Applied Energy 281 (2021) 116019

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Energy savings in greenhouses by transition from high-pressure sodium to LED lighting

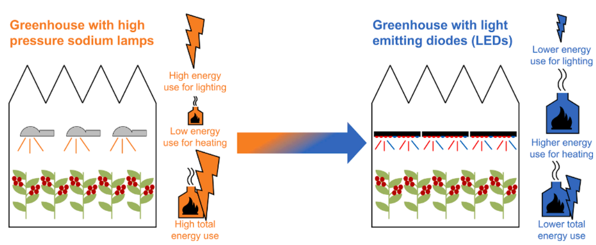
David Katzin[a,*], Leo F.M. Marcelis[b], Simon van Mourik[a]

[a] Farm Technology Group, Department of Plant Sciences, Wageningen University, PO Box 16, 6700 AA Wageningen, The Netherlands
[b] Horticulture and Product Physiology Group, Department of Plant Sciences, Wageningen University, PO Box 16, 6700 AA Wageningen, The Netherlands

HIGHLIGHTS

- A novel analysis of the effect of LEDs on the greenhouse energy budget is presented.
- The total energy system, including heating and lighting demand, was examined.
- Energy savings in multiple climate scenarios from around the world were examined.
- Energy for light was reduced by 40% while energy for heating increased by 9–49%
- A transition to LEDs was predicted to save 10–25% of total greenhouse energy demand.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Greenhouse
Energy saving
Energy use efficiency
LED
Greenhouse lighting
Greenhouse model

ABSTRACT

Greenhouses in high latitudes consume vast amounts of energy for heating and supplemental lighting. Light emitting diodes (LEDs) have been suggested as having great potential for reducing greenhouse energy use, as they are extremely efficient at converting electricity to light. However, LEDs emit very little heat, which must be compensated by the greenhouse heating system. Thus, it is unclear how much energy can be saved by LEDs when the need for extra heating is taken into account. This study presents a first analysis of the energy demands for greenhouses transitioning from high-pressure sodium (HPS) to LED lighting, providing a quantification of the total energy savings achieved by LEDs. Model simulations using *GreenLight*, an open source greenhouse model, were used to examine a wide range of climates, from subtropical China to arctic Sweden, and multiple settings for indoor temperature, lamp intensity, lighting duration, and insulation. In most cases, the total energy saving by transition to LEDs was 10–25%. This value was linearly correlated with the fraction of energy used for lighting before the transition, which was 40–80%. In all scenarios, LEDs reduced the energy demand for lighting but increased the demand for heating. Since energy for lighting and heating is often derived from different origins, the benefits of a transition to LEDs depend on the environmental and financial costs of the available energy sources. The framework provided here can be used to select lighting installations that make optimal use of available energy resources in the most efficient and sustainable manner.

* Corresponding author.
E-mail address: david.katzin1@gmail.com (D. Katzin).

https://doi.org/10.1016/j.apenergy.2020.116019
Received 7 July 2020; Received in revised form 1 October 2020; Accepted 9 October 2020
Available online 4 November 2020

1. Introduction

Greenhouse horticulture in high latitudes requires vast amount of energy input. In northern latitudes, heated glasshouses consume energy at a rate of 1100–1900 MJ m^{-2} $year^{-1}$ [1]. With an estimated 40,000 ha of vegetable glasshouses worldwide [2], and at least that much area for ornamental production [3], greenhouses consume more than 880 petajoule (PJ) of energy every year. In the Netherlands, the greenhouse industry consumes 113 PJ of energy per year [4], resulting in 5.7 megatons of CO_2 emissions, nearly 25% above the targets set for the sector by the government [5].

Worldwide, greenhouse energy use is increasing, due to wider and more intense use of heating and supplemental lighting [1]. Heating is used to maintain indoor temperatures that are favorable for the crop year-round, while supplemental lighting is used either for daylength control, in order to regulate plant developmental processes such as flowering, or as assimilation lighting to increase crop growth [6].

Assimilation lighting requires substantial electrical input. An illustrative example comes from the Netherlands, where production of tomatoes is possible with or without supplemental light [7]. It is estimated that a greenhouse with lamps requires more than double the energy input, and has more than triple the carbon footprint, compared to a greenhouse without lamps. At the same time, the illuminated greenhouse is estimated to provide only 27% higher yields [7]. Another illustrative example comes from Ontario, Canada, where illuminated vegetable greenhouses consume 10 times more electricity than unilluminated greenhouses [8].

These examples illustrate how supplemental lighting enhances greenhouse production but carries high financial and environmental costs. High-pressure sodium (HPS) lamps are currently the most prevalent lamp type used for supplemental lighting in greenhouses, but light emitting diodes (LEDs) are progressively being adopted as an alternative for, or in addition to, HPS lamps [9].

The main advantage of LEDs over traditional lamps is that they are better at converting electrical power to photosynthetic light [1]. For horticultural lamps, the conversion rate from electrical input to photosynthetically active radiation (PAR) is termed as the lamp's photosynthetic photon efficacy (PPE), or efficacy in short. This value is expressed in mols of photons of PAR emitted per energy input, measured in μmol J^{-1} [10]. While the efficacy of HPS lamps is between 1.7 [10] to 1.85 [7] μmol J^{-1}, commercial LEDs currently provide 3 μmol J^{-1} [11]. In other words, LEDs have a 60% higher efficacy than traditional horticultural lamps, and this value is expected to rise in the future [12].

The increase in efficacy of LEDs is promising to bring about meaningful energy savings in greenhouses [1]. At the same time, uncertainty regarding the financial consequences of transitioning to LEDs is a critical factor preventing adoption of this technology by growers [13]. One factor contributing to this uncertainty is the fact that LEDs provide less heat than the lamps that are currently used. HPS lamps emit considerable amounts of radiative heat [14], which reduces the load on the greenhouse heating system [15]. When HPS lamps are replaced by LEDs, some of the heat that is no longer provided by the lamps must be provided in other ways, and the total energy saving in the greenhouse could be less than expected.

Despite this, many studies that examined the energy saving potential of LEDs in greenhouses focused on the savings of the lighting system only [10,12,16,17], and did not quantify the influence of the lighting system on heat demand. Only a few limited studies reported on how LEDs influence the total energy demand of the greenhouse [18], and these suggest that effects on total energy saving might be disappointing. For example, a hybrid system combining LEDs and HPS lamps was compared to a full-LED system. The savings in electricity by using full LEDs were 37%, but the total energy saving was only 11% [19]. Another trial found a 60% savings on lighting by the use of LEDs, but only a 6.5% savings on total energy use, due to a higher heat demand under LEDs [20]. These studies show that the total energy savings achieved by a transition to LEDs are considerably lower than the savings on lighting alone. However, it is not clear what the actual savings may be in a commercial greenhouse, or which factors influence these savings.

A thorough analysis quantifying how much energy can be saved by using LEDs is currently missing in the literature. Such an analysis should also include an assessment of the separate lighting and heating demands of the greenhouse, since these two uses often originate from different energy sources. Heating energy can originate from boilers fueled by natural gas or other fuels, geothermal heat, heat pumps, heat buffers, combined heat and power (CHP) generators, and others [3]. Similarly, electricity for lighting can come from fossil-fueled power plants, photovoltaic cells, wind turbines, CHPs, and more. Each of these sources and systems carries different financial and environmental costs. Since a transition from HPS lamps to LEDs generally involves lower lighting demands but higher heating demands, it is important to quantify these changes, so that they can be evaluated against the available energy sources for each respective greenhouse or region. In this way, greenhouse growers at an individual level, and policymakers at a regional level, can ensure that the lighting and heating systems in greenhouses are compatible with the available energy resources, such that energy is being used in an optimal manner.

Experimental trials comparing HPS and LED lamps in greenhouses are costly and limited in scope. Ideally, such trials should be performed in neighboring, but not bordering greenhouses, so that the weather influence is equivalent but border effects are prevented. Even so, such trials can only provide information for a single greenhouse setting in a single weather scenario, and cannot shed light on general phenomena.

Process-based mathematical modelling of the greenhouse climate is a widely recognized discipline used for the evaluation of greenhouse energy demands. This approach has been used since the 1960′s [21], developed throughout the following decades [22], and used to analyze energy-saving scenarios since at least the 1990′s [23]. Optimal control techniques have been combined with process-based modelling to create methods for reducing the applied heating and cooling [24] and minimizing the energy use [25] of advanced greenhouses. More recently, models have been proposed for predicting the heating demands specifically for greenhouses in cold regions [26], and for analyzing energy saving techniques in those greenhouses [15]. Other recent studies incorporated detailed crop models to more accurately predict both crop yield and energy demand [27]. Nevertheless, process-based models that include both HPS and LED lighting are rare. Two recent exceptions are a model by Righini et al. [28], and the GreenLight model [29].

GreenLight is a novel, open-source model for illuminated greenhouses with a tomato crop. It has several advantages which make it suitable for the analysis of energy demands in illuminated greenhouses. First, it has been evaluated against a dataset of an experimental trial where HPS and LED lighting was compared. The error in predicting energy use was in the range of 1–12% [29]. Second, GreenLight is available as open source MATLAB code at https://github.com/davkat1/GreenLight. The availability of the source code makes the model transparent and extendable. Researchers and practitioners who wish to evaluate, extend, or adjust the model to their own scenarios can freely do so. The framework provided in this study may thus be further applied to investigate in detail the energy balance and the consequences of transitioning to LEDs in any local scenario.

The objective of this study was to systematically quantify how much energy can be saved by transitioning from HPS to LED lighting in greenhouses, under various control and design settings and in a wide range of climates. To the best of our knowledge, this is the first thorough analysis on the influence of LEDs on the greenhouse energy budget. In particular, we quantified the changes in the separate energy demands for heating and lighting. Such an analysis is crucial for growers and policymakers to choose the best form of lighting technology with respect to their local climate and energy market, in a way that makes use of the available energy resources in the most efficient and environmentally sustainable manner. For this purpose, simulations were performed using the GreenLight model, allowing us to closely examine the greenhouse energy system, and to test how various components of the system influence the energy budget, providing a comprehensive view which is impossible to attain in isolated empirical trials. We tested how much energy can be saved by transitioning from HPS lamps to LEDs in terms of lighting and heating, and which energy fluxes in the greenhouse system are responsible for these changes. We examined how the local climate influences the potential energy savings by simulating greenhouses in various locations around the world, ranging from subtropical China to arctic Sweden. Several greenhouse settings were considered, including various indoor temperatures, light intensities, lighting durations, and structure insulations. We further examined which energy fluxes are most influenced by the change from HPS to LED lighting, and how these fluxes change throughout the year. Lastly, we discuss what these results could mean in practice for growers and policy makers, and how they may be further extended.

2. Methods

2.1. Potential energy savings considering only the lighting system

As a first analysis, the expected energy savings were calculated in cases where a transition to LEDs does not influence the greenhouse heating requirement. This means that the energy savings are a direct result of the higher efficacy of LEDs. The efficacy of current HPS lamps was assumed to be 1.8 μmol J^{-1} [10, including comments to the online article]. For LEDs, two efficacies were considered: an efficacy of 3.0 μmol J^{-1}, which is the highest efficacy found in independent tests, and an efficacy of 4.1 μmol J^{-1}, representing the limit of current technology [12]. LEDs with these efficacies would require 40% and 56% less energy per photon, respectively, than an HPS lamp.

The resulting energy saving by a transition to LEDs was expressed as a fraction of the energy requirement of the HPS greenhouse. For this, we denote Q_{Light}^{HPS} (MJ m^{-2} year^{-1}) as the amount of purchased energy used for lighting in the HPS greenhouse. Similarly, Q_{Heat}^{HPS} (MJ m^{-2} year^{-1}) is the amount of purchased energy used for heating the HPS greenhouse. The total energy use of the HPS greenhouse is thus:

$$E^{HPS} = Q_{Light}^{HPS} + Q_{Heat}^{HPS}. \quad \left(\mathrm{MJ\ m^{-2}\ year^{-1}}\right) \tag{1}$$

Assuming the heating requirements remain equal, the energy requirements of a greenhouse with LEDs is:

$$E^{LED} = \frac{\epsilon_{HPS}}{\epsilon_{LED}} Q_{Light}^{HPS} + Q_{Heat}^{HPS} \quad \left(\mathrm{MJ\ m^{-2}\ year^{-1}}\right) \tag{2}$$

where E^{LED} (MJ m^{-2} year^{-1}) is the total energy input of the LED greenhouse; ϵ_{HPS}=1.8 μmol J^{-1} is the efficacy of the HPS lamp and ϵ_{LED} = 3 μmol J^{-1} or 4.1 μmol J^{-1} is the efficacy of the LED lamp. Compared to the original energy input, this results in a total relative energy saving of:

$$Savings = 100 \cdot \frac{E^{LED}}{E^{HPS}} = 100 \cdot \left(1 - \frac{\frac{\epsilon_{HPS}}{\epsilon_{LED}} Q_{Light} + Q_{Heat}}{Q_{Light} + Q_{Heat}}\right) = \frac{100 \cdot \left(1 - \frac{\epsilon_{HPS}}{\epsilon_{LED}}\right) Q_{Light}}{Q_{Light} + Q_{Heat}}$$
$$= 100 \cdot \left(1 - \frac{\epsilon_{HPS}}{\epsilon_{LED}}\right) F_{Light} \quad (\%) \tag{3}$$

where $F_{Light} = \frac{Q_{Light}}{Q_{Light} + Q_{Heat}}$ (-) is the fraction of energy input used for lighting in the HPS greenhouse.

In addition, we calculated the energy savings that can be achieved if a hypothetical infinitely efficient lamp was used, i.e., if the energy input for lighting the greenhouse could be reduced to zero. Following a similar calculation to the one above, in this case the savings are equal to F_{Light}.

2.2. Model simulations using various climate locations

In order to evaluate the influence of local climate on the energy use of HPS and LED greenhouses, 15 locations around the world were selected and weather data from these locations was used as input to the model. The locations were chosen such that a varied set of climates would be represented, with a focus on locations where illuminated greenhouses are present. Climate data was retrieved from the EnergyPlus website [30], which compiles standard weather data from various sources. The chosen locations, as well as their latitude, longitude, elevation, and the originating dataset, are presented in Table 1.

For each of the climate datasets listed in Table 1, the following variables, given in 1-hour intervals, were used: Global solar radiation I_{Glob} (W m^{-2}); Air temperature T_{Out}(°C); Relative humidity RH_{Out} (%); Wind speed v_{Wind} (m s^{-1}); Horizontal infrared radiation from the sky I_{Sky} (W m^{-2}). These values were interpolated to 5-minute intervals by using a piecewise cubic Hermite interpolating polynomial. Soil temperatures T_{SoOut} (°C) were given in monthly average values; these were interpolated to 5-minute intervals by fitting the values to a sine function. Outdoor CO_2 concentration value was set at 410 ppm.

Fig. 1 and Fig. 2 present an overview of the weather patterns in the locations used in this study. Fig. 1 provides the monthly means of solar radiation and outdoor temperatures, and their progression throughout the year. Fig. 2 presents the yearly means of solar radiation and outdoor temperature.

2.3. Model simulations of HPS and LED greenhouses

The GreenLight model [29] was used for all simulations performed in the study. This model simulates an advanced, Venlo type greenhouse with a tomato crop, equipped with various types of supplemental lights. GreenLight was evaluated against measurements in greenhouse compartments with either HPS or LED top lighting throughout an entire winter season and was found to estimate the greenhouse's heat demand by an error of 1–12%. When taking into account the entire energy demand of the greenhouse, including lighting, the prediction error was

Table 1
The 15 locations selected for the simulations used in this study and the originating datasets. The various datasets were retrieved from the EnergyPlus website [30].

Abbreviation	Location	Latitude (°N)	Longitude (°)	Altitude (m)	Dataset
AMS	Amsterdam, The Netherlands	52.30	4.77	−2	[31]
ANC	Anchorage, Alaska, USA	61.22	−149.85	42	[32]
ARK	Arkhangelsk, Russia	64.53	40.47	13	[31]
BEI	Beijing, China	39.80	116.47	31	[33]
CAL	Calgary, Canada	51.12	−114.02	1084	[34]
CHE	Chengdu, China	30.67	104.02	506	[33]
KIR	Kiruna, Sweden	67.82	20.33	452	[31]
MOS	Moscow, Russia	55.75	37.63	156	[31]
SAM	Samara, Russia	53.25	50.45	44	[31]
SHA	Shanghai, China	31.40	121.45	6	[33]
STP	St Petersburg, Russia	59.97	30.30	4	[31]
TOK	Tokyo, Japan	36.18	140.42	35	[31]
URU	Urumqi, China	43.78	87.65	935	[33]
VEN	Venice, Italy	45.50	12.33	6	[31]
WIN	Windsor, Canada	42.27	−82.97	190	[34]

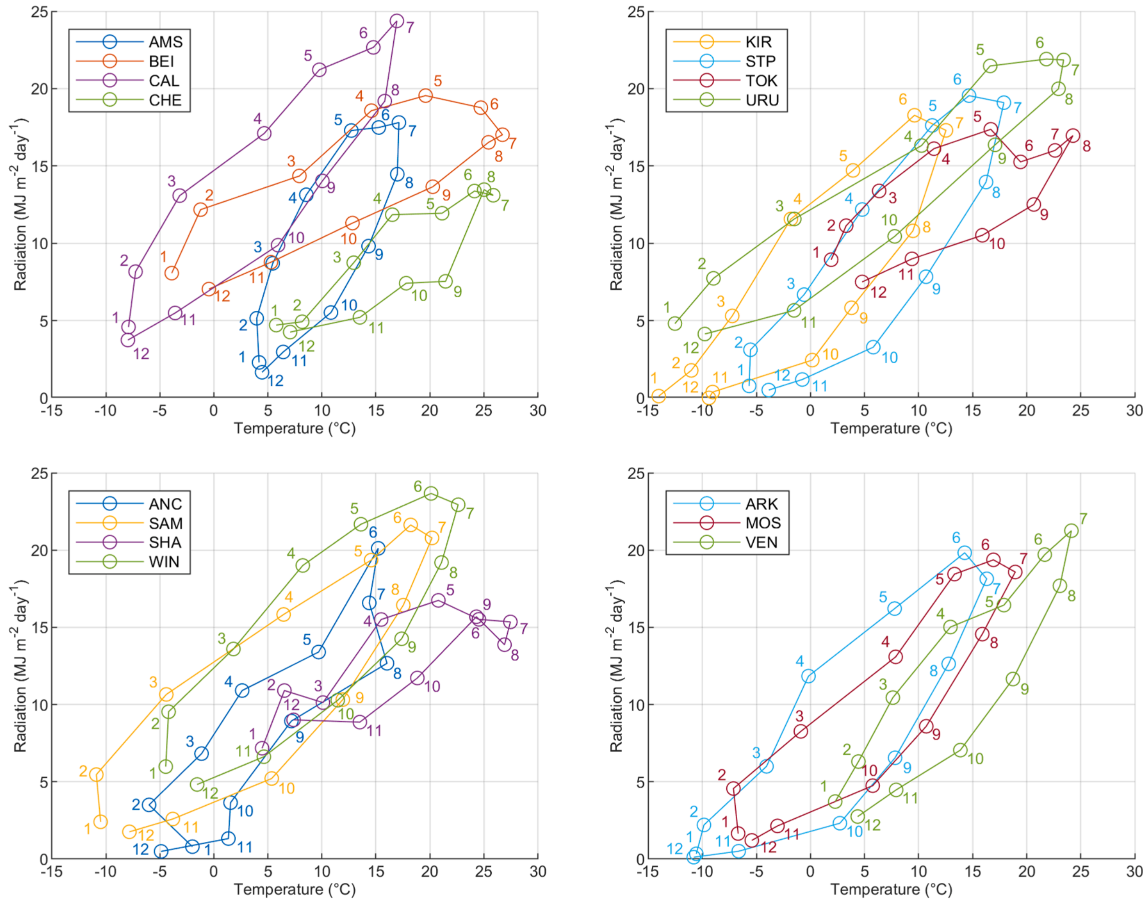


Fig. 1. Yearly cycle of global solar radiation vs outdoor air temperature in the 15 locations considered. Circles indicate average monthly values; numbers indicate the month of the year.

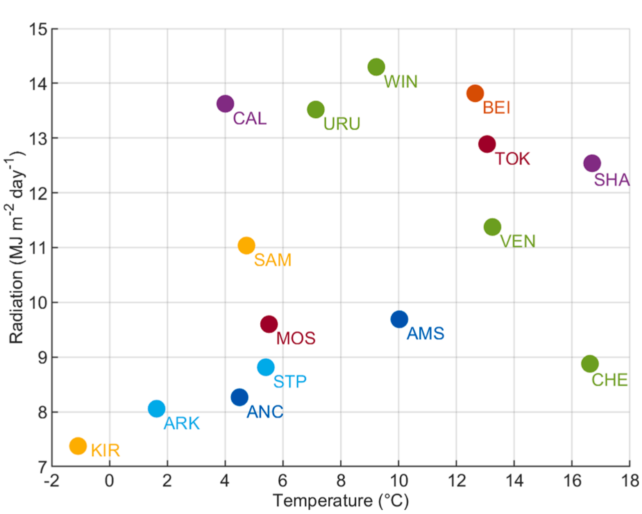


Fig. 2. Yearly means of solar radiation and outdoor air temperature in the 15 locations considered.

0.5–5% [29]. In this study, the case of either HPS or LED top lights was considered. The simulated season was 350 days long, from September 27 until September 11 the next year.

2.3.1. Reference greenhouse settings

A 4-hectare Venlo type glasshouse was considered for this study, measuring 200 m in width and 200 m in length. The gutter height of the greenhouse was 6.5 m, and the ridge height was 7.3 m. The slope of the roof was 22°. The roof was composed of glass panels measuring 2.16 m by 1.67 m. A ventilation window was installed in 1 out of every 6 panels, measuring 1.40 m by 1.67 m. The maximal opening angle for the window was 60°. Thermal screens were installed at a height of 6.3 m. Path width was 1.6 m, and a pipe rail system was installed in the paths, with a total pipe length of 1.25 m m^{-2} and a pipe diameter of 51 mm. The maximal rate of the CO_2 injection system was 185 kg ha^{-1} h^{-1}. The

Table 2
Greenhouse design parameters used for the simulated greenhouses with reference settings. Parameters not included were taken from the Dutch greenhouse setting described in the electronic appendix of [35].

Notation	Meaning	Unit	Value
ψ	Mean greenhouse cover slope	°	22
A_{Cov}	Surface area of the cover including side walls facing the outside	m^2	48,400
A_{Flr}	Surface area of the greenhouse	m^2	40,000
h_{Rf}	Thickness of the glass in the cover	mm	4
h_{Air}	Height of the main compartment (below the screen) in the greenhouse	m	6.3
h_{Gh}	Mean height of the greenhouse	m	6.9
A_{Roof}	Maximum roof ventilation area	m^2	4,676
h_{Vent}	Vertical dimension of single ventilation opening	m	1.3
$c_{Leakage}$	Leakage coefficient	–	0.0001
l_{Pipe}	Length of the heating pipes per square meter greenhouse	m m^{-2}	1.25
p_{Boil}/A_{Flr}	Capacity of the heating system	W m^{-2}	300
ϕ_{ExtCO_2}/A_{Flr}	Capacity of the external CO_2 source	mg m^{-2} s^{-1}	5.14

parameters used for simulating the greenhouses with the reference settings are given in Table 2. Parameters not included in the table were taken from the Dutch greenhouse setting described in the electronic appendix of [35].

For the lamp settings, the photon content of PAR emitted by the lamp $\zeta_{LampPAR}$ was set at 4.9 μmol (PAR) J^{-1} (PAR) for the HPS lamp [36]. For the LEDs, the modelled lamp consisted of 6% blue LEDs and 94% red LEDs, a combination that was found to be optimal for tomatoes [37]. Assuming the blue LEDs emit at a wavelength of 450 nm, the red LEDs at 660 nm [12] and using Planck's equation [12], the resulting PAR photon content is 5.4 μmol (PAR) J^{-1} (PAR). The fraction of input energy converted to PAR $\eta_{LampPAR}$ was set at 0.37 for HPS lamps and 0.55 for LEDs in order to achieve an efficacy of the lamps ($\eta_{LampPAR}\cdot\zeta_{LampPAR}$) of 1.8 μmol (PAR) J^{-1} (input) for the HPS lamps [10, including comments to the online article] and 3 μmol (PAR) J^{-1} (input) for the LEDs [12]. The lamp energy input $\theta_{LampMax}$ was set at 111 W m^{-2} for the HPS lamps and 66.7 W m^{-2} for the LEDs in order to achieve an equivalent photosynthetic photon flux density (PPFD, $\eta_{LampPAR}\cdot\zeta_{LampPAR}\cdot\theta_{LampMax}$) of 200 μmol m^{-2} s^{-1} in both greenhouses. The parameters used for the lamps in the HPS and LED greenhouses are given in Table 3. A full description of the lamp model and its parameters is given in [29].

Table 3
Parameters used for the HPS and LED lamps in the reference simulations. See [29] for a full description of the lamp model and its parameters.

Notation	Meaning	Unit	HPS	LED
$\eta_{LampPAR}\cdot\zeta_{LampPAR}$	Photosynthetic photon efficacy (PPE)	μmol (PAR) J^{-1} (input)	1.8	3.0
$\eta_{LampPAR}\cdot\zeta_{LampPAR}\cdot\theta_{LampMax}$	Photosynthetic photon flux density (PPFD)	μmol (PAR) m^{-2} s^{-1}	200	200
$\theta_{LampMax}$	Electrical energy input to the lamps	W m^{-2}	111	66.7
A_{Lamp}	Surface area of the lamps per area of greenhouse floor	m^2 m^{-2}	0.02	0.02
$\tau_{LampPAR}$	Transmission of sun's PAR through the lamp layer	–	0.98	0.98
$\rho_{LampPAR}$	Reflection of sun's PAR through the lamp layer	–	0	0
$\tau_{LampNIR}$	Transmission of sun's NIR through the lamp layer	–	0.98	0.98
$\rho_{LampNIR}$	Reflection of sun's NIR through the lamp layer	–	0	0
$\tau_{LampFIR}$	Transmission of FIR through the lamp layer	–	0.98	0.98
$\eta_{LampPAR}$	Fraction of lamp electrical input converted to PAR	–	0.37	0.55
$\eta_{LampNIR}$	Fraction of lamp electrical input converted to NIR	–	0.22	0.02
ε_{Lamp}^{Top}	Emissivity of the top side of the lamp	–	0.10	0.88
$\varepsilon_{Lamp}^{Bottom}$	Emissivity of the bottom side of the lamp	–	0.90	0.88
$\eta_{LampCool}$	Fraction of lamp energy input that is removed by active cooling	–	0	0
$capLamp$	Heat capacity of the lamp	J K^{-1} m^{-2}	100	10
$c_{HECLampAir}$	Heat exchange coefficient between the lamp and surrounding air	W K^{-1} m^{-2}	0.09	2.3
$\zeta_{LampPAR}$	Photons per joule in PAR emitted by the lamp, depending on the spectral output of the lamp	μmol (PAR) J^{-1} (PAR)	4.9	5.4
$p_{HeatAdjLamp}$	Adjustment to the greenhouse's heating set point when the lamps are on (see Section 2.3.3)	°C	0	0

2.3.2. Reference control settings

In order to make a valid comparison between various locations and lamp settings, a general climate control regime was devised. In the following, "daytime" refers to the period from sunrise to sunset and "nighttime" from sunset to sunrise; "light period" refers to the daytime as well as the nighttime when the lamps are on; "dark period" is the part of the nighttime when the lamps are off.

1. **Lamps:** lamps were on every day between midnight and 18:00 with the following exceptions:
   - o The lamps were switched off whenever global solar radiation outside the greenhouse was above 400 W m^{-2}.
   - o The lamps were off if the predicted global solar radiation sum outside the greenhouse during that day was above 10 MJ m^{-2} day^{-1}.
2. **CO_2 injection:** CO_2 was injected during the light period, whenever the indoor CO_2 concentration was below the target setpoint of 1000 ppm.
3. **Heating:** Heating was applied whenever the indoor temperature was below the target setpoint, which was 19.5 °C during the light period and 18.5 °C during the dark period.
4. **Roof ventilation:** ventilation was applied in any of the following cases:
   - o **Ventilation due to excess heat:** the roof openings were opened whenever the indoor temperature was 5 °C above the target setpoint for heating.
   - o **Ventilation due to excess humidity:** the roof openings were opened whenever the indoor relative humidity was above 87%.
   - o However, the ventilation was forced to close if the indoor temperatures were 1 °C below the heating setpoint.
5. **Thermal screens:** thermal screens were closed during the day if the outdoor temperature was below 5 °C, and during the night if the outdoor temperature was below 10 °C. However, the screens were opened whenever ventilation was needed:
   - o **Screen opening due to excess heat:** the screens were opened whenever the indoor temperature was 4 °C above the target setpoint for heating.
   - o **Screen opening due to excess humidity:** the screens were opened whenever the indoor relative humidity was above 85%.

The reference control settings are summarized in Fig. 3.

The heating, ventilation, thermal screens and CO_2 injection were controlled using a smoothed proportional controller, which was defined using a sigmoid function:

$$Action = \frac{1}{1+exp\left(\frac{-2ln100}{pBand}(x-setPoint-0.5pBand)\right)} \quad [0-1] \tag{4}$$

where x is the controlled variable (e.g., the indoor temperature), $setPoint$ is the desired setpoint for the controlled variable (e.g., 18.5 °C during the dark period), $pBand$ is a band defining the width of the proportional control, and $Action$ defines the controller action. At $Action = 1$, the controller is at full capacity (e.g., heating is at full power), at $Action = 0$ the controller is off. As can be seen from Equation (4) and Fig. 4, the controller is close to full action at $x = setPoint + pBand$, and close to no action at $x = setPoint$. Note that $pBand$ may also be negative, in which case Fig. 4 would be flipped horizontally.

The $pBand$ values for the proportional controllers were: −1°C for heating; −100 ppm for CO_2 injection; −1°C for thermal screen closure due to cold outdoor temperatures; 1 °C for thermal screen opening due to excess indoor heat; 10% relative humidity for thermal screen opening

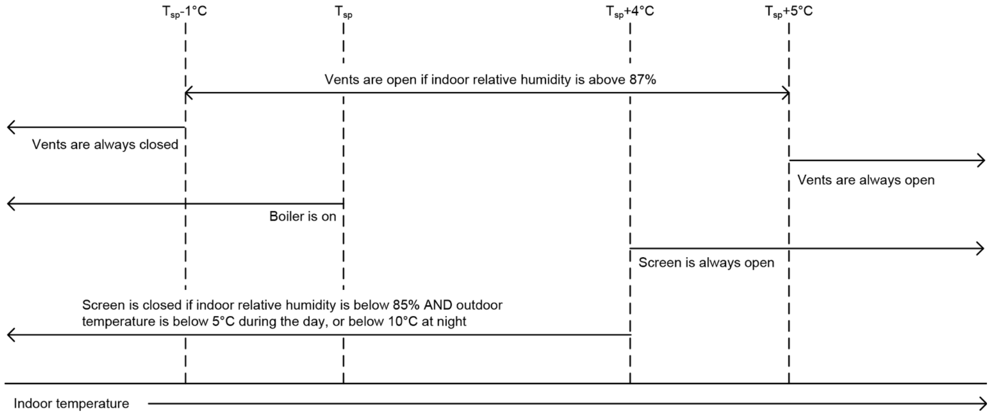


Fig. 3. Control of heating, ventilation and thermal screen in the reference setting. T_{sp} is the temperature setpoint for heating. CO_2 was injected during the light period if the indoor CO_2 concentration was below 1000 ppm. Lamps were on from midnight to 18:00 unless momentary solar radiation was above 400 W m^{-2} or daily solar radiation was above 10 MJ m^{-2} day^{-1}. Figure adapted from [38].

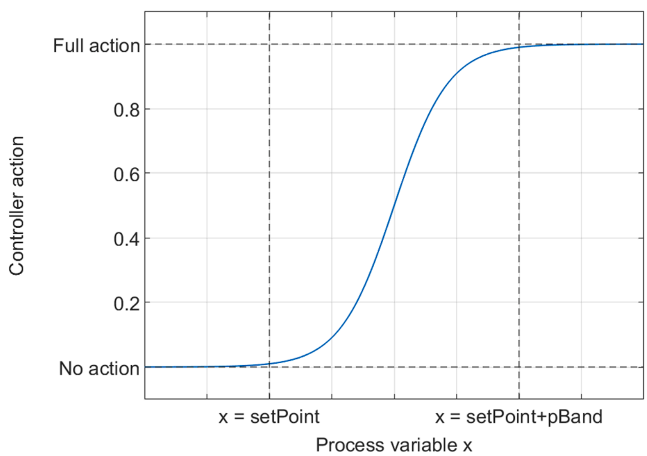


Fig. 4. Response of a smoothed proportional controller to a process variable × according to a sigmoid function (Equation (4)). The controller is close to full action when the process variable × is equal to setPoint + pBand. The controller is close to no action at x = setPoint. If pBand is negative, the curve is flipped horizontally.

due to excess humidity; 4 °C for ventilation opening due to excess heat; −1°C for ventilation closure due to low indoor temperature; 50% relative humidity for ventilation opening due to excess humidity [23].

2.3.3. Adjustment of heating setpoint under LEDs

Studies have shown that crops under LED lights are colder than those under HPS lamps [36]. In practice, a greenhouse with LEDs may need to increase the air temperature setting in order to achieve the same crop performance as a greenhouse with HPS lamps [39]. To take this into account, a new parameter, $p_{heatAdjLamp}$ (°C) was introduced to the model. This parameter influenced the greenhouse control settings such that whenever the lamps were on, the heating setpoint for the greenhouse air T_{sp} was increased by the value of $p_{heatAdjLamp}$. The value for $p_{heatAdjLamp}$ was 0 °C for the HPS greenhouse in all settings. The value for $p_{heatAdjLamp}$ was 0 °C for the LED greenhouse in the reference setting, but was modified to 1 °C in one of the additional scenario simulations, see Section 2.3.4.

2.3.4. Additional scenario simulations

In addition to the reference settings, several other scenarios were examined to test the model predictions under a wider range of greenhouse structure designs and climate control settings. These additional simulations were (adjustment to the reference settings are in bold):

1. **Temperature adjustment:** air temperatures of the LED greenhouses were increased by 1 °C whenever the lamps were on, i.e., $\boldsymbol{p_{heatAdjLamp}}$ **was set at 1 °C for the LED greenhouse.**
2. **Extended lamp hours:** The lamps were switched off whenever global solar radiation was above **600 W m^{-2}**, or if the predicted radiation sum from the sun during that day was above **14 MJ m^{-2} day^{-1}**.
3. **Lower indoor temperature:** heating setpoints were set **2 °C lower**, i.e., 16.5 °C and 17.5 °C during the dark and light period, respectively.
4. **Higher indoor temperature:** heating setpoints were set **2 °C higher**, i.e., 20.5 °C and 21.5 °C during the dark and light period, respectively.
5. **Low insulation:** a greenhouse with lower insulation was considered, namely, with a **leakage coefficient $\boldsymbol{c_{Leakage}}$ of 0.0002**, and a **glass width $\boldsymbol{h_{Rf}}$ of 2 mm.**
6. **High insulation:** a greenhouse with higher insulation was considered, namely, with a **leakage coefficient $\boldsymbol{c_{Leakage}}$ of 0.00005**, and a **glass width $\boldsymbol{h_{Rf}}$ of 8 mm.**
7. **Low lamp intensity:** the PPFD for the lamps was halved to a **PPFD of 100 µmol m^{-2} s^{-1}**. This was done through halving the electrical input of the lamps $\theta_{LampMax}$ to 55 W m^{-2} for the HPS lamps and 33 W m^{-2} for the LEDs. Accordingly, the lamp area A_{Lamp}, the heat capacity *capLamp*, and the heat exchange coefficient $c_{HEClampAir}$ were halved. The transmissivities of the lamp layer $\tau_{LampPAR}$, $\tau_{LampNIR}$, $\tau_{LampFIR}$ were set at 0.99.
8. **High lamp intensity:** the PPFD for the lamps was doubled to a **PPFD of 400 µmol m^{-2} s^{-1}**. This was done through doubling the electrical input of the lamps $\theta_{LampMax}$ to 222 W m^{-2} for the HPS lamps and 134 W m^{-2} for the LEDs. Accordingly, the lamp area A_{Lamp}, the heat capacity *capLamp*, and the heat exchange coefficient $c_{HEClampAir}$ were doubled. The transmissivities of the lamp layer $\tau_{LampPAR}$, $\tau_{LampNIR}$, $\tau_{LampFIR}$ were set at 0.96.

Simulations with heat adjustment (scenario 1 above) were performed for all 15 locations considered in this study. The other scenarios (2–8) were tested for 3 locations: Amsterdam (AMS), Calgary (CAL), and Chengdu (CHE), representing three different climates: low radiation and high temperatures in Chengdu, high radiation and low temperatures in Calgary, and mild temperatures and radiation in Amsterdam (Fig. 2).

2.4. Analysis of energy fluxes

In order to better understand which factors influence the greenhouse energy demands, further analysis of the simulation results was performed for the greenhouse in Amsterdam. This location was chosen since it has a relatively mild climate in terms of yearly temperature and radiation, located close to the average of the climates tested in this study, and those that are typical for regions with illuminated greenhouses (Fig. 2). The insights gained from analyzing the greenhouse in Amsterdam can expose general phenomena that apply to greenhouses all over the world.

Once the simulations were performed, the yearly sum of the energy inputs and outputs out of the greenhouse system were calculated, to quantify and explain the differences in energy requirements between greenhouses with HPS lamps or LEDs. These inputs and outputs (all in MJ m^{-2} year^{-1}) are given below, together with their notation in the studies where they were first described [29,35] (see also glossary):

1. Energy absorbed from the sun by the greenhouse structure, the canopy, and the floor $R_{Glob\_SunAir} + R_{PAR\_SunCan} + R_{NIR\_SunCan} + R_{PAR\_SunFlr} + R_{NIR\_SunFlr} + R_{Glob\_SunCov,e}$
2. Energy input to the heating pipes $H_{BoilPipe}$
3. Energy input to the lamps Q_{LampIn}
4. Energy output to the soil $H_{So5SoOut}$
5. Thermal radiation output emitted towards the sky from the greenhouse cover, screens, lamps, canopy, pipes, and floor $R_{Cov,eSky} + R_{ThScrSky} + R_{LampSky} + R_{CanSky} + R_{PipeSky} + R_{FlrSky}$
6. Energy output to the outdoor by convection through the cover $H_{Cov,eOut}$
7. Energy output through ventilation $H_{AirOut} + H_{TopOut}$
8. Latent heat output, representing the net loss of sensible heat by conversion to latent heat. This value is composed of loss of sensible heat due to transpiration minus gain of latent heat due to condensation on the screens and cover: $L_{CanAir} - L_{AirThScr} - L_{TopCov,in}$

2.5. Model code and execution

The model simulations were executed in MATLAB (MATLAB R2016b-R2019b, The MathWorks). Code used for running the simulations is available at https://github.com/davkat1/GreenLight. The data resulting from the simulations is available on the 4TU.ResearchData database, https://doi.org/10.4121/13096403 [40].

3. Results

3.1. Potential energy savings considering only the lighting system

In cases where a transition from HPS lamps to LEDs does not alter the heating demand, the expected energy savings realized by transitioning to a more efficient lamp were influenced by two factors: the efficiency of the new lamp and the fraction that lighting takes up out of the total greenhouse energy demands (Fig. 5). Naturally, a greenhouse with very little assimilation lighting (fraction for lighting close to 0%) gained very little energy savings by changing the lighting system. On the other extreme, in a greenhouse where the energy input was only used for lighting (fraction for lighting is 100%), the energy savings of the lighting system was equivalent to the total energy savings. Even with an infinitely efficient lamp, the total energy savings percentage was limited by the fraction of the energy input going to lighting.

3.2. Energy balance considering both the lighting and heating system

The energy demands as simulated by the GreenLight model varied greatly in the different world locations under the reference settings. In the HPS greenhouses, the total energy demands varied from less than 1400 MJ m^{-2} year^{-1} in Shanghai (SHA) to nearly 3400 MJ m^{-2} year^{-1} in Kiruna (KIR) (Fig. 6). As expected, in all locations the change from HPS to LEDs resulted in a 40% reduction in lighting demand, which ranged from a saving of 315 MJ m^{-2} year^{-1} in Beijing (BEI) to 662 MJ m^{-2} year^{-1} in Kiruna (KIR). At the same time, in all locations the LED greenhouse required more heating than the HPS greenhouse. The extra heating needed ranged from 79 MJ m^{-2} year^{-1} in Beijing (BEI) to 224 MJ m^{-2} year^{-1} in Anchorage (ANC). In relative terms, the increase in heating demands ranged from 9% in Calgary (CAL) to 49% in Chengdu (CHE). The resulting total energy savings ranged from 13% in Calgary (CAL) to 27% in Chengdu (CHE).

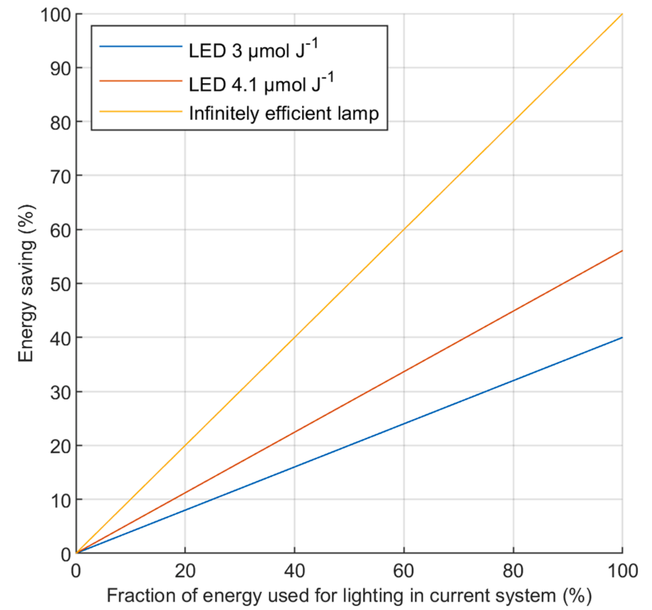


Fig. 5. Potential fraction of energy saved by transitioning from HPS lamps with an efficacy of 1.8 µmol J^{-1} to a more efficient lamp, assuming that the heat requirements remain equal.

In the simulations performed with the reference settings, the fraction of energy that goes to lighting in the HPS greenhouses ranged from 45% in Calgary (CAL) to 85% in Chengdu (CHE). Increasing the temperature setpoint by 1 °C under LEDs, in line with common practice (see Section 2.3.3), reduced the predicted energy savings by around 1.5% (Fig. 7). There is a positive linear correlation between the predicted relative energy savings when transitioning to LEDs and the fraction of energy inputs that goes to lighting in the HPS greenhouse. A linear regression based on the model outputs predicts that the relative energy savings are 0.37x-5.41 percent, where x is the percent of energy that goes to lighting in the HPS greenhouse. This linear model provides an accurate prediction of the relative energy savings, with a coefficient of determination (R^2) of 0.90, and a root mean squared error (RMSE) of 1.90%.

3.3. Yearly incoming and outgoing energy fluxes

The energy savings achieved by a transition to LEDs are further elucidated by looking at the ingoing and outgoing yearly energy fluxes in the HPS and LED greenhouses, using Amsterdam as a representative case (Fig. 8). Since the greenhouse energy system was on average in steady state, for each greenhouse the sum of its incoming fluxes is almost equal to the sum of its outgoing fluxes. Thus, the savings in energy inputs correspond to a reduction in energy outputs. The biggest change in outgoing energy fluxes when transitioning to LEDs was a reduced loss to latent heat resulting from less crop transpiration. Smaller decreases are seen in the losses due to ventilation and convection through the cover. The LED greenhouse with temperature adjustment, i.e., where the air temperature setpoint was increased by 1 °C whenever the lamps were on, consumed 61 MJ m^{-2} year^{-1} more in heating compared to the LED greenhouse in the reference setting. This increase was mainly due to more convection through the cover.

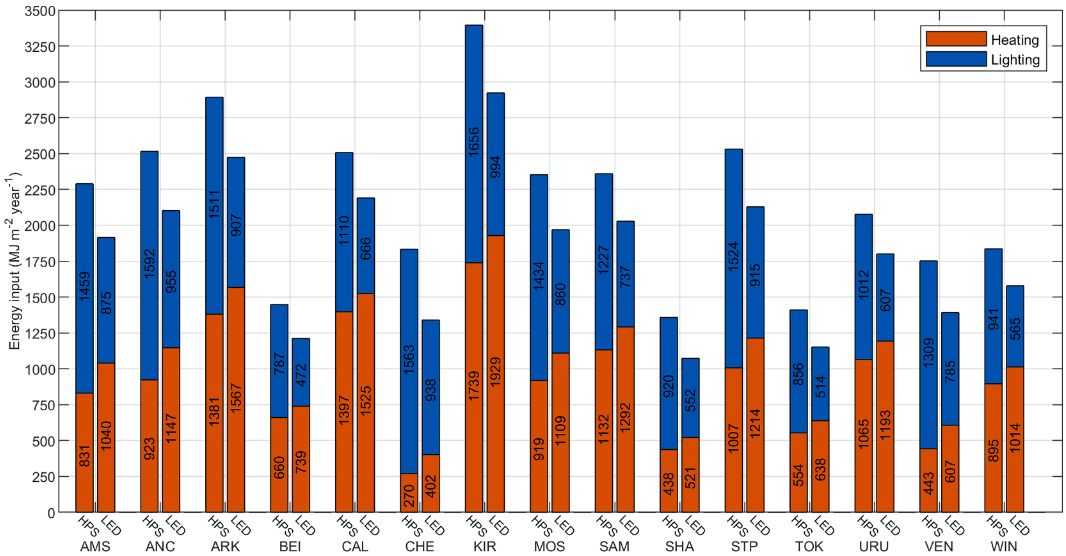


Fig. 6. Heating and lighting demand of HPS and LED greenhouses in different locations, under the reference settings.

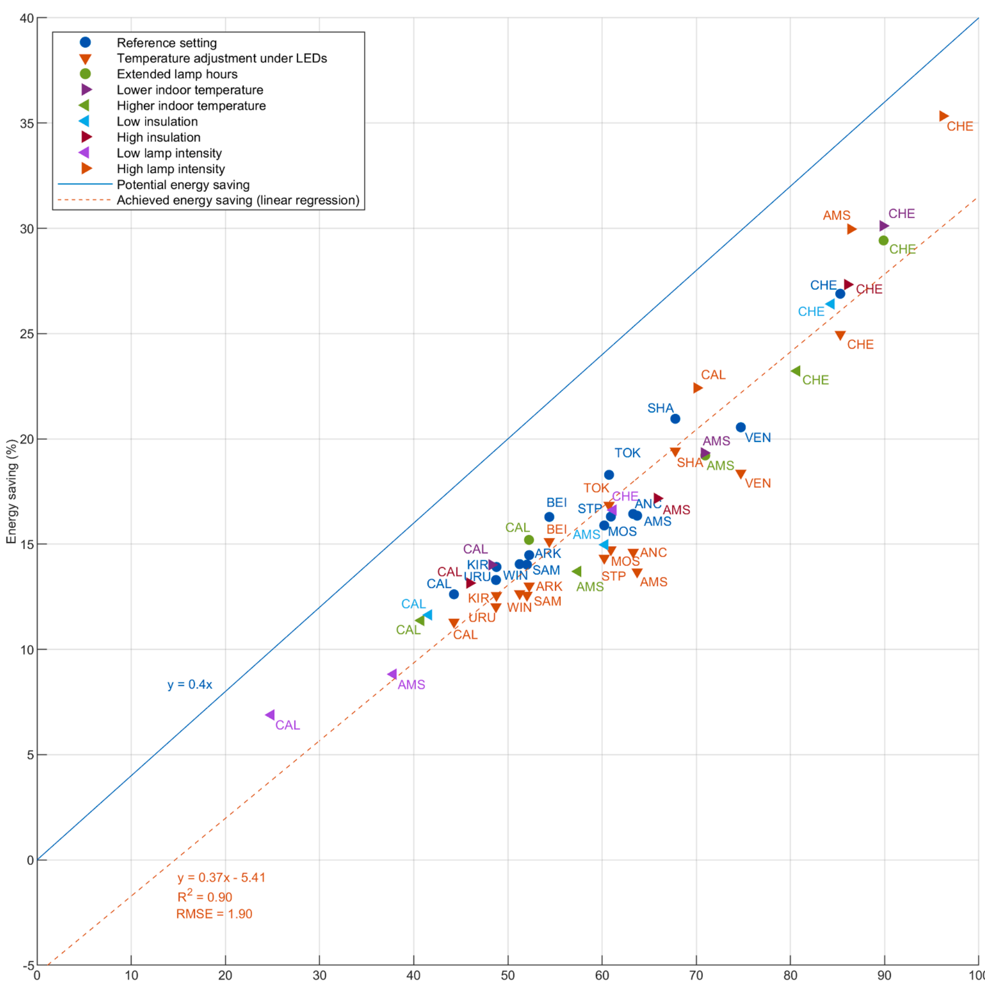


Fig. 7. Simulated savings in total energy input by transitioning from HPS to LEDs in relation to the energy input used for lighting in the HPS greenhouse. 15 locations throughout the world (Section 2.2) and 9 control and design scenarios (Section 2.3) are given. The efficacy of the HPS and LED lights was 1.8 and 3 μmol J^{-1}, respectively. Potential energy saving represents energy saving if a transition to LEDs does not increase heating needs. Achieved energy saving is a linear regression based on the given data points.

3.4. Seasonal variation in energy savings

A clear variation in energy inputs can be seen throughout the year. In winter (22–153 days after planting, corresponding to October 19 to February 27), the lamps were on for their maximal duration every day, resulting in a constant input of lighting energy, and a constant daily saving in lighting input of 2.9 MJ m^{-2} day^{-1} by using LEDs (Fig. 9). At the same time, throughout winter the LED greenhouse in Amsterdam required on average 1 MJ m^{-2} day^{-1} more heating than the HPS greenhouse. From day 154 lamps were only occasionally used. When the

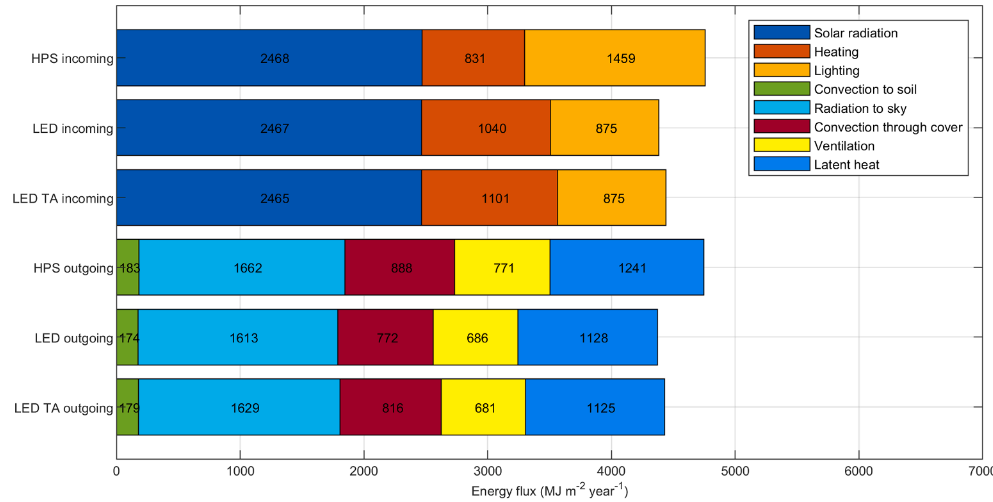


Fig. 8. Yearly incoming and outgoing energy fluxes for the HPS, LED, and LED with temperature adjustment (LED TA) greenhouses in Amsterdam. Air temperature setpoints where identical in the HPS and LED greenhouses. In the LED TA greenhouse, air temperature setpoint was raised by 1 °C whenever the lamps were on.

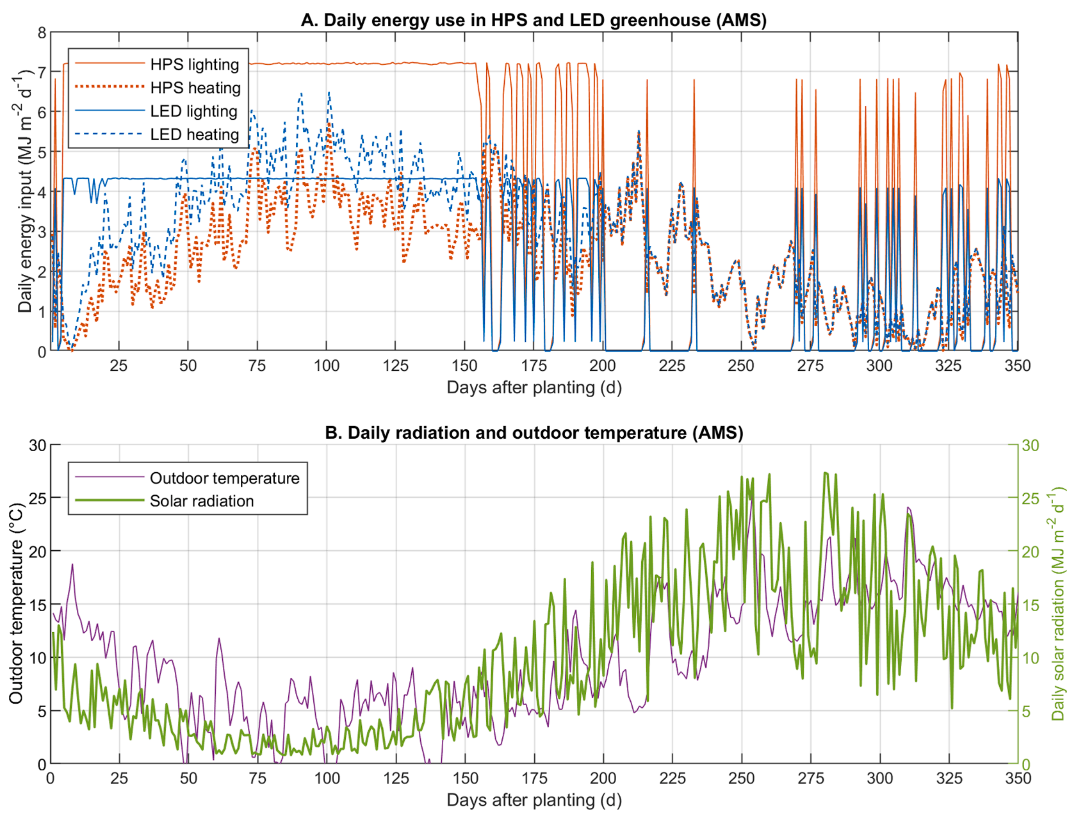


Fig. 9. Time course during the year for (A) daily energy inputs (heating and lighting) in the HPS and LED greenhouses in Amsterdam with the reference setting and (B) daily outdoor temperature and outdoor global radiation throughout the simulated season. The planting date was September 27.

lamps were off, the energy requirements of both greenhouses were similar. When the lamps were on (e.g., days 191–194), more heating was often needed in the LED greenhouse.

An examination of the greenhouses' energy fluxes on a typical winter and summer day when lighting was used provides further detail. As seen earlier (Fig. 9), on days when lamps were on for their maximum duration of 18 h, the HPS lamps consumed 7.2 MJ m^{-2} day^{-1} and the LEDs consumed 4.3 MJ m^{-2} day^{-1}, saving 2.9 MJ m^{-2} day^{-1} in lighting (Fig. 10). On a typical winter day, this reduced energy input was counteracted by an added 1.3 MJ m^{-2} day^{-1} for heating, resulting in a total saving of 1.6 MJ m^{-2} day^{-1} (Fig. 10). On a typical summer day, the LED greenhouse used only 0.1 MJ m^{-2} day^{-1} more heating, resulting in a total saving of 2.8 MJ m^{-2} day^{-1}. Considering the outgoing energy fluxes, in winter the main difference when using LEDs is less convection through the cover (0.8 MJ m^{-2} day^{-1}), followed by lower losses to latent heat (0.4 MJ m^{-2} day^{-1}) and less ventilation (0.3 MJ m^{-2} day^{-1}). In summer, the main difference is reduced latent heat (1.2 MJ m^{-2} day^{-1}), followed by less ventilation (0.8 MJ m^{-2} day^{-1}) and convection (0.3 MJ m^{-2} day^{-1}).

The difference in effects of transitioning to LEDs between winter and summer is further detailed by looking at the trajectories of the energy fluxes throughout a representative day. In winter, heating was similar

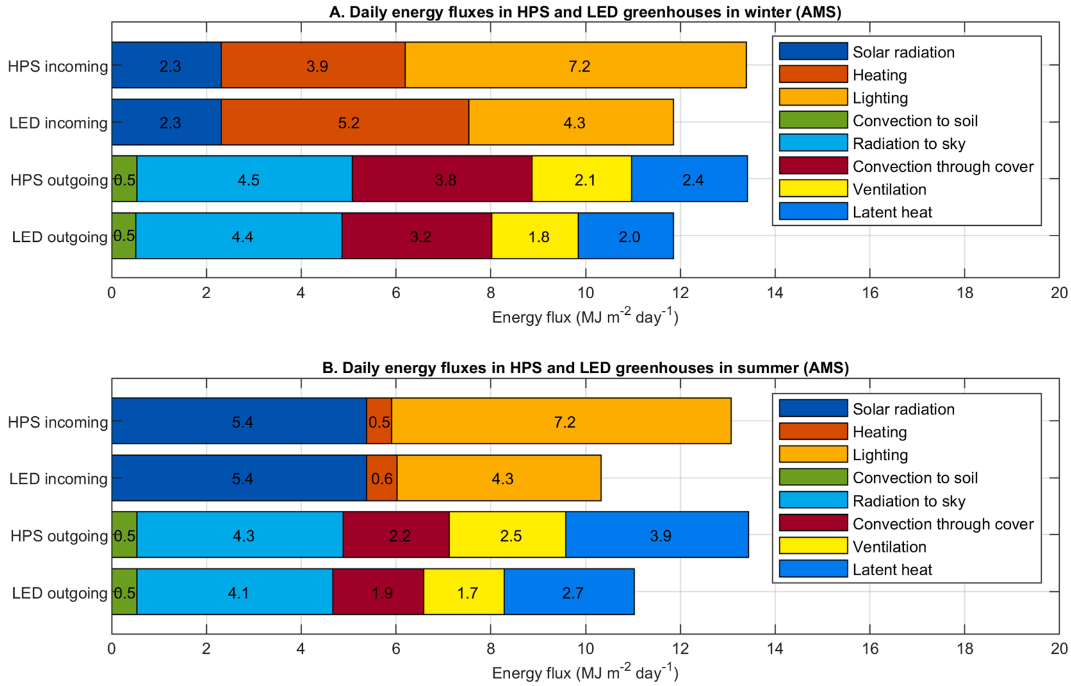


Fig. 10. Incoming and outgoing energy fluxes in the HPS and LED greenhouses in Amsterdam with the reference setting on a representative winter (January 21, A) and summer (July 15, B) day.

between the greenhouses when the lamps were off (18:00–24:00), but higher in the LED greenhouse when the lamps were on. Ventilation in both greenhouses was very small, with slightly more ventilation in the HPS greenhouse (Fig. 11A). In summer, some heating was applied when the lamps were off (18:00–24:00) in both greenhouses, and ventilation was considerably higher in the HPS greenhouse compared to the LED greenhouse (Fig. 11B). Ventilation was applied either when indoor humidity or indoor temperature were too high. In winter, the higher ventilation in the HPS greenhouse was due to excess humidity, as the greenhouse air temperature in both greenhouses was far below the ventilation setpoint due to excess heating (Fig. 11E). Higher humidity in the HPS greenhouse was due to higher transpiration, which resulted in more losses to latent heat (Fig. 10).

The CO_2 concentration and injection were influenced accordingly: in winter, both greenhouses reached the desired setpoint of 1000 ppm during the light period (0:00–18:00), with slightly more CO_2 injected in the HPS greenhouse (Fig. 11C). In summer, considerably more injection was needed in the HPS greenhouse, to the extent that in the middle of the day the desired setpoint could not be reached (Fig. 11D). In summer, ventilation was also needed to remove excess heat (Fig. 11F).

4. Discussion

4.1. *Energy savings in the greenhouse by transitioning to LEDs*

This study showed that only a comprehensive approach to the greenhouse energy system, where the various components of the greenhouse energy balance are considered, can provide an insightful quantification of the energy saving by a transition to LEDs in greenhouse horticulture. While using more efficient lamps resulted in direct savings on energy inputs for lighting (Fig. 5), a transition from HPS lamps to LEDs was associated with an increase in the greenhouse's heating demands, resulting in lower total energy savings (Fig. 7). Using a mechanistic and dynamic model such as GreenLight allowed us to quantify these demands, and understand how they depend on the greenhouse settings and the evolving outdoor climate. Especially during cold weather, the heat emitted by the HPS lamp contributed to heating the greenhouse, and this loss of heat had to be compensated by the heating system when LEDs replaced HPS lamps.

The simulations performed in this study, using several greenhouse design and control settings and various climates around the world, predicted that in most cases transitioning to LEDs will save 40% on electricity input for lighting, but will increase the heating demand by 9–49%. The result is a saving of 10–25% of the total energy inputs in nearly all cases (Fig. 7). The relative energy savings correspond to the inputs of the HPS greenhouse: denoting x as the percent of energy inputs that is used for lighting in the HPS greenhouse, the percent of energy savings predicted by a transition to LEDs is estimated as $0.37x - 5.41$ (Fig. 7). These savings are lower than $0.4x$, which is the predicted saving when only lighting was considered (Fig. 5).

4.2. *Changes in balance between energy sources and uses*

A switch to LEDs influenced not only the total energy inputs to the greenhouse, but also the ratio between the heating and lighting needs (Fig. 6, Fig. 8). In general, converting to LEDs resulted in a lower energy input for lighting and a higher input for heating. A decision on whether this transition is favorable or not, for instance in terms of costs for the grower or environmental footprint, depends on the energy sources used. For example, consider a greenhouse where heating is supplied by a boiler burning natural gas, and lighting is supplied by wind or solar power. In this case, a switch to LEDs will reduce the use of clean energy and increase the use of fossil fuels. On the other hand, if a cheap and environmentally clean source of heating such as geothermal heat is available, the benefits of lower electrical inputs for the lamps might outweigh the costs of extra heating in the LED greenhouse. The model simulations presented in this study quantify the benefits of a transition to LEDs to support practitioners in choosing the best lighting system for their local situation.

Furthermore, many greenhouses use a combined heat and power (CHP) generator to produce both electricity, heating, and CO_2 by burning natural gas [1]. The CHP in the greenhouse may produce electricity in a cleaner manner than the public power plant, since the CHP also makes use of the heat and CO_2 that is generated when burning

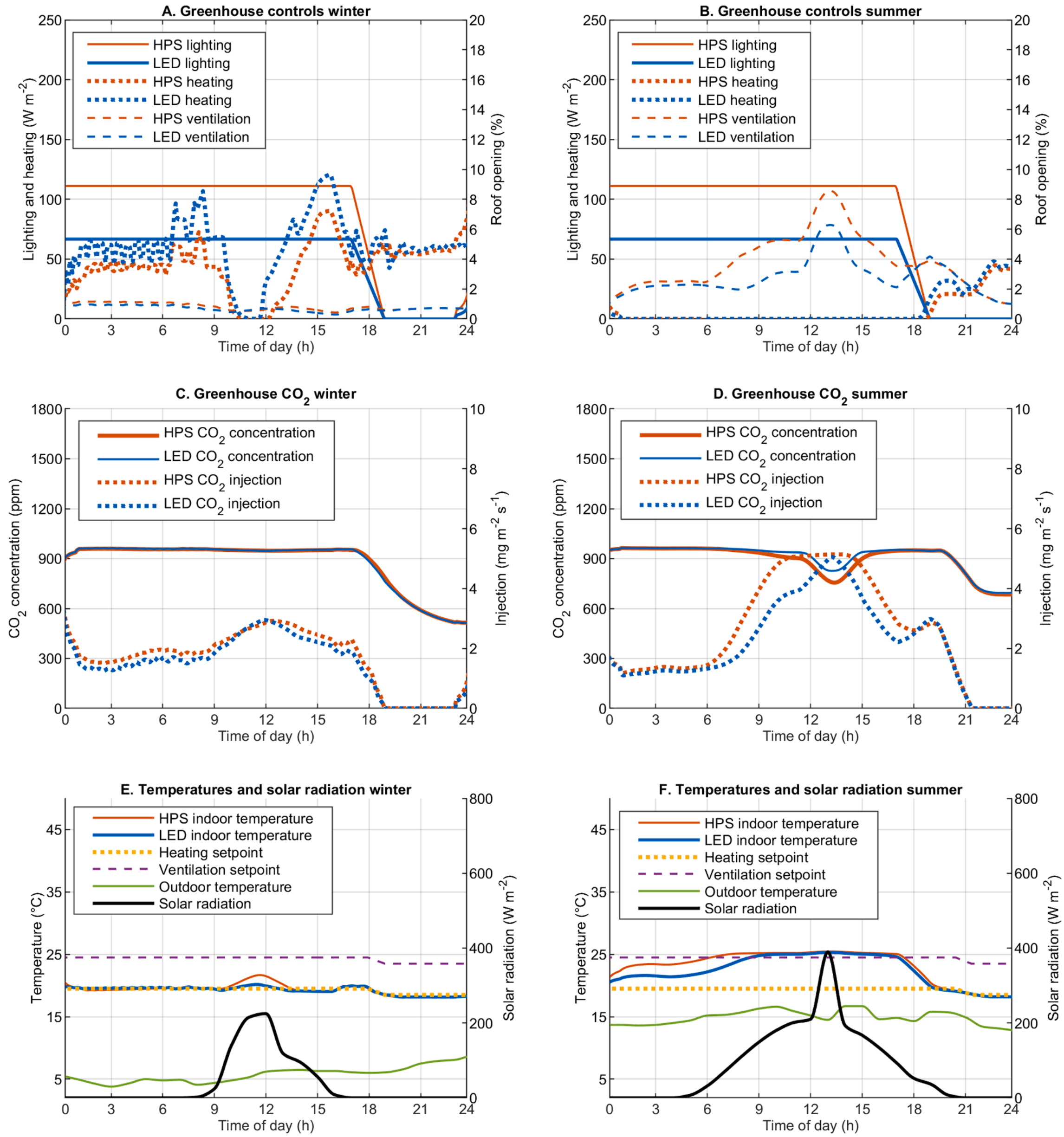


Fig. 11. Time course of a representative winter (January 21) and summer (July 15) day in the HPS and LED greenhouses in Amsterdam with the reference setting. (A, B): lighting, heating, and ventilation controls. (C, D): Indoor CO_2 concentration and CO_2 injection. (E, F): indoor air temperature and setpoints for heating and ventilation, outdoor temperature and solar radiation.

gas. This electricity, if not used in the greenhouse itself, may be sold back to the public grid, resulting in a reduction of emissions on a national level [5] which can be counted as a negative carbon footprint for the greenhouse, as well as an extra source of income for the grower [7]. In a greenhouse where both a boiler and a CHP are available, choosing which of the two to use at what time is a complicated problem [41]. If a grower wishes to use the CHP for electricity, the heat that is generated must be used simultaneously in the greenhouse or stored in a buffer. If the heat buffer is full and the greenhouse does not require heating, the CHP cannot be used without wasting heat, for instance by simultaneously heating the greenhouse and cooling it through ventilation.

A typical CHP generates around 1.25 MJ of heat for every 1 MJ of electricity [41]. This ratio is very close to the energy demands found for a Dutch LED greenhouse in winter (Fig. 10) and over a full year (Fig. 8). In contrast, the heat to light ratio in an HPS greenhouse is 0.5–0.6. This means that in principle, an LED greenhouse can supply all its lighting needs using a CHP without wasting heat. In contrast, an HPS greenhouse that would use a CHP for even half its lighting demand would still need to waste some of the generated heat. It follows that a greenhouse with a CHP will likely see larger energy savings when transitioning to LEDs, compared to those found in the current study. This potential for energy savings by combining LEDs and a CHP should be further explored in future studies.

4.3. Daily and seasonal patterns of transition to LEDs

The main influence of a transition to LEDs on the greenhouse energy demand was seen in winter, when light from the sun was limited and lamps were used extensively (Fig. 9). Later in the year the lamps were used less frequently and thus the choice of lamp had little influence on the energy demand. In winter, HPS lamps provided heat which was used in the greenhouse. Replacing HPS lamps with LEDs resulted in a higher heat demand when the lamps were on (Fig. 10), but not when the lamps were off (Fig. 11). In contrast, in summer when the lamps were on there was a need to ventilate the extra heat, and the demands from the heating system were minimal under both lamp types. Since the greenhouses consumed considerably more energy in winter compared to summer, the energy savings in winter had a meaningful impact on the total yearly energy demand.

As noted previously [36], transpiration is higher under HPS lamps compared to LEDs. This effect was seen both in winter and summer (Fig. 10) and resulted in a higher ventilation rate in the HPS greenhouse, which increased the heating demand in winter. In summer, the main driver for ventilation when the lamps were on was excess heat, but during those times the choice of lamp did not influence the heating demand of the greenhouse, which was minimal for both HPS and LED lighting. However, there is an advantage for LEDs during warm days when supplementary lighting is needed, as these lamps reduce the problem of over-heating the greenhouse.

4.4. Influence of model assumptions and settings

The focus of this study was the energy balance of the greenhouse, while the influence on crop growth and yield were not studied in detail. A main assumption during simulations was that the crop behaves similarly under HPS and LED lights. In practice, the different spectral outputs of HPS and LEDs could have an influence on crop behavior (see Section 4.5). Furthermore, the HPS greenhouses required more ventilation, which resulted at times in lower indoor CO_2 concentration (Fig. 11), which could lead to reduced growth under HPS lamps.

While this study focused on energy use alone, further studies may consider the influence of the lamps on crop growth and development. As described in Section 2.3.3, crops under LEDs may require different temperature settings to achieve growth and development comparable to crops under HPS lamps. Here, we considered the effect of increasing the air temperature by 1 °C whenever the LEDs were on and examined the influence on energy demands. Including this temperature adjustment reduced the expected relative energy savings by around 1.5% (Figs. 7, 8), indicating that it has a relatively small influence on total energy savings.

Weather inputs used in this study describe standard meteorological years in each of the considered locations. These datasets were compiled between the years 1999 and 2008 and may not take into account recent changes in climate such as rising temperatures. Nevertheless, our findings regarding the energy savings when transitioning to LEDs were consistent throughout all weather scenarios considered (Fig. 7), and thus provide a reliable initial assessment. When using the framework offered here, users may provide their own weather scenarios as input, which may be more recent standard meteorological years, measured data, or predicted scenarios of a future climate.

The study was based on model simulations performed using the GreenLight model, which has been tested against greenhouse data and found to estimate the greenhouse's heating needs by an error of 1–12% [29]. To the best of our knowledge, this is the only process-based model which includes both HPS and LED lighting and has been evaluated against energy use measurements. As such, it provides the best currently available predictions regarding the energy use of illuminated greenhouses. GreenLight is offered in an open-source format and can therefore be used by more researchers to evaluate against measurements. Further studies should continue to evaluate the model in various climates and greenhouse settings, and validate our findings using data from commercial greenhouses.

4.5. Further opportunities

The current study focused on the energy savings that can be achieved by switching from HPS lamps to LEDs, while maintaining all other factors (light intensity, light duration, air temperature) equivalent. However, LEDs offer a vast range of new opportunities in the greenhouse. One of the reasons direct comparisons between HPS lamps and LEDs are rare is that in fact, LEDs offer the ability to increase the supplemental light intensity or duration in the greenhouse, in a way that is impossible with HPS lamps alone. Using HPS lamps in warm weather [42], or with a very high lamp intensity [43], could result in too high temperatures inside the greenhouse, especially if a blackout screen is used, which in some regions is required in order to prevent light pollution to the environment. Growers often use LEDs in addition to HPS lamps in order to increase supplemental lighting [44]. The trend is thus towards a higher use of supplemental lighting in greenhouses [5]. Further studies should examine how energy efficiency can be maintained, or even improved, while supplying increasingly more light.

LEDs offer new possibilities on greenhouse and crop manipulation that are impossible with HPS lamps. It has been suggested that dynamic control of the intensity of LEDs may reduce the energy consumption for lighting while achieving similar yields [45] and increasing profits [46]. The ability to control the spectrum of light emitted by LEDs can offer greater control of the crop, realizing more efficient production. In particular, far-red light (701–750 nm) has been shown to have the potential to increase growth through a higher photosynthesis rate [47], promote light capture due to higher leaf area [48], and increase the partitioning of assimilates to fruits [49], although at a possible cost of reduced resistance to disease [50].

Transpiration played an important role in the greenhouse energy balance by converting sensible heat to latent heat (Figs. 8, 10) and by driving ventilation needed for dehumidification (Fig. 11). Further studies on the influence of lamp type and light spectrum on crop transpiration will increase the accuracy of the GreenLight model and its applicability to a wider range of scenarios.

Furthermore, the greenhouses considered in this study used passive ventilation through the windows to control humidity, which is the traditional dehumidification method in northern latitudes [1]. While our analysis considered energy inputs to the heating and lighting systems, in effect some of the energy demand of the heating system was used for dehumidification, when both heating and ventilation were used simultaneously to reduce the indoor relative humidity. It is estimated that 10–20% of the energy demands of the greenhouse are due to humidity control [51]. Future studies may further analyze how the lighting system influences the energy demand for dehumidification, for instance by comparing various methods for humidity control under different lamps.

The advantage of using a model such as GreenLight for assessment of the greenhouse behavior is that it offers a systematic approach, which considers the various greenhouse balances and components. Since GreenLight is a process based, open source model, it can be used to examine scenarios that were not included in the current study, such as any particular greenhouse attribute or local climate. Furthermore, new model components can be integrated into the model to include crop physiological mechanisms, as well as novel control strategies or other developments in greenhouse technology.

5. Conclusion

Simulations using a process-based greenhouse model were performed in order to evaluate how much energy can be saved in greenhouses by transitioning from high-pressure sodium (HPS) to light-emitting diode (LED) lighting, and how these savings were affected by greenhouse control, design, and outdoor climate. The key findings of the study were as follows:

1. A transition from HPS lamps with an efficacy of 1.8 μmol J^{-1} to LEDs with an efficacy of 3 μmol
2. J^{-1} resulted in a 40% saving on the greenhouse's lighting demand. However, in all cases, the LED greenhouse required more heating than the HPS greenhouse. Since heating and lighting are often derived from different energy sources, a detailed analysis

considering the local conditions is required in order to assess the desirability of transitioning to LEDs.

3. A linear correlation ($R^2 = 0.90$, RMSE = 1.90) was found between the total relative energy savings by transitioning to LEDs and the fraction that lighting takes up out of the total energy demand in the HPS greenhouse: $0.37x - 5.41$ percent of the energy was saved by transitioning to LEDs, where x is the fraction (%) that lighting makes up out of the total energy needs before transitioning.
4. For HPS greenhouses, the fraction of energy input that was used for lighting varied considerably between the different climates, ranging between 45% and 85%.
5. The energy savings that were predicted by a transition to LEDs were in the range of 10–25% of the total energy use; the outdoor climate was the most important factor determining how much energy could be saved.
6. Crop transpiration was found to be higher under HPS lamps, resulting in greater energy losses to latent heat, and an increased need for dehumidification through ventilation.
7. The higher heat demands in the LED greenhouses occurred mostly in winter, when the excess heat from the lamps in the HPS greenhouses reduced the load on the heating system. In summer, the heating needs were low for both HPS and LED greenhouses, and the HPS greenhouses required more ventilation.

Data availability

The code used for generating the data in this study is available at https://github.com/davkat1/GreenLight. The data resulting from the simulations is available on the 4TU.ResearchDate database, https://doi.org/10.4121/13096403 [40].

CRediT authorship contribution statement

David Katzin: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Leo F.M. Marcelis:** Writing - review & editing, Supervision, Funding acquisition. **Simon Mourik:** Conceptualization, Writing - review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The code used for generating the data in this study is available at https://github.com/davkat1/GreenLight. The data used in this study and simulation outputs generated by the model are available at the 4TU database.

Acknowledgements

The authors would like to thank Eldert J van Henten, Frank Kempkes, Ilias Tsafaras, Celine CS Nicole, Arjan Vervoort, Max van den Hemel, Mitch Meulensteen, Bert van 't Ooster, Wouter JP Kuijpers and Marinus JG van de Molengraft for advice, suggestions, and fruitful discussions. Additional thanks to Henry Payne for proofreading the manuscript.

Funding sources

Funding for this study was provided as part of the "LED it be 50%" Perspectief program number 14217, supported by the Netherlands Organization for Scientific Research Domain Applied and Engineering Sciences (NWO-AES), Glastuinbouw Nederland, Signify, B-Mex, and Ridder Growing Solutions. The funding bodies had no role or influence in the design and conduct of the study; collection, management, analysis, and interpretation of the data; preparation, review, or approval of the manuscript; and decision to submit the manuscript for publication.

References

[1] Hemming S, Bakker JC, Campen JB, Kempkes F. Sustainable use of energy in greenhouses. In: Marcelis LFM, Heuvelink E, editors. Achiev. Sustain. Greenh. Prod. 1st ed., Cambridge: Burleigh Dodds Science Publishing; 2019, p. 445–92. https://doi.org/10.19103/AS.2019.0052.07.

[2] Rabobank. World Vegetable Map 2018 2018. https://research.rabobank.com/far/en/sectors/regional-food-agri/world_vegetable_map_2018.html (accessed August 17, 2020).

[3] Stanghellini C, Van 't Ooster B, Heuvelink E. Greenhouse horticulture: technology for optimal crop production. 1st ed. The Netherlands: Wageningen Academic Publishers; 2019. https://doi.org/10.3920/978-90-8686-879-7.

[4] Moerkerken A, Gerlagh T, De Jong G, Verhoog D. Energie en klimaat in de agrosectoren. Utrecht 2014.

[5] van der Velden NJA, Smit P. Energiemonitor van de Nederlandse glastuinbouw 2018. Wageningen: Wageningen Economic Research; 2019.

[6] Dutta Gupta S, Agarwal A. Artificial Lighting System for Plant Growth and Development: Chronological Advancement, Working Principles, and Comparative Assessment. In: Dutta Gupta S, editor. Light Emit. Diodes Agric., Singapore: Springer Singapore; 2017, p. 1–25. https://doi.org/10.1007/978-981-10-5807-3_1.

[7] Raaphorst M, Benninga J, Eveleens BA. Quantitative information on Dutch greenhouse horticulture 2019. Bleiswijk 2019.

[8] Toronto, Posterity Group. Greenhouse Energy Profile Study; 2019. http://www.ieso.ca/-/media/Files/IESO/Document-Library/research/Greenhouse-Energy-Profile-Study.pdf, Accessed Oct 15, 2020. p. 150.

[9] Marcelis LFM, Costa JM, Heuvelink E. Achieving sustainable greenhouse production: present status, recent advances and future developments. In: Heuvelink E, Marcelis LFM, editors. Achieving sustainable greenhouse production. 1st. Burleigh Dodds Science Publishing; 2019. p. 1–14. https://doi.org/10.19103/AS.2019.0052.01.

[10] Nelson JA, Bugbee B. Economic Analysis of Greenhouse Lighting: Light Emitting Diodes vs. High Intensity Discharge Fixtures. PLoS One 2014;9:e99010. https://doi.org/10.1371/journal.pone.0099010.

[11] The DesignLights Consortium. Horticultural lighting qualified products list 2019. https://www.designlights.org/horticultural-lighting/ (accessed May 1, 2020).

[12] Kusuma P, Pattison PM, Bugbee B. From physics to fixtures to food: current and potential LED efficacy. Horticulture Res 2020. https://doi.org/10.1038/s41438-020-0283-7.

[13] Both A-J, Bugbee B, Kubota C, Lopez RG, Mitchell C, Runkle ES, et al. Proposed Product Label for Electric Lamps Used in the Plant Sciences. Horttechnology 2017;27:544–9. https://doi.org/10.21273/horttech03648-16.

[14] Mitchell CA, Dzakovich MP, Gomez C, Lopez R, Burr JF, Hernández R, et al. Light-Emitting Diodes in Horticulture. Hortic. Rev. (Am. Soc. Hortic. Sci)., vol. 43, Hoboken, New Jersey: John Wiley & Sons, Inc.; 2015, p. 1–88. https://doi.org/10.1002/9781119107781.ch01.

[15] Ahamed MS, Guo H, Tanino K. Energy saving techniques for reducing the heating cost of conventional greenhouses. Biosyst Eng 2019;178:9–33. https://doi.org/10.1016/j.biosystemseng.2018.10.017.

[16] Gómez C, Morrow RC, Bourget CM, Massa GD, Mitchell CA. Comparison of Intracanopy Light-emitting Diode Towers and Overhead High-pressure Sodium Lamps for Supplemental Lighting of Greenhouse-grown Tomatoes. Horttechnology 2013;23:93–8. https://doi.org/10.21273/HORTTECH.23.1.93.

[17] Kumar KGS, Hao X, Khosla S, Guo X, Bennett N. Comparison of HPS lighting and hybrid lighting with top HPS and intra-canopy LED lighting for high-wire mini-cucumber production. Acta Hortic 2016;1134:111–7. https://doi.org/10.17660/ActaHortic.2016.1134.15.

[18] Dueck TA, Janse J, Eveleens BA, Kempkes F, Marcelis LFM. Growth of tomatoes under hybrid LED and HPS lighting. Acta Hortic 2012;1:335–42. https://doi.org/10.17660/ActaHortic.2012.952.42.

[19] Dieleman A, de Visser PHB, Vermeulen PCM. Reducing the carbon footprint of greenhouse grown crops: re-designing LED-based production systems. Acta Hortic 2016:395–402. https://doi.org/10.17660/ActaHortic.2016.1134.51.

[20] Ouzounis T, Giday H, Kjaer KH, Ottosen CO. LED or HPS in ornamentals? A case study in roses and campanulas. Eur J Hortic Sci 2018;83:1611–4434. https://doi.org/10.17660/eJHS.2018/83.3.6.

[21] Businger JA. The glasshouse (greenhouse) climate. In: Van Wijk WR, editor. Phys. plant Environ., Amsterdam: North-Holland; 1963, p. 277–318.

[22] Bot GPA. Greenhouse climate: from physical processes to a dynamic model. 1983.

[23] De Zwart HF. Analyzing energy-saving options in greenhouse cultivation using a simulation model. Landbouwuniversiteit Wageningen 1996.

[24] Van Beveren PJM, Bontsema J, van Straten G, van Henten EJ. Minimal heating and cooling in a modern rose greenhouse. Appl Energy 2015;137:97–109. https://doi.org/10.1016/j.apenergy.2014.09.083.

[25] van Beveren PJM, Bontsema J, van Straten G, van Henten EJ. Optimal control of greenhouse climate using minimal energy and grower defined bounds. Appl Energy 2015;159:509–19. https://doi.org/10.1016/j.apenergy.2015.09.012.

[26] Ahamed MS, Guo H, Tanino K. A quasi-steady state model for predicting the heating requirements of conventional greenhouses in cold regions. Inf Process Agric 2018;5:33–46. https://doi.org/10.1016/j.inpa.2017.12.003.

[27] Golzar F, Heeren N, Hellweg S, Roshandel R. A novel integrated framework to evaluate greenhouse energy demand and crop yield production. Renew Sustain Energy Rev 2018;96:487–501. https://doi.org/10.1016/j.rser.2018.06.046.
[28] Righini I, Vanthoor B, Verheul MJ, Naseer M, Maessen H, Persson T, et al. A greenhouse climate-yield model focussing on additional light, heat harvesting and its validation. Biosyst Eng 2020:1–15. https://doi.org/10.1016/j.biosystemseng.2020.03.009.
[29] Katzin D, van Mourik S, Kempkes F, van Henten EJ. GreenLight – An open source model for greenhouses with supplemental lighting: Evaluation of heat requirements under LED and HPS lamps. Biosyst Eng 2020;194:61–81. https://doi.org/10.1016/j.biosystemseng.2020.03.010.
[30] EnergyPlus. EnergyPlus Weather Data 2020. https://energyplus.net/weather (accessed April 6, 2020).
[31] ASHRAE. International Weather for Energy Calculations (IWEC Weather Files) Users Manual and CD-ROM. Atlanta: ASHRAE; 2001.
[32] Wilcox S, Marion W. User's Manual for TMY3 Data Sets. Golden, Colorado: National Renewable Energy Laboratory; 2008.
[33] China Meteorological Bureau, Climate Information Center CDO, Tsinghua University D of BS and T. China Standard Weather Data for Analyzing Building Thermal Conditions. Beijing: China Building Industry Publishing House; 2005.
[34] Logics Numerical. Canadian Weather for Energy Calculations, Users Manual and CD-ROM. Downsview, Ontario: Environment Canada; 1999.
[35] Vanthoor B, Stanghellini C, van Henten EJ, de Visser PHB. A methodology for model-based greenhouse design: Part 1, a greenhouse climate model for a broad range of designs and climates. Biosyst Eng 2011;110:363–77. https://doi.org/10.1016/j.biosystemseng.2011.06.001.
[36] Nelson JA, Bugbee B. Analysis of Environmental Effects on Leaf Temperature under Sunlight, High Pressure Sodium and Light Emitting Diodes. PLoS ONE 2015;10:e0138930. https://doi.org/10.1371/journal.pone.0138930.
[37] Kaiser E, Ouzounis T, Giday H, Schipper R, Heuvelink E, Marcelis LFM. Adding blue to red supplemental light increases biomass and yield of greenhouse-grown tomatoes, but only to an optimum. Front Plant Sci 2019;9:1–11. https://doi.org/10.3389/fpls.2018.02002.
[38] Vanthoor B, van Henten EJ, Stanghellini C, de Visser PHB. A methodology for model-based greenhouse design: Part 3, sensitivity analysis of a combined greenhouse climate-crop yield model. Biosyst Eng 2011;110:396–412. https://doi.org/10.1016/j.biosystemseng.2011.08.006.
[39] Dueck TA, Janse J, Schapendonk AHCM, Kempkes F, Eveleens B, Scheffers K, et al. Lichtbenuttig van tomaat onder LED en SON-T belichting. Wageningen; 2010.
[40] Katzin David, Marcelis Leo F.M., Van Mourik Simon Data from: Energy savings in greenhouses by transition from high-pressure sodium to LED lighting Year. 2020, https://doi.org/10.4121/13096403.
[41] van Beveren PJM, Bontsema J, van Straten G, van Henten EJ. Optimal utilization of a boiler, combined heat and power installation, and heat buffers in horticultural greenhouses. Comput Electron Agric 2019;162:1035–48. https://doi.org/10.1016/j.compag.2019.05.040.
[42] Vanlommel W, Fabri S, Wittemans L, Vermieren J, Steppe K. Leds aan of uit in de zomer: een verschil van 4% in tomatenproductie. Proeftuinnieuws 2018:16–7.
[43] Vanlommel W. Tomaten telen met 300 umol/m2/s led-licht kan maar is duur. Proeftuinnieuws 2019;4:22–3.
[44] Van Baar PH. Combining HPS and LED lights for higher tomato yields and longer illumination periods. Philips Light Hold 2019. https://www.lighting.philips.com/main/products/horticulture/hortiblog/vegetables-and-fruits/combining-hps-and-led-lights-for-higher-tomato-yields-and-longer-illumination-periods (accessed April 8, 2020).
[45] Weaver GM, van Iersel MW, Mohammadpour Velni J. A photochemistry-based method for optimising greenhouse supplemental light intensity. Biosyst Eng 2019;182:123–37. https://doi.org/10.1016/j.biosystemseng.2019.03.008.
[46] Wang Y, Xu L, Wei R. Economic-based dynamic control of top-lighting and inter-lighting for greenhouse. Eur J Hortic Sci 2018;83:329–33. https://doi.org/10.17660/eJHS.2018/83.5.6.
[47] Zhen S, Bugbee B. Far-red photons have equivalent efficiency to traditional photosynthetic photons: Implications for redefining photosynthetically active radiation. Plant Cell Environ 2020:1–14. https://doi.org/10.1111/pce.13730.
[48] Kalaitzoglou P, van Ieperen W, Harbinson J, van der Meer M, Martinakos S, Weerheim K, et al. Effects of continuous or end-of-day far-red light on tomato plant growth, morphology, light absorption, and fruit production. Front Plant Sci 2019;10:1–11. https://doi.org/10.3389/fpls.2019.00322.
[49] Kim HJ, Lin MY, Mitchell CA. Light spectral and thermal properties govern biomass allocation in tomato through morphological and physiological changes. Environ Exp Bot 2019;157:228–40. https://doi.org/10.1016/j.envexpbot.2018.10.019.
[50] Ji Y, Ouzounis T, Courbier S, Kaiser E, Nguyen PT, Schouten HJ, et al. Far-red radiation increases dry mass partitioning to fruits but reduces Botrytis cinerea resistance in tomato. Environ Exp Bot 2019;168:103889. https://doi.org/10.1016/j.envexpbot.2019.103889.
[51] Montero JI, Zhang Y, Yang Q, Ke X. Advances in greenhouse design. In: Marcelis LFM, Heuvelink E, editors. Achiev. Sustain. Greenh. Prod. 1st ed., Cambridge: Burleigh Dodds Science Publishing; 2019, p. 17–52. https://doi.org/10.19103/AS.2019.0052.02.

Glossary

AMS: Amsterdam, The Netherlands
ANC: Anchorage, Alaska, USA
ARK: Arkhangelsk, Russia
Assimilation lighting: Supplemental lighting used in the greenhouse to enhance crop growth
BEI: Beijing, China
CAL: Calgary, Canada
CHE: Chengdu, China
CHP: Combined heat and power generator
E^{HPS}: Total energy use of an HPS greenhouse (MJ m^{-2} year^{-1})
E^{LED}: Total energy use of an LED greenhouse (MJ m^{-2} year^{-1})
FIR: Far infrared radiation, wavelength above 2500 nm
F_{Light}: Fraction of energy input used for lighting in an HPS greenhouse
H_{AirOut}: Convection from the main greenhouse compartment to the outside air
$H_{BoilPipe}$: Energy transfer from the greenhouse boiler to the heating pipes
$H_{Cov,eOut}$: Convection from the greenhouse cover to the outside air
HPS: High-pressure sodium
$H_{So5SoOut}$: Convection from the greenhouse floor to the soil
H_{TopOut}: Convection from the top greenhouse compartment to the outside air
I_{Glob}: Global solar radiation (W m^{-2})
I_{Sky}: Horizontal infrared radiation from the sky (W m^{-2})
KIR: Kiruna, Sweden
$L_{AirThScr}$: Latent heat converted to sensible heat by vapor condensation on the thermal screen
L_{CanAir}: Sensible heat converted to latent heat by crop transpiration
LED: Light emitting diode
$L_{TopCov,in}$: Latent heat converted to sensible heat by vapor condensation on the internal side of the greenhouse cover
MOS: Moscow, Russia
NIR: Near infrared radiation, wavelength of 700–2500 nm
PAR: Photosynthetically active radiation at a wavelength of 400–700 nm, that is used by plants for photosynthesis
PPE, efficacy: Photosynthetic photon efficacy, a measure of a horticultural lamp's efficiency in converting input energy to PAR (μmol J^{-1})
PPFD: Photosynthetic photon flux density (μmol m^{-2} s^{-2})
Q^{HPS}_{Heat}: Energy used for heat in an HPS greenhouse (MJ m^{-2} year^{-1})
Q^{HPS}_{Light}: Energy used for light in an HPS greenhouse (MJ m^{-2} year^{-1})
Q^{LED}_{Heat}: Energy used for heat in an LED greenhouse (MJ m^{-2} year^{-1})
Q^{LED}_{Light}: Energy used for light in an LED greenhouse (MJ m^{-2} year^{-1})
Q_{LampIn}: Energy used by the greenhouse lamps
R^2: Coefficient of determination
R_{CanSky}: Thermal radiation from the crop to the sky
$R_{Cov,eSky}$: Thermal radiation from the greenhouse cover to the sky
R_{FlrSky}: Thermal radiation from the greenhouse floor to the sky
R_{Glob_SunAir}: Global solar radiation absorbed by the greenhouse structure and transferred to the greenhouse air
$R_{Glob\_SunCov,e}$: Global solar radiation absorbed by the greenhouse cover
RH_{Out}: Outdoor relative humidity (%)
$R_{LampSky}$: Thermal radiation from the lamps to the sky
RMSE: Root mean squared error
R_{NIR_SunCan}: NIR from the sun to the canopy
R_{NIR_SunFlr}: NIR from the sun to the floor
R_{PAR_SunCan}: PAR from the sun to the canopy
R_{PAR_SunFlr}: PAR from the sun to the floor
$R_{PipeSky}$: Thermal radiation from the heating pipes to the sky
$R_{ThScrSky}$: Thermal radiation from the thermal screen to the sky
SAM: Samara, Russia
SHA: Shanghai, China
STP: St Petersburg, Russia
Supplemental lighting: Lighting in the greenhouse coming from lamps, including lighting for daylength control and assimilation lighting
T_{Out}: Outdoor air temperature (°C)
T_{SoOut}: Soil temperature (°C)
TOK: Tokyo, Japan
URU: Urumqi, China
v_{Wind}: Outdoor wind speed (m s^{-1})
VEN: Venice, Italy
WIN: Windsor, Canada
ϵ_{HPS}: Efficacy of an HPS lamp (1.8 μmol J^{-1})
ϵ_{LED}: Efficacy of an LED lamp (3 or 4.1 μmol J^{-1})