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Effect of Reflection of Sunlight on Illuminance and Energy Gain of Greenhouses

Mila Pucar

Institute of Architecture and Urban Planning of Serbia, Beograd, Serbia and Montenegro

ABSTRACT: A reflecting wall was built into a greenhouse which provided for the reflection back to the ground of sun rays arriving at the northern wall of a greenhouse. Thus, the ground illuminance/irradiance could be substantially increased. The effect is particularly significant in winter when the sun is low throughout the day, so that most of the radiation goes through the greenhouse and the ground radiant power is small. Four types of greenhouses with reflecting walls were considered with increasing efficiency of insolation. A theory was developed, showing that a several-fold enhancement of the ground irradiance and radiant energy should be achievable. The effect of sky (diffuse) radiation is also considered, both in the case of a clear and of a cloudy day. An experimental model as well as a full-scale greenhouse with a reflecting wall with the provision for measuring the ground illumination was built and exposed to the sun. Measurements were made over an extended period of time and the results confirmed qualitatively those obtained from the theory.

Keywords: reflection, greenhouse energy efficiency, energy gain

1. INTRODUCTION

In recent years general awareness has been achieved of the necessity of energy savings in all aspects of life and of the use of new and renewable energy sources. Although it has been used as a source of life ever since human race exists, solar energy, as a freely available and ecologically impecable energy source has drown particular attention in our times in two general directions: (a) in finding a variety of new ways of converting it into other forms of useful energy for different applications and (b) in increasing the efficiency of its conventional use. Use of solar radiation in greenhouses of different types and applications (urban, agricultural, in-house gardens etc.), both for photosynthesis in plants and as heat source, has been a common practice for many centuries. However, it is only that part of sunrays which illuminates the ground that is effectively absorbed by plants, stimulating their development, while a major part is either lost as it passes through glass-structures or is converted into heat when striking walls and other obstacles. It was the purpose of investigations whose results are presented here, to explore different ways of enhancing the use of solar energy in glass-constructions by reducing the amount of sunrays which pass through them.

It is the principle of interrupting sunrays on their course and reflecting them back to the ground, which is used in this case.

The principle of reflection of sun rays is used for concentrating them onto the reactors of solar power plants. The application for enhancing the insolation for other purposes has, so far, scarcely been used [1], [2]. Some time ago, one of the authors (M.P.) proposed the use of this principle in several applications, such as increasing the ground irradiance in greenhouses [3], in glass covered extensions in buildings and for the illumination of northward oriented walls of buildings [4].

In this communication only the use in greenhouses is described, other uses having been elaborated elsewhere [4]. The application of the reflection of sun rays was motivated by the fact that ground illuminance/irradiance due to direct sunlight is of very low intensity in the winter months, even in the case of a clear sky, due to the low incident angle of the radiation during most of the day, the more so the larger is the geographic latitude. Most of the sun rays go through a greenhouse during most of the day (Fig. 1).

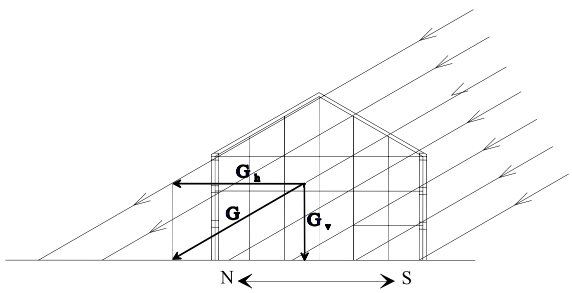

Figure 1: Relative horizontal and vertical component of solar radiation on December 21 for 44° N L.

The diffuse solar radiation is the one which then makes a major contribution to the overall ground irradiation. In order to increase the energy gain (reduce needs for additional energy) and increase illumination of plants, the author had the idea to catch the horizontal component of the sun rays at the northern wall of a greenhouse (in the northern hemisphere) and by reflecting it, direct it to the ground by a suitably inclined reflecting wall [4] made of a material possessing high reflectivity. Four different types of greenhouses were envisaged in the order of increasing sophistication (Fig. 2).

a) a classical greenhouse whose vertical part of the northern wall is covered by a reflecting material (e.g. aluminium foil, spray-metallization of existing glass);
b) a specially constructed greenhouse with the northern wall inclined at the optimum angle and covered by a reflecting material for directing sun rays to the ground;
c) a classical greenhouse with a reflecting panel placed at the northern wall, the inclination of which could be changed by a special mechanism, as to provide the maximal return with the changing incident angle of the sun during a day;
d) a greenhouse with a reflecting wall divided into sections (louvers) which could turn on a vertical axis so as to provide the maximal return with the changing azimuth angle of the sun.

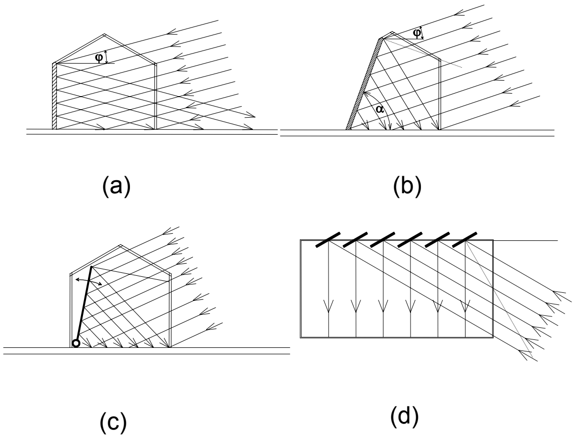

Figure 2: Types of greenhouses using reflection of solar radiation.

It is clear at the first sight that, with any of the above types of greenhouses, a significant increase of insolation of the ground could be achieved. The enhancement of insolation should be larger the lower the sun is, and from dawn to dusk the gain of the ground illuminance and/or irradiance should be larger, the lower the maximum incident angle for the day is.

However, on the other hand, the reflecting wall obstructs a part of the diffuse sky radiation, thus lowering the overall irradiance, the more so the more inclined the wall is.

In this communication the gains which could be achieved in ground radiation by direct sunlight were examined, both theoretically and experimentally. The contributions of the diffuse sky radiation on clear and in cloudy days, were also considered.

2. THEORETICAL ESTIMATES

A quantitative theory was developed based on the Laws of geometrical optics [3,4] which enabled comparative calculations of enhancements of ground illuminance/irradiance in greenhouses of the different types described above.

2.1 Ground irradiance due to direct illumination in a classical greenhouse

The ground irradiance due to direct illumination during a clear sunny day in a classical greenhouse was calculated using an appropriate equation as well as the data on the position of the sun at a geographic latitude of 44°, at different dates of the year.

The dependence of the ground illuminance on the time of a day, for three characteristic dates of the year, based on the value of the normal illuminance of 160 Wm^{-2} is given in Fig. 3.

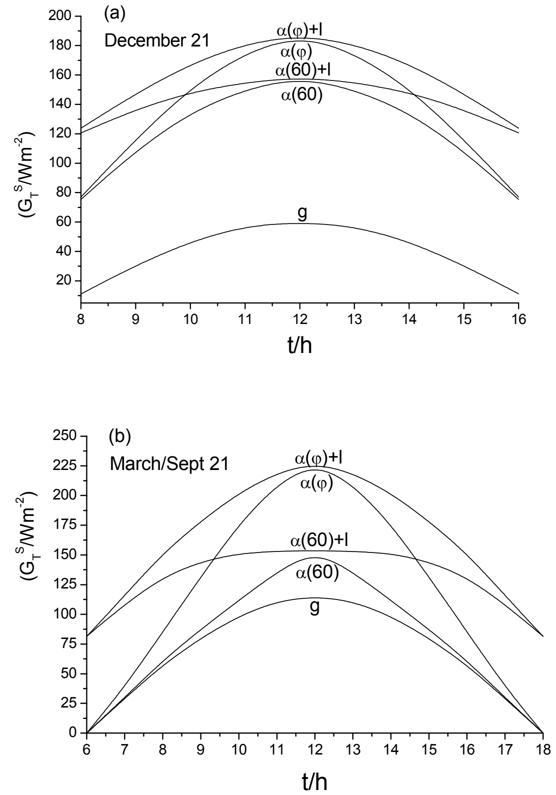

Figure 3: Calculated dependence of the ground irradiance on time for the shortest day of the year (a) and for the equinoces (b) in a greenhouse without (g) and with a reflecting wall inclined at an angle of 60°, (α(60)), as well as with that of changing inclination, (α(φ)), without louvres and the same with louvres (α(60) + l and α(φ) + l).

2.2. Ground irradiance in greenhouses with reflecting walls

In the presence of a reflecting wall of height equal to the width of the greenhouse, the overall ground irradiance due to direct solar radiation was calculated, using the same normal illuminance value as well as the time dependence of φ. The calculation was made for a fixed reflecting wall inclined at an optimum angle of 60°, without and with louvres, taken as an example. Calculations are also made for a reflector with adjustable inclination to follow the increase /decrease of φ during a day ((type (c) as well as type (d)). A greenhouse 9m by 3m in dimensions was taken for the calculations. The results are shown in Fig. 3 as well.

Dividing the calculated illuminances on different days as well as at different times of day, by the ground illuminances obtained in the absence of a reflector, enhancement coefficients were obtained (Fig. 4). One should note that these are independent of the normal illuminance, as it can celles out. It can be seen that significant values of the enhancement coefficients were obtained, particularly in the winter and in the morning and evening hours.

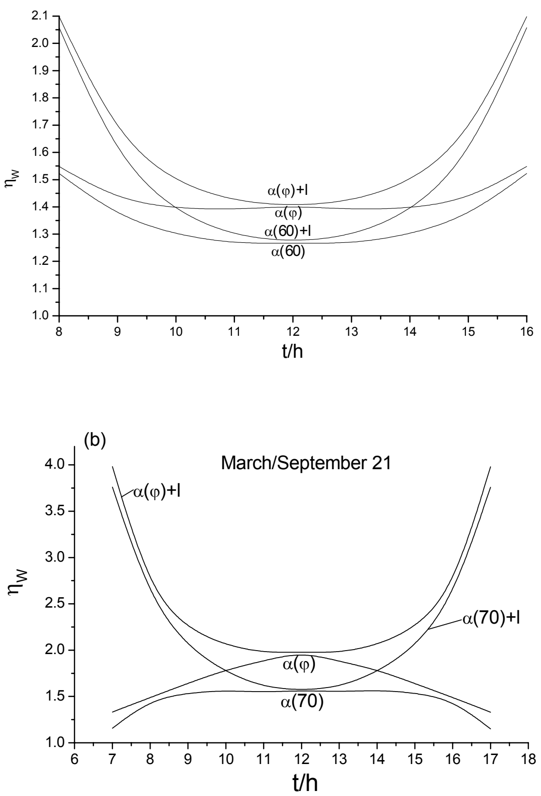

Figure 4: The dependence of the irradiance enhancement coefficient on time, on the shortest day of the year (a) and on the equinoces (b), at 44° NL in a greenhouse with reflecting walls inclined at optimum angles, α(60) and α(70), as well as with those of changing inclination.

One should note that in the case of reflectors with fixed incination there is a dependence of the distance away from the reflecting wall covered by the reflected light on the incident angle of the sunrays. For certain fixed angles α and certain φ , some of the reflected radiation falls outside the greenhouse and the ground irradiance is even, while for others the insolation of the ground is not even. Some parts of the ground, away from the reflecting wall and close to the greenhouse south front, stays without reflected radiation. The advantage of a reflecting wall with adjustable inclination is that the reflected radiation at all times covers the entire ground in the greenhouse and, hence, the irradiance is even throughout the day.

As can be deduced from Figs. 3 and 4, if compared with the irradiance and energy values obtainable in a classical greenhouse (daily energy gains are obtained by integrating the functions of Fig.4), on short winter days there is indeed a significant enhancement of both the average irradiance at the greenhouse ground and the overall energy gain during the entire day. The enhancements increase in the order of increasing sophistication of the greenhouse type and are particularly large in the morning and evening hours. As the length of the day increases, with widening of the span of changing azimuth angle, the enhancement is reduced, so that at the equinox and in the case of reflecting walls of fixed, north-to-south orientation, it becomes negligible, as most of the reflected radiation misses the greenhouse ground. In such a situation the use of the louvres becomes essential. It can be seen that the enhancement of the insolation is indeed very large, which was to be expected, taking into account the situation shown in Fig. 1.

One should note that in the type (d), each louvre, when turned to the angle needed in order to cope with the azimuth angle of the sun, shades part of the neighbouring louvre. The effect is significant particularly in the early morning and late evening hours. Hence, unless the entire reflecting wall is made as a single louvre, the result is expected to be somewhat smaller than the calculated one.

2.3. Effects of diffuse radiation.

Diffuse (sky) radiation can make significant contribution to the overall illuminance of the greenhouse ground [5]. This is particularly the case even with a partly cloudy sky. With heavy overcast skies this becomes the dominant contribution. This affects the result of the use of the reflecting wall in two ways.

On the one hand it increases the overall illuminance of the ground and the daily energy gain. However, as it supplements the illuminance due to direct sunlight equally in greenhouses with reflecting walls and those without them, the enhancement coefficients calculated by dividing the two, are somewhat smaller than those calculated without taking this effect into account.

On the other hand, a reflecting wall prevents sky radiation from the part of the sky behind the wall from reaching the ground. At the same time it also reflects the sky radiation coming from the sky in front of it. It can be calculated that the overall effect of the presence of a reflecting wall is negative as far as the sky radiation alone is concerned. It can further be shown that the two effects compensate each other so that the sky radiation received by the ground is even, but equals about 80% of the radiation received in the absence of the wall. This is a small effect on clear sunny days, but is dominant in cases of heavy overcast skies.

3. EXPERIMENTAL RESULTS

Two kinds of experiments were performed: (a) on a reduced size model construction, simulating a large scale greenhouse and (b) in two full size greenhouses, one of the classical type for control and the other containing a versatile reflecting wall.

3.1. Greenhouse model experiment

A model was made, shown in Fig. 5, which could simulate all the four types of greenhouses with reflecting walls (a) to (d) (Fig. 2). It consisted of a square horizontal panel, 20 cm x 20 cm, with a commercial luxmeter (ELVOS LM-1010) fixed in the center, a vertical panel with a mirror of the same dimensions which could be tilted to selected angles and turned on the vertical axis by 180°. The light illuminance in luxes could be read directly from the attached instrument. With the mirror tilted back by 180°, in order not to obstruct or reflect any radiation from the sky, it represented a classical greenhouse. With the mirror placed vertically it represented the type (a) greenhouse, while by tilting the mirror at different angles it represented cases (b) and (c). Finally, by turning the mirror on the vertical axis to correspond to different azimuth angles of the sun, it represented the type (d) greenhouse.

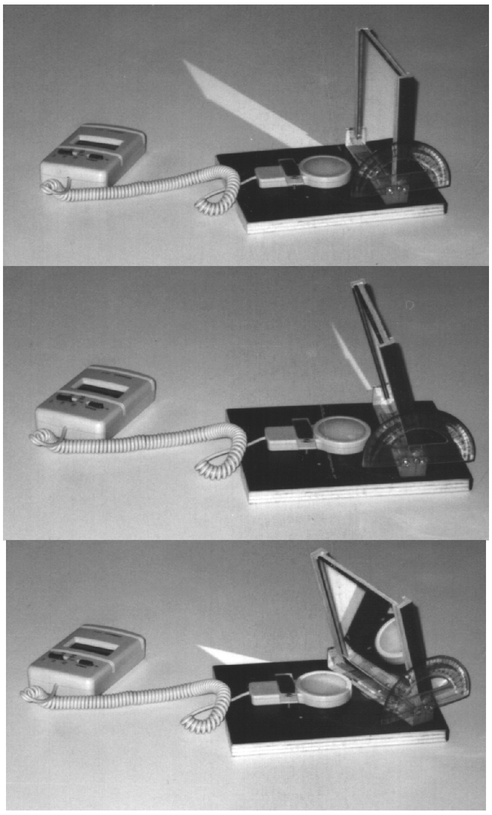

Figure 5: The model simulates the types of greenhouses with reflecting walls

The model was placed on a horizontal support on the roof of the building of the Faculty of Technology and Metallurgy of the University of Belgrade (Serbia) so as to have 360° access to radiation.

Measurements were made from sunrise to sunset at regular time intervals. Also, they were made under different weather conditions, i.e. on an entirely clear day, a partly cloudy day and on a day evenly covered by a heavy overcast.

The effect of the diffuse light in the case of a clear day, was measured by turning the model by 180°, so that the reflecting panel faced south and prevented direct sunbeam from illuminating the luxmeter.

The above theoretical results were confirmed by experimental measurements using the model. The results of measurements of the ground illuminance obtained during 3 different winter days with reflecting walls with different fixed values of α are exemplified by Fig. 6. The time dependence of the illuminance is seen to depend on the situation of the sky. The morning was cloudy on January 24 with subsequent clearance and occasional scattered clouds. A similar situation existed on March 1, while February 1 was a cloudy day. It can be seen that, from the point of view of overall enhancement, the best inclination of the fixed wall is 70°.

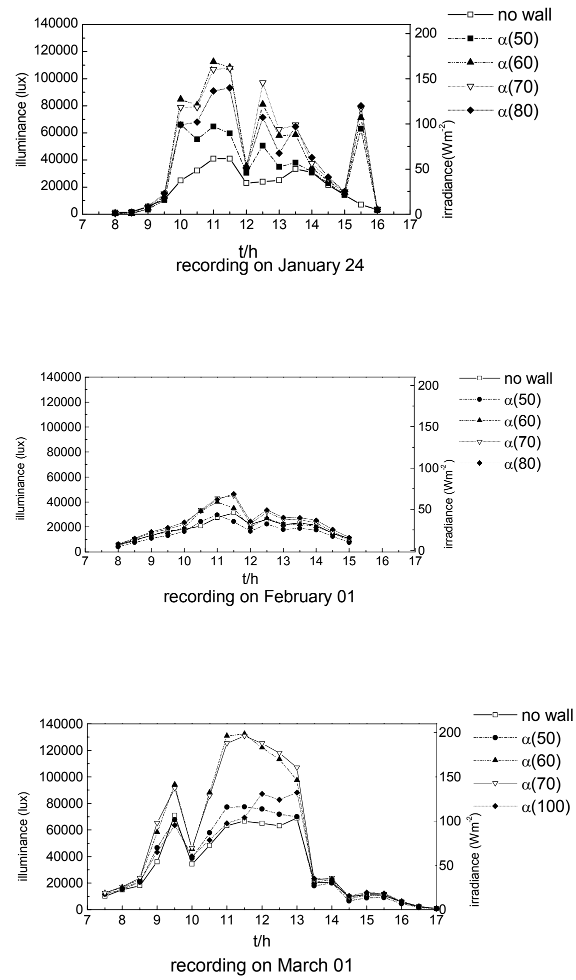

Figure 6: Measured ground illuminances at three different dates without and with a reflecting wall inclined at different angles.

The comparison of the cases when α was adjusted to follow the change of φ during the day, with a classical greenhouse, as well as with the case of a vertical reflecting wall is shown in Fig. 7. It can be seen that a very large increase in the overall ground radiation is obtained with type (c) and (d) greenhouses. The rotation of the wall louvres (type (d)) is seen to have a dominant effect in the morning and evening hours.

The corresponding enhancement coefficients are shown in Fig. 8. They are seen to replicate the general shape derived from the theory (Fig. 4) with a maximum enhancement of up to 400%.

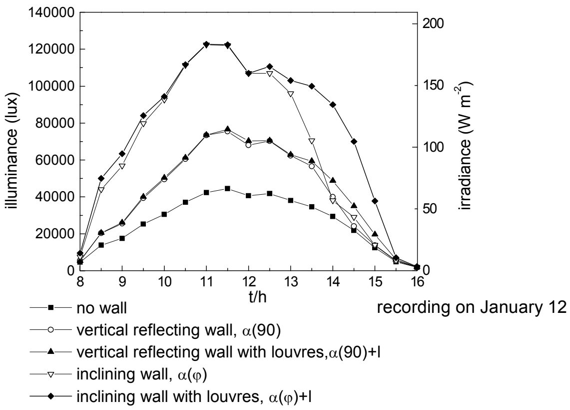

Figure 7: Measured ground illuminances without and with reflecting walls of different types without and with inclination angle adjusted to the sun elevation and to the azimuth angle.

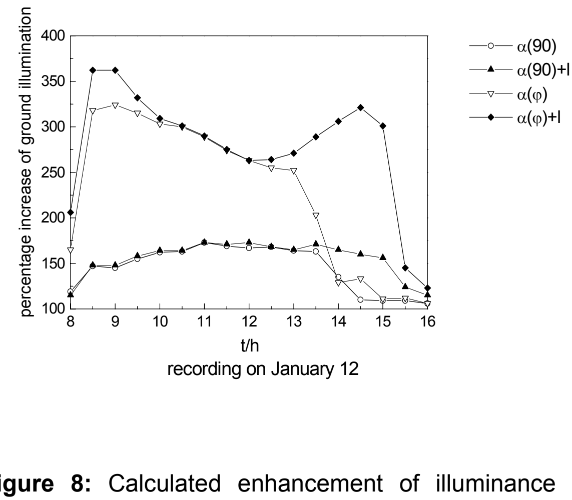

Figure 8: Calculated enhancement of illuminance based on the measurements shown in Fig. 7.

Unsymmetry between morning hours and evening hours in figures 7 and 8 exists because weather conditions were different.

3.2. Full size greenhouses in the field

Two commercial greenhouses, 9 by 3 m in size, were built on the grounds of the "City Greenary" of Belgrade in an open field providing 360° availability of radiation. One of the greenhouses was equiped with a reflecting wall with louvres, which could represent all the four types of reflectors. The other greenhouse was built for control. Instruments were provided for recording illuminance, temperature and humidity, equal in both greenhouses. A special computer programme was made with two functions: a) to provide for the inclination of the wall and the position of the louvres in accordance with the position of the sun (from astronomical data) and b) to provide continuous recording (every five minutes) of the above mentioned physical quantities.

The effect of the reflecting wall on the ground illuminance, temperature and humidity in the greenhouse equiped with the wall, compared to the control-greenhouse, on a relatively sunny winter day is shown as an example in Fig. 9. The enhancement coefficient of illuminance, for the same case, is shown in Fig. 10.

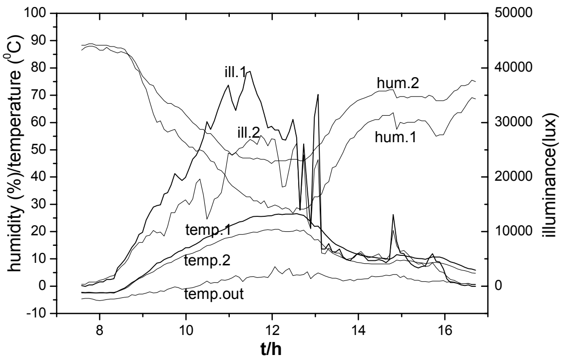

Figure 9: Experimental measurements of illuminance, temperature and humidity in the greenhouse with a reflecting wall with the inclination fixed at 70^0, without the use of louvres, compared to those taken in the control-greenhouse.

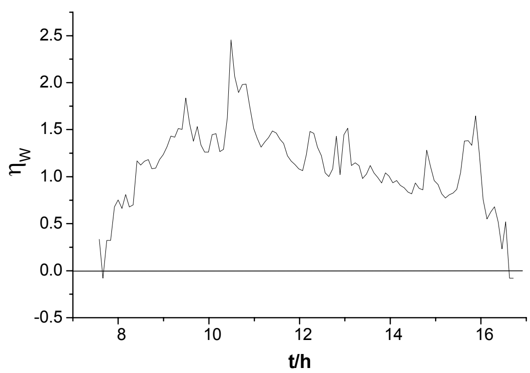

Figure 10: Enhancement coefficient of illuminance for the case shown in Fig. 9.

4. CONCLUSIONS

As shown in the previous sections, the introduction of a reflecting wall at the back of a greenhouse results, both in theory and in the experiment., in a significant enhancement of solar radiation at the ground, at any particular time of the day. Experimental results are seen to confirm qualitatively the calculated ones. The discrepancies are likely to be due to non-ideal weather conditions.

The azimuth angle different from zero, is seen in all the cases to have a dominant effect, in morning and evening hours in particular, the more so the closer the date is to the equinox. At the equinox, at sunrise and sunset, when θ = 90° the reflected light completely misses the greenhouse. However, the overall effect on the energy gain is not very large. The use of louvres (type d) eliminates the θ effect to a significant degree.

The energy yield of the greenhouse with any type of reflecting wall is also significantly increased. Especially large increase is obtained with a reflecting wall with adjustable inclination and louvres. The integrals of the average irradiance during an entire day are shown in Fig. 9, for the shortest winter day and for the equinox. The values for other days would be expected to lie in-between these two extremes.

The increase in energy efficiency is obtained by calculating the ratio between the total energy received during a day in a greenhouse with a reflecting wall and that in a classical greenhouse, η_{Wh} . The values of η_{Wh} for the two dates at walls without louvres amount to 3.17 and 1.51 respectively. Addition of louvres increases those values to 3.64 and 2.12 resp. In the case of a reflecting wall with adjustable inclination the η_{Wh} at December 21 amounts to 3.49 without louvres and 4.06 with louvres. At the equinoxes the values are 1.74 and 2.45 respectively. Hence, in general the energy balance is significantly shifted towards saving classical energy for heating or lighting. The four times larger amount of energy received with the help of the reflecting wall with the adjustable inclination and louvres in winter times obtained in theory attracts special attention to this project.

The experimental measurements in the greenhouses in the open field with and without the reflecting wall are encouraging. In the preliminary results, as are those presented here, the wall was fixed at an inclination of 70° and the louvres were placed flat. The results of course, fall significantly behind the theoretical ones mostly because of the effect of cloudiness. Still, significant enhancement is found both of illuminance at a moment of clear sky and of the overall daily energy gain (36% in the case shown in Fig. 9).

Plants that were planted late in the autumn exhibited differences in their growth, the ones in the greenhouse with the reflecting wall being significantly richer in appearance and larger in size. This was likely to be due to some synergetic effect of increased illuminance and of higher temperatures recorded in that greenhouse.

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