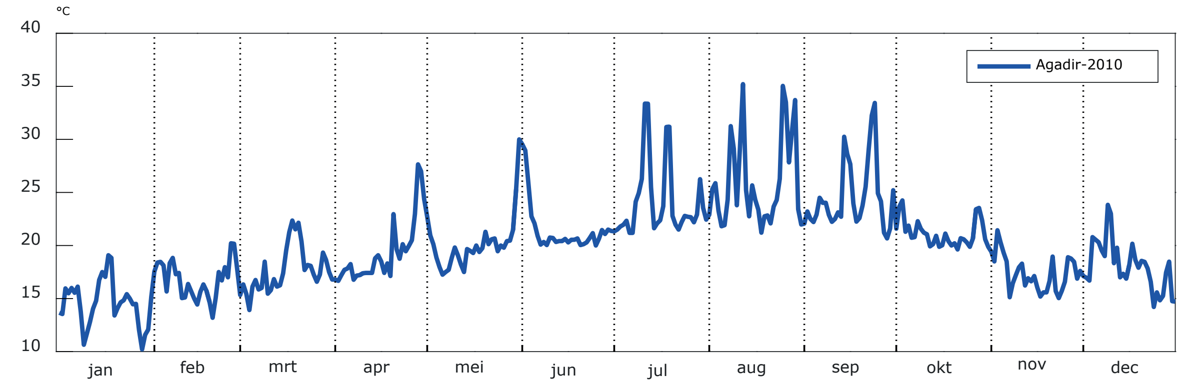

Figure 3.3 *Yearly evolution of daily average temperature(°C) in Agadir (2010).*

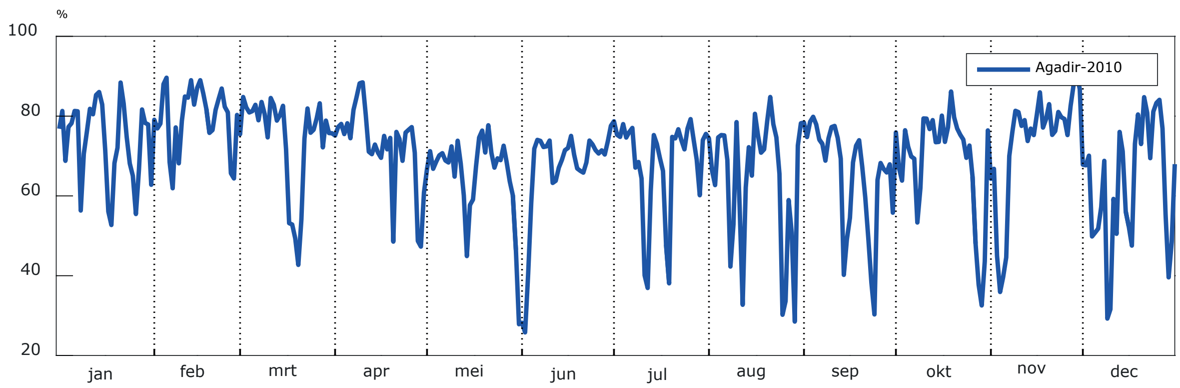

Figure 3.4 *Yearly evolution of daily relative humidity(%) in Agadir (2010).*

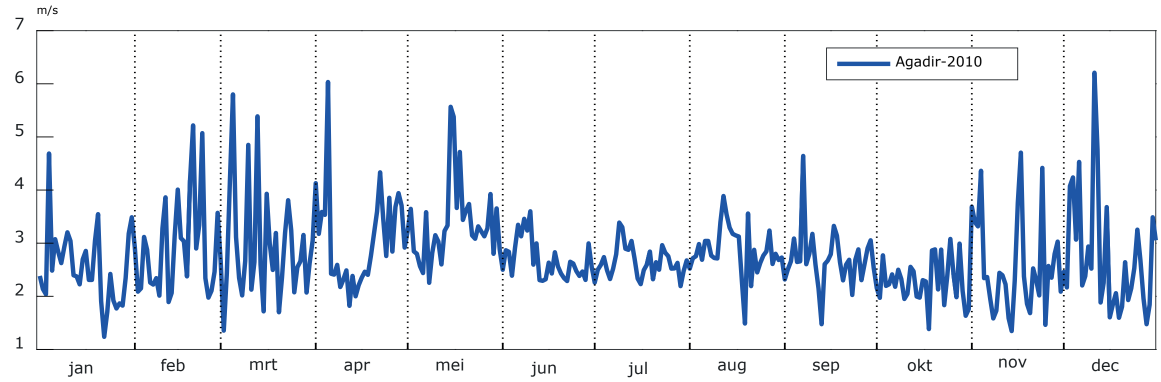

Figure 3.5 *Yearly evolution of daily average wind speed(m/s) in Agadir (2010).*

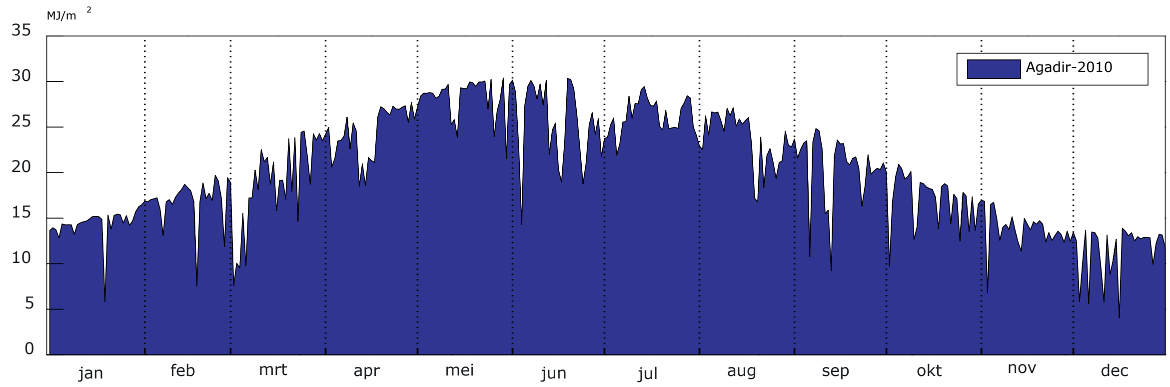

Figure 3.6 *Evolution of solar radiation daily sum (MJ/m^2) in Agadir (2010).*

3.2.2 Tropical lowland region: Kuala Lumpur (Malaysia)

Unlike tropical highlands, climate in the tropical lowlands is more extreme; the tropical lowland climate is characterized by prevailing high levels of irradiation, high air temperature and high air humidity (Von Zabeltitz, 1999). In this region, conventionally crops are grown in the open field year round with up to three successive growing seasons. On the first sight these conditions do not demand the application of greenhouses. However, harsh outdoor climate-related events (such as seasonally high wind speed and heavy rainfall in the wet season or water shortage in the dry season) together with high level of infestation of pests and diseases often damage field grown crops, strongly reducing crop production and crop quality. Protection of high value crops in a greenhouse may offer an alternative to cope with these problems.
As an example of tropical lowland region we have chosen Kuala Lumpur (Malaysia), due to easy accessibility to good quality airport climate data. Most complete climate year data set available for this location was 2010, which was chosen to perform the simulations. Mean yearly temperature on this year was 27.6°C .

Figures 3.7, 3.8 and 3.9 show the daily mean values of temperature(°C), relative humidity(%), and wind(m/s) for the chosen year in Kuala Lumpur (Malaysia) and Figure 3.10 shows the daily sum of solar radiation (MJ/m^2).

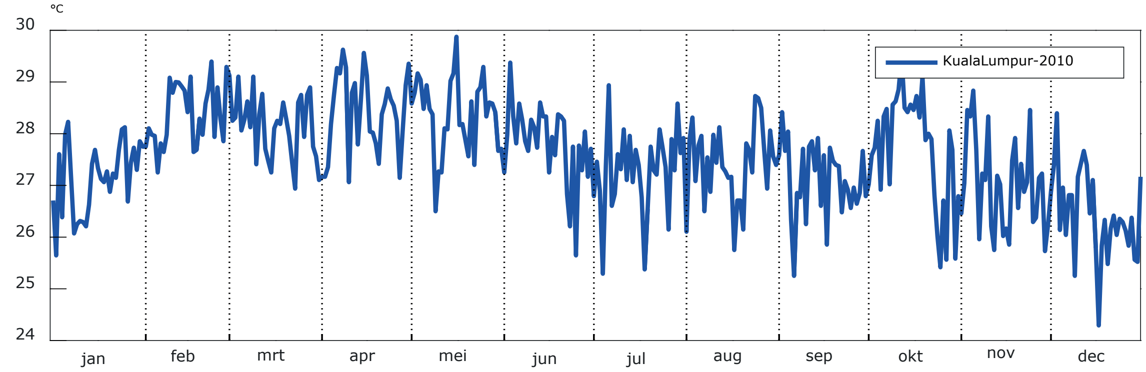

Figure 3.7 *Yearly evolution of daily average temperature(°C) in Kuala Lumpur (2010).*

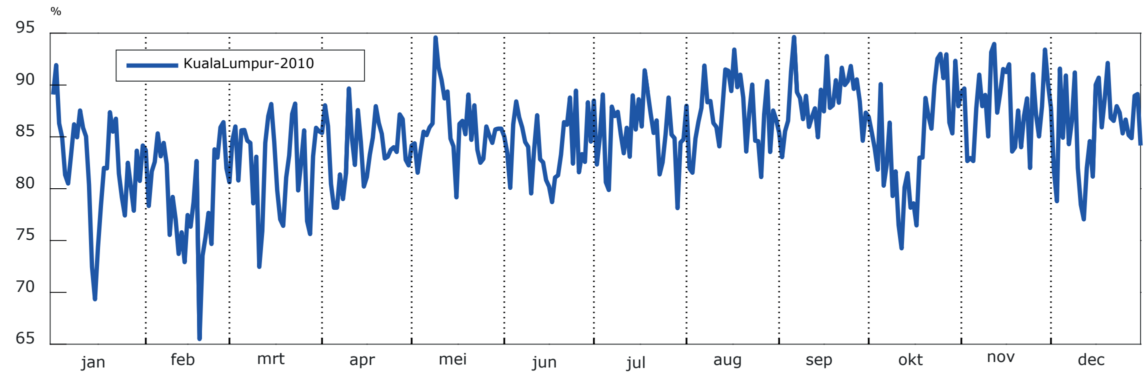

Figure 3.8 *Yearly evolution of daily relative humidity(%) in Kuala Lumpur (2010).*

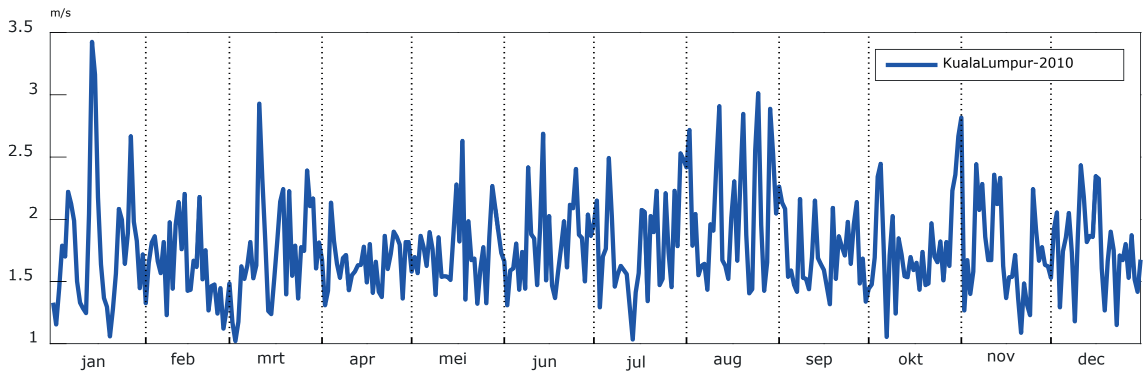

Figure 3.9 *Yearly evolution of daily average wind speed(m/s) in Kuala Lumpur (2010).*

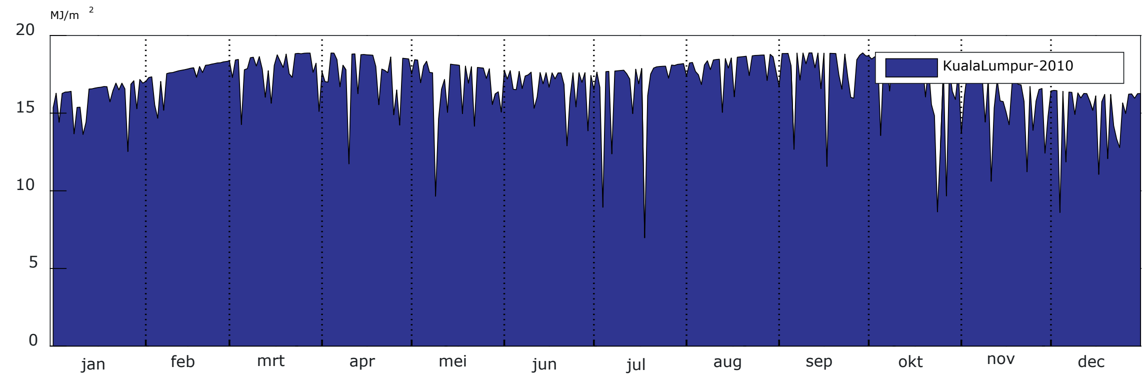

Figure 3.10 *Evolution of solar radiation daily sum (MJ/m²) in Kuala Lumpur (2010).*

3.2.3 Cold region: de Bilt (The Netherlands)

For The Netherlands, a typical meteorological year (SEL2000, Breuer and van de Braak, 1989) was chosen for the simulations, in order to account as accurately as possible with inter-year variability.
Figures 3.11, 3.12 and 3.13 show the daily mean values of temperature(°C), relative humidity(%), and wind(m/s) and Figure 3.14 shows the daily sum of solar radiation (MJ/m^2).

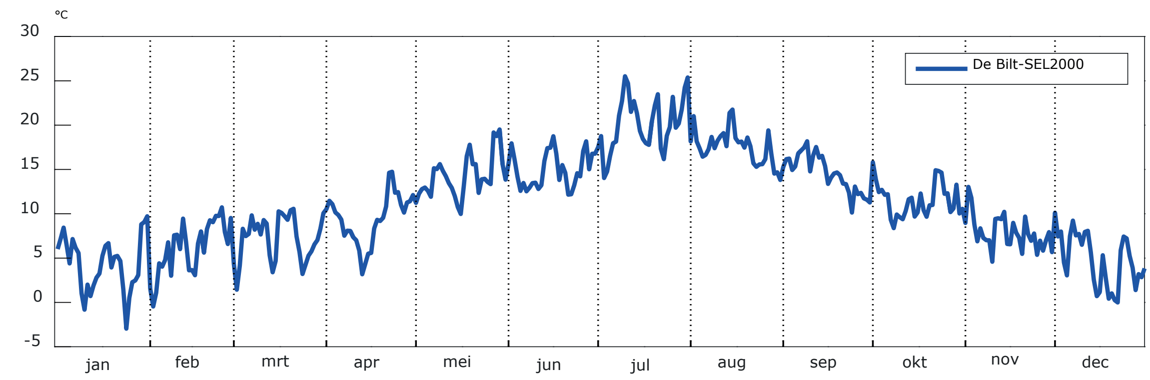

Figure 3.11 *Evolution of daily average temperature(°C) in the selected SEL-year in de Bilt (The Netherlands).*

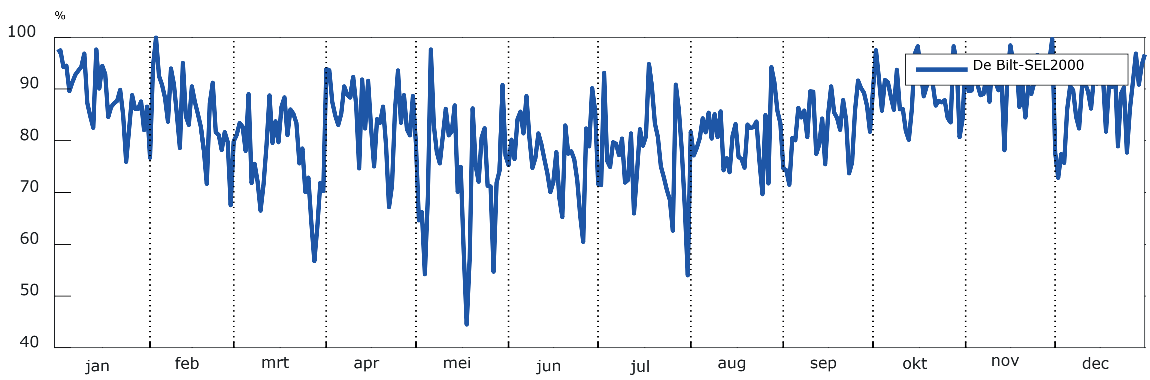

***Figure 3.12** Evolution of daily average relative humidity(%) in the selected SEL-year in de Bilt (The Netherlands).*

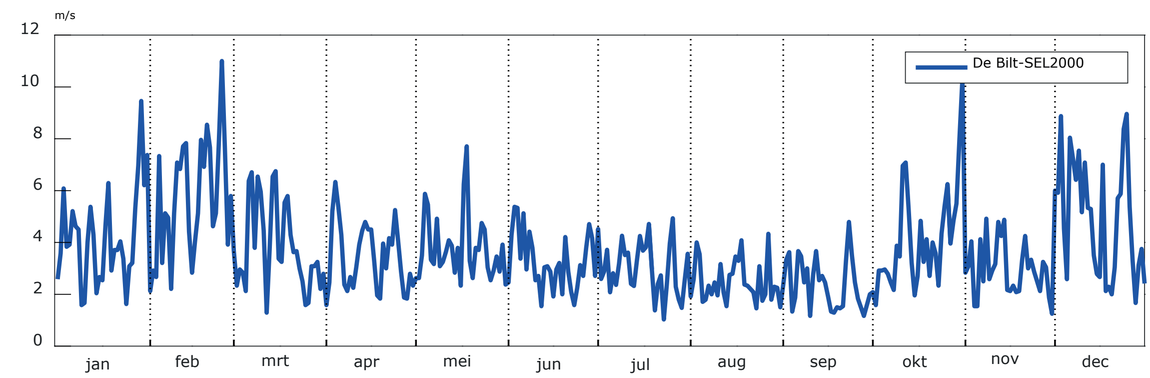

***Figure 3.13** Evolution of daily average wind velocity(m/s) in the selected SEL-year in de Bilt (The Netherlands).*

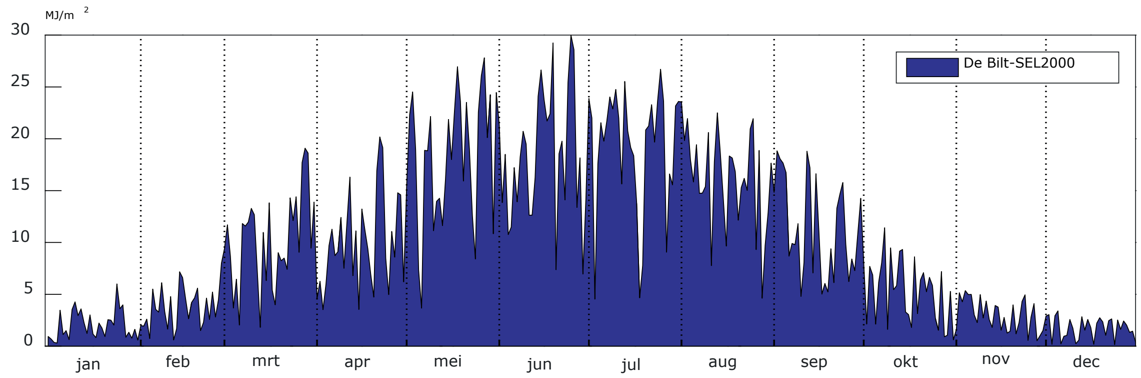

Figure 3.14 *Evolution of solar radiation daily sum (MJ/m²) in the selected SEL-year in de Bilt (The Netherlands).*

1.1.1 Desert region: Riyadh (Saudi Arabia)

Riyadh has a desert climate. During the year, there is very low rainfall. The average annual temperature is 25.4°C. Precipitation here averages 111 mm. For Riyadh, the most complete weather data set, corresponding to 2015 was selected.

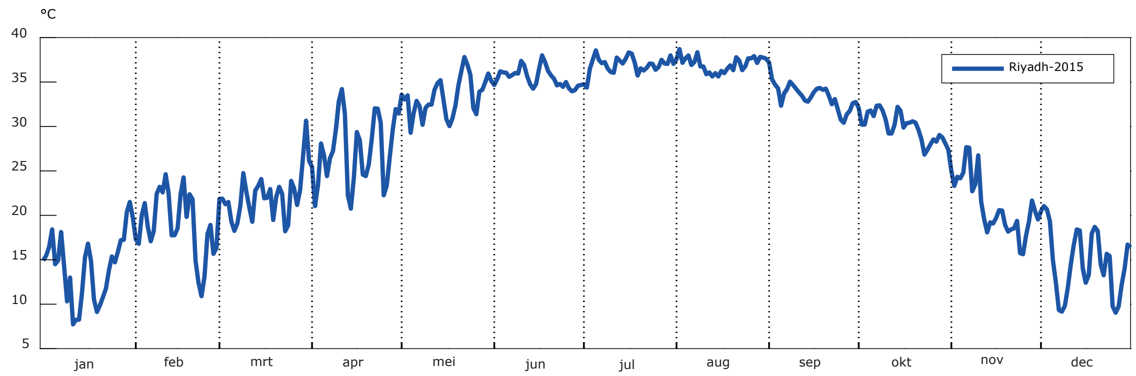

Figure 3.15 *Evolution of daily average temperature(°C) in year 2015 in Riyadh (Saudi Arabia).*

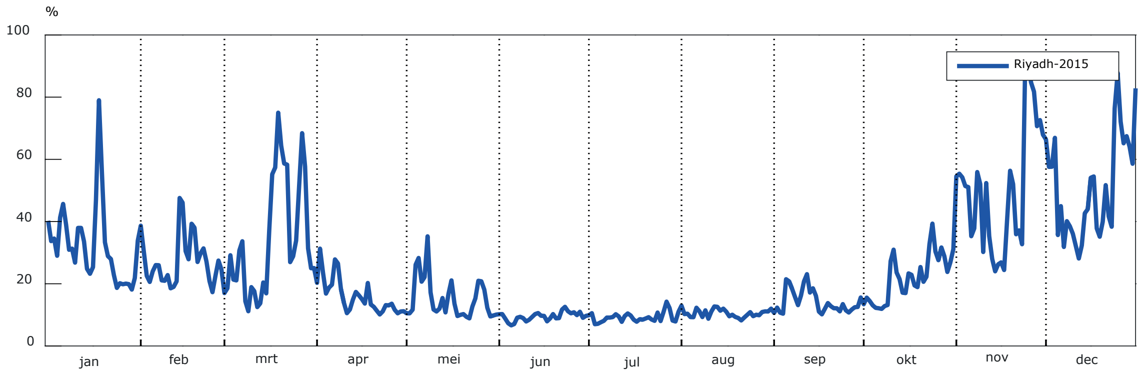

Figure 3.16 *Evolution of daily average relative humidity(%) in year 2015 in Riyadh (Saudi Arabia).*

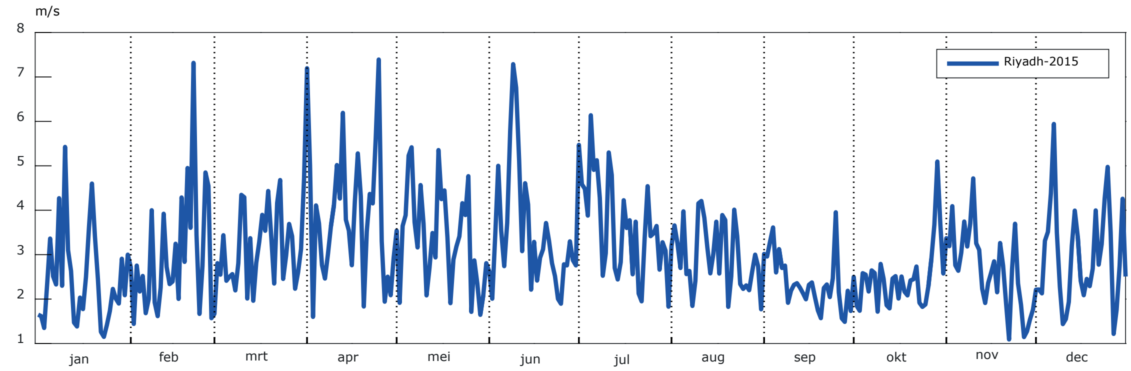

***Figure 3.17** Evolution of daily average wind velocity(m/s) in year 2015 in Riyadh (Saudi Arabia).*

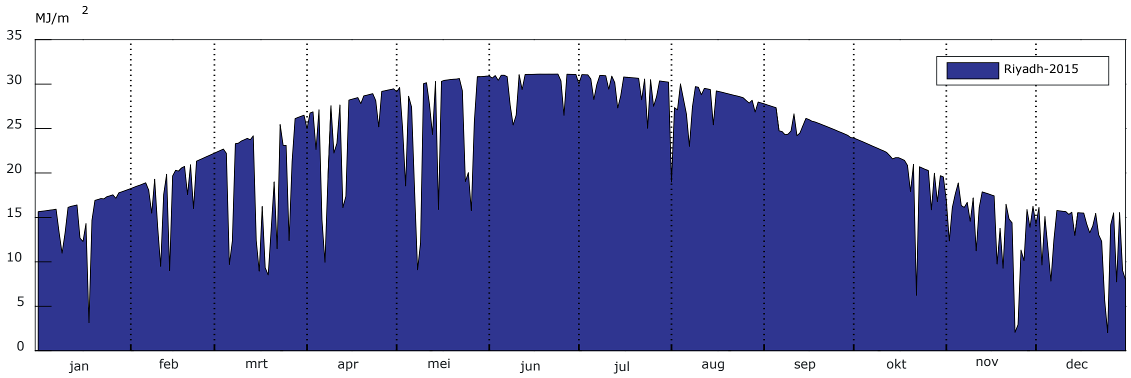

***Figure 3.18** Evolution of solar radiation daily sum (MJ/m²) in year 2015 in Riyadh (Saudi Arabia).*

3.3 Results

3.3.1 Local (Canarian) greenhouse in Agadir (Morocco)

For the Canarian greenhouse, five simulations have been performed: a first one in which no whitewash was applied (which was used to identify the optimum moments for the application of whitewash), a reference simulation, which represents the standard procedure in this regions, in which a whitewash with shading factor for shortwave radiation of 60% was considered; two switchable non-selective filters with a shading factor for shortwave radiation of 60%, but one of them activated when greenhouse air temperature reached 28°C and the other activated at 30°C; finally, a switchable non-selective filter with a shading factor for shortwave radiation of 30%, always activated whenever 30°C air temperature was reached.

The simulations without a whitewash indicated that the best moments to apply/remove the whitewash were 1st October and 29th March, respectively. This decision was made analyzing the daily cyclic mean of greenhouse air temperature, identifying when average number of hours inside the greenhouse above 30°C became higher than 5, and considering this moment as the application of whitewash was applied, which was removed again when hours above 30°C during the 24 hours become lower than 5.

3.3.1.1 Effect on greenhouse air temperature

One of the main reasons to use shading is to decrease maximum greenhouse temperatures in the greenhouse, trying to prevent the harmful effects of supra-optimal temperatures on crop growth and development and in fruit set and quality.

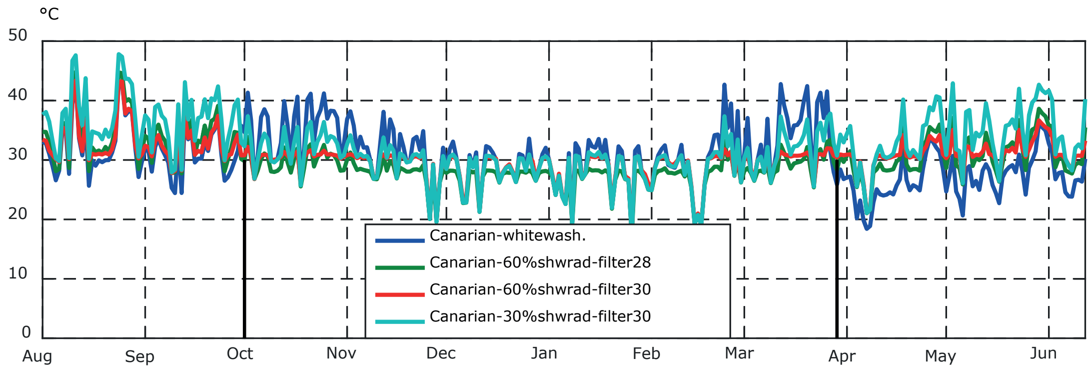

Figure 3.19 *Evolution of daily maximum air temperatures(°C) along the growing cycle under the 3 evaluated scenarios: reference-whitewash and the three switchable filters.*

Figure 3.19 shows the daily maximum simulated greenhouse air temperatures under the reference scenario (whitewash) and with the non-selective filters. The two vertical black lines represent the moments where whitewash was removed (1-10-2010) and applied again (29-3-2010), respectively, in the reference scenario. We can clearly identify three different periods. During the first 2 months of the growing cycle, with a small crop, and with the presence of a whitewash in the reference greenhouse, we can observe negligible differences on peak temperatures between the reference greenhouse and the two covers with a 60% switchable filter because maximum temperatures on this period are always above the thresholds of the filters. The 30% filter, allows more radiation in, thus higher peak temperatures than in the reference and for the 60% reduction filters are achieved. During the second period, the whitewash has been removed from the reference greenhouse, and that ensures that most days, peak temperatures are much lower than under the switchable filters, because the poor ventilation capacity of this type of greenhouse, makes temperatures inside the greenhouse to rise high (above 30°C) even during the sunny days on autumn, winter and early spring, so filters are activated controlling peak temperatures, especially the 60% earlier activated filter (28°C), unlike in the reference greenhouse.
In the third period, the reference greenhouse is whitewashed again, and since external air temperatures and radiation levels are not as high as during the first period and crop is fully developed and intercepts most of the solar radiation, the peak values are again very similar when the 28°C and 30°C activation points are exceeded. When filters are not activated, obviously temperatures are higher under the materials with the switchable filter, whereas in the reference, whitewash shading is permanent. Table 3.12 summarizes the number of hours that the greenhouse air temperature is above a threshold of 31°C which would have a harmful effect on the tomato crop under the 3 evaluated scenarios along the whole cycle.

Table 3.12

Summary of hours that greenhouse air temperature (°C) are above a physiological threshold for affected dry matter production and quality under the evaluated scenarios on a Canarian type greenhouse for Agadir (Morocco).

	Hours that Tair>31°C
Reference (whitewash)	533
Switchable filter 60% (28°C)	381
Switchable filter 60% (30°C)	327
Switchable filter 30% (30°C)	1137

Overall, the number of hours at risky temperatures for a tomato crop is higher under the 30% shading filter and under the reference whitewash, differences mostly occurring during period 2, followed by the 28°C activation filter and the 30°C activation filter (Table 3.12).

Figure 3.20 shows the daily minimum temperatures along the whole growing cycle. We can see that the filters do not have an effect on minimum night temperatures during most of the growing cycle, except during the third period, when relatively warm days are followed by still relatively cool nights. Under these conditions, the reference greenhouse with a permanent whitewash has a lower daytime radiation sum than the greenhouses with the switchable filters, due to the permanent nature of the shading by whitewash. Since we are simulating passive greenhouses, the heat stored mainly in the soil, during the daytime, is emitted in the form of long wave radiation and if the cover is not fully permeable, part of this energy warms the internal air. Therefore, heat stored in the reference greenhouse is lower than under the three switchable filters, resulting in lower night temperatures, as we can see on Figure 3.21, which shows the 24 hours cyclic mean of the temperatures for this third period.

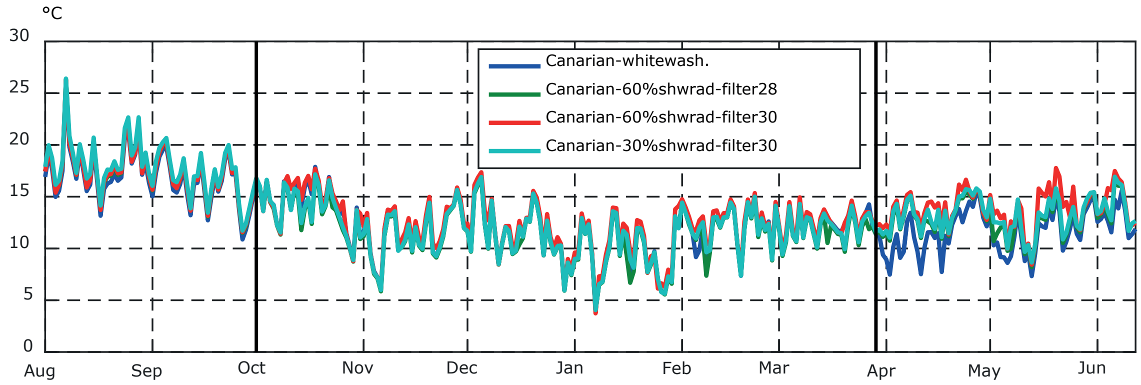

Figure 3.20 *Evolution of daily minimum air temperatures (°C) along the growing cycle under the 4 evaluated scenarios: reference-whitewash and the three switchable filters.*

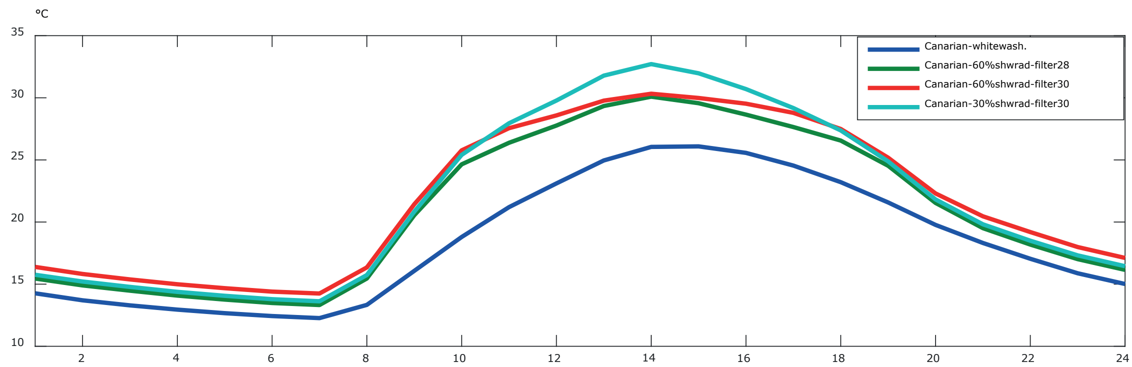

Figure 3.21 *Daily cyclic mean of greenhouse air temperature (°C) during the third period (April-June) under the 4 evaluated scenarios: reference-whitewash and the three switchable filters.*

3.3.1.2 Effect on PAR available for the crop

One of the potential advantages of using a switchable non-selective filter activated by temperature in the greenhouse cover, in relation to other traditional shading techniques, such as whitewash, should be that the amount of PAR radiation available for the crop is higher under the smart covers with a switchable filter than in the cover coated with a whitewash, during the periods that the whitewash is used, as the last is permanently shading, whereas the filters are only activated when greenhouse air temperature reaches critical values, in a similar way as a shading screen is managed. On the other hand, during the period where whitewash is removed (period 2), the amount of PAR available for the crop should be equal under the reference greenhouse and under the covers with a switchable filter on those days where greenhouse air temperature does not reach the threshold activation values for the filter, and higher on those days that filter is activated because greenhouse air temperature exceeds the thresholds.

Figures 22 and 23 show the cyclic mean of PAR radiation (μmol m^{-2} s^{-1}) available for the crop under the 4 evaluated scenarios for periods 1 and 2, respectively.

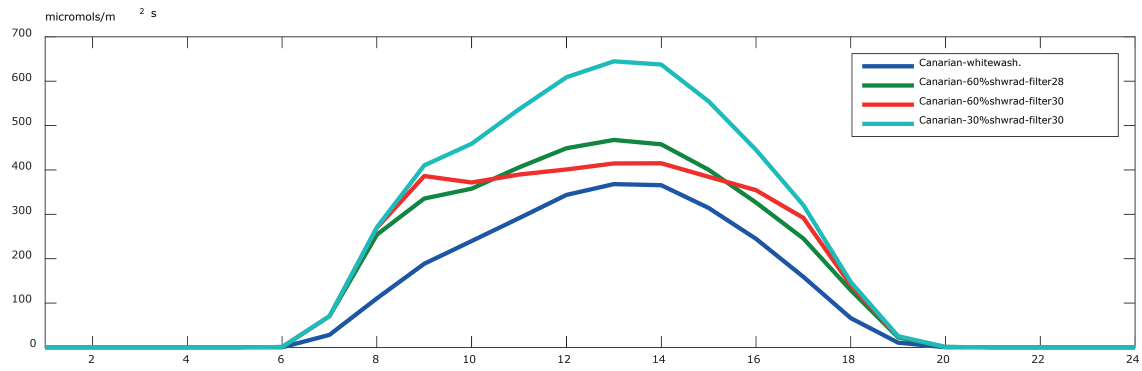

Figure 3.22 *Daily cyclic mean of available PAR for the crop (μmol m^{-2} s^{-1}) during the first period (1st August-1st October) under the 4 evaluated scenarios: reference-whitewash and the three switchable filters.*

Figure 3.22 confirms that during the first period, the amount of PAR available for the crop is higher under the covers with switchable filters than under the reference whitewash, as expected. PAR available is, obviously higher under the 30% shading filter than for the 60% shading filters, and within these filters, higher for the filter activated later (at higher temperature, 30°C), and this is achieved at the expense of higher air temperatures, as we saw in the previous section. During period 2, whitewash was removed from the cover in the reference greenhouse. Figure 3.23 confirms that PAR available for the crop was higher on average under the reference greenhouse, than under the covers with a filter, due the relatively large number of days that the filters where activated, despite of being in the colder months of the cycle. This is caused by the very poor ventilation and relatively sunny climate on this location, as we saw on Figures 3.3 and 3.6.

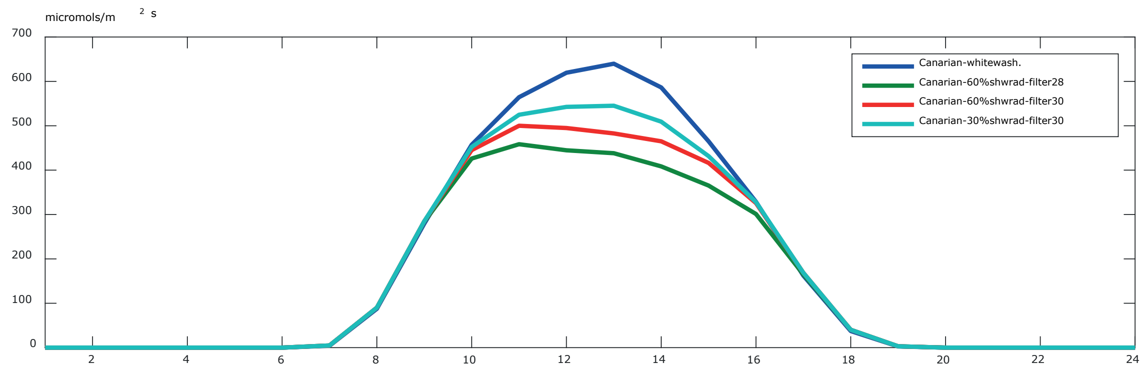

Figure 3.23 *Daily cyclic mean of available PAR for the crop (μmol m^{-2} s^{-1}) during the second period (1st October-1st April) under the 4 evaluated scenarios: reference-whitewash and the three switchable filters.*

Finally, Figure 3.24 shows the accumulated values of PAR radiation (mol m^{-2}) along the whole growing cycle under the 4 simulated scenarios. As expected, the 30% shading filter allows for a higher amount of PAR available for the crop. During the periods that the whitewash is applied, the 60% filters allow for more light, whereas in the winter differences are compensated. Overall, the later activation filter, as expected, gets a higher PAR sum at the end of the cycle than the earlier activation one and that the reference whitewash.

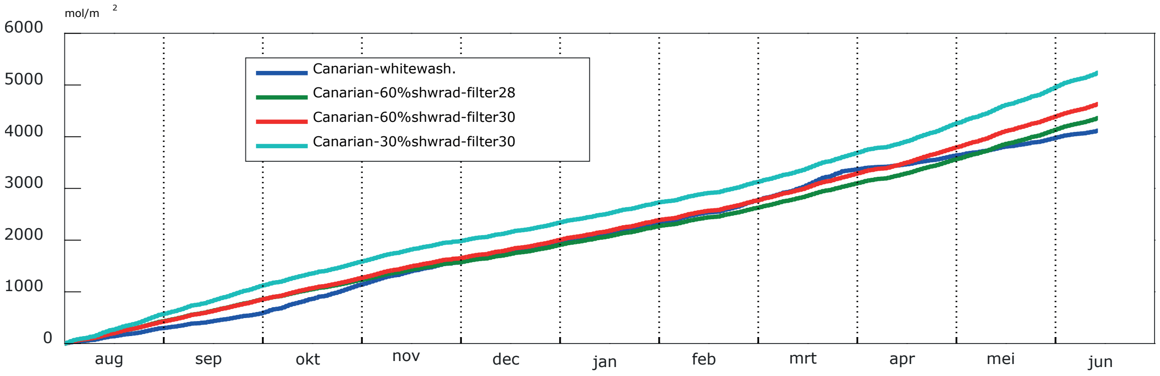

Figure 3.24 *Accumulated values of PAR (mol/m²) available for the crop along the growing cycle for the 4 evaluated scenarios.*

3.3.1.3 Effect on tomato productivity

The main question is whether the largest number that the reference greenhouse supports temperatures above a physiological threshold for which photosynthesis is negatively affected, is compensated by the total higher amount of PAR available for the crop with the switchable filters, as shown in Figure 3.24. Figure 3.25 shows the evolution of the potential daily tomato fresh weight production (kg/m²) along the growing cycle, for the 4 evaluated scenarios.

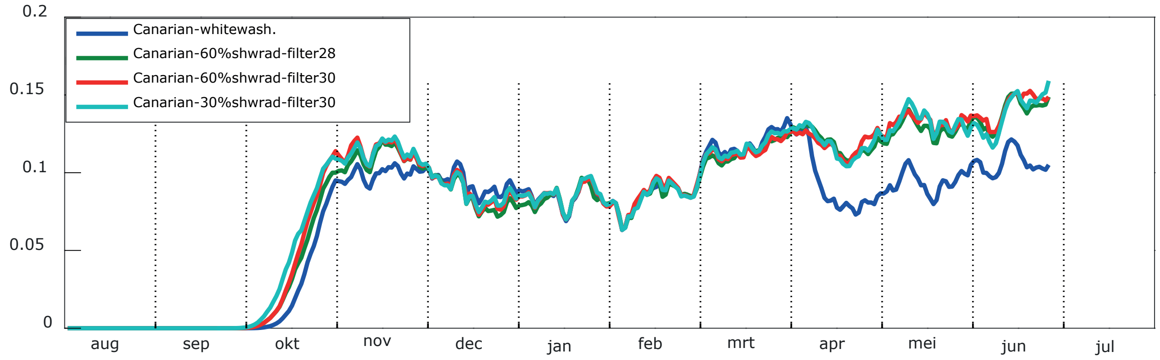

Figure 3.25 *Daily tomato fresh weight production (kg/m²).*

Until end of December, potential productivity is slightly earlier and higher under the switchable filters, mostly due to higher PAR availability than in the reference during this period. After that, there is a small period of slightly higher productivity for the reference greenhouse (in December), followed by a winter period of almost equal productivity in all scenarios. Then, from the moment the whitewashed is applied again, productivity grows again larger under the three switchable filters, thanks to higher PAR radiation availability for the crop. It is interesting to highlight that for the 30% filter, despite of the very large number of hours above 30°C, potential simulated yield loss is partially compensated by the higher amount of PAR. However, we must highlight that high temperatures during long periods of time may have other harmful effects besides the direct effect on dry matter production, such as increase of incidence of physiological disorders (i.e. BER or cracking) or fruit set and quality issues, which the model used to estimate the productivity does not quantify.

Table 3.13 summarizes the final tomato yields obtained for each simulated scenario, showing that both switchable filters allow for an increase in final yield in relation to a traditional whitewash, being yield with a higher activating temperature (30°C) higher than for the earlier activating filter (28°C). This suggest the possibility of exploring what is the threshold activation temperature at which yield stops growing as temperatures are more detrimental than the extra light available for the crop.

Table 1.13

Summary of final tomato potential yields simulated under each one of the four evaluated scenarios on a Canarian type greenhouse for Agadir (Morocco).

	Final yield (kg/m^2)	Increase/decrease(±%)
Reference (whitewash)	22.9	---
Switchable filter 60% (act. 28°C)	25.7	+12.2
Switchable filter 60% (act. 30°C)	26.3	+14.8
Switchable filter 30% (act. 30°C)	26.4	+15.3

3.3.1.4 Effect on tomato productivity of decreasing levels of PAR.

As we explained earlier, in many regions, shading in the form of whitewash or screens (fixed or mobile) is applied during large parts of the growing cycle. It is the case, for instance, of Mediterranean greenhouses or in tropical regions. Often, these greenhouse have a poor ventilation capacity and therefore, cooling by natural ventilation is insufficient. In addition, evaporative cooling would not perform well due to poor ventilation too (or due to the humid climate in the case of the tropics). Thus, growers choose to shade during large periods of the growing cycle and with extremely high shading factors, leaving out more than half of the incoming solar energy. In practice, this shading prevents the incidence of different physiological problems, many of them affecting the fruits (i.e. BER). Unfortunately, the existing tomato growth models only account for the harmful effect of high temperatures on photosynthesis, and not the possible incidence of other disorders that increase the amount of non-marketable yield.

Therefore, how can we answer the question of what is the optimum shading? For that we have used the following procedure. First, we have made simulations for increasing levels of shading by whitewash (No shading, 30% shading factor, 60% shading factor and 75% shading factor). Applying Vanthoor's model we have obtained a potential total tomato yield. These values have been converted in a marketable yield by considering a certain percentage of non-marketable yield. These percentages have been obtained after analyzing the results obtained in different experimental studies performed in similar climate conditions and similar greenhouse types with tomato and other similar greenhouse crops, all of them reviewed by Ahemd *et al.* 2016, (Figure 3.26). It is interesting to highlight, in view of the data, that optimum shading factor for this regions and this type of greenhouse is somewhere between 50-60%

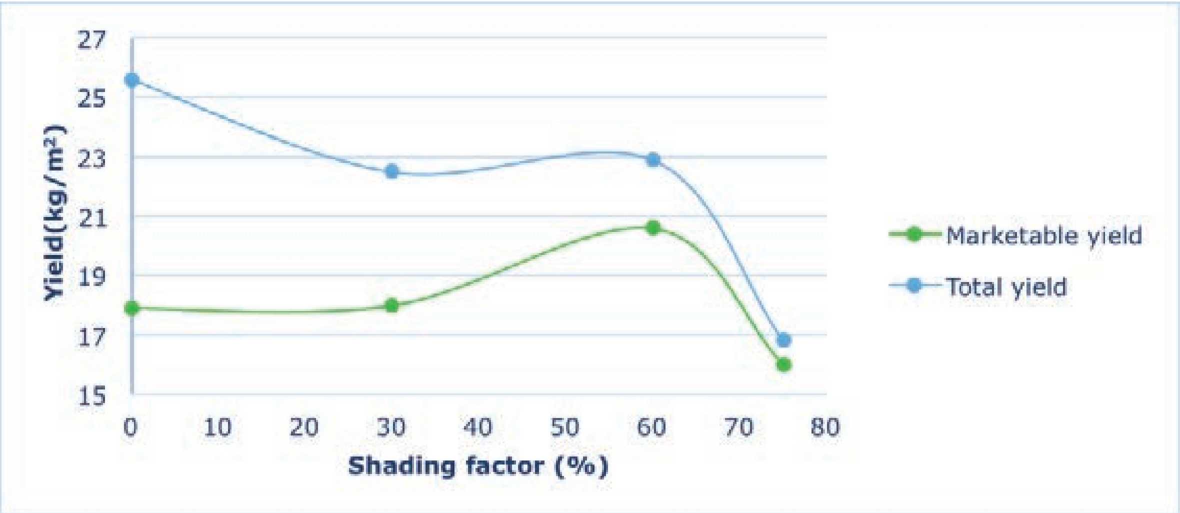

Figure 3.26 *Total and marketable tomato yields (kg/m^2) predicted by the model and corrected with literature data, respectively, for a Canarian greenhouse in Agadir (Morocco).*

3.3.1.5 Improved greenhouse structure (Venlo-plastic film) in Agadir, Morocco

For the Venlo greenhouse, the same simulations have been done as for the Canarian type greenhouse, including the simulation without any kind of shading used to identify the moments of "application/removal" of the whitewash. This decision was made analyzing the weekly 24 hours cyclic means of greenhouse air temperature, so that the week when average number of hours inside the greenhouse above 30°C became higher than 5 hours per day, whitewash was applied, and removed again when hours above 30°C, become lower than 5. This simulation indicated that apply/remove the whitewash September 23rd and April 26th , respectively. In other words: the improved ventilation of the greenhouse delayed the need of application of whitewash by about one month and allowed its removal about one week earlier than in a Canarian greenhouse.

3.3.1.6 Effect on greenhouse air temperature

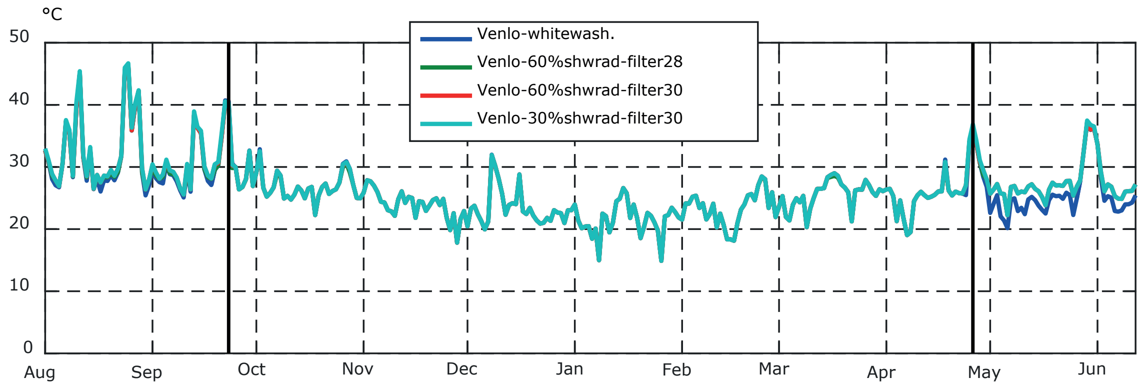

Figure 3.27 *Evolution of daily maximum air temperatures (°C) along the growing cycle under the 4 evaluated scenarios: reference-whitewash and the three switchable filters.*

Figure 3.27 shows the daily mean of simulated greenhouse air temperature under the reference scenario (whitewash) and with the non-selective filter switched at temperatures of 28°C and 30°C, respectively. The two vertical black lines represent the moments where whitewash was removed (23-09-2010) and applied again (26-04-2010) respectively in the reference scenario. The whitewash application and removal allow for 3 different periods to be identified:

The first 2 months of the growing cycle, with a small crop, and with the presence of a whitewash in the cover of the reference greenhouse, we can observe almost irrelevant differences on peak temperatures between the reference greenhouse and the two covers with a switchable filter. The higher ventilation capacity of the Venlo greenhouse, equalized peak temperatures under all evaluated scenarios. Thus, for the switchable filters, vents simply will open more to try to stay as close as possible to the required temperature set point.

During the second period, the whitewash has been removed from the cover of the reference greenhouse and given the larger ventilation capacity of this greenhouse type, activation temperatures for the filters are hardly ever reached, and therefore there are virtually not differences between the peak temperatures for the different covers.

In the third period, the cover of the reference greenhouse is whitewashed again and the peak values are very similar when the 28°C and 30°C thresholds are exceeded, and when not, temperatures are higher under the materials with the switchable filter since their shading is not activated yet, unlike the whitewash, permanently on the cover during this period.

Summarizing, when a better ventilated greenhouse structure is used (e.g. Venlo greenhouse) there are hardly any differences between the three simulated filters in terms of peak temperatures, which proves that the greenhouse has enough ventilation capacity to maintain lower temperatures despite of one filter being activated slightly later than the other.

Table 3.14 summarizes the number of hours that the greenhouse air temperature is above a threshold of 31°C under the 4 evaluated scenarios along the whole cycle.

Table 3.14

Summary of hours that greenhouse air temperature (°C) are above a physiological threshold for negatively affected dry matter production and quality under each one of the evaluated scenarios on a Venlo type greenhouse for Agadir (Morocco).

	Hours that Tair>31°C
Reference (whitewash)	234
Switchable filter 60% (act. 28°C)	238
Switchable filter 60% (act. 30°C)	243
Switchable filter 30% (act. 30°C)	253

The higher ventilation capacity of the Venlo and the control possibilities makes the number of hours at risky temperatures for a tomato crop to be very similar in the three analyzed scenarios. It is only slightly higher under the 30% filter (with 30°C activation, Table 3.14). In the previous example the difference was originated in period 2, due to removing of the whitewash in the reference combined with poor ventilation, which is not the case for the Venlo.

Figure 3.28 shows the daily minimum temperatures along the whole growing cycle. In this case minimum temperatures are almost exactly the same all along the second period. We only see very small differences in minimum temperatures in periods 1 and 3, caused by lower heat storage capacity in the greenhouse soil under the whitewash greenhouse (Figure 3.29).

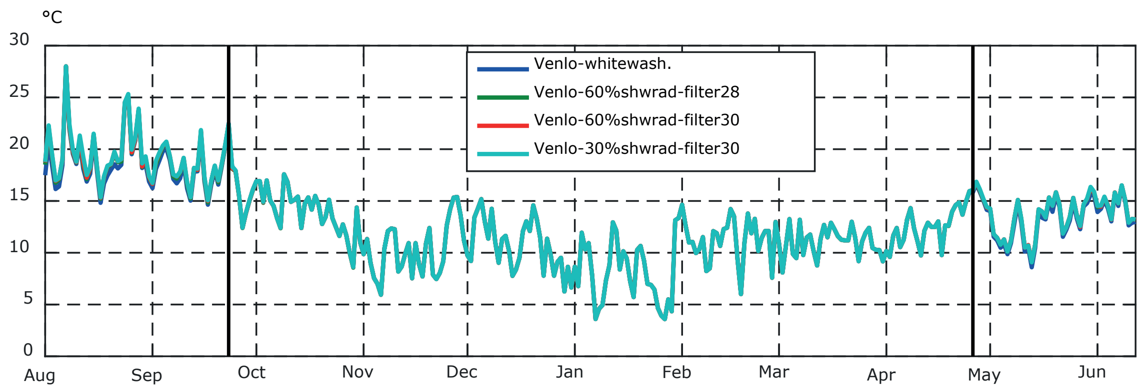

Figure 3.28 *Evolution of daily minimum air temperatures (°C) along the growing cycle under the 4 evaluated scenarios: reference-whitewash and the three switchable filters.*

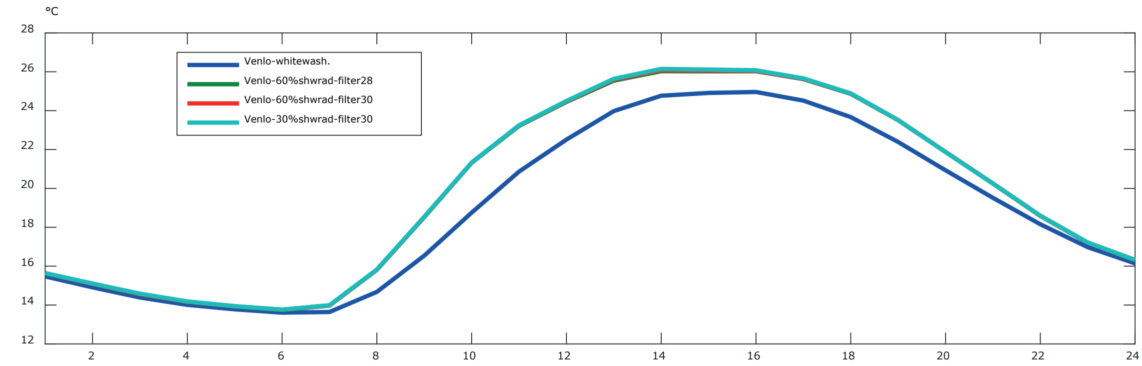

Figure 3.29 *Daily cyclic mean of greenhouse air temperature (°C) during the third period (April-June) under the 4 evaluated scenarios: reference-whitewash and the three switchable filters.*

3.3.1.7 Effect on PAR available for the crop.

Again, the switchable filters allow for a higher amount of PAR available for the crop during period 1, when whitewash is permanent, although differences in this case are higher, as the high ventilation capacity allows for lower number of hours of activation of the filters. Here we can also see that the higher cooling capacity of the Venlo greenhouse, thanks to higher ventilation air exchange, delays the activation point, and therefore, allows for an even higher difference in relation to the 28°C filter, regarding PAR availability for the crop.
This can be observed in figures 30 and 31, showing the cyclic mean of PAR radiation (μmol m^{-2} s^{-1}) available for the crop under the 4 evaluated scenarios for periods 1 and 2, respectively.

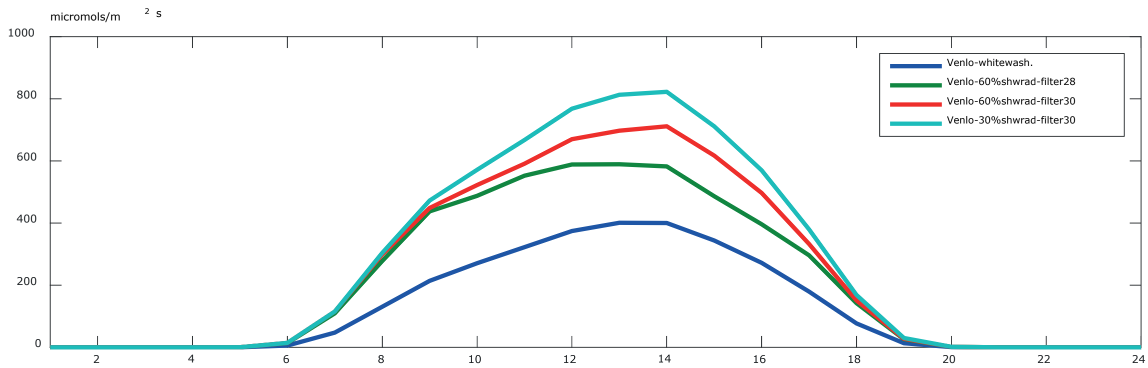

Figure 3.30 *Daily cyclic mean of available PAR for the crop (μmol m^{-2} s^{-1}) during the first period (1st August-23rd September) under the 4 evaluated scenarios: reference-whitewash and the three different switchable filters.*

During the cold period (period 2) the filters are hardly ever activated for the Venlo greenhouse due to efficient cooling by natural ventilation, making the PAR available for the crop to be almost equal, on average, under all the studied scenarios (Figure 3.31).

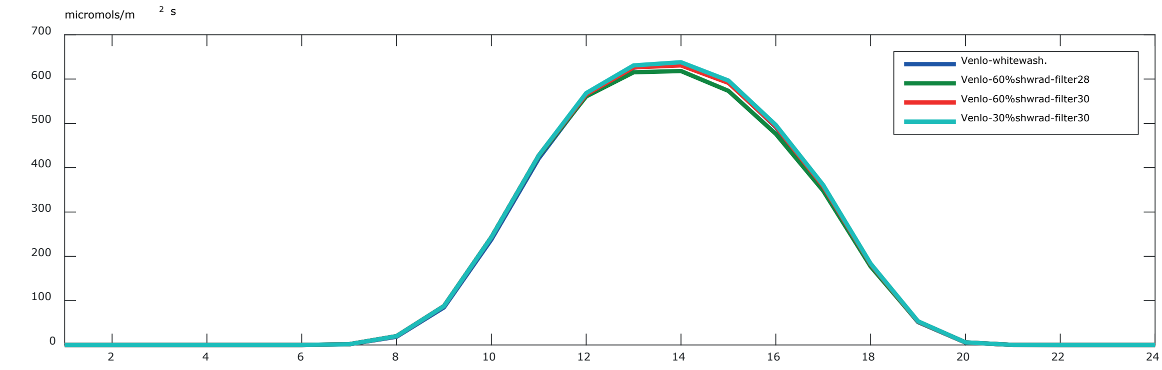

Figure 3.31 *Daily cyclic mean of available PAR for the crop (μmol m^{-2} s^{-1}) during the second period (23rd September-26th April) under the 4 evaluated scenarios: reference-whitewash and the three different switchable filters.*

Finally, Figure 3.32 shows the accumulated values of PAR radiation (mol/m^2) along the whole growing cycle under the 4 evaluated scenarios. Results indicate clearly for the Venlo greenhouse an advantage for the switchable filters (especially for the 30% shading filter, as would be expected) analyzed in comparison with the reference-whitewash; differences originate in periods 1 and 3, when the reference greenhouse has a permanent whitewash, whereas the filters are only activated when temperature exceeds the activation points.

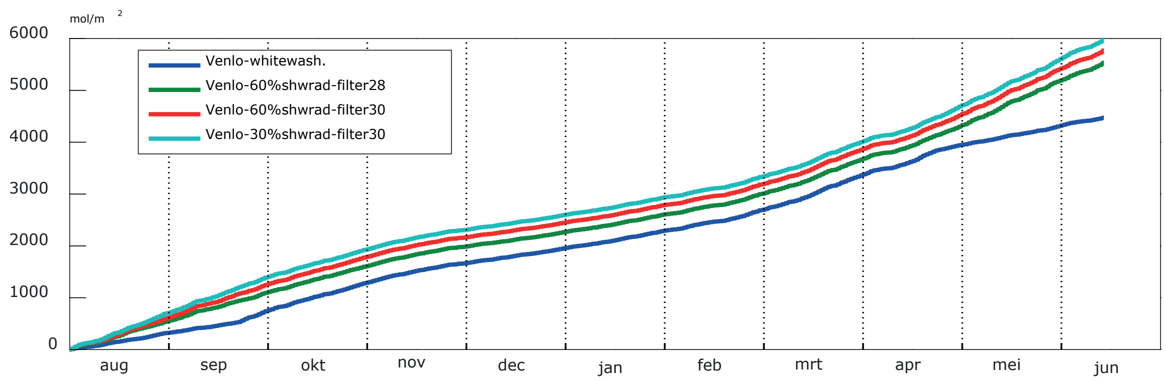

Figure 3.32 *Accumulated values of PAR (mol/m^2) available for the crop along the growing cycle for the 4 evaluated scenarios.*

3.3.1.8 Effect on CO_2 concentration in the presence of artificial CO_2 enrichment

The effect of the different filters in CO_2 concentrations in a greenhouse where CO_2 is not artificially added to the greenhouse environment are discussed in an Appendix, due to their very limited effect in this scenario. However, new simulations were also performed assuming artificial CO_2 enrichment with pure CO_2 trying to maintain a set point concentration of 800 ppm with a dosing capacity of 100 kg_{CO2} ha^{-1} h^{-1}. Figure 3.33 shows the 24 hour cyclic mean of CO_2 concentration (ppm) along the whole cycle for the four simulated scenarios; the lower ventilation requirements of the whitewash greenhouse during periods 1 and 3 cause a slightly higher CO_2 concentration under this scenario than under the three simulated switchable filters. Among the filters, there are virtually no differences between the two 60% shading filters, whereas the higher ventilation required by the 30% filter results in a slightly lower average CO_2 concentration.

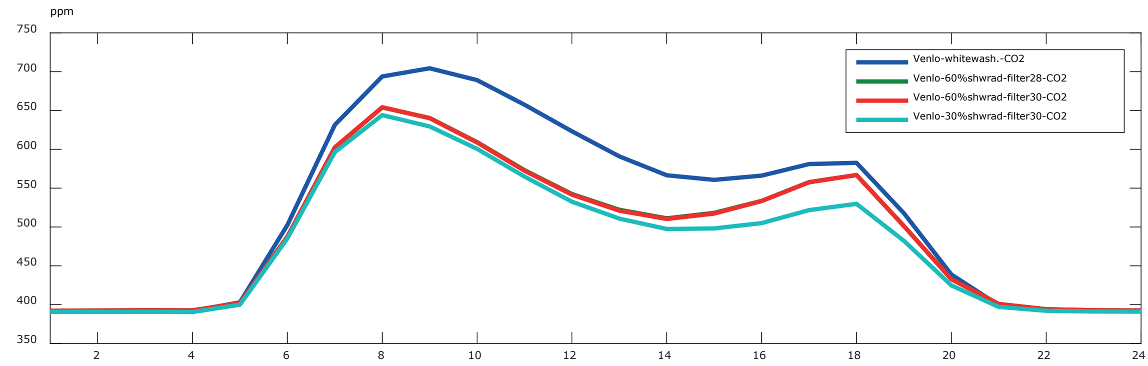

Figure 3.33 *Daily cyclic mean of CO_2 concentration (ppm) in the greenhouse with artificial CO_2 enrichment during whole cycle under the 4 evaluated scenarios.*

3.3.1.9 Effect on tomato productivity

Figure 3.34 shows the evolution along the growing cycle of potential daily tomato fresh weight production (kg/m²) under the 4 simulated scenarios without artificial CO_2 enrichment. Simulations also estimate for the Venlo greenhouse higher yields and earliness for the switchable filters than the reference whitewash scenario, with minor differences between them.

When CO_2 enrichment is simulated, an even more clear difference is observed; the switchable filter with a 30% shading factor shows a slightly higher potential production at the end of the cycle than the filters with higher shading, which could be explained by the fact that for a greenhouse with a good natural ventilation capacity, such as the one simulated, the shading factor (%) should be minimized to increase PAR use efficiency due to lower risk of extremely high temperatures to occur thanks to improved natural ventilation capacity (Figure 3.35).

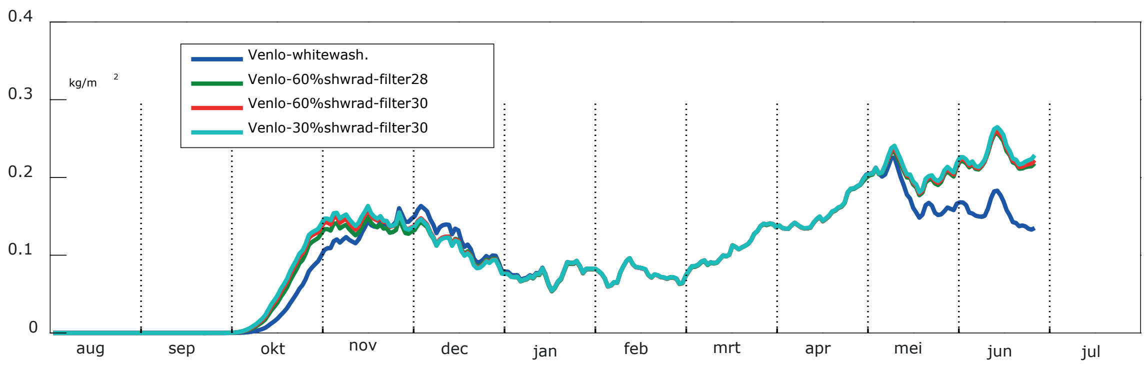

Figure 3.34 *Evolution of daily tomato fresh weight production (kg/m²) for the scenarios without CO_2 enrichment.*

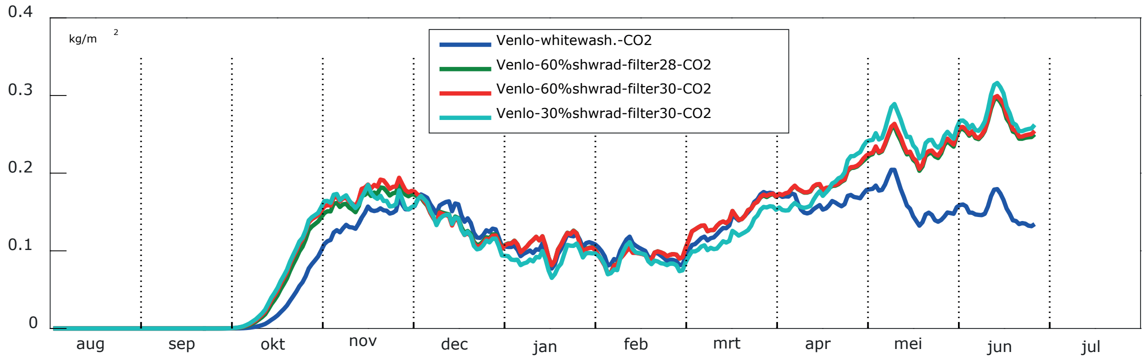

Figure 3.35 *Evolution of daily tomato fresh weight production (kg/m²) for the scenarios with CO_2 enrichment.*

Table 3.15 summarizes for the Venlo type greenhouse in Agadir (Marocco), tomato final potential yields obtained for each simulated scenario. This table has been built with the aim of discerning how much of the increase in the yield obtained with the Venlo greenhouse structure is caused by the filters and how much by the use of an improved structure (higher volume and higher ventilation capacity) or in the case of CO_2 enrichment, how much of the increase is caused by the application of CO_2 and how much to the switchable filters.

Interestingly, the simulations show that potentially, switchable filters improve the performance of the whitewash, even in a higher percentage than they did in the Canarian type greenhouse. Thus, we could argue that the filters perform with higher efficiency in improved greenhouse structures, mostly with better natural ventilation. The application of CO_2, as expected, increases yield, but no synergy with the switchable filters is observed, as the increase in yield caused by the filters in relation to the reference with CO_2 is not very different than when no CO_2 is applied. In fact, if the filter has a lower shading percentage (30%), the need to ventilate more to maintain the temperature set points makes CO_2 enrichment to be slightly less effective. Finally, we see that for the 60% shading filter, the highest yield is obtained with activating temperature 30°C. This suggest the possibility of exploring what is the threshold activation temperature at which yield stops growing as temperatures are more detrimental than the extra light available for the crop.

Table 3.15

Summary of final tomato potential yields simulated under each one of the simulated scenarios of a Venlo type greenhouse for Agadir (Marocco).

Venlo no CO_2 enrichment	Final yield (kg/m²)	Yield increase caused by the switchable filters in the Venlo greenhouse in relation to reference (±%)	Yield increase in relation to the reference Canarian greenhouse (±%)	
Reference (whitewash)	29.5	---	+28.8	
Switchable filter 60% (28 °)	32.3	+16.6	+41	
Switchable filter 60% (30°C)	32.8	+18.4	+43.2	
Switchable filter 30% (30°C)	33	+19.1	+44.1	
Venlo CO_2 enrichment	**Final yield (kg/m²)**	**Potential yield increase caused by the filters in the Venlo greenhouse in relation to the reference (%)**	**Potential yield increase of the Venlo in relation to the reference Canarian greenhouse (%)**	**Potential yield increase in relation to the reference Venlo without CO_2 (%)**
Reference (whitewash)_CO2	34.6	---	+55	+17.3
Switchable filter 60% (28°)_CO2	37.7	+8.9	+69	+27.8
Switchable filter 60% (30°C)_CO2	38.3	+10.7	+71.7	+29.8
Switchable filter 30% (30°C)_CO2	38.6	+11.6	+73.1	+30.8

3.3.1.10 Effect on tomato productivity of decreasing levels of PAR.

When an improved greenhouse structures is used, with much more efficient natural ventilation, we must expect that the percentage of non-marketable harvest of the greenhouse when shaded must be smaller than in a poorly ventilated greenhouse. Thus, for this type of greenhouse we have followed the same procedure than for the Canarian type. First, we have made simulations for increasing levels of shading by whitewash (No shading, 30% shading factor, 60% shading factor and 75% shading factor). Applying Vanthoor's model (2011) we have obtained a potential total tomato yield. These values have been converted into marketable yield by considering a certain percentage of non-marketable yield. These percentages have been obtained after analyzing the results obtained in different experimental studies performed in similar climate conditions and improved greenhouse types (multi-span) with tomato and other similar crops and summarized by Ahemd *et al.* (2016) (Figure 3.36). It is interesting to highlight, in view of the data, that optimum shading factor for this regions and this type of greenhouse is somewhere around 30%, thus approximately half of the shading that would be required for a traditional type greenhouse in this location.

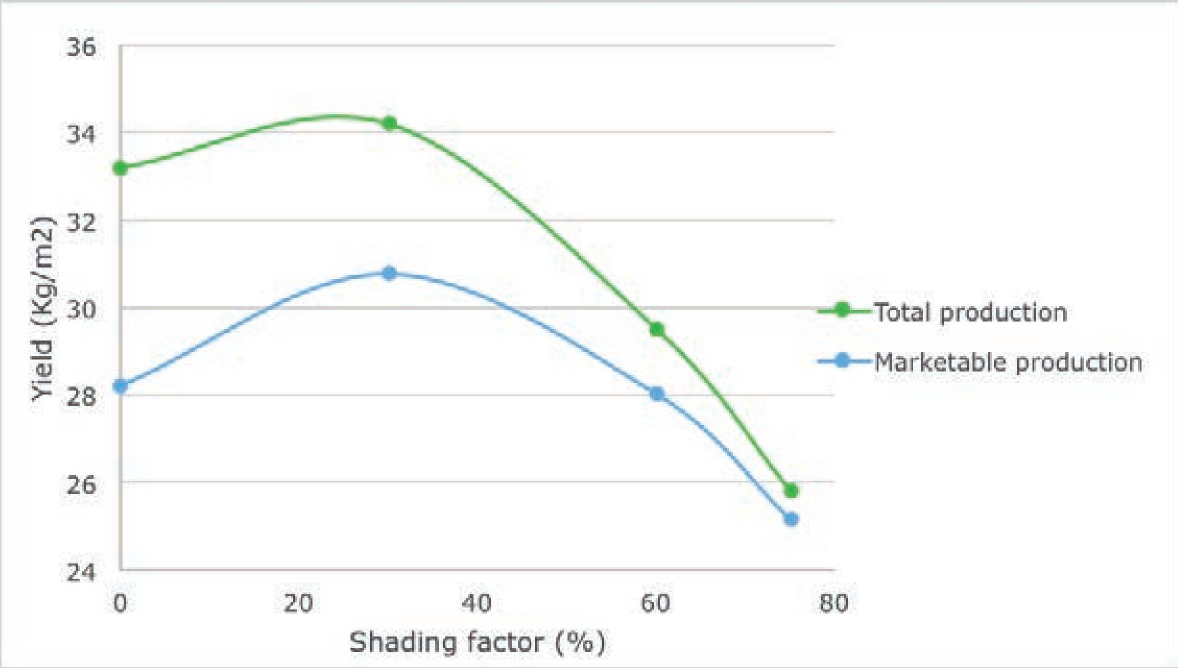

Figure 3.36 *Total and marketable tomato yields (kg/m²) predicted by the model and corrected with literature data, respectively, for a Venlo greenhouse in Agadir (Morocco).*

3.3.2 Tropical lowland location: Kuala Lumpur (Malaysia)

For tropical locations, whitewashing does not seem the best option to shade, due to heavy rainfalls, so the reference scenario simulated uses an external fix shading screen with a shading percentage in direct and diffuse light of 60%, which makes this screen to have a shading level identical to the one simulated for the switchable filters. The same switchable filters simulated for Agadir (Morocco) have been simulated here as well.

3.3.2.1 Effect on greenhouse air temperature

Figure 3.37 shows the daily mean of simulated maximum greenhouse air temperatures under the reference scenario (fixed external shading screen) and with the non-selective filters. In this figure we can see that maximum temperatures are consistently higher under the switchable filter with the lower (30%) shading factor. Since the screen is located outside the greenhouse it can decrease the energy entering the greenhouse without affecting air exchange by natural ventilation just like the switchable filters. Under the 30% shading factor filter temperatures are higher than under the two scenarios with 60% shading filter; the earlier activation filter (28°C) ensures lower peak temperatures during the whole cycle than the late activation one.
Table 3.16 summarizes the number of hours that the greenhouse air temperature is above a threshold of 31°C under the 4 evaluated scenarios along the whole cycle.

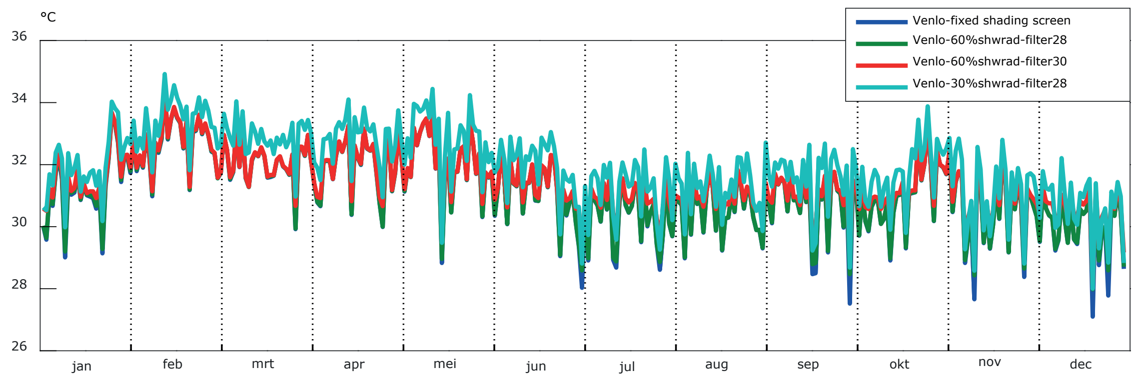

Figure 3.37 *Evolution of daily maximum air temperature (°C) along the growing cycle under the 4 evaluated scenarios: reference-shading screen and the three switchable filters.*

Table 3.16

Summary of hours that greenhouse air temperature (°C) is above a physiological threshold for affected dry matter production and quality under each one of the evaluated scenarios on a Venlo type greenhouse for Kuala Lumpur (Malaysia) as well as external temperature.

	Hours that Tair>31°C
Outside	958
Reference (fixed external shading screen)	772
Switchable filter 60% (28°C)	780
Switchable filter 60% (30°C)	846
Switchable filter 30% (28°C)	1230

Despite of the high ventilation capacity of the simulated Venlo plastic greenhouse the number of hours at risky temperatures for a tomato crop is rather high for all simulated cases. This is caused by the fact that also outside is very warm, with a large number of hours at temperatures that are higher than the selected threshold temperature; this is usual in this type of climate, and this is why greenhouses of relatively small size and large sidewall and roof ventilation area are recommended for this type of climate. Unfortunately the software used for the simulations does not allow for the simulation of the combined sidewall and roof ventilation, essential to accurately model the climate of such small greenhosue, and that is why the Venlo greenhouse option was selected instead.

Both the fixed external screen and the switchable filters perform relatively similar, especially the 60% shading filter with 28°C activation temperature. All of them even, except the one with 30% shading, decrease the number of hours below the threshold below those on the outside, as a consequence of the combined effect of the shading and the cooling effect of the crop.

Figure 3.38 shows the daily minimum temperatures along the whole growing cycle. Minimum temperatures are almost exactly the same all along the growing cycle for the evaluated scenarios, as such temperatures usually occur at night, when neither the screen or the filters are being used.

Figure 3.39 shows the 24 hours cyclic mean of greenhouse air temperature under the four simulated scenarios. In this figure we can see that differences start to occur around 08:00 a.m., with maximum differences been reached around 14:00 p.m. The fixed external shading, given its permanent nature, ensures lower temperatures durign the morning period. Afterwards, when the 60% shading switchable filter with earlier activation starts shading, it performs as expected, very similar to the fix screen, so peak temperatures are very much the same. The later activation filter (30°C) and the lower shading switchable filter (30%) obviously cause higher average peak temperatures.

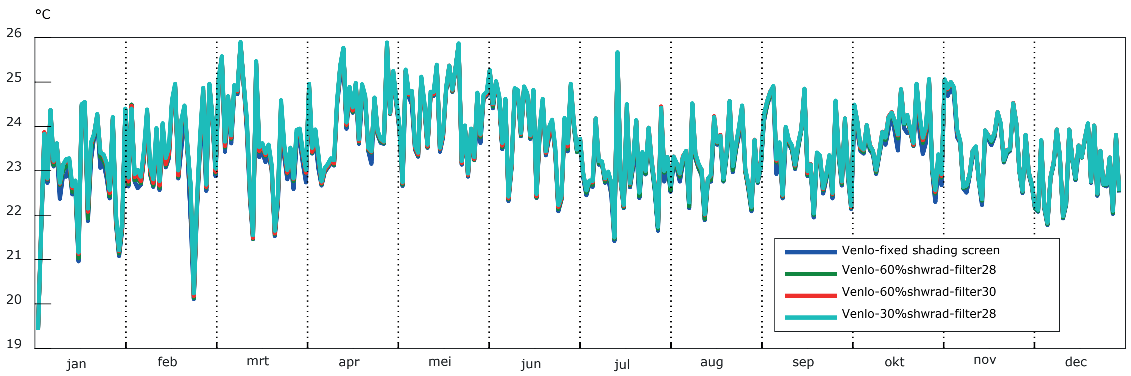

Figure 3.38 *Evolution of daily minimum air temperatures(°C) along the growing cycle under the 4 evaluated scenarios: reference-shading screen and the three switchable filters.*

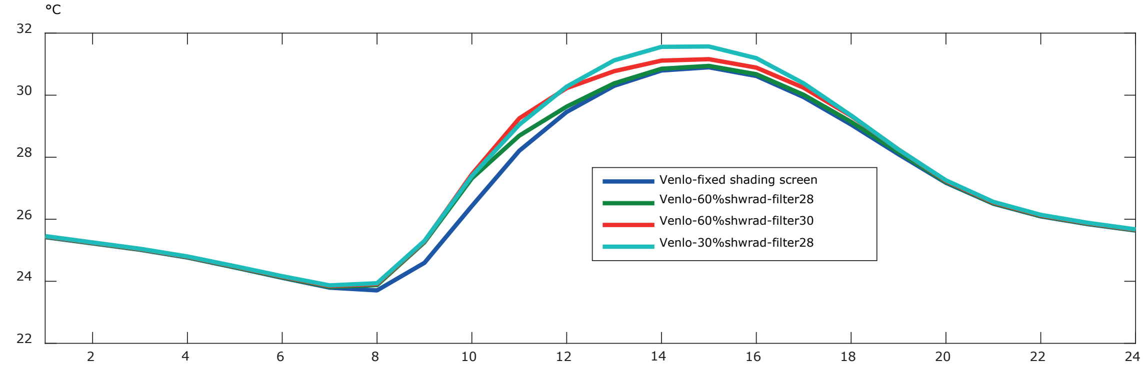

Figure 3.39 *Daily cyclic mean of greenhouse air temperature (°C) during the third period (April-June) under the 4 evaluated scenarios: reference-whitewash and the two switchable filters with activations temperatures of 28°C and 30°C.*

3.3.2.2 Effect on PAR available for the crop

The use of switchable filters should allow for a more efficient use of PAR radiation in the greenhouse than a fixed shadign screen, as the shading screen is permanently over the roof.

Figure 3.40 shows the cyclic mean of PAR radiation (μmol m^{-2} s^{-1}) available for the crop under the evaluated scenarios for the whole cycle. In this figure we can see that during most of the daytime hours, the 30% shading factor filter allows for a larger amount of PAR inside the greenhouse, followed by the 60 % shading factor with later (30°C) activation temperature, the 60% shading switchable filter with earlier activation temperature and, finally, the fixed shading screen.

A higher activation set point for the filters also allows for more available PAR, but at the expense of higher temperatures, and this may penalize dry matter production, as we will see later.

Thus, we must carefully analyze if the detrimental effect of high temperatures on crop growth, development and fruit quality is compensated by the larger amount of intercepted PAR. We can have a partial answer to this question when the crop growth model is run, but we must also think that not all crops have same temperature thresholds for physiological detrimental effects to occur, and even different cultivars may behave differently.

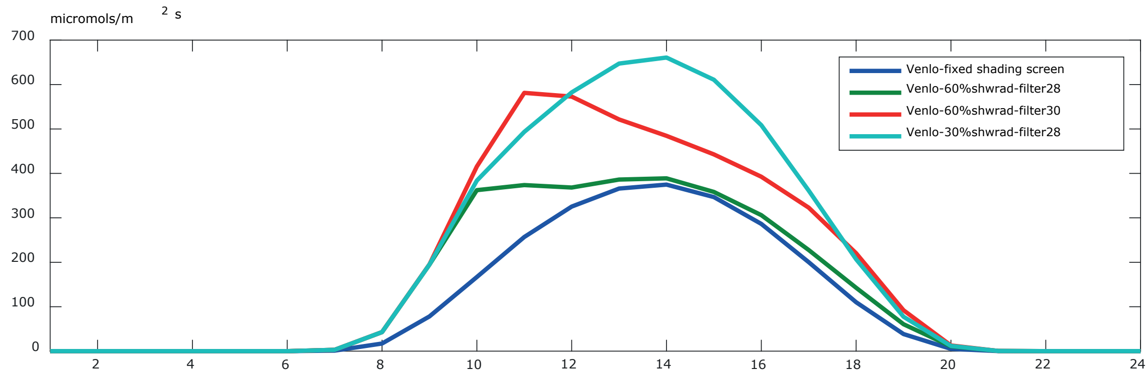

Figure 3.40 *Daily cyclic mean of available PAR for the crop (μmol m^{-2} s^{-1}) under the evaluated scenarios: reference-shading screen and the three switchable filters for the whole growing cycle.*

Finally, Figure 3.41 shows the accumulated values of PAR radiation (mol/m^2) along the whole growing cycle, which corroborates what we already analyzed:for a tropical lowland climate and with the simulated greenhouse configuration, the 30% filter allows for the most of PAR transmitted; also, the 60% filter activated at 28°C induces a larger amount of shading hours than the 30°C activation filter and very similar to that of a fixed shading screen.

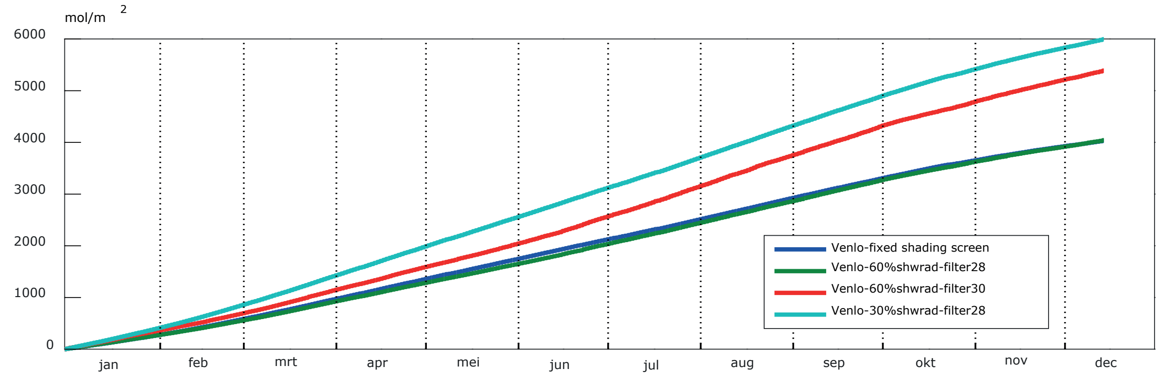

Figure 3.41 *Accumulated values of PAR (mol/m^2) available for the crop along the growing cycle for the 4 evaluated scenarios.*

3.3.2.3 Effect on tomato productivity

Figure 3.42 shows the evolution of potential daily tomato fresh weight production (kg/m^2) under the 4 analyzed scenarios. For a tropical lowland climate, simulations show several interesting facts. On one hand, for this type of greenhouse, which is not the ideal for this climate, a switchable filter with shading factor 30% induces a too large number of hours at high temperatures, which greatly penalizes dry matter production. The same applies for a 60% filter activated late (at 30°C). Only a 60% switchable filter with earlier activation has a performance that is similar to that of a fixed external screen with the same shading factor. We see than during the colder months of the cycle, the switchable filter outperforms the fixed screen, thanks to the extra PAR available for the crop, whereas during the warmer months, the fixed screen performs relatively better, thanks to better 24 hours mean temperature. Differences are rather large between the 28°C activation filter and the 30°C filter. It would be interesting to explore how low the activation can be set without penalizing yield for this climate.

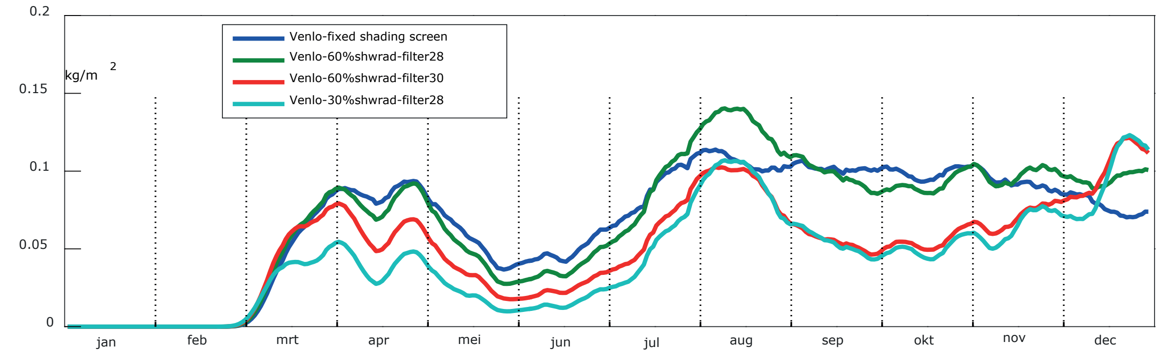

Figure 3.42 *Evolution of daily tomato fresh weight production (kg/m^2).*

Table 3.17 summarizes the final tomato yields obtained for each simulated scenario, showing that switchable filters allow for a very large increase in final yield in relation to an internal mobile screen, being yield with a lower activating temperature (28°C) higher than at 30°C. This suggest the possibility of exploring if a lower activation temperature would also allow for an even higher yield increase at the expense of lower PAR light interception by the plant. Also filters and screens with lower shading level (50 %, for instance) should be investigated.

Table 3.17

Summary of final tomato potential yields simulated under each one of the evaluated scenarios on a Venlo type greenhouse for Kuala Lumpur (Malaysia).

	Final yield (kg/m²)	Yield increase/decrease caused by the switchable filters(±%)
Reference (shading screen)	23.4	---
Switchable filter 60% (28°C)	23.8	+1.7
Switchable filter 60% (30°C)	17.6	-24.8
Switchable filter 30% (30°C)	15.1	-41.1

3.3.3 Cold climate location: de Bilt (The Netherlands)

For most vegetables (tomato, pepper, cucumber, etc.) using non selective shading in a cold climate (The Netherlands) is not an optimal solution to prevent too high temperatures , since the level of light at which canopy photosynthesis is saturated is very high. This means that shading leads to undesired decrease in dry matter production;thus it is preferable to manage temperature with natural ventilation and, when necessary, with some help of evaporative cooling. However, there are other crops for which optimum solar radiation in the greenhouse must be kept during part of the cycle or during the whole crop cycle, at values which are relatively low, thus, non-selective shading is used mostly in the form of shading screens. A good example of this type of crop is Anthurium. For this crop, simulations have been performed comparing the performance of an internal mobile shading screen and a switchable filter on the greenhouse cover, activated when solar radiation exceeds 300 W/m². The total shading factor caused by the filter and the simulated screen is been kept the same: 53%.

3.3.3.1 Effect on greenhouse air temperature

Figure 3.43 shows the daily mean of simulated maximum greenhouse air temperatures under the reference scenario (aluminized interior mobile shading screen) and with the non-selective switchable filter activated by solar radiation. In this figure we can see that maximum temperatures are only slightly higher under the reference greenhouse, with an internal mobile shading screen, than under the simulated cover with a switchable filter, only relevant during some days of the summer months. This is the period when the screen is more extensively used and external temperatures are higher. Since the mobile screen is located inside the greenhouse it decreases air exchange by natural ventilation in relation to the filter, which is in directly in the cover and does not interfere with air exchange. Therefore, temperatures become higher under the screen. However, given the smoothness of Dutch summers compared to other latitudes previously analyzed, such as the tropica lowland regions, the total number of hours at high temperatures is relatively limited (Table 3.18). It summarizes the number of hours that the greenhouse air temperature is above a physiologica threshold of 28°C for anthurium, under the 2 evaluated scenarios along the whole cycle and for the exterior climate.

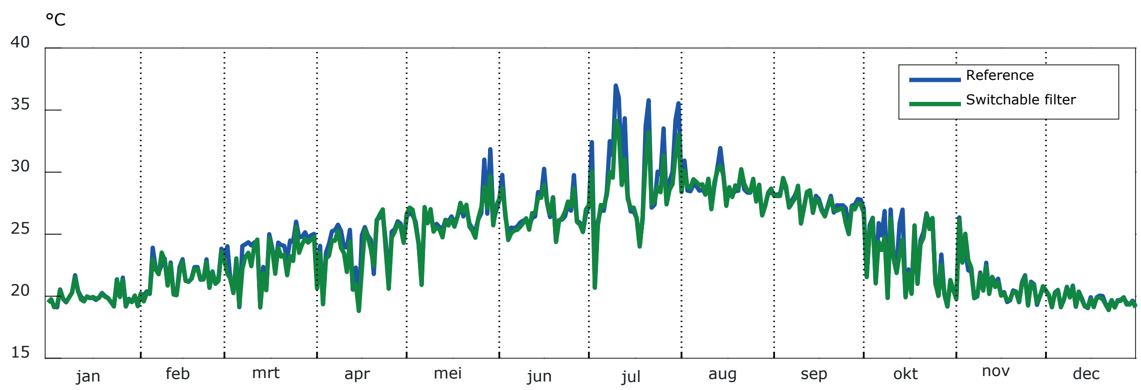

Figure 3.43 *Evolution of daily maximum air temperatures (°C) along the growing cycle under the 2 evaluated scenarios: reference-shading screen and the switchable non-selective filter.*

Table 3.18
Summary of hours that greenhouse air temperature (°C) is above a physiological threshold for affected dry matter production and quality for anthurium under each one of the evaluated scenarios on a Venlo type greenhouse for de Bilt (The Netherlands) and outside.

	Hours that Tair>28°C
Outside	54
Reference (shading screen)	326
Switchable filter	275

Regarding the daily minimum temperatures, they are almost exactly the same all along the growing cycle to the use of the simulated heating system, which has enough power to maintain the established set points (Figure 3.44). However, in the simulated reference scenario, the shading screen is also used at night for energy savingin combination with the energy saving screen. Therefore, the energy use for heating must be higher when a switchable filter is used, as only one energy saving screen is used Table 3.19 gives the energy used for heating in both scenarios in m^3/m^2 of natural gas confirming the previous statement. This means that if growers would want to use a switchable non selective filter for this crop, instead of a shading screen, they should maybe also consider the acquisition of a second energy saving screen to compensate for the increase in energy use.

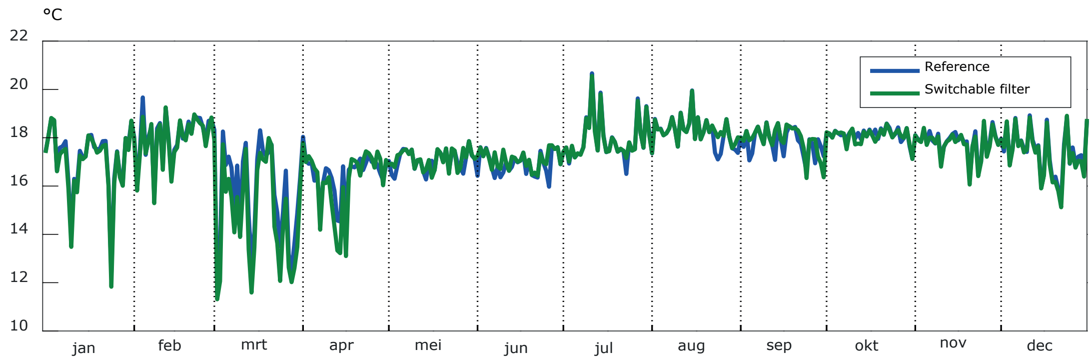

Figure 3.44 *Evolution of daily minimum air temperatures (°C) along the growing cycle under the 2 evaluated scenarios: reference-shading screen and the switchable filter.*

Table 3.19
Total energy use for the two simulated scenarios.

	Gas use (m^3/m^2)
Reference (shading screen)	35.3
Switchable filter	38.3

3.3.3.2 Effect on CO_2 concentration

The presence of the shading screen represents a barrier for energy and mass exchanges between the lower and top compartment when it is used, and therefore, decreases the air exchange by natural ventilation in the greenhouse. This has an effect on the internal CO_2 concentrations (Figure 3.45).Indeed, simulation shows that CO_2 concentration is slightly higher under the cover with the switchable filters. The explanation could be that screen is insulating more, so even if the amount of energy to discharge is the same, more will have to go through the windows to maintain the temperature set points.

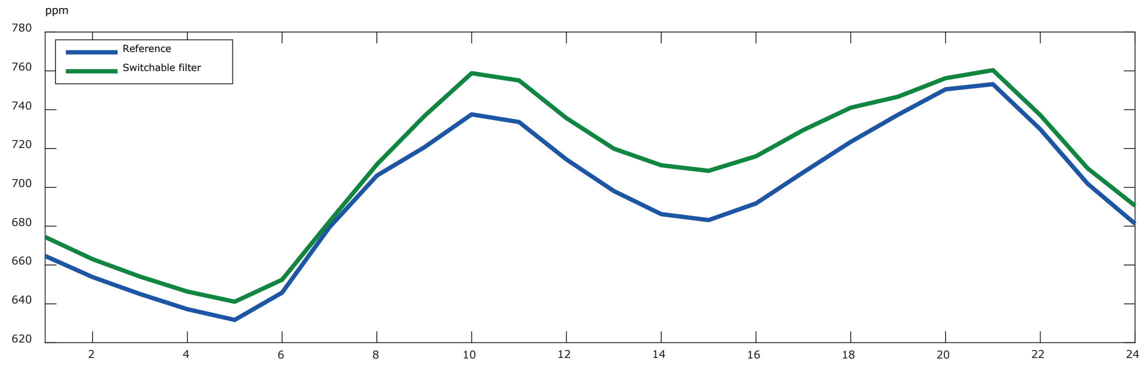

Figure 3.45 *Daily cyclic mean of CO_2 concentration (ppm) in the greenhouse under the 2 evaluated scenarios (with artificial CO_2 enrichment).*

3.3.3.3 Effect on dry matter productivity

The accumulated sum of biomass (dry matter) production (kg/m^2) under the 2 analyzed scenariosis shown in Figure 3.46. The use of the switchable filter induces a small increase in dry matter production, thanks to the reduced need for ventilation, and as a consequence,higher CO_2 concentrations inside the greenhouse. The simulated final dry matter production for the reference greenhouse is 4.2 kg/m^2, whereas for the switchable filter it is 4.4 kg/m^2. A later economic study should determine whether this yield increase compensates for the extra costs of the switchable filter in relation to the screen as well as the extra energy used for heating. However, for this crop other factors like quality and which can not be modeled could also be affected by the possibility of changing the ligth levels in a more inmedieate way.

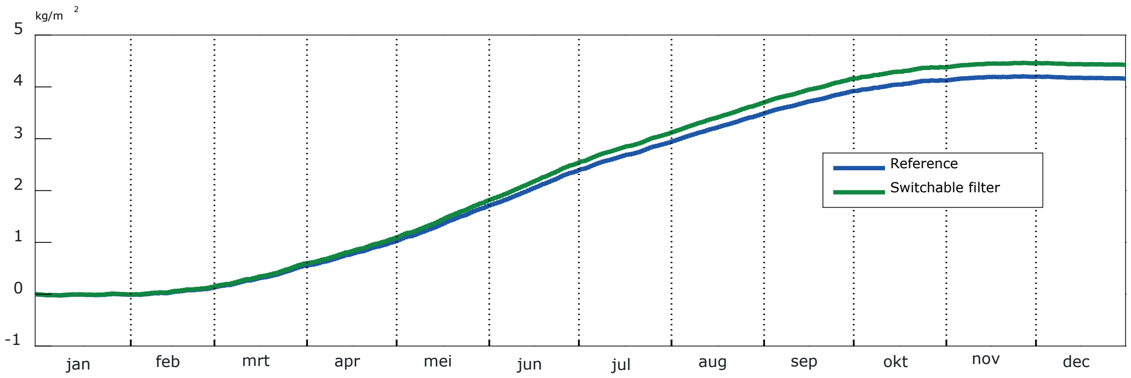

Figure 3.46 *Accumulated dry matter production along the cycle for both scenarios (kg/m^2)*

3.4 Conclusions

I. In mild winter climate regions (Agadir, Morocco), the simulations have shown that the use of switchable non-selective filters has improved internal microclimate in relation to the use of a temporary whitewash, for both a tradiational (far from optimal) greenhouse and for an improved greenhouse structure.

- The swithchable filters allows for a much more efficient management of PAR than the whitewash.
- Simulation results show that improving the greenhouse structure (mostly increasing its ventilation capacity) already causes a very important improvement in the greenhouse microclimate and should be prioritized before even considering the use of smart covers.
- The swithchable filters also allow for a very relevant reduction in the amount of hours that the greenhouse air temperature exceeds the thresholds than may cause a decrease in net photosynthesis and potentially induce physiological problems affecting fruit quality in tomato crops.
- The delayed activation filter (30°C) performs slightly better than early activation (28°C) for both simulated greeenhouse structures.
- As a consequence of the improved micrclimate, the crop growth model predicts an increase in potential yield with switchable filters of approximately 20% in relation to the use of a whitewash.
- An optimization of the activation moment of the filter could lead to an even larger increase in potential productivity.
- No synergy was observed between the application of artificial CO_2 in the greenhouse (CO_2 enrichment) and the use of the switchable filters.
- Further research would be required to elucidate what is the optimum shading factor for the switchable filters, since the results of the present study do not indicate a clear advantage of the 30% shading in relation to the 60% shading. The combination of modeling and a literature study shows that for a good ventilated structure the optimal shading value would be around 30%, whereas for a poorly ventilated greenhouse this value could be around 60%.

II. In tropical lowland regions (represented in this work by Kuala Lumpur, Malaysia) the switchable non-selective filters have been compared with the use of an external shading net. Results show little advantage of the filter being switchable.

III. Non selective shading is mostly used in cold climate regions for some ornamental crops, with low solar radiaton requirements for optimal production and quality, such as anthurium. In the present study, simulatioins have been done for de Bilt (The Netherlands), comparing the performance of an internal shading screen with the use of a switchable non selective filter in the cover for a Venlo glasshouse.

- Results indicate a very minor positive effect on summer peak temperatures and CO_2 internal concentrations, whis translates also in a very limited increase in dry matter production.

4 NIR selective filter

(decreasing transmission in the NIR band)

4.1 Introduction

A selective switchable filter, which increases NIR reflection of the cover has been simulated. In all cases, it has been assumed that NIR represents 50% of the global radiation. A necessary observation is that even imperfect NIR selective filters would need to reflect a large portion of the NIR, as otherwise the already high crop reflectivity for NIR would induce multiple reflections between the cover and the crop, in fact "trapping" the NIR radiation, which would limit their effectiveness (Stanghellini *et al.* 2011).

For the the various climates different non selective reference scenarios have been simulated (whitewash, shading screens and even no shading at all). An additional reference has been added, a cover with a permanent NIR filter with 100% reflection. Two switchable NIR filters have been simulated, one which fully reflects NIR and one that reflects 50% NIR, both with no effect in decreasing PAR transmission (to explore the potential of an optimum material). It is important to highlight, that when a filter is not reflecting a very large fraction of the NIR, the fraction of NIR transmitted is to a large extent, reflected back from the crop (leaves have a rather large NIR reflectivity, close to 50%) and subsequently, re-reflected back from the cover and so on. Thus, a large fraction of the transmitted NIR is trapped inside the greenhouse. Final effect on greenhouse air temperature of such a partially reflecting filter is very limited.

Two more realistic scenarios with 10% decrease in PAR transmission have also been simulated, though not analyzed in detail. Simulations have been done for the same 3 different locations (climate regions) analyzed in the previous section, plus a desert climate location, represented by Riyadh (Saudi Arabia).

Table 4.1 summarizes all the simulations that have been done for the switchable selective NIR filter. As for the non-selective filter, the swithcable NIR reflection filters are are triggered when the internal air temperature reaches threshold value.

Crop parameters:

- Tomato growing cycle: Planting date 15-08 and end of cycle 15-06 (For Agadir).
- Tomato growing cycle: Planting date 23-12 and end of cycle 1-12 (For de Bilt).
- Tomato growing cycle: Planting date 01-01 and end of cycle 15-12 (For Kuala Lumpur).
- Tomato growing cycle: Planting date 01-01 and end of cycle 15-12 (For Riyadh).

The simulated greenhouse types and their cover properties as well as the climate data sets used are the same as those already described in the previous section for the non-selective filters. The same applies for the climate set points. For the closed greenhouse in Riyadh, a cooling power of 700 W/m^{-2} was simulated. A boiler with a maximum heating power of 80 W/m^2 was also used for heating in this location during the winter using a typical Dutch metallic pipe heating system.

Table 4.2 is a summary of the most important set points used in the simulation for heating, active cooling, CO_2 enrichment and the fogging system in this location and for the closed greenhouse case.

Table 4.1

Summary of scenarios to be simulated in the analysis of the NIR selective switchable filter.

	Regions	Year	Crops	Greenhouse type		Shading/filter activation temperature/s set point (°C)		CO_2 enrichment simulation
Reference						Whitewash*		
Permanent NIR filter (100%)						Permanent°		
Switchable 100% NIR reflection	Agadir (Marocco)	2010	Tomato	Canarian	Venlo			Only in Venlo scenarios
Switchable 100% NIR reflection-10% PAR reduction						28°C/30°C Canarian	28ºC Venlo	
Switchable 50% NIR reflection								
Reference						No shading		
Permanent NIR filter (100%)								
Switchable 100% NIR reflection	De Bilt (The Nether-lands)	SEL2000	Tomato	Venlo (Glass)				Yes
Switchable 100% NIR reflection-10% PAR reduction						28°C		
Switchable 50% NIR reflection								
Reference						Fixed external shading screen		
Permanent NIR filter (100%)						Permanent°		
Switchable 100% NIR reflection	Kuala Lumpur (Malaysia)	2010	Tomato	Venlo PE film		28ºC		No
Switchable 50% NIR reflection								
Reference						No shading		
Permanent NIR filter (100%)	Riyadh (Saudi Arabia)	2015	Tomato	Venlo closed greenhouse (glass cover)	Venlo pad and fan (glass cover)	Permanent		Yes in closed greenhouse simulation
Switchable 100% NIR reflection						24°C/28°C		

* To decide on date of application of whitewash, a simulation has been made in which no shading is used, and then weekly cyclic mean of greenhouse air temperature has been calculated to find when greenhouse temperature is above 30°C more than 5 hours per day. That is taken as the activation day of whitewash, which is removed when greenhouse temperature values above 30°C happens for less than hours per day.

In desert climates, the standard greenhouse relies more on evaporative cooling rather than on active cooling, due to large investment and running costs associated to the latter, despite of the water scarcity typical of these regions. The standard system cooling system is thus, the pad and fan. Given the large scarcity of water, any system that can help to save water while not affecting too much yield potential is of large interest.

Obviously, for the pad and fan simulation, we have deactivated the fogging option as well as the CO_2 enrichment. Also the cooling set point has been risen to 28°C, in order to save as much water as possible. We have tested a fan capacity of 180 m^3/m^2 h, and a pad efficiency of 85%, typical values for a commercial pad and fan installation for the conditions in Riyadh.

Table 4.2
Most relevant set points used for the different climate control equipment used in the simulations of the closed greenhouse.

Heating temperature set point (day/night):	21 18	°C
Activation time:	Sunrise Sunset	
Cooling temperature set point:	25 19	°C
Set point Rel. Hum.:	85	%
Set point CO2:	800	ppm
CO_2 source:	Pure	
CO_2 dosing capacity:	150	Kg/ha h
Fogging dose:	300	gr/m^2 h
Min. Temp. Fogging*:	15	°C
Min. Rel. Hum.**:	70	%

* Fogging is only activated in closed greenhouse and only when temperature is above this set point.

**Fogging is only activated in closed greenhouse and only if relative humidity drops below this set point.

4.2 Results

4.2.1 A local (Canarian) greenhouse in Agadir (Morocco)

A switchable perfect NIR reflection filter would have the advantage of eliminating a part of the spectrum that only contributes to warming up of the greenhouse air and to a certain extent, of the canopy, without affecting PAR transmission, only during the warm periods of the growing cycle, allowing for NIR radiation to enter the greenhouse during the winter, which in passive greenhouse, such as the Canarian type, is essential to ensure some daytime heat storage. This enables maintaining night-time greenhouse temperature above outside, preventing thermal inversion.

4.2.1.1 Effect on greenhouse air temperature

First microclimate parameters to examine is temperature, as the NIR switchable filter aims to decrease peak values by removing a large fraction of the solar energy. Figure 4.1 shows the daily maximum simulated greenhouse air temperatures under the reference scenario (whitewash) and with the NIR-selective perfect filter switched at temperatures of 28°C and 30°C, respectively. The two vertical black lines represent the moments where whitewash was removed (1-10-2010) and applied again (29-3-2010) respectively, in the reference greenhouse. Three different periods delimited by the application/removal of the whitewash in the reference greenhouse can be indentified.

During periods 1 and 3, those with a whitewash coating in the cover of the reference greenhouse, greenhouse air temperatures under the two covers with a perfect NIR switchable filter (no PAR reduction) and with the permanent perfect filter exceed those obtained under the reference-whitewash greenhouse. Ovbiously, reduction of half of the incoming energy to zero when filter is activated, is less effective to decrease temperature than the whitewash, which cuts off in the whole solar spectrum.

During the second period, the whitewash has been removed from the reference greenhouse, and now peak temperatures are slightly lower under the switchable filters. For the permanent filter reudction in temperatuer is much higher since the NIR radidation is cut during all daytime hours. In fact, this may have a negative effect in a passive greenhouse, as the greenhouse welcomes part of the NIR energy in winter, in order to gain heat storage in the soil and increase night time temperatures. In addition, since the Canarian greenhouse is poorly ventilated, switchable filters activate even during the colder months because their threshold activation points are exceeded, juts like we saw in the previous section with the non-selective filters. Only in this case, PAR is still allowed inside (with consequent benefit for photosynthesis), so temperature decrease is lower, since the reference greenhouse gets all the spectrum from the sun.

Table 4.3 summarizes the number of hours that the greenhouse air temperature is above a threshold of 31°C under the 4 evaluated scenarios along the whole cycle.

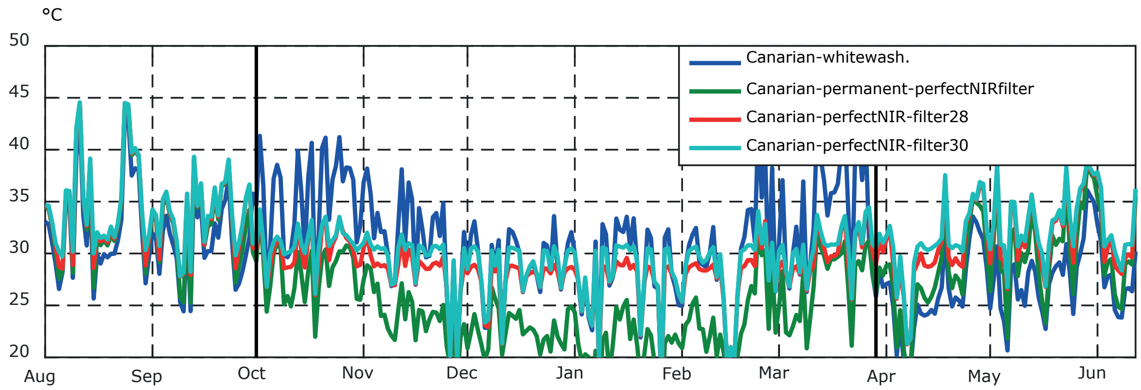

Figure 4.1 *Evolution of daily maximum air temperatures (°C) along the growing cycle under the 4 evaluated scenarios: reference-whitewash, permanent NIR filter and the two perfectly NIR reflecting switchable filters with activations temperatures of 28°C and 30°C.*

Table 4.3

Summary of hours that greenhouse air temperature (°C) are above a physiological threshold for affected dry matter production and quality under each one of the evaluated scenarios on a Canarian type greenhouse for Agadir (Morocco).

	Hours that Tair>31ºC
Reference (whitewash)	533
Permanent NIR filter	318
Switchable filter (28°C)	424
Switchable filter (30°C)	507

The simulations show that the number of hours in which greenhouse air temperatures exceed a physiological threshold for which tomato crop productivity and quality are affected is lower for the NIR permanent filter, as this filter is reflecting all the NIR during the whole cycle. For thie rest of scenarios, values are quite similar, although the early activation NIR filter ensures slightly less hours at non optimal temperatures than the late activation filter or the whitewash (Table 4.3).

The use of switchable NIR filters does not have major effect on minimum temperatures (Figure 4.2). This is specially true during the first two growing periods, but during the third period, when relatively warm days are followed by still relatively cool nights, some small differences occur. On these days, the reference greenhouse (with a permanent whitewash) receives a lower daytime radiation sum than the greenhouses with the perfect NIR switchable filters. Since we are simulating a passive greenhouse, witohout any automation in the ventilation, the greenhosue ventilates always equally despite of what is the greenhouse air temperature, thus, the heat stored in the soil during the daytime is lower than under the two switchable filters, resulting in lower night temperatures. If we look at the permanent NIR filter, which is cutting the energy load in the greenhouse permanently during the whole daytime period, the same effect on decrased energy storage in the soil is observed in the third period, and even more marked in winter, thus inducing the coldest climate inside the greenhouse during the winter months. We can also see this on Figure 4.3 the 24 hours cyclic mean of the temperatures for the third period. Summarizing, the combination for a mild winter climate region of a cover with a 100% NIR reflection filter in a passive greenhouse with non automated vents (which therefore can not remain closed to store more energy during daytime), induces lower night time temperatures, which is not a desirable effect.

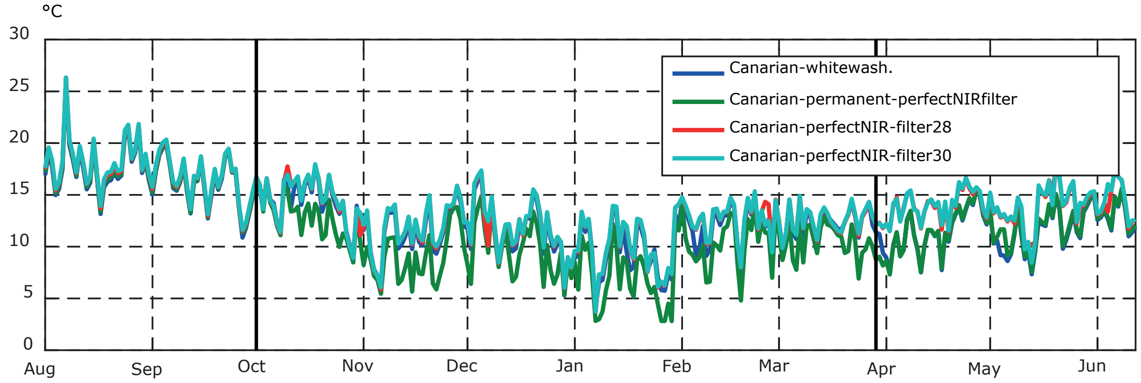

Figure 4.2 *Evolution of daily minimum air temperatures (°C) along the growing cycle under the 4 evaluated scenarios: reference-whitewash, permanent NIR filter and the two perfectly NIR reflecting switchable filters with activation temperatures of 28°C and 30°C.*

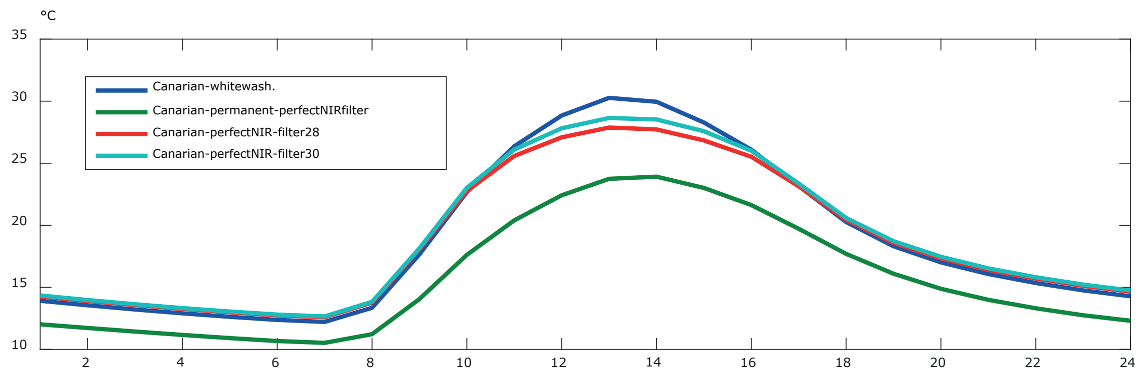

Figure 4.3 *Daily cyclic mean of greenhouse air temperature (°C) during the second period (October-March) under the 4 evaluated scenarios: reference-whitewash, permanent NIR filter and the two perfectly NIR reflecting switchable filters with activations temperatures of 28°C and 30°C.*

4.2.1.2 Effect on PAR available for the crop and NIR

Essentially, the main advantage of a perfect NIR selective reflection filter in relation to a non-selective filter is that when the filter is activated, NIR radiation (which does not contribute to photosynthesis) is reflected, helping to control greenhouse air temperatures, whereas PAR radiation transmission is essentially unaffected. And this is proved when we look at Figure 4.4, which shows the 24 hours cyclic mean of PAR radiation (micromoles/m^2 s) available for the crop under the 4 evaluated scenarios for period 1. Period 3 can be considered similar to period 1 and in period 2 the amount of PAR transmitted is obviously the same for the 3 cases.

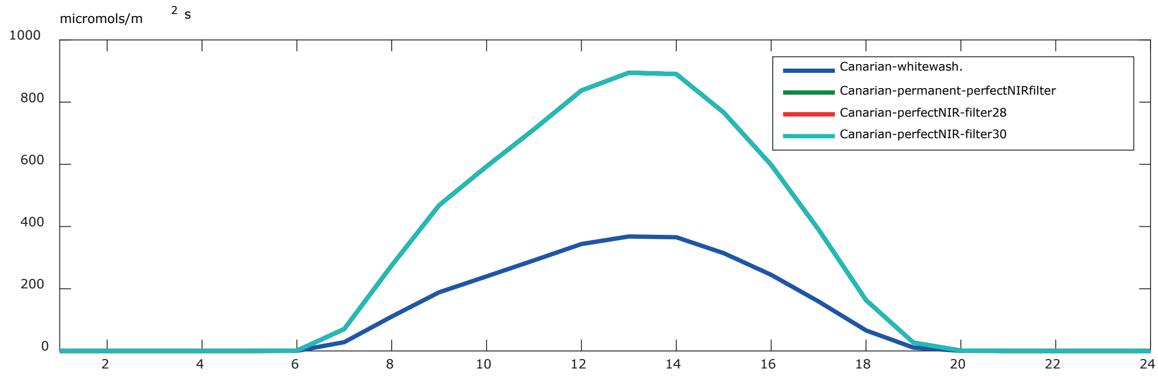

Figure 4.4 *Daily cyclic mean of available PAR for the crop (micromoles/m^2 s) during the first period (1st August-1st October) under the 4 evaluated scenarios: reference-whitewash, permanent NIR filter and the two perfectly NIR reflecting switchable filters with activations temperatures of 28°C and 30°C.*

Sure enough, during the first period, the amount of PAR available for the crop is much higher under the covers with the perfect NIR switchable filters and the permaneant NIR filter than under the reference whitewash.

The accumulated values of PAR radiation (mol/m^2) along the whole growing cycle indicate, as expected, no differences in accumulated PAR radiation between the filters activated at different temperatures and the permanent filter, because PAR transmission remains unaltered despite of filters been activated or not. However, PAR transmission of the reference greenhouse is lower due to the permanent nature of the whitewash during periods 1 and 3 (Figure 4.5).

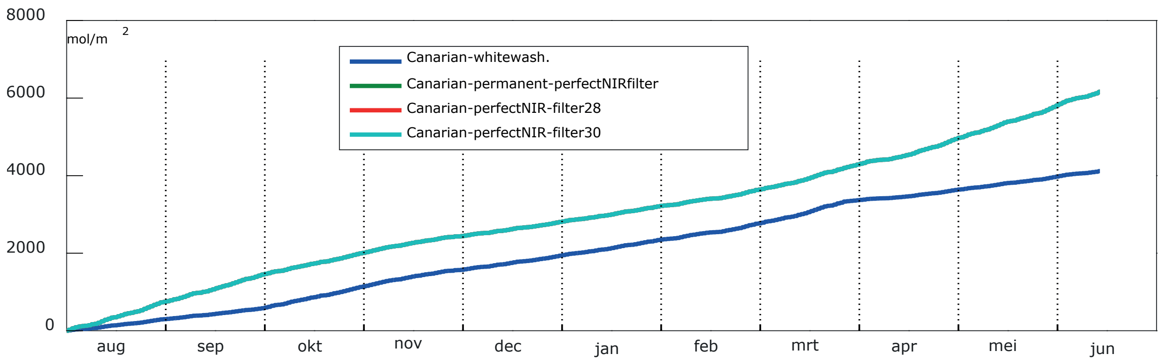

Figure 4.5 *Accumulated values of PAR (mol/m^2) available for the crop along the growing cycle for the 4 evaluated scenarios.*

Finally, it is of interest to verify the functioning of the switchable perfect NIR filters. In Figure 4.6 the hourly values of NIR transmitted radiation for a period of a few days during period 1 (warmest of the growig cycle) are shown. The figure clearly shows how the filters completely cut NIR transmission when they are activated, and go back to normal NIR transmission when deactivated, whereas the permanent NIR filter is always completely cutting NIR.

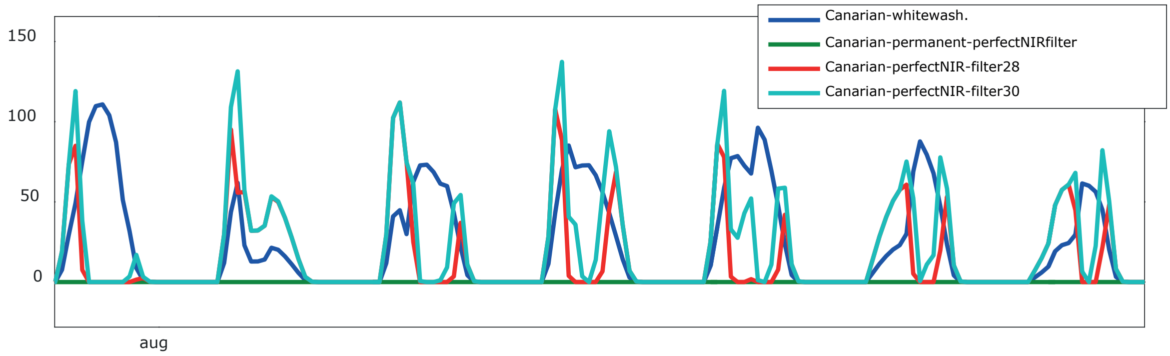

Figure 4.6 *NIR transmitted inside the greenhouse during some days at the beginning of the cycle under the 4 evaluated scenarios.*

4.2.1.3 Effect on tomato productivity

For the analysis of productivity, other variants of the perfect NIR filter have been analyzed. A perfect 100% NIR reflection filter, but with a 10% reduction in PAR transmission and a 50% NIR reflection filter, with no effect on PAR transmission, have also been simulated.

For the sake of clarity, results have been divided in two graphs: a first one (Figure 4.7) shows the comparison for the 28°C activiation filters, whereas the sencond one (Figure 4.8) shows the comparison for the 30°C activation filter.

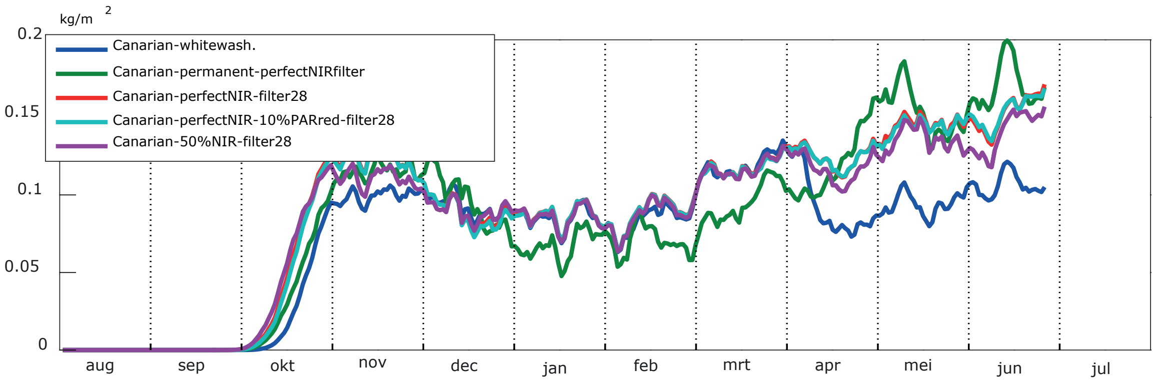

Figure 4.7 *Evolution of daily tomato fresh weight production (kg/m²) with 28°C activated NIR filters and the reference withewash.*

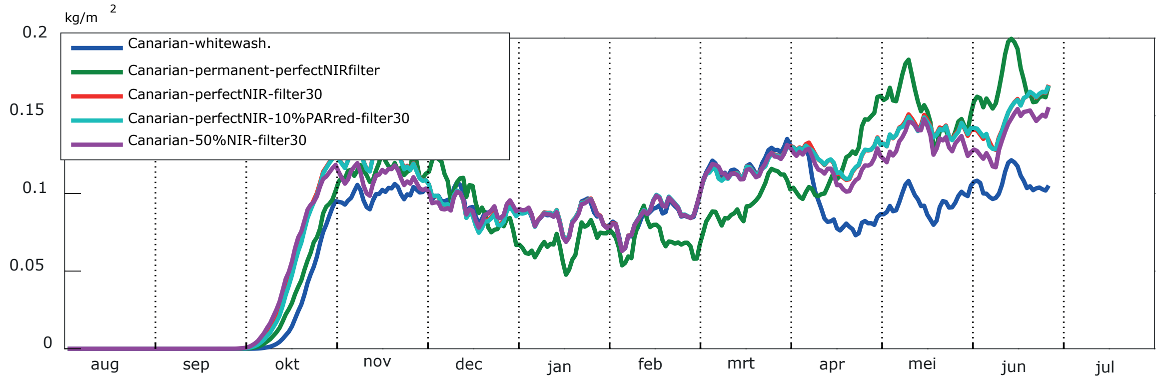

Figure 4.8 *Evolution of daily tomato fresh weight production (kg/m²) with 30°C activated NIR filters and reference whitewash.*

In both cases, the simulated NIR filters, exhibit a potential increase of both final productivity but also on earliness in relation to the reference whitewash, with the 100% reflections filters overperforming the 50% filters, and with minor differences between the NIR filter that does not affect PAR transmission and the one decreasing 10% PAR transmission. The last can be attributed to the fact that in this type of traditional greenhouse there are limiting factors during many moments of the growing cycle (high temperatures) which limit the positive effect that extra PAR can have on dry matter production. The permanent filter also induces a slight advance in harvest, though lower than the switchable filters, a poorer performance during the winter, in virtue of the colder climate and a better performance during may and June, when for this greenhouse, cutting NIR permanently during the warm months is a good solutions. This suggests also that for the switchable filters it would be better to have an earlier activation temperature in this period.

Table 4.4 summarizes the final tomato yield obtained for each simulated scenario, showing that the best performer is the 100% reflection filter with no detrimental effect on PAR transmission, activated at 28°C. The poorest performer is the 50% NIR reflection filter activated at 30°C. For this type of greenhouse the increase in yield of the best performing filter improves the increase on yield of the non-selective filter. Finally, the model shows that the increase in yield obtained with the use of NIR perfect filters is not substantially higher than that obtained with a non-selective filter (also around 20%), despite of the crop receving a considerable higher amount of PAR radiation. The explanation can be found in the fact that the greenhouse is poorly ventilated, so other limiting factors such as high temperature and even CO_2 concentration are prenventing the tomato crop from making a profitable use of the extra PAR received. It is therefore very interesting to analyze the performance of this same filters in an improved structure with optimized natural ventilation.

Table 4.4

Summary of final tomato potential yields simulated under each one of the evaluated scenarios on a Canarian type greenhouse for Agadir (Marocco).

	Final yield (kg/m²)	Increase/decrease in yield (±%)
Reference (whitewash)	23.3	---
Permanent NIR filter	26.2	+12.4
Switchable perfect NIR filter (28°)	28	+20.2
Switchable perfect NIR filter (28°)-10% PAR reduction	27.8	+19.3
Switchable perfect NIR filter (30°C)	27.6	+18.4
Switchable perfect NIR filter (30°C) -10% PAR reduction	26.8	+15
Switchable 50% NIR filter (28°)	27.5	+18
Switchable 50% NIR filter (30°C)	26.6	+12.4

4.2.2 Improved greenhouse structure (Venlo-plastic film) in Agadir, Morocco.

The following section analyzes the effect of switchable NIR reflecting filters in an improved greenhouse structure, a Venlo plastic greenhouse, which has a much more efficient natural ventilation system, and therefore, should have less hours at critically high temperatures, and higher supply of external CO_2 due to higher ventilation rates. Since for the Canarian type greenhouse, it was proved that the 28°C activation point filter performed better than the 30°C filter, only the 28°C activation point filter has been simulated for this greenhous type. As discussed in §1.3.2, a major effect of the improved ventilation is a reduction in the period whitewash needs to be applied.

4.2.2.1 Effect on greenhouse air temperature

In the more efficiently ventilated greenhouse, differences in maximum temperatures are almost inexistent between the whitewash and the switchable filter during periods 1 and 2, whereas during period 3, the whitewash ensures a better control of air temperatures when they do not exceed the activation point, but when they exceed the thresholds, the filters are activated and almost equal values are obtained. It is remarkable to see that the improved ventilation capacity prevents almost completely the activation of the filters during the cold months, very much different from the Canarian greenhouse (Figure 4.9). Differences in period 3 occur when peak temperatures do not reach the activation points, in which case, the whitewash greenhouse remains colder, given the permanent shading. During winter, maximum temperatures are consistently lower under the permanent filter, as expected.

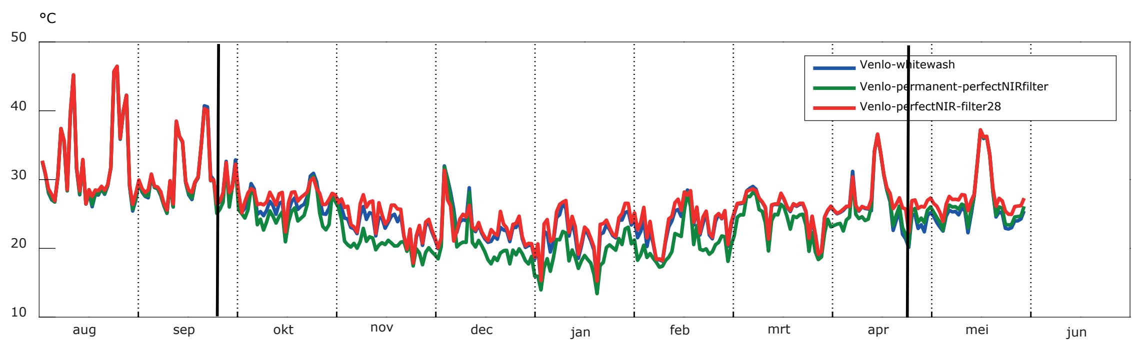

Figure 4.9 *Evolution of daily maximum air temperatures (°C) along the growing cycle under the 2 evaluated scenarios of perfect NIR filter with no PAR reduction: reference-whitewash and the two NIR reflecting switchable filters with an activation temperature of 28°C.*

Table 4.5 summarizes the number of hours that the greenhouse air temperature is above a threshold of 31°C under the 2 evaluated scenarios along the whole cycle.

Table 4.5
Summary of hours that greenhouse air temperature (°C) are above a physiological threshold for affected dry matter production and quality under each one of the evaluated scenarios for a Venlo type greenhouse for Agadir (Marocco).

	Hours that Tair>31ºC
Reference (whitewash)	229
Permanent NIR filter	237
Switchable filter (28 °)	242

Overall, the number of hours at risky temperatures for a tomato crop is quite similar under the three analyzed scenarios, only slightly higher under the switchable perfect NIR reflecting filter (Table 4.5), mostly caused during period 3, as we saw in Figure 4.9.

Non significant differences in daily minimum temperatures are observed along the whole growing cycle, except for the permanent filter, just as with the Canarian greenhouse, although in this case, the effect is compensated by a larger closing of the vents (less ventilation) during the daytime period. (Figure 4.10).

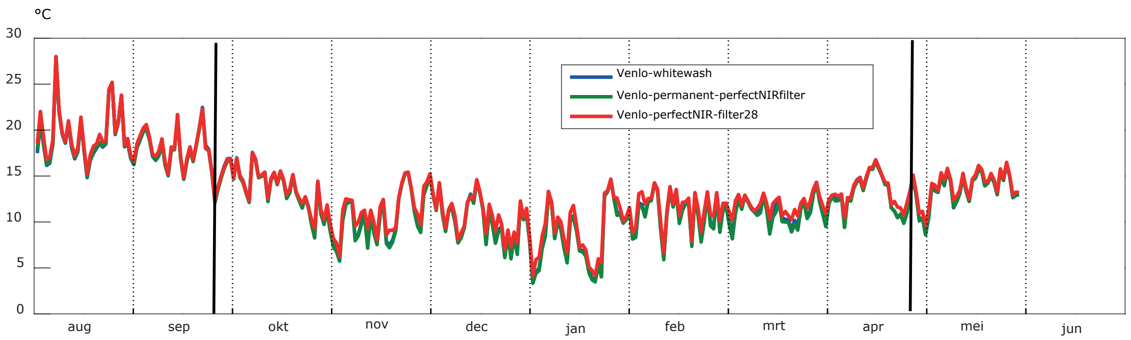

Figure 4.10 *Evolution of daily minimum air temperatures (°C) along the growing cycle under the 3 evaluated scenarios: reference-whitewash, permanent NIR filter and the perfect NIR reflecting switchable filter with an activation temperature of 28°C.*

4.2.2.2 Vents opening and CO_2 enrichment

In a greenhouse like the simulated Venlo, the possibility to automate the opening and closing of the greenhouse vents, may make CO_2 enrichment worthwhile. Thus, additional simulations were done, with a target set point of CO_2 concentration of 800 ppm (dosing capacity of 100 kg CO_2/ha h). The lower ventilation requirements of the greenhouse with a whitewash applied in the cover during periods 1 and 3, enables for slightly higher CO_2 concentrations than under the two simulated filters, for which no relevant differences are observed (Figure 4.11).

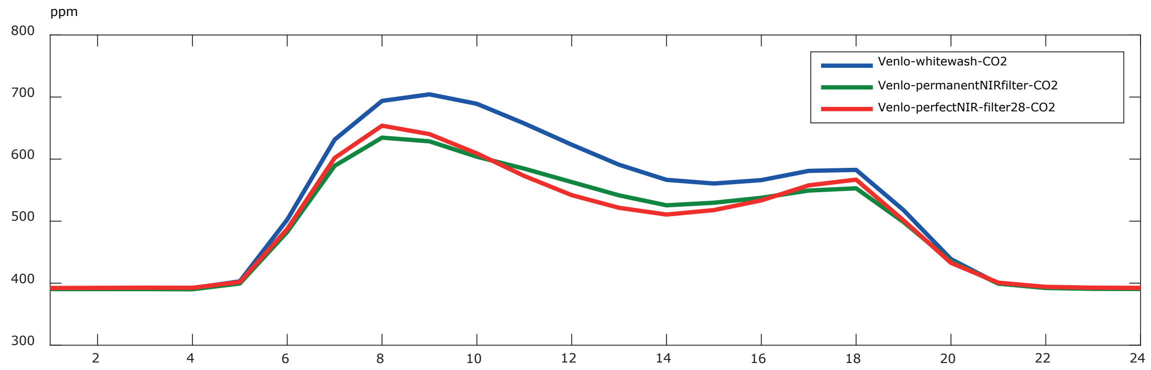

Figure 4.11 *Daily cyclic mean of CO_2 concentration (ppm) in the greenhouse with artificial CO_2 enrichment along the whole cycle under the 3 evaluated scenarios.*

4.2.2.3 Effect on tomato productivity.

In a similar way as for the Canarian type greenhouse, productivity analysis has incorporated other variants of the NIR filter: a perfect 100% NIR reflection filter with a 10% reduction in PAR transmission, and a 50% NIR reflection filter, with no effect on PAR transmission.

To simplify the graphs, the productivity results of simulations with and without artificial CO_2 enrichment are shown in separate graphs. The first one (Figure 4.12) shows comparison without artificial CO_2 enrichment, whereas the second (Figure 4.13) shows the comparison when CO_2 is applied to the greenhouse air.

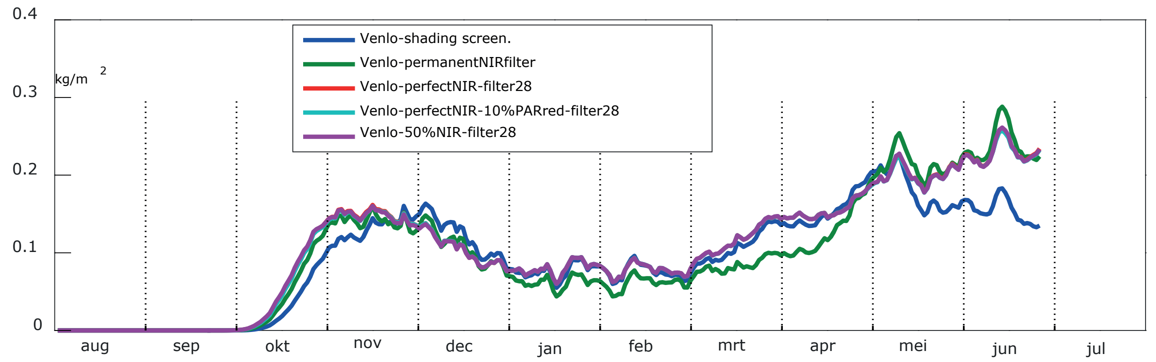

Figure 4.12 *Daily tomato fresh weight production (kg/m²) with 28°C activated NIR filters and reference (No artificial CO_2 enrichment).*

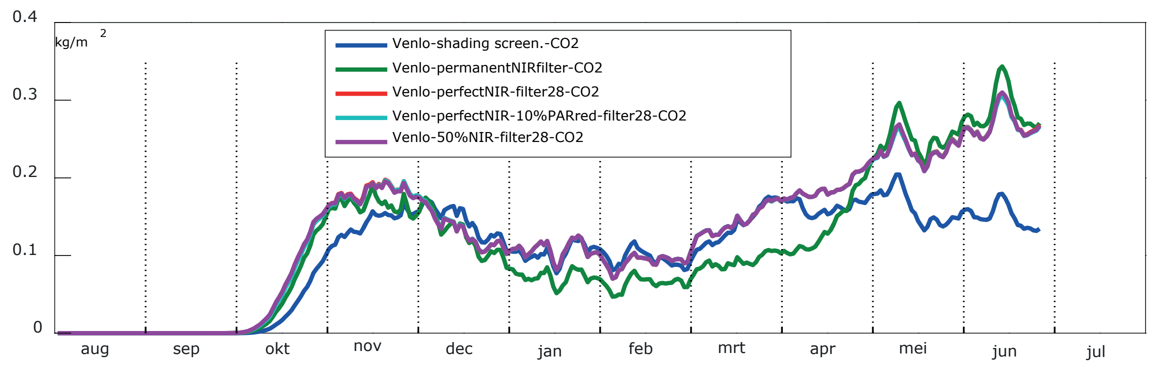

Figure 4.13 *Daily tomato fresh weight production (kg/m²) with 28°C activated NIR filters and reference (with artificial CO_2 enrichment).*

The productivity simulation results indicate that regardless of the artificial application of CO_2, the three switchable NIR reflecting filters perform quite similarly, and all of them improve the performance and earliness of a whitewash and a permanent filter (except during the last two months of the growing cycle), being the differences established on periods 1 and 3, when whitewash was present and temperatures were higher, which activated the filters.

Table 4.6 summarizes the final tomato yields obtained for each simulated scenario, showing that almost negligible differences for the performance of the different tested switchable NIR filters, followed by the permanent NIR filter, which improves the whitewash, but certainly not the switchable filters, especially because of poor winter performance. For this type of greenhouse the increase in potential yield of the NIR filters is in percentage very similar to that observed for the Canarian greenhouse when no artificial CO_2 is applied. The problem is that when NIR filters are activated during the warm season, temperatures and also CO_2 concentration in the greenhosue are still a limiting factor for photosythesis, so the extra PAR cannot be efficiently used. This is proved by the fact that the percentage increases in yield observed when filers are used, and CO_2 is artificially applied, are slightly higher than when not, as CO_2 is no longer a limiting factor. Possibly adding extra [evaporative] cooling, would also enable a higher yield increase under the filters.

Finally, when compared with the non-selective filters, the NIR filters exhibit in general a slightly higher performance in both greenhouse types, thanks to the extra PAR available when filters are active, although we have seen that in oder to make the most use of it, other limiting factors such as ventilation and CO_2 enrichment should be optimized.

Table 4.6

Summary of final tomato potential yields simulated under each one of the evaluated scenarios on a Venlo type greenhouse for Agadir (Marocco).

	Final yield (kg/m^2)	%
Reference (whitewash)	27.7	-
Permanent NIR filter	30.5	+10.2
Switchable perfect NIR filter (28 °)	33.1	+19.5
Switchable perfect NIR filter (28 °)-10% PAR reduction	33	+19.1
Switchable 50% NIR filter (28 °)	33.1	+19.5
Reference (whitewash)-CO2	32.3	-
Permanent NIR filter	35.3	+9.3
Switchable perfect NIR filter (28 °)-CO_2	40.1	+24.1
Switchable perfect NIR filter (28 °)-10% PAR reduction-CO_2	40	+23.8
Switchable 50% NIR filter (28°C)-CO_2	40	+23.8

4.2.3 Cold climate region: de Bilt (The Netherlands)

The following section analyzes the effect of a perfect (100%) switchable NIR filter in a glasshouse structure, a tomato crop in a modern Venlo glasshouse. In this case, the reference scenario does not use any kind of shading during the whole cycle, given the smoothness of the Dutch summers.

4.2.3.1 Effect on greenhouse air temperature

In a Dutch greenhouse, with a fully developed tomato crop, the number of days that air temperatures exceed the thresholds for optimum productivity are quite scarce (Table 4.7). The NIR reflecting filter is only activated during a few days, and of course it helps decreasing the already relatively low peak temperatures. The rest of the year, the temperatures are not high enough to activate the NIR reflection filter, and therefore, no differences occur (Figure 4.14).

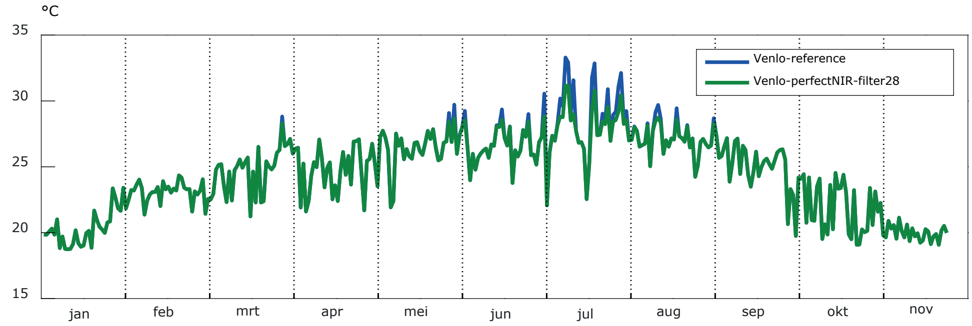

Figure 4.14 *Evolution of daily maximum air temperatures (°C) along the growing cycle under the 2 evaluated scenarios of perfect NIR filter with no PAR reduction: reference and the NIR reflecting switchable filter with activation temperature of 28°C.*

Table 4.7

Summary of hours that greenhouse air temperature (°C) are above a physiological threshold for affected dry matter production and quality under each one of the evaluated scenarios on a Venlo type glasshouse for De Bilt (The Netherlands).

	Hours that Tair>28°C
Reference (whitewash)	87
Switchable filter (28°)	35

4.2.3.2 Effect on tomato productivity.

Again, for the analysis of productivity, we have included the same variations analyzed in the previous sections of the perfect NIR reflecting filter: A perfect 100% NIR reflection filter with a 10% reduction in PAR transmission and a 50% NIR reflection filter, with no effect on PAR transmission.

We have previously seen that the filters are activated only during very limited moments during the cycle, and that translates in the fact that the have a negligible effect on dry matter production (Figure 4.15). Only in an unusually hot summer, this filter could have shown some clear advantage.
Indeed we must also take into account that the climate year used, sel2000, is ¨colder¨ than recent years, where summers with more episodes of high temperatures have occurred as a consequence of climate change. In any case, the potential of these filters is higher in much warmer regions which makes it use in Dutch greenhouses almost unnecessary, at least for crops with relatively high optimum temperatures for growth and development, such as most fruit crops.

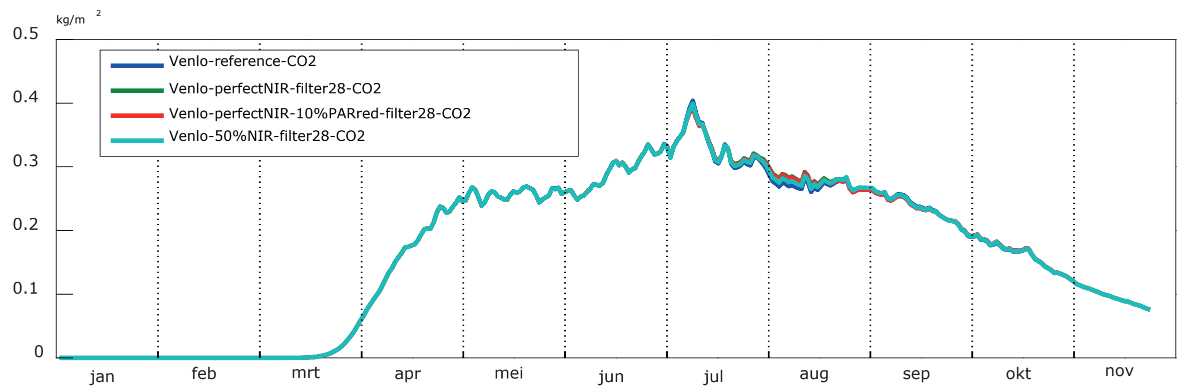

Figure 4.15 *Daily tomato fresh weight production (kg/m²) with 28°C activated NIR filters and reference with no shading.*

Table 4.8 summarizes the final tomato yields obtained for each simulated scenario

Table 4.8
Summary of final tomato potential yields simulated under each one of the evaluated scenarios on a Venlo type greenhouse for De Bilt (The Netherlands).

	Final yield (kg/m^2)
Reference	57.3
Switchable perfect NIR filter (28°C)	57.6
Switchable perfect NIR filter (28°C)-10% PAR reduction	57.5
Switchable 50% NIR filter (28°C)	57.4

4.2.4 Tropical lowland climate region: Kuala Lumpur (Malaysia)

Given the very extreme climate in this region, with year round high radiation levels and temperatures, the use of a perfect (100%) NIR reflecting switchable filter, in an improved greenhouse structure (a Venlo plastic greenhouse) might yield positive results, when compared with the use of a fixed external shading screen, with the possible advantage of allowing PAR radiation inside the greenhouse.

4.2.4.1 Effect on greenhouse air temperature

Under the shading screen we observe consistently very similar peak temperatures than under the perfect NIR reflecting switchable and permanent filters. This happens despite of the non-selectivity of the screen, which cuts off both PAR and NIR. The explanation lies in the fact that in all cases, very similar amount of solar energy is reflected in the cover of the greenhouse (Figure 4.16).

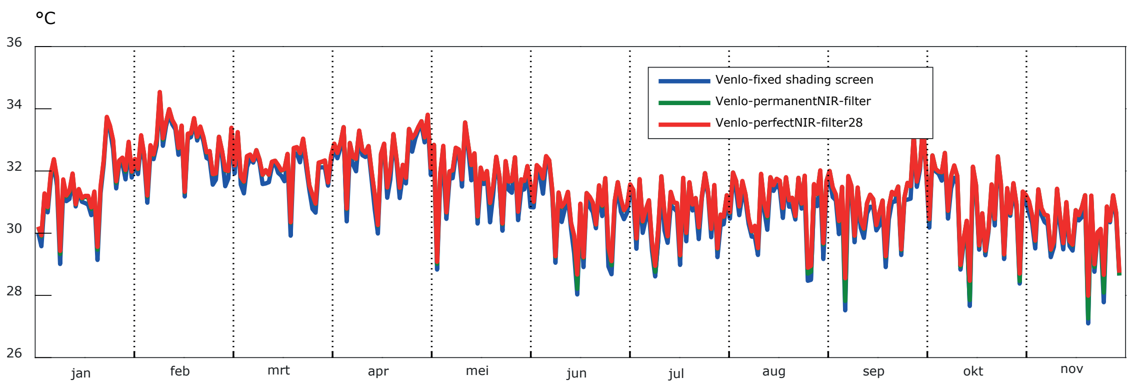

Figure 4.16 *Evolution of daily maximum air temperatures (°C) along the growing cycle under the 3 evaluated scenarios of perfect NIR filter with no PAR reduction: reference internal mobile shading screen, permanent NIR filter and the switchable filter with activation temperature of 28°C.*

The decrease in peak temperaures caused by the NIR reflecting switchable filters, though notable, is less pronounced that the one obtained with non-selective filters and lower than that obtained with a fixed external shading screen. Certainly, part of the PAR radiation transmitted when the PAR filter is activated is also contributing to increase temperature as not all is intercepted by the crop.

Table 4.9
Summary of hours that greenhouse air temperature (°C) are above a physiological threshold for highly affected dry matter production and quality under each one of the evaluated scenarios on a Venlo type greenhouse for Kuala Lumpur (Malaysia) and outside.

	Hours that Tair>31°C
Outside	958
Permanent filter	925
Reference (fixed shading scren)	772
Switchable filter (28°C)	934

4.2.4.2 Effect on PAR available for the crop

The fixed screen cuts during the whole period, both PAR and NIR transmission, which is not the case for PAR with the switchable NIR filter (Figure 4.17). However, temperatures are very high and limiting all along the cycle, so the extra PAR radiation may not have a positive effect on dry matter production, also because this extra PAR contributes to increase greenhouse air temperature, which was not the case with the non selective filters.

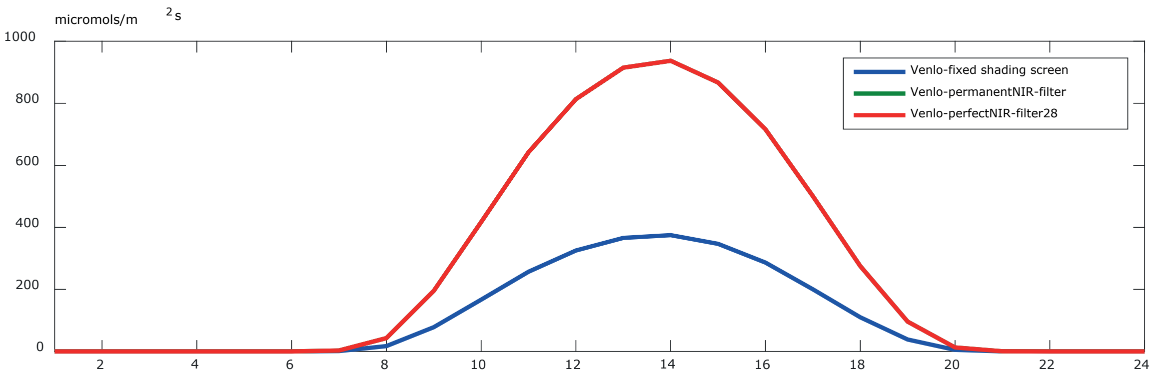

Figure 4.17 *Daily cyclic mean of available PAR for the crop (micromoles/m^2 s) during the whole growing cycle under the 2 evaluated scenarios: reference-shading screen and the switchable perfect NIR reflection filter with activation temperature of 28°C.*

4.2.4.3 Effect on tomato productivity

When we add the extra two variations of the NIR reflecting switchable filters (100% NIR reflection with 10% PAR reduction and 50% NIR reduction), and we obtain a very interesting picture of how these filters affect dry matter tomato production in an extreme tropical lowland climate and a large greenhouse. Figure 4.18 shows the comparison of the reference with the 3 simulated NIR switchable filters.

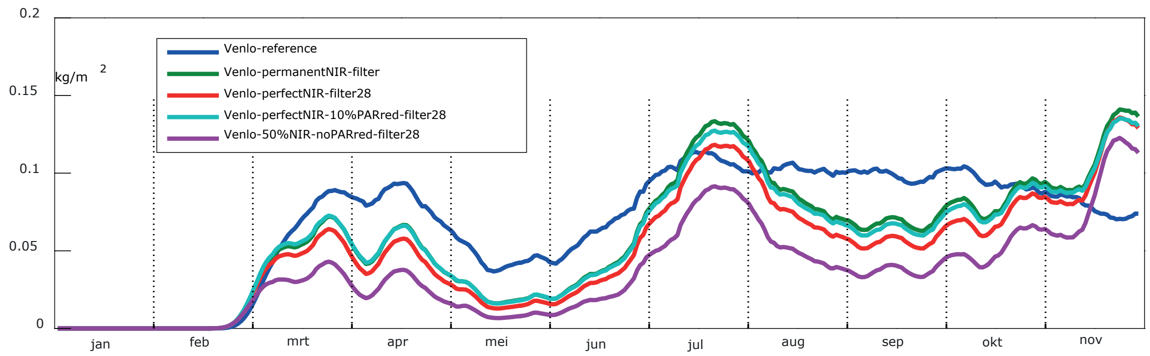

Figure 4.18 *Daily tomato fresh weight production (kg/m²) with 28°C activated NIR filters and reference.*

Surprising as it may look, the best performer is still the permanent external screen, followed by the permanent NIR filter and the switchable filter that reflects 100% NIR, but also a 10% of PAR, that is, the filter that cuts off the largest amount of solar energy. In fact, the decrease in 10% of PAR performs even better than the filter with no PAR reduction. The filter which only reflects 50% of the NIR radiation and has no effect on PAR transmission is the poorest performers. This is explained by the fact that, unless the filter is permanent, reflecting all NIR at a relatively high activation temperature is not enough in this climate to make greenhouse temperatures to drop below the threshold level for affected dry matter production. Therefore, cutting off an extra 10% energy in the form of PAR, has a better result in yield than letting it through, because the amount of this PAR that would be intercepted by the crop can not be efficiently used given the fact that temperatures (and CO_2) are limiting efficient net photosysthesis. And the part that is not intercepted contributes to increasing temperature even more. This is also the reason why the non-selective filter with 60% shading factor and early activation (28ºC) performs better in the simulations than the simulated NIR filters (Table 4.9).

We can conclude that choosing for a permanent perfect NIR filter would be a good option but for this filter or for a perfect switchable filter to perform better than a permanent external shading screen in this climate, we need to improve greenhouse cooling (i.e. optimized greenhouse desing for this climate). Table 4.10 summarizes the final tomato yields obtained for each simulated scenario.

Table 4.10
Summary of final tomato potential yields simulated under each one of the evaluated scenarios on a Venlo type greenhouse for Kula Lumpur (Malaysia).

	Final yield (kg/m²)	Increase/decrease in yield (±%)
Reference (shading screen)	23.4	-
Permanent NIR filter	20	-14.5
Switchable perfect NIR filter (28 °)	17.5	-25.2
Switchable perfect NIR filter (28 °)-10% PAR reduction	19.4	-17.1
Switchable 50% NIR filter (28 °)	12.5	-12.5

4.2.5 Closed greenhouse in a desert climate region: Riyadh (Saudi Arabia)

4.2.5.1 Effect on greenhouse microclimate, use of resources and potential yield

The use of covers with different types of perfect NIR reflecting filters (permanent and switchable) results in interesting effects on the internal greenhouse temperatures along the growing cycle for a closed greenhouse. For instance, if we analyse the load duration curve of temperature (Figure 4.19), we can distinguish 2 areas of interest (marked with a circle).

- 1st: The lower solar energy load under the permanent and switchable filters minimizes the number of hours in the greenhouse above 31°C, in comparison with a normal glass cover. This also proves that the simulated cooling power does not completely allow for maintaining the selected set point at peak moments. However this is physiologically acceptable for a tomato crop in a closed greenhouse with higher CO_2 concentrations, and prevents an over dimensioning of the system.
- 2nd : We see that the permanent filter has the larger effect decreasing greenhouse temperatures on the range comprised between 30°C and 20°C, whereas the switchable filter performs equally well as the permanent when it is activated (above 24°C).

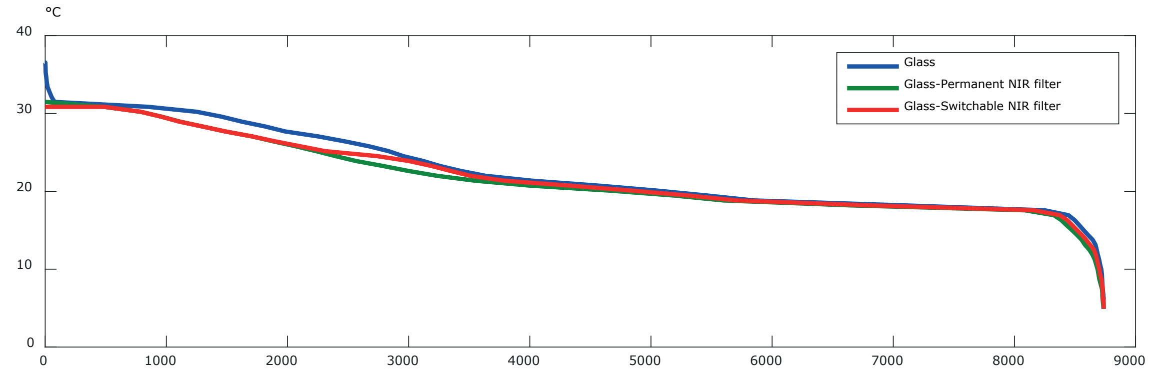

Figure 4.19 *Load duration curve of greenhouse air temperature (ºC) under the two simulated covers for a maximum cooling power available of 700 W/m²*.

Under the glass, the number of hours above 30°C is also 1891 hours, and both NIR filters cause a decrease of 31% in the amount of hours at these high temperatures.

The lower solar energy load must also involve a much lower energy use for active cooling in the greenhouse under the two NIR reflecting covers. Indeed, Figure 4.20 shows the load duration curve of cooling power required. We see that with NIR reflecting covers (both of them) ,the maximum cooling power used in the grenhouses is far below 700 W/m², with minor differences between them.

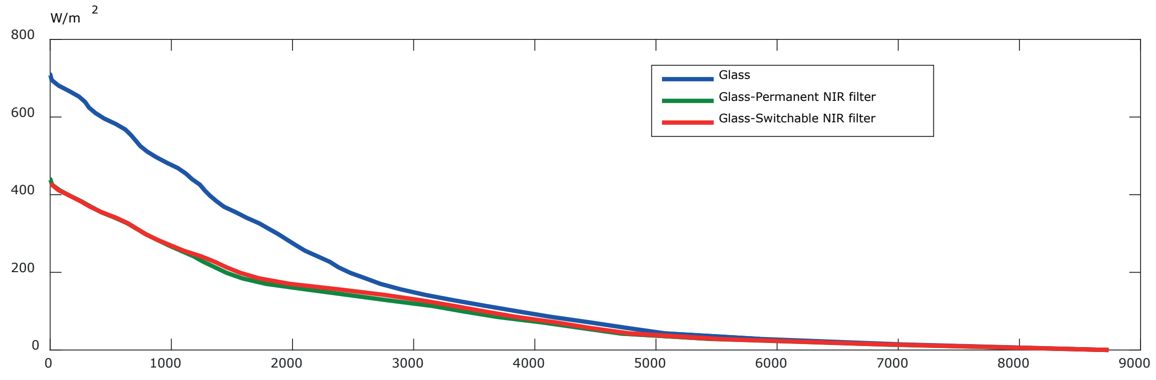

Figure 4.20 *Load duration curve of cooling power (W/m²) required in the greenhouse under the three simulated covers for a maximum cooling power available of 700 W/m²*.

The final electricity consumption for cooling (including the chillers and the heat exchangers) is 562 Kwh/m² for the standard glass and 354 Kwh/m² and 368 Kwh/m² the for permanent and switchable NIR filtering covering materials (Figure 4.21). This means a 36% saving on cooling energy, which is quite high. We can see that for this climate and type of greenhouse, and low activation point of the switchable filter, there is very little difference with the permanent filter, which would be easier to obtain in principle.

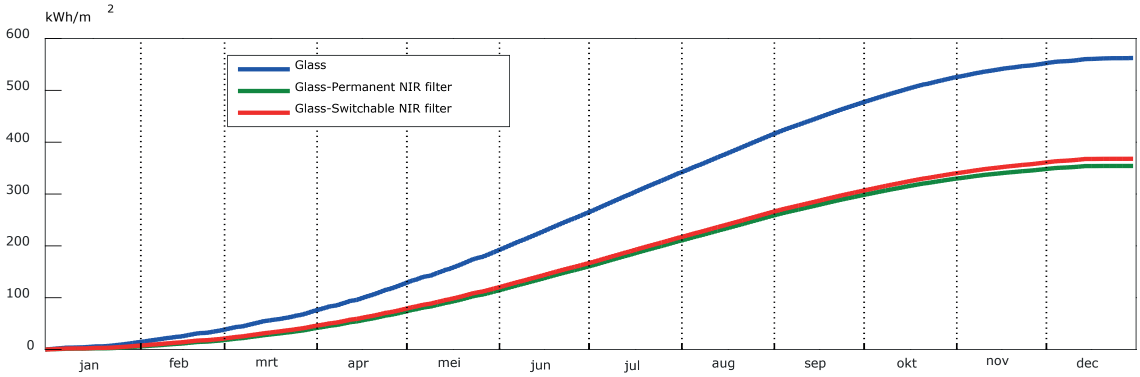

Figure 4.21 *Accumulated electricity use for cooling (KWh/m²) under the three simulated scenarios for a maximum cooling power of 700 W/m².*

Finally, we need to verify the effect on yield. If we apply the tomato crop growth model proposed by Vanthoor (2011) we see that there is a strong positive effect of the NIR reflecting filter from April to October, the warm period, in relation to standard glass (Figure 4.22). Indeed, we are simulating perfect NIR filters which do not affect PAR transmission, which decrease to a large extent the amount of hours in which temperature inside the greenhouse is above 28°C, which the model penalizes decreasing the dry matter production to the fruits. During the colder months, the three covers perform very similarly, when PAR radiation and not temperature becomes a more limiting factor.

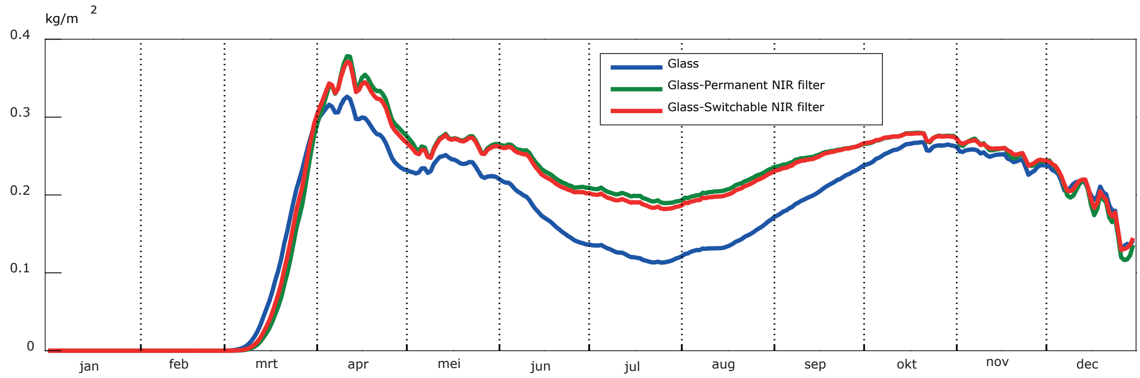

Figure 4.22 *Evolution of tomato fresh weight production (kg/m²) along the growing cycle for the three simulated covers.*

The final estimated potential yield under standard glass is 60 kg/m² whereas the NIR reflecting cover with a permanent and switchable filters the predicted value is 69 kg/m² in both cases.

Overall, results show that a perfect NIR filter would be ideal for closed greenhouses in desert climates, as it would, not just decrease the required cooling power and thus, the energy uses for cooling, but could potentially increase the yield by limiting the number of hours at detrimental temperatures for may crops. Results do not show a big advantage of a switchable filter activated early (24°C) in relation to a permanent filter if heating is also used during the winter months.

4.2.6 Pad and fan greenhouse in a desert climate region: Riyadh (Saudi Arabia)

4.2.6.1 Effect on greenhouse microclimate, use of resources and potential yield

There are, as expected, minor differences in microclimate between the simulated materials, as the system simply operate less hours and at lower capacity to maintain a similar microclimate under the NIR reflecting materials, as we can see for instance in the Figure 4.23, which shows the duration load curve for temperature. Still, under the standard glass the number of hours that crop temperature is above 28°C is much larger than under the NIR reflecting covers (24% larger).
Indeed, only minor differences between the materials occur, as expected, at the lower temperature range, when it becomes cold enough so the heating system cannot to maintain the set point, and then temperatures are slightly larger under the standard glass material, which accumulates slightly more solar energy during the daytime period.

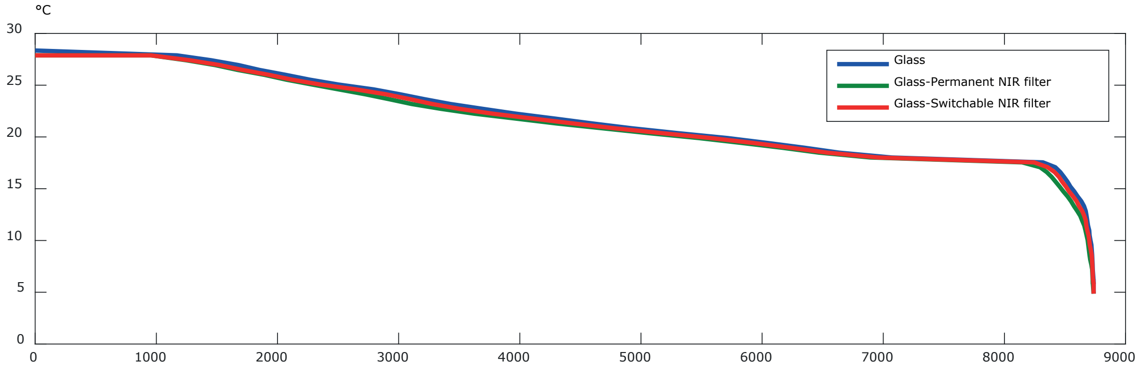

Figure 4.23 *Load duration curve of greenhouse air temperature (°C) under the three simulated greenhouse covers in a pad an fan cooled greenhouse.*

It is pertinent as well, to analyse the amount of water consumed by the pad and fan system under the simulated covers. Figure 4.24 shows the daily sum of water used by the pad (kg/m²). The simulation confirms that under the two NIR reflecting covers we can achieve the desired temperature set point with a consistently much lower water use by the pad. Very small differences are observed in favour of the permanent filter in relation to the switchable. The total amount of water consumed by the pad an fan system is 1215 l/m² for the standard glass and 765 l/m² and 811 l/m² for the perfect permanent NIR filter and the switchable perfect NIR filter, respectively. This a water saving of 37%, for the permanent NIR filter, which is very interesting in a place, like Saudi Arabia, where water is extremely scarce.

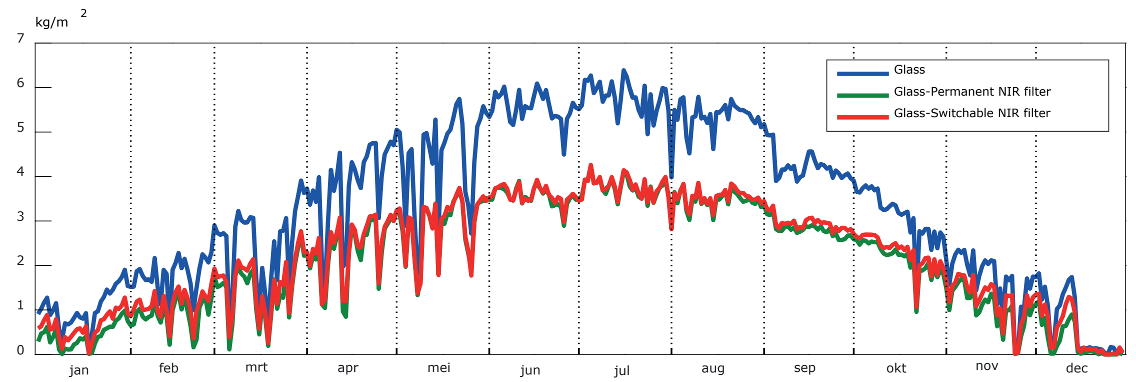

Figure 4.24 *Evolution of the daily sum of water (kg/m²) evaporated in the pad along the growing cycle under the three simulated greenhouse covers in a pad an fan cooled greenhouse.*

Besides, there is also an extra energy saving as the fans should run at lower capacity under the NIR selective covers. The model estimates an energy saving in electricity to run the fans of 24.5% of the permanent NIR filter in relation to the standard glass (20% in the case of the switchable filter).

Finally, the NIR selective filters are penalized in the energy used for heating, as less solar energy enters the greenhouse on winter days. The model estimates a use of potential use of natural gas for heating of 11 m^3/m^2 for standard glass and 13.6 m^3/m^2 and 12.4 m^3/m^2 for the permanent and the switchable filter, respectively (23% and 12.7% more energy for heating).

If we analyse the potential tomato yield (kg/m^2 day) predicted by the model (Figure 4.25), we see that under the NIR reflecting filters, we have consistently more yield during the warmer months, than under the standard glass, which can be explained by the largest number of hours that air and especially, crop temperature are above values that affect dry matter production in the model. The final predicted yield under the glass and the NIR reflecting covers are 56.5 kg/m^2 fan 61 kg/m^2 (for both NIR reflecting covers),respectively. Thus, a 8% increase in final yield, which adds to the savings in water, electricity for the fans but with a slightly higher energy use for heating in winter (Table 4.11).

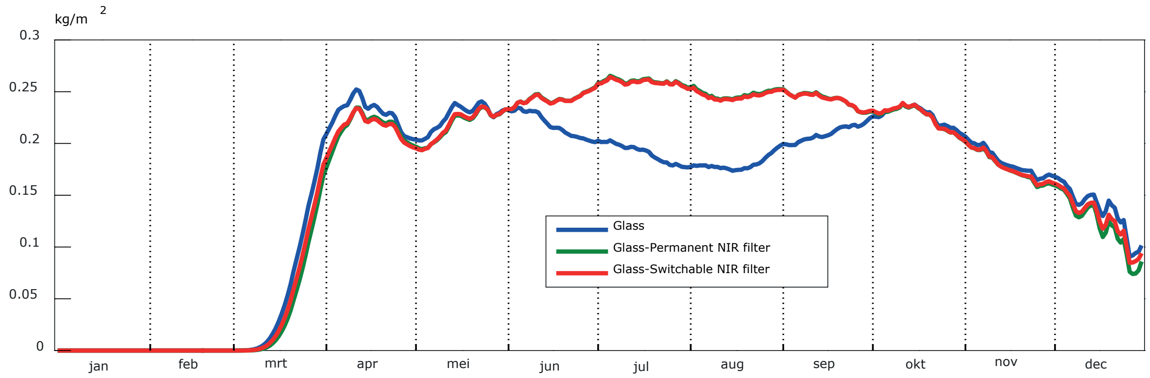

Figure 4.25 *Evolution of potential tomato fresh weight daily harvest (kg/m^2) along the growing cycle under the two simulated greenhouse covers in a pad an fan cooled greenhouse.*

Table 4.11

Summary of most relevant figures on resource use and yield obtained from the simujlations of a pad and fan greenhouse with a standard glass and two types of NIR reflecting covers (switchable and permanent).

		Water use for cooling (L/m^2)	Energy used by fans for cooling (KWh/m^2)	Energy (natural gas) used for heating (m^3/m^2)	Final potential yield (kg/m^2)
Cycle	Glass	1215	42.5	11	56.5
	NIR permanent	765	32.1	13.6	61
	NIR switchable	811	34	12.4	61

4.3 Conclusions

I. For mild winter climate regions (Agadir, Morocco), and the two simulated greenhosue types (traditional Canarian and Venlo type) the simulated NIR filters have both improved the greenhouse air temperatures and the potential dry matter productivity in relation to the reference whitewash, with more availabilty of PAR for the crop.
   - Despite of the higher availability of PAR, the switchable NIR filters did not notably increase yield in percentage, in relation to the non selective filters.
   - The explanation for this is that when the extra amount of PAR was available, temperatures and CO_2 were still limiting factors for dry matter produciton.
   - This is proved by the fact that when artificial CO_2 enrichment is used, a higher increase caused by the fiters is observed, as the CO_2 is no longer a limiting factor. It is also well known that at higher CO_2 concentrations, optimum net photosynthesis temperature increases.
   - A 10% reduction in PAR does not cause a similar decrease in yield, also proving that productivity is limited by other factors than PAR availability for the crop.
   - The partial NIR filters are not a good solution, due to multiple re-reflectionns between crop and cover.
   - The permanent filters perfom better than the whitewash, but not than the switchable filters, mainly because they decrease temperatures too much in the winter period, although they perform slightly better during the last two months of the crop.
   - Unlike for the non selective filters, the early activation filter (28°C) perform slightly better for both simulated greeenhouse structures.
   - An optimization of the activation moment of the filter could lead to an even larger increase in potential productivity.

II. NIR reflecting filters, in principle, have little interest in cold climate regions, such as The Netherlands, as maximum temperatures only occur during a very limited amount of hours in the year.

III. The behaviour observed for the NIR reflecting filters in a mild winter climate region is similar to that observed in in a tropical lowland regions (represented in this work by Kuala Lumpur, Malaysia).
   - The NIR filters improve the performance with respect to an internal shading mobile shading screen.
   - The permanent NIR filters are a the best option for this extreme climates, as we need to cut as much energy as possible and during as much time as possible to decrease the air temperatures, which are the main limitting factor.
   - The extra amount of PAR that is tranmitted when the filters are activated (or by the permanent) in relation to the shading screen (or to the high shading factor of the non selective filters) cannot be efficiently used as the reflection of all the NIR is not enough to maintain the temperatures below the threshold that makes them limiting.
   - This is also proved by the fact that an extra 10% of energy cut in the form of PAR translates in a positive results in dry matter production.
   - For an optimal use of these filters in this region the greenhouse structure must be optimized to decrase internal air temperatures as much as possible, enabling the extra PAR to be efficiently used by the crop.
   - For the future, a reference simulation using an external mobile shading screen should be performed for this climate, as it represents a potential alternative to the internal shading with less interference on natural ventilation.

IV. In desert regions, NIR reflecting filters perform extremely well, both in a closed greenhouse (with active cooling) and in a pad and fan greenhouse which relies on evaporative cooling:
   - In a closed greenhouse simulations indicate a large energy saving (36%) when both a permanent and switchable perfect NIR reflecting filters (with early activation temperature) are used. The use of the filter would also allow to lower the maximum cooling power by 40%, which would involve a large investment saving.
   - The models also predict an increase of 15% in potential tomato yield under the NIR reflecting covers in relation to a standard glass for a closed greenhouse. This increase is related to a decrease in the number of hours that air and canopy temperatures are above a threshold of 28°C.
   - The results indicate that there is no advantage of a switchable filter with early activation temperatuer in relation to the permanent filter.

- In a greenhouse with pad and fan cooling, simulations show that the use of the NIR reflecting filters in the glass cover involves a decrease in water used for cooling (37 %), in energy used by the fans (20-25% for the switchable and permanent filters, respectively). However, the use of this filters also involves an small increase in use of energy for heating (12.7-23 % for the switchable and permanent filters, respectively).
- The use of the NIR reflecting filters also allows for an increase of 8% in the potential tomato yield estimated by the model (for both filter types, permanent and switchable). This increase in yield is mostly caused by a decrease in the number of hours that both air and canopy temperature are above a physiological threshold of 28°C.
- The simulations show no clear advantage of a switchable filter with early activation temperature (24°C) in relation to a permament filter.

In very well ventilated tropical greenhouse, such as small greenhouses with combined sidewall and roof ventilation, which were not analysed here, switchable NIR reflecting filters could perform better than the non-selective filters. The optimum performance of perfectly reflecting NIR filters is obtained in desert climates, both with closed greenhouses (active cooling) or when evaporative cooling (pad and fan) is used instead. In all cases the use of the filter induces a saving in water, in energy and also a potential increase in yield. However, a switchable filter does not show any advantage with a permanent filter in this extreme climates.

5 Far InfraRed selective filter

5.1 Introduction

All internal elements of a greenhouse (soil, crop, heating pipes, cover, etc.) exchange long wave radiation in virtue of their temperatures. All these elements are partially "seeing the sky", which is usually colder than the mentioned elements and therefore, is a radiative sink. Therefore, the thermal properties of the cover, that is, how much of the radiative energy emitted from the greenhouse elements is absorbed (and re-emitted) and/or transmitted by/through the cover are very important to determine the air temperature of the greenhouse. The sky temperature plays therefore a major role in the radiative exchanges and therefore in the overall energy balance of the greenhouse. Most meteorological stations do not measure sky temperature directly with the help of a pyrgeometer. What is often measured is cloud cover, in fractions in steps from 0 (clear sky) to 8 (fully overcast). That is also the case of the three different locations evaluated in the present study (Agadir, Kuala Lumput and de Bilt). The calculation of sky temperature has been obtained using the following empirical equation(1):

$$Tsky=(Tair-((8-Cloudiness)/8)*18)-2 \quad [1]$$

Where Tsky is the sky temperature, Tair is the air temperature and Cloudiness [1-8] is a factor measuring the level of cloud covering in the sky. Thus, sky temperature is much lower when sky is clear and free of clouds.

In order to prevent too much far infrared radiation to be lost to the sky, it would be ideal to have a cover that instead of transmitting of absorbing this radiation (FIR), would reflect it back. That is the idea behind the use of aluminized energy saving/thermal screens. However, the need to cool the greenhouse (except in very cold climates) during daytime makes radiative losses through the cover necessary and complementing to other cooling mechanisms such as convection or natural ventilation.

Therefore, the goal is to simulate a selective 100% TIR reflecting switchable filter, capable of reflecting thermal radiation when temperature falls below a certain threshold value. This filter is particularly interesting in passive greenhouses, as it would allow to retain inside the greenhouse during the night, the small amount of heat stored in the greenhouse soil and possibly other passive heat storage elements (e.g. PCM's, plastic sleeves filled with water, etc.), while allowing to loose thermal radiation during the daytime for cooling purposes. Obviously, such as filter could also help to save energy in heated greenhouses.
Therefore, this filter has been simulated for both a region with majority of passive greenhouses such as Agadir (Marocco) and a region with heated greenhouse represented by De Bilt (The Netherlands). A non-perfect 50% FIR reflective filter has also been simulated in both regions (Table 5.1).

In Agadir, the switchable filter has been compared with a PE film with thermicity (FIR transmission) of 0.65 and rest of optical properties as shown in Table 3.3, and a material with zero thermicity and rest of optical properties again as shown in Table 3.3. For Agadir, the switchable filter is assumed to be activated when internal greenhouse temperature drops below 16°C.

As a matter of fact, in cold regions, growers already use one or multiple screens to save energy, thus, the use of a highly reflective FIR switchable filter may be interesting if it would significantly reduce energy use, when added to existing screens. Therefore in the simulation the filtes has been complemented with either of two different types of energy saving screens: a semi-transparent energy saving screen, with possible use also during daytime, and an aluminized screen, only to be used during night-time. A permanent 100% reflecting filter has also been used as a second reference.
In the case of the heated greenhouse in The Netherlands, a higher activation point for the filter has been taken: 19°C, which is one degree above the highest heating temperature set point used.

Table 5.1
Summary of scenarios simulated in the analysis of the selective FIR switchable filter.

	Regions	Year	Crops	Greenhouse type	Cover/energy saving screen type	Activation temperature set point (°C)
Reference	Agadir (Morocco)	2010	Tomato	Venlo plastic film	100 % FIR transmission/no screen	--
					35% FIR transmission/no screen	
	The Netherlands	Sel2000		Venlo glass	Standard glass/semi transparent	19
					Standard glass/ aluminized screen	
Permanent FIR filter with 100% reflection °	Agadir (Morocco)	2010	Tomato	Venlo plastic film	Permanent FIR reflective film/no screen	Permanent
	The Netherlands	Sel2000		Venlo glass	Permanent FIR reflecting glass/ semi-transparent screen	
					Permanent FIR reflecting glass/ aluminized screen	
Switchable filter 100% FIR reflection	Agadir (Morocco)	2010	Tomato	Venlo plastic film	100% switchable reflecting cover/ no screen	16
	The Netherlands	Sel2000	Tomato	Venlo glass	100% switchable FIR reflection/ semitransparent screen	19
					100% switchable FIR reflection/ aluminized screen	
Filter 50% FIR reflection	Agadir (Morocco)	2010	Tomato	Venlo plastic film	50% switchable FIR reflecting cover/no screen	16
	The Netherlands	Sel2000	Tomato	Venlo glass	50% switchable FIR reflection/ semitransparent screen	19
					50% switchable FIR reflection/ aluminized screen	

5.2 Results

5.2.1 Improved greenhouse structure Mild winter climate: Agadir (Morocco)

For this filter, whose main purpose is to decrease night-time (or cold period) radiative losses in the greenhouse, simulations have been performed only for the Venlo greenhouse type, since the presence of constantly open vents (day and night) on the Canarian type greenhouse may mask the real contribution of the FIR reflecting filter to increase night time temperatures.

The following section analyzes the effect of a perfect (100%) and a non-perfect (50%) switchable FIR reflecting filter in an improved but still unheated greenhouse structure, a Venlo plastic greenhouse. For the simulations, it has been considered that the filter activates when greenhouse air temperature falls below 16°C. The references are a Venlo greenhouse with two different PE films in terms of thermicity (FIR transmission): a 100% thermicity plastic and a 35% thermicity film (FIR transmission 35%-FIR absorption 65%) without any thermal screen. For all analyzed scenarios, a whitewash with 60% shortwave reflection has been simulated as well during the same periods described in previous sections for a Venlo greenhouse in Agadir.

5.2.1.1 Effect on greenhouse air temperature

A FIR switchable filter activated when temperatures drop below a certain threshold in a passive greenhouse should have the same maximum temperatures during daytime as the non thermic reference, while permantly thermic PE's will results in higher daytime temperatures, all year. This is accounted for in the yield results shown later.

Anyhow, as thermal radiation exchange is relatively less important at daytime, the most notable effect of thermicity is on minimum daily temperatures. As we can see on Figure 5.1, the permanent FIR filter ensures the best performance during the winter months, but we can also see that during the warm months, the minimum air temperatures are rather high, given the impossibility of the greenhouse of cooling by radiation. The switchable filters both allow for maintaining higher minimum temperatures all along the cycle than both the films with standard FIR absorption and the film with zero FIR absorption. The perfect filter performs slightly better than the 50% filter during the coldest months and during part of the spring. The lowest temperatures, as expected, occur under the zero thermicity material. Regarding the effect of the FIR filters on the radiative cooling capacity of the greenhouse during the daytime period, Figure 5.2 shows that the during the warm months, there is no effect on the maximum temperatures, as the radiative cooling mechanism is neglibible in relation to cooling by natural ventilation or by convection. Only during the winter months, on clear and colder days, we can see that the permanent filter induces higher maximum air temperatures by the limitation of the radiative cooling during the daytime.

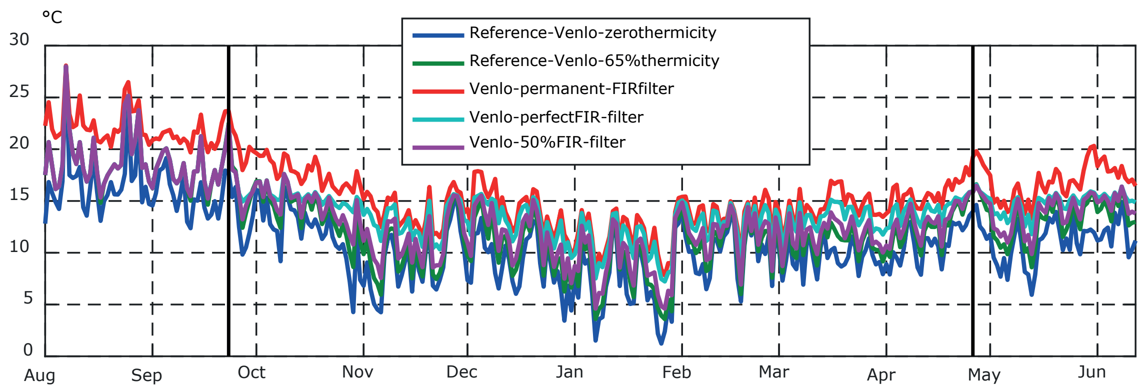

Figure 5.1 *Evolution of daily minimum air temperatures (°C) along the growing cycle under the 5 evaluated scenarios with no use of thermal screens in Agadir (Morocco): reference-zero thermicity, reference-standard thermicity, a permanent FIR filter and the two FIR reflecting switchable filters (100% and 50% reflection) with activation temperature of 16°C.*

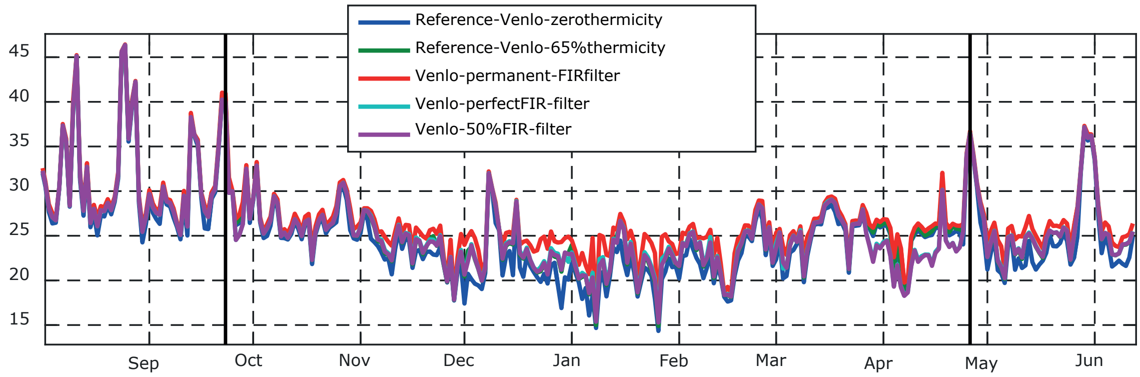

Figure 5.2 *Evolution of daily maximum air temperatures (°C) along the growing cycle under the 5 evaluated scenarios with no use of thermal screens in Agadir (Morocco): reference-zero thermicity, reference-standard thermicity, a permanent FIR filter and the two FIR reflecting switchable filters (100% and 50% reflection) with activation temperature of 16°C.*

Table 5.2 summarizes the number of hours that the greenhouse air temperature is below a physiological threshold of 12°C under the 4 evaluated scenarios along the whole cycle.

Table 5.2
Summary of hours that greenhouse air temperature (°C) is below a physiological threshold for affected dry matter production and quality under each one of the 4 evaluated scenarios on a Venlo type greenhouse for Agadir (Marocco).

	Hours that Tair<12°C
Reference (zero termicity)	1663
Reference (65% thermicity)	1037
Permanent FIR filter	135
Switchable perfect FIR filter (16°C)	256
Switchable 50% FIR filter (16°C)	693

Overall, the number of hours at risky low temperatures for a tomato crop is clearly higher with the reference plastic films (zero and 65% FIR aborption) tested in the reference scenarios. The permanent FIR reflecting filter is the best performer, strongly decreases the number of hours below 12°C, followed by the switchable filters, whith the 100% performing better, whereas the 50% FIR filter also decreases the number of hours, but to a lower extent. In any case, we can clearly state that FIR reflection is a much better option to maintain night time temperature higher in passive greenhouses than cover FIR absorption.

5.2.1.2 Effect on tomato productivity

Figure 5.3 shows the comparison of the reference covers with the 2 simulated FIR switchable filters. In it we can see that all the simulated FIR FIR reflection filters (permanent and switchable) allow for higher productivity during the most of the growing cycle, except during the last warmer months of the cycle, where the excessive minimum and maximum temperatures under the FIR reflecting cover are penalize productivity. The permanent FIR filter performs slightly better than the switchable filters. The increased earliness is also very valuable, since prices in the period Nov-Feb are the highest, thanks to export to Europe.

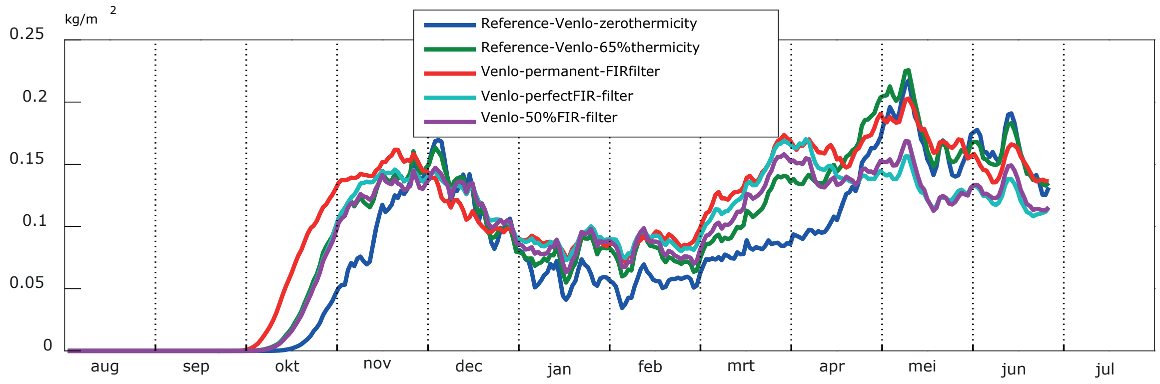

Figure 5.3 *Daily tomato fresh weight production (kg/m²) with 16°C activated FIR filters and reference.*

Table 5.3 summarizes the final tomato yield obtained for each simulated scenario. An extra simulation showing the effect of having an aluminized thermal screen instead of the FIR switchable filters in the cover has also been included. First thing we can state is that the increase in productivity obtained when using FIR reflecting filters is higher than that obtained with a FIR absorbing permanent filter and much higher than using a plastic with no thermal properties. If we focus on the effect of using an aluminized thermal screen (80% aluminum and 20% transparent plastic), we can see that it has a very similar effect on final potential yield that the switchable FIR reflecting filters simulated, but lower than the permanent filter, mainly because of the shading caused by the screen when not used and by the 20% non reflecting gaps. Thus, the price of a hypothetical smart cover with switchable FIR reflection should be competitive in price with that of an energy saving screen in order to have market opportunities.

Table 5.3
Summary of final tomato potential yields simulated under each one of the evaluated scenarios on a Venlo type greenhouse for Agadir (Morocco).

	Final yield (kg/m²)	Increase/ decrease in yield(±%)
Reference (zero thermicity)	24.9	--
Reference (65% thermicity)	29.5	+18.4
Permanent FIR filter	32	+28.5
Switchable perfect FIR filter (16°C)	31.2	+
Switchable 50% FIR filter (16°C)	30.4	+10.8
Reference (65% thermicity + energy saving screen 80% aluminium+20% transparent)	29.8	+19.7

5.3 Cold region: De Bilt (The Netherlands)

FIR switchable reflective filters may also have a positive effect on the greenhouse microclimate and in decreasing fossil energy use for heating.

5.3.1.1 Effect on greenhouse air temperature

A FIR switchable filter activated when temperatures drops below a certain threshold in a heated greenhouse should have a positive, though limited effect on minimum daily temperatures, if the heating system has been properly dimensioned. As we can see on Figure 5.4, differences are very small (lower than 1°C) and almost negligible, as expected, and heating set points are maintained without problems all along the cycle by the 3 simulated covers.

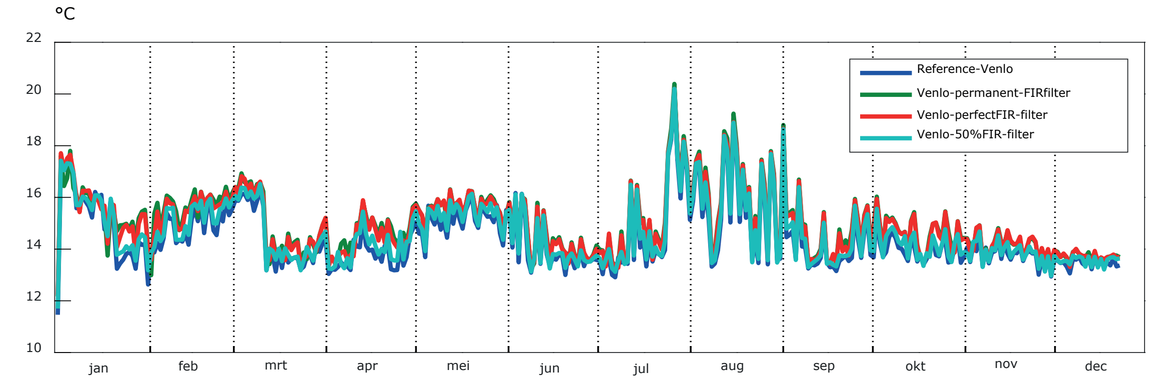

Figure 5.4 *Evolution of daily minimum air temperatures (°C) along the growing cycle under the 3 evaluated scenarios of perfect NIR filter with no PAR reduction: reference and the switchable filter with activation temperature of 19°C.*

5.3.1.2 Effect on energy use for heating

In addition to the most common semi-transparent energy saving screen (that allows also for daytime use on very dark days, or early and late hours of the day), simulations have also been done using an aluminized screen with 80% aluminum and 20% semi-transparent stripes. In all simulated cases we can see a positive effect of using FIR reflecting covers, with the permanent filter over-performing the switchable type, in decreasing the fossil energy use, as we can see in Figures 5 and 6 and Table 5.4. The reason why the total gas use is lower with the semi-transparent screen is that unlike the alumnized screen, the semi-transparent screen is also used during daytime hours when solar radiation is lower than 50 W m^{-2} (3276 hours of use with the semi-transparent screen and 2445 hours with the alumized screen).

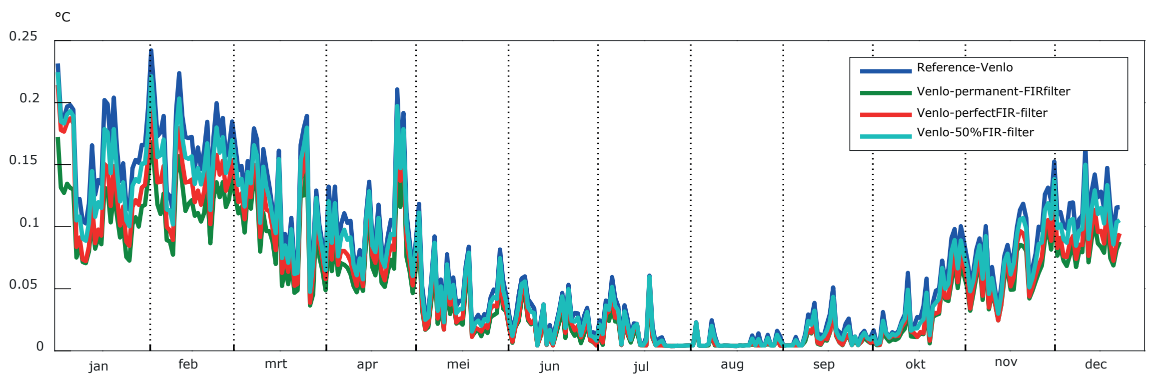

Figure 5.5 *Daily sum of natural gas (m^3/m^2) used for heating in a Venlo glasshouse on a typical meteorological year under the 3 evaluated covers with a semi-transparent thermal screen.*

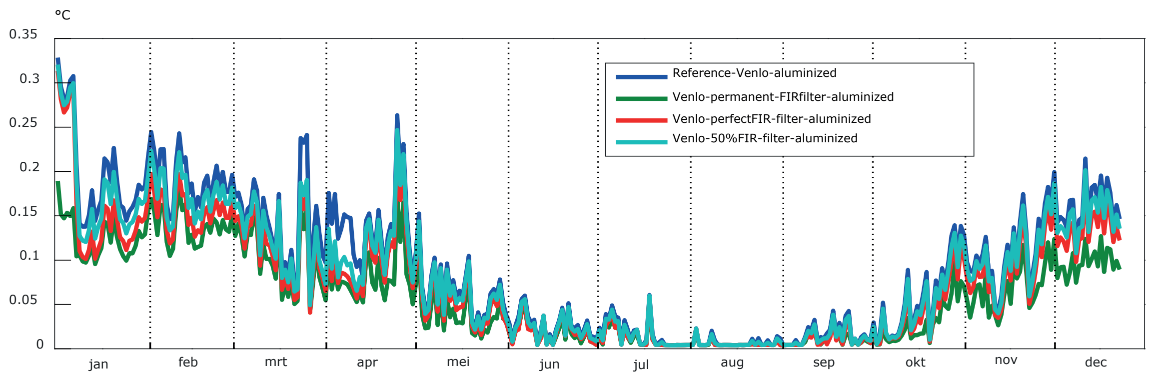

Figure 5.6 *Daily sum of natural gas (m^3/m^2) used for heating in a Venlo glasshouse on a typical meteorological year under the 3 evaluated covers with an aluminized thermal screen.*

Table 5.4
Summary of final simulated energy used under each one of the evaluated scenarios on a Venlo type greenhouse for De Bilt (The Netherlands) with two different types of thermal screens (aluminized and semi-transparent).

		Final natural gas use (m^3/m^2)	Increase/decrease in energy use(±%)
Semi-transparent thermal screen	Reference	25.8	--
	Permanent FIR filter	17.9	-30.6
	Switchable perfect FIR filter (19°C)	20.3	-21.3
	Switchable 50% FIR filter (19°C)	23.3	-9.7
Aluminized thermal screen	Reference	31.6	-
	Permanent FIR filter	20.2	-36.1
	Switchable perfect FIR filter (19°C-	25.3	-19.9
	Switchable 50% FIR filter (19°C)	28.4	-10.12

5.3.1.3 Effect on tomato productivity

Figure 5.7 shows the comparison of the reference with the 2 simulated FIR switchable filters. In it we can see that there are virtually no differences on tomato productivity caused by the use of the FIR reflecting filters, as it could be expected.

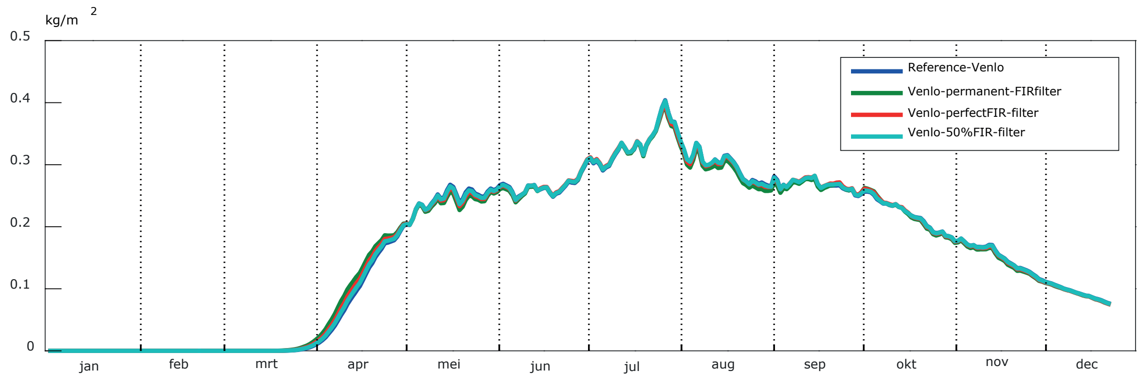

Figure 5.7 *Daily tomato fresh weight production (kg/m²) with 19°C activated FIR filters and reference.*

Table 5.5 summarizes the final tomato yields obtained for each simulated scenario, showing again that virtually, yields are essentially the same.

Table 5.5
Summary of final tomato potential yields simulated under each one of the evaluated scenarios on a Venlo type glasshouse for De Bilt (The Netherlands).

	Final yield (kg/m^2)
Reference (whitewash)	57.3
Switchable perfect FIR filter (19°C)	57.4
Switchable 50% FIR filter (19°C)	57.3

We can conclude that the most interesting effect of a switchable FIR reflective filter in heated greenhouses is that it can ensure an important decrease in energy use for heating.

5.4 Conclusions

I. A FIR reflecting filter (both permanent, with the best result, and switchable) performs very well in passive (non-heated) greenhouses in mild winter climates. It increases night time air temperature, while still allowing for enough cooling of the greenhouse by radiation during the sunny winter days typical of these regions.
    - The difference in potential productivity in relation to a standard film which absorbs more than half of the FIR (65%) is relatively small (around 7%), but increased earliness is a very important advantage.
    - In addition there are other possible benefits of FIR reflection, instead of absorption. For instance, FIR reflection increases nighttime crop temperature, helping to prevent condensation on the plants, which should limit the incidence of fungal and bacterial diseases.
    - The performance of an aluminized internal mobile thermal screen is very similar to that of a cover with a switchable FIR reflecting filter.

II. The interest of a FIR reflecting filter in heated, high-tech greenhouses cold climates lies not in the effect in yield, which is almost inexistent, but on the decrease of fuel use for heating. An analysis would still be required to verify if such a cover can be an alternative to at least one of the energy saving screens used by cold climate growers.

Results for the non-selective switchable filter show a very positive effect in the two warm climate regions simulated, clearly over performing the reference whitewash and internal mobile shading screens. The effectiveness of the these filters is very marked in extreme climates, where extremely high temperatures are the main limiting factor for greenhouse production.

The NIR selective filters also performs well, but in this case, they need to reflect a large portion of the NIR, as otherwise the already high crop reflectivity for NIR induces multiple reflections between the cover and the crop, in fact "trapping" the NIR radiation, which would limit their effectiveness. In very well ventilated tropical greenhouse, such as small greenhouses with combined sidewall and roof ventilation, which were not analysed here, switchable NIR reflecting filters could perform better than the non-selective filters. The optimum performance of perfectly reflecting NIR filters is obtained in desert climates, both with closed greenhouses (active cooling) or when evaporative cooling (pad and fan) is used instead. In all cases the use of the filter induces a saving in water, in energy and also a potential increase in yield. However, a switchable filter does not show any advantage with a permanent filter in this extreme climates.

Finally, FIR reflection switchable filters would be revolutionary for passive greenhouses in mild winter climate regions, if they could have a price that could compete with the price of internal aluminized screens. In cold regions, these filters could help to save an interesting amount of energy, but again, their price should be competitive with that of an energy saving screen.

6 Indirect effect of the filters on CO_2 concentration

6.1 Effect of non-selective switchable filters in greenhouses without CO_2 supply

6.1.1 An improved Venlo greenhouse in Agadir, Morocco

Since the Venlo greenhouse has the possibility of control the opening and closing of the vents, it is interesting to analyze the patterns of opening/closing of the greenhouse vents, to verify if the different shading alternatives caused any major differences. A major effect of higher or lower ventilation opening would be the CO_2 flow into the greenhouse from external air. Figure 6.1 shows the daily cyclic mean of leeward ventilators opening percentage on period 1. First, we can see no difference between the switchable filters, in virtue of the high ventilation capacity of the greenhouse. It can also be clearly seen that since shading is permanent under the whitewash, lower opening of the vent is required, which in case of a greenhouse with no CO_2 enrichment, involves also less supply of CO_2 from the external air (Figure 6.2)

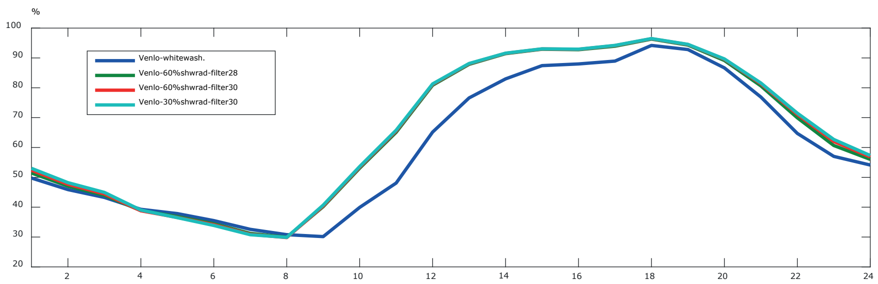

Figure 6.1 *Daily cyclic mean of leeward vent opening percentage (%) during period 1 under the 4 evaluated scenarios.*

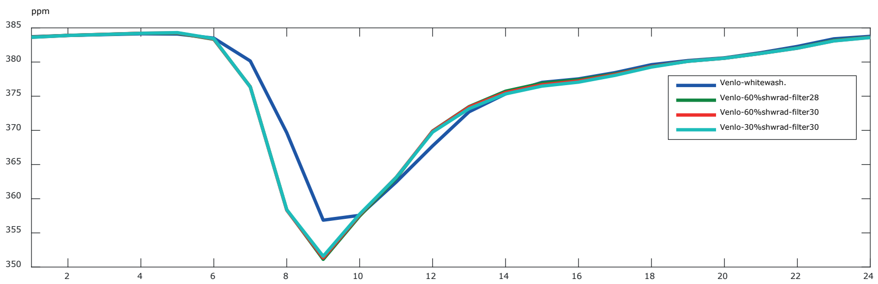

Figure 6.2 *Daily cyclic mean of CO_2 concentration (ppm) in the greenhouse during period 1 under the 4 evaluated scenarios (No artificial CO_2 enrichment).*

6.1.2 A Venlo plastic greenhouse in Malaysia

Since the simulated Venlo has the possibility of control the opening and closing of the vents, it is interesting to analyze the patterns of opening/closing of the greenhouse vents, to verify if the different shading alternatives caused any major differences. A major effect of higher or lower ventilation opening would be the CO_2 flow into the greenhouse from external air.

Figure 6.3 shows the daily cyclic mean of windward ventilator opening percentage along the whole growing cycle. We can see no differences during night-time period and early morning, but when screen is used and filters activated, some differences appear. We can see the percentage of opening is slightly higher when the screen is used. Since the screen interferes with air exchange by natural ventilation, vents open to a higher percentage to try to achieve the desired ventilation temperature set point. That is also the case with the higher temperature activation filter.
In practice, the lower air exchange caused by the screen also causes a lower input of external CO_2 into the greenhouse, as we can see in Figure 6.4, that shows the 24 hours cyclic mean of greenhouse air CO_2 concentration. In this figure we can also see only minor differences in average CO_2 concentration between the two filters. We can also see that the large percentage of opening required for tropical climates along the whole year during the daytime period does not make economically feasible to apply CO_2 enrichment.

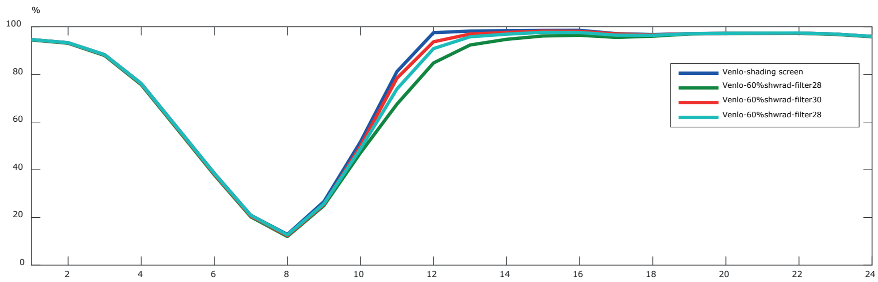

Figure 6.3 *Daily cyclic mean of leeward vent opening percentage (%) during the whole growing cycle under the 4 evaluated scenarios.*

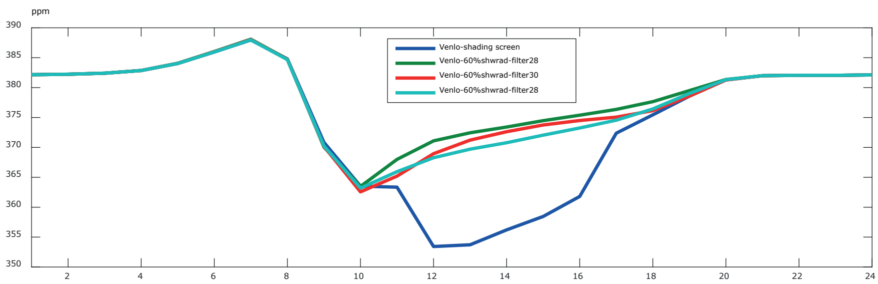

Figure 6.4 *Daily cyclic mean of CO_2 concentration (ppm) in the greenhouse under the 4 evaluated scenarios (No artificial CO_2 enrichment).*

6.2 Effect of NIR-selective switchable filters in greenhouses without CO_2 supply

6.2.1 A Canarian greenhouse in Morocco

Since the simulated greenhouse has no kind of control on opening and closing of the vents, irrelevant differences are to be expected. Figure 6.5 shows the daily cyclic mean of CO_2 concentration in the greenhouse under the 3 evaluated scenarios during the whole growing cycle. As we expected, they are very similar, with some minor difference for the whitewash greenhouse, which has slightly higher values during the daytime hours, likely caused by lower crop absorption when whitewash is present, in relation to the switchable filters, which enjoy higher PAR radiation values during periods 1 and 3.

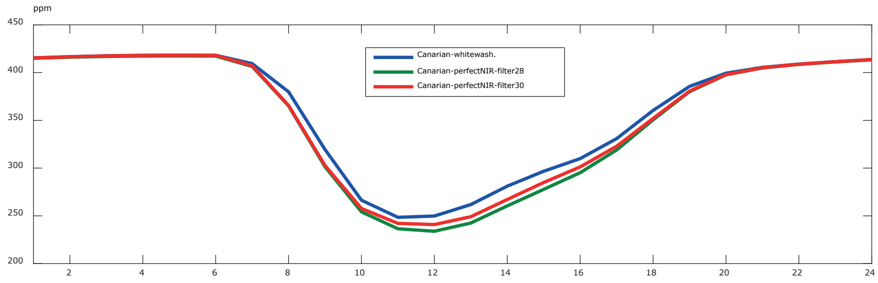

Figure 6.5 *Daily cyclic mean of CO_2 concentration (ppm) inside the greenhouse during the first period (1st August-1st October) under the 3 evaluated scenarios: reference-whitewash and the two switchable filters with activations temperatures of 28°C and 30°C.*

6.2.2 A Venlo plastic greenhouse in Morocco

It is also interesting to analyze the patterns of opening/closing of the greenhouse vents, to verify if the different shading alternatives caused any major differences. A major effect of higher or lower ventilation opening would be the CO_2 flow into the greenhouse from external air. Figure 6.6 shows the daily cyclic mean of leeward ventilators opening percentage on period 1. Since shading is permanent under the whitewash, lower opening of the vent is required, which in case of a greenhouse with no CO_2 enrichment, involves also slightly less supply of CO_2 from the external air (Figure 6.7)

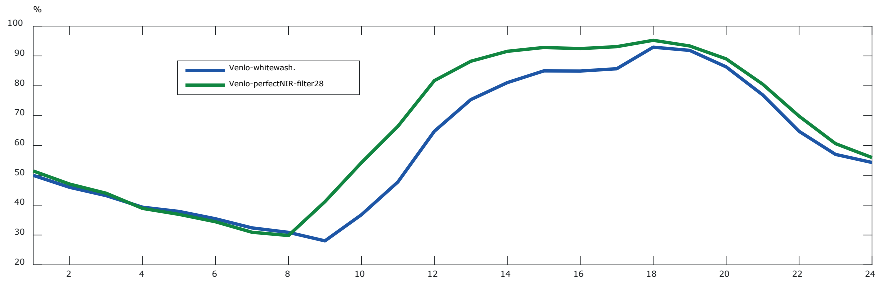

Figure 6.6 *Daily cyclic mean of leeward vent opening percentage (%) during period 1 under the 2 evaluated scenarios.*

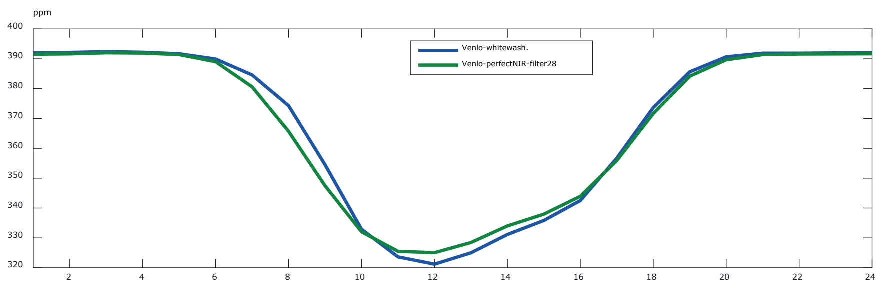

Figure 6.7 *Daily cyclic mean of CO_2 concentration (ppm) in the greenhouse during period 1 under the 3 evaluated scenarios (No artificial CO_2 enrichment).*

6.2.3 A Venlo plastic greenhouse in Malaysia

A major effect of higher or lower ventilation opening would be the CO_2 flow into the greenhouse from external air. Figures 6.8 and 6.9 show the daily cyclic mean of leeward and windward ventilators opening percentage, respectively. In these graphs we observe minor differences, except for a slightly larger opening percentages with the shading screen, but the climate in this region, forces fully opening of the vents during the whole of the daytime and part of the night.

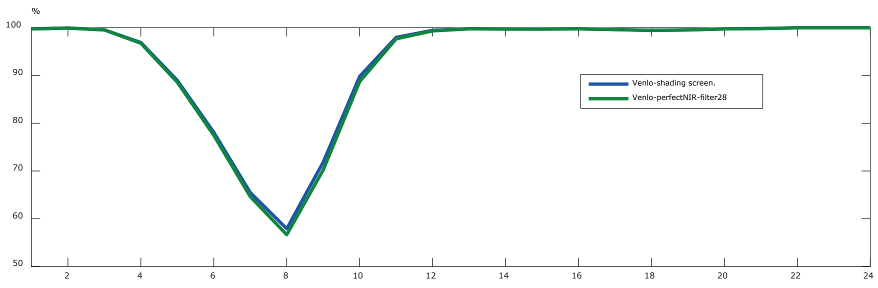

Figure 6.8 *Daily cyclic mean of leeward vent opening percentage (%) during period 1 under the 2 evaluated scenarios.*

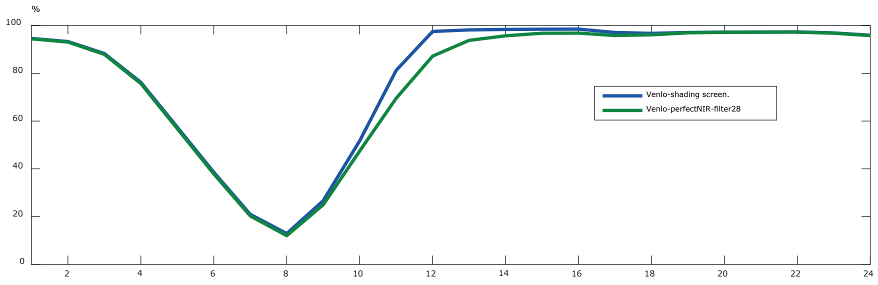

Figure 6.9 *Daily cyclic mean of windward vent opening percentage (%) during period 1 under the 2 evaluated scenarios.*

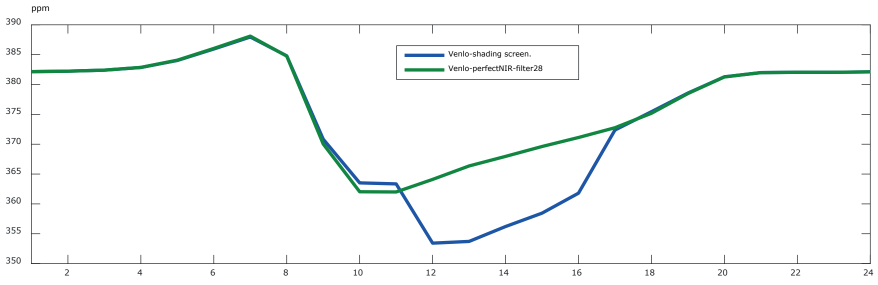

Figure 6.10 *Daily cyclic mean of CO_2 concentration (ppm) in the greenhouse during the whole cycle under the 2 evaluated scenarios (No artificial CO_2 enrichment).*

Figure 6.10 shows, that despite of this slightly larger opening of the vents with the shading screen, the lower air exchange by natural ventilation induced by the presence of the screen when it is used involves also a slightly lower input of CO_2 from the external air.

6.3 Effect of NIR-selective switchable filters in a Venlo glasshouse in The Netherlands, with CO_2 supply

The aim is to verify if the perfect NIR reflecting filter caused any major difference in vent opening andt thus, in CO_2 internal concentrations. In principle, the lower need for ventilation should limit window opening and therefore, increase the number of hours inside the greenhouse at higher CO_2 concentrations.

As we can see in Figure 6.11, the lower ventilation requirements of the whitewash greenhouse for the warm period of the cycle (1st June-1st September) has a minor effect decreasing the windward ventilation opening percentage, whereas the leeward ventilation opening is virtually unaffected.

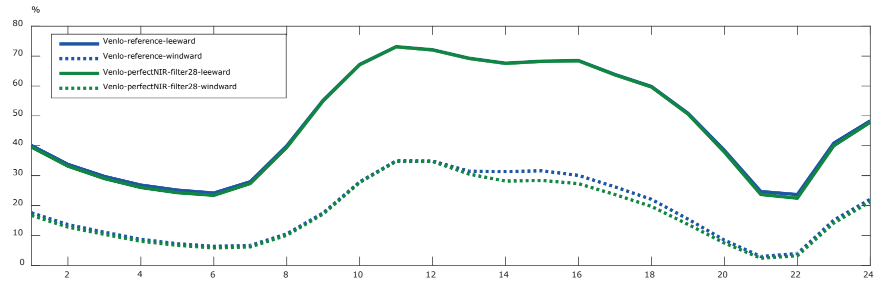

Figure 6.11 *Daily cyclic mean of leeward and windward vents opening percentage under the 2 evaluated scenarios, during the warm period of the growing cycle.*

The repercussion, therefore, on internal greenhouse CO_2 concentration inside the greenhouse in this period, is therefore, minimal, as we can see in Figure 6.12.

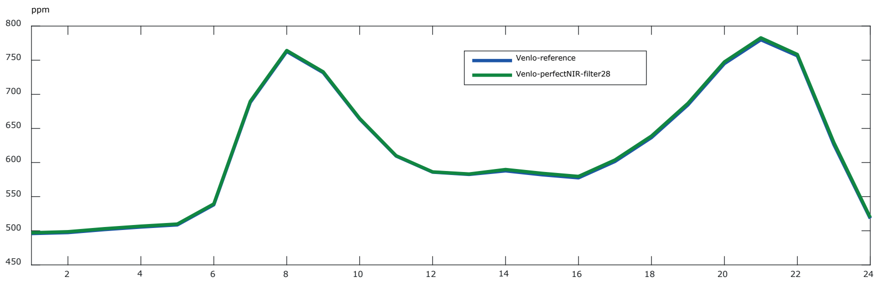

Figure 6.12 *Daily cyclic mean of CO_2 concentration (ppm) in the greenhouse with artificial CO_2 enrichment along the whole cycle under the 2 evaluated scenarios.*

7 Indirect effect of the FIR-switchable filters on condensation on the cover

7.1 A Venlo plastic greenhouse in Morocco

When thermal radiation is emitted from the crop and reflected from the cover, the greenhouse air becomes warmer, as we saw earlier. Therefore, the cover temperature should also become warmer, as cover temperature must take a value between internal and external air temperature. In the reference plastic, although part of the thermal energy is absorbed, it is re-emitted to the sky and the plastic becomes colder.
Figure 7.1 shows the daily cyclic mean of cover temperature (°C) of the reference covers and the two covers with a switchable FIR filter along the cold months of the cycle (period 2). This graph clearly shows that the cover temperature is always higher for the two switchable filters, being higher for the 100% filter than for the 50%.

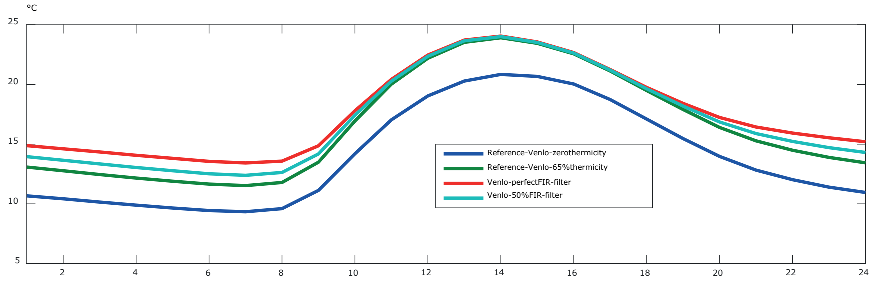

Figure 7.1 *Daily cyclic mean of cover temperature (°C) during the 2nd period (1st October-1st April) under the 4 evaluated scenarios: reference-zero thermicity, reference-65% thermicity and the switchable perfect and 50% FIR reflection filters with activation temperature of 16°C.*

As a consequence, as we can see in Figure 7.2, condensation on the covers with absorption and especially, with reflection of FIR, is much less than in the reference cover with zero thermicity. This also means that absolute humidity in the air should be higher under the filters, as we can see in Figure 7.3.

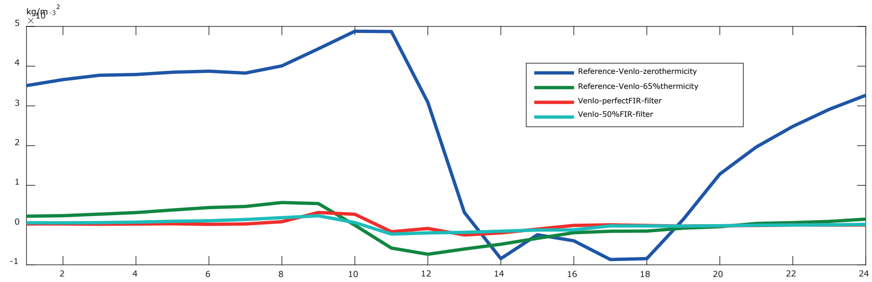

Figure 7.2 *Daily cyclic mean of condensation/evaporation to/from the cover (kg/m²) along period 2 (1st October-1st April) of the growing cycle under the 4 evaluated scenarios: reference-zero thermicity, reference-65% thermicity and the switchable perfect and 50% FIR reflection filters with activation temperature of 16°C.*

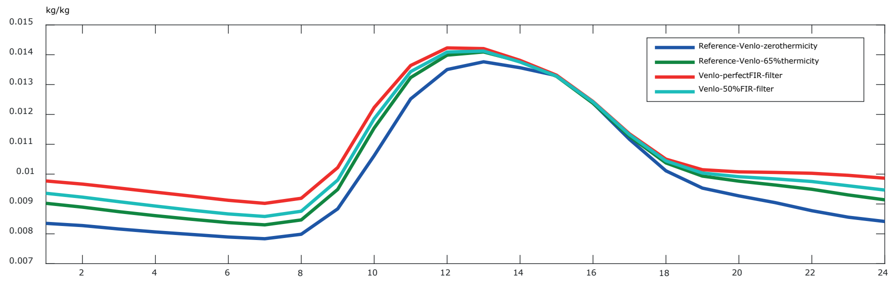

Figure 7.3 *Daily cyclic mean of absolute humidity (kg/kg) during the second period (1st October-1st April) under the 4 evaluated scenarios: reference-zero thermicity, reference-65% thermicity and the switchable perfect and 50% FIR reflection filters with activation temperature of 16°C.*

Limiting condensation on the roof to such low values is a positive side effect of using a FIR filter, as it also prevents possible dripping over the crop. Another positive effect of the filters is that canopy temperature becomes higher during the night and part of the morning and afternoon, decreasing the possibility of condensation on the crop, which enables the incidence of some fungal and bacterial diseases (Figure 7.4).

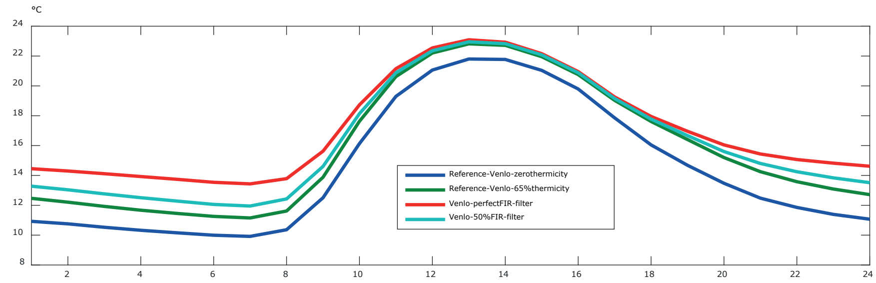

Figure 7.4 *Daily cyclic mean of canopy temperature (°C) along period 2 (1st October-1st April) of the growing cycle under the 4 evaluated scenarios: reference-zero thermicity, reference-65% thermicity and the switchable perfect and 50% FIR reflection filters with activation temperature of 16°C.*

7.2 A Venlo glasshouse in The Netherlands

Unlike in the passive greenhouse, in the Dutch greenhouse an energy saving screen is used on most nights and the cover is glass instead of PE, so fully absorbing FIR, and therefore, gets warmer than the FIR reflecting filters. Figure 7.5 shows the daily cyclic mean of cover temperature (°C) of the reference cover and the two covers with a switchable FIR filter along the cold months of the cycle (period 2). In it, we can see clearly that the cover temperature is always higher at night for the reference glass.

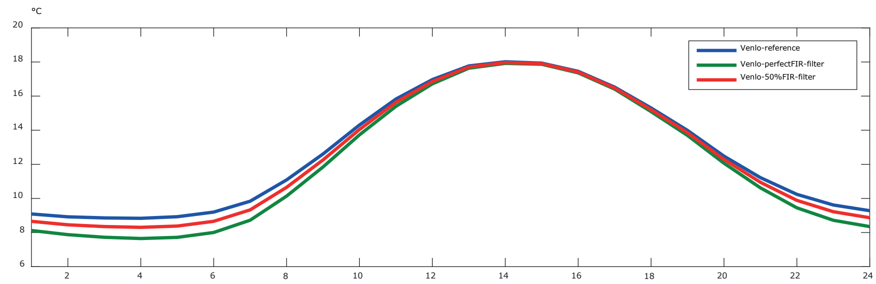

Figure 7.5 *Daily cyclic mean of cover temperature (°C) along the whole cycle under the 3 evaluated scenarios: reference-cover and the switchable perfect and 50% FIR reflection filters with activation temperature of 19°C.*

As a consequence, as we can see in Figure 7.6, condensation on the FIR reflective covers is higher than in the reference cover.

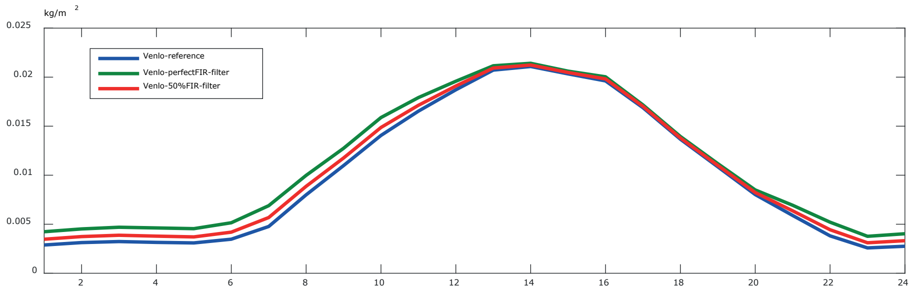

Figure 7.6 *Daily cyclic mean of condensation/evaporation to/from the cover (kg/m^2) the wholesycle of the growing cycle for the 3 evaluated scenarios: reference and the perfect and 50% FIR reflecting switchable filter with an activation temperature of 19°C.*

A positive effect of the filters is that canopy temperature becomes higher during the night and part of the morning and afternoon, decreasing the possibility of condensation on the crop, which enables the incidence of some fungal and bacterial diseases (Figure 7.7).

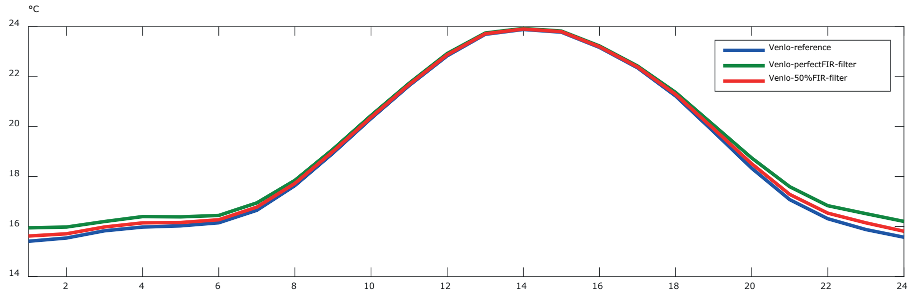

Figure 7.7 *Daily cyclic mean of canopy temperature (°C) along period 2 (1st October-1st April) of the growing cycle for the 3 evaluated scenarios: reference and the perfect and 50% FIR reflecting switchable filter with an activation temperature of 19°C.*

8 Conclusions

8.1 Non-selective solar filters

1. A permanent filter could have an application as greenhouse cover in tropical lowlands, where it would compete with the present use of fixed shading nets lain over the polyethylene cover.

2. A switchable filter would be a huge improvement (increase in yield by some 20%) wherever whitewash is applied (the whole Mediterranean-Subtropic region)
   - The swithchable filters allows for a much more efficient management of PAR than the whitewash.
   - Simulation results show a large synergy between the filter and improvement of the ventilation capacity. That is, the filetr would perform equally well also in improved greenhouse structures.
   - The swithchable filters also allow for a very relevant reduction in the amount of hours that the greenhouse air temperature exceeds the thresholds than may cause a decrease in net photosynthesis and potentially induce physiological problems affecting fruit quality in tomato crops (that were not part of this study).
   - The delayed activation filter (30°C) performs slightly better than early activation (28°C) for both simulated greeenhouse structures.
   - An optimization of the activation moment of the filter could lead to an even larger increase in potential productivity.
   - No synergy was observed between the application of artificial CO_2 in the greenhouse (CO_2 enrichment) and the use of the switchable filters.
   - Further research would be required to elucidate what is the optimum shading factor for the switchable filters, since the results of the present study do not indicate a clear advantage of the 30% shading in relation to the 60% shading. The combination of modeling and a literature study shows that for a good ventilated structure the optimal shading value would be around 30%, whereas for a poorly ventilated greenhouse this value could be around 60%.

3. For ornamental crops in The Netherlands, application of a switchable, non-selective screen in the cover of a Venlo glasshouse would yield minor improvement with respect to the present use of movable shading screens.
   - Quality aspects of the crop have not been modelled
   - A filter with variable shading factor would certainly be an improvement, both in terms of quality and in terms of dry matter production.

8.2 NIR-Selective solar filters

4. A permanent filter with higher reflectivity in the NIR than in the PAR would be most desirable in the tropical region, as it would improve on what has been said in point 1. above.

5. A permanent filter would give mpore yield than the whitewash in the mild-winter-climate region, but would decrease winter wild (which is usually the most valuable), mainly because it would decrease temperature too much in the winter period.

6. For mild winter climate regions (Agadir, Morocco) a switchable, selective filter perform only slightly better than the non-selective one, both in the traditional and in the better vemntilated one.
    - The explanation for this is that when the extra amount of PAR was available, temperatures and CO_2 were still limiting factors for dry matter produciton.
    - This is proved by the fact that when artificial CO_2 enrichment is used, a higher increase caused by the fiters is observed, as the CO_2 is no longer a limiting factor. It is also well known that at higher CO_2 concentrations, optimum net photosynthesis temperature increases.
    - A 10% reduction in PAR does not cause a similar decrease in yield, also proving that productivity is limited by other factors than PAR availability for the crop.
    - The partial NIR filters are not a good solution, due to multiple re-reflectionns between crop and cover.
    - Unlike for the non selective filters, the early activation filter (28°C) perform slightly better for both simulated greeenhouse structures.
    - An optimization of the activation moment of the filter could lead to an even larger increase in potential productivity.

7. NIR reflecting filters, in principle, have little interest in cold climate regions, such as The Netherlands, as maximum temperatures only occur during a very limited amount of hours in the year.

8. In desert regions, permanent NIR reflecting filters perform extremely well (little advantage of being switchable), both in a closed greenhouse (with active cooling) and in a pad and fan greenhouse which relies on evaporative cooling:
    - In a closed greenhouse simulations indicate a large energy saving (36%) when both a permanent and switchable perfect NIR reflecting filters (with early activation temperature) are used. The use of the filter would also allow to lower the maximum cooling power by 40%, which would involve a large investment saving.
    - The models also predict an increase of 15% in potential tomato yield under the NIR reflecting covers in relation to a standard glass for a closed greenhouse. This increase is related to a decrease in the number of hours that air and canopy temperatures are above a threshold of 28°C.
    - In a greenhouse with pad and fan cooling, simulations show that the use of the NIR reflecting filters in the glass cover involves a decrease in water used for cooling (37%), in energy used by the fans (20-25% for the switchable and permanent filters, respectively). However, the use of this filters also involves an small increase in use of energy for heating (12.7-23 % for the switchable and permanent filters, respectively).
    - The use of the NIR reflecting filters also allows for an increase of 8% in the potential tomato yield estimated by the model (for both filter types, permanent and switchable). This increase in yield is mostly caused by a decrease in the number of hours that both air and canopy temperature are above a physiological threshold of 28°C.

8.3 Far/Thermal InfraRed reflecting filters

9. A permanent FIR reflecting filter performs very well in passive (non-heated) greenhouses in mild winter climates. It increases night time air temperature, while still allowing for enough cooling of the greenhouse by radiation during the sunny winter days typical of these regions.
    - The difference in potential productivity in relation to a standard film which absorbs more than half of the FIR (65%) is relatively small (around 7%), but increased earliness is a very important advantage.
    - In addition there are other possible benefits of FIR reflection, instead of absorption. For instance, FIR reflection increases nighttime crop temperature, helping to prevent condensation on the plants, which should limit the incidence of fungal and bacterial diseases.
    - The performance of an aluminized internal mobile thermal screen is very similar to that of a cover with a switchable FIR reflecting filter.

10. The interest of a FIR reflecting filter in heated, high-tech greenhouses cold climates lies not in the effect in yield, which is almost inexistent, but on the decrease of fuel use for heating. An analysis would still be required to verify if such a cover can be an economic alternative to at least one of the energy saving screens used by cold climate growers.

9 Literature cited

Ahemd, H.A., Abdulelah A. Al-Faraj, Ahmed M. Abdel-Ghany, 2016,
Shading greenhouses to improve the microclimate, energy and water saving in hot regions: A review, Scientia Horticulturae, Volume 201,Pages 36-45, ISSN 0304-4238

Bot, G.P.A. (1983)
Greenhouse climate: from physical processes to a dynamic model. Ph.D. Thesis, Agricultural University, Wageningen.

Breuer, J.J.G. en van de Braak, N.J. 1989.
Reference Year for Dutch Greenhouses, Acta
Hort. 248:1989.

Capri, E. ; Pardossi, A. ; Stanghellini, C. ; Linden, T. van der (2010)
Scientific Opinion on emissions of plant protection products from greenhouses and crops grown under cover: outline for a new guidance EFSA Journal 8 (4). - p. 1567 - 1567.

Casini, M. 2018.
Active dynamic windows for buildings: A review. Renewable Energy 119:923-934

Fleischer, M., Dinar, M. 2014.
How to Tailor-Made a Greenhouse Cover". Acta Hort. 1015:259-262

Goudriaan, J. and Van Laar, H.H. 1994.
Modelling Potential Crop Growth Processes: Textbook with Exercises, Kluwer Academic Publishers, Dordrecht, 238 pp.

Graamans, Luuk ; Baeza, Esteban ; Dobbelsteen, Andy Van Den; Tsafaras, Ilias ; Stanghellini, Cecilia (2018)
Plant factories versus greenhouses: Comparison of resource use efficiency. Agricultural Systems 160 . - p. 31 - 43.

Hickman, G. 2017.
International Greenhouse Vegetable Production – Statistics: A review of Currently Available Data on the International Production of Vegetables in Greenhouses. Cuesta Roble Greenhouse Consultants, all rights reserved, 152 p.

Luo, Weihong ; Zwart, H.F. de; Dail, J. ; Wang, Xiaohan ; Stanghellini, C. ; Bu, Chongxing (2005)
Simulation of greenhouse management in the subtropics, Part 1: Model validation and scenario study for the winter season. Biosystems Engineering 90 (3). - p. 307 - 318.

Luo, Weihong ; Stanghellini, C. ; Dai, Jianfeng ; Wang, Xiaohan ; Zwart, H.F. de; Bu, Chongxing (2005)
Simulation of Greenhouse Management in the Subtropics. Part II: Scenario Study for the Summer Season. Biosystems Engineering 90 (4). - p. 433 - 441.

Pérez-Parra, J., Baeza, E., Montero, J.I. and Bailey, B.J. 2004.
Natural ventilation of parral greenhouses. Biosystems Engineering 87(3), 89-100.

Soto Agudelo, A.L., Patarroyo, Y., Merchán, O. F. 2011.
Metodología del Censo de Fincas Productoras de Flores Bajo Invernadero y a Cielo abierto. DANE, Bogotá, D.C., 39 p.

Stanghellini, C.; Jianfeng, D.; Kempkes, F.L.K. (2011)
Effect of near-infrared-radiation reflective screen materials on ventilation requirement, crop transpiration and water use efficiency of a greenhouse rose crop. Biosystems Engineering , Volume 110, Issue 3, November 2011, Pages 261–271.

Vanthoor, B.H.E.; Visser, P.H.B. de; Stanghellini, C.; Henten, E.J. van (2011)
A methodology for model-based greenhouse design: Part 2, description and validation of a tomato yield model. Biosystems Engineering 110 (4). - p. 378 - 395.

Vanthoor, B.H.E. (2011)
A model-based greenhouse design method. PhD Wageningen University - 307 p.

Zabeltitz, C. von. 1999.
Greenhouse structures. p.17-71. In: G. Stanhill and H. Zvi Enoch (eds.), Ecosystems of the world, Vol. 20, Greenhouse ecosystems, Elsevier, Amsterdam, Lausanne, New York, Oxford, Shannon, Singapore, Tokyo

Zwart, H.F. de (1996)
Analyzing energy-saving options in greenhouse cultivation using a simulation model. PhD thesis, Agricultural University, Wageningen 236 p.

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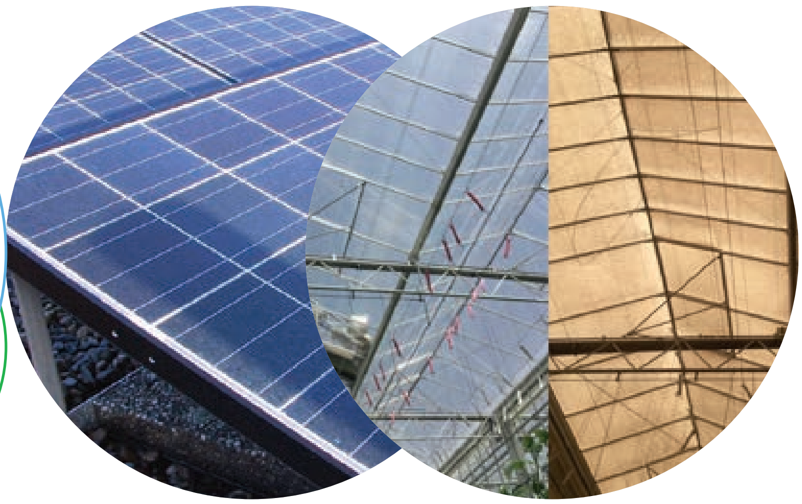

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