Feasibility study thin glasses for greenhouse roof designs

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Referaat
In deze studie is de haalbaarheid van de toepassing van flexibele dunne glazen in kassen onderzocht. Met de ontwikkeling van dunne maar zeer sterke glasplaten zoals bijv. voor mobiele telefoons ontstaan nieuwe mogelijkheden voor nieuwe kasdekvormen en nieuwe mogelijkheden om deze in meerlaagse beglazing toe te passen als hoogisolerend kasdek. Flexibel dun glas is een gehard glas. Terwijl standaard gehard glas een thermisch proces doorloopt gaat het hier om een chemisch proces, waardoor het glas veel sterker wordt, waardoor de mogelijkheid ontstaat het dunner te maken en te buigen. Door het toevoegen van nanocoatings kan de reflectie verminderd en de lichttransmissie verhoogd worden. Zo kunnen meerlaagse kasdekken worden gemaakt met als resultaat een hogere lichttransmissie dan nu beschikbare meerlaagse polycarbonaat kanaalplaten (PC), maar ook een hogere transmissie dan nu gebruikt dubbel isolatieglas. De studie laat zien dat dit tot 20% additionele energiebesparing gebaseerd op warmte leidt bij Phalaenopsis. Dunne glazen zijn bijzonder sterk en kunnen ook in gebogen vorm worden toegepast. Hierdoor worden nieuwe kasdekvormen met glas mogelijk. Vooral het lage gewicht biedt hier voordelen. Belangrijke mechanische aspecten en bottlenecks hiervoor zijn in kaart gebracht. Door beperkingen in beschikbare afmetingen en hoge prijzen zal de toepassing van dunnen glazen in kassen verder weg in de toekomst liggen.

Abstract
In this study, the feasibility of the application of flexible thin glass in greenhouses was investigated. With the development of thin but very strong glass plates like for mobile phones, new possibilities are being created for new greenhouse roof designs, the usage in multi-layered glass roof give possibilities for high-insulation greenhouse coverings. Flexible thin glass is a tempered glass. While standard tempered glass goes through a thermal process, this is a chemical process, which makes the glass five times stronger, creating the possibility of thickness reduction and bending. By adding nanocoatings the reflection can be reduced and the light transmission can be increased. Multi-layered greenhouse roofs can be created, resulting in a higher light transmission than currently available multilayer polycarbonate (PC) sheets, but also a higher transmission than today's insulating double glass. The study shows that such glass combinations lead to an additional 20% energy savings based on heat demand for Phalaenopsis. Thin glasses are particularly strong and can also be used in curved form. This makes new greenhouse roof designs with these glasses possible. Especially the low weight offers advantages here. Important mechanical aspects and bottlenecks for the use in greenhouses have been mapped out. Due to limitations in today's available dimensions and high prices, the use of thin glass in greenhouses will be further away in the future.

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1 Samenvatting

1.1 Achtergrond

Uit eerder onderzoek in de VenLowEnergy kas is gebleken dat met een dubbel kasdek met additionele schermen meer dan 50% energie kan worden bespaard in groenteteelten vergeleken met de gangbare praktijk. Bij de op hoge temperaturen geteelde sierteeltgewassen wordt kasisolatie vaak gerealiseerd door gebruik van meerdere schermen en gebruik van meerlaagse polycarbonaat platen (PC) met een zeer lage lichtdoorlatendheid van ca. 60%. In het verleden werd als alternatief meerlaagse polymethylmethacrylaat platen (PMMA, acrylaat) gebruikt, welke een hogere transmissie hebben maar i.v.m. brandveiligheid niet meer verzekerd kunnen worden. Alternatieve oplossingen zijn daarom nodig. Een zeer hoge isolatiewaarde van het kasdek samen met energiezuinige teeltmethodes maakt het ontwerp van een klimaatneutraal kasproductiesysteem voor onbelichte teelten mogelijk.
Met de ontwikkeling van dunne maar zeer sterke glasplaten voor mobiele telefoons (bijv. Leoflex™, Falcon™ van Asahi Glass) ontstaan nieuwe mogelijkheden voor nieuwe kasontwerpen en nieuwe mogelijkheden om deze in meerlaagse vormen toe te passen als hoogisolerend kasdek. Flexibel dun glas is een gehard glas. Terwijl standaard gehard glas een thermisch proces doorloopt gaat het hier om een chemisch proces, waardoor het glas veel sterker wordt, waardoor de mogelijkheid ontstaat het dunner te maken en te buigen. Dunne glazen hebben een verminderde absorptie en door het toevoegen van coatings een verminderde reflectie en verhoogde lichttransmissie en kunnen naar verwachting in drie of meer lagen worden toegepast als kasdek met als resultaat een beduidend hogere lichttransmissie dan nu beschikbare meerlaagse PC platen, maar ook een hogere transmissie dan nu incidenteel gebruikt dubbel isolatieglas. Met nieuwe technieken kan ook een diffuse coating met een goed lichtverstrooiingspatroon worden aangebracht. Door deze aan de binnenkant te leggen van een glaspakket, ontstaat er geen verhoogd risico op vervuiling. In geval van enkellaagse coatings kunnen deze aan de binnenzijden worden aangebracht waardoor ze minder slijtgevoelig zijn. Dunne glazen zijn, door de combinatie van de kleine dikte en hoge sterkte, zeer buigzaam en kunnen daarom ook in gebogen vorm worden toegepast. Hierdoor worden nieuwe kasdekvormen met glas mogelijk. Ze zijn licht in gewicht, waardoor de kasconstructie niet zwaarder hoeft te worden en nieuwe ontwerpen mogelijk worden. Qua kosten is te verwachten dat er minder glasmateriaal nodig is, het chemisch hardingsproces op termijn vergelijkbaar is met het traditionele harden en kosten voor coatings of diffuus behandelingen ook vergelijkbaar zijn met huidige bekende methodes. Het maken van isolatieglas brengt op dit moment hogere kosten met zich mee, in toekomstige oplossingen moet erover nagedacht worden of er meerlaags isolatieglas gemaakt moet worden of dat meerdere lagen glas in nieuwe dekprofielen geïnstalleerd kunnen worden. Slimme en goedkope oplossingen hebben altijd de voorkeur. In deze studie wordt de haalbaarheid van de toepassing van flexibele dunne glazen in kassen onderzocht.

1.2 Doelstelling

1.2.1 Technische doelstellingen

De studie richt zich op de haalbaarheid van de toepassing van flexibele dunne beglazing in kassen om hierdoor óf extra hoge isolatie óf nieuwe kasdekvormen te realiseren.
In het geval van het technische doel van extra hoge isolatie worden materialen ontwikkeld die een vergelijkbare of hogere energiebesparing realiseren dan huidige polycarbonaat platen met gelijktijdig een aanzienlijk hogere lichttransmissie.
Er wordt naar gestreefd dat (op termijn) een meerlaags nieuw flexibel glas traditioneel dubbel glas qua isolatie of qua kosten kan verslaan en dat het polycarbonaat qua lichttransmissie en qua isolatie kan verslaan.

1.2.2 Energiedoelstellingen

In het geval van toepassing van flexibele dunne glazen in drie of meer lagen ontstaat een kasomhulling met extra hoge isolatie. Uit eerder onderzoek in de VenLowEnergy kas is gebleken dat met een dubbel kasdek met additionele schermen meer dan 50% energie kan worden bespaard in groenteteelten. Uit eerder onderzoek is ook gebleken dat teeltmethodes die de verdamping beperken in perioden dat er verwarmd wordt en het gebruik van energiezuinige ontvochtigingsinstallaties met warmteterugwinning het energieverbruik op warmte met 70% kunnen verlagen. Met meerlaagse isolatie neemt de warmtevraag verder af zodat de totale energiebesparing hoger zal zijn dan in de VenlowEnergy kas. Het energieverbruik van een tropisch potplanten gewas zal uitkomen op ca. 10-15 m^3/m^2/jaar.

1.2.3 Nevendoelstellingen

In het geval van toepassing van flexibele dunne en lichte beglazing als vervanging van folies worden nieuwe kasdekvormen mogelijk en kan een kasdek conceptueel nieuw worden ontworpen.

1.3 Werkpakketten en resultaten

In verschillende werkpakketten is onderzoek naar de optische, thermische en mechanische eigenschappen van ultra dun glas uitgevoerd. Hiervoor heeft AGC glasmonsters in verschillende diktes (0.55-1.3 mm) aangeleverd, zijn er verschillende oppervlaktebehandelingen (diffuus, AR) opgebracht door Glascom/DA Glass en AGC, werden glaspakketten met een verschillend aantal lagen (1-4) geproduceerd door WUR voor diverse metingen en heeft WUR de energiebesparing voor een Phalaenopsis teelt berekend. De resultaten van het onderzoek zijn in detail weergegeven in hoofdstukken 4 t/m 7, een samenvatting volgt hieronder.
Daarnaast werd in een aantal workshops en bedrijfsbezoeken gebrainstormd over nieuwe mogelijke kasdekvormen en nieuwe kasconcepten. Deze zijn in detail weergegeven in hoofdstuk 8.

1.3.1 Optische eigenschappen

Glazen in verschillende diktes (0.55-1.3 mm) zijn aangeleverd door AGC, verschillende oppervlaktebehandelingen (diffuus, AR) zijn opgebracht door Glascom/DA Glass en AGC en er werden glaspakketten met een verschillend aantal lagen geproduceerd door WUR. Hiervan werden de optische eigenschappen bepaald. In de resultaten is te zien dat de invloed van de dikte op de hemisferische lichtransmissie gering is (max. 0.5%), dit komt door een wat kleinere absorptie door de geringere dikte. Het toevoegen van een AGC AR coating leidt tot verhoging van de hemisferische lichttransmissie van 7% op een enkellaags glas. Hierdoor wordt het mogelijk om ook meerlaagse glazen te produceren. Een dubbel dun glas met 2xAR heeft een 11% hogere transmissie dan een dubbel dun glas zonder AR. Vergeleken met een enkellaagse dun glas zonder AR heeft hetzelfde dubbel dun glas met 2xAR nog steeds een 2% hogere transmissie. Een drielaags dun glas met 6xAR verliest maar 2% licht ten opzichte van een enkellaags dun glas zonder AR, bij een vierlaags dun glas met 8xAR is dat 6%. Tijdens het project is geprobeerd dun glas te voorzien met een diffuse oppervlaktebehandeling. Dit is echter maar beperkt gelukt. Glazen met een gemiddelde haze, een hoge en zeer hoge haze konden op kleine (9cm*9cm) afmetingen worden gemaakt. De productie van lage haze is echter nog niet gelukt. Het laatste zou echter wenselijk zijn voor toepassing in meerlaagse oplossingen in de toekomst.

1.3.2 Thermische eigenschappen

De thermische eigenschappen van dunne glazen zijn bepaald met behulp van metingen aan verschillende glastypes en berekeningen van de u-waarde van diverse configuraties van deze glastypes. Hoe meer glaslagen worden toegepast hoe lager de u-waarde. Indien de spouw wordt gevuld met krypton in plaats van met lucht leidt dit tot een lagere u-waarde. Met toenemende afstand van de spouw neemt de u-waarde af. Dit is het geval tot ca. 8-10 mm. De glasdikte heeft weinig invloed op de u-waarde, echter maakt het lagere gewicht van dunne glazen de toepassing van meerlaagse systemen pas mogelijk.

1.3.3 Energiebesparing

Voor een Phalaenopsis teelt is de energiebesparing van verschillende dunne glazen (enkel, dubbel, tripel, quadrupel) uitgerekend voor de warme teeltfase (jonge planten) en de koude teeltfase (bloei). Hierbij valt op dat er 20-25% warmte energie kan worden bespaard door beide fases door de toepassing van een quadrupel glas met AR coatings. Dit wordt met name veroorzaakt door de hogere isolatie. Gelijktijdig kan ca. 20% op elektra energie voor belichting worden bespaard in de warme teeltfase indien een dubbel dun glas met AR coatings wordt toegepast vergeleken met een PC kanaalplaat welke een vergelijkbare isolatie maar een lagere lichttransmissie heeft. In dat geval hoeft er onder een dubbel dun glas met AR minder worden belicht om een gelijke productie te krijgen. In de koude teeltfase is de elektra energie besparing beperkt tot maximaal 4%. Hier heeft een isolerend dek geen voordelen aangezien dit het bereiken van lagere teeltemperaturen bemoeilijkt.

1.3.4 Mechanische eigenschappen

De mechanische eigenschappen van dunne glazen (Leoflex™ en Falcon™ van AGC) zijn vergeleken met traditioneel tuinbouwglas. Hierbij valt vooral op dat het gewicht van een 0.55 mm Leoflex™ glas maar 1.4 kg/m^2 is vergeleken met 10 kg/m^2 van 4 mm tuinbouwglas. Daarnaast is het chemisch geharde dunne glas veel sterker dan het typisch gebruikte thermisch gehard glas. Nadelen zijn beschikbare afmetingen. Zo zijn dunne glazen van AGC nu en in de nabije toekomst maar met een maximale breedte van ca. 1.20 beschikbaar, terwijl in de tuinbouw minimaal 1.67 m nodig is om voordelen door afmetingen te kunnen behalen. In het algemeen is de relatief grote doorbuiging van dunne glazen een uitdaging bij gebruik in een kasdek. Enkellaagse dunne glazen zouden danwel opgebogen danwel opgespannen moeten worden om te grote doorbuiging te voorkomen. Dubbel- of meerlaagse dunne glazen kunnen mogelijkerwijs als sandwichpanelen worden gemaakt.

1.4 Conclusies

1.4.1 Voordelen dunne glazen

De projectgroep identificeert de volgende toegevoegde waarde van dunne glazen, die kunnen worden samengevat als:

- Hoge lichttransmissie van AR-gecoate glazen in combinatie met een lager gewicht (in vergelijking met traditioneel gecoat dubbel glas).
- Hogere lichttransmissie van meerlaagse glazen in vergelijking met PC kanaalplaten (met vergelijkbaar gewicht).
- Hoge buigsterkte geeft mogelijkheden om nieuwe kasdakconstructies te ontwikkelen (gebogen, koud gebogen).
- Hoge slagvastheid (betere hagelbestendig) van een chemisch gehard glas.
- Meerlaagse glazen zijn mogelijk bij nog steeds hoge lichttransmissie, maar lager gewicht.
- Lagere transportkosten door lager gewicht.
- Voordelen bij nieuwbouw en onderhoud van de kas door het lagere gewicht.
- Energiebesparing (warmte) ca. 20% (Phalaenopsis) kan worden bereikt met meerlaagse glaspanelen naast de beschikbare energiebesparende oplossingen (PC kanaalplaten).
- Toekomstige energieprijzen zullen echter de economische haalbaarheid bepalen. Daarnaast zal de toekomstige beschikbaarheid van energie en de doelstellingen van een nul-CO_2-uitstoot van kassen in 2050 de introductie van geïsoleerde kassystemen kunnen versnellen.

1.4.2 Uitdagingen dunne glazen

Naast bovengenoemde voordelen worden de huidige uitdagingen van dunne glazen gezien:

- De huidige nog hoge materiaalkosten beperken de introductie. Verwacht wordt dat de kosten zullen dalen als dun glas ook op grote schaal wordt toegepast voor gebouwen (?).
- De momenteel beschikbare afmetingen van dunnen glazen zijn beperkt in de breedte. In de glastuinbouw gebruiken we meestal glazen van 1,67 m breed. Dunne glazen kunnen mogelijk breder zijn vanwege de hogere sterkte, met tegelijkertijd een lager gewicht. De huidige en nabije afmetingen zijn echter nog beperkt.
- Enkellaagse glazen moet worden verstijfd door deze koud te buigen of voor te spannen.
  Meerlaagse sandwichpanelen gemaakt van dun glas of nieuwe materiaalcombinaties geven meer toepassingsmogelijkheden.

1.4.3 Conclusies

- Aangezien de eisen aan dunne glazen vergelijkbaar zijn voor de toepassing in een kas en voor de toepassing in gebouwen (kosten, isolatie, afmetingen), kan mogelijkerwijs in de toekomst glas beschikbaar komen voor kassen.
- Op dit moment beperken praktische beperkingen op beschikbare afmetingen en hoge kosten nog de toepassing.
- Er moet gedetailleerder worden gewerkt aan het verstevigen en verbinden van glazen voor meerlaagse toepassing als er dunne glazen met de vereiste afmetingen beschikbaar komen.
- Nieuwe kasdakconstructies moeten meer in detail worden uitgewerkt als er glazen met de vereiste afmetingen beschikbaar komen voor een redelijke prijs.
- Applicaties van meerlaagse glazen in een kasdek kunnen als haalbaarder worden beschouwd dan een enkellaagse glazen in de toekomst.

2 Introduction

2.1 Background

Previous research in the VenLowEnergy greenhouse has shown that with a double greenhouse roof with additional screens, more than 50% energy can be saved in vegetable cultivation compared to current practice. In the case of ornamental cultivated plants grown at high temperatures, greenhouse insulation is often realized through the use of multiple screens and the use of multilayer polycarbonate sheets (PC) with a very low light transmittance of about 60%. In the past, multilayer polymethylmethacrylate sheets (PMMA) have been used as an alternative, which have a higher transmission, but fire safety can no longer be insured. Alternative solutions are therefore required. A very high insulation value of the greenhouse roof together with energy-efficient cultivation methods makes it possible to design a climate-neutral greenhouse production systems for cultivation without artificial lighting.
With the development of thin but very strong glass plates for mobile phones (e.g. Leoflex™, Falcon™ from Asahi Glass), new possibilities for new greenhouse designs and the application of multilayer glasses in a highly insulating greenhouse roof occur. Flexible thin glass is a tempered glass. While standard tempered glass goes through a thermal process, this is a chemical process, which makes the glass five times stronger, creating the possibility of thickness reduction and bending. Thin glasses have a reduced absorption and due to the addition of coatings a reduced reflection. An increased light transmission can be expected if glasses are applied in three or more layers as a greenhouse cover resulting in a significantly higher light transmission than currently available multilayer PC sheets, but also a higher transmission than today's double glazing. With new techniques a diffuse coating with a good light scattering pattern might also be applied. By placing coatings on the inside of a glass package, the risk of contamination by dust or ageing is limited. Thin glasses are particularly strong and can also be used in curved form. This makes new greenhouse roof designs with glass possible. Thin glasses are light in weight, so the greenhouse construction does not have to become heavier and new designs become possible. In terms of costs, it might be expected that less glass material is needed, the hardening process in the long term is comparable to traditional hardening and costs for coatings or diffuse treatments are also comparable to current known methods. Making insulating glass currently involves higher costs, in the future new solutions it must be considered to install multilayer insulating glass in new deck profiles. In this study the feasibility of the application of flexible thin glass in greenhouses is investigated.

2.2 Goals

2.2.1 Technical goals

The study focuses on the feasibility of using flexible thin glass in greenhouses to achieve either extra high insulation or new greenhouse roof designs. In the case of the technical goal of extra high insulation, materials are developed that achieve comparable or higher energy savings than current polycarbonate sheets with simultaneously a considerably higher light transmission. In the case of the technical goal of new greenhouse roof designs, materials are developed which serve as a replacement for flexible plastic films with, in addition to a potential improvement of the transmission, simultaneously a long service life. A long-term goal is that a multilayer new flexible glass can beat traditional double glazing in terms of insulation or cost and that it can beat polycarbonate sheets in terms of light transmittance and insulation.

2.2.2 Energy saving goals

In the case of using flexible thin glasses in three or more layers, a greenhouse covering is created with extra high insulation. Previous research in the VenLowEnergy greenhouse has shown that with a double greenhouse roof with additional screens more than 50% energy can be saved in a vegetable cultivation. Previous research has also shown that cultivation methods that limit evaporation during periods of heating and the use of low-energy dehumidification systems with heat recovery can reduce energy consumption by 70%. With multilayer insulation, the heat demand will decrease further so that the total energy saving will be higher than in the VenlowEnergy greenhouse. The energy consumption of a tropical pot plant crop will reach approx. 10 15 m^3/m^2/year for a production.

2.2.3 Other goals

In the case of using flexible thin and light glasses as a replacement for flexible plastic films, new greenhouse coverings and new conceptual greenhouse roof designs become possible.

3 Thin glass material technology

3.1 Basic glass

Soda-lime glass, also called soda-lime-silica glass, is the most prevalent type of glass, used for windowpanes, but also for glass containers (bottles and jars) for beverages, food, and some commodity items. Soda-lime glass accounts for about 90% of manufactured glass. Soda-lime glass is prepared by melting the raw materials, such as sodium carbonate (soda), lime, dolomite, silicon dioxide (silica), aluminium oxide(alumina), and small quantities of fining agents (e.g., sodium sulphate, sodium chloride) in a glass furnace at temperatures locally up to 1675 °C. The temperature is only limited by the quality of the furnace superstructure material and by the glass composition. Relatively inexpensive minerals such as trona, sand, and feldspar are usually used. Soda-lime glass is divided technically into glass used for windows, called flat glass, and glass for containers, called container glass. The two types differ in the application, production method (float process for windows, blowing and pressing for containers), and chemical composition. Flat glass has a higher magnesium oxide and sodium oxide content than container glass, and a lower silica, calcium oxide, and aluminium oxide content (Wikipedia, 2017).
Traditional greenhouse glass is flat glass made from soda-lime usually processed in a float process.

Another group of glasses are the so-called **aluminosilicate glasses**. Aluminosilicate minerals are minerals composed of aluminium, silicon, and oxygen, plus counter cations. They are a major component of kaolin and other clay minerals. The AI2O3 content of alkali aluminosilicate glasses is typically 10-25% and the alkali content over 10%. The high alkali content prepares the glass for ion exchange with bigger alkali ions in order to improve the surface compressive strength. Due to this particular feature, this glass type is especially suitable for the use in touch displays, solar cells cover glass and laminated safety glass. High transformation temperatures and outstanding mechanical properties, e.g. hardness and scratch behaviour, are characteristic of this glass type (Wikipedia, 2017).
Different producers manufacture types of aluminosilicate glasses under different trade names. Among them are: AGC (Japan) producing e.g. Leoflex™ or Falcon™ (produced in Mol, Belgium), Corning Inc. (U.S.) producing e.g. Gorilla glass®, Schott AG (Germany) producing e.g. Xensation®, Pilkington/NSG Group (U.S.) producing e.g. Microfloat® or Microwhite®.
Thin glasses can be defined as glasses with a thickness of 0.03 mm – 2 mm. These types of glasses are considered here in the feasibility study. In the future, also ultra-thin glasses with thicknesses of <0.03 mm may be widely available. These ultra-thin glasses have thicknesses more closely to plastic films than to glass (Figure 1).

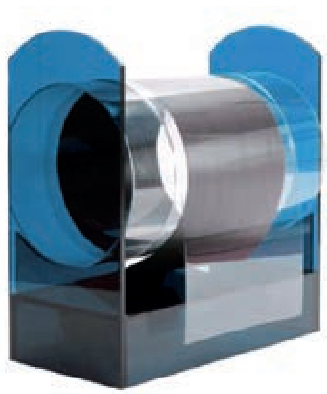


Figure 1 *Ultra-thin glass on a roll (source: http://www.schott.com/d/tubing/c3fb6f14-beae-4571-82bb-a989308ffe2a/1.1/schott-brochure-technical-glasses_english.pdf).*

3.2 Toughening process

Toughened or **tempered glass** is a type of safety glass processed by controlled thermal or chemical treatments to increase its strength compared with normal (annealed) glass. Tempering puts the outer surfaces into compression and the core into tension. Such stresses cause the glass, when broken, to crumble into small granular chunks instead of splintering into jagged shards as plate glass (a.k.a. annealed glass) does. The granular chunks are less likely to cause injury.
As a result of its safety and strength, toughened glass is used in a variety of demanding applications, such as greenhouse roofs. Toughened glass is physically stronger than normal glass. The contraction of the core of the glass during manufacturing induces compressive stresses in the surface of the glass balanced by tensile stresses in the core of the glass. It is this compressive stress that gives the toughened glass increased tensile strength and thus greater resistance to mechanical and thermal load. This is because annealed glass, which has almost no internal stress, usually forms microscopic surface cracks, and any applied tension gets magnified at the surface, reducing the applied tension needed to propagate the crack. Once it starts propagating, tension gets magnified even more easily, causing it to propagate at the speed of sound in the material. Any cutting or grinding must be done prior to tempering. Cutting, grinding, and sharp impacts after tempering will cause the glass to fracture (Wikipedia, 2017).
Toughened glass can be made from annealed glass via a **thermal tempering process**. The glass is placed onto a roller table, taking it through a furnace that heats it well above its transition temperature of 564°C to around 620°C. The glass is then rapidly cooled with forced air drafts while the core remains free to flow for a short time (Wikipedia, 2017). This process is usually used for tempered greenhouse glass.
An alternative **chemical toughening process** involves forcing a surface layer of glass at least 0.1 mm thick into compression by ion exchange of the sodium ions in the glass surface with potassium ions (which are 30% larger), by immersion of the glass into a bath of molten potassium nitrate. Chemical toughening results in increased tensile strength compared with thermal toughening and can be applied to glass objects of complex shapes (Wikipedia, 2017). This process is used for the production process of thin glasses and ensures high bending strength.

3.3 Greenhouse covering materials

In order to compare the thin glass technology with already available covering materials in greenhouses, the following table can be produced.

Table 1
Overview available greenhouse covering materials and their properties.

Material name	coating side #1	Material/ Tradename	thickness [mm]	coating side #2	spacer thickness [mm]	airfiller	coating side #3	Material/ Tradename	thickness [mm]	coating side #4	hemispherical light transmission	u-value	Source
Glass	na	sodalime	4	na	na	na					82%	7,6	Hemming et al., 2004, WUR report A&F 100
Glass ARAR	AR	sodalime	4	AR	na	na					89%	7,1	Hemming et al., 2011, Acta Horticulturea 893
Glass AR-low-e	low E	sodalime	4	AR	na	na					84%	5,7	Hemming et al., 2011, Acta Horticulturea 893
Double glass	na	sodalime	4	na	8	air	na	sodalime	4	na	72%	3,5	Hemming et al., 2011, Acta Horticulturea 893, Tantau, Landtechniek 68(1), 2013
Double glass ARARARAR	AR	low-iron	4	AR	8	air	AR	low-iron	4	AR	85%	3,6	Hemming et al., 2011, Acta Horticulturea 893
Double glass AR-lowe-ARAR	AR	low-iron	4	AR	8	air	low E	low-iron	4	AR	79%	2,4	Hemming et al., 2011, Acta Horticulturea 893
Polycarbonate	na	Lexan™	16	na	12	air					61%	3,5	Hemming et al., 2004, WUR report A&F 100
PMMA	na	Altop®	16	na	12	air					76%	2,8	Hemming et al., 2004, WUR report A&F 100
ETFE	na	F-Clean®	80 micron	na	na	na					87%	8,2	Hemming et al., 2004, WUR report A&F 100, Tantau, Landtechniek 68(1), 2013
Double ETFE	na	F-Clean®	80 micron	na	100?	air	na	F-Clean®	80 micron	na	73%	3,5	Hemming et al., 2004, DeGa 44, Tantau, Landtechniek 68(1), 2013
Glass ARAR ETFE	AR	sodalime	4	AR	50	air	na	F-Clean®	80 micron	na	81%	4,0?	Kempkes et al., 2014, WUR rapport GTB-1307

4 Optical properties

In order to evaluate the optical properties of thin glasses, AGC provided Leoflex® basic glasses in different thickness. Glascom/DA Glass has added an anti-reflection (AR) surface treatment (etching) in order to increase light transmission and added different diffuse surface treatment (etching) for different degrees of light scattering.
Different samples were combined in different numbers of layers in order to create insulation glass.
All samples measured at WUR Lightlab concerning their optical properties: Perpendicular light transmission, hemispherical light transmission, light scattering.

4.1 Single thin glasses with different thicknesses

Leoflex® glasses have been produced by AGC and measured at WUR Lightlab concerning their optical properties. We have received glasses with different thicknesses: 0.55 mm, 0.85 mm, 1.1 mm, 1.3 mm. The size of all samples was 50 cm x 50 cm. In Table 2 the results are summarized.

Table 2
Optical properties of Leoflex® thin glasses with different thicknesses.

WUR code	Glass description	Hemispherical light transmission	Perpendicular light transmission NEN 2675
HK16A	Single Leoflex 0.55 mm	84.0 ± 0.5%	91.6 ± 0.5%
HK16E	Single Leoflex 0.85 mm	84.1 ± 0.5%	91.7 ± 0.5%
HK16G	Single Leoflex 1.1 mm	84.0 ± 0.5%	91.6 ± 0.5%
HK16I	Single Leoflex 1.3 mm	83.5 ± 0.5%	91.1 ± 0.5%

We can observe the following:
- Increasing thickness from 0.55 mm to 1.3 mm of single glasses leads to a very small decrease in hemispherical light transmission from 84% to 83.5%.
- The reason is that the thickness mainly influences light absorption. In general light absorption is low, small variation in light absorption with result in small variation in light transmission.

4.2 Insulating thin glasses with different number of layers

Glasses of the same thickness have been combined to insulating glass with different number of layers. In Table 3 the results are summarized.

Table 3
Optical properties of Leoflex® thin glasses with different thicknesses and different numbers of layers.

WUR code	Thin glass description	Hemispherical light transmission	Perpendicular light transmission NEN 2675
HK16A	Single Leoflex 0.55 mm	84.0 ± 0.5%	91.6 ± 0.5%
HK16B	Double Leoflex 0.55 mm	75.3 ± 0.5%	84.5 ± 0.5%
HK16C	Triple Leoflex 0.55 mm	68.9 ± 0.5%	78.3 ± 0.5%
HK16D	Quadruple Leoflex 0.55 mm	63.7 ± 0.5%	73.0 ± 0.5%
HK16E	Single Leoflex 0.85 mm	84.1 ± 0.5%	91.7 ± 0.5%
HK16F	Double Leoflex 0.85 mm	75.3 ± 0.5%	84.7 ± 0.5%
HK16G	Single Leoflex 1.1 mm	84.0 ± 0.5%	91.6 ± 0.5%
HK16H	Double Leoflex 1.1 mm	75.2 ± 0.5%	84.5 ± 0.5%
HK16I	Single Leoflex 1.3 mm	83.5 ± 0.5%	91.1 ± 0.5%
HK16J	Double Leoflex 1.3 mm	74.3 ± 0.5%	83.5 ± 0.5%

We can observe the following:

- Multiple layers of 0.55 mm thin glasses (without AR coating) leads to a decrease in hemispherical light transmission from 84% to 63.7%.
- An increasing number of layers leads to an increased light reflection, and therefore to an increased reduction in light transmission.
- A relatively higher decrease in hemispherical light transmission can be observed with higher thickness of glasses. Comparing double 0.55 mm with double 1.3 mm we observe a 1% difference in hemispherical light transmission, while the difference in single glasses is only 0.5%.

4.3 Diffuse thin glasses with different light scattering

Leoflex® glasses (size 9 cm x 9 cm, 1.1 mm thickness) have been processed by DA Glass and measured at WUR Lightlab concerning their optical properties. Glasses with different processing have been received. In Table 4 the results are summarized.

Table 4
Optical properties of Leoflex® thin glasses (1.1.mm) with different light scattering treatments.

WUR code	Type of diffusion	Glass processing description	Hemispherical light transmission	Perpendicular light transmission NEN 2675	F-scatter	Haze ASTM D-1003
DA16Q	Extra high diffusion	1800 LTF	68.8 ± 0.5%	83.8 ± 0.5%	87 ± 5%	96 ± 5%
DA16R	Extra high diffusion	1800 LTF AR	70.7 ± 0.5%	85.6 ± 0.5%	88 ± 5%	97 ± 5%
DA16S	High diffusion	1000 LTF	77.1 ± 0.5%	91.9 ± 0.5%	73 ± 5%	92 ± 5%
DA16T	High diffusion	1000 LTF AR	79.8 ± 0.5%	94.2 ± 0.5%	70 ± 5%	90 ± 5%
DA17A	Medium diffusion	300 LTF	82.2 ± 0.5%	92.0 ± 0.5%	35 ± 5%	61 ± 5%
DA17B	Medium diffusion	300 LFT AR	89.2 ± 0.5%	98.3 ± 0.5%	36 ± 5%	61 ± 5%
HK16I	Clear	Single Leoflex 1.1mm	84.0 ± 0.5%	91.6 ± 0.5%	-	-

All measurements are indicative, since sample size is too small for complete measurements

We can observe the following:

First series diffuse treatment (**high diffusion**):
- All diffuse treatments lead to a very high F-scatter. Samples 1800 LTF show a F-scatter of almost 90%, samples 1000 LTF show a F-scatter of minimum 70%.
- The very high light diffusion (F-scatter) leads to a decreased hemispherical light transmission. Compared with the single clear glass with the same thickness (84.0%) the hemispherical light transmission is 68.8% in case of 1800 LTF and 77.1% in case of 1000 LTF. High light diffusion decreases hemispherical light transmission with 7-15%. Here it will be interesting to see the performance of low diffusion treatments in the future.
- Adding an AR treatment increase the hemispherical light transmission almost 2% in case of 1800 LTF and almost 3% in case of 1000 LTF.

Second series diffuse treatment (**mid diffusion**):
- The treatment leads to medium diffusion with a medium F-scatter around 35%.
- The hemispherical light transmission of the second series samples is with the 300 LTF treatment 5% higher than earlier high diffusion treatment, with the 300 LTF AR treatment the hemispherical light transmission is 10% higher than the 1000 LTF AR treatment.

4.4 Insulating glasses with AR treatment

For DA Glass it was difficult to apply AR surface treatments to the thin glasses. The reason was that the chemical AR treatment was more difficult on the chemically tempered glasses than on regular thermally tempered glasses. After several months of trials project time was running short. Therefore, AGC provided us with their regular AR treatment applied to regular glasses (4 mm thickness) to experiment with different number of glass layers and the effect on optical properties. AGC provided glasses with 1 and 2 side AR treatment. Optical properties of the samples are measured individually and in multiple layer combination at WUR LightLab. In order to construct double layer samples, the original samples are cut in half and stacked on each other, see pictures below (Figure 2).

Figure 2 *Triple and quadruple glasses of 4 mm glasses coated with AGC AR coating*

The result of measurements are presented in Table 5.

Table 5

Optical properties of 4 mm clear glass samples with AGC AR treatment.

WUR Code	Glass description	Hemispherical light transmission	Perpendicular light transmission NEN 2675
AGC17A	Extra clear SN 1, no AR	83.9 ± 0.5%	91.5 ± 0.5%
AGC17B	Extra clear SN 2, no AR	83.8 ± 0.5%	91.5 ± 0.5%
AGC17I	AGC17A+AGC17B 7mm gap, no AR	74.7 ± 0.5%	84.2 ± 0.5%
AGC17C	Clear sight SF REF34 1, 1xAR	86.8 ± 0.5%	94.4 ± 0.5%
AGC17D	Clear sight SF REF34 2, 1XAR	86.8 ± 0.5%	94.4 ± 0.5%
AGC17H	AGC17C+AGC17D 7mm gap, 2xAR	78.9 ± 0.5%	89.4 ± 0.5%
AGC17E	Clear sight DF REF35 1, 2xAR	90.9 ± 0.5%	98.1 ± 0.5%
AGC17F	Clear sight DF REF35 2, 2xAR	90.8 ± 0.5%	98.0 ± 0.5%
AGC17G	AGC17E+AGC17F 7mm gap, 4xAR	85.5 ± 0.5%	96.0 ± 0.5%
AGC17J	AGC17E+AGC17E+AGC17F 2mm gap, 6xAR	81.5 ± 0.5%	94.0 ± 0.5%
AGC17K	AGC17E+AGC17E+AGC17F+AGC17F 2mm gap, 8xAR	77.9 ± 0.5%	92.3 ± 0.5%
AGC17L	AGC17E+AGC17E+AGC17F+AGC17F 4mm gap, 8xAR	77.6 ± 0.5%	92.3 ± 0.5%

We can observe the following:

- The AR treatment on one or two side of single glass increases the hemispherical light transmittance with ca. 3 and 7%, respectively.
- The hemispherical light transmittance decreases about 9% if two untreated samples (no AR) are stacked on each other.
- Multilayer AR treated samples show less decrease in light transmittance which is logically due to AR treatment.

In Figure 3 the perpendicular wavelength depended transmission of sample AGC17A (no AR) and the Quadruple glass stack AGC17K (with 8xAR) is shown. We can observe a ca. 6% loss in PAR transmission. However, as Figure 3 shows, the AR coating also leads to a large reduction in the NIR spectrum. While the quadruple layered glass has a high insulation value, this reduction in NIR transmission will have an opposite effect on the energy use. On the other hand, this reduced NIR transmission will lead to lower heat load during summer period. The calculated reduction in heat load by the (assumed) reflection properties in the NIR spectrum is around 51% of the NIR radiation.

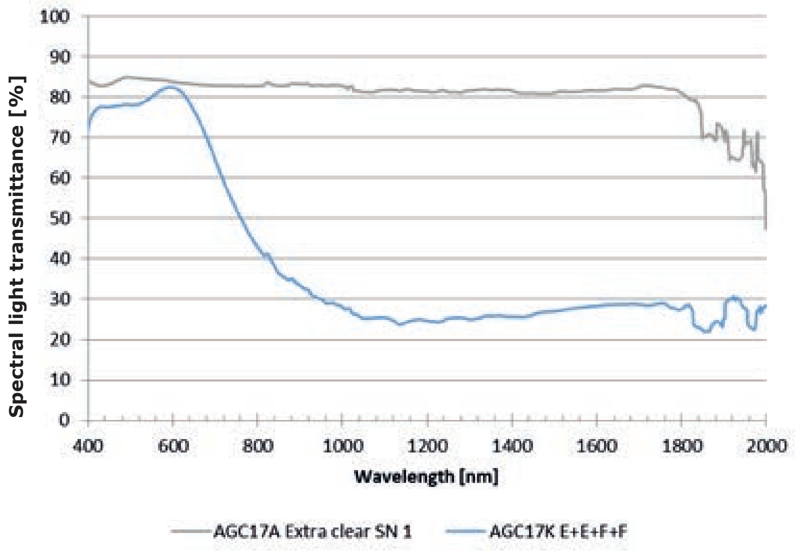


Figure 3 *Perpendicular wavelength depended transmission of sample AGC17A and AGC17K.*

Measurement results in Table 5 show the effect of AR treatment in interaction with the number of layers. Table 2 shows the effect of the number of layers on thin glasses. If we take the optical properties measured of thin glasses (Table 2) and the effect of AR only (extracted from Table 4) we get the theoretically calculated optical properties of AR coated thin glasses in different thicknesses and number of layers as presented in Table 6.

Table 6
Calculated (*) optical properties of thin clear glass samples with AGC AR treatment.

WUR Code	Glass description	Hemispherical light transmission	Perpendicular light transmission NEN 2675
HK16A	Single Leoflex 0.55 mm no AR	84.0	91.6
HK16B	Double Leoflex 0.55 mm no AR	75.3	84.5
HK16C	Triple Leoflex 0.55 mm no AR	68.9	78.3
HK16D	Quadruple Leoflex 0.55 mm no AR	63.7	73.0
HK16A*	Single Leoflex 0.55 mm 2xAR	91.1	98.0
HK16B*	Double Leoflex 0.55 mm 4xAR	86.1	96.3
HK16C*	Triple Leoflex 0.55 mm 6XAR	82.1	94.3
HK16D*	Quadruple Leoflex 0.55 mm 8xAR	78.5	92.6
HK16E	Single Leoflex 0.85 mm	84.1	91.7
HK16F	Double Leoflex 0.85 mm	75.3	84.7
HK16E*	Single Leoflex 0.85 mm 2xAR	91.1	98.1
HK16F*	Double Leoflex 0.85 mm 4xAR	86.1	96.5
HK16G	Single Leoflex 1.1 mm	84.0	91.6
HK16H	Double Leoflex 1.1 mm	75.2	84.5
HK16G*	Single Leoflex 1.1 mm 2xAR	91.0	98.0
HK16H*	Double Leoflex 1.1 mm 4xAR	85.9	96.3
HK16I	Single Leoflex 1.3 mm	83.5	91.1
HK16J	Double Leoflex 1.3 mm	74.3	83.5
HK16I*	Single Leoflex 1.3 mm 2xAR	90.5	97.5
HK16J*	Double Leoflex 1.3 mm 4xAR	85.1	95.3

We can observe the following:

- An 2xAR coating leads to an increase of light transmission of 7% on a single layer glass. On a double glass a 4xAR coating leads to an increase of 11%, on a triple glass 6xAR increases light transmission by 14% and on a quadruple glass with 8xAR this value is 15%.
- The influence of materials thickness is limited.
- A quadruple glass with 8xAR only shows a 6% light loss compared to a single glass without AR. A triple glass with 6xAR shows only a 2% light loss.

In order to validate the theoretically calculated optical properties of AR coated thin glasses AGC delivered real samples of AR coated thin glasses at the end of the project. The results of the real measured samples are presented in Table 7.

Table 7
Measured optical properties of real thin clear glass samples with AGC AR treatment compared with calculated AR treatment on samples at two different thicknesses.

WUR Code	Glass description	Hemispherical light transmission	Perpendicular light transmission NEN 2675
Samples with AR calculated			
HK16A*	Single Leoflex 0.55 mm 2xAR	91.1	98.0
HK16B*	Double Leoflex 0.55 mm 4xAR	86.1	96.3
HK16C*	Triple Leoflex 0.55 mm 6XAR	82.1	94.3
Samples with AR measured			
AGC17N	Single Leoflex 0.5 mm 2xAR	90.5	98.4
2xAGC17N	Double Leoflex 0.5 mm 4xAR	85.1	96.5
3xAGC17N	Triple Leoflex 0.5 mm 6XAR	80.8	94.9
Samples with AR calculated			
HK16G*	Single Leoflex 1.1 mm 2xAR	91.0	98.0
HK16H*	Double Leoflex 1.1 mm 4xAR	85.9	96.3
	Triple Leoflex 1.1 mm 6XAR	81.6	95.3
Samples with AR measured			
AGC17P1	Single Leoflex 1.1 mm 2xAR	90.3	98.1
2xAGC17P1	Double Leoflex 1.1 mm 4xAR	85.3	96.6
3xAGC17P1	Triple Leoflex 1.1 mm 6XAR	81.0	95.0

We can observe the following:
- Real thin glasses with AR coating were produced at the end of the project. The performance of the glasses were good. Hemispherical light transmission was cs. 0.5-0.6% less than expected from earlier calculations.
- Producing double and triple glasses form the real AR coated thin glasses showed that earlier calculated hemispherical light transmission values were ca. 1% higher than real values.
- Further optimisation of AR coated thin glasses is possible.

5 Thermal properties

In order to determine the U-value of different thin glasses, the thermal properties were investigated. For a good comparison 3 samples were chosen:

- 4 mm standard glass as a reference.
- 4 mm AGC glass with AR treatment on both sides (AGC17F) in order to investigate the thermal behaviour of the AR treatment.
- 1.1 mm Leoflex™ with no treatment.

5.1 Emissivity

The emissivity is the part of infrared radiation which is not transmitted or reflected by the material. The spectral transmittance and reflectance of 3 chosen samples are measured at WUR Lightlab. The results of measurements are summarized in Table 8.

Table 8
MaxPlanck weighted transmittance, reflectance and emissivity in the thermal infrared region.

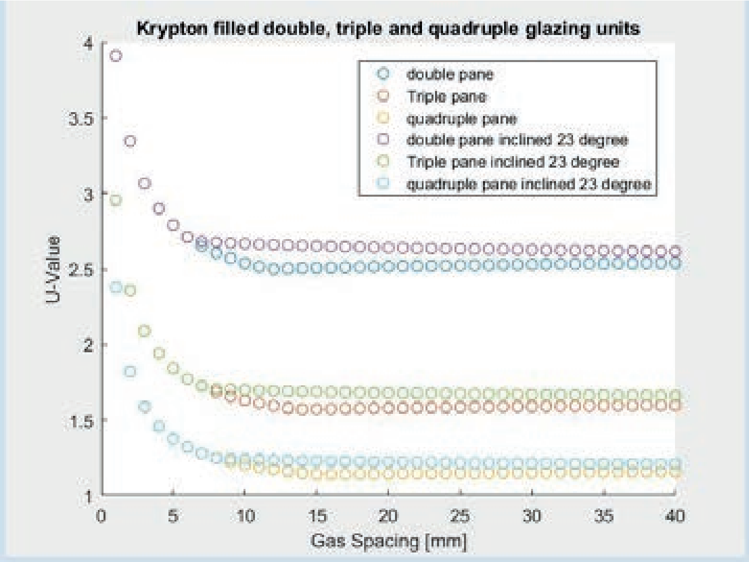
WUR code	Glass Description	Thermal infrared transmittance [%]	Thermal infrared reflectance [%]	Emissivity[%]
AGC17A	Single clear glass 4 no AR	0.1	10.2	89.7
AGC17F	Single clear glass 4 mm^2xAR	0.1	12.6	87.3
HK16G	Single Leoflex 1.1 mm no AR	0.4	10.1	89.5
	Single Leoflex 1.1 mm 2x AR			

5.2 U-value

In order to assess the u-value of different glass combinations, calculations based on NEN-EN 673 are carried out. An assessment is made how a low U-value can be created. In the calculations, a U-value based on the dictated boundary conditions and a design U-value where the boundary conditions applicable to greenhouses with a non-vertical inclination of the greenhouse cover are taken into account. Basically, a quick parameter study with the U-values as output is carried out.

5.2.1 Number of glass layers

Calculations have been carried out with double, triple and quadruple glass panes. All without AR coating. It can be observed that with the increasing number of glass layers the U-value decreases. A minimum difference of can be observed between vertical and 23^{o} inclined glasses.

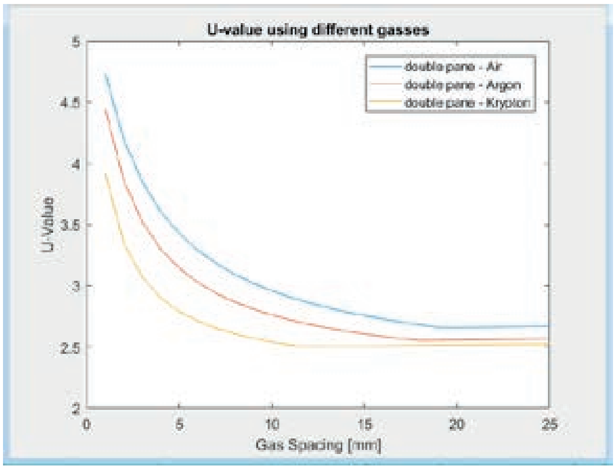


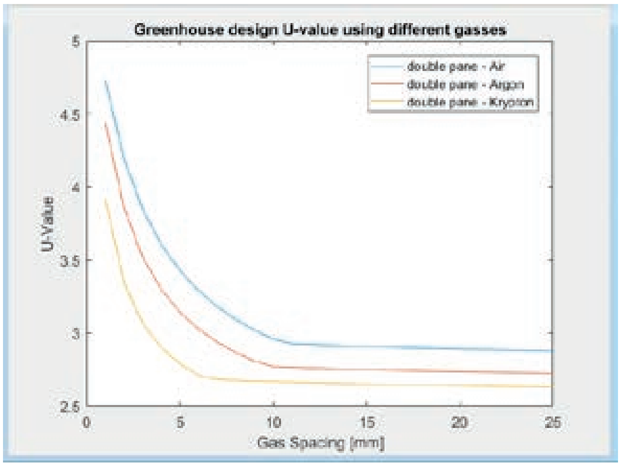
5.2.2 Glass thickness

There was no significant difference between different thicknesses (data not shown).

5.2.3 Type of gas filling

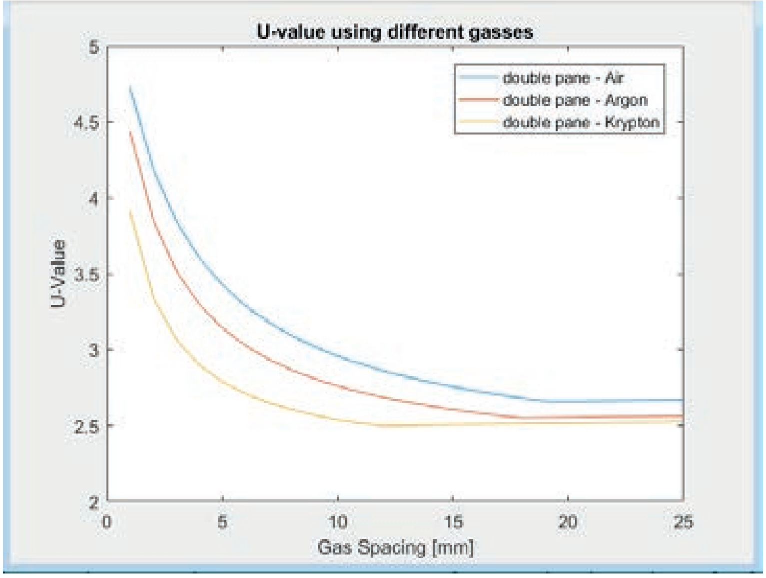
Different types of gas filling in the spacing have been taken into account in the calculations: air, argon and krypton. It can be observed that krypton leads to the lowest U-value, followed by argon and air, left figure. However, krypton is more expensive than argon and is subject to large price fluctuations. Therefore, argon is commonly used as gas for insulating glasses when a low U-value is needed.
Comparable conclusions can be made for an inclined greenhouse roof (23°), right figure.





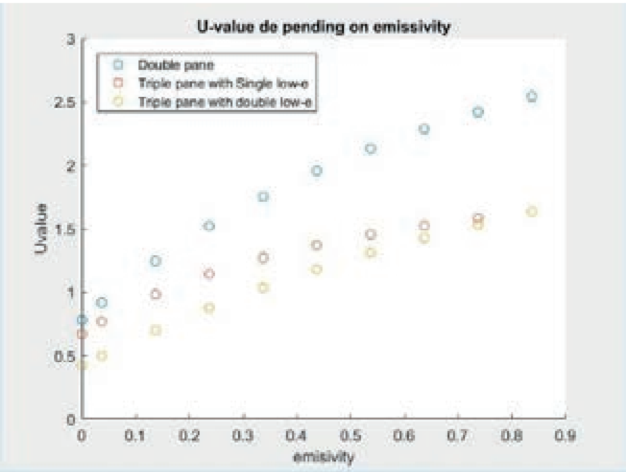
5.2.4 Distance glass spacing

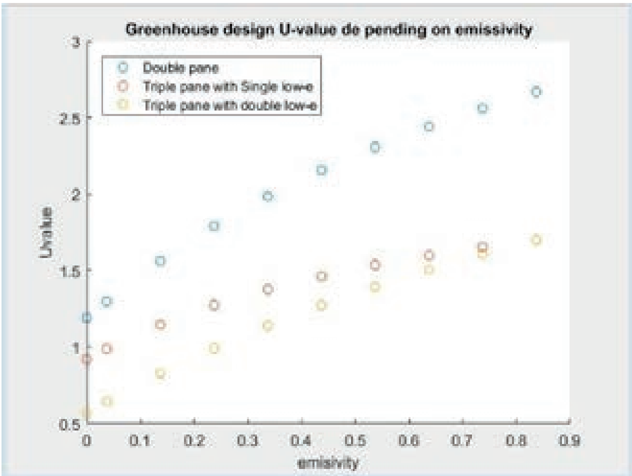
Calculations with different distances of glasses in the spacing are carried out. We can observe that the u-value drops with spacing distance up to ca. 10 mm if mounted under a slope of 23° on the greenhouse. A u-value lower than 3 can already be reached by a spacing of 8 mm in case of air filling or 4 mm in case of argon filling.



5.2.5 Emissivity

In the following figures the influence of the emissivity on the U-value is shown.





5.2.6 Leoflex

AGC gives the following U-values of standard Leoflex™ glasses:

- 0.85mm: 1250W/m².K.
- 1.1mm: 1000W/m².K.

Based on these values, thermal conductivity shall be 1.04W/m/K.

6 Energy saving performance

In order to estimate the significance of optical properties and thermal properties of different thin glasses for practical greenhouse production, the energy saving performance has been estimated for a chosen crop. Calculations of the energy saving performance of different glass combinations were carried out by using the KASPRO climate model (de Zwart, 1996). The model uses three different types of input.

1. Most important for this study is to feed the model with the right optical properties. The results of the Lightlab measurements of the samples mentioned in Table 2 and Table 4 are used to calculate a transmission table of the greenhouse roof. In this case it is assumed that all different materials can be fit in the same roofing system of bars, gutters and ridges. Although for some, especially the multilayer samples, this will not be possible, at this stage of the project this simplified approach is used. The multilayer samples will have some (small) advantage of this approach.
2. Weather conditions are represented by de SEL2000 selection year. This selection year is not the average climate over a decade but of a decade typical months who represent the best the average climate of that month over the decade are combined to one complete year. By this approach the dynamics caused by the weather on greenhouse climate are assured.
3. A representative crop with typically high energy use to show the potential energy savings. For this Phalaenopsis is chosen. A crop with two important crop stages, during the vegetative stage during the first half year of the crop gets warm temperatures of at least 28°C followed by a cooling phase during flower production in which the greenhouse air temperature should not exceed 19°C. In appendix 1 the complete list with parameter settings in the model is presented.

6.1 Phalaenopsis young plant production (warm phase)

From expert view 8 most interesting materials and combinations are chosen (Table 9) to calculate the climate and energy effects beside the reference of standard glass and PC sheet. Although in Figure 3 it is shown that there is an effect of the AGC AR coating on the NIR reflectance, only for one case it will be shown what the effect is on the energy balance of the greenhouse is, AGC17K NIR. For all other cases we assume that in the future a AR coating with no effect on NIR reflectance can be produced.

Table 9

Materials chosen with some important parameters.

WUR code			Transmittance hemispherical cover [%]	K-split [W/m²]	Screens 2)	NIR-reflection [%]
ref	PC sheet	no AR	63.5	4.5	1,2	-
HK16A	Single Leoflex 0.55 mm	2 x AR	86.5	-	1, 2, 3	-
HK16B	Double Leoflex 0.55 mm	4 x AR	83.3	5	1,2	-
HK16C	Triple Leoflex 0.55 mm	6 x AR	80.2	3.5	1,2	-
HK16D	Quadruple Leoflex 0.55 mm	8 x AR	77.5	2	1,2	-
AGC17E	Clear glass 4 mm	2 x AR	86.2	-	1, 2, 3	-
AGC17G	Double clear glass 4 mm	4 x AR	82.7	5	1,2	-
AGC17J	Triple clear glass 4 mm	6 x AR	79.7	3.5	1,2	-
AGC17K	Quadruple clear glass 4 mm	8 x AR	76.8	2	1,2	-
AGC17K NIR	Quadruple clear glass 4 mm NIR reflection	8 x AR	76.8	2	1,2	51

) assumed absorption for Leoflex™ 0.55 is 0.55% per layer and for the 4mm AGC17 1.5% per layer.

2) There are up to three screens installed: [1] blackout - to avoid light pollution, at day time always opened, [2] shading during day time in case off high light levels closed, [3] energy high transparent (always closed).

Savings are expected on two levels, heat and electricity. The reference greenhouse has polycarbonate sheets as cover, it represents a higher energy saving compared to single glass but it also has a low light transmission compared to single glass.
In case the cover consists of multi-layer materials heat energy can be saved during winter. The temperature setpoint during the warm phase of Phalaenopsis production is 28°C.
In case the cover of multi-layer glass has a higher transmission in winter electricity for artificial lighting can be saved. This is shown in Figure 4 The total daily light sum (sun + artificial), the light sum of the artificial lighting and the gained light sum by the improved cover (reference versus double Leoflex). The goal is to supply the plants daily with 8 mol of PAR light. In case more than 8 mol is supplied and the artificial lighting was used, the difference between 8 mol and the realized light sum can be saved from the artificial lighting. In Figure 4 the gained light can be saved from artificial light. This can save up to 25 kWh/m^2 on yearly base. A summary of the results is shown in Table 10.
Beside saving on electricity, an increase of the insulation will reduce the heat consumption. These effects can be smaller than expected because the reference case has already an insulating cover and in case of single glass due to the lower need for light year-round a transparent screen is closed. Increase of insulation of the roof can have a drawback in the dehumidification. The Phalaenopsis crop is grown at rather low humidity levels (setpoint RH is around 70%). Although the transpiration capacity of the plant is limited, every 4-7 days the plants are abundant irrigated by an overhead sprinkler, around 12 l/m^2/irrigation. After the irrigation, all effort is taken to dry the plant as fast as possible to avoid diseases. By increasing the roof insulation, the roof temperature (inside) will increase as well, leading to a decrease condensation. Water vapor which is not condensated has to be released from the greenhouse by ventilation, causing a loss of sensible and latent heat. To show this effect the condensation to the roof is presented in Table 10.

Table 10
Yearly heat and electricity consumption and condensation of water vapour on the roof.

WUR code	description	heat	electricity	condensation
		[GJ/m^2]	[kWh/m^2]	[l/m^2]
ref	PC sheet	1.47	124.9	24.8
HK16A	Single Leoflex 0.55 mm	1.51	119.3	42.7
HK16B	Double Leoflex 0.55 mm	1.47	98.0	34.7
HK16C	Triple Leoflex 0.55 mm	1.37	103.6	19.7
HK16D	Quadruple Leoflex 0.55 mm	1.21	108.9	6.3
AGC17E	Clear glass 4 mm	1.50	119.6	41.5
AGC17G	Double clear glass 4 mm	1.47	99.3	32.6
AGC17J	Triple clear glass 4 mm	1.36	105.1	18.0
AGC17K	Quadruple clear glass 4 mm	1.18	110.1	5.4
AGC17K NIR	Quadruple clear glass 4 mm NIR reflection	1.30	110.1	5.5

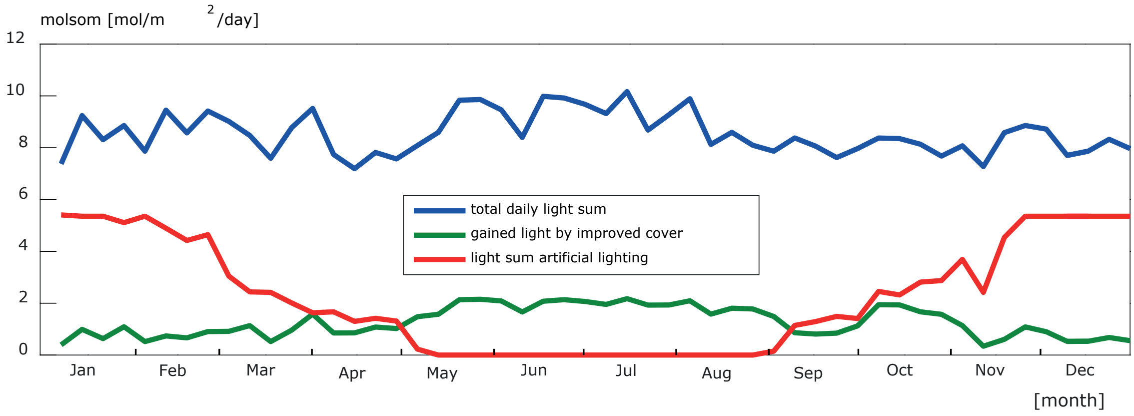


Figure 4 *The total daily light sum (sun + artificial), the light sum of the artificial lighting and the gained light sum by the improved cover (reference versus double Leoflex™).*

The table shows the savings on heat consumption can run up to 20% in some cases and for some other cases the electricity consumption is decreased by 22%. It is also shown that the condensation on the roof in some cases is reduced by 75% (ref vs HK16D). The difference between the different thin Leoflex™ combinations (HK16*) and the 4 mm AGC glasses (AGC17*) is limited if it comes to energy saving. However, only thin glasses make the application of triple and quadruple layers possible in practice due to a substantial reduction in weight.
Special attention has to be paid to the NIR effect of the current AGC coating which is connected to an increase in heat consumption of around 10%. Due to this coating around 25% of the solar radiation is not available for heating up the greenhouse (in winter). The effect on the greenhouse air temperature is shown in Figure 5 where for July the average temperature as a cyclic average is presented. Beside (not shown) is the smaller opening of the roof vents in the case with the NIR reflection.
It can be concluded that energy saving of 20-25% can be reached by double glasses compared to polycarbonate sheets because of higher light transmission and thus electricity saving and by quadruple glasses because of higher insulation and thus saving on heat. These savings are caused by the covering only.

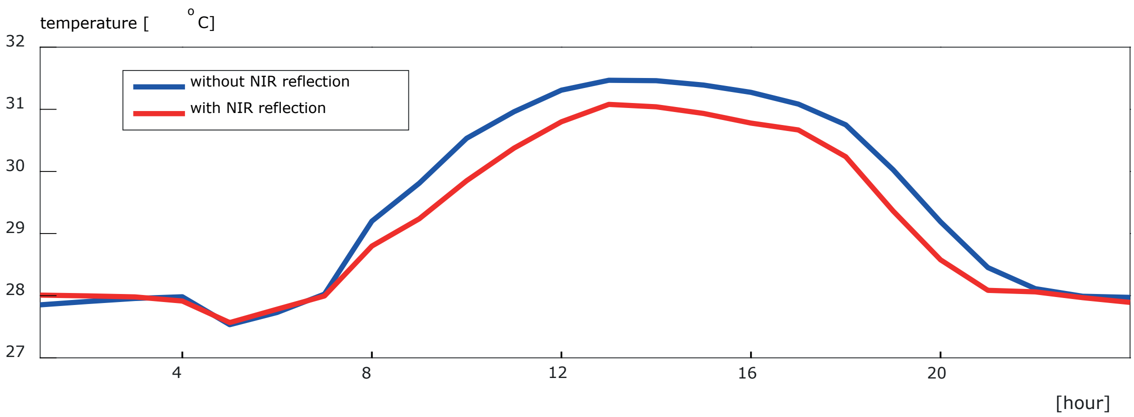


Figure 5 *The cyclic average greenhouse air temperature in July for the AGC17K cover with and without NIR reflection.*

6.2 Phalaenopsis flower production (cold phase)

The calculations in paragraph 5.1 have shown that the differences between Leoflex™ glass combinations (HK16* samples) and the 4mm AGC17* samples are limited. Therefore, in this paragraph only results of the AGC17* samples will be presented.
Main difference between warm and cold phase are the allowed daily PAR sum (10 mol/day instead of 8 mol/day in the warm phase) and the mechanical cooling when greenhouse air temperature exceeds more than 19°C (instead of setpoint of 28°C in the warm phase). In that case the greenhouse is controlled as a closed greenhouse. The cold is produced by a heat pump. For the calculations, the reference is a single glass greenhouse and the single glass case (AGC17E) will be used as reference. Due to the lower greenhouse temperatures, the high insulation of a polycarbonate panel is not required, therefore, this case is not taken into account. The capacity of the artificial lighting is increased to 120 μmol/m^2.s (instead of 93 μmol/m^2.s in the warm phase). Material properties are the same as mentioned in Table 9 (paragraph 5.1).
In Table 11 the heat and electricity requirements for lighting and cooling are shown.

Table 11
Heat and electricity consumption and the condensation on the roof.

WUR code	description	heat	electricity lighting	electricity cooling
		[GJ/m^2]	[kWh/m^2]	[kWh/m^2]
AGC17E	Clear glass 4 mm	1.20	157.6	58.8
AGC17G	Double clear glass 4 mm	0.94	156.5	60.2
AGC17J	Triple clear glass 4 mm	0.93	159.5	62.3
AGC17K	Quadruple clear glass 4 mm	0.90	162.8	67.0
AGC17K NIR	Quadruple clear glass 4 mm NIR reflection	0.93	162.8	44.2

The results show that increase of insulation from double to triple or even quadruple glass can increase energy saving on heat with ca. 20-25% with almost no differences between the different layers of glasses. That is mainly caused by the artificial lighting. From this lighting, many hours there is an overload of heat in the greenhouse which is released by the ventilators. Increase of insulation increases the ventilation requirement in this case and due to the reduced light transmission, the lighting is even used some more hours leading to a higher heat load with higher insulation. More usage of artificial lighting increases electricity consumption for lighting with increasing of the insulation in the roof.
From the electricity requirement for the cooling we see an increase of cooling requirement with an increase of the insulation. With a higher insulation it is more difficult to reach the relatively low temperature setpoint during summer, therefore more artificial cooling is required leading to an increased electricity consumption for cooling. Adding a coating with NIR reflection the cooling requirement of the greenhouse can be significantly reduced since the solar heat load is reduced. Although these effects are around or even over the limit of the model boundaries it is at least a good indication. Effects of NIR reflectance can easily be overestimated while the crop itself has also rather good NIR reflection properties. (Stanghellini, 2011). In Figure 6 the effect of cooling requirement of the month July is presented as a cyclic average. The peak load is reduced by around 25%. The cold water for the cooling is produced by a heat pump of which it is assumed the Coefficient Of Performance on the cold side is 3.
It can be concluded that for the cold phase of Phalaenopsis production a 20-25% energy saving based on heat can be realised with a quadruple glass. However, the energy saving based on electricity with a highly insulated roof (quadruple) with AR and NIR reflection is only small with 4%.

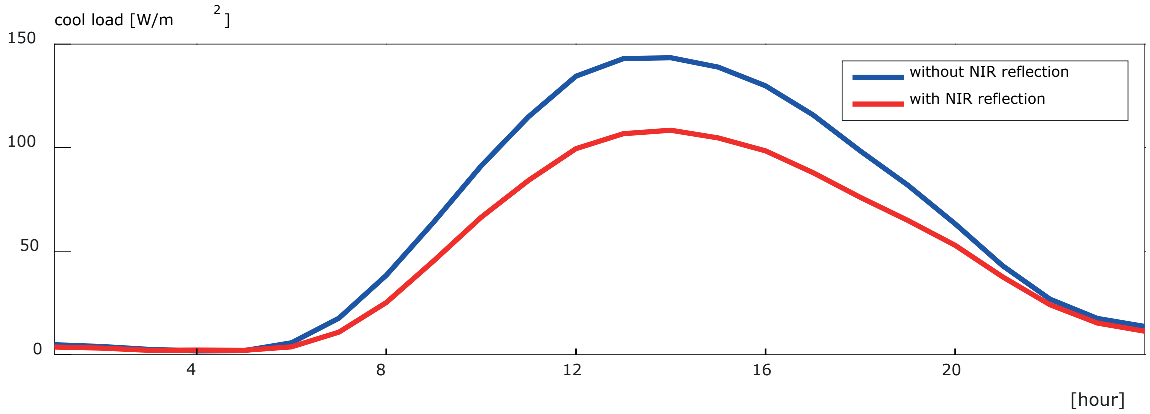


Figure 6 *The cyclic average cooling load in July for the AGC17K cover with and without NIR reflection.*

7 Mechanical properties

Information on mechanical properties of Leoflex™ and Falcon™ is provided by AGC. Both types of thin glasses are based on aluminosilicate glass and are chemically tempered. Due to the different type of basic glass and the chemically tempering better mechanical properties are reached. That allows it to produce glasses with a lower thickness and even better mechanical properties. We compare the mechanical properties of thin glasses with traditional greenhouse glass. This type of glass is based on sodalime glass and is thermally tempered.

7.1 Leoflex™ properties

7.1.1 Weight

Leoflex™ density is 2.48 kg/m^2/mm.
Consequently, the following weights of materials result:

- Leoflex™ 0.55 mm weight is about 1,4 kg/m^2.
- Leoflex™ 0.85 mm weight is about 2.1 kg/m^2.
- Leoflex™ 1.1 mm weight is about 2.7 kg/m^2.
- Leoflex™ 1.3 mm weight is about 3.2 kg/m^2.

The weight of 4 mm sodalime glass (traditional greenhouse glass) with a density of 2.5 kg/m^2/mm is about 10 kg/m^2.

7.1.2 Mechanical properties

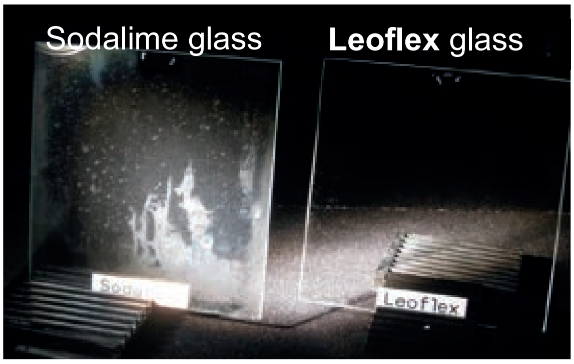
In Table 12 the main mechanical and thermal properties of Leoflex™ chemical and Sodalime thermally tempered are shown.

Table 12
Mechanical and thermal properties of Leoflex™ chemical and Sodalime thermally tempered.

	Leoflex^{Ò} chemical tempered (0.85mm)	Sodalime thermally tempered (3.2mm)
MECHANICAL CHARACTERISTICS		
Strength / Marginal stress (MPa)	260	80
Young modulus (GPa)	74	70
Poisson ratio	0.23	0.2
Density (g/cm^3)	2.48	2.5
Vickers Hardness	673	527
THERMAL CHARACTERISTICS		
Expansion coefficient (10^{-6} 1/K)	9.8	9
Strain point (°C)	556	500

7.1.3 Chemical Stability against Weathering

In Figure 7 the chemical stability against weathering for the sodalime and Leoflex™ glass is shown (A) and the change in haze in time (B).



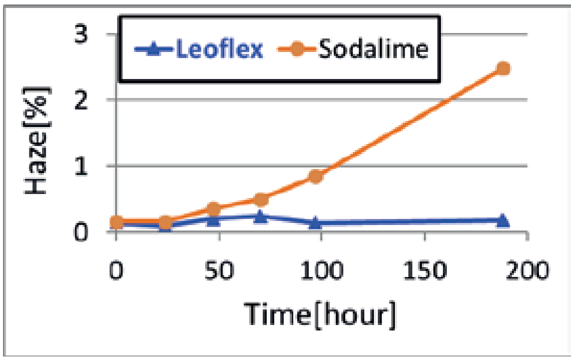


Figure 7 *The chemical stability against weathering for the Sodalime and Leoflex™ glass (A) and the change in haze in time (B).*

7.1.4 Resistance to Scratches

Results of the scratch mark made by scratching by intensity tester HEIDON with a velocity of 2 mm/s is shown in Figure 8. The tempered Leoflex™ show a higher resistance to cracks. The load of lateral crack is presented in Table 13

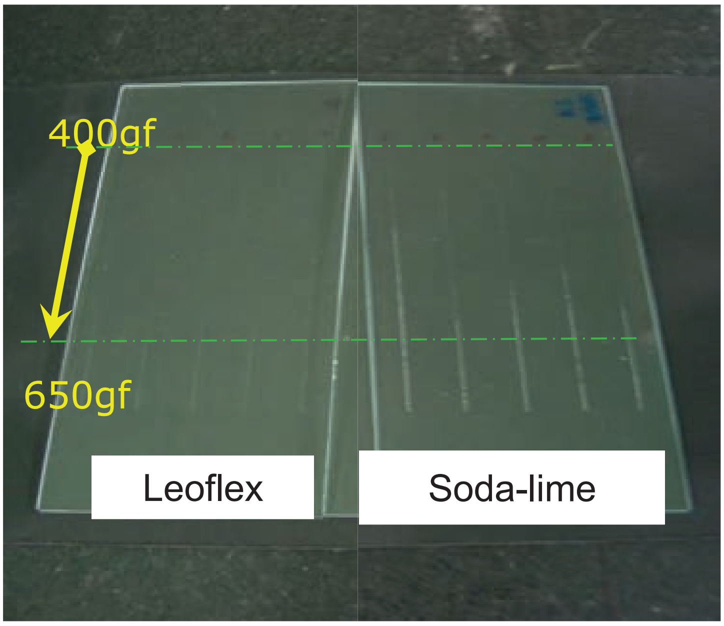


Figure 8 *The resistance to scratches chemically tempered Leoflex™ and thermally tempered Sodalime.*

Table 13

Load of lateral crack of the chemically tempered Leoflex™ and thermally tempered Sodalime.

Scratch resistance	Leoflex (chemically tempered)	Soda-lime (thermally tempered)
Load of lateral crack [gf]	around 600	425~550

7.2 Falcon™ properties

7.2.1 Dimensions

The typical maximum dimensions of the Falcon™ glass are:

- 1600 x 3210 mm (2,1 mm).
- 1480 x 3210 mm (1,1 mm).
- 1350 x 3210 mm (0,7 mm).
- 1245 x 3210 mm (0,5 mm).

From this list we can conclude that currently necessary glass width of 1.67 which are typically needed for Venlo greenhouses cannot be reached. Unfortunately, larger sizes are not foreseen in the near future.

7.2.2 Design loads

Based on a depth of layer of 17 micron the compressive stress of Falcon™ is 200-250 Mpa and the bending Stress is around 200 Mpa. In Figure 9 the compressive stress and depth of layer of standard Sodalime, Falcon™ and Standard aluminosilicate is presented.

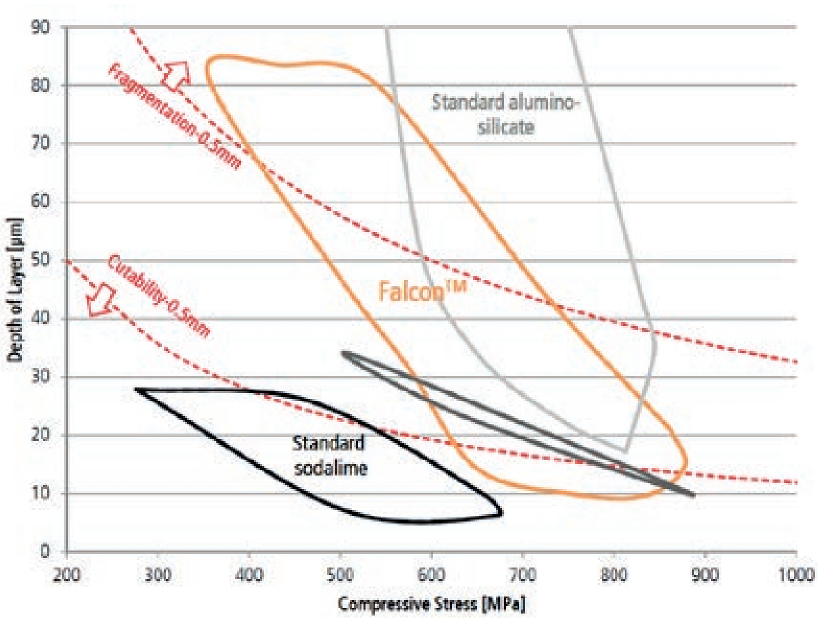


Figure 9 *The compressive stress and depth of layer of standard Sodalime, Falcon™ and Standard aluminosilicate.*

8 New greenhouse roof designs

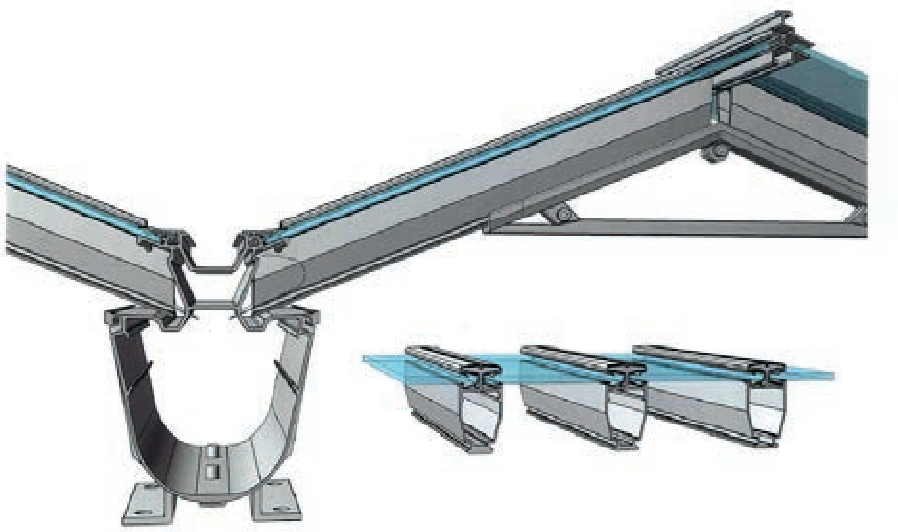
8.1 Introduction

The working group consisting of Boal, AGC, Glascom and WUR held several brainstorm sessions and exchanged ideas on new possible greenhouse roof designs. All drawings below have been either provided by Boal or by AGC.

8.2 Roof designs in greenhouse industry

8.2.1 Greenhouse roofs with glass

Typical technical roof profiles used in Venlo-type roofs are:



8.2.2 Greenhouse roof with plastic covering



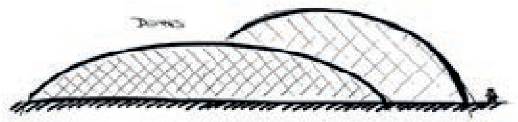
8.3 Roof designs in building industry







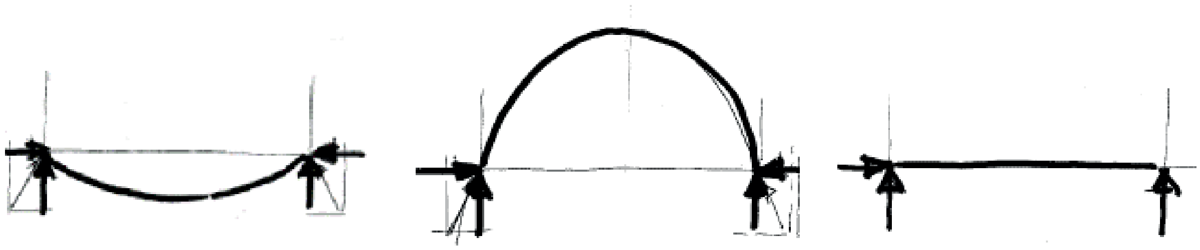




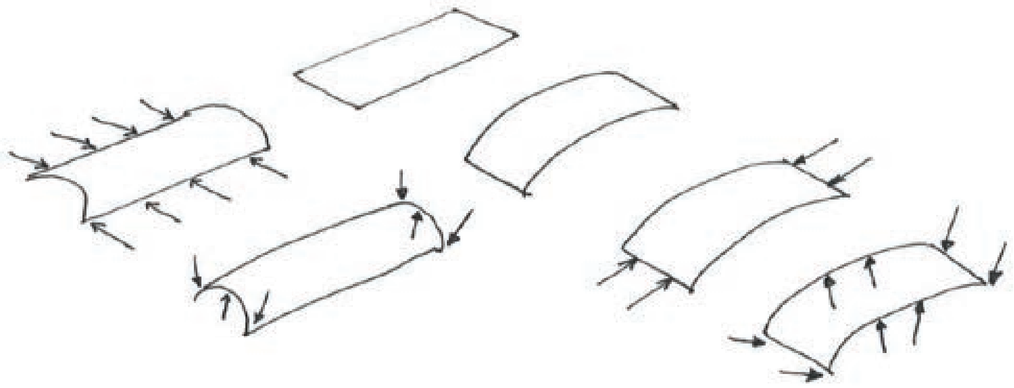

8.4 Principles of thin glass fixing on greenhouse roofs

8.4.1 Single glasses

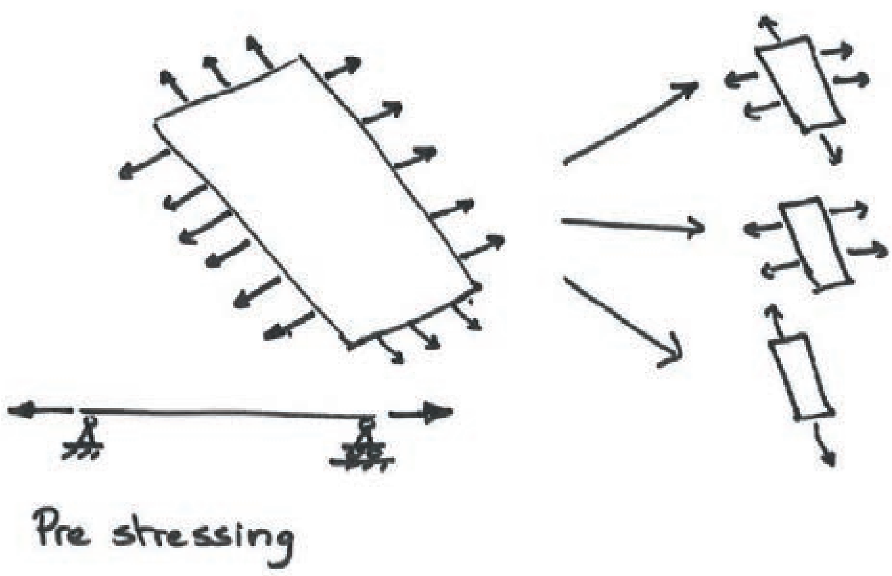
In order to reach mechanical stiffness of single glasses on the roof we can apply the following basic principles for single glass fixing, namely, pre-stressing or cold-bending. By cold-bending form stiffness is achieved.



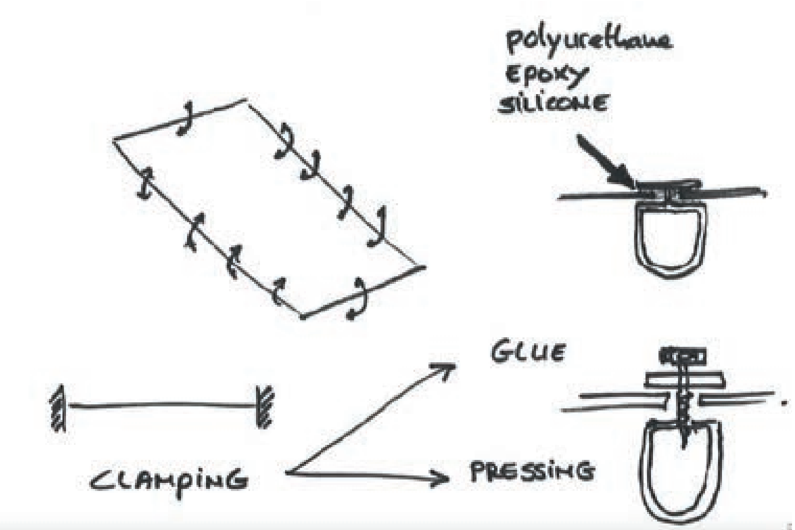
Solutions for cold-bended roofs are displayed below:



Principles for pre-stressing can be divided in pre-stressing in all four directions, in length-direction only or in width-direction only:



In order to fix single thin glasses in existing technical profiles the glass should be clamped thoroughly. This can potentially be done with a glue or by pressing. Neither of the solutions has been tested so far. More detailed research would be needed here.

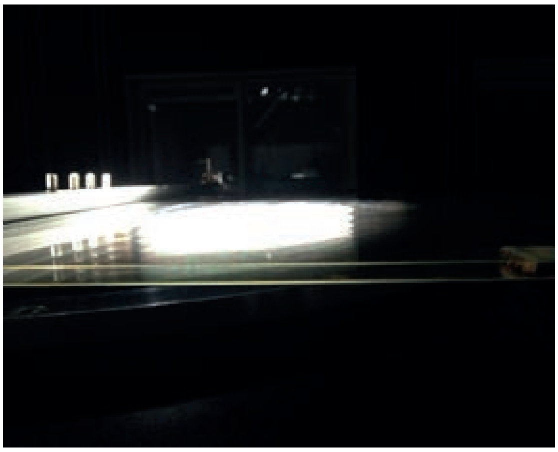


8.4.2 Insulating glass

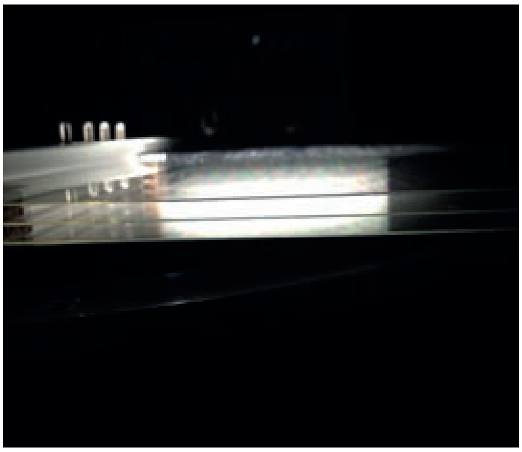
During the project, we produced different insulating glasses with different number of layers.

Double insulating glass made from 2x 0.55 mm thin glass, weight of 1,4 kg/m² (instead of 10 kg/m² for double insulating greenhouse glass made from 2x4 mm glass)

Difference between double insulating glass made from 2x thin glass (left) and 2x4 mm glass (right)

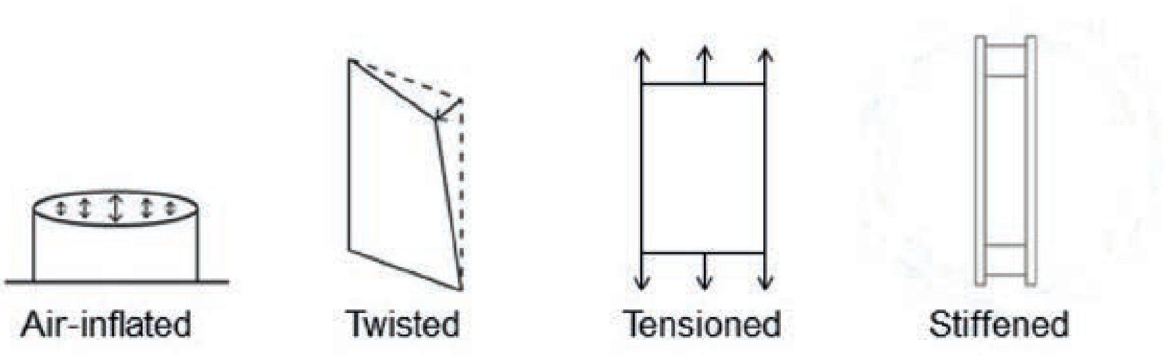


Double glass made from 2 x 0.55 mm thin glass



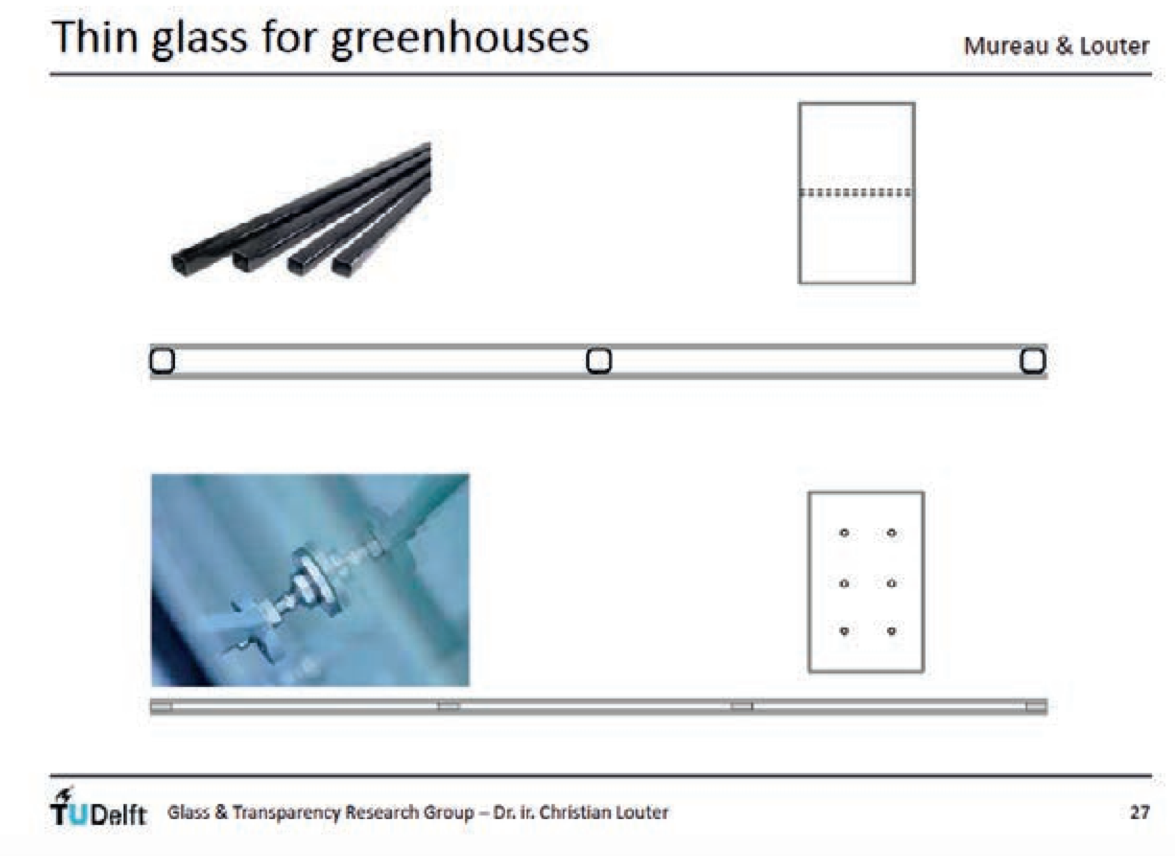
Triple insulating thin glass 0.55 mm

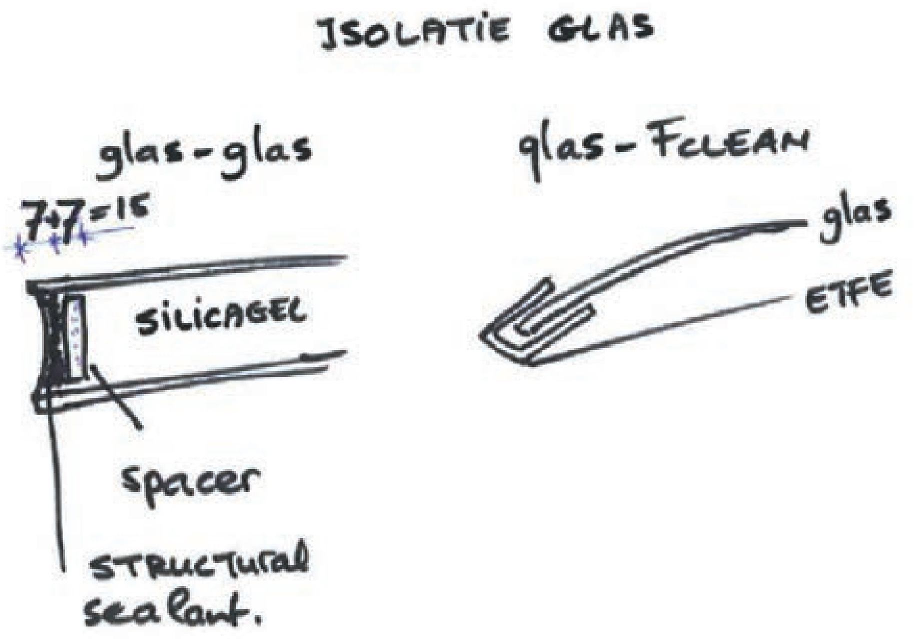
In order to reach mechanical stiffness Mureau (2017) identified the following possibilities for thin glasses.



In order to reach mechanical stiffness for greenhouse roofs the following principles for double glass fixing seem to be most feasible, namely, a spacer over the whole width or lengths of the glass, a point spacer placed in a grid over the glass. Next to that a combination of two pre-stressed or clamped flat glasses or a combination of cold-bended glass with glass or plastic film can lead to new roof designs.

Mureau & Louter, TU Delft, investigated the possibilities of using (transparent) spacers. They found that sandwich structures are suitable to decrease deflections and therefore reach the required mechanical stiffness. However, more detailed calculations and trials would be needed for full-size glasses if they become available in the future. Now the research had been limited to available glass sizes.

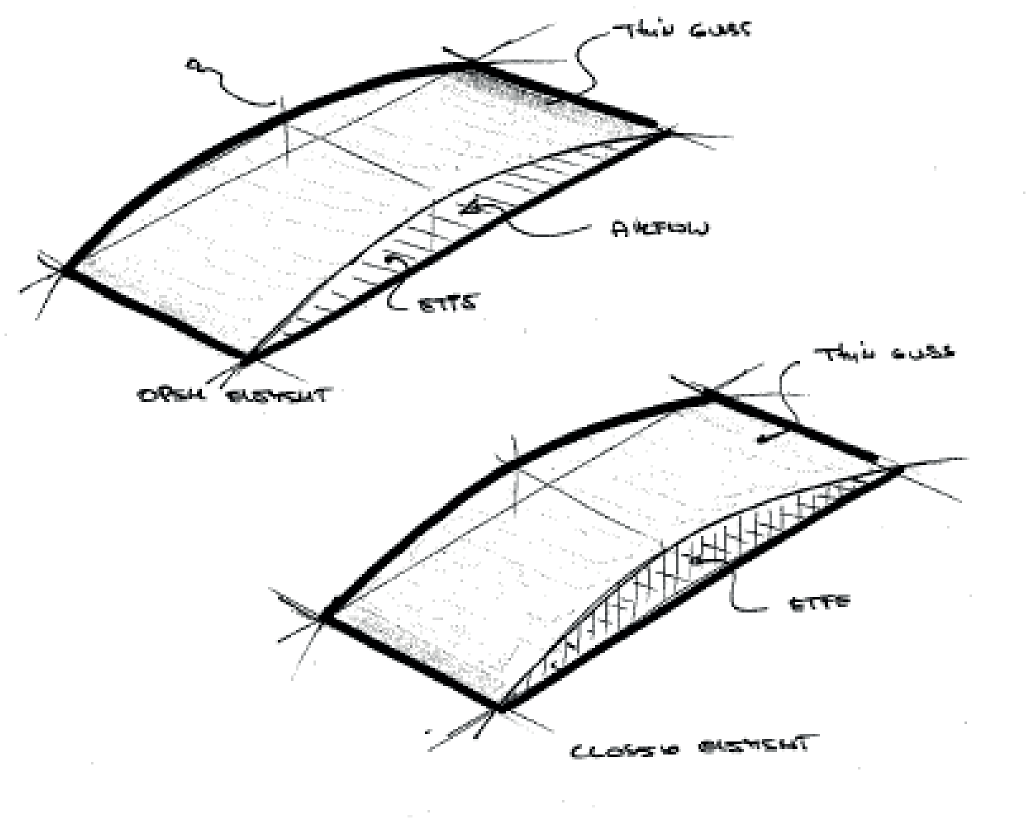




8.5 Feasible new greenhouse roof designs

8.5.1 Sketches

The following sketches of insulating roof designs resulted from our brainstorms.



8.5.2 Demonstrators

Based on the sketches of roof designs above two demonstrators have been produced to show the possibility of new insulated greenhouse roof in which the unique mechanical properties of the materials are taken into account.

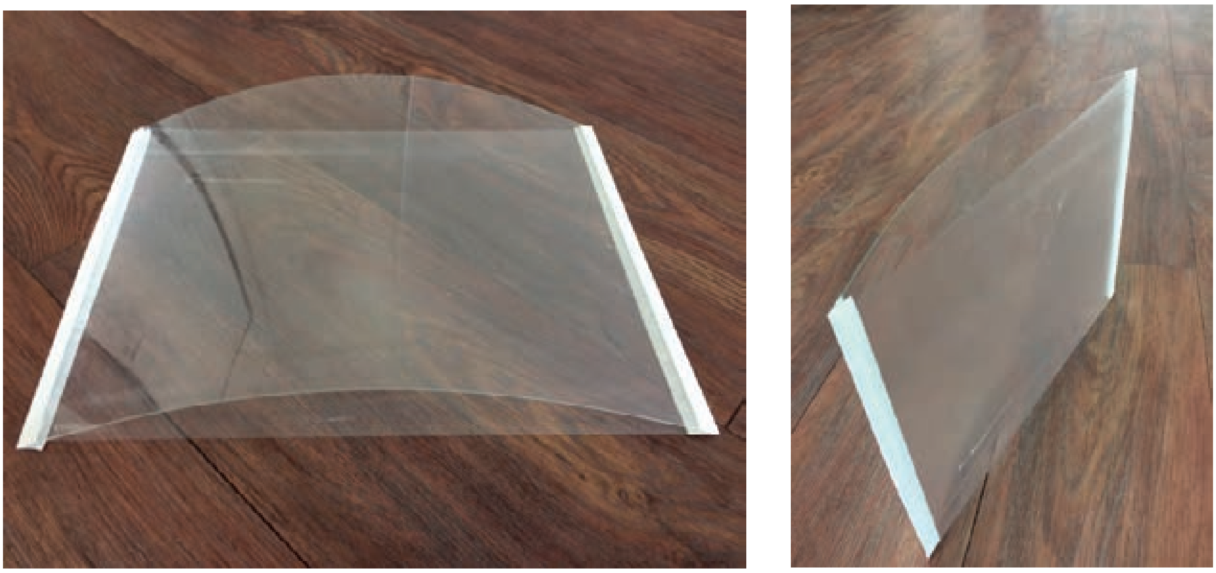


Figure 10 *Insulating roof with cold bended thin glass (Leoflex™ or Falcon™) on top and flat ETFE foil (F-Clean®) below.*

Figure 11 *Insulating roof with cold bended thin glass (Leoflex™ or Falcon™) on top and flat glass below, or vice versa.*

9 Conclusions

9.1 Advantages thin glasses

The project group identifies the following additional value of thin glasses, which can be summarised as:

- High light transmission of AR coated glasses combined with lower weight (compared to traditional coated double glass).
- Higher light transmission of multi-layered glasses compared to PC sheets (with comparable weight).
- High bending strength gives possibilities to work on new greenhouse roof structures (curved, cold-bended).
- High impact strength (better hail resistant) of a chemically strengthened glass.
- Multi-layer glasses are possible with still high light transmission, but lower weight.
- Lower transportation costs due to lower weight.
- Advantages during initial construction and maintenance of the greenhouse due to lower weight.
- Energy savings (heat) ca. 20% (Phalaenopsis) can be reached with multi-layered glass panels additionally to available energy-saving solutions (PC sheets). However, future energy prices will determine economic feasibility. Next to that the future availability of energy and goals of zero CO_2 emission of greenhouses in 2050, might accelerate the introduction of insulated greenhouse systems.

9.2 Challenges thin glasses

Next to above listed advantages the current challenges of thin glasses are discussed:

- Currently high materials costs limit introduction. Cost can be expected to drop if thin glass is also applied on large scale for other industries since thin glasses are strongly under development.
- Currently available dimensions of glasses are limited in width. In greenhouse industry, we typically use glasses up to 1.67 m wide. Thin glasses could be potentially wider because of higher strength, with at the same time lower weight. However, current production sizes are limited. Production sizes can be expected to be increased if thin glass is also applied on large scale for other industries since thin glasses are strongly under development.
- Due to the chemical strengthening process, the glass surface has different properties. The application of surface treatments and coatings is still under development. It can be expected that new surface treatments and coatings become available in the near future.
- Single layered glasses need to be stiffened by cold-bending or pre-stressing. Multi-layered sandwich panels or new material combinations give higher potential for application. Details of application for greenhouse roofs need to be investigated as soon as other challenges are solved.

9.3 Conclusions

- Optical properties of AR coated thin glasses are very good. Compared to a single non-insulating glass without AR the light transmission is still increased by 2%. A triple insulating thin glass with 6xAR shows only a 2% light loss compared to the single non-insulating glass without AR. For a quadruple thin glass with 8xAR this value is 6%. Compared to a polycarbonate sheet (PC) a quadruple thin glass with 8xAR has a 15% higher light transmission.
- Thermal properties of thin glasses are also good. It is theoretically possible to produce double, triple or even quadruple insulating glasses since the weight of such glasses (5.6 kg/m^2 for a quadruple glass of 4x0.55 mm) is still only half of a traditional double greenhouse glass (10 kg/m^2 for a double glass of 2x4 mm).

- For Phalaenopsis cultivation, the energy savings of various thin glasses (single, double, triple, quadruple) were calculated for the warm cultivation phase (young plants) and the cold cultivation phase (flowering). It is shown that 20-25% heat energy can be saved by both phases through the use of a quadruple glass with AR coatings. This is mainly caused by the higher insulation. At the same time, about 20% of electricity for energy can be saved in the warm cultivation phase if a double thin glass with AR coatings is used compared to a PC sheet which has a comparable insulation but a lower light transmission. In that case, under a double thin glass with AR less need to be illuminated to get an equal production. In the cold cultivation phase, the electricity energy saving is limited to a maximum of 4%. Here an insulating deck has no advantages since this makes it difficult to reach lower growing temperatures.
- Currently, practical limitations on available sizes and high costs limit application.
- Since the requirements on thin glasses are comparable for greenhouse application and for other industries such as building or automotive (costs, insulation, sizes), glass might become available for greenhouses in the future.
- More detailed work needs to be done on stiffening glasses for multi-layer application if full-size glasses become available.
- New greenhouse roof constructions need to be developed in more detail if full-size glasses become available for a reasonable price.
- Multilayer applications can be considered as more feasible that single layered application in greenhouse roofs in the future.

10 Literature

Mureau, M.D.A. 2017.
Thin Glass – A study on the application in greenhouse coverings. MSc thesis TU Delft. https://repository.tudelft.nl/islandora/object/uuid:6460db68-76a2-495d-9a71-136e0112895b/datastream/OBJ/download.

Stanghellini, C., Jianfeng D. and F.L.K. Kempkes 2011.
Effect of near-infrared-radiation reflective screen materials on ventilation requirement, crop transpiration and water use efficiency of a greenhouse rose crop. Biosystems Engineering 110 (3): 261-271. https://doi.org/10.1016/j.biosystemseng.2011.08.002

Zwart, H.F. de 1996.
Analyzing energy-saving options in greenhouse cultivation using a simulation model. IMAG-DLO rapport 96-05.

Annex 1 Setpoints and greenhouse layout

Parameternaam	datum	waarde		Omschrijving
Akas:		40000	m²	Kasoppervlak
Padbreedte:		3	m	
hGutter:		5	m	Goothoogte
Roofslope:		22	deg	Dakhelling
Kapbreedte:		4	m	
Vakmaat:		5	m	
frSunAir:		0.075		
Leakage:		2.00E-04	m3/(m2 s)/(m/s)	Dit geeft bij 4 m/s windsnelheid een uitwisseling van 2.9 m3/m2/uur
Windowlength:		2.25	m	
Windowheight:		1.5	m	
fr_Window:		0.05		in een standaard Nederlandse kas is ongeveer 5% van het dekoppervlak een raam
PrimNet:		Low		Is het primaire net het bovennet (Upp) of het ondernet (Low)
Ondernettype:		51-er		
nLowPerKap:		8		aantal buizen in het ondernet per kap van 4 meter
Bovennettype:		51-er		
nUppPerKap:		4		aantal buizen in het bovennet per kap van 4 meter
Pketel:		200	W/m2	
Ketelverlies:		0.5	W/m2	
Buffervolume:		200	m3/ha	m3/ha
Vultemp:		90	oC	
AlsBufVol:		stoppen		kies hier tussen 'stoppen', 'vernietigen' of 'afluchten', 'afluchtenLow' of 'afluchtenUpp'
Gewas:		phalenopsis		
Plantdatum:		01-01		Denk er aan dat je evenveel plantdata als ruimdata hebt
Ruimdatum:		31-12		
StookTemp:		28		
StookTempTijdstip:		0		Tijdstippen kunnen afhankelijk van zon op en zon onder (bijv op+1 of on-1)
DodeZone:		2		Hoe ver staat de ventilatielijn t.o.v. de stooklijn
DodeZoneTijdstip:		0		
PbandTemp:		(5,20);(20,5)		Proportionele band voor raamopening als functie van de buitentemperatuur
LichtVBeg:		100		Begin stralingstraject lichtverhoging
LichtVEnd:		300		Eind stralingstraject lichtverhoging
LichtV:		0		Over een traject (nu van 100 tot 300 W/m2) loopt de stooklijn op met 0 graden
LichtVVent:		1		Over een traject (nu van 100 tot 300 W/m2) loopt de dode zone van de ventilatie op met 1 graden
Vocht				
SpVocht:		70		
SpVochtTijdstip:		0		
PBandVocht:		(5, 20);(15, 10)		
SpCO2:		600		
SpCO2Tijdstip:		0		
CO2bron:		zuiver		kies hier tussen 'zuiver', 'WKK' of 'ketel'
kgCO2:		100		maximale CO2-dosering in kg/ha uur
Luchtramen				
Vorstgrens:		-4		Als de buitentemperatuur onder de -4 komt blijven de ramen dicht
StartWhet:		50		Als loefzijdige ramen meer dan 50 % open zijn gaan de windramen meelopen
WinLeeMin:		0		Minimale raamstand lijzijde
WinLeeMax:	15-02	60		Maximale raamstand lijzijde
"	15-05	100		
"	15-10	30		
WinWhetMax:	15-02	40		Maximale raamstand windzijde
"	15-05	100		
"	15-10	10		
MaxWin:		50		Maximale openingshoek van de ramen
SideVentilation:		0		m2 per m2 greenhouse surface
Buizen				
MinBuisLow:		32		
MinBuisUppTijdstip:		0		
MinBuisBeg:		200		Beginpoint of radiation where minimum pipe temperature is lowered
MinBuisEnd:		400		Endpoint of radiation where minimum pipe temperature is at greenhouse setpoint
MaxBuisLow:		70		
MaxBuisUpp:		65		
T2ndAcc:		45		Temperatuur van het primaire net (Low) waarboven het secundaire net bijkomt
Fogging:		1		
FoggingDose:		200		Maximale vernevelingscapaciteit in gram/(m2 uur)
MinTempFogging:		25		Minimale kasluchttemperatuur waarboven de verneveling aan mag als het droger wordt dan 60% RV
MinVocht:		60		
Belichting:	01-09	yes		
"	01-05	No		
Lampvermogen:		50		Vermogen in W/m2 -> levert 93 umol/(m2 s)
MaxIGlob:	15-02	200		
"	01-04	100		
"	01-10	150		
"	15-11	400		
MaxLichtsom:	01-03	250		
"	01-04	50		
"	01-10	200		
"	15-11	500		
UitPerEtmaal:		8		
BlokUitBegin:		17		Tijdstip waarop de donkerperiode begint (17:00 uur)
Lampeigenschappen				
FracPAR:		0.43		Dit betekent 1.85 umol/J
FracNIR:		0.22		
FracSens:		0.35		

Gevelscherm:		beweegbaar		kies 'beweegbaar'of 'geen'
S c h e r m 1				
ScreenInUse1:		1		
Screensystem1:		ShadeScreen		The term 'Blackout' is a reserved term
Screentype1:		SLS10UltraPlus		
MaxToutScreen1:		30		Screen is not used when temperature is above 30oC
ScrCloseBelow1:		1000		
ChinkOnTempExc1:		(2 ,5);(5,10)		If temp excess exceeds 1st parameter, screen is opened with a chink of 2nd parameter
ChinkOnHumExc1:		(90,2);(95,5)		If humid excess exceeds 1st parameter, screen is opened with a chink of 2nd parameter
S c h e r m 2				
ScreenInUse2:		1		
Screensystem2:		Blackout		
Screentype2:		XLSObscura		
MaxToutScreen2:		22		Screen is not used when temperature is above 22oC
ScrCloseBelow2:		20		
ChinkOnTempExc2:		1		If temp excess exceeds 1st parameter, screen is opened with a chink of 2nd parameter
ChinkOnHumExc2:		5		If humid excess exceeds 1st parameter, screen is opened with a chink of 2nd parameter
S c h e r m 3				
ScreenInUse3:		1		
Screensystem3:		ShadeScreen		
Screentype3:		XLS16F(schaduw)		
MaxToutScreen3:		-5		#REF!
ScrCloseBelow3:		2		
ScrCloseAbove3:	01-03	(250, 100)		
"	01-05	(275, 100)		
"	01-09	(175, 100)		
"	15-11	(225, 100)		
ComplementaryTo3:		SC2		Scherm3 ligt op hetzelfde dradenbed als SC2 en kan dus niet gelijktijdig dicht
Krijten:		1		
Krijtfactor:	04-03	0.15		0 means no whitewhash-effect
"	10-04	0.3		
"	15-09	0.1		
"	01-11	0.01		

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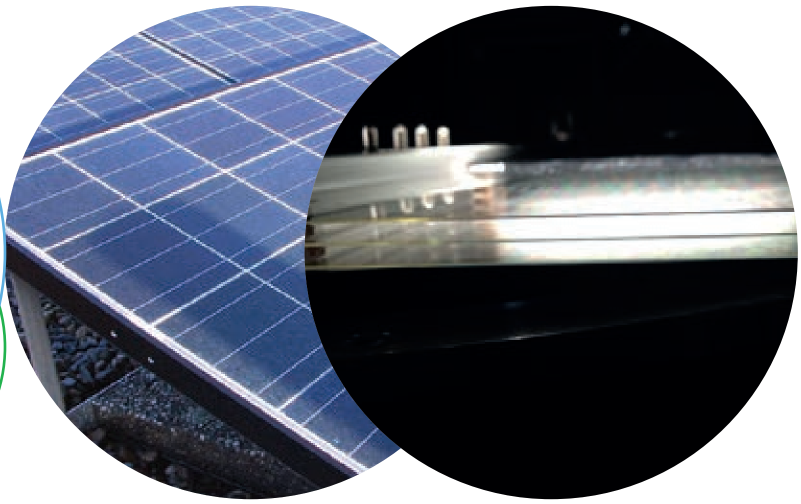

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Greenhouse Horticulture Report WPR-732

Wageningen University & Research, BU Greenhouse Horticulture initiates and stimulates innovations for a sustainable protected horticulture and a better quality of life. This is achieved by partnering with primary producers, the supply sector, plant breeding companies, the scientific community and governments in applied research.

The mission of Wageningen University & Research is 'To explore the potential of nature to improve the quality of life'. Within WUR, nine specialised research institutes of the DLO Foundation have joined forces with WUR to help answer the most important questions in the domain of healthy food and living environment. With approximately 30 locations, 6,000 members of staff and 9,000 students, WUR is one of the leading organisations in its domain worldwide. The integral approach to problems and the cooperation between the various disciplines are at the heart of the unique Wageningen Approach.