Downloading the Sun. Optimising the use of Solar Radiation in Horticulture and otherwise, with special regard to Latitude and Cross-Section.

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Abstract

We depend on green plants for survival and in self-defence, as a species, should plan ever more intensive horticulture to support increasing populations; yet photosynthesis is a process so inefficient in energy terms that staple foods cannot be grown competitively using artificial light from commercially-priced electricity alone. Our response should include better direct use of solar radiation, alternative sources of electric power, and cooperation between approaches. Strikingly, in summer, total solar radiation on a horizontal surface increases with latitude, an effect magnified by vertical surfaces which add to cross-section of an installation. Stationary, convex mirrors deflecting light down to target areas can provide radiation optimal for plant growth, and require minimal adjustment or maintenance so costs are kept low. Such mirrors may be useful also as adjuncts to solar panel arrays.

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Introduction

The total amount of radiation incident on our planet is colossal and the sum of all human energy uses, including by way of burning fossil fuels, is a very, very small fraction of it[i]. Even so, it will be wise to prepare for future uncertainty by devising the most efficient ways of using this freely-available energy and so minimise our dependence upon fossil or nuclear fuels and our pressure on that finite resource, land. As has been well understood for centuries, the growth of green plants is dependent on sunlight and we humans in turn are dependent on them for sustenance; directly or indirectly. Therefore, as well as studying solar or wind power for generation of electricity, we should examine how best to use solar energy in support of agriculture, all year long and in all parts of the world. This paper uses simple models to explore how incident radiation depends upon latitude, season, and vertical versus horizontal components of the receiving surfaces, the limits of photosynthetic productivity, and applications to solar electricity, vertical farming and intensive horticulture generally.

Radiant Energy; Definitions, Terminology and Symbols

There are many different application-specific ways of expressing quantity of radiant energy and this may cause confusion when ranging widely across systems. In the hope of achieving clarity, therefore, terms are defined locally rather than relying on those in general use. For example, an accounting of photosynthesis in energy terms has to take note of every photon involved, energies varying with wavelength, so that writing intensity in the currently popular way as number of photons per second does not completely describe energy balance. Even within the narrow wavelength range of visible light photon energies vary nearly two-fold.

Chemical energy means energy of formation of the products of photosynthesis from carbon dioxide and water.

Intensity of radiation (I) is defined as the radiant energy, per second, per unit area *normal to the direction of travel of the radiation concerned*, and may be expressed using any kind of energy units or any quantity capable of conversion into energy units, though that may require knowledge of the wavelength distribution of radiation. The intensity of full sunlight at any given location, irrespective of solar altitude, is written i, and in a few places where it is thought necessary to emphasise the maximum possible intensity with the unobstructed sun directly overhead, this is written i_{90}. Naturally and properly many authors use actual radiation intensities as measured or estimated for particular locations: for the purposes of this paper that is neither possible nor useful, and would make surprisingly little difference.

Incident radiation (R) is the radiant energy falling upon a defined target irrespective of its shape or orientation: its dimensions are of energy/time. The term can be used in reference to a portion of an object, or unit area of an object, not only to entire objects, so the nature, extent and orientation of the target must be fully understood. R is expressed per second, or summed over a longer period.

'Target' (as in the preceding paragraph) may refer to any natural or artificial object, or portion thereof, or area on the earth's surface, to which radiation is directed.

Cross-section is or was a term familiar in particle physics where its SI unit is the barn, 10^{-28} m^2. In this paper we do not need to use so small a unit. Here, the cross-section (C) of a target is its functionally-apparent size (in respect of the absorption or deflection of radiant energy) expressed as the equivalent area lying normal to the direction of travel of the radiation.

Thus R = I x C

We may wish to consider also the cross-section that would apply to a beam of light which is horizontal (C_0) or vertical (C_{90}). Evidently, the former is the equivalent vertical surface area of an object *normal to the horizontal beam,* the latter its area as viewed from directly above.

(Solar) altitude and azimuth are expressed with reference to the centre of the sun's disc.

Altitude (θ) is the elevation of the sun, in degrees. In general only positive values are taken into account (altitude > zero, sun above the horizon) and it seems unnecessary to distinguish this situation by use of a different symbol.

Azimuth (ς) is the compass direction of the sun, in degrees, on the cartographic convention

Declination is that of the sun's apparent orbit, 0^o at the equinox and here taken to be $+23.5^o$ at midsummer, -23.5^o at midwinter (in the Northern hemisphere).

Sundownloader is as described in text.

Photosynthesis and its Limitations

Photosynthesis and horticulture take pride of place because some of the principles are unique to them. They serve best to illustrate the whole even if those unique features add complexity. Other mechanisms of solar-energy-capture appear simple in comparison though the physical principles are the same.

Overall 'Efficiency of Photosynthesis'

Efficiency expressed as the chemical energy captured and stored as a fraction of R, must seem very poor; under field conditions commonly less than 1% of 'photosynthetically active radiation' (PAR) (which equates roughly with visible light) - a figure widely quoted though misleading because much of this so-called PAR is of little or no use in photosynthesis. A quantitative analysis appears below, in relation to the economics of intensive horticulture.

Rate of photosynthesis and level of incident radiation

In low light conditions (low R), green plants consume more energy than is available from photosynthesis. Above a 'compensation point' which varies with species and local conditions there is net gain: this region is of particular interest; we expect the net rate of photosynthesis to be proportional to R: that is approximately true, up to a 'saturation point' above which no further increase in rate occurs and there may be a decrease due to photo-inhibition and/or physical damage to the plants. In this paper we are mainly interested in ways of increasing R. When discussing applications in direct support of photosynthesis we mean only up to the saturation point, and the proportion of R converted into chemical energy is a secondary issue for so long as we can treat it as remaining constant. This is not to question the value of increasing photosynthetic efficiency including by artificial means. What happens in deep layers of plants is also of interest.

Optimum or maximum rate

If sunlight falls directly on a plant target lying normal to the direction of the beam (so that the area of the target (A) is equal to C), R/A is equal to i and is above saturation for all species. Because of the saturation effect, maximum rates of photosynthesis are reached when R/A is still below 0.5i and often well below. Expressing these relationships in symbols,

$$R = iC = iA, \quad R/A = i, \quad R/A \text{ for maximum rate } [(R/A)_{max}] < 0.5i,$$

Thus the subject is slightly more complex than it seems at first sight because of the need to treat R separately from I, and C from A.

If a leaf target lies at an angle to an incident beam of sunlight, the quantum of R/A is reduced (cross-section less than A, C < A), and it has long been known that in some species the leaves actually do twist in bright sunlight in such manner as to bring this about[ii].

Depth of target

If plants are present in an assembly of different species and at great depth, light that bypasses or is scattered or re-radiated by the highest leaves may be absorbed lower down including by species better adapted to low light levels. The opportunities for absorbing photons increase so that even if some leaves are overloaded and photo-inhibited the proportion of radiant energy converted into chemical energy is higher than that facile '1%'. Ritchie[iii] concludes that, in tropical rainforest, enhancement of overall photosynthetic efficiency does occur in this way (and it must be similar in a relatively deep suspension of microalgae).

In ordinary agriculture a single layer of plants is exposed to the sun, and all of one kind, so the effect does not occur unless the plants grow tall[iv]. In greenhouse conditions (including one kind of 'vertical farming') there may be a considerable height of plants arranged on racks, one above the other, and it is worth examining what may happen in consequence. Even limiting ourselves to truly usable radiation, only part of what falls on a target is absorbed and used in photosynthesis, part is absorbed and not so used (some of it may be re-radiated) and part is reflected. If there are other plant surfaces available to intercept the reflected and re-radiated light this gives a second chance for the photons to be captured. As in a tropical rainforest, we expect a higher rate of photosynthesis overall from a given R (R for the whole target) than in the case of a single layer of plants, though we cannot by that thought experiment alone determine whether the additional rate is sufficient to be useful.

To express this effect in terms of I and R helps clarify the meaning of C. Suppose that radiation of intensity I falls upon a target of cross-section C, R = CI. Assuming as above that the rate of photosynthesis is proportional to R but taking I as constant, an increase of rate can only happen if there is an increase of C. That is how an increase of overall photosynthetic efficiency might occur in a greenhouse or vertical farm and accounts at least in part for the high efficiency in a tropical rainforest. C expresses the probability of capture of photons.

A corollary is that the maximum rate of photosynthesis in a greenhouse unit or other target *as a whole* may be at incident radiation per unit area (*of the whole target*) greater than that giving maximal rate for an *individual plant* as the defined target. Over-heating is a likely constraint but we need not as a matter of principle shy away from increasing R for an entire target, provided that there are ways to avoid excessive R/A for individual plant targets; a paradox more apparent than real, open to solutions through design and as we have just seen already achieved in Nature!

The biology of plants

Photosynthesis is also constrained by biological/evolutionary influences. Plants have evolved to deal with particular conditions of light and climate so that a large part of the skill of the gardener or farmer lies in matching plants to conditions, or *vice versa*. Variation between species may be less for commercial crop plants than generally because of a selection process that has eliminated extremes; nevertheless there are always stringent biological influences upon what plants can be grown, where and when. In this paper all these biologically-important influences including day length, temperature and humidity are left aside to allow concentration on improving the quantity, distribution and duration of solar illumination.

Incident radiation varies with (solar) altitude, latitude and season.

Horizontal target

Computer-based systems exist which (with input from satellite-based instruments) give exact information about the intensity of solar radiation at the outer edge of the atmosphere (the quantum has been long known in principle [i]) and the extent to which it is refracted, scattered, reflected or absorbed by the atmosphere, clouds, dust and smoke so as to limit the intensity at ground level [iii]. For the narrow purposes of this paper only a broad understanding is needed, and for that it will be clearer to base the analysis upon a very simple model in which the earth is considered a perfect sphere and i treated as constant.

Solar altitude may be calculated as a function of latitude, solar declination (and thus also day of year) and time. One equation is:-

Sine altitude = (sin latitude)(sin declination) + (cos latitude)(cos declination)(cos hour-angle)

In respect of direct radiation from the sun, the cross-section of a flat, horizontal, non-shadowed target varies as the sine of altitude, which is zero at horizontal sun, and 0.5 at 30^{o} altitude. In our model, (sin altitude) x (time interval) is taken as a surrogate indicator of the potential incident radiation upon a horizontal target during a sufficiently brief interval. Summed over the hours of daylight, Σ(sinθ.t), we find that at midsummer the total over the whole day broadly *increases with latitude* (Fig. 1) and is greatest at the Pole; counterintuitive results that are only occasionally noticed in writings about agriculture though they help to explain the extraordinary biological productivity seen in summer in the Arctic and Antarctic and are well-known in other scientific milieux[v] - even down to the reverse tendency at mid-latitudes, such that there is little difference between 30 and 60 degrees and a small minimum near 60 degrees that shifts to higher latitudes either side of midsummer.

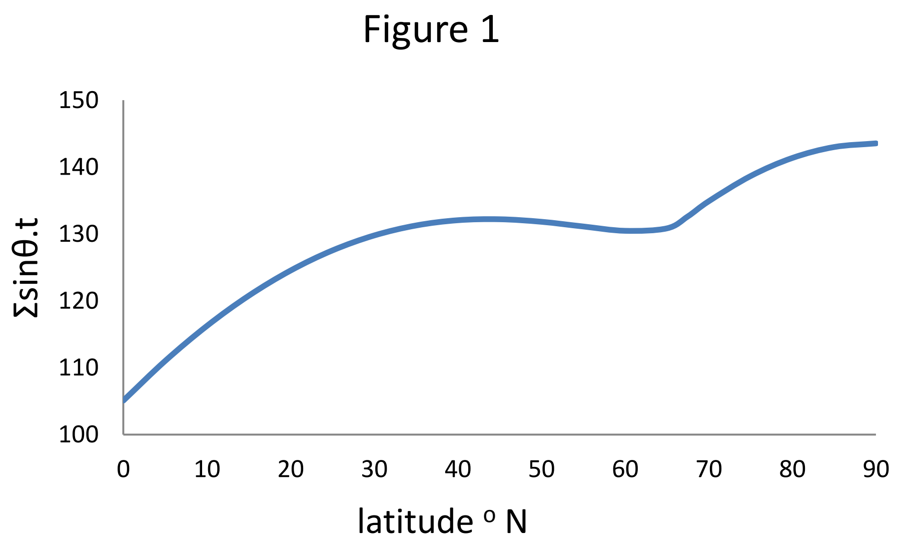

Figure 1: **Incident Radiation, variation with latitude at midsummer**
The ordinate is a surrogate for (maximum possible) incident solar radiation per unit area of a horizontal surface over the whole of mid-summer day, from latitude 0^{o} - 90^{o}. Sine of solar altitude was calculated at 4 minute intervals throughout daylight hours for solar declination +23.5 degrees and summed to give Σsinθ.t (time interval of 4 minutes is set as unity).

Vertical target and combined target with horizontal and vertical components
It is very different for a vertical target. Cross-section varies instead as the cosine of altitude; maximum when the sun is horizontal, zero when the sun is directly overhead; suggesting at once that a combination of horizontal and vertical surfaces will often be more useful than either alone and especially at high latitudes where the sun is lower for longer. To show what might follow, calculations of Σcosθ.t have also been made and appear in Figure 2A - D (together with Σsinθ.t) for declinations of, respectively, +23.5, +20.0, zero and -23.5^{o}

Figure 2

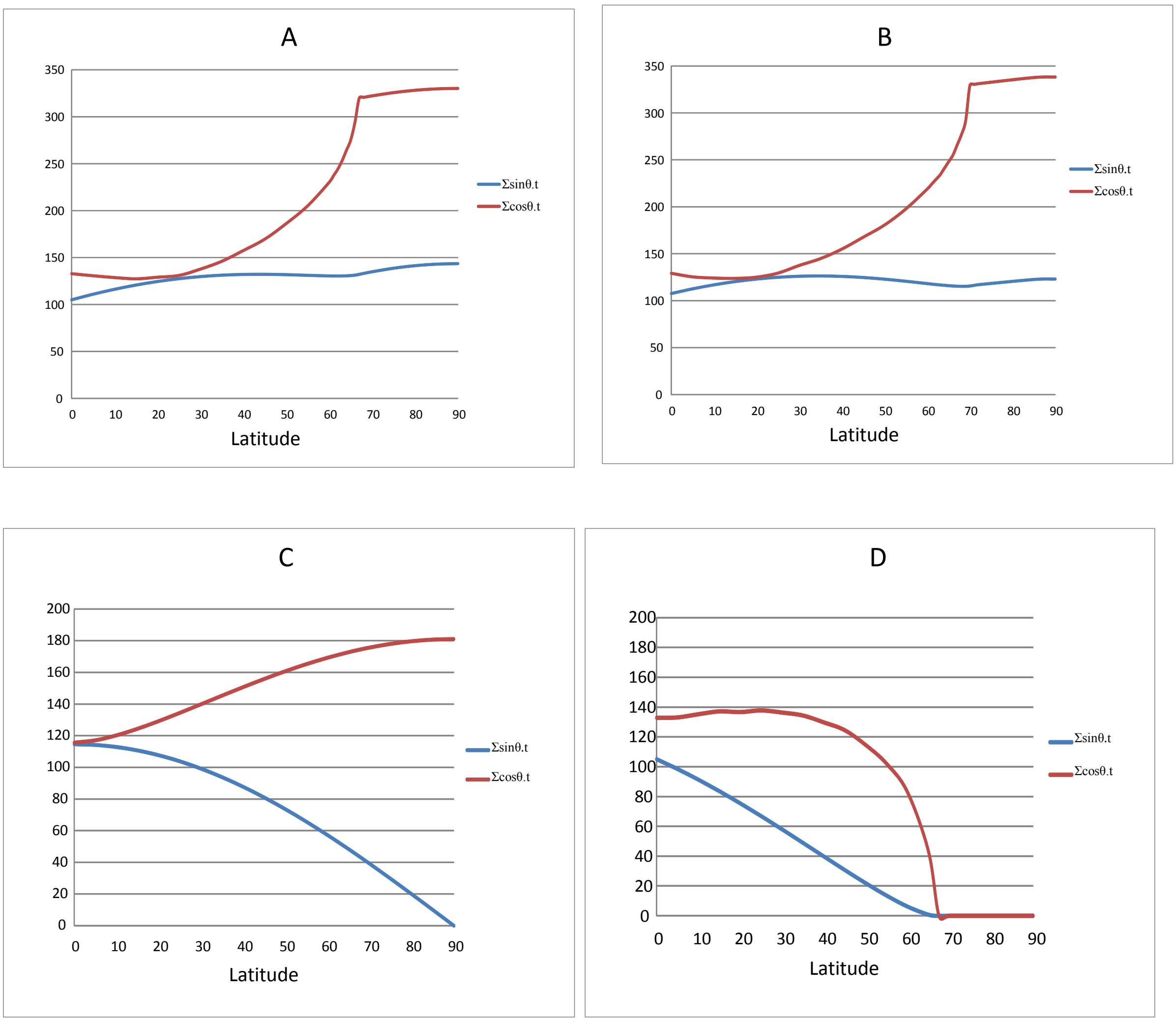

Figure 2: **Incident radiation, horizontal and vertical surfaces, variation with latitude**
The calculation is similar to that for Figure 1. Ordinates are the sums of sine and cosine of solar altitude, calculated at 4-minute intervals over the whole of daylight hours on four different days. This time interval (t) is set as unity. The resulting numbers are surrogates for (maximum possible) incident solar radiation on respectively horizontal and vertical surfaces of equal area, the latter arranged such that the vertical surface or equivalent always faces the sun's azimuth; northern hemisphere on the following days and declinations:-
A] Midsummer, +23.5^{o}, B] May 21st and July 24th, +20.0^{o}, C] Equinox, 0^{o}, D] Midwinter, -23.5^{o}.

Σcosθ.t is always greater than the sine function, at times more than double. Particularly striking are the potential benefits at high latitudes throughout the summer months (meaning from equinox to equinox) and at mid-latitudes even in winter.

Figure 3 shows Σsinθ.t and Σcosθ.t averaged over all days of the year, including even the dark months of Arctic or Antarctic winter so not confined to days when the sun appears. Summing the two [Σsinθ.t + Σcosθ.t] points to a total annual incident radiation that is almost invariant with latitude, though of course this is for the simplest of all possible models and with $C_0 = C_{90}$

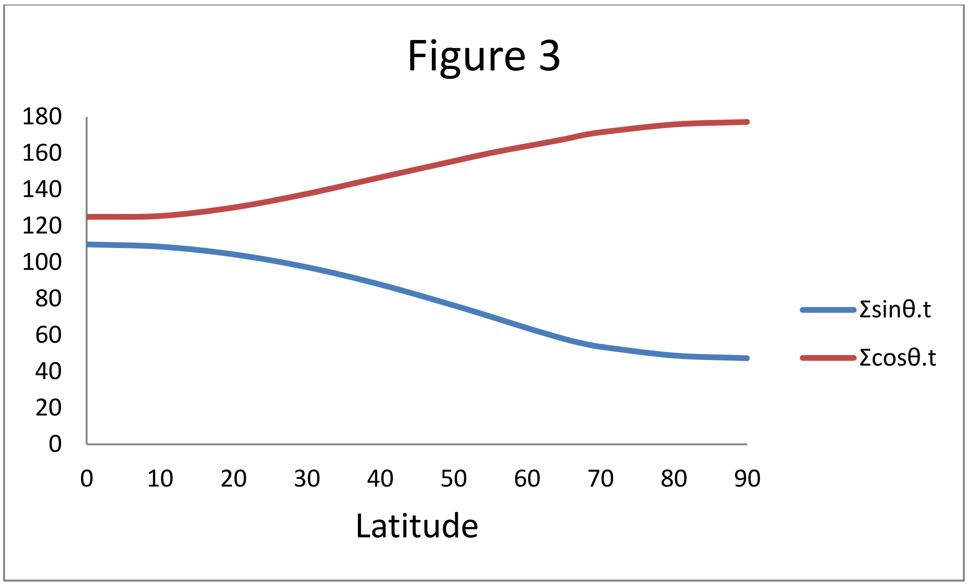

Figure 3: **Incident radiation and latitude, whole year, horizontal and vertical surfaces**
Sine θ and cosine θ were calculated as in Figure 2 at 4-minute intervals over all daylight hours (θ > zero) for 37 days at 5-day intervals from June 23rd (declination 23.43°) to December 20th (declination -23.42°); summed and divided by 37 to give a surrogate for (maximum possible) annual incident solar radiation expressed as an average per day. The average is for all days and not only for days during which there could be daylight: wholly dark days at latitudes 70° - 90° in winter are included in the summations: the results are for equal areas or per unit area.

The 'cosine' function is progressively greater at higher latitudes and the sum of cosine and sine functions changes little from Equator to Pole. At high latitudes a vertical receiving surface or equivalent may make an especially large contribution to collection of solar energy.

The Figures show results for equal horizontal and vertical areas (or per unit area) and the vertical surface must face the solar azimuth at all times for the calculations to hold true; a scenario which may at first seem implausible. However, a cylindrical building of height h with a circular flat roof of radius r has a cross-section to horizontal radiation from any direction (C_0) of 2rh and to radiation from vertically above (C_{90}) of πr^2.

$$\text{Set } C_0 = C_{90}: \quad 2rh = \pi r^2,\ h = \pi r/2 \text{ or} \approx 1.57r$$

For r = 10m this gives a structure ≈16m high and 20m wide, resembling a large commercial greenhouse, whilst r = 2m gives ≈3m high and 4m wide, like a small home greenhouse.

Another simple calculation may be illuminating as showing that for most structures and at intermediate values of altitude the total cross-section of a target exceeds C_0 or C_{90}. Consider a building such as the above having in effect equal and continually illuminated horizontal and vertical surfaces, each of area α, with the sun at altitude θ. Total cross-section is α(sinθ + cosθ) and the greatest possible value of R will occur at θ = 45°.

$$R_{max} = i\alpha(\sin 45^o + \cos 45^o) \approx 1.414\ i\alpha.$$

The same principles can be applied to tall buildings where the equivalent vertical surface may exceed the horizontal 'footprint'; equally well to low buildings where the vertical surface is less than the horizontal. Also, there is no reason why the target areas for receiving radiation should be confined to the functional parts of a building.

It seems proper to conclude that, varying with location, non-horizontal elements of a target may contribute usefully to total incident radiation even if their area is less than the horizontal elements, and where the area is greater their contribution may be dominant. The potential varies with latitude and season though always important when the sun is low, including near dawn and dusk. It is clearly necessary, however, that means can be found to distribute and utilise radiation without exceeding the capacity of the receptor systems or causing damage. In a review of the possibilities of microalgal culture, Ooms *et al*[vi] show general awareness of the principles, advantages and consequences of deploying vertical elements, and re-distributing incoming solar radiation. Concerning solar electricity production the question is explored and the vertical-element-cross-section effect illustrated using data from on-site measurements at 59°, 40° and 5° latitude by Hall *et al* 2005[vi], whilst more recently it is recommended to arrange solar panels vertically if in mountains at mid-latitudes (Kahl et al, 2019[vi]).

Radiation Collectors and Distributors

We revert to photosynthesis and horticulture as the stalking horses for a discussion that may have wider applicability. The above analysis shows that, in theoretical principle, total daily incident solar radiation on a target can be modulated to an unexpectedly high level; we are not even limited to $R = \alpha.i$, nor to the envelope of a building as ordinarily understood. There is no doubt that solar radiation can be better deployed than has been customary.
In horticulture these are not new concepts - arranging that plants receive enough light is standard practice with many centuries of history, so also is shading plants from excessive radiation. Ask not whether these things can be done, but how and at what cost.

Heliostats

Mechanical devices to follow the sun (heliostats)[vii] have been used for this purpose and can be combined with means for secondary distribution of the radiation. Large ones are costly and troublesome, requiring frequent maintenance and often an external source of power though others operate on solar electricity: a small solar-powered unit for home gardens has been on the market for several years. As shown by the calculations above, a relatively small receiving area delivers a surprising amount of radiant energy, nevertheless devices of this kind have been most used for indoor illumination (rather than gardening) because the intensities needed for indoor human activities are much less than for photosynthesis. Even so few installations have survived beyond the initial period of high public interest, because of the difficulties in keeping them operative. Notably, the frequently-cited system in the HSBC headquarters building in Hong Kong never worked as intended.

Other systems and distributors.
Means of directing light to where it is most needed are of great antiquity: we can begin with simply painting walls white! For horticulture there are reflectors within ‘cold frames’ or the upper parts of greenhouses, or closely beside a plant container, and the local landscape may be re-shaped or a suitable pond provided to serve as reflector. Advantageous also is to distribute incoming radiation efficiently[viii] within a greenhouse and include an element of shading at certain times of day and year: both of these have been standard practice in horticulture for millennia and are the subject of much recent inventive activity. The subjects are huge and cannot be reviewed in detail here.
In architecture, the ‘light pipe’ or ‘light guide’ brings natural light from outdoors to the indoors workplace. This too is standard practice with a long history but of little interest in the present discussion because as mentioned before the intensity required is a small fraction of that for either photosynthesis or electricity generation, and so the means are also insufficient.

Download the Sun
The simplest means is the most recent[ix]: a Sundownloader both collects and distributes light.
A convex mirror is specifically shaped such that when suitably fixed above or outside a building or other target it will deflect light directly or obliquely downwards to the desired target area at all times when sunlight strikes the mirror, requiring no adjustment throughout a period of use that may extend even to a whole year. Installations exist. Though invented with ordinary gardens and leisure activities in mind, there is no reason why they should not be applied in solar energy generation, intensive greenhouse horticulture and vertical farming.
The reflecting surface is usually not vertical although obviously an equivalent vertical area can always be calculated. Curvature varies with compass direction and the simple, single mirror may be replaced by an equivalent composite.
A common reaction is to think of mirrors that concentrate light on a particular spot and might damage plants, but a convex mirror does not do that, dispersing or spreading light out rather than focussing it. Intensity of the deflected light does not approach that of full sun. Design may vary with requirements at each particular site, the weather likely to be experienced and whether the installation must also provide shade at certain times. Inexpensive and light-weight polymers can be used: a high-quality reflecting surface is neither necessary nor desirable.

The Money Cost of Food Production by Artificial Light

Using a Commercial Electricity Supply
It was asserted above that the ‘efficiency of photosynthesis’ is commonly less than 1%. We justify and expand upon this in the Appendix but a summary is appropriate here. For precision, we must first make clear what are the photosynthetic products being considered and choose glucose as representing them all because once a sugar has been made all the other products can be synthesised in the living cell with (relatively) little energy change. Also we

must work with dry weight of product (where the energy content is found) whereas crops like lettuce and tomatoes are about 95% water.

1 mole of glucose (180 g): chemical energy = 670 kcal = 2.805 MJ. Therefore one kg glucose, or 5.5555 moles, corresponds to 3722 kcal = 15.58 MJ. From this it follows that at 1% efficiency it will require 1558 MJ to make 1kg of glucose and, since 1 unit of electricity (1 kWh) = 3.6 MJ, the electricity required is 1558/3.6 = 432.8 units.

Therefore at 1% efficiency and US$ 0.10 per kWh, the cost of electricity alone is US$ 43.28 per kilogram, whereas the wholesale price of sugar on 1st April 2017 was $1.00/kg and that of wheat FOB Gulf of Mexico $210 per metric tonne on 1st October 2018. Higher guesses for efficiency bring down the cost somewhat, but, for example, 2% yields ≈$22/kg; even the probably unattainable 8% gives a product cost of ≈$5.4/kg in electricity alone; still utterly uncompetitive unless electricity is made available free of charge.

So far just one clear public statement has been found about electricity usage in a commercial operation[x] - 307 kWh per day to yield 1080 pounds wet weight of leaves per 3.6-week growing cycle. At US$0.10 per unit the total electricity cost would be US$774 or US$ 0.72 per pound wet weight. Lettuce is over 95% water; we multiply by 20 to get the cost for dry weight of product, namely US$14.4/lb or US$31.6/kg, which is good but still over thirty times the wholesale price of sugar, and more one hundred times that of wheat (and note that the cost of electricity in Britain (retail tariff) is double that assumed in calculation).

It is certain that photosynthesis using only artificial light powered by electricity at commercial rates cannot provide all the food needed for the human population of the world.

Can Electricity be Provided at Lower Cost?

Yes, up to a point. Night-time rates (in the USA) may be lower than used in calculation and electricity that is made on site from wind, solar panels or geothermal sources may be cheaper still once capital cost has been discounted. Every encouragement should be given to this kind of approach, and its combination with the use of redirected sunlight.

Is Non-Photosynthetic Food Production an Option?

The 'inefficiency' of photosynthesis as a means of energy capture is not due to incompetence of scientists and engineers; rather the root cause lies deep in thermodynamics. Photons are a 'dilute' form of energy. There is huge entropy loss involved in bringing together some 50 photons to make a single molecule of glucose and this leads to the suggestion that there may be a better way of using electrical energy to produce useful foodstuffs (even if aesthetically unattractive) - say by microbial processing of directly-synthesised hydrocarbons, or feeding methanogens on carbon dioxide plus hydrogen produced by electrolysis of water.

Intensive Horticulture, including Vertical Farming.

In Vertical Farming less ground area is used for crop production because plants are stacked vertically; thus making it possible to produce more vegetable foods in or close to the cities where they will be consumed - seen as in itself a good thing, which is reasonable. But enthusiasts for this approach often make the assumption, unconsciously, that photosynthesis will have to be by using electricity to produce artificial light, and conducted in closed sheds. To be fair, there are already large, automated, profitable commercial production units of that kind, though growing only lettuce, other leafy plants, and tomatoes, for reasons which are plain from the calculation above - staple foods cannot be grown profitably this way. That assumption about electricity is unnecessary for Vertical Farming as it is defined by Dickson Despommier, the originator of the term, who is himself fully cognisant of the thermodynamic/energetic limitations and an advocate for alternative energy sources, pointing out for example that geothermal energy is in fact nuclear energy[xi].

According to Dr. Despommier, Vertical Farming means multi-storey farming. Others have not always followed him in that, so we too shall consider two options, the shed on one level and the vertical-farming tower.

In all kinds of intensive horticulture, including Vertical Farming, we should consider how best to use the freely available energy of sunlight, and there are just two possibilities; either deflect the light to where is needed directly for photosynthesis, or generate electricity. They are not necessarily opposed and indeed both positively should be used, cooperatively, so that artificial light from solar panels is provided at places and times within the growing unit when illumination from deflected light is below optimum. Why not use solar electricity alone? One answer is that to transduce solar radiant energy to electricity at, say, 20% efficiency, generate light and use that for photosynthesis at, say, 2% efficiency gives overall 0.4% as an optimistic estimate. Everything will turn on economics and practical considerations. The position adopted here, if only to permit further pursuit of the argument, is that properly distributed sunlight will prove so much less expensive, as a photosynthesis energy source, that in most situations, most of the time, the former will be used alone or alongside solar panels,.

Deflected Sunlight in Intensive Horticulture: The Shed on One Level

Most intensive horticulture at present is in sheds or plastic tunnels that are operationally on one level however high the plants may be stacked, and in most cases illumination from the sun is allowed in through transparent walls and roof (notwithstanding the prejudice in favour of closed sheds and artificial light). In brief, they are greenhouses. If additional solar radiation is desired the obvious option is mirrors installed above the shed, deflecting light downwards. They constitute a ‘vertical’ component of the overall target, capturing especially low-angle solar radiation, expanding cross-section with the advantages already discussed.

As the sun rises higher such mirrors contribute progressively less to overall target cross-section, which is not necessarily a bad thing, and they may be arranged to shade the plants at appropriate times.

Deflected Sunlight in Intensive Horticulture: The Vertical Farming Tower

A growing unit arranged over more than one floor of a building (a ‘tower’) requires us to re-think how sunlight can be delivered to the plants; downwards through the roof alone is no longer enough. Note, however, that such a growing unit may well be higher than it is wide, at once suggesting exploitation of what was shown earlier, that the cross-section proffered by a vertical surface is remarkably large. As we have seen, a building of this nature may receive much more incident radiation than expected from its ‘footprint’ though it is obvious that this must also result in shadowing of other land/houses/properties - an important limitation to be considered in every case, having legal and political consequences which may stymie certain projects but cannot be usefully discussed here.

Necessarily, deflecting sunlight in this way requires that it will be directed in through transparent portions of the walls of the building perhaps from mirrors fixed outside the walls which will further increase the cross-section of the unit to low-angle light. Workable designs exist for this application, though no physical installation as yet. Delivering a worthwhile amount of solar radiation to plants inside must depend upon design of the building and internal layout, in particular the width of the floor, width and shape of aisles between plant racks, actual and relative areas of wall and floor on each storey. It should be re-emphasised that the architectural practice of light-guides or light-pipes bringing light into buildings, long-known and the subject of hundreds of patents, may mislead readers about the possibilities. Using a familiar unit for light intensity, most human indoor activities need no more than 200 lux. The extreme limits for photosynthesis may be roughly 2,000 - 50,000 lux, detail varying with species, and light-guides cannot deliver these intensities.

Vertical Farming towers are widely discussed in theoretical business studies[xii] and web-publications[xiii], though it is hard to get accurate information. Generally, the assumption is that photosynthesis will be by means of artificial light powered by the public electricity supply. The energetic-thermodynamic-economic argument developed above clearly shows that such units will not be viable except for the production of the kind of crops mentioned earlier, which cannot alone sustain human life and for which the market, though large, has clear limits. It follows that, if vertical-farming towers are to be built, their design should use solar radiation as much as possible, which may mean solar panels as well as deflected light and if the latter is used, multiple, narrow towers disposed to simplify and optimise the use of deflected radiation, rather than a single tower.

The Business Case for Solar Radiation in Vertical Farming

Using reflected solar radiation in vertical farming instead of or in addition to artificial light has to be justified by one or more of the following:

1] Cost: savings in respect of installation, maintenance and electricity.
2] Yield: better yields of higher-quality products, contributing directly to profits.
3] Health of plants, contributing to [2].
4] Respect for Nature: independently of other considerations, we positively should minimise use of electricity and fossil fuels, and in general work with Nature rather than against.

The last of these may be termed the ‘Green’ argument, and is not pursued further here though it is a line of thought deserving sympathy at the very least. About plant health, there is already a strand of opinion among the indoor horticulture community that plant health is benefitted by using the greatest convenient contribution of natural sunlight. Although artificial light may be used to keep production going throughout the year, there are also benefits from keeping plants healthier by exposure to the natural balance of wavelengths including some wavelengths not used in photosynthesis itself.

Properly and unavoidably, the direct business arguments, [1] and [2], will determine whether and when the new light-deflection technology comes into widespread use and the trials necessary to establish the degree of benefit will take some time. We may consider this new technology as supplementary to the use of artificial light, or *vice versa*. Some contributing factors that will affect this question of the degree of benefit are now reviewed.

With artificial light, specifically by using LEDs, selected wavelengths can be provided to suit photosynthesis better than the balance of wavelengths that constitute natural sunlight. Energy efficiency of photosynthesis may be thereby improved, and two potential advantages follow - better productivity per unit area of shed and less waste heat to be disposed of. Further, the continuing improvements in solar-cell generation of electricity might conceivably lead to a situation where the most cost-effective way of using locally available solar radiation is by converting it to electrical energy and deploying that as the electricity source for artificial light, rather than simple re-direction.

It is not so yet and even if it becomes so that does not necessarily mean that it will be best overall. Indeed, it seems highly probable that for many years to come, if photosynthetically-effective radiation is made available in the way described *at zero cost in electricity, whenever the sun is above the horizon*, it will be beneficial for many or all vertical farming operations, whether or not artificial light is used also, and will provide the side-benefits to society of economising on fossil fuels and making better use of the finite land area available.

Solar Farms

Though treated here with extreme brevity, because most of what is needed has already been said in relation to horticultural applications, the solar electricity industry may well be where sundownloaders are first and most extensively applied on a considerable scale, if only because the benefits will emerge early and be easily measured in money terms. If such devices can deflect solar radiation directly or obliquely downwards to a plant target, they can do the same for a target composed of solar panels, just as well.

First, two statements that are true but irrelevant *to this present discussion*:-
a] The efficiency and durability of solar panels are much better than they were.
b] Considering a sufficiently large area of the earth's surface, the total amount of incident solar radiation can be neither increased nor varied by tricks with mirrors.

Next, three relevant statements:-
c] However good solar panels may be, for maximum output they must be correctly oriented to incoming radiation *or vice versa*.

d] Stationary solar panels oriented to maximise output when the sun is high provide less output when the sun is low.
e] It is precisely during periods of low sun that their output is most valuable.

To improve performance, we must move either the solar panels or the incoming radiation, and the latter should prove much easier, because light has (almost) no mass. There is much information available about the optimum angle for solar panels, as influenced by season and latitude, whether the panels should be adjusted, and how often. However, unless the panel array moves continually to follow the sun in the manner of a heliostat, mentioned earlier, there will always be a period during the day when greater output can be had by means of a light-deflecting system external to the solar panel array, and if that system is stationary, there is no machinery to go wrong.

For a small solar panel array, sundownloaders may increase incident radiation overall, at the cost of some shadowing of neighbouring land or sea. For a really large solar farm that is not possible, but then it may be enough for improved business performance to have a more nearly even output, smoothing out peaks and troughs. In either case it must be worth considering using the mirrors, which might be best adjusted, say twice yearly near the equinoxes, to suit the different azimuths of low-altitude sun during winter and summer. A minimal maintenance cost is envisaged in such a case, the period of use without adjustment being 6 months rather than a whole year. Readjustment could be combined with cleaning which is obviously necessary for an outdoors installation of any kind, including the solar panels themselves.

Conclusions

Growing crops by artificial light at commercial electricity prices cannot produce basic foodstuffs cheaply enough: the ‘efficiency’ of photosynthesis is too low, and for reasons that lie deep in physics there are limitations upon what improvements can ever be made. Yet for the foreseeable future, human life will depend on photosynthesis. Of the huge amount of solar radiation that reaches the earth, very little is used at present. Necessity and advantage combine to argue that whatever can be done to improve deployment and utilisation of solar radiation should be done, especially but not exclusively in horticulture. No one means is obviously better than others; rather all should be studied including how they may be used in combination. One such means is convex, stationary mirrors, designed to deflect sunlight to a selected target, neither focussing the deflected beam nor requiring adjustment during a period of use, yet able to achieve desired levels of incident radiation.
Such mirrors add vertical surface area to a complete installation. The total annual incident radiation on a vertical surface at high latitude is comparable with any in the tropics, while for horizontal surfaces, in summer, daily incident radiation increases with latitude.

Appendix: Photosynthesis, 'Efficiency', Energy Cost.

Many published statements as to 'efficiency of PS' do not clarify the assumptions upon which they are based: here we try to be explicit in all respects and give examples which show why there is variation between authors and the importance or otherwise of that variation.

Abbreviations:
PS = photosynthesis or photosynthetic
C3 = most terrestrial green plants (the other kind, C4, are slightly more efficient, sometimes)
PAR = 'photosynthetically active radiation' which is a bad name because a large proportion of photons included as PAR are not used by plants; it means radiation of wavelengths from 400 to 700 nm, approximating the distribution in visible light from the sun.

Photosynthesis and what we mean by 'Efficiency'
Usage in biology differs from thermodynamics and between authors. 'Efficiency of PS' is here used to mean the proportion or percentage of radiant energy falling on a target that is converted into plant material; that is to say from the beginning to the end of the process. Results in the literature vary, the higher ones arising because consciously or otherwise the writer has selected part of the process whereas here we concentrate on energy input and end-product. Arbitrary definitions and assignments must be introduced; somewhat different results appear if alternatives are chosen: this does not affect the logic or the overall conclusions although, as will appear in an example below, such a choice of alternatives may indeed amount to selecting a small segment of the overall process.

Total solar radiation includes a wider range of wavelengths than PAR. PS in green plants requires more than one wavelength. Energy per photon declines with wavelength so theoretical 'efficiency of PS' increases with the assumed average. The number of photons at each wavelength varies according to the source of radiation, local conditions, time of day, cloudiness etc. No calculation whatever can be made without choosing what wavelengths and what distribution of photon energies shall be used - our initial choice is to deal with only PAR and photons evenly distributed.

'Plant material' here means dry weight, the whole plant unless otherwise stated and likewise the energy content of the product is usually equated with the chemical energy of the same weight of glucose - at best an approximation, but sugars are early products of PS and further metabolic changes to produce other kinds of molecules involve (relatively) small further energy exchanges.

Because of the nature of the apparatus in the chloroplast it is difficult to be quite sure of the number of photons needed to make a molecule of product, it is not even necessary in principle for the number to be an integer. This is unlike ordinary, test-tube chemical reactions where the constant proportions between amounts of reactants and products led to the atomic theory of matter! Our first assignment is 54 photons per molecule of glucose.

Equating one molecule of glucose with a definite chemical energy and a definite number of photons, we address the questions:- 1] What might be achievable theoretically and what is achieved in practice by the use of natural light in photosynthesis. 2] What is the actual cost in electrical energy and money of producing food with artificial light. There is no single, simple answer to either.

Conversion factors and Assumptions:
1kcal = 1,000 x 4.186 J
1mol glucose corresponds to 670 kcal = 2805 kJ = 2.805 MJ
1 kg glucose = 1000 / 180 = 5.5555 moles, corresponds to 3,722 kcal = 15.58 MJ
1 kWh = 1,000 x 3600 J = 3.6 MJ = 1 unit of electricity; cost is taken as US$0.10 / kWh

Energy Capture from PAR. Performance and Theoretical Limits.
Accepted facts and arbitrary assignments (Ritchie 2010, *op cit*):
1] 54 photons are required for the synthesis of 1 molecule of glucose.
2] 34.6 % of PAR photons are usable for PS
3] Quantum efficiency of photon capture is less than 1, even for truly usable photons. A reasonable average is 0.785
4] The energy of PAR photons is spread over a range and any averaging is either correct for a particular place, day and time, or incorrect, or arbitrary. The value taken here for calculation is that of the median wavelength, 550nm, corresponding to a Planck/Heisenberg energy of
$6.626 \times 10^{-34} \times 2.99792458 \times 10^{8} / 5.50 \times 10^{-7}$ = 3.6117×10^{-19} Joules per photon
or per mole ($\times 6.123 \times 10^{23}$) = 2.1753×10^{5} = 217.53 kJ
(or, for 200 moles of photons = 43506 kJ per 200 moles)

Deductions:
i] From [1] & [2], the number of PAR photons necessary to provide the 54 useful and necessary photons is 54 / 0.346 which is more than 156, therefore we take 157 as the minimum number.
ii] From [i] + [3] the actual number of PAR photons required is 157 / 0.785 = 200
iii] From [ii] & [4], the radiant PS energy required to form 1 mole of glucose is 43506 kiloJoules.
iv] From [iii] and the conversion factor cited above, the chemical energy of 1 mole of glucose can be compared with the energy of the photons required to make it, and is 2805 / 43506 = 0.0645 = 6.45% - this is the theoretical, maximum limit for ‘efficiency of photosynthesis’ *under that particular set of assumptions*.

Comments on the theoretical ‘efficiency of PS’:

6.45 % may seem a low figure but in agricultural practice, in the open field, 1% is about the limit. Photon capture involves huge loss of entropy - many free-living photons must be tied down to produce one sedentary molecule of glucose. The above result can be altered by adjusting the parameters in the equations and there may be sound scientific reasons to do so with no real disagreement about the principles or the method of calculation. Things that cannot be altered are the logic and that the percentage will never approach 100.

Making the most favourable changes imaginable, to whit 48 photons only per molecule of glucose, all photons potentially usable (instead of only 34.6% of PAR), photon energy calculated on the basis of 680nm wavelength (instead of 550 nm), quantum yield = 1, we arrive at a total photon energy (48 moles of photons) of 8742 kJ. Calculated theoretical efficiency is then 2805 / 8742 = 0.3209 or 32.1%.

So a very different and far more favourable result! Which should be used in further discussion? Can we make the result appear to be whatever we want?

Note that these were ‘the most favourable changes imaginable’ (beyond reason); also one effect of those new assignments is to give a result for the photon-energy-conversion part of the overall process, on its own, ignoring the photon-collection part with its greater inefficiencies. The new result is useful only in relation to studies of engineering, genetic or otherwise, directed at improving photon-collection. It does not reflect reality.

Possible favourable adjustments:
Adjust wavelengths to an ideal balance for the plants concerned,
and genetically-engineered plants with better photon-capture performance.
C4 plants or alterations in metabolic process, including by genetic engineering.
Plant species using other chlorophylls than a and b.
Plant species using quite different photon-capture molecules.

Adverse effects and adjustments:
Photosynthetic product consumed by the plants themselves. This is not allowed for in our calculations so that our theoretical percentage figures are exaggerated.
Any defect in weather, supply of water or nutrients, or husbandry; damage to plants.
Much radiation never reaches the photoreceptors.
Photoinhibition or actual damage at higher intensities.
Adaptation of plants to particular conditions so that measurements are inappropriate.

‘Efficiency of photosynthesis’ in practice

As stated, ‘efficiency of PS' in agricultural practice is usually less than 1% of PAR energy and the acknowledged current best performance under artificial light (in private conversation, by people from lighting-manufacture companies engaged in this field) is 2%. In experimental conditions claims have been made for 4% or even 6% and up to 2.8% for tropical rain-forest (Ritchie, *op cit*). Some more definite practical examples follow.

World record wheat yield.
The world record yield of wheat (1.65 kg/m^2, 16.5 tonnes / hectare) was obtained in 2015 at 55.7^{o}N: it was an exceptionally good summer in North-East England as can be attested from a chance personal visit to the area in June 2015, quite unlike when living on Tyneside from 1959-68. The farm concerned already held the previous record. We may attempt to calculate total incident radiation as follows, making no allowance for cloudiness:-
Growing season 26th March to 16th September, 175 days divided into 5-day periods, $\Sigma\sin\varphi.t$ (time interval, t = 4 minutes, units t.i) was calculated from declination for the middle day of

each period, summed, multiplied by 5 to give the total incident radiation per m^2 for the whole 5-day period, divided by 15 to convert the time element to hours (units now hours.i) and i is is equated to 1kW. The result is 1212.4 kWh or 4364.5 MJ per m^2.
The product was grain. Assume 10% water content, 1.65 x 0.9 gives 1.485 kg dry weight/m^2. The chemical energy is equated to that of glucose: 1.485 x 15.58 = 23.14 MJ

Then 'PS efficiency' overall is 23.14/4364.5 = 0.0053 or 0.53%

This is for marketable product rather than for all plant material. No allowance has been made for cloudiness. If the assumed value for i is too high the result may be an underestimate, and *vice versa*. Probably, i = 1kW would be reasonable for total solar radiation rather than PAR alone so the 'PS efficiency' result should be understood on that basis. We might calculate a higher figure for PAR alone, even double, but for any certainty such estimates require actual climatic records from the place and time.

Micro-algal productivity, in theory.

Micro-algal systems may have the advantage that all PAR photons may be eventually usable after re-radiation processes have occurred and therefore test the limit of what is achievable. Ooms *et al* (*op cit*) give a highest-theoretically-possible figure for outdoor production (in Australia at year-average solar incident radiation of up to 277W/m^2), namely 18g/m^2 per day dry weight; which is 6.6kg/m^2 per year; in weight terms over four times the cited record figure for wheat grain. Since this is microalgae with up to 50% of (high-energy-content) fats rather than only carbohydrate, we use in calculation their own figure for chemical energy, which is 23kJ/g dry weight. Then daily energy capture is 18x23 = 414kJ/m^2: daily energy input at (say) 250W/m^2 is 250x3600x24/1000 = 21600kJ/m^2: 'PS efficiency' = 414/21600 = 1.9% (of total incident radiation so ≈4% of PAR) - very good indeed but theoretical, not an experimental or practical figure. The authors also compute the cost of electricity for microalgal culture using artificial light, though using a high figure for 'PS efficiency'.

Using artificial light. Electricity cost.

Whenever artificial light is used alone there must always be someone who could calculate the actual electricity cost to produce a crop of known weight and little more effort is required to ascertain the dry weight of both the marketable product and all plant material. However, it has been difficult to find any published information.

Blanken *et al*[xiv] estimate $25.3/kg overall for the increased cost of using artificial light in micro-algal culture, though as low as $16.1/kg dry weight for electricity alone, close to the projection of Ooms *et al* (c.f. above). Both papers assume high figures for 'PS efficiency', do not describe their experimental basis, and yet both conclude that electricity costs alone rule out 'commodity' or 'bulk' production (Ooms *et al* - 'two orders of magnitude').

Zhang *et al* [xv], grew lettuce under LED light and show the extra yield obtained by providing extra upwardly-directed light. Their best example, with *white* LEDs, was 500kWh of electricity per kilogram dry weight of extra lettuce produced; say $50.00 / kg.

A case published on the internet in 2017 is mentioned in the body of the paper. An equipment-supply business suggests electricity consumption of about US$31.6/kg dry weight - corresponding to an 'efficiency of PS' somewhere between 1 and 2% .

Conclusion.
Although further modest improvement in 'PS efficiency' seems possible, beyond 2%, no method yet known or envisaged is anywhere near good enough to allow *staple* foodstuffs grown under artificial light alone to compete commercially with those from ordinary agriculture; since the cost of electricity alone per kg dry weight of product is more than one hundred times the bulk price of wheat. The case of fresh foods such as lettuce and herbs is quite different and their nutritional value in other respects is not in dispute, merely they cannot supply the quantum of energy that must be provided from food to sustain human life.
Statements concerning efficiency of photosynthesis (or electricity costs for artificial light) deserve credence only if they rely on actual experimental results or all assumptions required for calculation are clearly stated.

References and Notes.

i] a] G. S. Schlau-Cohen, Principles of light harvesting from single photosynthetic complexes, Interface Focus 2015 5 20140088; DOI: 10.1098/rsfs.2014.0088.
b] J.L. Monteith, Solar radiation and productivity in tropical ecosystems, Journal of Applied Ecology, Vol. 9, No. 3 (Dec., 1972), pp. 747-766. This paper incorporates a reference to Lord Kelvin and 'the solar constant'.

ii] C. Darwin, 'The Power of Movement in Plants', Murray, 1880, Chapter 8, "Paraheliotropism".

iii] R.J. Ritchie, Modelling photosynthetic photon flux density and maximum potential gross photosynthesis, Photosynthetica, 48(4)(2010)596-609.

iv] J.H. Chang, 'Climate and Agriculture, an Ecological Survey' (1968), Routledge 2017, Chapters 4 and 6.

v] a] J.A. Duffie and W.A. Beckman, 'Solar Engineering of Thermal Processes', 4th Edition, 2013, Wiley, NJ, USA, especially pages 38-9.
b] downloaded May 31st 2017; https://en.wikipedia.org/wiki/File:InsolationTopOfAtmosphere.png,
c] downloaded 9th September 2017; http://nit.colorado.edu/atoc5560/week13.pdf; http://www.applet-magic.com/insolation01.gif; https://www.slidedoc.us/seasonal-changes-in-insolation-with-latitude;

vi] a] M.D.Ooms, C.T.Dinh, E.H Sargent and D.Sinton, Photon management for augmented photosynthesis, Nature Communications, 2016; 7: 12699, doi 10.1038/ncomms12699. ("Artificial light, in particular LEDs, are not currently practical for commodity production .. ", " .. two orders of magnitude.. ")
b] M. Hall, A. Roos and B. Karlsson, Reflector materials for two-dimensional low-concentrating photovoltaic systems: the effect of specular versus diffuse reflectance on the module efficiency, Photovoltaics Research and Applications, 2005: 13: 217-233
c] A. Kahl, J. Dujardin, and M. Lehning, The bright side of PV production in snow-covered mountains, Proceedings of the National Academy of Sciences (USA), 2019: 116: 1162-1167. doi.org/10.1073/pnas.1720808116

vii] a] A.C. Burrage, US patent1703388, granted 1929 (- a greenhouse moved manually to maximise benefit from solar radiation).
b] A. Bayle, US patent 1938003, granted 1933 (- a sun-power-controlled heliostat, not dedicated to horticultural applications).

viii] R.J.Pati and M.Abelar, The application and optimization of metal reflectors to vertical greenhouses to increase plant growth and health, Journal of Agricultural Engineering and Biotechnology, 3 (2) (2015) 63-71 (- an experimental study on redistribution of sunlight within a greenhouse, conducted at a U.S. high-school!) – and there are numerous patents.

ix] T.R.C.Boyde, Solar Radiation Enhancement, Jacobs Journal of Agriculture, 1 (1) (2015) 1-4. See also PCT/GB2015/054102, WO 2016/110669 A1

x] https://blog.brightagrotech.com/indoor-hydroponic-farming-costs-profits, downloaded 20th June 2017

xi] Personal communication, 'Seeds and Chips', Milan, May 8th 2017

xii] C. Banerjee, Up, up and away! The economics of vertical farming, Journal of Agricultural Studies 2 (2014) 40-60 (- a purely theoretical business case for a tall vertical farm, acknowledging product cost of €3.5 per kg, say €70 or about US$80 per kg dry weight)

xiii] http://www.cityfarmer.info/2011/07/23/south-korean-city-of-suwon-has-a-vertical-farm;

xiv] W.Blanken, M.Cuaresma, R..H.Wijffels and M.Janssen, Cultivation of microalgae on artificial light comes at a cost, *Algal Research* 2 (2013) 333-340. ("Although the economic disadvantages of artificial light are customarily referenced, the actual costs and energy balance are disregarded." "Microalgae cultivation programmes should therefore focus on employing sunlight." "Calculated electricity costs are more than one order of magnitude too high for the production of bulk ...").

xv] G.Zhang, S.Shen, M.Takagaki. T.Kozai and W.Amori, Supplemental upward lighting from underneath to obtain marketable lettuce (Lactuca sativa) leaf fresh weight by retarding senescence of outer leaves, *Frontiers in Plant Science* 6 (2015) 1110 doi: 10.3389/fpls2015.01110