Determination of the effective operating hours of the intermittent lighting system for growing vegetables

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Abstract. Around the world, one of the key challenges is the provision of food for a growing urbanized population. A vertical farming system will help solve this problem. Vertical farming in a controlled environment provides 4-6 times higher yields per unit area, but requires more electricity. The most economical light sources are light-emitting diodes but it is important to determine the rational operating mode of the lighting system. The aim of the study was to determine the specific operating hours of the intermittent lighting system to reduce the cost of electricity consumption when growing vegetables in vertical farming in a controlled environment. Continuous and periodic modes of operation of the lighting system with a total operating time of 16 hours per day were considered. In Russia, there are six price categories for consumed electricity. Research has shown that price level II is economically viable and a rational operating mode: 8 hours of light/4 hours of darkness, etc. Thus, the intervals of operation of the lighting system are 11.00-19.00 and 23.00-7.00. The study of this regime for microgreening of Mitsun head cabbage showed that the productivity of the plants was preserved, since the length of the leaves did not change.

1. Introduction
One of the key challenges in the ongoing urbanization around the world is delivering large quantities of food to serve the needs of the growing population. One of the solutions to this problem might be offered by the vertical farming system [1]. This technology is aimed at its active participation in food security for the constantly growing urban population of the world [2,3]. Vertical farms are understood as individual buildings or structures on the roofs of old and new buildings with several levels of beds with artificial lighting [4,5]. These small farms are sprung up all over the world. Many cities are adopting this model in new and old buildings, including warehouses or containers, which the owners have converted to agricultural activities. Vertical farms can make food production more efficient and sustainable. It is possible to get a crop all year round without interruption due to climate change, season or extreme natural events (droughts, floods, etc). Indoor vertical farming in a controlled environment provide 4-6 times higher yields per unit area than traditional greenhouses [6,7] and...
require less water for irrigating plants [8]. However, vertical farms technology requires far more energy [9].

Photosynthesis forms up to 95% of the yield and depends on the light characteristics of the lighting device. In greenhouses, lighting accounts for up to 30% of electricity. Therefore, it is necessary to use energy-saving light-emitting diodes (LED) installations for irradiating plants. LEDs can change the spectrum and level of irradiation [10,11], their electrical characteristics are weakly dependent on the deviation of the supply voltage [12]. The cost of electricity consumed for lighting installations depends on the photoperiod and on the inclusion of the intermittent irradiation system during the effective hours when the cost of electricity is minimal. Experiments on the irradiation of lettuce with a photoperiod of 14 and 16 per day showed that the mass of fresh leaves and roots of the harvested lettuce was higher at a photoperiod of 16 hours per day [13]. The effects of photoperiods of 12, 15 and 18 hours per day in interaction with the concentration of the nutrient solution were investigated. The largest amounts of leaves and plant matter were found in lettuce leaves with a lighting period of 18 hours per day. With a decrease in the photoperiod, the amount of nitrates and free amino acids and vitamin C decreases [14]. Experiments on the effect of the photoperiod (12, 16, 18 and 24 hours a day) on green and red lettuce showed that the greatest weight was at a photoperiod of 16 hours a day for both red and green lettuce [15]. Studies [16] confirmed the conclusions of studies [14-15] that an increase in the photoperiod from 16 to 24 hours a day does not lead to an increase in plant mass. Thus, the analysis of the works shows that the photoperiod of 16 hours a day can be considered effective. In [17], the effect of intermittent irradiation on the growth of lettuce (Lactuca sativa L.) was studied. Three options for intermittent irradiation were considered: 18 hours light and 6 hours dark (one cycle), 9 hours light and 3 hours dark (two cycles) and 6 hours light and 2 hours dark (three cycles). The best option was 9 hours. light and 3 hours darkness.

Various alternatives of intermittent irradiation for lettuce were compared: 16 hours of light and 8 hours of darkness - control; 8 hours of light and 4 hours of darkness twice a day; 6 hours of light and 3 hours of darkness three times a day; 4 hours of light and 2 hours of darkness three times a day [18]. The most effective was 4 hours of light and 2 hours of darkness, which increased the biomass by 15.8% compared to the control. Thus, intermittent irradiation turned out to be more effective than traditional irradiation.

The studies analyzed do not address the issue of specific hours of activation of the irradiation system during the day (morning, afternoon or night). Clarification of the operating hours will reduce the cost of consumed electricity, since according to the price category, the cost of electricity depends on the intervals of the day.

The aim of the study was to determine the specific operating hours of the intermittent lighting system to reduce the cost of electricity consumption when growing vegetables in vertical farming in a controlled environment.

2. Materials and methods

In Russia, there are currently six price categories (CP) for the consumed electricity [19,20]. The first price category (I) is applied to the volumes of electric energy carried out as a whole for the billing period. The cost of electricity is determined by the expression (1)

\[ C_I = W \cdot T \]  

where \( W \) – the amount of electricity consumed for the billing period, kWh; \( T \) – electricity tariff, rub/kWh.

The second price category (II) is used for the volumes of electrical energy, the accounting of which is carried out by intervals of the day of the settlement period. The billing period can include two or three intervals of the day.

The settlement period for two intervals of the day includes the night time (23.00-7.00) and the day time (7.00-23.00). The electricity cost for the intervals of the day is determined by the expression (2):
\[ C_{II-I} = W_1 \cdot T_1 + W_2 \cdot T_2 \]

where \( W_1, W_2 \) – the amount of electricity consumed during the night/day time, kWh; \( T_1, T_2 \) – electricity tariff during the night/day time, rub/kWh.

The settlement period for three intervals of the day includes: the night interval (23.00-7.00), the half-peak interval (10.00-17.00 and 21.00-23.00), and the peak interval (7.00-10.00 and 17.00-21.00). The cost of electricity for three intervals of the day is determined by the expression (3):

\[ C_{II-II} = W_1 \cdot T_1 + W_2 \cdot T_2 + W_3 \cdot T_3 \]

where \( W_1, W_2, W_3 \) – the amount of electricity consumed during the night/half-peak/peak intervals, kWh; \( T_1, T_2, T_3 \) – electricity tariff during the night/half-peak/peak, rub/kWh.

The third price category (III) is applied to the volumes of purchased electrical energy, hourly accounting is carried out for the billing period, but hourly planning is not carried out. The cost of energy transmission services is determined according to the tariff for services in one-rate expression. The cost of electricity is determined by the expression (4):

\[ C_{III} = P \cdot T_p + \sum_{i=1}^{24} W_i \cdot T_i \]

where \( W_i \) – the volume of consumed electricity during the \( i \)-th hour, kWh; \( T_i \) – electricity tariff for the \( i \)-th hour, rub/kWh; \( P \) – installed capacity, kW; \( T_p \) – tariff for the power purchased by the consumer, rub/kWh per month.

The fourth price category (IV) is applied to the volumes of purchase of electrical energy, in respect of which hourly accounting is carried out for the billing period, but hourly planning is not carried out. The cost of energy transmission services is determined according to the tariff for the energy transmission services in two-parts expression. The cost of electricity is determined by the expression (5):

\[ C_{IV} = P_w \cdot T_w + P \cdot T_p + \sum_{i=1}^{24} W_i \cdot T_i \]

where \( P_w \) – power transmitted through power grids, kW; \( T_w \) – tariff rate for energy transmission services for the maintenance of electrical networks at the maximum level of unregulated prices, rub/kW per month.

The fifth price category (V) is applied to the volumes of purchase of electrical energy (capacity), in respect of which hourly planning and accounting are carried out for the billing period, and the cost of energy transmission services is determined according to the tariff for energy transmission services in one-part expression. The consumer plans his consumption for a month by every hour and provides data to the supplier. The cost of electricity is determined by the expression (4).

The sixth price category (VI) is used for the volumes of purchase of electrical energy, in respect of which hourly planning and accounting are carried out for the billing period, and the cost of energy transmission services is determined according to the tariff for services for the transmission of electrical energy in two-parts expression. The consumer plans his consumption for a month by every hour and provides the data to the supplier. The cost of electricity is determined by the expression (5).

For the calculations the limit levels of prices for electrical energy supplied by ‘TNS energo NN’ to consumers with a maximum power receiving devices of less than 670 kW were used [21]. The calculations were carried out for a farm with an electric power of 0.5 MW for growing microgreens. The growing period is 10 days. The operating modes of the irradiation systems during the day are shown in figure 1.
Figure 1. Modes of operation of various irradiation systems during the day: Light (red color), Darkness (gray color).

The control is the irradiation system with a continuous mode of operation for 16 hours per day when the cost of consumed energy is counted in the I price category used by agricultural enterprises. As a comparison, there are irradiation systems with a continuous mode of operation for 16 hours per day with the cost for consumed electricity in the II-VI price category, and irradiation systems with a periodic mode of operation with a total volume of 16 hours per day with the cost for consumed electricity in the II price category, differentiated in three intervals of the day (II-III-II and II-III-III). Research was conducted on Japanese cabbage Mizuna. Irradiation 80±5 mmol/(m²·s), air temperature 22±2 °C and relative humidity 75±2%. Each group contained 50 plants. The experiments were repeated four times. The length of the sheet was measured with a ruler.

3. Results and discussion
The results of calculating the cost of consumed electricity for different operating modes of irradiation systems and different price categories are shown in figure 2.

Analysis of irradiation systems with continuous operation (figure 2) shows the following results. When switching from price category I to price category II-II and II-III, the costs are comparable (<1%). When switching to the III or V price category, the costs increase by 2%. When switching to IV or VI price category, the costs increase by 11%. Therefore, for systems with continuous operation (II-II, II-III, III, IV, V, VI), leaving the I price category is not economically feasible.

Analysis of irradiation systems with periodic operation (figure 2) shows the following results.

Figure 2. Electricity cost under different operating modes of the irradiation system and different price categories.

When switching from price category I to price category II with a differentiated electricity tariff for three intervals of the day and a periodic mode of operation of the light/darkness irradiation system in a 8/4 ratio, the financial costs for consumed electricity are reduced by 4%. When switching from price
category I to price category II with a differentiated electricity tariff for three intervals of the day and a periodic operation of the light/darkness irradiation system in a 4/2 ratio, the costs increase by 3%. Therefore, for systems with a periodic mode of operation, it is economically expedient to move away from the I price category to the II price category with a differentiated tariff for electricity for three intervals of the day with an operating mode of the irradiation system 8/4.

Research has been carried out on the effect of the 8/4 intermittent mode (experiment) on the development of microgreens in Mitsuna cabbage in comparison with the 16/8 continuous mode (control). It was found that the characteristics of plants at the time of harvest are comparable (table 1).

Table 1. Influence of intermittent and continuous irradiation of LED light on the characteristics of microgreen plants of cabbage ‘Mizuna’ during harvest.

| Measurements | Parameter, mm | 16 hours light/8 hours dark (control) | 8 hours light/4 hours dark |
|--------------|---------------|--------------------------------------|---------------------------|
| after 10 days| Sheet length  | 8.38±0.65                           | 8.27±0.83                 |
| after 20 days| Sheet width   | 11.67±0.97                           | 11.62±1.24                |
| after 30 days| Stem height   | 59.13±1.48                           | 58.94±2.13                |

Table 1 shows that the difference in leaf length in the control and in the experiment when measured after 10, 20 and 30 days is less than 1%. The length of the sheet in the control (59.13 mm) and in the experiment (58.94 mm) also differ within 1%. Our results have confirmed the positive effect of intermittent illumination in experiments [15,17]. We propose to turn on the light during the periods of the lowest cost of electricity, which will reduce the cost of production.

4. Conclusion
For growing plants in vertical farming in a controlled environment in Russia, the most economically profitable is the II price category with a differentiated electricity tariff for three intervals of the day for a periodic operation of the lighting system.

The periodic mode of operation should provide a change of light and darkness in the ratio of 8/4 hours, with two cycles during the day. The periods of operation of the lighting system are 11.00-19.00 and 23.00-7.00.

A study of the effect of an intermittent mode of 8 hours light/4 hours of darkness (experiment) on the development of microgreening in Mitsun cabbage in comparison with a continuous mode of 16 hours light/8 hours of darkness (control) showed that the length of cabbage leaves differs by less than 1%.

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