ASSESSMENT OF THE CURRENT STATE AND PROSPECTS FOR DEVELOPMENT OF IRRADIATION SYSTEMS IN MODERN GREENHOUSE FACILITIES

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ABSTRACT

An analysis of the artificial irradiation system used in modern greenhouses using photoculture is conducted. An assessment of the prospects for the introduction of irradiators with LEDs into this system is given, taking into account the payback period in comparison with traditional irradiators with specular sodium HP lamps.

Keywords: greenhouse irradiation, photoculture, discharge sodium lamps, sodium specular lamps (SSL), light emitting diodes, effective systems of irradiation, irradiating installations, pay-off period

Industrial vegetable cultivation in protected soil is a key segment of the agro-industrial complex of the domestic economy; it is currently undergoing a period of rapid development.

According to the Greenhouse Association of Russia, the total area of industrial greenhouses in the country is at 2500 hectares, with more than 500 hectares equipped with systems of technological irradiation, providing year-round vegetables cultivation, Fig. 1. Intensive construction of new greenhouses is enabled by growing consumer demand for fresh vegetables out of season and a state ban on the import of greenhouse vegetables to Russia. The programme of agricultural development in Russia for the period 2013–2020 includes projects creating and developing of greenhouse facilities with artificial irradiation. These projects are a part of a list of actions with priority financing. Just in 2017, the size of the photoculture enabled area grew by 150 %.

Amongst the photoculture enabled greenhouse cultivation, cucumbers represent 60 % of all cultivation, tomatoes account for 30 %, and 10 % is covered by leaf vegetables, i.e. salad cultures. Cucumbers are most sensitive to change in the level of irradiation. Upgrading greenhouses with irradiation systems increases cucumber yield from (40–50) kg/m^2 to (120–150) kg/m^2. The main increase comes in the winter period, when prices for fresh vegetables are at their highest.

Greenhouse irradiation is one of the most energy-intensive uses of light. To provide for the normal growth of plants and achieve a high yield capacity, a high illuminance level is required: from 10 to 30 klx. Large-scale greenhouse facilities are compara-

Fig. 1. Winter greenhouse using artificial irradiation systems (Maysky greenhouse facility, Kazan)

Fig. 2. Cucumber photoculture

ble with small cities or settlements by their energy consumption,. Their light can be seen at a distance of many kilometres. It is obvious that with such power consumption, the cost of electricity is a considerable part of the product cost, reaching as much as (30–40)%. Consequently, raising the efficiency of the radiation sources (RS) and irradiator optical equipment becomes a critical challenge for lighting manufacturers for the greenhouse industry.

More than 20 years ago, a Russian greenhouse facility (GF) called Maysky in Kazan pioneered experiments with various systems of preliminary irradiation for plant cultivation. The managers were interested in specular *Reflux* HP sodium lamps (HPSLs), which had just appeared on the greenhouse market. The first batch of lamps showed good results and became the main RSs for plant irradiation at this facility. Specular HPSLs of *Reflux* LLC production are still used at Maysky GF today. More than 120,000 irradiators with *Reflux* specular sodium lamps (SSL) HPSLs of 600 W are installed there today.

After Maysky, other greenhouse facilities also caught on to the economic benefits, and began to introduce artificial irradiation. The development of photoculture evolved an effective process which is based on the use of irradiators with HPSLs of 600 and 1000 W. This process is applied today by an absolute majority of greenhouse facilities in Russia and around the world. Using this technology, leading domestic greenhouse enterprises like LipetskAgro, Vyborzhets, Novosibirsky, Churilovo, Teplichny and Yaroslavskyl harvest cucumber yields of (130–150) kg/m^2 every year, and Maysky GF is the greenhouse industry leader, collecting up to 180 kg/m^2, Fig. 2.

Fig. 3. Irradiator and HP specula sodium lamp *Reflux* SSL

It should be noted that the use of irradiating installations (II) with HPSLs in the GF not only raises the yield capacity, but also ensures higher levels of profitability demonstrated by GF economic indicators.

Today about 80 % of Russian GFs use effective irradiation systems based on specular *Reflux* SSL HPSLs, exclusive to Russia, Fig. 3.

Due to the design features of the*Reflux* SSL HPSL, (its reflector is a specularised part of a spe-

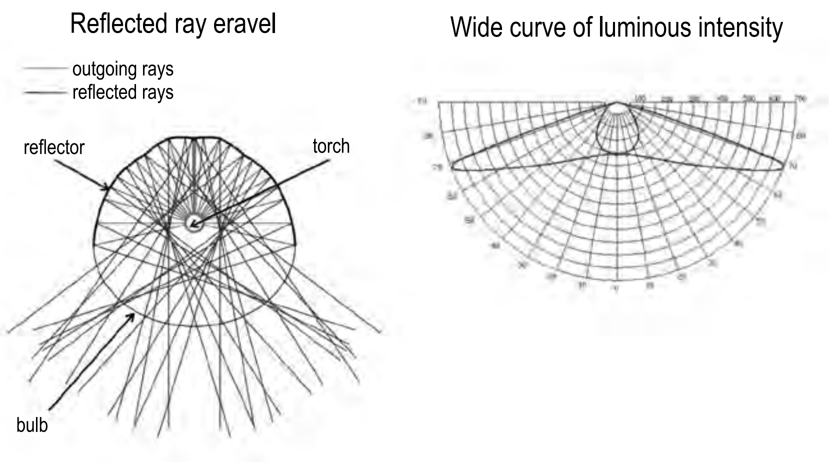

Fig. 4. Optical layout of a SSL *Reflux* lamp

cial configuration envelope on the inner surface) these lamps of identical rated capacity generate a higher irradiance compared with normal HPSLs. The envelope is designed in such a way that reflected rays do not reflect back onto the torch. This provides a high efficiency (more than 95 %), a stable luminous efficacy and a long lifetime of the *Reflux* SSL HPSLs, Fig. 4.

Specular HPSLs have a wide luminous intensity distribution curve (LIDC) in the transverse plane, Fig. 4, which makes the irradiation uniform and extensive. This type of irradiation facilitates a strong plant growth and development. This is especially important for tall plants, such as cucumbers and tomatoes, because as the plant grows the effective penetration of vertical radiation abruptly decreases as each lower leaf receives five times less radiation than the upper leaves. Taking into consideration the direction of growth and leaf structure, most effective type of irradiation for these plants combines vertically directed upper radiation and lateral penetrating into the growing plant uniformly and deeply. Specular HPSLs with a wide luminous intensity curve in the transverse plane, installed above the spaces between each row, create rays, which fall not only from the top but also laterally onto the external surface of a leaf at an angle close to 90º, whilst not overheating the plants. In this case, extra lamps in the spaces between the rows are not needed, Fig. 5.

The inner surface of the lamp is itself a reflector in a vacuum and loses none of its properties, avoiding oxidation and dust pollution, which can decrease the luminous flux. The deposition material for the *Reflux/Ag 600W/400V* lamps is made of fine silver with the highest reflection factor of 99.9.

Fig. 5. *Reflux* SSL lamps in a greenhouse

Additional benefits of *Reflux* HPSLs arise from the use of electron ballasts with at least 96 % efficiency.

Greenhouse installations use highly efficient irradiators enabling high yield and profitability. Irradiators in use today have electron ballasts and (mainly specular) HPSLs with passive optical systems. They have a luminous efficacy of up to 150 lm/W, radiation efficiency factor (Φ_{PPF}/P_W) equal to 2 µmol/s·W and a lifetime of over 20,000 h.

However, technologies continue to change and evolve, and today there is an active search for new

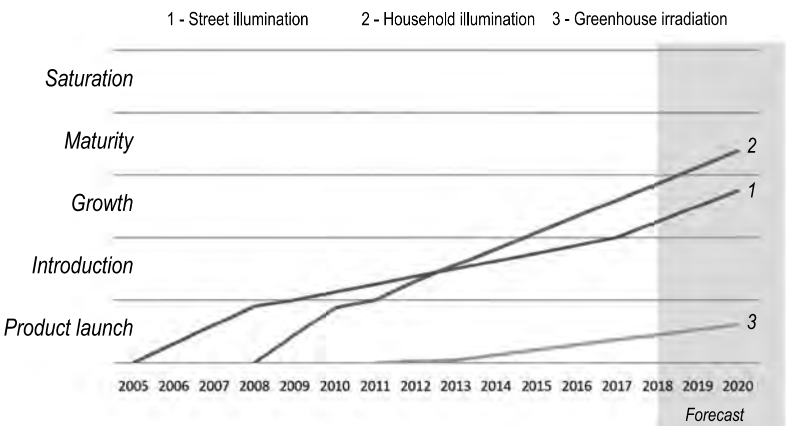

Fig. 6. Stages of light emitting diodes introduction by directions

Fig. 7. LED irradiators for plant cultivation

effective radiation sources (RSs) on the greenhouse irradiation market. LED RSs are competitors in this race for improved methods.

The introduction of LED light sources is an iterative process, which involves promoting them on the market, whilst simultaneously improving their performance and driving down their cost. Logically, those market segments where LEDs can bring the greatest economies are first to respond to these new technologies.

According to the theory of product service life, market capture occurs in six steps: introduction to the market, implantation, growth, maturity, saturation and decay, Fig. 6.

Fig. 6 shows that the development of LED RS in the three applications mentioned above is at different stages; this largely depends on the competitiveness of traditional RSs forced out by LED RSs. The replacement process is most successful where energy inefficient RSs are replaced: incandescent lamps in household illumination or mercury arc lamps (MAL) in street illumination. However, in the greenhouse irradiation space, where massive radiation is required, LED RSs have a very strong competitor in HPSLs, which lose slightly to LED RSs by their performance features, but are significantly cheaper.

Currently, in the sphere of greenhouse irradiation LED RSs are at the initial stage of market introduction, which implies many experimental application projects, with a high uncertainty of success. At this stage, it is difficult to determine the likely economic benefit. The products are expensive due to their continuing modernisation and a limited scale of production. There is also a need to dramatically improve and adapt their output characteristics to the requirements of the market. These are the processes taking place today in the sphere of greenhouse irradiation.

LED manufacturers propose different types of LED irradiators, promising considerable electric energy savings, increased harvest yields, or both. Many greenhouse facilities have taken an interest in irradiation using these RSs, and experiment with their installation, so far with mixed results, Fig. 7.

Considering the tangible interest in this technology expressed in the greenhouse industry, the following section attempts to compare payback periods for artificial irradiation with traditional HPSLs and LEDs, and estimates the prospect LED RS introduction.

As there are no objective economic results of the commercial use of LED irradiators available, only approximate evaluations based on generalised expert estimates are possible.

We will consider a hypothetical case, when managers of a modern greenhouse facility decide to introduce an artificial plant irradiation system to increase the profitability of growing cucumbers during winter and spring periods.

Photoculture technology increases yield during winter periods by an average of 60 kg per 1m^2 of greenhouse area per year. With a price of 80 roubles for 1 kg, the assumed additional income for the greenhouse can be around 4800 roubles per 1m^2.

As a rule, achieving this level of yield increase needs about 200 W/m^2 of irradiance or photosynthesis photon flux density (PPFI) of about 300 µmol / m^2·s. This can be generated by irradiator type ЖСП 25 with electron ballast and complete with a lamp type *Reflux/Ag 600W/400V*. The cost of equipment per 1m^2 in this case is 2500 roubles, as one SSL RS irradiates 3m^2 area and costs 7500 roubles.

For the comparison we will take an irradiator set of the *GreenPower LED* series by Philips used for upper irradiation and for inter-row reirradiation. According to the manufacturer, the *GreenPower LED* irradiators surpass HPSL irradiators by 25 % in respect of photosynthesis photon flux (PPF). These irradiator sets would cost greenhouses about 25,000 roubles per 1m^2, based on average market prices.

If the cost of electricity for these facilities, taking into account depreciation and operational costs, is 2.5 rub/kW·h and the operating time is 4000 h per

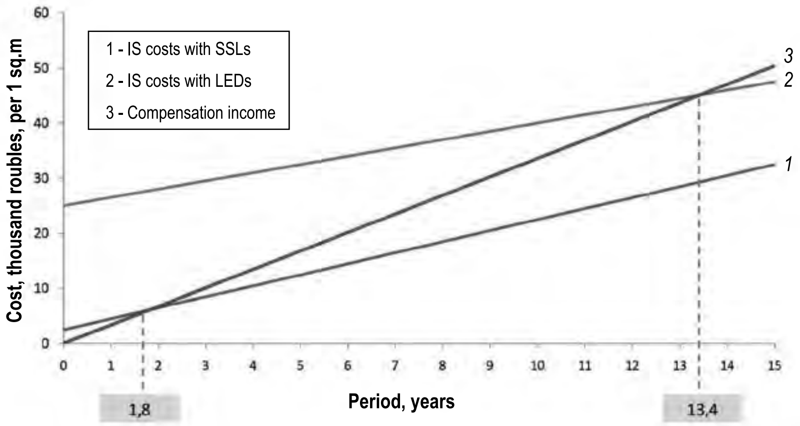

Fig. 8. An evaluation of irradiating installation pay-off period in greenhouse irradiation

year, then the annual specific cost of electricity is as follows:

- For an irradiator with *Reflux/Ag 600/400* SSL:

200 W/m^2 · 2.5 rub/kW·h · 4000 h = 2000 rub/m^2;

- For an irradiator with *Philips GreenPower LED*:

2000 rub/m^2 · 0.75 = 1500 rub/m^2.

Assuming that about 30 % of the additional income generated as a result of the introduction of photoculture covers the expenses for product cost, not related to irradiation, 70 % is the available to pay back on capital expenditure and electricity costs. This is equal to 3360 rub/m^2 per year, and represents a compensation income (I_{comp}).

Irradiation expenditure consist of capital expenditure for the purchasing of equipment and of electricity costs. In this calculation, SSL replacement and the decrease of radiation flux of LED irradiators, as well as assembly cost and expendable material cost for light point installation are not accounted for as they are approximately identical in both cases.

The pay back period of the project finishes when capital and operational costs for the adoption of artificial irradiation in a greenhouse are covered by an additional (compensation) income I_{comp} accumulated for a certain period:

$$C + E \cdot T_{pay\text{-}off} = I_{comp} \cdot T_{pay\text{-}off},$$

where C is equipment capital expenditure; E is annual electricity costs; $T_{pay\text{-}off}$ is pay-off period, years.

It follows here from:

$$T_{pay\text{-}off} = C/(I_{comp} - E), \quad (1)$$

and incorporating C, I_{comp} and E values from the above, the results are:

- For *Reflux/Ag 600/400* SSL irradiators;

$T_{pay\text{-}off}$ = 2500 rub / (3,360 rub/year – 2000 rub/year) = 1.8 years;

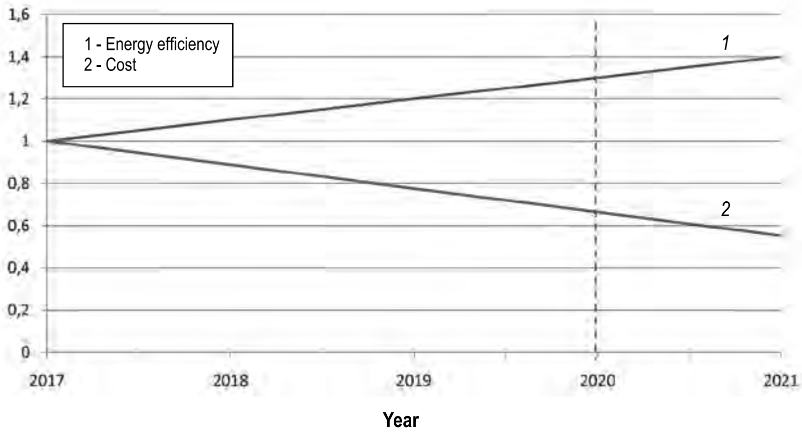

Fig. 9. An evaluation of relative dynamics of LED irradiating installation indicator change in greenhouse irradiation

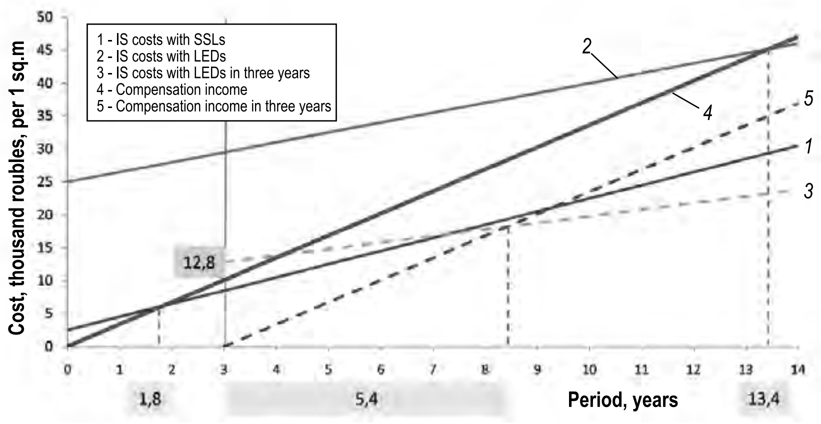

Fig. 10. An evaluation of irradiating installation payback periods in greenhouse irradiation, accounting for LED parameter change

- For *Philips GreenPower LED* irradiators

$T_{pay\text{-}off}$ = 25,000 rub/(3360 rub/year – 1500 rub/year) = 13.4 years.

Clearly, such a drastic difference in $T_{pay\text{-}off}$, Fig. 8, restricts the transition to LED irradiators for greenhouse facilities.

Nevertheless, LEDs for greenhouse irradiation are being developed, and in the years to come a considerable decrease in their cost can be expected, together with further gains in their efficiency, further reducing the annual electricity consumption and number of LED irradiators.

Taking Fig. 9 as the base assumption for cost reduction and efficiency gains, LED irradiator prices will fall by 1.5 times in three years, and their energy efficiency will increase by 1.3 times: based on preliminary estimates, this will allow saving up to 30 % on electricity costs (in this case it will cost about 1000 roubles per 1m^2).

Taking into account the projected improvement in LED characteristics, a new capital expenditure level can be estimated using the following formula:

$$C_{new} = C_{base} /(1.5 \cdot 1.3),$$

where C_{new} is capital expenditure in the context of improved LED parameters (in three years); C_{base} is capital expenditure today.

According to this expression, and to the values given above, C_{new} = 25,000 rub / (1.5 · 1.3) = 12,820 rub.

Therefore, the capital expenditure for LED irradiation will decrease almost twice in three years, Fig. 10.

Using these data, a new payback period $T_{pay\text{-}off\text{-}n}$ can be estimated taking into account the improved LED parameters with a formula similar to formula (1):

$$T_{pay\text{-}off\text{-}n} = C_{new} / (I_{comp} – E_{new}),$$

where E_{new} is electric energy cost a year taking into account improved LED parameters (in three years):

$T_{pay\text{-}off\text{-}n}$ = 12,800 rub / (3,360 rub/year-1000 rub/year) = 5.4 years.

It can be seen from Fig. 10 that LED irradiation equipment installed in three years' time will pay off twice as quickly, as and much earlier than any equipment bought and installed today.

Anyone in a big hurry to install now will lose out in the long term due to large investments and a long pay back period; they will miss out on the gains which will become available three or five years later. By waiting, it will be possible not only to pay off the LED irradiation source (IS) but also to generate profit once the LED IS pay back is reduced.

At present, the large-scale introduction of LED irradiators into greenhouse facilities implies unreasonable economic risks. But to become a pioneer in this industry requires the gradual introduction of these irradiators experimentally. In this case, the LED equipment manufacturer should take on all of the financial risk and compensate any incurred costs. If as a result an increased yield capacity is obtained and the economic benefit is obvious, then in due course the uptake of LED irradiators will increase.

In the case of a positive outcome, LED manufacturers will be interested in expanding their market outlet as much as possible. The greenhouse facilities participating in the experimental installation will gain a small increase in yield with great risks and labour expenditures, whilst their competitors will benefit from maintaining approved technology without additional costs and efforts. During this experimental phase, new LED irradiator models will appear, which will be twice as efficient and significantly cheaper. The competitors will install these models having avoided costs previously, and will reap the benefits over those who were first to market in their increased yields and energy efficiency, Fig. 10.

Financing such volatile market experiments can only be undertaken by large-scale LED equipment manufacturers, or by state investors ready to promote these products and to invest long term into the introduction of LEDs into greenhouse irradiation.

CONCLUSION

- The process of introducing light emitting diodes into greenhouse irradiation is significantly restricted by proven technologies, like HPSL irradiators with highly effective *Reflux/Ag* SSLs, the technological parameters of which are similar to LED irradiators, but their cost is ten times lower. A comparative evaluation of pay back periods gives evidence against LED ISs.
- With the present LED irradiator prices and performance characteristics, HPSL irradiator replacement with LED ISs is premature. Additional inter-row irradiation (reirradiation) options with upper radiation remaining as HPSL, for example for tomatoes, can be an option. However, this raises the capital expenditure without guaranteeing an tangible increase in harvest. LEDs can also be used to grow herbs, salads and other plants with a short vegetation period, as well as different types of seedlings using rack cultivation.
- LED irradiators have strong prospects in terms of their future efficiency and lifetime. But in order to become competitive in the greenhouse market, their profitability through reduced electricity costs must increase further, and their price must fall. Their technologies must be developed and approved. Intensive work is currently under way to achieve this, which allows predicting that significant gains will be made in the next three or five years. Until then, the commercial introduction of LEDs into greenhouse irradiation is a gamble, when business profits are at stake, and probability of success is not more than 10 %.

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Fig. 1. Winter greenhouse using artificial irradiation systems (Maysky greenhouse facility, Kazan)

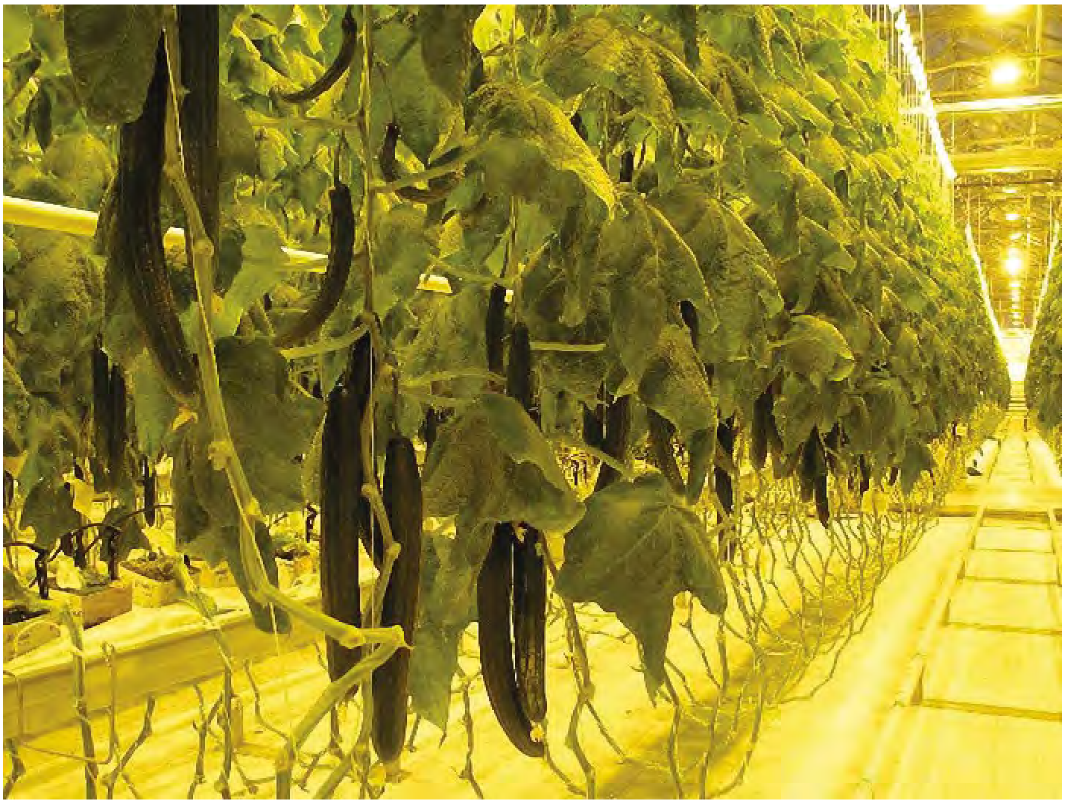

Fig. 2. Cucumber photoculture

Fig. 5. *Reflux* SSL lamps in a greenhouse

Fig. 7. LED irradiators for plant cultivation