

# COST EFFECTIVENESS OF GROWING PLANT LIGHTING SYSTEM

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**Abstract:** Since plants are biologically-based and since controlled environment plant production demands significant electrical-energy inputs, the paper propose an economic comparative analysis on four growing plant lighting systems (fluorescent, metal halides, high pressure sodium and LED), in order to determine the most efficient type of lamp that can be used in a specific crop or greenhouse. As every investment in crop production has the implicit aim to reduce the electrical-power load required for plant production and to harvest as much, the analysis took into account the cost components. There were not taken into account the expenditures of heating plants in winter. There is demonstrated that the best long term investment is in LED lighting system, as predictable. Further, this study was conducted in accordance with all European norms and sustainable strategies.

**Key words:** Growing lamp, efficiency, lighting system, costs.

## 1. Introduction

In recent years, in economic developed countries appeared a new concept regarding farming; that is "precision agriculture". That comprises a set of technologies combining sensors, information systems, enhanced machinery, and informed management to optimize production by accounting for variability and uncertainties within agricultural systems [1]. The incorporation of technology in farming techniques requires effective equipment that could lead to increased profitability overall. ESA Talking Fields Demonstration Study from 2009 shows that traditional farming techniques do not always make an efficient utilization of resources, which eventually leads to an unnecessary increase of production costs, so it is implied that precision agriculture is related to cost savings.

As the most ascensive form of vegetal production, greenhouse structures are of great importance in supporting industry of agriculture. New greenhouse technologies contribute constantly to increasing the production per cultivated unit area firstly by the optimization of greenhouse structures and coverings for better light transmissivity [2].

In winter plant growth in greenhouses is strongly limited by the amount of solar radiation. This leads to long propagation periods and high energy demand for greenhouse heating. Since mechanical cooling is expensive, both in terms of investments and running costs, the typical modern greenhouses have a large air exchange rate with the environment [3].

The use of artificial light can improve the growth

rate considerably but causes high consumption of electric energy. In literature, there are simulation models that describe the interactions between greenhouse crop processes (photosynthesis and transpiration) and indoor and outdoor climate, accounting for the effects of greenhouse structure: utilities, cover materials, light, outside weather conditions, and action of controllers [4], such as KASPRO [5], SERRISTE [6], HORTEX [7] or GTa-Tools [8]. The comparison of the energy demands for seedling production, resulted from this models above, shows that a reduction of energy input is possible, with no quantitative effect on harvesting.

Grow lamps are effective, energy-saving, reliable, low heat generating, with lower operating costs for all indoor growers. Their artificial light can be used in three different ways:

- To provide all the light a plant needs to grow.
- To supplement sunlight, especially in winter months when daylight hours are short.
- To increase the length of the "day" in order to trigger specific growth and flowering.

The optimum growing light system must be ecofriendly and must supply only the colors of light used by plants for healthy growth. Table 1 shows a comparison of different light sources [9], [10] suited for growing light.

Table 1  
Characteristics of Common Light Sources

Light source	Efficiency (Lumens/Watt)	Average Lamp (Life)	Color Rendering Index (CRI)	Approx. ratio of radiant fluxes in three PAR ranges, %
Standard Incandescent	5-20	750-1000	100	14
Tungsten Halogen	15-25	2000-4000	100	-
Compact Fluorescent	20-55	10000	80	7
Mercury Vapour	25-50	Up to 24000	15-30	26
Metal Halide	45-100	10000-20000	60-90	39
High Pressure Sodium	45-110	Up to 24000	9-70	35
LED	25-60	50000-100000	70-95	-

A number of issues determine the efficiency of a lighting system [11]. They include:

- The fraction of the light used by plants
- Heat generated by the bulbs
- Heat generated by ballasts
- Service and maintenance costs.

## 2. Grow lights

Investigating the effects of light intensity (irradiance) and temperature on the rate of carbon assimilation of the plants, it results:

- At constant temperature, the rate of carbon assimilation varies with irradiance, initially increasing as the irradiance increases. However at higher irradiance this relationship no longer holds and the rate of carbon assimilation reaches a plateau.
- At constant irradiance, the rate of carbon assimilation increases as the temperature is increased over a limited range. This effect is only seen at high irradiance levels. At low irradiance, increasing the temperature has little influence on the rate of carbon assimilation.

The plant's absorption spectrum is the spectrum of radiant energy whose intensity at each wavelength is a measure of the amount of energy at that wavelength that has passed through a selectively absorbing substance [12]. The similarity of the action spectrum of photosynthesis and the absorption spectrum of chlorophyll emphasizes the most important wavelengths in the process (Fig. 1). Chlorophyll a, the most common and predominant in all plants gives the blue-green pigment. Chlorophyll b functions as a light harvesting pigment (yellow-green) that pass on the light excitation to chlorophyll a. Only the light absorbed by the leaf can be used for photosynthesis. Transmitted or reflected light will not be used. The spectrum of light absorbed is typically measured using a spectroradiometer and an integrating sphere. Plants convert light into chemical energy with a maximum photosynthetic efficiency of approximately 6%.

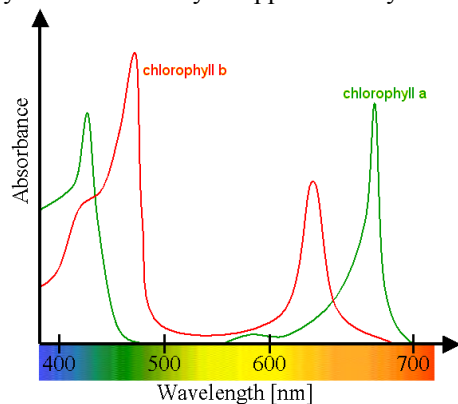


Fig. 1. Absorbance spectra of free chlorophyll a (green) and b (red) [13]

Plants need both red and blue light for photosynthesis. Red light is very important to plant reproduction and is essential for stimulation of flowering and fruiting. Blue light stimulates chlorophyll production more than any other color. The amounts of blue light required for optimum growth can depend on the variety of plant and on the stage of growth.

Young plants like more blue light than mature plants. Orange light stimulates creation of carotenoids, which are required for plant health, but also add to photosynthesis, since the carotenoids pass their absorbed energy to chlorophyll. The green and yellow spectrums provide very little to no benefit to growing plants. Green light is not used or absorbed, which is why most foliage looks green in sunlight.

The light's wavelength is also important, as it's correlated with the color and light absorption (table 2).

Table 2  
Influences of the light's wavelength on plants

Wavelength	Characteristics
280-320nm (Ultraviolet-B)	In general the effects of UV-B are deleterious to plant growth and development
320-400nm (Ultraviolet-A)	May have an additive effect with the requirement for blue.
400-500 nm (Blue)	An absolute quantity for elongation control is required for higher plants.
500-600nm (Green)	Not necessary for photosynthesis, but contributes to photosynthesis and is a significant component of most radiation sources.
600-700nm (Red)	Optimize output for maximal photosynthesis. Monochromatic red will cause abnormal development in some species.
700-750nm (Far-red)	Enhancement of flowering, stem elongation, etc. of certain species (as a function of the red/far-red ratio) with the quantity centered around 725 nm equal to or greater than the quantity centered around 660 nm.

Plants also require both dark and light ("photo"-) periods. Therefore, lights need to be timed - to switch them on and off at set intervals after 12 hours. The optimum photo/dark period depends specifically on the species and variety of plant. The optimal lighting parameters for growing plants are: photosynthetically active radiation (PAR) and the total irradiance.

Total solar irradiance describes the radiant energy emitted by the sun over all wavelengths (fig.2), but the plants' response is based only on the daily irradiance, so they use a ratio of total irradiance to PAR [10].

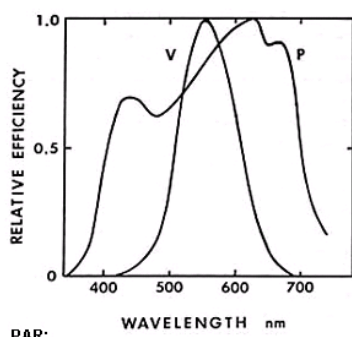


Fig. 2. PAR: V – relative luminous efficiency of equal incident radiant fluxes as function of wavelength; P – relative photosynthetic efficiency as function of wavelength of the average green leaf

### 3. Lamps for growing light

a) Incandescent grow lights (fig.3) have a red-yellowish tone and low color temperature (2700°K), an average life span of 750 hours and are less energy efficient than fluorescent or high-intensity discharge lamps, converting much of the electricity consumed into heat (rather than light).

b) Fluorescent grow lights (fig.4) are available in any desired color temperature, from 2800°K to 6000°K. This excess heat must be ventilated. Standard fluorescents produce twice as many lumens per watt of energy consumed as incandescent and have an average usable life span of up to 20,000 hours.

High Output Fluorescent/HID hybrids combine cool burning with the penetration of high intensity discharge technology. The primary advantage to these fixtures is their blend of light colors and broad even coverage.

c) High pressure sodium growing lamps (fig. 5) yield yellow lighting (2200K) and have a very poor color rendering index, that's why the plants grown under these lamps do not appear very healthy (although they usually are). They are used for the second (or reproductive) phase of the growth. Due to their high efficiency and the fact that plants grown in greenhouses get all the blue light they need naturally, these lamps are the preferred supplemental greenhouse lights. High pressure sodium lamps emit a lot of heat controlled by using special air cooled bulb reflector/enclosures.

d) The lighting efficiency of LED growing light is more than eight times that of incandescent lights, and twice as high as compact fluorescent lights. LED emits a much higher percentage of light in the desired direction (fig. 6). All of the light output from led bulbs can be a specific color. With other light sources, much of the light produced consists of unwanted colors which are filtered out. This wastes energy. Led lights produce pure color (monochromatic light) which requires no filtering [16].

Led lights also generate very little heat, so plants will transpire less under LED, extending the time between watering cycles. Led lighting instantly achieves full brightness with no warm up time. Leds do

not contain dangerous substances. Fluorescent lights contain mercury and must be treated as hazardous waste. Led lighting does not produce any ultraviolet (UV) light, so they will not cause fading and aging of artwork or other sensitive materials. Led bulbs can operate for 30,000 hours or more, are not affected by frequent on-off switching. The long life of led light bulbs reduce the time, effort and cost of replacement.

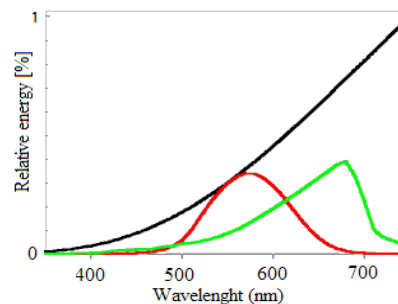


Fig. 3. Incandescent lamp performance (black curve – lumens output, the red curve is the way a human sees the light, the green, the way a plant sees it)

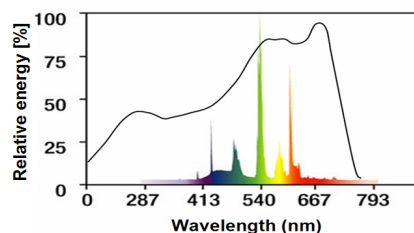


Fig. 4. Fluorescent lamp full spectrum [14]

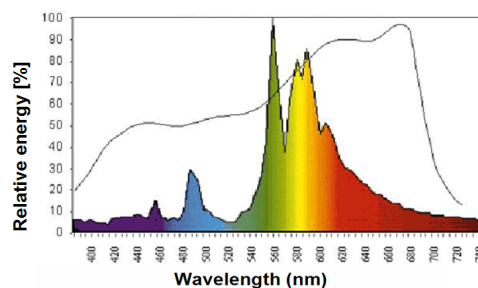


Fig. 5. HPS Spectrum shown against the plant sensitivity curve

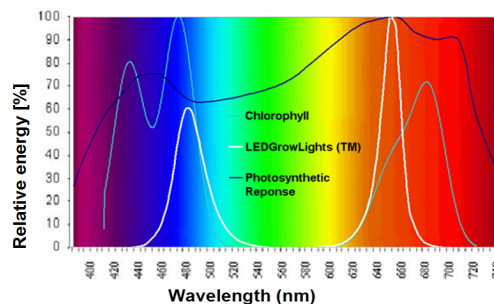


Fig. 6. LED's spectrum [15]

#### 4. The need for artificial production of vegetables in the context of the food chain evolution

The greenhouse vegetables are strongly contested by some health and nutrition organizations because they contain nitrates, nitrites and other toxic substances, being defined as outcomes of a process of "plasticulture" [17]. The disadvantage of this type of production consists only in the fact that vegetables don't have the same nutritional value (vitamins and minerals) that naturally grown vegetables, not in the fact that they could harm human health. Furthermore, economically and demographically annual statistics, all sustain the need to invest financial resources and modern technology in vegetable greenhouses to sustain the consumption level of the population. According to Eurostat, there is a major discordance between the consumption of vegetables (fig. 7) and the natural crop vegetables production (fig. 8). If we consider that [18] defines fruit and vegetables consumption as a key indicator for healthy eating in general and therefore it marks the occurrence of mal nutrition as well, the need

of greenhouses that produce continuously is right justified. Vegetable supply per capita declined by 8.3% compared to the average of the previous five years and reaches 81.2 kg in 2010 [19]. This arises due to deepening of economic crisis worldwide. But if there is taken into account the price index evolution (fig. 9), can be seen that it is not increasing overall, so the vegetables are still accessible for consumption. In countries where this indicator tends upward, one can encourage the import of vegetables. A higher availability of vegetables in one of the EU countries not cause an increase in local consumption, in the advantage of those countries where the production infrastructure is weak or where are no conditions conducive to natural or artificial agriculture. With a general trend of increasing consumption of vegetables, natural or processed, regardless of economic or climatic conditions, it is obvious that the greenhouses will have to produce more and faster, using biological and engineering techniques increasingly effective.

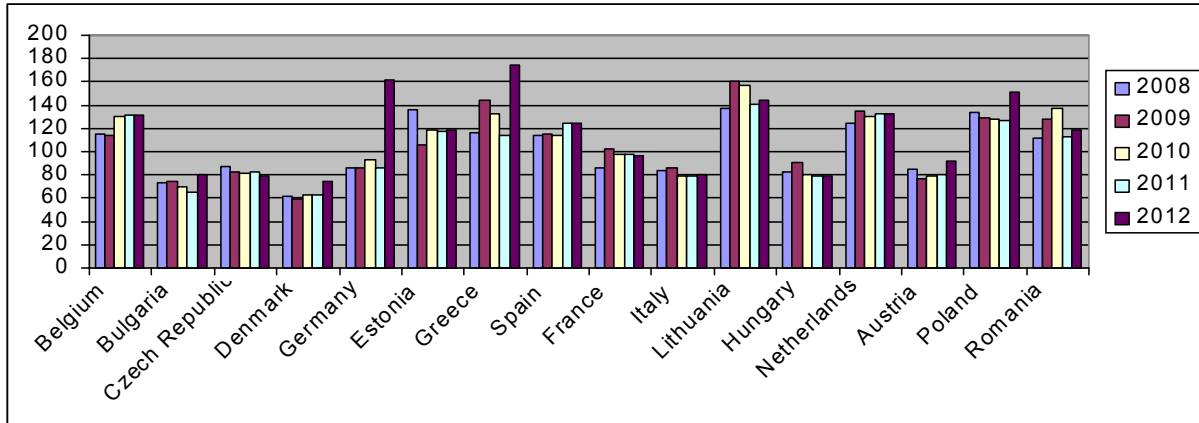


Fig. 7. Gross human apparent consumption of vegetables per capita, kg/head

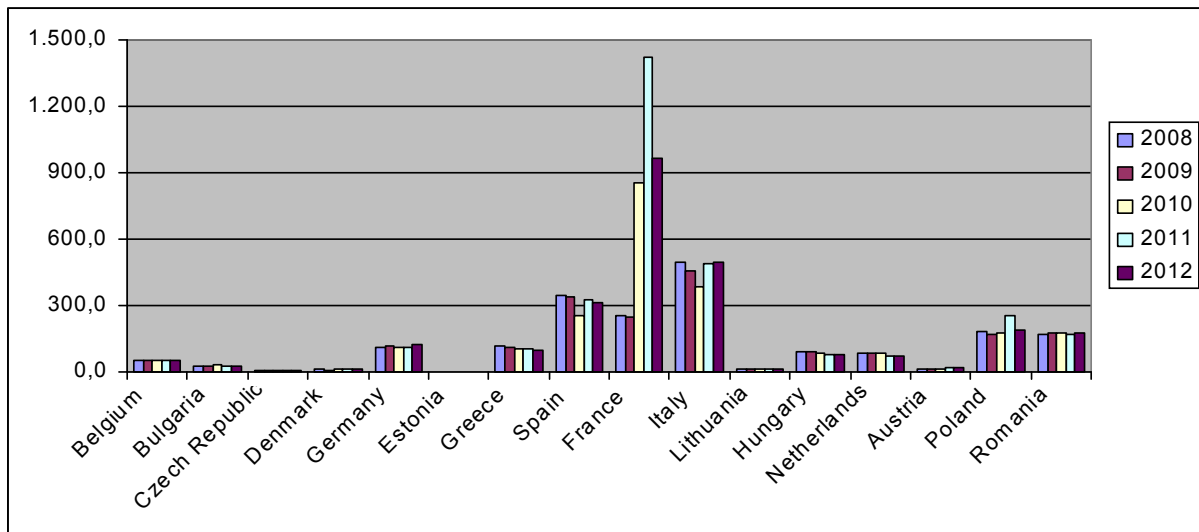


Fig.8. Natural crop vegetables production in selected countries, tones/ha

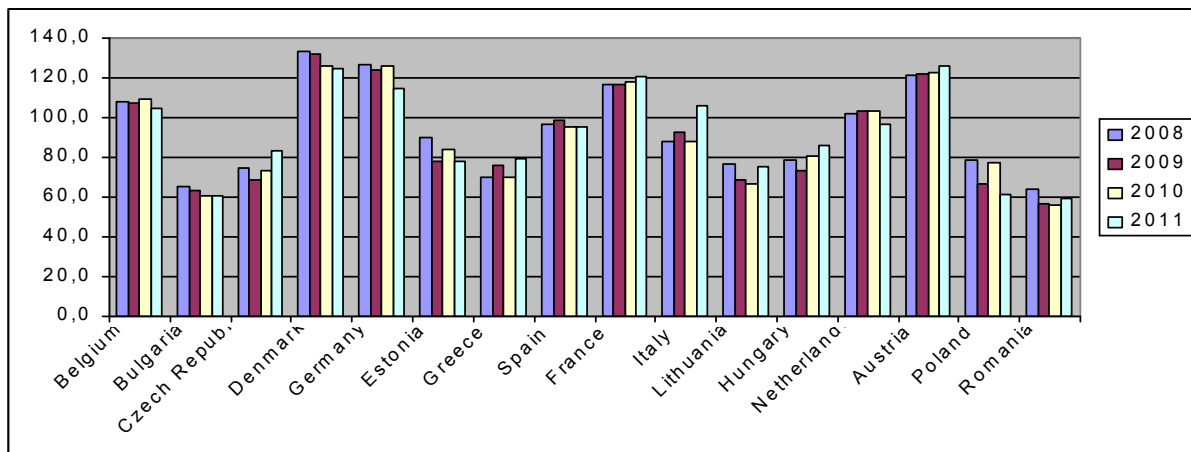


Fig. 9. Price level indices for vegetables in selected countries for the EU-27 average index value of 100

### 5. Cost effectiveness of tomatoes growing light system

Plants "see" light differently than human, as they use mostly blue and red light. Lumens, lux or footcandles should not be used to measure light for plant growth since they are measures used for human visibility. More correct measures for plants are PAR watts, PPF (Photosynthetic Photon Flux) PAR and YPF (Yield Photon Flux) PAR. In addition to quantity of light, considerations of quality are important, since plants use energy in different parts of the spectrum for critical processes.

Designing an efficient grow plants system concerns the following steps:

- determine required irradiance levels in PAR watts/square meter,
- establish the area to be illuminated in square meters,
- calculate total PAR watts required as the area x required PAR watts per square meter,
- select a lamp of appropriate wattage and calculate its PAR watt rating,
- calculate the total number of lamps (or fixtures) needed.

A local farmer produces tomatoes in growing modules of 12\*3m each. His intension is to be on the market earlier and to compete with the tomatoes importer. Taking into account the Mediterranean climate in Romania, he needs a growing light system and the problem is to choose the most efficient one at this moment. In order to simplify the modeling and the interpretation of the results, the entire greenhouse area is assumed to be planted with the same crop at the same time.

For this application were compared the lighting systems based on fluorescent, metal halides, high pressure sodium and LED. For all this light sources, the PAR factors are specified in the technical brochures. There has to be calculated the light necessary for the specified 12\*3m growing area of tomatoes, which needs 16-18 hours of light and 6 hours

of darkness daily for vegetative growth phase, and 12 hours of light combined with 12 hours of complete darkness for the fruiting and flowering phase. These plants will reach normally fruit bearing maturity in 40 days [20]. Tomatoes require large quantity of light to grow into sturdy plants, so there is necessary a high light intensity to cover all the leaves. In these conditions, a module with the area 12\*3m needs a light covering of 4430 watts.

As tomatoes require 85 PAR watts/m<sup>2</sup>, for a plot having the area of 36m<sup>2</sup> are needed 3060 PAR watts. This level can be reached with 102 LED of 10Watts/30PAR, 77 fluorescent bulbs of 23Watts/38PAR, 21 metal halide lamps of 400Watts/140PAR or 23 HPS lamps of 400Watts/130PAR, as can be seen in table 3.

The lamp's cost includes the accessories of all light sources. Because the operating time is the same for all analyzed systems, the cost of electricity was considered 0.4 \$/kWh, without taking into account tariff components and tariff differences on hourly periods. The total cost was calculated with the formula:

$$C = n \cdot P \cdot 10^{-3} \cdot h \cdot d \cdot e \quad (1)$$

where

C = energy cost [\$],

n = number of lamps of each lighting system,

P = power of one lamp [W],

h = number of lighting hours required by the tomatoes

d = days of one flowering cycle,

e = electricity price = 0.4 \$/kWh.

Results in Table 3 suggest that the most efficient system in this case is the one based on LED's light.

The fluorescent lamp's operating cost includes ancillary units' price, respectively starter and ballast. During operation the fluorescent lamp suffers badly with any effort to reduce costs by turning it off due to the fact that this function reduces the lamp life. The LED has no such reduction in life due to re-strike and thus picks up all the benefits of off-time energy and cost savings.



Table 3

Effective costs in growing application for four different lighting systems

Lighting system	No. of lamps	Watts equivalent to PAR watts	Lamp cost [\$]	Energy cost [\$]	Labor [\$]	Total cost [\$]
LEDs	102	10/30	40	244.8	45	4370
Fluorescent	77	23/38	105	425	70	8580
Metal halides	21	400/140	550	2016	90	13656
HPS	23	400/130	570	2016	240	15366

## 6. Conclusions

Vegetables' producers are more interested in growing light systems in their competition to permeate the specific market. Even this growing plant method is more expensive than the classic one and sometimes challenged as being unhealthy, using special lighting installations in greenhouses for vegetable crop has the advantage of continuity of harvesting in the current context of increased demand for food. In addition, vegetables production in greenhouses does not depend on climatic factors and could be a continuous process.

There is a variety of sources, from incandescent growing light to LEDs, but their efficiency must be compared using photosynthetically parameters (PAR), not the parameters based on the sensitivity of the human eye.

The comparative study performed on tomatoes growing module shows that for the same growth conditions, the LED lighting system is the most efficient, reducing with 51% the overall growing costs from the case of using the fluorescent lighting system. More, even if most conservative horticultural experts still promote HPS lamps, it is obvious that in terms of cost/benefit, the LED system transforms the growth process into one with 71,5% more economical.

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