Closed Loop Control Systems for Supplementary Lighting in Smart Greenhouses

Viktor Zseller, Budapest, HUNGARY — ARROW Electronics EMEA
Dr. Krisztian Samu, Budapest, HUNGARY — Budapest University of Technology

Abstract— **With the global trend of increasing urban population, there is therefore an observably growing demand for fresh, high quality, flavor and nutrition-rich food to be supplied for the consumers. The main market drivers of LED based Greenhouse, Hydroponic and Aeroponic food production are increasing production- and labor costs, challenging weather- and climatic conditions and increasing electricity prices; combined with the higher achievable profit by consistent production and premium quality products.**
While pure natural lighting is considered to be the most energy efficient for growing plants, for the increased yield, continuous production and forecast-able yield, it is often financially beneficial to apply supplementary lighting; especially during seasons with lower Daily Light Integral (DLI). Then the goods sell prices are higher and in some instances, the production was to be suppressed for this time frame due to inappropriate light conditions. This paper focuses on the estimation of DLI per-region as well as per-season in the EMEA region, the lighting requirements of a certain plant and introduces a method for calculating the peak Return on Investment (RoI) therefore of artificial lighting systems. The aim is to compare fixed Photosynthetic Photon Flux (PPF) systems with adaptive spectral- and intensity controlled solutions from a Total Cost of Ownership (TCO) point of view and briefly introduce core technologies available for the latter technical approach.

I. Introduction

Systems, where the quantitative output has no effect on the input to the control process are called open-loop control systems. In the lighting practice, this covers those installations, where the luminaires are either not dimmable at all, or are being dimmed according to a preset scheme that is pre-programmed. This covers over 99% of all the artificial lighting installed in the agriculture landscape [1]. Closed loop control systems on the other hand utilize sensory data as a feedback for a basis of actuation correction and thus reducing the error between the controlled variable and the reference value. While Carbon Dioxide (CO2), Plant Nutrition and Temperature Control systems are well established in the grower market, precise light measurement and tuning is a long standing technical challenge.
The basis for the need of these advanced irradiation capabilities roots in the nature of plants. All-around from the different species down to the minor alternations of sub-breeds; varied with the current life-cycle, growth phase and stage, plants have different lighting needs for Photosynthesis, healthy rooting, biomass increase and even for protection against infections or pesticides. Both undergoing a certain threshold and surpassing an upper limit can lead to reduced yield [2], lower quality and even to the forfeiture of an entire harvest [3] in extreme cases.

II. Lighting requirements

For the proper development of any given plant, there are two metrics of irradiation to be controlled. Photosynthetic Photon Flux Density (PPFD), measured in [uMol/m2/s] is the number of photons of the Photosynthetic Active Radiation (PAR) reaching a given surface unity.The PAR is a slice of the electromagnetic radiation that is considered to be the useful region of the visible light spectrum for stimulation of photosynthesis, meaning that any photons within this spectrum that are absorbed by the plant might contribute to photosynthesis. PPFD is the timid differential of this energy, yielding the flux to a surface area.
While too low PPFD is generally not an issue - as plants have always experienced this during their evolutionary life-cycle within nighttimes, over-lighting (the term generally used for providing an extreme amount of lighting for a brief period of time) leads to tissue damage, mostly observable as leaf yellowness and tip-burn [2].
The other approach for the control of growth is the integration of the PPFD on a reasonable time frame. This is known as the Daily Light Integral (DLI), measured in [Mol/m2 day], that describes the number of photosynthetically active photons that are delivered to a specific area over a 24-hour period.
The DLI has a significant impact on a number of plant variables, including rooting, stem thickness, plant height, branching and flowering. **Figure** 1 shows the effect of different average cultivation DLI levels on yield for butterhead lettuce [4]. It can be seen that with higher Daily Light Integral, the Shoot Dry Mass was higher, as described in Both et als experiments.
Figure 2 describes a linear correlation between DLI and yield on the range of about 300 [mol/m2] to 820 [mol/m2] which means with high confidence that for this specific breed, under similar circumstances, the following equation describes the total Shoot Dry Mass:

$$DM = -1.886 + \alpha \tag{1}$$

$$R^2 = 0.87 \tag{2}$$

This linear fitted curve might induce that more light will always increase production for butterhead lettuce. Obviously though, production can not be increased infinitely in a given surface area.
Even with fine tuned environmental conditions, the excess

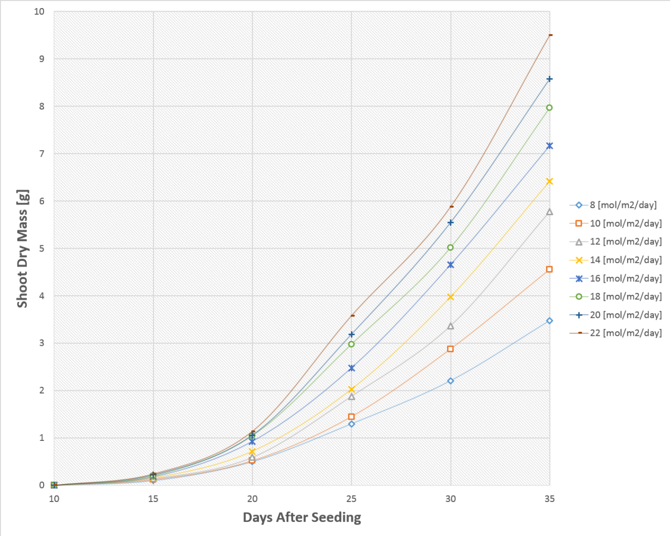

Fig. 1. Fitted growth curves for butterhead lettuce (cultivar Ostinata) based on the daily integrated light level maintained during the production cycle (35 days)

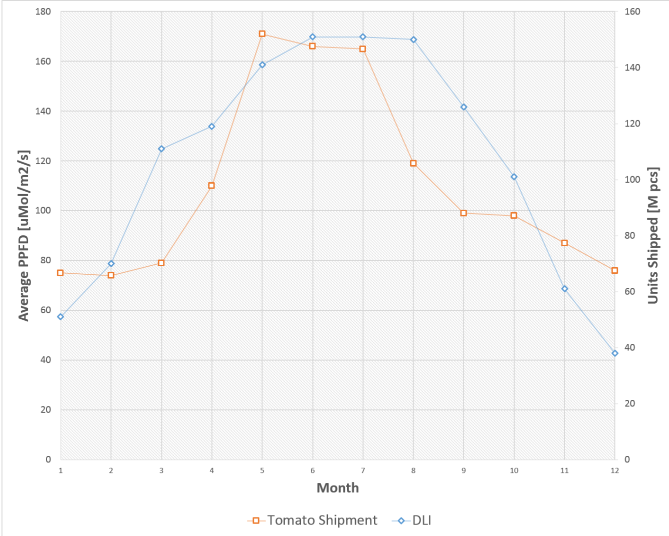

Fig. 3. Regional Tomato shipment and average solar PPFD

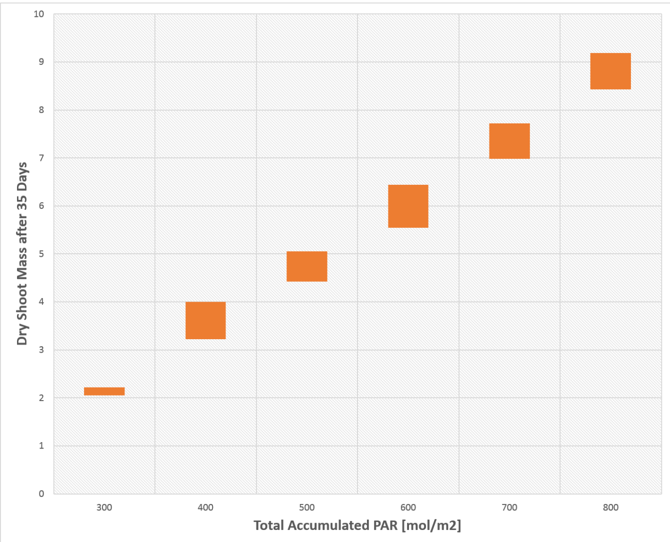

Fig. 2. Shoot Dry Mass as a function of Total Accumulated Light levels (since seeding)

PAR lighting reaches a saturation in Photosynthesis. The butterhead lettuce example to be continued, Daily Light Requirement can be divided into four morphological phases of development, as shown in [5].
For a practical explanation of the effect of DLI on yield, **Figure** 3 shows the average daily PPFD of a specific region and the corresponding Tomato shipments.

A. Seedlings

During the seeding phase, about 50 [uMol/m2/s] irradiance in a 24 [hr/day] photoperiodism is usual in Hydroponic greenhouse production, as introduced in [5]. This results a DLI of about 5 [Mol/day]. Seedlings can be successfully cultivated under either low-level natural light or even artificial light only. Very shortly after the seedlings are germinated, and even before the first true leaf is visible, the plant starts responding to environmental light levels. If the seedling is not getting enough light, the cells in the plant stem will elongate, pushing the cotyledons and the first leaf upwards, to seek more light. As a result, a thin-stemmed, weak plant is produced. If the plant survives, the stem will never thicken to equal the normal size at the base of the plant [6]. However, if there is enough light for the young seedlings while the first true leaf is developing and is about to expand, the base of the stem will remain compact and the cotyledons will not rise to an excessive height. Seedlings are typically germinated on 10” by 20” or similar sized trays (seedbeds) per 200 [pcs] of seedlings - or in similar densities - in production environments. In order to provide optimized cultivation conditions, the plants are to be morphologically controlled by artificial lighting in this first phase of the generative cycle for optimum yield and plant quality.

B. Nursery operations

Continuing the planting, from the first day after seedling to about the 10th day, a minimum of 200 [uMol/m2/s] to an average of 250 [uMol/m2/s] is to be provided, again, in a 24 [hr/day] photoperiodism. The DLI can reasonably be pushed all the way up to 30 [Mol/day] or even higher for some breeds. This 30 [Mol/day] setup means a continuous 350 [uMol/m2/s] irradiance throughout the entire day. This is only possible with the application of artificial lighting. Controlling both the minimum and the maximum of the irradiance are both important for proper generative phase. In practice, usually, the same seedbeds are being used before the first re-potting after the 10th day. Hence, the density is still about 1000 plants per m2. Over-lighting the plants prohibits a race amongst the plants and one will develop to the harm of an other; while plants will distort due to rapid development that is not beneficial for further growth phases and overall yield. Excess over-lighting also causes leaf damage [7].

C. First re-potting and Phytochrome photoperiodism

As the seedbeds are physically saturated, there is a need to re-pot the plants. This usually happens in 2 phases for space utilization. In the first stage, density is decreased to about 80 plants per m2. This gives more space to grow independently, while also enables proper light utilization. This is often referred to as lighting task efficiency. Photoperiodism decreases to 20 [hr/day]. There are several papers to claim that a 'resting period' is necessary at this stage of growth. DLI is between 15 to 17 [Mol/day]. With the period introduced, there is an additional term to be considered for the transition of day and night cycles.
Phytochrome is a plant pigment protein that absorbs red light and then initiates physiological responses governing light sensitive processes such as germination, growth and flowering. This exists in two forms, pr and pfr, that are interconverted by light. A plant pigment that exists between two forms, phytochrome 660 and phytochrome 725. They switch between one or the other depending on what time of the day it is, daytime or night time [8]. The practical application of this is the simulation of nighttime transition with Photo Red and Far Red LEDs selective dimming. This function can lead to increased yield with many plant types [9].

D. Second re-potting

The second re-potting happens for the same reason as the first, on about day 20 from seedling. Economically, it is not beneficial in the EMEA region to further tear down the utilization with finer steps, as this process also has substantial resource requirements. DLI should be kept around 15 to 17 [Mol/day] with the same 20 [hr/day] photoperiodism. Using (or abusing) Phytochrome reactions is also beneficial hereby [9].

E. General rules

As shown, both a minimum and a maximum of both the irradiance and the DLI can be defined for the different growth stages for leafy greens. The definition of the values shall be based on growing efficacy; considering the resource requirement of a given setup compared to the yield and the product quality. **Figure** 4 shows the light response curve of Photosynthesis for A. longicaulis, a typical shade-tolerant plant [9]. This is a great example of a saturation point. Up until a certain level, more light results higher Net Photosynthetic Rate in a linear correlation and thus higher net yield.

III. Natural DLI in Greenhouses

As in every single functional artificial lighting scenario, energy consumption and Return on Investment is a key factor when considering the installation of a set of luminaries. The key goal of greenhouse supplementary lighting is to provide sufficient PPFD for a growing task. This can be covered either fully from natural daylight or with the help of light

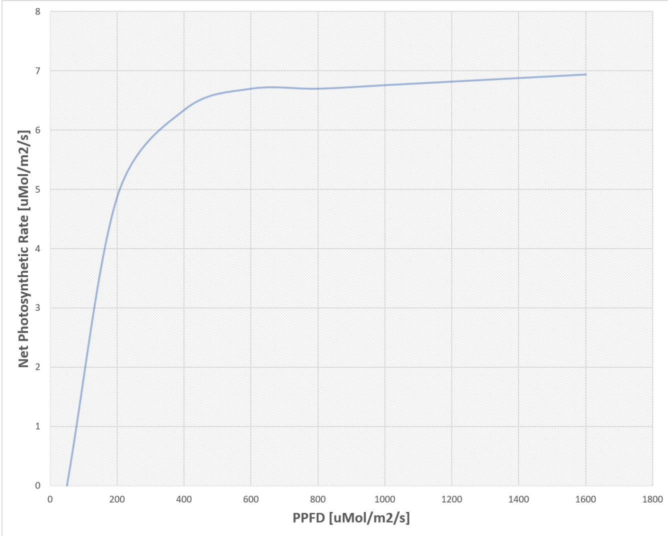

Fig. 4. Light response curves of net assimilation rate for A. longicaulis plants

sources. When there is plenty of natural sunlight, as shown in the previous section, it is not always rational to turn on this extra source of PPF as the excess electrical consumption will not be paid off of the additional yield achieved.
Figure 5 shows the DLI requirement for butterhead lettuce (generative) and the Average Natural DLI Availability in a specific European greenhouse. It is very important for a reliable lighting design to consider geographic location based natural PPFD for a Year span. This is a key enabler for an accurately planned cost analysis of a lighting project; in order to estimate Yield increase, productivity time-frame enhancement and Total Cost of Ownership (TCO).

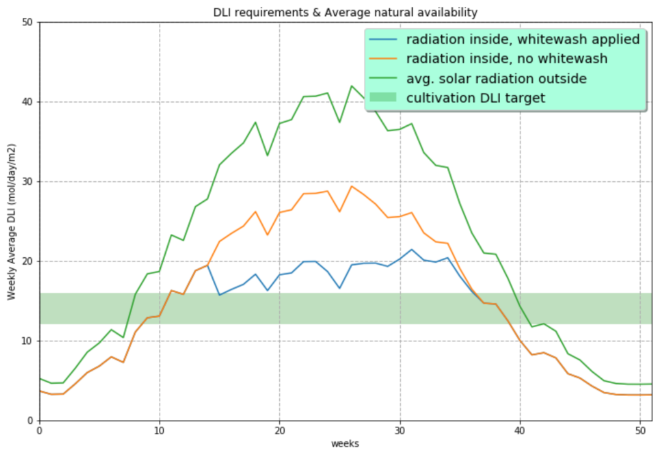

Fig. 5. DLI requirement for butterhead lettuce (generative) and Average natural DLI availability in an European greenhouse

Figure 5 highlights the region specific DLI throughout the Year. This however, is not equal at all with the DLI inside the construction. For some part of the Year, there is only a loss on the semi-transparent, slightly diffuse walls. From Calendar Week (CW) 14 though, there is a whitewash applied

to the shell of the building. The main purpose is to reflect unnecessary light and heat during the months with extreme natural irradiation. This normally wears off around CW 35 to 40, when the average solar radiation falls below the critical level for cultivation.
Figure 6 indicates the same overhead analysis for seedlings. In this case, neither the additional heat, nor the additional daylight are to be limited and thus, no whitewash is applied. In this era, the recommended DLI was designed for 21.6 [Mol/day] and the minimum to 17.3 [Mol/day] in this specific case. Photoperiod was set to 24 [hr/day]. This setup is capable of a production of 110 plants per m2 per day.

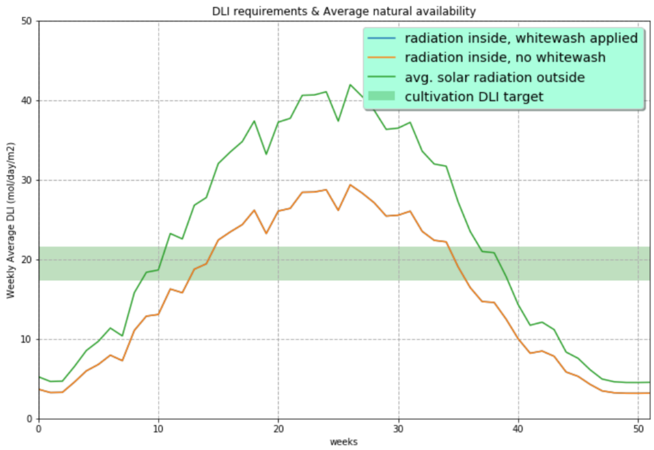

Fig. 6. DLI requirement for butterhead lettuce (seedling) and Average natural DLI availability in an European greenhouse

In this case, for this region, the supplementary lighting has to provide 174 [UMol/m2/s] at its peak power for reaching the minimum production PPFD target statistically in at least 70% of the days with 95% confidence. **Figure** 7 shows us the necessary supplementary lighting level throughout the Year, aiming for a solution, where the minimum DLI is reached at maximum power and this PPF is used as long as it will cover the maximum of the cultivation DLI target. After that level, the value fills only the gap to the maximum and never more.

IV. Growing Strategy

As shown, the rationality of artificial lighting is always dependent of several key factors. The main points for TCO analysis to be considered are:

- Natural Solar DLI in the Greenhouse
- Cultivation DLI target
- Sales price of the product
- Sales price of the product when Natural Solar DLI does not cover the cultivation DLI requirements
- Electricity cost
- Cost of the lighting installation
- Maintenance costs

While lower maintenance cost and savings on electricity are obvious aspects of profit, quantifying the additional revenue on the extra sales when the product can be sold

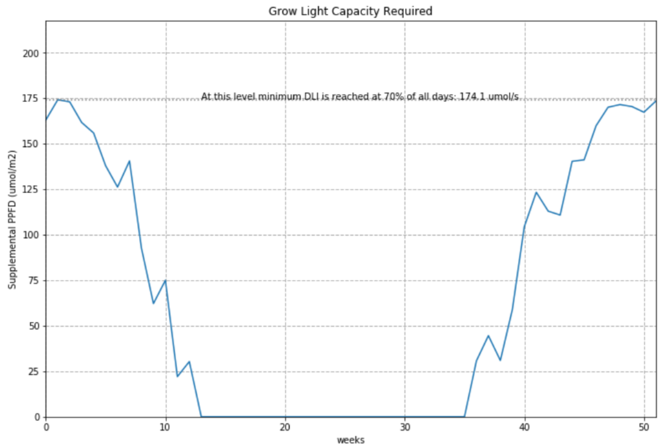

Fig. 7. PPDF Grow light capacity requirement for meeting growth targets

at a higher price is not always easily forecast-able. **Figure** 8 shows the correlation of average sales price with natural DLI for Tomato in a South European territory. This is very much plant dependent, and can be a good indication of the profitability of a supplementary lighting investment.

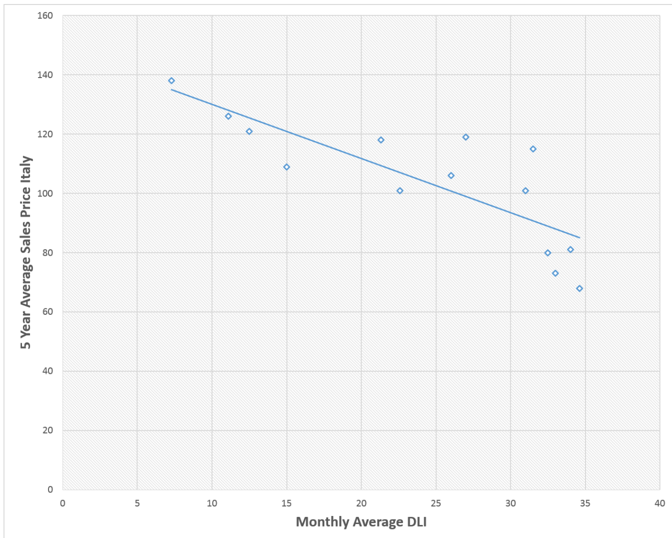

Fig. 8. Average sales price to Solar DLI

Continuing the example with butterhead lettuce, **Figure** 9 shows the dimming levels of an intelligent growing system, where the PPF of the fixtures is controlled in order to meet the cultivation target as introduced before.

In this setup, the luminaires have 4096 [hr] annual ontime of which in 1018 [hr] are operating at full power and for the remaining time are dimmed to a desired level. **Figure** 10 shows the operational time accumulation over a Year for such a fixture (left) and the additional PAR photons compared to the Solar PAR.

A. *Production analysis*

Another way to instantiate the Yield increase is plotting the production time through each CW of the Year; with and

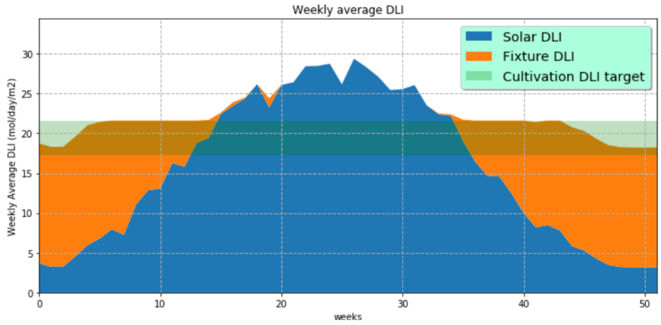

Fig. 9. Supplementary PPFD with intelligent Greenhouse lighting

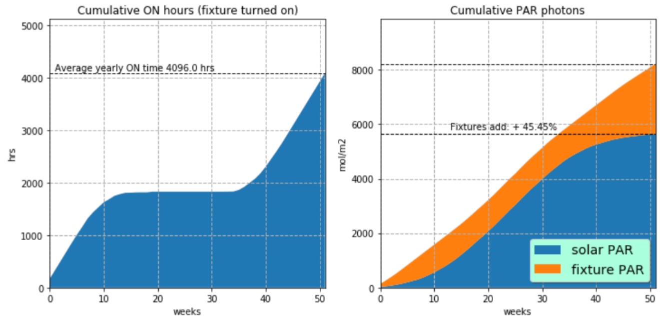

Fig. 10. Supplementary light accumulation and PAR Photon comparison

without artificial lighting and comparing results considering electricity costs for each period. In some cases, it is worthy to go for the saturation point of irradiance, in some cases it will not cover the cost of the photon production. **Figure** 11 shows the unit production time of a lettuce production facility per plant on average. Optimal cycle is 25 days from seeding, with respect to processing and quality. In this specific case, revenue was maximized by letting the production time per unit to be increased to 32 days during darker periods of the Year. This also includes reduced workforce labor costs.

Figure 12 introduces the extra expected yield per growing area for this case study.

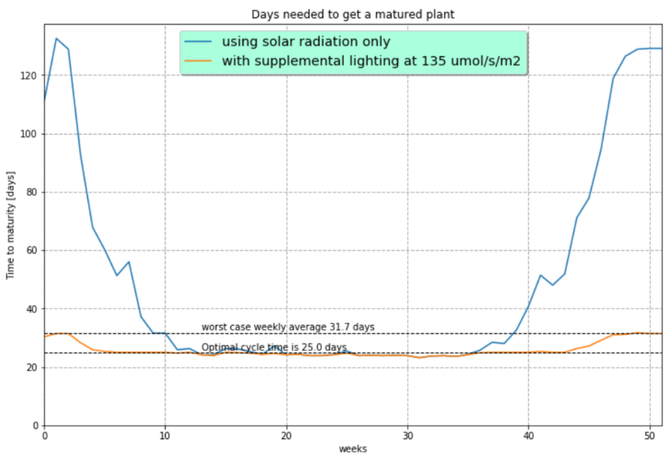

Fig. 11. Supplementary light accumulation and PAR Photon comparison

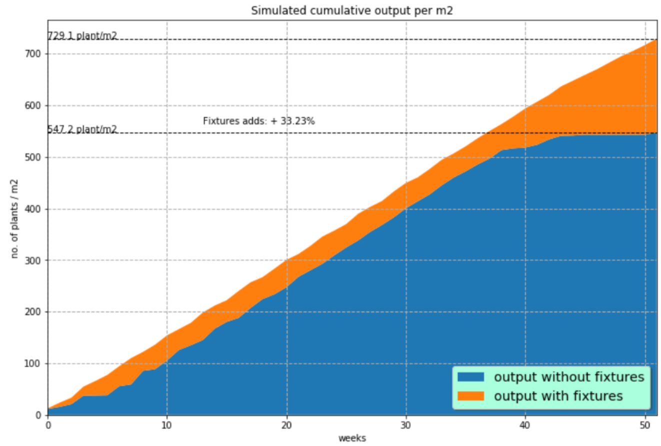

Fig. 12. Supplementary light accumulation and PAR Photon comparison

V. CONCLUSIONS

There was a trend for long in Agriculture of establishing automatic systems that have been doing repetitive processes with less and less involvement of human operators. The next step of such infrastructures will be smart systems with programed decision making algorithms maximizing profit for growers. This inevitably leads to artificial intelligences controlling artificial lighting, planting, watering, gas controlling systems for modern food production.

As for the current state of the art; it is possible to accurately measure PPFD and spectral distribution of the incoming light at task planes that opens the way to event driven, closed loop light control in machine-supervised growing environments.

It was shown that these systems have several increased benefits over conventional systems, including maximizing RoI and Production while optimizing costs and controlling quality.

REFERENCES

[1] marketsandmarkets.com, Grow Light Market by Technology (HID, Fluorescent, LED, Induction, and Plasma), Type of Installation (New and Retrofit), Application (Indoor Farming, Commercial Greenhouse, Vertical Farming, Research), and Geography - Global Forecast to 2022, March, 2017, SE 4140

[2] A. Brazaityt, A. Viril, G. Samuolien, J. Jankauskien, S. Sakalauskien, R. Sirtautas, A. Novikovas, L. Dabainskas, V. Vatakait, J. Miliauskien, P. Duchovskis, Light quality: growth and nutritional value of microgreens under indoor and greenhouse conditions. 10.17660/ActaHortic.2016.1134.37, ISHS Acta Horticulturae 1134: VIII International Symposium on Light in Horticulture

[3] Andrea J. Buonassisi, M.Sc, P. Ag, Consulting Plant Pathologist 1762 Taralawn Court, Burnaby, BC, V5B 3H5, Biosecurity Guidelines for Post-harvest Greenhouse Tomatoes: Prevention of Post-harvest and Storage Rot. B.C. Ministry of Agriculture.

[4] A.J. Both, TEN YEARS OF HYDROPONIC LETTUCE RESEARCH, Rutgers, The State University of New Jersey.

[5] Dr. Melissa Brechner, Dr. A.J. Both, CEA Staff, Hydroponic Lettuce Handbook, Cornell Controlled Environment Agriculture, http://www.cornellcea.com/attachments/Cornell CEA Lettuce Handbook.pdf, referenced: 2018.05.04

[6] James W. Brown, Light in the Greenhouse: How Much is Enough?, https://www.hort.vt.edu/ghvegetables/documents/GH_Lighting /Light_in_the_Greenhouse_JBrown.pdf, referenced: 2018.05.04.

[7] Marina I. Sysoeva, Eugenia F. Markovskaya, Tatjana G. Shibaeva, Plants Under Continous Light: A Review, Institute of Biology, Karelian Research Centre, Planr Stress, Global Science Books, 2010

[8] Daedre S. Craig, Erik S. Runkle, A Moderate to High Red to Far-red Light Ratio from Light-emitting Diodes Controls Flowering of Short-day Plants, JASHS May 2013 vol. 138 no. 3 167-172

[9] Qiansheng Li, Min Deng, Yanshi Xiong, Allen Coombes, Wei Zhao, Morphological and Photosynthetic Response to High and Low Irradiance of Aeschynanthus longicaulis, ScientificWorldJournal. 2014; 2014: 347461. Published online 2014 Jun 30. doi: 10.1155/2014/347461