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Sabine Wittmann*, Ivonne Jüttner, Heike Mempel

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University of Applied Science Weihenstephan-Triesdorf,
Am Staudengarten 10, 85351 Freising, Germany;
sabine.wittmann@hswt.de, ivonne.juettner@hswt.de, heike.mempel@hswt.de

* Correspondence: sabine.wittmann@hswt.de

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Simplified energy modeling to investigate the effect of lighting strategies on the energy efficiency of container indoor farms

Sabine Wittmann*, Ivonne Jüttner, Heike Mempell

University of Applied Science Weihenstephan-Triesdorf, Germany

Abstract

Indoor farming offers a high potential to supplement plant production. Nevertheless, the high electrical energy consumption remains a challenge to achieve profitability. For a container indoor farm at the University of Applied Science Weihenstephan-Triesdorf (HSWT) a simplified model to estimate the total energy consumption was developed. The model was validated by prediction of two measurement times in January (regarding an empty cultivation unit) and august (during pepper cultivation) ($R^2 = 0.913$ / RMSE = 1.6). The model was then used to analyze the impact of two set points for air temperature (20 °C and 25 °C), changes in the switch-on time of the LED over 24 h as well as varying photoperiods and light intensities with mean daily light integral (DLI) levels of 21 and 14 mol m^{-2} d^{-1} on the total electrical consumption. As expected a lower DLI needs up to 23-33 % less energy. Nevertheless, the results suggest a potential to reduce energy consumption by higher temperature of 2-8 %.

1. Introduction, Knowledge, Objectives

Indoor farming offers a high potential to supplement plant production, due to the considerable increase in the efficiency of land and water use as well as precise control of culture management parameters. Hence, indoor farming is becoming increasingly important both for producers and for industry, especially with a view to the future challenges for the plant-based production of fresh goods and raw materials (Wittmann et al., 2020). However, the operation of an indoor facility is controversial with regard to its economic efficiency and sustainability due to the high-energy consumption. In order to achieve a higher profitability of indoor farms in the future, the minimization of the input costs, in relation to the energy demand, is of primary importance (Mempel et al., 2021). Indoor farms are defined as highly insulated and airtight structures. In contrast to greenhouses with a high interaction of internal and external climate, these interactions are in most literature and existing models expected to be highly limited. Smaller structures such as indoor container farms are often neglected and the external influence is more significant. While indoor farms are at the moment still mainly used to produce leafy greens or herbs, it is assumed that indoor vertical farming will reach its greatest potential globally with the production of higher value plants like fruit, fruit vegetables and plant raw materials (O'Sullivan et al., 2020). While lettuce and leafy vegetables grow well at a DLI of 8-14 mol m^{-2} d^{-1} and temperatures of 18-21 °C (Dorais, 2003; Baumbauer et al., 2019; Pennisi et al., 2020), a DLI of at least 17-20 mol m^{-2} d^{-1} and 20-25 °C is required for the production of fruit vegetables such as tomatoes, pepper or strawberries (Schwarz et al., 2014). The high proportion of LED lighting on energy consumption as well as on the internal heat load of the cooling devices has been shown (Graamans et al., 2018). In order to still achieve a higher DLI, the photoperiod would have to be extended accordingly. For lettuce as well as for pepper, positive effects on the photosystem, leaf area or the yield were reported by extended photoperiods (Dorais et al., 1996; Elkins and van Iersel, 2020; Kelly et al., 2020). To produce fruit vegetables, strategies to optimize energy consumption have to be found. Therefore, the objective of this study was to compare and analyze the impact of varying lighting strategies on the total electrical energy consumption of the container indoor farm regarding a cultivation of fruit vegetables at a defined DLI of 14 and 21 mol m^{-2} d^{-1} as well as an increased cultivation temperature of 25 °C compared to 20 °C.

2. Data, Methods and Approach

The examined container indoor farm is placed in a west-east orientation located on the site of the University of Applied Science Weihenstephan-Triesdorf (HSWT). The structure was redesigned to achieve a high degree of insulation, little condensation on thermal bridges and a low air exchange. The indoor farm is divided lengthways by an entrance area into two identical cultivation units (A/B) with a floor area of 15.5 m^2 each (Fig. 1). The multilevel system consists of 6 shelves (4 levels) on each long side with a central aisle, resulting in a cultivation area of 20.2 m² respectively. Every layer is equipped with LEDs and irrigation which were both adapted to the respective experimental questions during the time of the modeling. Although the environment inside each unit can be controlled individually, the cooling capacity of the climatisation is restricted and influenced by the external environment. The electrical energy requirements such as air conditioning, LED, air circulation and humidification were monitored on a 5-minute basis for both cultivation units separately (Saia-Burgess Controls, Switzerland).

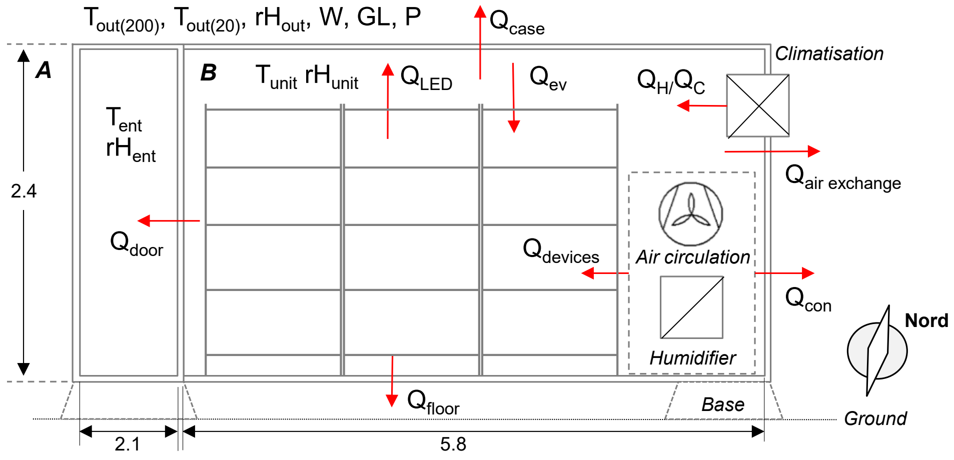

Figure 1: System components of the container indoor farm and considered energy balance using the example of cultivation unit B. Dimensions in meters (depth: 2.4 m)

As total energy consumption of one cultivation unit air conditioning, LED, air circulation and humidification was considered (eq. 1). Please not the abbreviations listed in Table 1. Since the irrigation was done manually, irrigation was not included.

$$E_{cultivation\ unit} = \sum \left(E_{climatisation}+E_{LED}+E_{air\ circulation}+E_{humidifaction}\right) \quad (1)$$

Table 1: List of important symbols, a short description and the units used for modeling

Symbol	Description	Unit	Symbol	Description	Unit
T	air temperature	°C	COP	coefficient of performance for heating	-
rH	relative humidity	%	EER	energy efficiency ratio for cooling	-
out, unit, ent	outside, cultivation unit, entrance	-	u	u-value of container case	$W*m^{-2*-1}$
200, 20	measuring point above the ground	cm	A	floor area	m²
h,c	heating, cooling	-	V	air volume	m³
Q	thermical energy	kWh	h	enthalpy of water vapor	$kJ*kg^{-1}$
E	electrical energy	kWh	ρ	density of air	$kg*m^{-3}$
t	time (1152 h = 48 days)	h	e_s	saturation vapor pressure	mbar
A, B	cultivation unit	-	H	absolute humidity	$g*kg^{-1}$
W	wind	$m*s^{-1}$	e	actual vapor pressure	mbar
GL	global radiation	$W*m^{-2*-1}$	a, b, c, d, e	Trans-coefficients	-
P	precipitation	mm			

To take the influence of the exterior environment for the more exposed structure of a container indoor farm into account the calculation for heat dissipation of regular greenhouses (Meyer, 2010) was adapted to include the heat load of the LEDs as well as the other electrical devices inside the cultivation unit (eq. 2).

$$Q_{H/C}=\sum_{t=1}^{1152}(Q_{case}+Q_{floor}+Q_{door}+Q_{air\ exchange})-(Q_{LED}+Q_{devices}) \tag{2}$$

$$Q_{case\ /\ entrance}=\left(\left(\left(u+(a*W)+(b*P)\right)*A*\left(\frac{Tunit}{Tout(200)}\right)-(c*GL)\right)\right)/1000\Big) \tag{2a}$$

$$Q_{floor}=\left(((u+(a*W))*\mathrm{A}*\left(\frac{\mathrm{Tunit}}{Tout(20)}\right))/1000\right) \tag{2b}$$

$$Q_{door}=\left((u*\mathrm{A}*(\frac{\mathrm{Tunit}}{Tent}))/1000\right) \tag{2c}$$

$$Q_{air\ exchange}=\left(V*(\frac{150}{\sqrt{V}}*24^{-1})*\rho*(\frac{\mathrm{hout-hunit}}{86400})\right) \tag{2d}$$

$$Q_{devices}=\left(E_{Humidifier}+E_{air\ circulation}\right)/1000\Big) \tag{2e}$$

$$Q_{LED}=((E_{LED})/1000) \tag{2f}$$

To calculate the electrical energy consumption of the air conditioning, the energy for heating or cooling was divided by the coefficient of performance (COP) for heating or Energy efficiency ratio (EER) for cooling respectively (eq. 3).

$$E_{climatisation}=E_h+E_C \tag{3}$$

$$E_h=\frac{Qh}{COP+d} \tag{3a}$$

$$E_C=\frac{Qc}{EER+e} \tag{3b}$$

The model was iterative adjusted by coefficients to minimize the RMSE value (Tab. 2). Based on the monitored energy consumption air circulation and humidification were considered as static electrical consumers. After calibration (set a), the model was subsequently validated by the prediction of two further measurement times (set b and c) (Tab. 3). During the measured time “set c” pepper plants were cultivated inside Unit A at set temperatures of 20 ± 2 °C. The simulations were done with the calibrated model for cultivation unit A and the energy consumption calculated as monthly sum (kWh) per cultivation area (m²). The calculation werde done with Excel (Version 2202). The model was then used to analyze two set points for temperature as well as varying photoperiods and

Table 2: calibration coefficients for both cultivation units

coefficient	A	B	model parameters	A & B	devices	Wattage (W)	Running time (h)
a	0.06	0.06	COP	3.41*	humidification	162**	24
b	0.10	0.10	EER	3.01*	air circulation	139**	24
c	0.20	0.20	u-Value (W m^{-2} K^{-1})	0.57**	LED (A)***	1619**	18
d	0.81	1.81	air exchange rate (1 d^{-1})	24.5**	LED (B)***	2302**	18
e	0.71	0.81			LED (A)****	2273**	18

* according to manufacturer | ** based on own measurements | *** calibration and validation I | **** validation II

Table 3: Specifications on the measurement times used for calibration and validation

Model	set	begin of experiment	n (days)	min-max (Tout °C)	min–max (kWh)	cultivated plants	LAI (m^2 m^{-1})
air condition (Unit A & B)	a	12/19/2020	22	-10.8 to 12.5	7.0 to 20.1		
air condition (Unit A & B)	b	01/13/2021	20	-8.7 to 11.4	2.0 to 17.7	-	-
Air condition (Unit A)	c	06/30/2021	22	14.9 to 22.8	14.9 to 23.6	pepper*	3.7 ± 0.7**

*variety 'sweet heat‘ (graines voltz), total cultivation area: 2.7 m2 | **at harvest

light intensities with identical DLI levels (Tab. 4). A photoperiod of 18 h and 25 °C, which has been used for set c, was set as control for both DLI separately. Deviations were calculated as percentage between the average daily energy consumption (kWh m^{-2} d^{-1}) and the respective average daily energy consumption (kWh m^{-2} d^{-1}) of the control for each month separately.

Table 4: Set points regarding photoperiod and light intensity at the target DLI. Each simulation was done for air temperatures of 25 and 20 °C and a switch-on time at 6 pm.

	Light intensity (μmol m^{-2} s^{-1})				
Photoperiode (h)	16	18 * / **	20	22	24
DLI 14 ± 0.3 (mol m^{-2} d^{-1})	250	220	190	180	160
DLI 21 ± 0.3 (mol m^{-2} d^{-1})	370	330	290	260	240

*Setting defined as control by a temperature of 25 °C for both DLI
**Setting used for simulations of switch-on times

Furthermore, changes in the switch-on time of the LED were considered by shifting the switch-on time of 18 h over the entire course of the day by 2 hours. The connected load of the LEDs was extrapolated based on measurements at 330, 240 and 180 µmol m^{-2} s^{-1}. To include external environmental conditions a TRY (test reference years) climate set for the coordinates of the farm was used[1].

3. Results

Measurements of the electrical energy consumption inside the running container indoor farm showed a high variability in the energy consumption of climatisation compared to the other consumers which remained stable for the given set points (Fig. 2-A). Validation I and II could be predicted well by the model for the climatisation unit A ($R^2 = 0.913$) and good for unit B ($R^2 = 0.633$) (Fig. 2-B). The RMSE was calculated as 1.6 (Unit A) and 0.9 (Unit B).

The model was able to predict the energy consumption for an empty cultivation unit as well as for modeling with leaf mass and irrigation.

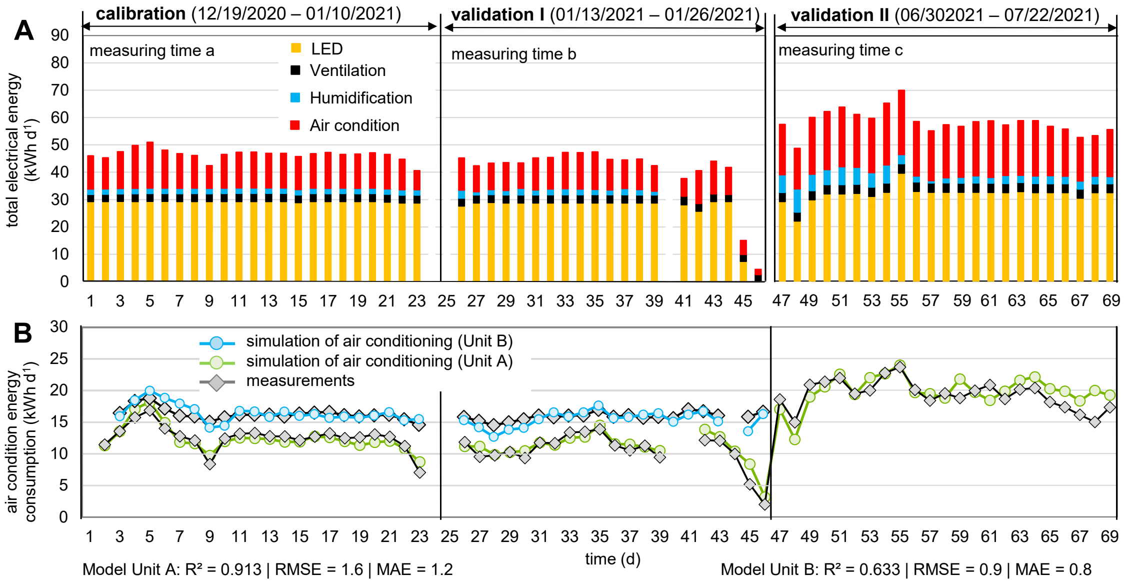

Figure 2: (A) Measured electrical energy consumption for the example of cultivation unit A. (B) Modelling results for the air conditioners in unit A and B.

It became clear that the influence of the switch-on times on the daily energy consumption is with ± 0.6 % negligible. Nevertheless, it is energetically preferable to choose a switch-on time between 6:00 to 8:00 p.m. based on the analyzed photoperiodes (data not shown). An increase in the internal temperature of 5 °C leads to an optimization of the energy consumption regardless of the lighting strategies of 2-8 % (Fig. 3-A). However, the absolute amount of energy savings is strongly influenced by a seasonal effect (Fig. 3-B). From may to september the lighting strategies showed only minor differences in comparison, but let to an overall increase in the energy requirement compared to the average consumption. This effect is similar at a DLI of 14 (data not shown). As expected a lower DLI of 14 compared

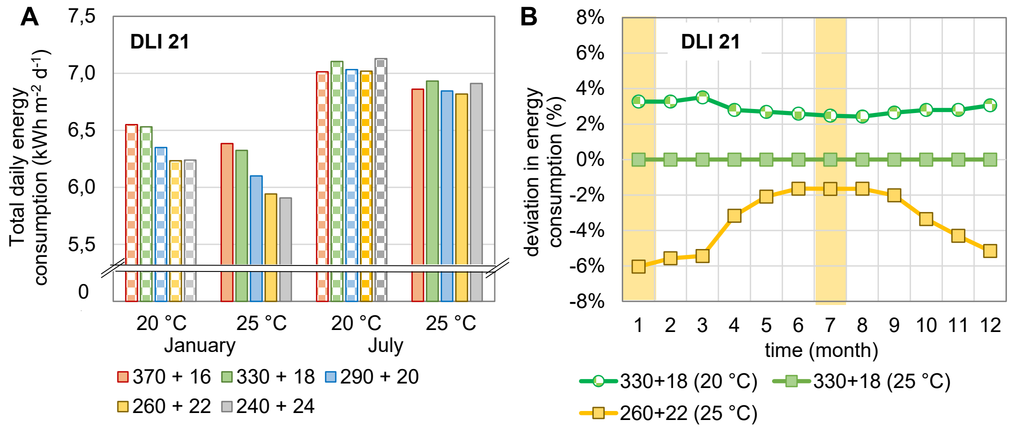

Figure 3: (A) Simulation of the total energy consumption at different light intensity (µmol m^{-2} s^{-1}) + photoperiode (h) and two temperatures. (B) Percentage deviation calculated per month from the daily energy consumption of the control

to 21 reduces the electrical energy consumption clearly. Even though this effect is slightly influenced by a seasonal effect, the reduction remains for all lighting strategies between 30-33 % in January and 23-26 % in July (data not shown).

4. Discussion

The calibrated model showed a sufficiently high R² for the predicted and the measured energy consumption of the air conditioning in cultivation unit A. Even though the model for the air conditioning in cultivation unit B was less pronounced, the RMSE showed a low error. Therefore, the lower r² can be safely attributed to the small range of the measured values. The discrepancies on the last days are not fully understood yet, but can be assumed to be influenced by human activities inside the indoor farm as well as measurement errors and will be further investigated. Indoor farms require a large input of electrical energy for cooling due to a high internal heat load which is mainly influenced by the inefficiency of the LED fixtures (Graamans et al., 2018). Without considering plant reaction at this point, our results of the energy simulations suggest to favor light intensities of 240-290 µmol m^{-2} d^{-1} and longer photoperiods to produce fruit vegetables purely in terms of energy consumption for the given container indoor farm. Especially since lower but longer illumination times reduce the overall cooling load. Furthermore, a higher temperature of 25 °C influenced the energy consumption positiv. The higher temperature, in combination with a higher CO_2 concentration could increase yield of fruit vegetables and might also effect energy efficiency. For this further studies on plant reaction will be done. Nevertheless, the energy consumption during summer months can only be marginally influenced by the simulated lighting strategies. Here the influence of the external climate on the internal conditions became very clear. Based on the results, it would make sense to change the DLI over the course of the year, switching from a higher DLI in the months of October to April to a lower DLI for the summer months and thereby lowering the heat load in the culture room. In general, the total energy consumption can be further reduced through optimized technical equipment such as LEDs, air conditioning, humidification and an improved surface use efficiency. In our model we used given efficiencies and a temperature scenario without night reduction which could also have a further effect on the energy consumption. We are also aware that the use of a rather simple model can lead to uncertainties especially regarding latent heat flows which have not been quantified and therefore have not been included in the model. Future work will further adjust the model to include effects of latent heat energy.

5. Conclusions

The developed simplified model showed good results in the prediction of the total electrical energy consumption of the container indoor farm. Nevertheless, for a higher accuracy latent heat should be included. For the container farm, the biggest influencing factor on energy consumption is a seasonal effect. It became clear that regardless of the lighting strategy, a significantly higher consumption must be assumed over the summer months. The production of plants with higher needs in DLI and temperature is therefore more attractive during winter months. Nevertheless, the use of lower light intensities over a longer photoperiod and a higher temperature, regardless of the plant requirements, is beneficial for container indoor farming in terms of energy savings.

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[1] https://www.dwd.de/DE/leistungen/testreferenzjahre/testreferenzjahre.html (abgerufen am 12.12.2021)