New Glass Coatings for High Insulating Greenhouses without Light Losses - Energy Saving, Crop Production and Economic Potentials

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Abstract

More than 90% of the Dutch greenhouse area is covered with single glass. Energy losses through the covering are high during the heating period (winter) but energy requirements are also high during the cooling period (summer) in the case of semi-closed greenhouses. Until now, light losses of insulating coverings prevented growers from using double glass or plastic film. However, increasing energy prices allow new developments. Wageningen UR Greenhouse Horticulture studied the possibilities to use modern glass coatings to increase light transmission and save energy. Several glass types (standard glass, 90+ glass, low-iron glass) were covered with different anti-reflection coatings from different producers. Double glasses were produced; their optical properties were determined. It was possible to produce double glasses with new coatings having a higher light transmission than traditional single greenhouse glass (83-85% for hemispherical (diffuse) light, compared to 82-83% for traditional single glass) and a k-value of 3.6 W m^{-2} K^{-1} (compared to7.6 W m^{-2} K^{-1} of a traditional single glass). Other double glasses were produced using a combination of anti-reflection and modern low-emission coatings, reaching an even lower k-value of ≈2.4 W m^{-2} K^{-1}, however, showing a slight light loss (78.5% for hemispherical (diffuse) light). Calculations of greenhouse climate (temperature, humidity, CO_2) and energy consumptions year-round were carried out with a validated dynamic climate model. Additionally the effects on tomato production (dry matter) were calculated for the different prototypes of coated and insulated glass. Double materials show the highest energy saving with 25-33%, depending on the composition but also low-emission coatings on single glass decrease the energy use with 15-20%. Economic calculations with current tomato and energy prices showed that single and double glasses with anti-reflection coating currently have the highest potential.

INTRODUCTION

With increasing energy prices the need for energy saving is high in horticulture. The energy saving potential of double layered covering materials for greenhouse applications have been pointed out in many research studies before (e.g., Zhang et al., 1996; Andersson and Nielsen, 2000; Bot, 2001; Villeneuve et al., 2005). However, until now suitable greenhouse covering materials combining both a high transmission and a high insulation value for greenhouse applications are missing. Though many studies focussed on the development of modern materials in order to save energy and/or achieve a better cooling of greenhouses (e.g., Swinkels et al., 2001; Waaijenberg et al., 2004; Hemming et al., 2006, 2007), the optimum combination of materials' properties is still not found. Since more than 90% of the Dutch greenhouse area is covered with single glass, energy losses through the covering are high during the heating period (winter) but also during the cooling period (summer) in semi-closed greenhouses. This research will show the future potentials of recently developed glass coatings (anti-reflection and low-emission) for single and double materials in order to have a high crop production as well

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as high energy savings year-round.

MATERIALS AND METHODS

Covering Materials

In a pre-study several glass types were evaluated: greenhouse glass, greenhouse glass 90+, greenhouse glass low-iron. Glasses were covered with different anti-reflection coatings by three different producers: SA, CS and GG, applied by sputtering or etching. Double glasses were produced from all glasses; their optical properties were determined using modern light measurement equipment. The materials used are shown in Table 1 and Figure 1. In a follow-up study different prototypes of covering materials produced by GG were evaluated in order to study their energy saving potential, and their plant performance. Glasses were covered with an anti-reflection coating having partly near infrared (NIR) reflective properties, others were combined with a low-emission coating for a higher NIR-reflection. All single glasses had a thickness of 4 mm, double glasses had a distance of 8 mm (split). The materials used are shown in Table 2 and Figure 2.

Optical Properties

The optical properties of the glasses described above were determined at Wageningen UR Greenhouse Horticulture laboratory in The Netherlands. The total light transmission in the PAR range (τ_{PAR} in 400-700 nm) of samples with the size of 50×50 cm was measured with a large and a small integrating sphere (port opening 40×40 cm or 8×8 cm). Data were gathered by means of a diode-array spectrophotometer with a resolution of 1 nm. The PAR transmission for perpendicular light ($\tau_{PAR\ p}$) and the PAR transmission for hemispherical (diffuse) light ($\tau_{PAR\ h}$) were determined following NEN 2675. The total solar spectrum (300-2500 nm) was measured on a Perkin Elmer spectrophotometer. The emission coefficient was determined following EN12898. All relevant data are shown in Table 1 and 2 and Figures 1 and 2. From measured optical data the amount of PAR energy (400-700 nm) and the amount of NIR energy (700-2500 nm) entering the greenhouse was calculated. For a clear sky the radiation energy per nanometer wavelength is defined by CIE 85 (1989). Multiplying the global radiation per wavelength (or spectral range) with the measured spectral transmission of a covering material gives the fraction of the energy entering through the material into the greenhouse.

Dynamic Climate Model

Model calculations of greenhouse climate and energy consumption were carried out with the KASPRO model developed by de Zwart (1996). The dynamic simulation model KASPRO can simulate a full-scale virtual greenhouse based on the construction elements, greenhouse equipment, different covering materials and their properties (transmission, reflection, emission), set points for inside climate and the outside climate of a given location. Output are several climate parameters, such as air temperature, relative humidity, CO_2-concentration and energy consumption. The model is based on the computation of relevant heat and mass balances (Bot, 1983). The heat balances describe both the convective and radiative processes. The mass balances are constituted from exchange processes through leakage and ventilation (de Jong, 1990). They include canopy transpiration (Stanghellini, 1987) and condensation at cold surfaces. The mass balances around the CO_2-concentration are based on losses of CO_2 by ventilation and photosynthesis, and gains of CO_2 by dosing and respiration. Greenhouse climate is controlled by a replica of commercially available climate controllers. A standard Venlo glass-greenhouse with a trellis bar of 9.6 m carrying two roofs of 4.8 m is assumed with a distance between two trellis of 5 m for all calculations. Three glass panes of 1.675 m are in between two trellis bars. A standard energy screen is installed inside the greenhouse. The total set of differential equations is solved numerically (de Zwart, 1996). Tomato is chosen as model crop. Plant datum is 8 December, last harvest takes place on 25

November the next year. Climate set points are according to Dutch horticultural practice. Crop production is calculated in terms of dry matter production.

RESULTS AND DISCUSSION

In a pre-study several glass types (greenhouse glass, greenhouse glass 90+, greenhouse glass low-iron) were covered with different anti-reflection coatings by three different producers (SA, CS, GG). Double glasses were produced from all glasses (Table 1). The light transmission of the basic materials greenhouse glass, greenhouse glass 90+, greenhouse glass low-iron differ, depending on their origin and their amount of iron content. Standard greenhouse glass single has a hemispherical (diffuse) light transmission of 82.4%, greenhouse glass 90+ single of 83.2% and greenhouse low-iron glass single of 84.4%. Applying an anti-reflection coating results in a decrease of reflection from about 12 to about 5.5-6.5% (data not shown). The coating from SA results in an increase of 6.8% transmission for hemispherical (diffuse) light in average. Applying an anti-reflection coating of CS or GG results in an increase of 7.3-7.4% transmission for hemispherical (diffuse) light. If double glasses are produced from these basic glasses, the application of an anti-reflection coating on all sides of the glasses has a large effect on the light transmission. While the light transmission of a double glass without any coating has a transmission for hemispherical (diffuse) light of 71.6-75.1% depending on the original glass type (Table 1), these transmission values are increased up to 82.2-86.0%. That means that, while traditional double glass is loosing about 10% of light, modern double glass, coated with an anti-reflection coating has comparable transmissions as traditional single greenhouse glass. Some glasses will even give higher light levels inside the greenhouse. From the spectral transmission of the different glasses with anti-reflection coating (Fig. 1) we see, that the CS and GG coating are increasing the whole range of PAR (400-700 nm), while the SA coating mainly increases the red part of the spectrum. It is remarkable that the GG coating cuts a large part of UV (300-400 nm) and is reflecting part of NIR (700-2500 nm).

For a follow-up study several prototypes of glass covering materials (single and double) were produced and covered with different coatings (anti-reflection coating with partly NIR reflection and low-emission coating with high NIR reflection). The aim was both to increase light transmission by adding an anti-reflection coating and/or to reduce energy losses by adding a low-emission coating and by producing double layered glass panes decreasing the k-value. Measurements of the optical properties (Table 2) combined with greenhouse light transmission data show that differences in global radiation sum and PAR radiation sum on crop level occur (Table 3). While the anti-reflection coating increases light transmission of single and double materials, the low-emission coating slightly reduces light transmission, when used as double material. On the other side the anti-reflection coating reduces the amount of global radiation by reflecting part of the NIR, which leads to an improved k-value, from 7.6 to 7.1 W m^{-2} K^{-1}. The low-emission coating reduces the amount of global radiation on crop level even more by reflecting higher amounts of NIR, decreasing the k-value to 5.7 W m^{-2} K^{-1}. Both double materials show a highly decreased k-value of 3.6 and 2.3 W m^{-2} K^{-1} in the case of only anti-reflective coating and combined anti-reflective and low-emission coatings respectively. That leads to energy savings in winter. One of the research questions is if this is also advantageous in summer, in cooled greenhouses.

Calculations for a virtual traditional tomato greenhouse equipped with different GG glasses were carried out. Table 3 shows the difference in modelled (inside) cover temperature at day and night time. The double glasses and the low-emission coating cause a higher cover temperature. This results in a lower condensation towards the inner surface of the cover and in an increase of humidity levels. Therefore a need for higher ventilation occurs (Table 3). Double layered coverings show a lower CO_2 concentration inside the greenhouse especially during spring until autumn.

Looking deeper into that mechanism, we can conclude that the CO_2 lack is on the one hand caused by a lower CO_2 production by the boiler, due to a lower energy consumption of the greenhouse with double glass or with low-emission coating. On the other hand it is caused by a higher need for ventilation due to higher humidity levels, but also because of higher temperatures and lower heat losses due to the lower k-value. This effect is explained in Figure 3. The single material with low-emission coating shows a much higher cover temperature than the reference material. This leads to higher convective energy losses. At the same time radiation losses are very low and compensate this effect. This situation is advantageous in winter, the result is a lower energy consumption than in the reference. However, in summer low radiation losses are disadvantageous, since that leads to higher temperatures inside the greenhouse and a higher need for ventilation. Double materials show comparable effects, energy losses are even lower in winter due to the insulating split (Fig. 3), in summer the low k-value leads to a higher need for ventilation (Table 3). In case of semi-closed greenhouses the need for cooling will be increased for materials with low-emission coating even though the amount of NIR coming inside the greenhouse is reduced (Table 6). The same is true for double materials, the low k-value does not seem to be advantageous during hot periods.

The combination of CO_2, temperature, humidity and PAR radiation results in a net photosynthesis production (dry weight). Year round dry weight production is shown in Table 4. While it is 8.3 kg m^{-2} in the reference situation (equal to about 54 kg fresh weight), it is increased by single glass with anti-reflection coating to 9.0 kg m^{-2} dry weight production. The double glass with anti-reflection coating gives the same result as the reference, since the PAR levels are higher but a lack of CO_2 occurs. The double glass with anti-reflection and low-emission coating results in a decreased dry weight production of 7.6 kg m^{-2}. The last is mainly caused, not by a lower PAR transmission, but by a large lack of CO_2 (Table 3). Additional CO_2 can be applied from an external source in order to compensate for this lack of CO_2. If this is done, the dry matter production can be increased to levels above the reference in case of GG single AR-AR and GG double AR-AR-AR-AR. GG single AR-lowε will be equal to the reference. In case of GG double AR-AR-lowε-AR dry weight production is still below reference since PAR transmission remains the limiting factor for production (Table 4).

The year-round gas consumption is 34.5 m^3 m^{-2} in the reference and 25.7 and 23.1 m^3 m^{-2} in case of the GG double materials without and with low-emission coating respectively (Table 3). Double materials are able to reduce the energy consumption with 25% for GG double AR-AR-AR-AR. GG double AR- lowε-AR-AR has the highest energy saving with 33%. Extra energy losses due to a higher need for ventilation caused by higher humidity levels are already included in these figures. The energy consumption of GG single AR-AR is slightly increased. Although PAR transmission of the glass is higher than the reference, the partly NIR blocking effect of the coating (Fig. 2) causes a higher energy consumption during the heating period. This is not the case for other anti-reflection coatings from SA and CS as used in the pre-study. Since those glasses increase the amount of global radiation coming inside the greenhouse (Fig. 1), energy consumption is decreased by 1-2% in case of single glasses (Hemming et al., 2006).

If we carry out an economical analysis, we can conclude that there is some possibility to invest in new materials (Table 5). In the economic analysis benefits from the changed crop yields under the different covering materials are considered, as well as energy costs related to changed gas consumption. Other variable costs like labour, water, nutrients, crop protection, substrate, packaging and auction costs vary with crop yield and are calculated on yearly base considering typical average Dutch costs and prices from KWIN (2008). Investment costs for greenhouse and equipment are not considered and are assumed to be equal in all situations. The result of the economic analysis is the possible extra yearly investment for the covering material and necessary adaptations of the greenhouse construction (in case of double materials). Single anti-reflection coated glass and also double anti-reflection coated glass are most beneficial with a possible yearly investment of € 2.0-2.5 per m^2. The latter is more sustainable in terms of lower energy consumption, however, also more expensive. The use of low-emission coatings does not seem to be very attractive (€ 0.90 possible investment per m^2 per year). The use of external CO_2 can overcome part of the disadvantages during summer and improves the possible yearly investment for the covering up to € 1.32 per m^2 per year (data not shown).

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Tables

Table 1. Optical properties of different greenhouse glasses from three different producers (SA, CS, GG) with anti-reflection coatings.

	Type greenhouse glass	Type coating	Transmission perpendicular $\tau_{PAR\ p}$ (-)	Transmission hemispherical $\tau_{PAR\ h}$ (-)
CS	basic single	no	0.893	0.824
CS	basic single	AR-AR	0.942	0.893
CS	basic double	no	0.808	0.716
CS	basic double	AR-AR-AR-AR	0.897	0.822
CS	low-iron single	no	0.910	0.844
CS	low-iron single	AR-AR	0.959	0.911
CS	low-iron double	no	0.840	0.751
CS	low-iron double	AR-AR-AR-AR	0.929	0.860
SA	90+ single	no	0.903	0.832
SA	90+ single	AR-AR	0.970	0.906
SA	90+ double	no	0.829	0.732
SA	90+ double	AR-AR-AR-AR	0.942	0.836
GG	90+ single	no	0.903	0.832
GG	90+ single	AR-AR	0.965	0.905
GG	90+ double	no	0.829	0.732
GG	90+ double	AR-AR-AR-AR	0.934	0.850

Table 2. Optical properties of different greenhouse glasses (GG) with anti-reflection and/or low-emission coatings.

Type greenhouse glass	Type coating	Transmission perpendicular $\tau_{PAR\ p}$ (-)	Transmission hemispherical $\tau_{PAR\ h}$ (-)	Emission coefficients $\varepsilon_{up}/\varepsilon_{inside\ up}$ / $\varepsilon_{inside\ down}/\varepsilon_{down}$ (-)	NIR reflection factor (-)	k-value material ($Wm^{-2}K^{-1}$)
Single (ref)	no	0.897	0.822	0.89/-/-/0.89	0.00	7.60
Single	AR-AR	0.965	0.905	0.85/-/-/0.85	0.24	7.14
Single	AR-lowε	0.901	0.838	0.85/-/-/0.11	0.32	5.73
Double	AR-AR-AR-AR	0.934	0.850	0.85/0.85/0.85/0.85	0.36	3.61
Double	AR-AR-lowε-AR	0.872	0.785	0.85/0.17/0.85/0.85	0.42	2.37

Table 3. Year-round global and PAR radiation, CO_2-concentration, covering temperature (inside), condensation at covering, vapour loss through ventilation openings and relative humidity under different greenhouse glasses calculated by KASPRO.

	Ref	GG single AR-AR	GG single AR-lowε	GG double AR-AR-AR-AR	GG double AR-AR-lowε-AR
Global radiation sum at crop level ($kJ.cm^{-2}$)	265.1	252.4	223.1	224.2	199.5
PAR radiation sum at crop level ($kJ.cm^{-2}$)	132.7	143.2	132.7	136.6	126.2
CO_2 concentration (ppm)	737	738	706	701	689
Window opening (%)	21.9	21.4	23.8	24.0	25.2
T_{cov} day (°C)	14.7	14.7	17.3	17.7	19.8
T_{cov} night (°C)	10.2	10.2	12.5	12.8	13.6
Relative humidity day (%)	85	85.4	86.5	87.1	87.2
Relative humidity night (%)	84.3	84.3	87.6	88.1	88.7
Condensation at covering ($kg.m^{-2}$)	113.6	114.9	49.7	36.5	10.5
Vapor loss by ventilation ($kg.m^{-2}$)	495.3	483.6	536.8	547.4	573.2

Table 4. Year-round energy consumption, dry weight production and CO_2 concentration under different greenhouse glasses calculated by KASPRO, CO_2 use from boiler only and additional CO_2 use from an external source.

CO_2 source		Ref	GG single AR-AR	GG single AR-lowε	GG double AR-AR-AR-AR	GG double AR-AR-lowε-AR
Boiler	CO_2 concentration 11:00-16:00 h (ppm)	747	750	721	715	704
	Gas use from boiler ($m^3.m^{-2}$)	34.5	35.5	28.4	25.7	23.1
	Dry weight production ($kg.m^{-2}$)	8.3	9.0	8.0	8.3	7.6
	Dosage CO_2 ($kg.m^{-2}$)	26.1	27.1	24.4	25.2	24.8
Boiler and external	CO_2 concentration 11:00-16:00 h (ppm)	798	800	794	790	787
	Gas use from boiler ($m^3.m^{-2}$)	33.7	34.7	27.7	25.0	22.4
	Dry weight production ($kg.m^{-2}$)	9.0	9.8	9.0	9.3	8.5
	Dosage CO_2 ($kg.m^{-2}$)	43.5	43.8	46.1	47.3	48.3

Table 5. Economic analysis of different covering materials considering benefits from the crop yield, energy costs related to gas consumption and other variable costs on yearly base (traditional greenhouse).

	Ref	GG single AR-AR	GG single AR-lowε	GG double AR-AR-AR-AR	GG double AR-AR-lowε-AR
Benefit/crop yield (€.m^{-2}.$year^{-1}$)	46.96	50.81	45.52	46.88	42.67
Energy costs/gas consumption (€.m^{-2}.$year^{-1}$)	10.40	10.70	8.66	7.91	7.16
Variable costs (€.m^{-2}.$year^{-1}$)	23.73	25.09	23.14	23.63	22.16
Total benefit - costs (€.m^{-2}.$year^{-1}$)	12.83	15.03	13.72	15.35	13.36
Possible yearly investment for greenhouse covering (compared to reference (€.m^{-2}.$year^{-1}$))	-	2.19	0.89	2.51	0.53

Table 6. Year-round energy consumption (m^3 gas m^{-2}) under different greenhouse glasses (GG) with anti-reflection and/or low-emission coatings calculated by KASPRO (semi-closed, cooled greenhouse).

	Ref	GG Single AR-AR	GG single AR-lowε	GG double AR-AR-AR-AR	GG double AR-AR- lowε-AR
Gas use ($m^3.m^{-2}$)	33.8	34.9	28.2	25.4	23.0
Gas use (%)		3.4	-16.5	-24.6	-32.0
Cool energy ($MJ.m^{-2}$)	450	409	470	481	524
Cool energy (%)		-9.3	4.4	6.9	16.3

Figures

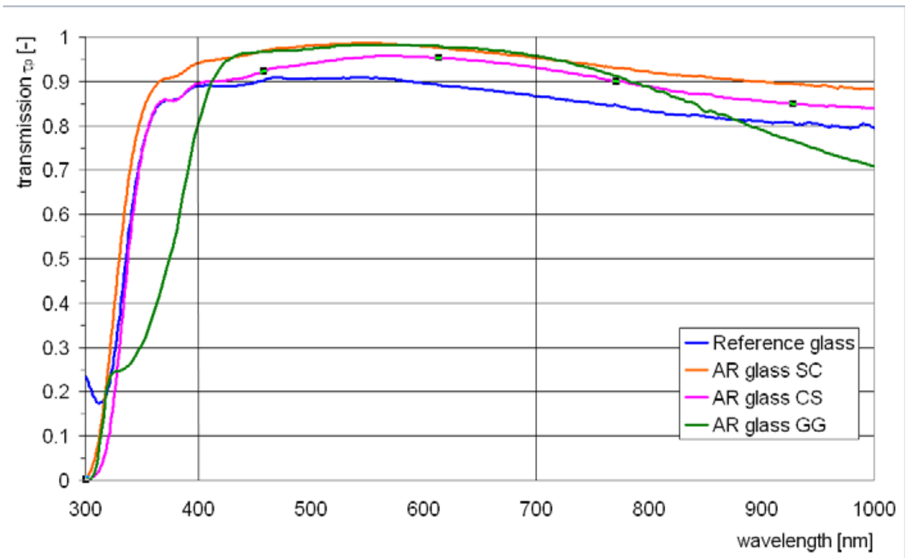

Fig. 1. Spectral transmission of glass with different anti-reflection coatings from three different producers (SA, CS, GG) for perpendicular PAR (400-700 nm).

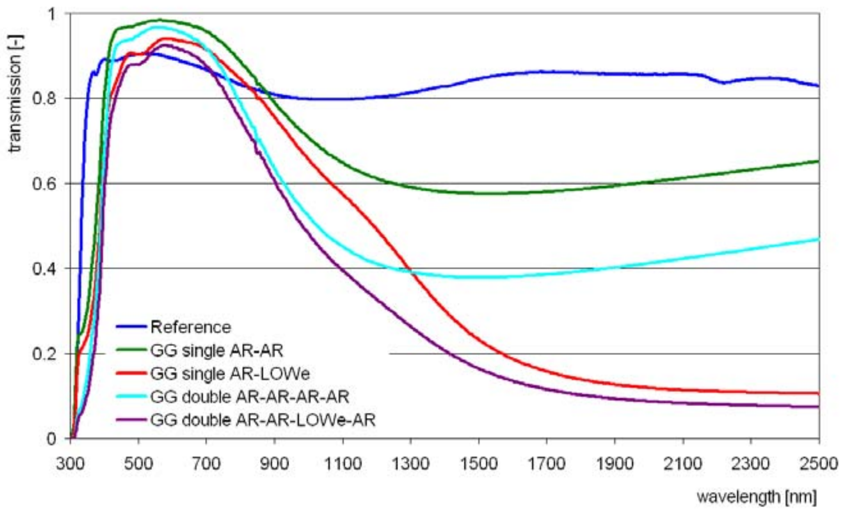

Fig. 2. Spectral transmission of glass with coatings (anti-reflection and low-emission) for perpendicular global radiation (300-2500 nm).

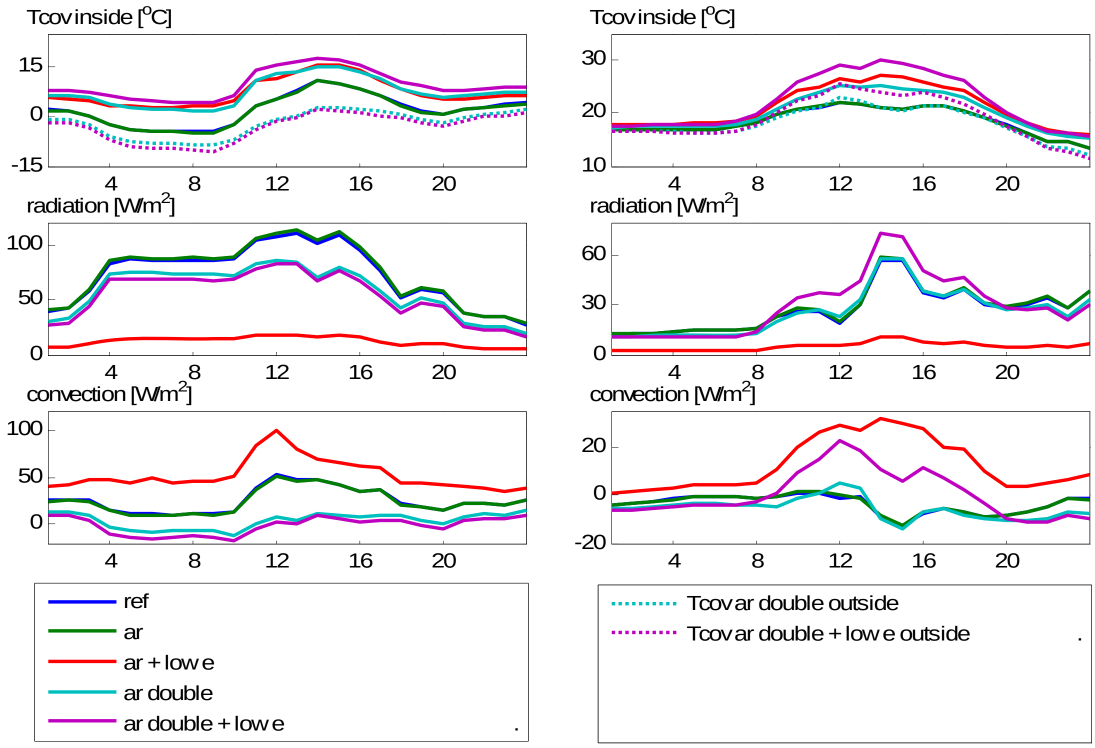

Fig. 3. Cover temperature, energy loss by radiation and convection under different greenhouse glasses (GG) with anti-reflection and/or low-emission coatings calculated by KASPRO on a typical winter (left) summer (right) and day.