

Energy saving potential of long-term climate adaptive greenhouse shells

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ENERGY SAVING POTENTIAL OF LONG-TERM CLIMATE ADAPTIVE GREENHOUSE SHELLS

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ABSTRACT

This paper describes yearly and monthly optimization of greenhouse shells. Simulations adopt a validated building energy simulation program, adapted and re-validated for simulation of commercial greenhouses, including a tomato crop model. The work focuses on multi-objective optimization of thermal and optical greenhouse shell properties using a genetic algorithm. Analysis of optimization results is supported by sensitivity analyses. The paper concludes that monthly adaptation of greenhouse shells provides little improvement in the crop production and energy performance of the greenhouse when compared to the yearly optimized greenhouse. In the case of adaptable shells, however, high-performance low-energy greenhouses can be achieved at a relatively low level of complexity.

INTRODUCTION

Commercial agricultural greenhouses are large low-rise structures, with shell properties rather different from shells of conventional buildings (such as high U-value and high glazed area). Greenhouse shells are designed to create more favourable growing conditions for the crop in comparison with the outdoor environment. In spite of improvements in indoor conditions, the use of active heating, ventilation and air conditioning (HVAC) systems is often needed to improve crop growth and quality, and as a result, economic returns (de Zwart, 1996; Chou et al, 2004; Vanthoor et al, 2011).

HVAC systems in greenhouses are responsible for a significant part of total energy consumption in many countries (Sethi et al., 2007; Sethi et al., 2008). In the Netherlands, for example, the agricultural sector is responsible for approximately 8% of the total energy use, and energy corresponds to 15% - 20% of the production costs of vegetables in greenhouses (Eurostat, 2010). Because of these wide-ranging impacts, research and development that aims at increasing energy efficiency of the greenhouse sector has been identified as a key factor in sustainability policies (Ardenne et al, 2012). For example, the ambitions in horticulture sector in the Netherlands are carbon neutral operation and introduction of more

renewable energy by 2020. A challenge in reducing energy consumption of the horticultural sector is the fact that greenhouses have to be operated in an economically viable way. Energy saving cannot come at the expense of product quality and throughput. To support these ongoing developments, there is a need for innovative greenhouse shell and HVAC system concepts.

This paper is part of the work developed in the project: "Climate adaptive greenhouses: inverse modelling" (CAGIM). The characteristic feature of this project is that it does not consider the greenhouse as static throughout the year. Instead, the project aims to investigate the potential of greenhouse shells and systems that have the ability to adapt in response to variations in boundary conditions and performance requirements throughout the year. By using simulation-based optimization techniques, optimum adaptable properties of the greenhouse shell and systems will be identified. The outcomes will be helpful in guiding the development of innovative concepts for greenhouse design and operation.

The objective of this paper is to show the potential of deploying computational methods to gain a better understanding of the potential of seasonal adaptation in greenhouse shell properties. We use a combination of simulation, optimization and sensitivity analysis techniques to analyze the trade-off between energy consumption and crop production. After presenting the research methods, the results of a case study with both optimal annual and monthly adaptable properties are discussed and analyzed.

METHODS

Greenhouse performance simulation

Simulations were carried out using a modified version of ESP-r, adapted for the simulation of greenhouses. The modified version includes a tomato crop model (photosynthesis and transpiration) fully coupled with the thermal model and airflow network models in ESP-r. Details of the simulation strategy and results of an inter-model comparison with a dedicated greenhouse simulation tool are described in (Lee et al., 2012).

Performance indicators

In this study, we use two performance indicators: primary energy consumption and crop production.

Primary energy consumption (kWh/m².y) is based on energy demand calculated using ESP-r. COP and heating efficiency are assumed for different scenarios. Electricity is converted into primary energy using a conversion factor of 2.5.

Crop production (kg/m².y) is calculated based on the amount of dry matter from the photosynthesis model, where the fresh tomato production is multiplied by a given coefficient to account for the fact that 6% of the tomato consists of dry matter and the rest is water. In part of the simulations, energy and crop production are combined in a single performance indicator, profit (€). In this case, the tomato price varies over time from 0.52 to 2.15 €/kg (KWIN monthly tomato average 2007~2009), and the energy price is 0.30 €/kWh of gas all over the year.

Crop model

The tomato crop model coupled with ESP-r calculates photosynthesis rate with PAR (photosynthetically active radiation), CO₂ concentration and temperature as inputs. It also calculates transpiration on the basis of leaf area index (LAI) and global radiation (see Figure1). These results are then recalculated to the tomato production and moisture production respectively. Latent heat exchange by transpiration model is fully coupled with the thermal model in ESP-r.. However, there is no feedback from the photosynthesis model to the thermal model since it is one-way coupling.

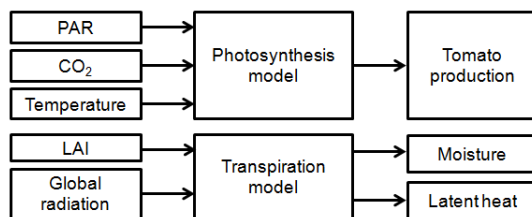


Figure 1. Inputs and outputs of crop model coupled with ESP-r

Photosynthesis model

Photosynthesis models quantify the net photosynthesis rate by the tomato crop. Net photosynthesis rate can be a performance indicator of the crop growth and production quantity. Photosynthetic activity and production are closely related to CO₂ concentration, temperature and PAR. Figure 2 shows example results of net photosynthesis rate for tomato obtained by using the photosynthesis model. The tomato production is largely influenced by PAR level and CO₂ concentration, while air temperature plays a secondary role.

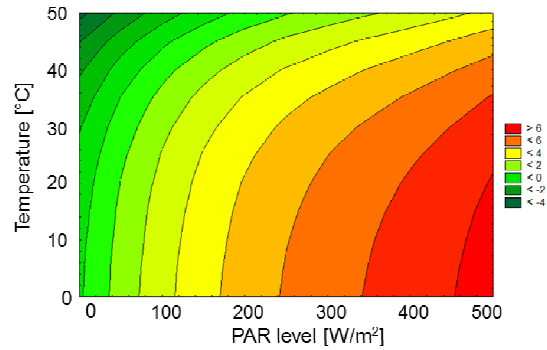


Figure 2. Net photosynthesis rate with photosynthesis model at 400 ppm CO₂ concentration.

Transpiration model

As a by-product of photosynthetic activity, crops release moisture (so-called transpiration). Transpiration increases indoor humidity and reduces crop temperature by evaporative cooling. The effects of transpiration are taken into account in the heat balance of the surface representing the canopy. Canopy temperature is then calculated by ESP-r based on the amount of evaporative cooling by transpiration and on the heat balance between canopy and its surroundings.

Optimization scenarios

The use of profit as performance indicator requires the adoption of scenarios for efficiency of the heating and cooling systems. This efficiency is then combined with the energy demands calculated by ESP-r to provide energy consumption values. The energy consumption is converted into energy costs using current energy prices.

Two scenarios are considered in this study regarding efficiency of the heating and cooling systems: (1) a conservative scenario and (2) a high-efficiency scenario. These scenarios are defined as extreme cases, and the relation between the greenhouse shell and systems will be addressed in-depth in future study.

Scenario 1 - conservative: the heating efficiency is assumed to be 0.9 (assuming gas boiler) and the COP of cooling is equal to 3. Energy use due to active dehumidification is also included. CO₂ is kept constant at 800 ppm.

Scenario 2 - high efficiency: the COP of the heating system is 5 (assuming a ground coupled heat pump, therefore using electric supply), and the COP of the cooling system is 100 (assuming passive cooling; energy is only used for fans and pumps). CO₂ is kept constant at 400 ppm and dehumidification load is not included in the energy consumption (assuming energy removal by ventilation).

In both scenarios, ventilation is not explicitly modeled, as the ventilation is seen as a cooling technique and should be addressed in system side.

Multi-objective optimization and Genetic algorithm

Multi-objective optimization (MOO) with genetic algorithms (GA) has proven to be an effective decision-support tool in the design of building envelopes (Wright et al., 2002; Hopfe, 2009; Hoes et al., 2011; Evins, 2013). In addition, multi-objective optimization can be useful for the testing/developing new design and control concepts for climate adaptive building shells (Boer et al., 2012; Hoes et al., 2012; Loonen et al., 2011).

In this study, GAs are applied to optimize the properties of commercial greenhouse shells. The optimization process is carried out for two objectives: to minimize primary energy consumption, to maximize tomato production. The non-sorting NSGA algorithm is applied for multi-objective optimization of the greenhouse shell. The MOO process in this study is as follows:

1. Generate initial population (set of optimization parameters) by Latin hypercube sampling;
2. Evaluate objective function by ESP-r and rank non-dominated solution (Pareto front) in order for the next generation;
3. Decide if stopping criterion (maximum 10 generations) is satisfied;
4. If stopping criterion is not satisfied, apply rank-based selection (elitism), crossover and mutation;
5. Go to step 2;

Sensitivity analysis (SA)

Sensitivity analysis provides information about which of the input parameters has a significant impact on the simulation output (Shen and Tzempelikos, 2013). Global sensitivity methods are approaches where output variability due to one design parameter is evaluated by varying all other design parameter and the influence of other optimization parameters in global sensitivity analysis is considered since the overall building performance is important (Tian, 2013). Global sensitivity analysis in this study is used to explore the impact on energy consumption in response to variations in optimization parameters.

CASE STUDY DESCRIPTION

Performance improvements due to adaptation of the greenhouse shell are defined in relation to a reference case. The reference case is defined independently of Scenarios 1 and 2, as it aims to reproduce features of existing greenhouses. The reference case and some

assumptions used in the simulations are described below:

- Performance of the greenhouse is evaluated under Dutch climate conditions (De Bilt)
- The case study focuses on tomato crop.
- Size of greenhouse: 100 * 100 * 6 m considering no side wall effect (adiabatic wall)
- A temperature scenario is used to maintain favorable conditions for the tomato crop (usually between 16 °C and 19 °C)
- Windows are opened when relative humidity (RH) exceeds 85%
- 0.2 ACH is used for infiltration rate (when greenhouse is closed)
- Unlimited heating capacity with ideal control is assumed
- Daily increase of leaf area index (LAI) tomato model is used
- Heating efficiency of 0.9
- Gas conversion factor ($m^3 \rightarrow kWh$): 11.0
- The optical and thermal properties of reference case greenhouse are shown in table 1

Table 1 . The optical and thermal properties of reference case greenhouse

OPTICAL PROPERTIES			
Transmittance	0.85		
Absorptance	0.00		
Reflectance	0.15		
THERMAL PROPERTIES	Glass	Floor	Ground
Conductivity [W/(m-K)]	1.05	0.50	0.85
Density [kg/ m ³]	2600	1050	1640
Specific heat [J/(kg-K)]	840	837	879
IR emissivity	0.84	0.6	-
Solar absorptance	0.00	0.25	-

RESULTS OF THE REFERENCE CASE

Results for the reference case indicate an annual primary energy consumption of 31.5 m³/y (gas). This value is in line with current practice in the Netherlands (~35.0 m³/y). Crop production is estimated at 108.4 kg/m².y of fresh matter, also in the same order of magnitude of values found in current practice. These results increase the confidence in the simulation approach (modified version of ESP-r and other assumptions) to be used in the optimization of the greenhouse shell.

ANNUAL OPTIMIZATION OF STATIC GREENHOUSE SHELL

Description of the annual optimization parameters

Before performing investigations on adaptable greenhouse shells, a study was conducted to evaluate the potential for improvement in non-adaptive shells. Typical commercial greenhouses have floor areas in few hectares. The effect of side-walls is negligible, and therefore, this study only focuses on optimizing roof properties. The range of values for the design variables, which is presented in Table 1, is chosen to be quite large and generic. The different combinations of properties cover conventional and state-of-the-art greenhouse shell products, such as: anti-reflection glazing, transparent insulation materials, whitewash, thermal screens and shading screens (Bakker, 2009). In this exploratory application of building performance simulation, however, we did not intend to limit the design option space to currently available materials. Instead, this study aims to foster the development of innovative greenhouse shell components and concepts.

Table 2 . Properties and range of values used for optimization of the greenhouse shell

PROPER-TIES	PARAMETERS	RANGE	STEP
Optical properties	Transmittance [-]	0.05~0.95	0.05
	Absorptance [-]	0.05~0.95	0.05
	Reflectance [-]	1-(T+A)	0.05
Thermal properties	Conductivity [W/mK]	0.05~1.05	0.05
	Outside emissivity [-]	0.10~0.90	0.10
	Inside emissivity [-]	0.10~0.90	0.10

The remaining properties follow the description in the Case study section.

Annual optimization results – Scenario 1

Figure 3 shows results of primary annual energy consumption and fresh tomato production for Scenario 1. The improvement in performance is shown by the comparison between the reference case (red) with the optimized static shell (blue). The optimized shell increases the tomato production by 14%, and reduces the energy consumption by 13%. Regarding the comparison with reference case values, the tomato production increases due to the higher transmittance as determined by the optimization. Regarding energy consumption in Scenario 1, the energy for cooling becomes dominating. This high cooling energy consumption is a consequence of two factors. Firstly, assumptions regarding active cooling (no ventilation, COP equal to 3) led to a large increase in the cooling demand. Secondly, the optimization resulted in a highly insulated shell, reducing significantly the heating demand.

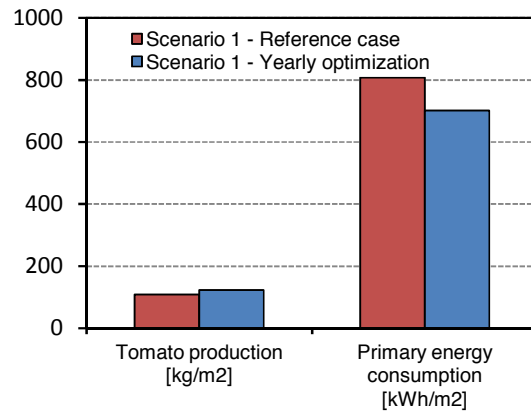


Figure 3. Performance of yearly optimization of greenhouse shell compared to current practice values

Figure 4 shows the sensitivity of the most relevant parameters in the yearly optimization. Results indicate that optical properties of glazing are the most important parameters, and the higher the transmittance; the higher will be the energy consumption (due to high cooling load in Scenario 1). Despite this effect, the optimum transmittance considering both objectives is equal to the maximum allowed value (0.95). This indicates that, even in a scenario with high energy costs (conservative scenario) the gains due to increased crop production surpass the increase in cooling demand. Optimization in monthly or hourly basis might show that at some point of the year the increase in cooling demand might not be larger than the increase in crop production (in terms of profit). However, in whole year terms, the more transparent the better for the tomato crop, independent of the cooling system. This result confirms common expectation from practice, and the challenges regarding increasing the transmittance of greenhouse are well known (Vanthoor, 2011).

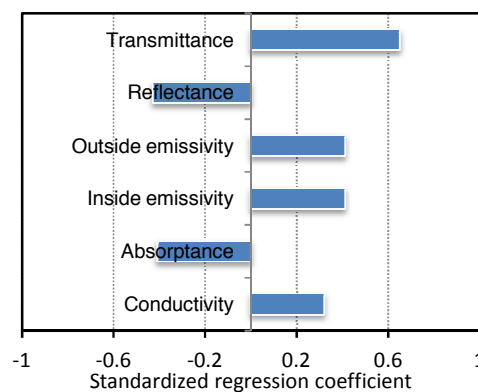


Figure 4. Most sensitive parameters in the yearly optimization of greenhouse shell in Scenario 1 (using the energy consumption as performance indicator)

Figure 4 also shows that parameters related to conduction and longwave radiation play a significant role in the results. Higher emissivity and conductivity lead to higher interaction with the outdoor environment, and higher energy demand in most cases. Optimum values for these three parameters are the lower boundaries of the range in Table 2, i.e. emissivity equal to 0.1 and conductivity equal to 0.05 W/mK. These values are rather low, and should be taken as an indication of the beneficial effect of reducing the interaction between indoor and outdoor in heavily conditioned greenhouses.

Annual optimization results – Scenario 2

Figure 5 shows results of tomato production and energy consumption for the reference case and the yearly optimized greenhouse shell with Scenario 2. The tomato production is slightly increased and the improvement in production is mainly due to the higher transmittance of greenhouse shells. The reduction in energy consumption is remarkable. This reduction is due to the combination of a highly insulated shell (low conductivity and emissivity as in the previous section) with efficient heating and very efficient (low cost) cooling.

Figure 5 shows that, using proper insulation, the energy consumption of greenhouses would drop to values commonly found in other buildings in the Netherlands. The challenge is, of course, to provide a low cost insulation material that does not reduce the income of solar radiation which is essential for crop growth.

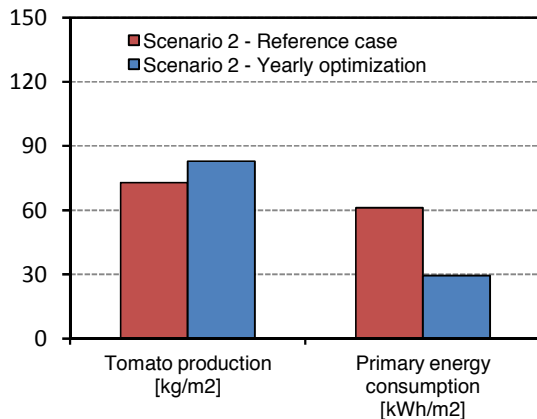


Figure 5. Performance of yearly optimization of greenhouse shell compared to current practice

Figure 6 shows the sensitivity of the most relevant parameters in the yearly optimization results for Scenario 2. The shift in trend for transmittance, when compared to Figure 4, is the main difference in the results. In Scenario 2, the energy consumption is mainly due to heating, therefore low transmittance values will reduce solar gains and increase the energy consumption. As in Scenario 1, the higher

transmittance, the better performance. In Scenario 2 this is valid not only in terms of tomato production but also in terms of energy.

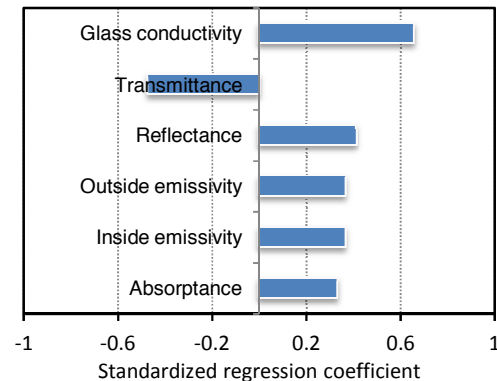


Figure 6. Most sensitive parameters in the yearly optimization of greenhouse shell in Scenario 2 (using the energy consumption as performance indicator)

Figure 7 shows clearly the relation between increase in energy consumption and increase in tomato production. The role of solar transmittance is also evident. In terms of profit, the optimum solution is the one with higher production, as the costs associated with conditioning are smaller than the additional value of tomato produced.

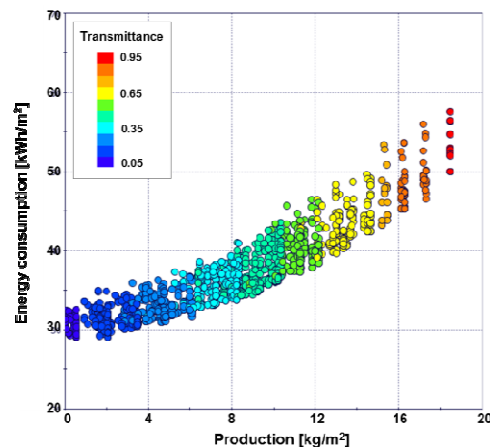


Figure 7. Energy consumption and tomato production of greenhouse in August with scenario 1

OPTIMIZATION OF MONTHLY ADAPTIVE GREENHOUSE SHELL

Description of the monthly optimization parameters

This section describes the activities and results aiming at the characterization of optimum monthly adaptable greenhouse shells. The work consisted of one separate optimization for each month, following the same method and parameters used in the previous section.

Monthly optimization results – Scenario 1

Figure 8 shows the performance of the monthly adaptive greenhouse shell in comparison to the yearly optimized greenhouse shell. The tomato production is not improved, as this performance indicator is highly dependent on the incoming photosynthetically active radiation (PAR), which is maximized by in the yearly optimized case (transmittance equal 0.95). Energy performance has a small improvement (around 3% reduction), mainly due to reduction of cooling load.

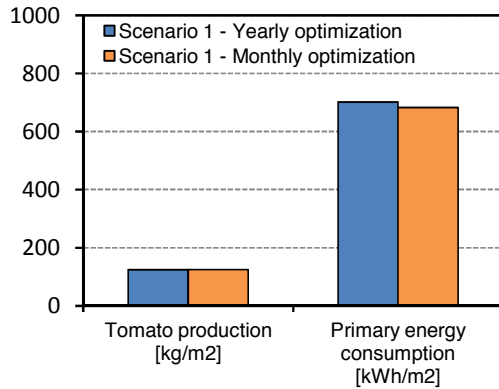


Figure 8 . Performance of monthly optimization of greenhouse shell compared to yearly optimized values

Figure 9 shows that in Scenario 1 the optical properties are key parameters in the cooling energy consumption (April to September). The sensitivity during the winter is reduced, as additional solar gains can reduce the heating demand but insulation also plays an important role. Figure 10 shows the importance of shell conductivity and emissivity during the winter, while their role in the summer is reduced.

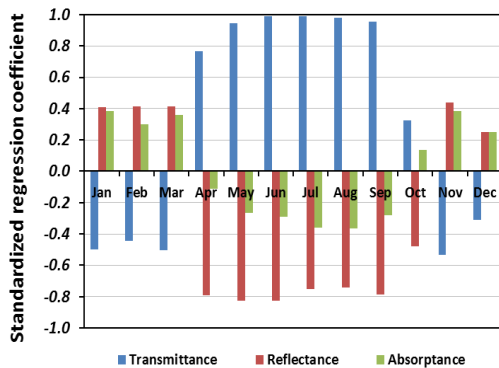


Figure 9 . Monthly sensitivity analysis of optical properties in relation to the energy consumption – Scenario 1

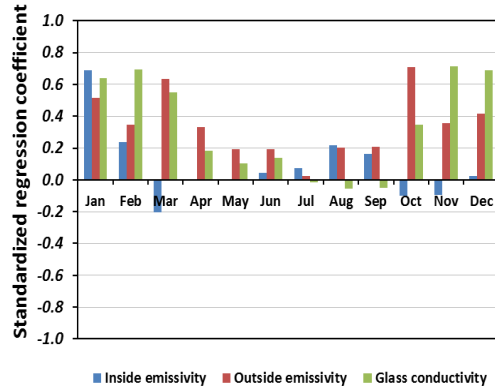


Figure 10 . Monthly sensitivity analysis of relevant shell properties in relation to the energy consumption – Scenario 1

Results in Figure 10 mask the role of conductivity and emissivity in the energy performance of the optimum solution. Transparency is indeed the most important parameter for cooling energy, but this parameter cannot be changed due to its impact on the other performance requirement; tomato production. This is not the case for conductivity and emissivity, and further analysis revealed that changes in these two parameters are responsible for the reduction in energy consumption of 3% in the monthly optimized case. Figure 11 shows the optimum value of glass conductivity and outside emissivity, indicating that the shell should be designed to maximize heat losses during the summer (as expected).

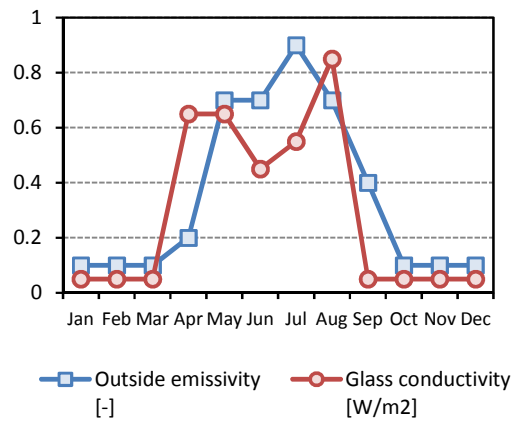


Figure 11 . Optimum value of glass conductivity and outside emissivity – Scenario 1

Although the additional saving potential that can be achieved by moving from the annual optimal, to an adaptable greenhouse shell is not remarkably high, there are important design implications, which are worth noting. The annual optimized shell presents complex requirements from the viewpoint of materials development. For example, a single shell

configuration needs to address the challenge of combining high thermal resistance with high transmittance, to guarantee high performance under the wide range of occurring conditions. An adaptable shell can relieve this demand, by accommodating design features with respect to the time-dependent variations in boundary conditions. With relatively simple, e.g., manual interventions, the greenhouse shell can be adjusted in response to the variations in trade-off in that time of the year. In state-of-the-art greenhouses, such effects are already partly incorporated through the application of seasonal whitewash and movable screens. The results presented in this paper suggest that future research in the direction of greenhouse shell materials with adaptable properties is worthwhile.

CONCLUSIONS

The simulations and analysis conducted in this research support the following conclusions:

- Optimized static greenhouse shells provide large improvements in the performance of a greenhouse
- Transmittance is the key parameter in yearly and monthly optimized shells, as any increase in production pays off additional costs for cooling; this warrants further research to investigate the effect of spectrally selective cover materials
- Conductivity and emissivity play an important role in reducing heating load of optimized greenhouse shells
- Different scenarios for HVAC system concepts lead to different optimum greenhouse shell properties; focusing only on the demand-side delivers limited insights
- Adaptable conductivity and outdoor emissivity are relevant adaptation measures in monthly adaptable shells
- Monthly adaptable shells provide minor improvements in the energy performance when compared to yearly optimized greenhouse shells
- Adaptable shells can achieve high performance with less extreme, and therefore more feasible, material properties

Future work should focus on short-term (e.g. hourly) adaptation and enhanced data analysis of simulation results.

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