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Windows – Optical Performance and Energy Efficiency

BY

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ABSTRACT

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This thesis treats angle-resolved optical properties and the energy efficiency of windows. A theoretical evaluation of optical and thermal properties of windows is briefly surveyed and the energy performance of a large selection of windows, under different conditions, is examined. In particular, angle dependent optical properties are analysed. A new model assessing angle dependence of the total solar energy transmittance, g, of windows is presented. A comparison of simple models for angle-dependence prediction has been performed, including both fictitious and measured real window glazings. The new proposed model illustrates low errors for both the real and the fictitious glazings. The impact of inaccuracy in the angle dependence of the g-factor has been assessed and found to be clearly noticeable but not necessarily critical.

A simple model for comparing the energy efficiency of different windows in different types of buildings and different climates has been further developed and analysed for several conditions. The energy performance of a large number of windows has been analysed using this model, and also by using other building and window simulation models. Typical savings when changing from a standard double glazed window to the optimal window for the investigated case is in the order of 100-150 kWh/m^{2}yr. The annual energy balance of modern low emittance windows illustrates that they can be annual energy savers rather than energy losers, unlike traditional windows. However, it is shown that it is not important to argue about small changes (~0.01) of the thermal emittance value. Furthermore, advance solar control glazings effectively reduce solar transmittance with maintained high light transmittance.

AR-coatings and low-iron glazings can increase the transmittance of glazings considerably. In fact, a "super" low emittance window with a U-value below 1 W/m^{2}K can have higher light transmittance than a common double-glazed unit. Windows with variable transmittance, switchable windows, are compared with high-performing solar control windows, illustrating some degree of potential energy savings compared to high performing static solar control windows, depending on the type of control that is used. This is accompanied by the potential for automatic thermal comfort- and glare control.

Different models for energy rating of windows have been evaluated, demonstrating that a simple linear rating depending on the U and g-factor of the window may be sufficient with certain restrictions. Division into climate zones is essential.

In all, the results demonstrate that energy-efficient windows provide huge energy-saving potentials on a large (regional, national, global) scale.

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TO FEDRA

AND OUR BABY

THAT SHE IS CARRYING

This thesis is conducted within the National research school Energy Systems. Energy Systems consists of a broad multidisciplinary graduate school aiming at creating competence in combining technical and social science for use in solving complex energy problems. The research programme analyses processes for the conversion, transmission and utilisation of energy, combined together in order to fulfil specific needs.

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VI. J. Karlsson and A. Roos, *Annual energy window performance versus glazing emittance - the relevance of very low emittance values,* Thin Solid Films, **392**, 2, (2001).

VII. J. Karlsson, B. Karlsson and A. Roos, *Performance of anti-reflection glazings in windows*, Proceedings, Glass Processing Days - 2001*,* Tampere, Finland, June 18-21, (2001).

VIII. J. Karlsson and A. Roos, *Angle resolved Optical characterization of an electrochromic device,* Solar Energy, **68**, 6, (2000).

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1. INTRODUCTION

The advantages of windows are indisputable, creating visual contact with the outside environment and letting in natural light in buildings. Nobody can imagine living without windows today. In contrast to these advantages, windows are traditionally week links in the building energy system with high thermal losses and high solar heat gain leading to increased heating or cooling need, respectively. Environmental and economic reasons thrive our motivation to reduce energy consumption. One of the areas providing large energy saving potentials is the building sector, both commercial and residential, which typically account for about a third of the total energy use in western countries. The ability to apply uniform thin film coatings on large areas of glass changed the window market drastically in the early eighties. The thermal losses of a window, which could be about ten times larger than that of the wall, could now be reduced to only about three times worse than the wall. Reflective coatings could be manufactured reducing problems with overheating and thus allowing buildings to contain very large areas of windows. In order to find suitable windows for given locations and buildings the optical and thermal properties of windows have to be understood as well as the complex interactions of the windows with the building, the occupants and the environment.

This thesis is focused on the optical properties and (mainly heating and cooling) energy performance of glazings. The sections preceding the papers treat the following issues: Section 2, "The spectral rules of nature", speaking for it self, investigates the environmental boundaries for what we can and cannot achieve. Section 3, "Windows – physical properties " discusses thermal and optical performance of windows including design and function. Section 4, "Solar irradiation", which is important input data for window energy calculations, discusses how this data is treated. Section 5, "Windows in buildings and energy efficiency" briefly discusses how the energy impact of windows is addressed. Section 6, "Results and discussion" contains a general discussion about the papers with some complementary results. Section 7, "conclusions and future work" brings the thesis to a close with some conclusions and ideas for future work.

The appended papers are referred to with Roman superscript [I,II,III,] etc., and other references with Arabic superscript. The topics in the papers can be divided in four subgroups:

1. The angle dependence of the transmittance of windows have been investigated, papers I, III and VIII.
2. A simple model for assessing the energy performance of windows, with only a limited knowledge of the building type, has been further developed and analysed, papers II, IV and XI.
3. The energy performance of a wide variety of different types of windows have been evaluated by the use of the tool mentioned in sub group 2 above and other building simulation programs, papers II, VI, VII, IX, X.
4. How to establish an energy rating of windows as a mean to demonstrate the gains in energy and economy of these products is mainly discussed in paper V, but also briefly in paper II and XI.

2. THE SPECTRAL RULES OF NATURE

In order to manufacture windows that perform well in terms of energy performance and visual comfort we have to understand our physical environment. When studying electromagnetic waves, such as visible light, it is important to understand that many physical variables are wavelength dependent. This dependency can create problems, for instance unwanted dispersion in optical fibres, but can also render possibilities, such as in the case of energy efficient windows as shall be outlined below.

The main part of the solar radiation is confined to a spectral region within about 0.3-2.5 μm as illustrated in figure 1. The extraterrestrial irradiation on a unit surface perpendicular to the direction of the sun is about 1367 W/m^2, normally referred to as the solar constant, G_{sc}, though it varies slightly over the year[1]. From this irradiation about 1000 W/m^2, corresponding to the area under the solar spectrum in figure 1, reaches earth bound objects under clear weather conditions. Thus, this is the maximum power directly collectable from the sun. The peak power is located at a wavelength of about 0.48 μm and the spectrum is pecked with absorption dips mainly from atmospheric water vapour, carbon dioxide and ozone[1].

All matter emits radiation according to Planck's law[1]. The wavelength region of this so-called blackbody radiation is uniquely defined if the absolute temperature of the body is known. If the temperature of the body is not extreme, here meaning 20°C ± 100°C, the emitted radiation resides in a spectral region of about 2-50 μm. In figure 1, three different blackbody radiation curves are plotted, corresponding to 20°C and 20°C ± 50°C. Wien's displacement law defines the wavelength corresponding to the maximum in the blackbody radiation by

$$\lambda_{\max} T = 2897.8 \quad \mu mK \qquad \textit{Eq. 1}$$

and the total energy emitted by a blackbody, i.e. an ideal, perfect absorber and emitter of radiation, is equal to

$$E_b = \sigma T^4 \qquad \textit{Eq. 2}$$

where σ is the Stefan-Boltzmann constant.

The relative spectral sensitivity of the human eye is confined to a region of about 0.38 to 0.76 μm in its light-adapted (photopic) state. Figure 1 illustrates the curve that has its peak at about 0.555 μm.

Unlike walls, which save more energy the more insulation, a window can gain a lot of energy by letting in solar energy and daylight. But it can also loose energy thermally, like the wall. The transmittance creates visibility towards the exterior and allows daylight to enter the building, but the solar throughput can also create unwanted overheating or glare and discomfort. The fact that the different spectra are confined to specific or separated regions as illustrated in figure 1 can be beneficially used for window design in specific climate regions or types of buildings, as shall be discussed in the following sections.

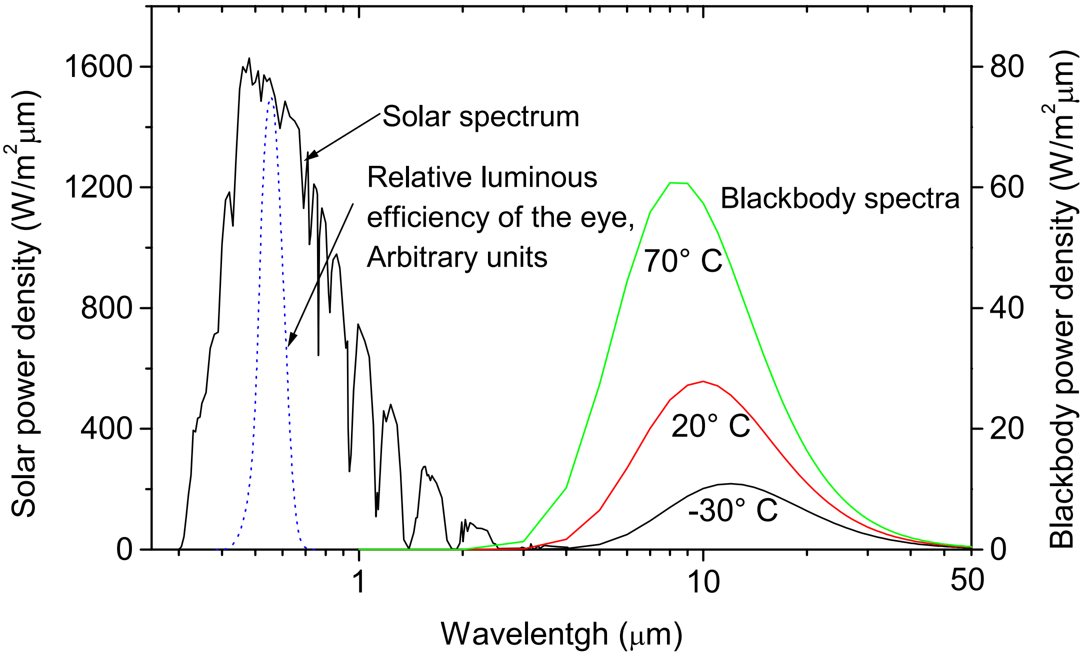

Figure 1: Solar irradiation spectra at air mass, AM 1.5 (ISO 9845-global[2]), the relative spectral sensitivity of the human eye (CIE 1931[3]) and blackbody spectra for three different temperatures. Note the different scales on the vertical axes and the logarithmic scale on the horizontal axes.

3. WINDOWS – PHYSICAL PROPERTIES

As illustrated in the simplified sketch in figure 2, the window consists of several parts, which all affect its physical properties. The obvious part is the glazing, which contains 1,2,3 or sometimes even 4 glass sheets separated by air gap(s). The glass sheets are sometimes mounted directly in the frame, which, depending on the frame makes the glazing accessible from both sides. Nowadays, it is getting more common to seal the glazed unit by the use of spacers, creating what is normally referred to as an insulated glass unit, IGU. This process facilitates the assembling and handling of the window and also makes it possible to fill the air gap with other gases and/or to apply coatings that require protection from the environment. The frame and spacer might be complex structures in themselves but this will not be treated in detail in this thesis, which focuses mostly on the glazed part of windows. In the front view in figure 2 the window is roughly divided into three areas or zones: frame-, edge- and glazed zone, which will facilitate simple thermal calculations. The edge zone is approximately taken as the area within about 6 cm (about 2.5 inch) of the window sight line[4,5]. Double-glazed units will be referred to as DGU's and triple glazed units will, consequently, be referred to as TGU's. Conventionally the panes and surfaces are numbered from the outside. The first pane will thus be the pane closest to the outside and the first surface is the surface facing the outside on the first pane, the second surface is the surface of the first pane facing inwards etc.

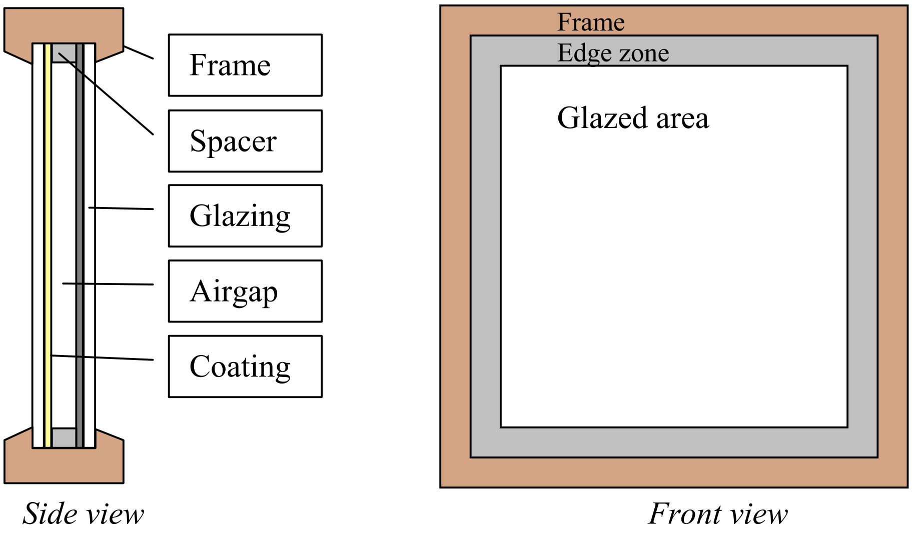

Figure 2: Schematic picture of the window, consisting of frame, spacers, glazing(s), air gap and coatings. An insulated glass unit, IGU is the sealed glass unit without the frame. The air gap might be filled with a low-conductive, heavy gas and the coatings are optional.

3.1. Thermal properties

The thermal performance of a window is categorised with a parameter known as the U-value, which is the thermal losses through the window per square meter window area and degree temperature difference between the outside and the inside of the window (W/m^{2}K). The total window U-value is normally taken as an area weighted U-value of the different zones as given in figure 2.

$$U_{tot} = \frac{U_{frame}A_{frame} + U_{edge}A_{edge} + U_{glass}A_{glass}}{A_{tot}} \qquad \textit{Eq. 3}$$

where U_{frame}, U_{edge} and U_{glass} are the U-values of the respective zones, A_{frame}, A_{edge} and A_{glass} are the respective areas and A_{tot} the total area. The U-values are here assumed constant over each area zone. In Europe it is more common to assign a linear heat transmission coefficient, Ψ_{fg} (W/mK), that takes the edge losses between the frame and glass into account. The total window U-value then becomes

$$U_{tot} = \frac{U_{frame}A_{frame} + \Psi_{fg}l_{fg} + U_{glass}A_{glass}}{A_{tot}} \qquad \textit{Eq. 4}$$

where l_{fg} is the length of the edge between the frame and the glazing[6]. Thus the total thermal performance depends on the different parts of the window and the advantage of a very good (i.e. low) U-value in one of the parts might be diminished if another part has a high U-value. Metal spacers, for instance, contribute to a considerable thermal bridging at the edge zone and can increase the total U-value by approximately 0.2 W/m^2K compared to "warm edge" technologies[6]. The material (and the thickness) of the frame can obviously have a tremendous impact on the total window U-value considering, for instance, that aluminium has about 1000 times higher thermal conductivity, λ, than wood. In reality the heat transfer is not merely one-dimensional, as presented above. More detailed procedures to compute the U-values of the frame- and edge zone can be found in, for instance, references Weitzmann et al.[7], Jonsson[8] and Huizenga et al.[9]. See also the new standard ISO 15099[10].

The heat transfer through the glazing occurs basically through three physical processes: radiation, convection and conduction. Radiation is the long wave radiation exchange between surfaces and surroundings, convection is the temperature induced movement of the air or gas that transfers heat between the panes or the wind that sweeps the window on the outside and conduction is the heat conduction through the medium. The European standard EN 673[11] describes a simple steady state procedure of how to calculate the centre-of-glass U-value according to the following.

$$\frac{1}{U_{glass}} = \frac{1}{h_e} + \frac{1}{h_t} + \frac{1}{h_i} \qquad \textit{Eq. 5}$$

where h_e and h_i are the external and internal heat transfer coefficients and h_t the heat conductance of the glazing unit.

$$\frac{1}{h_t} = \sum_{N_S} \frac{1}{h_s} + dr \qquad \textit{Eq. 6}$$

where h_s is the gas space conductance, N_s the number of spaces, d the total thickness of the glass and r the thermal resistivity of glass, which normally is negligible (about 1 mK/W). The gas space conductance can be written

$$h_s = h_g + h_r \qquad \textit{Eq. 7}$$

where h_r is the radiation conductance and h_g is the gas conductance. h_r depends on the thermal emittance (see definition in section 3.3) of the surfaces enclosing the space and the average temperature of the gas space. h_g depends on the thermal conductivity, density, dynamic viscosity, specific heat of the gas, the temperature difference between the outer glass surfaces, the average temperature of the gas space and the width of the space between the panes. The inclination of the window also affects the convective part of the heat transfer. The external heat transfer coefficient, h_e is a function of the emittance of the outer surface, the wind speed near the glazing and other climatic factors. The internal heat transfer coefficient, h_i, is a function of the emittance of the inner surface and the inside convection and thermal radiation situation. In EN 673 the values of h_e and h_i are standardised to 23 and 8 W/m^2K, respectively (see, for instance, ASHRAE[5] for more details).

The U-value of the glazed part is improved by using more panes, basically halved from 5.9 to 2.9 W/m^{2}K by increasing from single to a double glazed unit and by one third, from 2.9 to 1.9 W/m^{2}K, by increasing from double to a triple glazed unit. For an uncoated double glazed unit the radiation losses dominate with about 64 % of the losses over the gas space (i.e. h_r/h_s). A reduced emittance is thus the consecutive measure to improve the U-value. A thermal emittance of 5 % instead of 84 %, which is the thermal emittance of an uncoated glass surface, almost halves the centre of glass U-value from 2.9 to 1.7 W/m^{2}K for a DGU by reducing the radiative part of the space losses (h_r/h_s) to about 11 %. The final step to improve the U-value of the glazed part is to fill the spacing with a gas that has low thermal conduction and viscosity. According to EN 673 the U-value reduces from 1.7 to 1.3 W/m^{2}K using Argon and to 1.0 W/m^{2}K using krypton in a DGU with emittance of 5% on one of the panes. Thus, using all mentioned measures, the centre of glass U-value can be reduced from about 5.9 W/m^{2}K for a single glazing down to about 1 W/m^{2}K for a coated DGU with gas fill.

Figure 3 exemplifies how the centre of glass U-value depends of the thermal emittance of the third surface for a DGU with different type of gas filling. It is seen that a radical decrease in the centre of glass U-value is achievable with coatings exhibiting low-emittance. In figure 4 the centre of glass U-value is plotted versus the spacing distance in a double glazed unit with different gas fill and emittance of the third surface. It is seen that there is an "optimum" distance somewhere between 10 – 15 mm. It is also seen that a gas fill is more advantageous for glazings that have low emittance on one of the surfaces.

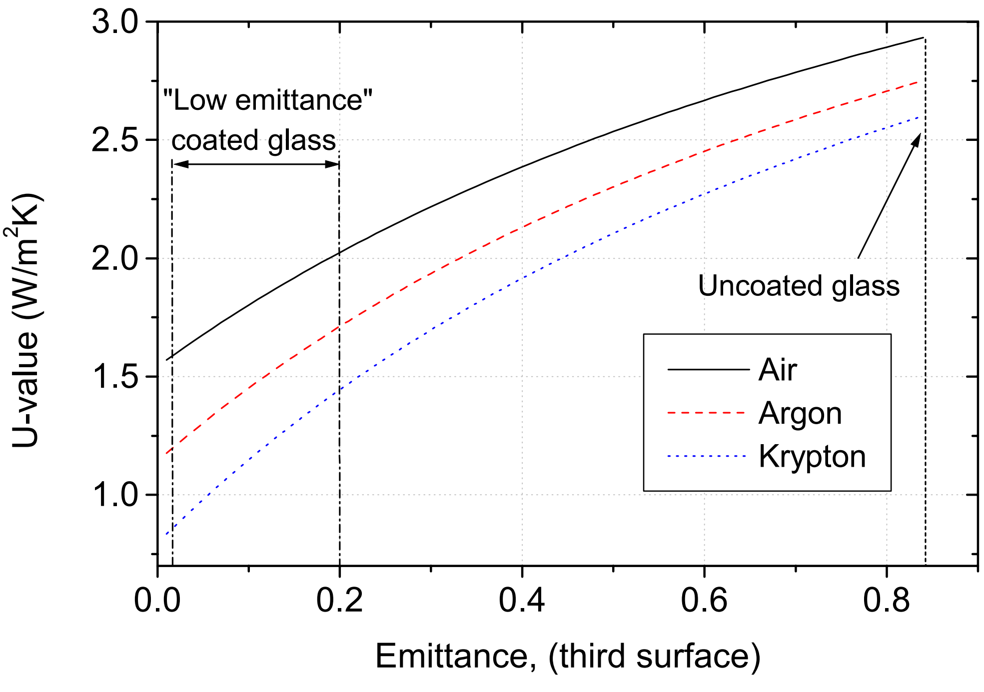

Figure 3: Centre-of-glass U-value calculated according to EN 673 vs. emittance for the third surface and for different gas fill. Low emittance glazings have emittance below 20 % and uncoated glass has about 84 %.

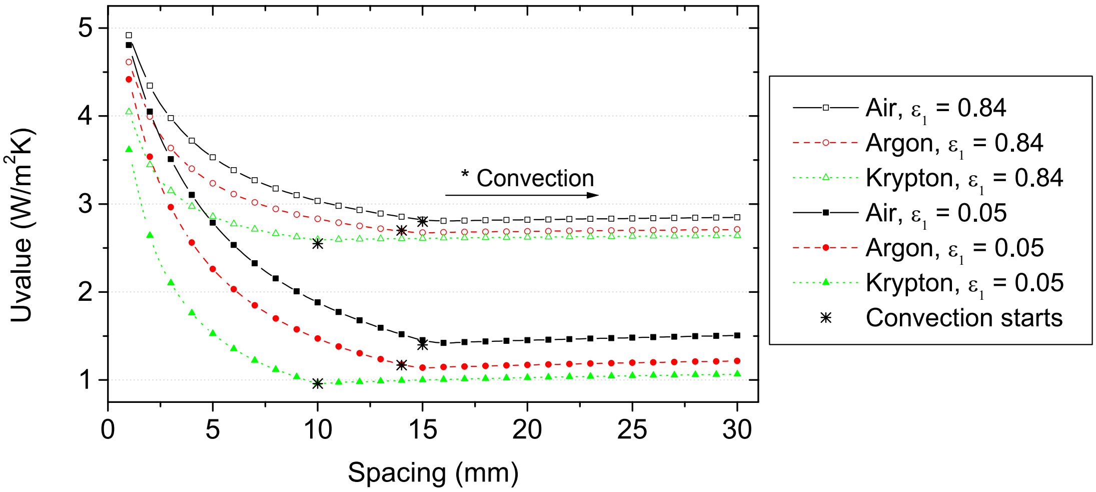

Figure 4: Centre of glass U-value vs. spacing distance according to EN 673 for different gas fill and emittance on the third surface of a DGU. The "" indicates were the convection loop starts.*

All the measures discussed above in this section are based on already available technologies. It is thus seen that a modern window can have U-values of the order of 1 W/m^{2}K, which is quite an improvement compared to old windows which have U-values of the order of 2.5 - 5.5 W/m^{2}K. For comparison, a modern wall used in a cold climate may have a U-value of about 0.2-0.4 W/m^{2}K.

It should be noted that the U-value of the window is not only important from an energy perspective since it determines the heat losses through the window, but also from a comfort perspective considering that windows with high U-values create heat sinks in their vicinity if it is cold outside.

3.2. Optical properties

The optical properties that are of concern for glazings are normally transmittance, reflectance and absorptance, which correspond to the fraction of the impinging radiation that is transmitted, reflected or absorbed, respectively. These properties are wavelength dependent and can in many well-defined cases be theoretically analysed or measured. Both for theoretical calculations and measurements, sample geometry, homogeneity, scattering etc., have to be taken into account.

When the dielectric properties of a medium is linear and isotropic the displacement **D** is directly proportional to the electric field intensity **E** by the relation[12]

$$\mathbf{D} = \varepsilon_0(1+\chi_e)\,\mathbf{E} = \varepsilon_0\varepsilon_r\mathbf{E} \qquad Eq.8$$

Where ε_0 is the permittivity of free space, ε_r is the complex dielectric permittivity and χ_e the electric susceptibility. The complex dielectric permittivity, sometimes referred to as the dielectric constant, is actually a function of wavelength and it is a measure of how easy it is to displace charges in the material. The dielectric permittivity shows complicated wavelength behaviour, but can in many cases be considered as a function of different elementary excitations[13]. In terms of susceptibilities

$$\varepsilon = 1+\chi^{VE}+\chi^{PH}+\chi^{FC} \qquad \textit{Eq. 9}$$

where the superscripts VE, PH and FC represent valance electrons, phonons and free carriers, respectively. For χ^{VE} and χ^{PH} the susceptibilities can often be approximately represented by a sum of damped Lorentz oscillators and for χ^{FC} the susceptibility can often be approximately expressed as a screened Drude oscillator[13]. In optics the complex refractive index, *N*, is normally used instead of the dielectric function. N is given by

$$N = n + ik = \sqrt{\varepsilon_r} = \sqrt{\varepsilon_1 + i\varepsilon_2} \qquad \textit{Eq. 10}$$

where ε_1 and ε_2 are the real and imaginary parts of the dielectric function respectively. Magnetic effects are neglected. n and k are normally referred to as the optical constants, *n* as the refractive index and *k* as the extinction coefficient. The term "optical constants" is unfortunate as both n and k are function of wavelength and not constants. The optical constants together with the geometry contain enough information to optically characterise surfaces, thin films and bulk.

If electromagnetic radiation impinges on an interface between two materials, the reflected and transmitted field amplitudes are determined by using the Fresnel equations[14] at each wavelength, polarisation and angle of incidence. With the definitions in figure 5a, the amplitudes are

$$r_s^{ij} = \frac{N_i\cos\theta_i - \sqrt{N_j^2 - N_i^2\sin^2\theta_i}}{N_i\cos\theta_i + \sqrt{N_j^2 - N_i^2\sin^2\theta_i}} \qquad \textit{Eq. 11}$$

$$r_p^{ij} = \frac{N_j^2\cos\theta_i - N_i\sqrt{N_j^2 - N_i^2\sin^2\theta_i}}{N_j^2\cos\theta_i + N_i\sqrt{N_j^2 - N_i^2\sin^2\theta_i}} \qquad \textit{Eq. 12}$$

$$t_s^{ij} = \frac{2N_i\cos\theta_i}{N_i\cos\theta_i + \sqrt{N_j^2 - N_i^2\sin^2\theta_i}} \qquad \textit{Eq. 13}$$

$$t_p^{ij} = \frac{2N_iN_j\cos\theta_i}{N_j^2\cos\theta_i + N_i\sqrt{N_j^2 - N_i^2\sin^2\theta_i}} \qquad \textit{Eq. 14}$$

s and p indicate polarisation, where s indicates radiation normal to the plane of incidence and p parallel to the plane of incidence. For a single thin film on a substrate the reflected and transmitted field amplitudes interfere, as illustrated in figure 5b, to form a geometric series yielding the reflected and transmitted amplitudes at each wavelength and incidence angle by

$$r_{2s}^{f} = \frac{r_s^{12} + r_s^{23} e^{2i\delta}}{1 + r_s^{12} r_s^{23} e^{2i\delta}} \qquad \textit{Eq. 15}$$

$$t_{2s}^{f} = \frac{t_s^{12} t_s^{23} e^{i\delta}}{1 + r_s^{12} r_s^{23} e^{2i\delta}} \qquad \textit{Eq. 16}$$

with the definitions in figure 5b. Equivalent expressions for p-polarised radiation are obtained by just replacing s with p in the above equations (15 and 16) and the following equations. Index f indicates the optical property seen from the front (from medium 1) and δ is the phase change of the light beam upon traversing the film given by

$$\delta = \frac{2\pi d}{\lambda} N_2 \cos(\theta_2) = \frac{2\pi d}{\lambda} \sqrt{N_2^2 - N_1^2 \sin^2(\theta_1)} \qquad \textit{Eq. 17}$$

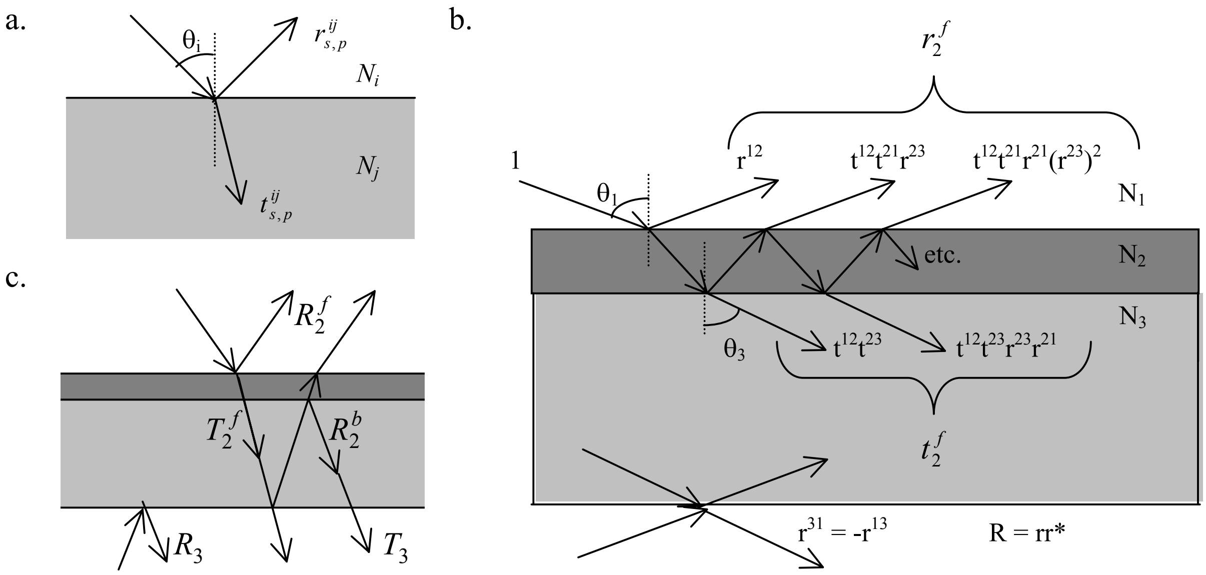

Figure 5a: Reflected and transmitted amplitudes at bulk interface ij. s and p denotes polarisation state, θ_i incidence angle and N the complex refractive index. Figure 5b: Multiply reflected and transmitted amplitudes for a thin film on a substrate, arbitrary polarisation. Figure 5c: Measurable intensities are denoted with capital letters

Measurable intensities (figure 5c) are denoted with capital letters and are given by

$$R_{2s}^{f,b} = \left| r_{2s}^{f,b} \right|^2 \qquad \textit{Eq. 18}$$

$$T_{2s}^{f} = \frac{N_3 \cos(\theta_3)}{N_1 \cos(\theta_1)} \left| t_{2s}^{f} \right|^2 \qquad \text{Eq. 19}$$

$$T_{2s}^{b} = \frac{N_1 \cos(\theta_1)}{N_3 \cos(\theta_3)} \left| t_{2s}^{b} \right|^2 \qquad \text{Eq. 20}$$

etc. Index b denotes optical property from the backside (from medium 3). In a glass substrate, which has macroscopic thickness but low absorption, the phase coherence is lost but multiple reflections occur. In this non-coherent case the intensities are added to form (absorption in the substrate neglected)

$$R_s = R_{2s}^{f} + \frac{T_{2s}^{f} T_{2s}^{b} R_{3s}}{1 - R_{2s}^{b} R_{3s}} \qquad \text{Eq. 21}$$

$$T_s = \frac{T_{2s}^{f} T_{3s}}{1 - R_{2s}^{b} R_{3s}} \qquad \text{Eq. 22}$$

where R_{3s} and T_{3s} are obtained from r_{s31} and t_{s31}. The above equations are straightforward but quite rigorous to generalise for multilayer coatings[14]. When the coatings are not homogenous effective medium theories[13] may be used to get the approximate optical constants. If the sample contain volume scattering films or have rough boundaries corrections to the Fresnel equations are required[15,16]. There are several available commercial programs with the ability to perform multilayer, thin film calculations[17,18,19]. In principle any kind of optical filter can be achieved, using multilayer stacks[20], for windows mostly low-e, solar control, anti-reflective (AR) or a combination thereof are of interest, see section 3.4 below. Coatings with switchable properties are also developed for window applications, see section 6.3.

3.3. Spectral averages

At each wavelength, energy conservation demands that the sum of the absorptance, reflectance and transmittance equals one

$$A(\lambda)+R(\lambda)+T(\lambda)= 1 \qquad \text{Eq. 23}$$

If the matter is at thermodynamic equilibrium

$$A(\lambda)=\varepsilon(\lambda) \qquad \text{Eq. 24}$$

where ε is the thermal emittance, compared to an ideal blackbody[13]. To compare the optical properties of a glass or a glazing within certain spectral regions, integrated optical parameters are defined with a general equation as[21]

$$P_x = \frac{\int_a^b P(\lambda)\Phi_x(\lambda)\Gamma_x(\lambda)d\lambda}{\int_a^b P(\lambda)\Gamma_x(\lambda)d\lambda} \qquad \text{Eq. 25}$$

with parameters defined in table 1. The integrated parameters represent the average transmittance, reflectance, absorptance or emittance within the specified region, denoted T_{sol}, T_{vis}, ε_{th} etc. at any angle of incidence. Spectral averages for colour rendering within the visible and for skin protection factor and damage to fabrics within the ultraviolet region also exist[21].

Property type, x	Lower wave-length, a (μm)	Upper wave-length, b (μm)	Source weighting function, Φ_x	Detector weighting function, Γ_x
Solar P_{sol}	0.3	2.5	AM 1.5 Global irradiance (ISO 9845[2])	1.0
Light P_{vis}	0.38	0.78	CIE D65 Illuminant (ISO/CIE 10526)[22]	CIE 1968 Observer (ISO/CIE 10527)3
Thermal P_{th}	5	50	Blackbody	1.0

Table 1: Property type (T, R, A or ε), wavelength integration limits and weighting functions used to calculate the integrated solar, visual and thermal properties[21].

3.4. Design and function of glazings

The transmittance, reflectance, absorptance and emittance as wavelength functions or as spectral averages represent the optical properties of the glazing. For a piece of clear glass, which has a very low extinction coefficient, the transmittance is high within the solar spectrum (see figure 8, below). By applying thin coatings to the glazing the spectral behaviour of the glazing can be changed in order to fit the different applications.

In a very cold climate that requires heating all year around, an energy efficient window should transmit as much of the solar radiation as possible and the thermal emittance should be low. Hence, the window will "collect" as much energy as possible from the sun and loose as little energy as possible to the outside. Regarding the averages above, this means that the window should have a high transmittance within the solar spectral region, high T_{sol}, and as low emittance, ε_{th}, (= high reflectance) as possible in the thermal spectral region. The spectral properties for this ideal window for cold climates are illustrated with the dashed and dotted lines in figure 6. This type of window is commonly referred to as a low-emittance window or simply low-e window.

In a very warm climate where overheating is a common problem, the part of the solar radiation that is outside the visible spectral region can be blocked leading to a window with a high transmittance within the visible spectral region, high T_{vis}, and low elsewhere, figure 7. About half of the solar energy is confined to the visible region, which means that about half of the solar energy can be reflected from the window without affecting its visual performance. Note that the wavelength scale in figures 6 and 7 is logarithmic, which makes the solar spectrum look "broader" at low wavelengths than on a linear scale. It is often acceptable, or even desired to have a somewhat reduced transmittance within the visible region, so a lot of the solar energy can be blocked before it enters the building where it needs to be actively (expensively) cooled away. A window with these properties will be referred to as a solar control window (also referred to as "spectrally selective" in the US). Note that a solar control window may have high differences in the transmittance in the visible region depending on the glazed area, solar availability and demands for visual quality.

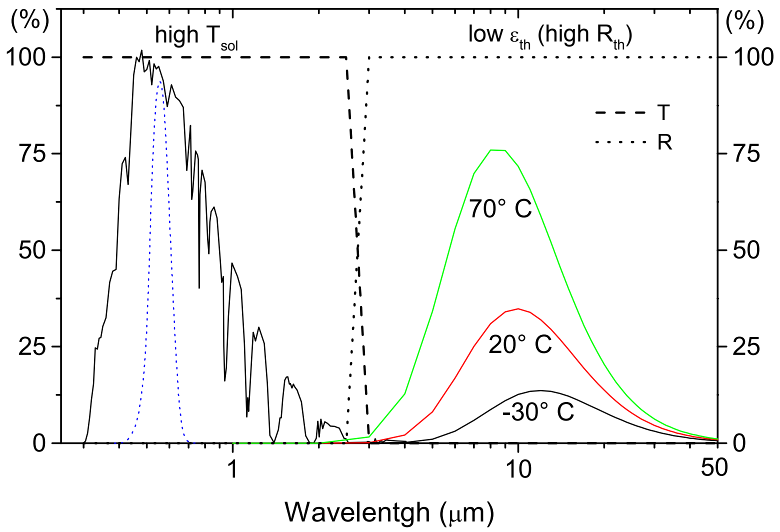

Figure 6: The spectral profile for an ideal low-e window. The transmittance is marked with a dashed line and the reflectance with a dotted line. The rest of the curves are identical to the ones in Figure 1.

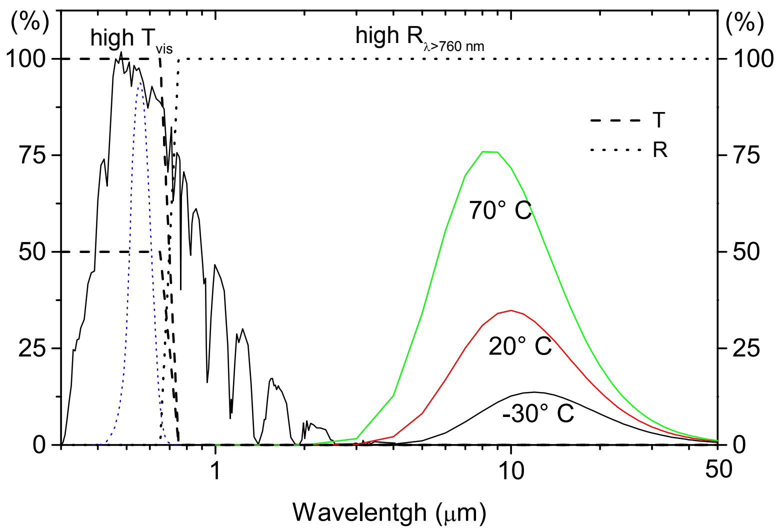

Figure 7: The spectral profiles for an ideal solar control window.

It is not always a clear-cut case whether the window is a low-e or a solar control window since a low-e window can have solar control properties and a solar control window often have low-e properties. Other categories of energy efficient glazings are: tinted glazings, which only reduce the transmittance within the visible and/or the solar spectral region and exhibits no low-e properties, anti-reflective glazings that increase the solar and light transmittance and switchable glazing that can change the transmittance depending on available daylight. Commonly, a coated or treated glazing, in some way, is referred to as an energy efficient window.

Several different ways exist to produce large area coatings[23]. In the window coating business mainly sputtering and spray pyrolysis are used[24]. The sharp ideal spectral profiles as exemplified in figures 6 and 7 above, are not easy to reproduce with only a few coatings. However, mastering the thin film physics and production techniques, it turns out that it is possible to get very close. There are a large variety of different low-e, solar control, and other energy efficient glazings commercially available. How to select an appropriate window among all these alternatives, for a given location and type of building, is discussed in section 5 below. An extensive library of optical properties of windows has been compiled by Rubin[25] and is available for free via the Internet.

As an example three different (fictitious) single glazings, whose composition are given in table 2 below, are analysed with the Fresnel equations. The first is just a clear float glass (named Float), the second a doped tin-oxide coating (SnO_2:F), normally produced directly on the glass production line by spray pyrolysis and the third is a thick silver coating (Ag+), protected by two dielectric tin-oxide layers, which also anti-reflect the silver layer. Coatings of this latter type are normally produced by sputtering techniques. The tin-oxide coated glazing perform as a low-e glazing having a T_{sol} of about 67 % and a ε_{th} of about 15 %, and the thick silver as a solar control glazing having a T_{sol} of about 38 % and ε_{th} of about 8 %. The transmittance and reflectance of the three exemplified samples are plotted within the solar wavelength region in figure 8 and their thickness and integrated properties are given in table 2.

	Float (4mm thick)	SnO_2:F "Low-e"	Ag+ "Solar control"
Coated layers	-	SnO_2:F/SiO_2	SnO_2/Ag/ SnO_2
Coating thickness	-	300/100 nm	30/20/60 nm
T_{sol} (%)	82	67	38
R_{sol} (%)	7	9	51
T_{vis} (%)	89	90	59
ε_{th} (%)	84	≈15	≈8

Table 2: Layer thickness and integrated parameters for float, SnO2 and Ag+ samples. ε_{th} – values are not calculated but estimated. Optical constants from Rubin[26] (float), Roos[27] (SnO_2:F), Palik[28] (Ag, Sio2).

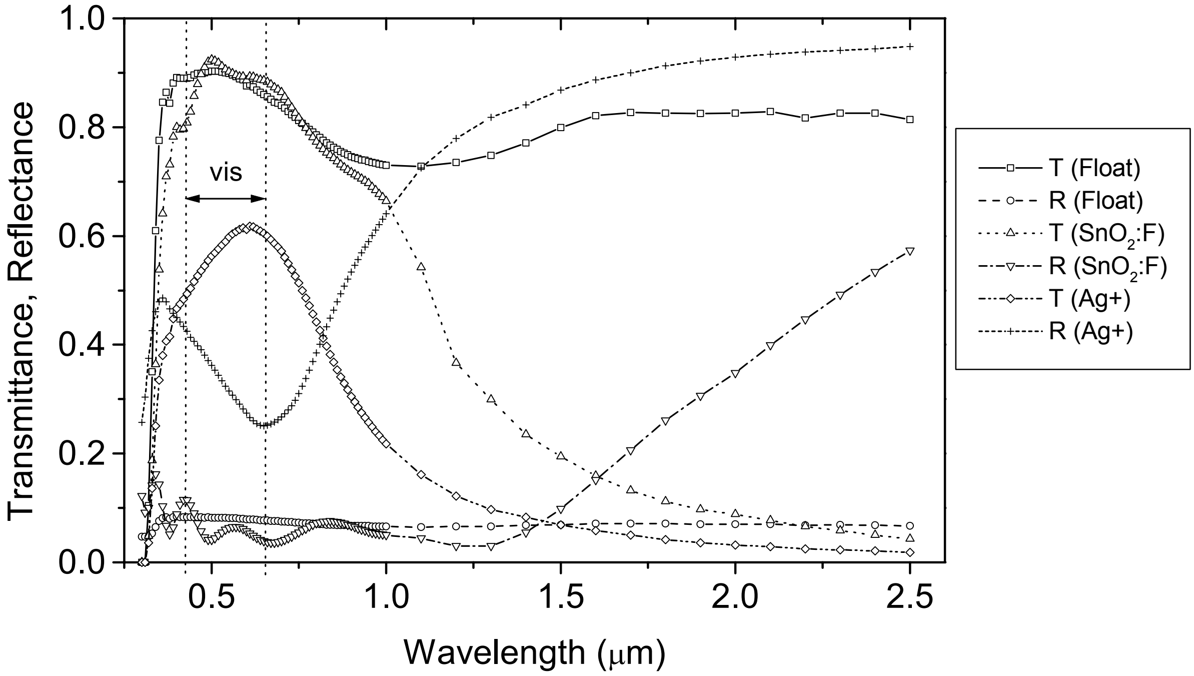

Figure 8: Spectral transmittance (T) and reflectance (R) for three theoretically calculated single glazings, float glass (Float), doped tin-oxide coated glass (SnO_2:F) and thick silver coated glass (Ag+). Reflectance is given from the coated side. All values are given for normal angle of incidence.

Tin-oxide coatings are often referred to as hard coatings, indeed being hard, and the silver coatings and other dielectric/metal/dielectric coatings as soft coatings. Soft coatings have to be used in an IGU in order to endure. The selected coatings represent two of the most commonly used types of coatings. Several other types of solar control coatings exist on the market and thin films of silicon, nickel, chromium, titanium-oxide and titanium-nitride are frequently used. All the coatings may also be used in combination with tinted glass.

Another important integrated property that is always used when it comes to building simulations and energy efficiency calculations of windows is the g-factor. g is simply the solar transmittance plus the absorbed part of the radiation re-emitted towards the inside of the building. The g-factor is sometimes referred to as TSET - Total Solar Energy Transmittance or SHGC - Solar Heat Gain Coefficient.

$$g = T_{sol} + q_i \qquad \textit{Eq. 26}$$

where q_i for a single pane is equal to

$$q_i = A_{sol} \frac{h_i}{h_e + h_i} \qquad \textit{Eq. 27}$$

where A_{sol} is the absorbed amount of solar energy in the pane and h_i and h_e as defined in section 3.1 above. Thus, *g* represents the total fraction of the impinging solar energy that enters the window. Considering the fact that the thermal performance of windows improves greatly when having an air gap, it is common to use double glazed units, but also triple (and, rarely, quadruple) glazed units. The integrated properties of whole windows are calculated by repeating the Fresnel equations. The computation of the g-factor become a little bit more complex for multiple pane windows since the absorption in each pane and the re-emitted fraction to the inside have to be computed. This procedure is given in the standards ISO 9050[29] and EN 410[30]. Roughly, most of the energy that is absorbed in the outer pane gets re-emitted to the outside because of the higher heat conductance to the outside. Most of the energy absorbed in the inner pane is re-emitted to the inside. Figure 9 illustrates some of the properties for an uncoated TGU (calculated according ISO 9050) at normal incidence. Normally the absorption is greater the farther out the glazing is situated. However, if a solar control glazing were used in the configuration the absorption in that pane would dominate over the absorption in the clear glazings. Invariably, the sum of T_{sol}, R_{sol} and A_{sol} (in all panes) and the sum of T_{vis}, R_{vis} and A_{vis} equals one.

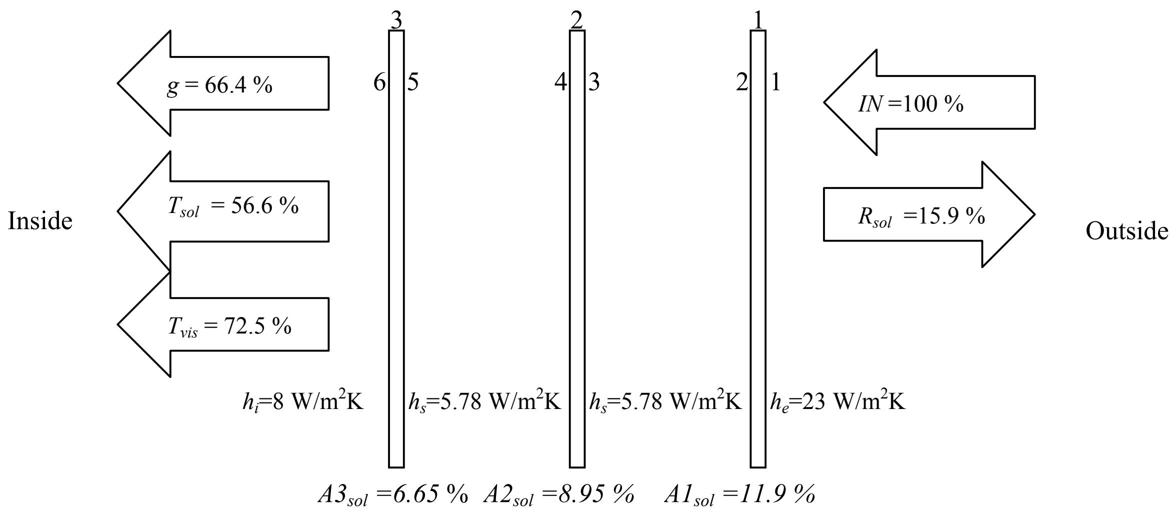

Figure 9: g-factor, solar and light transmittance, solar reflectance, heat transfer coefficients and the absorbed fraction of the solar energy in each pane for an uncoated TGU.

A solar control coating is normally placed on the second surface (i.e. on the first pane) in order to perform the best. A low-e coating is normally placed on the inner pane facing outward, i.e. the fifth surface if it is a TGU and the third surface if it is a DGU.

Necessary window data for calculating the energy efficiency of the window is at least the U-value (Including frame and spacer), the g-factor and the light transmittance. The g-factor and the light transmittance are required for all angles of incidence. Glazing U-values can vary from about 6 down to below 1 W/m^{2}K. The light transmittance can be about 2 times higher than the solar transmittance (see figure 7). This means that it is possible to get a glazing with T_{sol}/T_{vis} of about 0.35/0.70 or 0.20/0.40, depending on the application.

4. SOLAR IRRADIATION

The availability of climatic data depends on the country, but in many countries hourly data files with temperatures and solar irradiation data for several different locations are available. Solar irradiation data is normally available as direct and diffuse irradiation on a horizontal surface. The direct irradiation is the received irradiation without having been scattered by the atmosphere and the diffuse is the irradiation received after it has been scattered in the atmosphere. The total horizontal solar irradiation is thus the sum of the two. The horizontal irradiation needs to be converted to values valid for surfaces randomly oriented in space. The simplest way of doing this is to treat the diffuse irradiation as if it were isotropically distributed over the sky hemisphere and to include a ground reflected part. The total incident irradiation on the surface would thus be expressed as[1]

$$I_{pane} = I_{dirh}\frac{\cos\theta}{\cos\theta_z} + I_{diffh}\left(\frac{1+\cos\beta}{2}\right) + I_{toth}\rho_g\left(\frac{1-\cos\beta}{2}\right) \qquad \textit{Eq. 28}$$

where I_{pane} is the irradiation received by the surface and I_{dirh}, I_{diffh} and I_{toth} are the direct, diffuse and total horizontal irradiation intensities respectively. The incidence angle, θ, is the angle between a normal to the surface and the beam irradiation and θ_z is the zenith angle, i.e. the angle between the vertical and the line to the sun. The tilt angle, β, is the angle between the plane of the surface and the horizontal. ρ_g is the ground reflectance, normally referred to as the albedo.

Treating the diffuse part of the irradiation as totally isotropic is not a very good approximation, and several attempts have been made to refine this. Hay and Davies (see Duffie and Beckman[1]) use a circumsolar part to account for the forward-scattered diffuse irradiation concentrated in the part of the sky around the sun, transforming equation 28 to

$$I_{pane} = (I_{dirh} + I_{diffh}A_i)\frac{\cos\theta}{\cos\theta_z} + I_{diffh}(1-A_i)\left(\frac{1+\cos\beta}{2}\right) + I_{tot}\rho_g\left(\frac{1-\cos\beta}{2}\right) \qquad \textit{Eq. 29}$$

The anisotropy index, A_i, determines the portion of the horizontal diffuse irradiation considered as being circumsolar and is defined as

$$Ai = \frac{I_{beam}}{I_o} \qquad \textit{Eq. 30}$$

where I_{beam} is the solar irradiation in the direction of the sun at the surface and I_o is the extraterrestrial solar irradiation in the direction of the sun. The Hay and Davies model leads to slightly lower errors on the estimates of irradiation on tilted surfaces[1]. Moreover, additions have been made to account for horizon-brightening effects as a third sky diffuse contribution, see figure 10. The Perez model[31] is based on a detailed analysis of the diffuse components and contains statistically derived coefficients for the sky conditions and the authors have reported lower errors than for the above mentioned models on tilted surface irradiation estimates. Brunger and Hooper present another model[32] and Brunger and Holland[33] report that the Perez model highly over-estimate irradiances at high latitudes and recommend the Hay and Davies model or the Brunger model for these latitudes. For the Stockholm (TRY) climate, used in paper II, this appears to be true. When accumulating the irradiation on a south facing vertical surface with the Perez model the sum ends up at more than 850 kWh/m^{2}yr and using the Hay and Davies method results in less than 800 kWh/m^{2}yr. Note that this year (Stockholm TRY) already has relatively low solar irradiation levels compared to what is normal for this location (about 50 kWh/m^{2}yr less global horizontal than normal[34,35]).

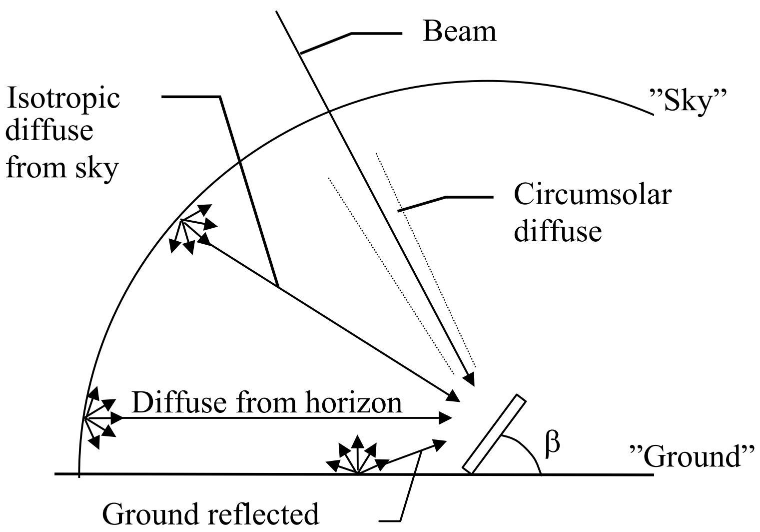

Figure 10: Beam, diffuse and ground reflected radiation on a tilted surface. The diffuse radiation from the sky is divided into three components: isotropic, circumsolar and horizon[1].

When the amount of irradiation impinging on the window is known, the incidence angle of the irradiation also has to be known since windows have different properties at different angles of incidence (see section 6.1 below). The incidence angle of the direct irradiation is calculated simply by calculating the sun's relative position for the location and to the surface normal[1]. For the diffuse irradiation integration over all angles can be performed to obtain an effective incidence angle, as has been done by Brandemuehl and Beckman (see Duffie and Beckman[1]), figure 11. The circumsolar contribution is normally considered having the same incidence angle as the direct irradiation and the horizontal, being a very small contribution, is taken as having the same incidence angle as the isotropic diffuse irradiation. The incidence angles of diffuse irradiation can also be accounted for by dividing the sky into several patches.

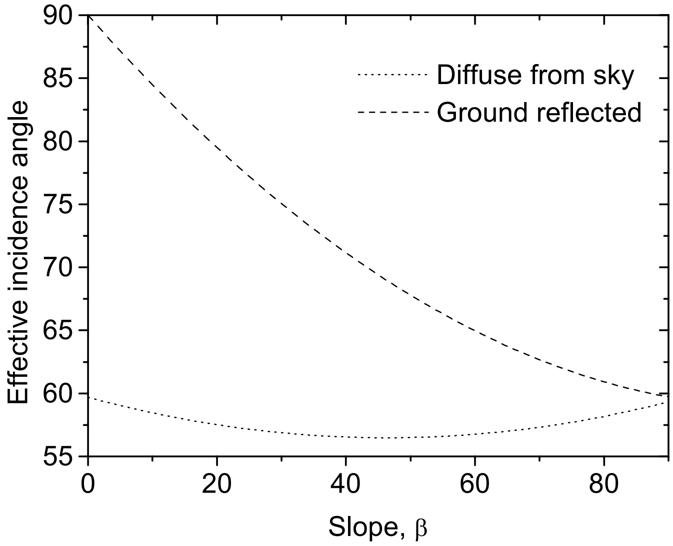

Figure 11: Effective incidence angle for isotropic diffuse irradiation and isotropic ground reflected irradiation on sloping surfaces[1].

5. WINDOWS IN BUILDINGS AND ENERGY EFFICIENCY

Knowing the actual energy saving potential of energy efficient windows is not trivial. Monitoring authentic buildings is very difficult, time consuming and expensive. Therefore the use of more or less advanced building simulation models has become common practice. The use of building simulation models can give quite high uncertainties in predicted energy saving potentials[36,37]. Depending on the occupant behaviour the final energy use off course varies even more[38,39]. However, models often predict energy consumption within reasonably reliable error limits when comparing with existing buildings. Furthermore, the fact that the impact of different energy conserving measures can be thoroughly and quickly analysed makes the use of these programs abundant.

Various models exist and they each have their advantages and disadvantages. The models normally include heat transfer through walls and roof, thermal coupling to the ground, solar throughput, internal energy sources and consumption, HVAC-system, dynamic heat storage effects in materials, etc. on different levels of detail[5,36,40,41,42,43]. The power of today's computers have made it possible to make programs that perform hourly calculations and takes several effects into account that simply were not possible before the "computer revolution". However, to perform a simulation is often a thorough work that calls for expertise in the specified model in order to describe the building correctly, although efforts are being made to simplify interfaces, to increase the modularity and usability of the models[44].

Computer power has also made optimisation procedures possible[45,46,47] where economic "optimum" for the building, including boundary conditions from a description of the possible components, can be found. Ray-tracing daylighting programs can imitate the lighting situation in a building[48,49] and computational fluid dynamics (CFD) can simulate the energy and mass flows within a building[50].

A combined effort to assess the energy efficiency of windows with building simulation models was performed in IEA/SHC TASK 18, where several countries were involved and different models were used[51]. The results illustrate that the optimum type of window depends very much on the type of climate that the building is located in. The type of building, generally divided in residential with low internal heat production and commercial with high internal heat production, is also very important for the choice of windows. In round figures, the annual energy saving potential with an advanced window is typically more than 100 kWh per square meter glazed area compared to a standard uncoated window. Hence, choosing the right window has a considerable effect on energy consumption, particularly on a large (regional, national, international) level[52,53].

Using detailed building simulation programs is probably the most efficient method to assess the impact of energy efficient windows. However, the complexity of the programs and the fact that a lot of information about the building has to be known has triggered the development of simplified models to assess the energy efficiency of windows[54,55,56,II,XI]. Suitable, simplified methods can be an important way to increase the usability of models and may be a key factor in the transfer of passive solar technology, such as energy efficient windows. As discussed by Balcomb[42], there seems to be the reverse order of usage compared to the order of development of building design tools, figure 12. The user, such as the architects and building designers, are concerned primarily with design guidelines and to a lesser extent with simplified methods, and rarely with simulation analysis. The developer designs simplified methods correlating them to previous advanced simulation models.

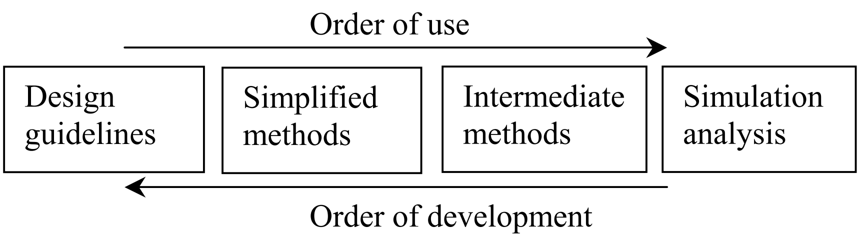

Figure 12: The order of development of a design tool is often opposite to the order of use by a practitioner, from Balcomb[42].

6. RESULTS AND DISCUSSION

As mentioned in the introduction the results from the papers in this thesis can be divided into four different groups: angle dependent transmittance properties, simplified window energy modelling, analysis of the energy efficiency of different windows and energy rating of windows. In this section, the results from the papers are overviewed and discussed, divided into these four groups, and some complementary results are added.

6.1. Angle dependence

The integrated properties discussed in section 3.3 above are usually quoted for near normal angle of incidence, but in practice they actually vary with angle of incidence. Since the solar irradiation strikes a window at all possible angles of incidence, it is important to be aware of and be able to account for this dependency. For many locations the main part of the irradiation impinge at an incidence angle (by definition measured against the normal of the window) of about 40-60° on a vertical surface, see figure 13. The transmittance data at normal incidence is thus of limited importance, when it comes to performing accurate building energy simulations. If the transmittance data for the glazing is not accurate at the most common angles of incidence it leads to errors in the building simulation.

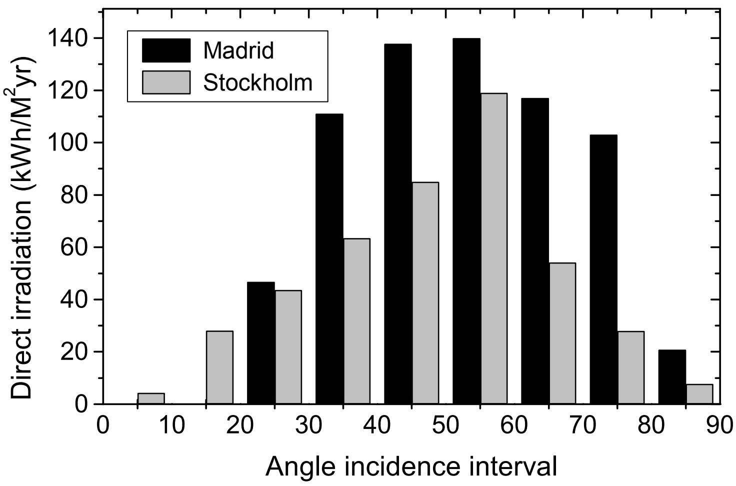

Figure 13: The direct annual irradiation impinging on a south directed, vertical window in Stockholm and Madrid respectively versus angle of incidence interval (10° interval). Climate: Stockholm TRY[II] and Meteonorm[57] simulated for Madrid

The necessity to know the optical properties at other angles than normal incidence, introduces a problem. Angular resolved optical measurements are very time consuming and difficult so that characterisation at normal incidence only is preferred. Theoretically, angular resolved properties are well defined by the Fresnel equations (section 3.2). This is a rigorous but conceivable way to get the data as long as the thickness of all the coatings and their optical constants are known. When it comes to uncoated glazings this theoretical approach is analytically functional since the optical constants can be deducted from R and T inverse methods[58]. The problem intensifies when coated glazings are treated. In many cases the properties, such as thickness, homogeneity and optical constants of the (often multiple) coatings are not known and may even be corporate secrets. Furthermore, multilayer Fresnel calculations would increase computer time in a building simulation program. As a consequence it has become common to use some kind of empirical function in order to simulate the angle dependence of the glass or the whole glazing unit.

If the properties of each layer are not known, roughly two different methods to confront the problem has been identified. Method A (figure 14) is to multiply the values at normal incidence (e.g. $T_{sol}(0)$) for the whole glazing with an approximate angular profile, which results in a function representing this optical property at all angles. This method is the simplest possible for the developer and requires data for normal incidence (always available) and an angular function. The angular function may be a fixed angular profile or a function of the number of panes and/or coating type. The simplest angular profile would be to use the angular profile for a known glazing, e.g. an uncoated glazing. Since the angle dependence change with number of panes[I], three different angular profiles can be used, depending on if it is a single, double or triple glazed configuration. Refined angular simulation models need to reproduce the angle dependence with lower errors than using just angular profiles of clear glass. Another common angular function is of the form: $1-\tan^x(\theta/2)$, where the exponent x can be arranged to fit for different types of coatings[59]. Paper I presents a polynomial model to simulate the angular function of the g-factor, which depends on number of panes, *p*, and type of coating, *q*.

In method B (figure 14) each glazing is treated separately. This approach normally needs *R* and *T* –values at normal incidence for each wavelength of the glazing. Furthermore it needs a model representing the glazing ("equivalent glazing") with its coatings, which may be more or less "physical" or alike the real glazing. From the *R* and *T* –data of the actual glazing, "pseudo" optical constants are extracted for the equivalent glazing, which is then used to represent the angle dependence profiling of the actual glazing. After that, the procedure is the same as for exact Fresnel calculations using ISO 9050 to obtain the window optical performance at the desired angles of incidence.

One proposed model (within method B) was to use spectral *R* and *T* for the coated glazing and then perform inverse calculations, as if the glazing was uncoated, to obtain pseudo optical constants for an equivalent bulk glazing[60,61]. This model will be referred to as the "bulk model". In its simplest form this model is not performing well (see paper III) for all types of glazings but expanding to single, double or triple thin film coated equivalent glazings may increase the accuracy[61]. Montecchi et al. recently presented another interesting development of the bulk model[62], which demonstrates very low errors. This model use double and triple bulk layers where only one of the layers have unknown optical constants. Thus, the calculation is similar to the simple bulk model with incoherent calculations but with additional defined bulk layers. A special model for antireflective glazings is defined. van Nijnatten[63] have proposed a method introducing simplified Fresnel equations.

The simplicity of using method A, multiplying the property at normal incidence by an angular profile is an advantage. No spectral information and no data files are needed, and computer simulation time is not increased. However, it is completely empirical and for high accuracy solutions it requires knowledge about the type of glazing[I,III]. Another drawback with method A is that it treats the whole glazing unit, which means that surface temperatures on each pane cannot be treated. Method B is "more physical" and might yield very low errors without knowledge of the coating[62]. This method can be "hidden" in a computer program that feeds spectral *R* and *T* values as input and then performs the inversion calculations followed by the ISO 9050-formalism at the desired angles of incidence.

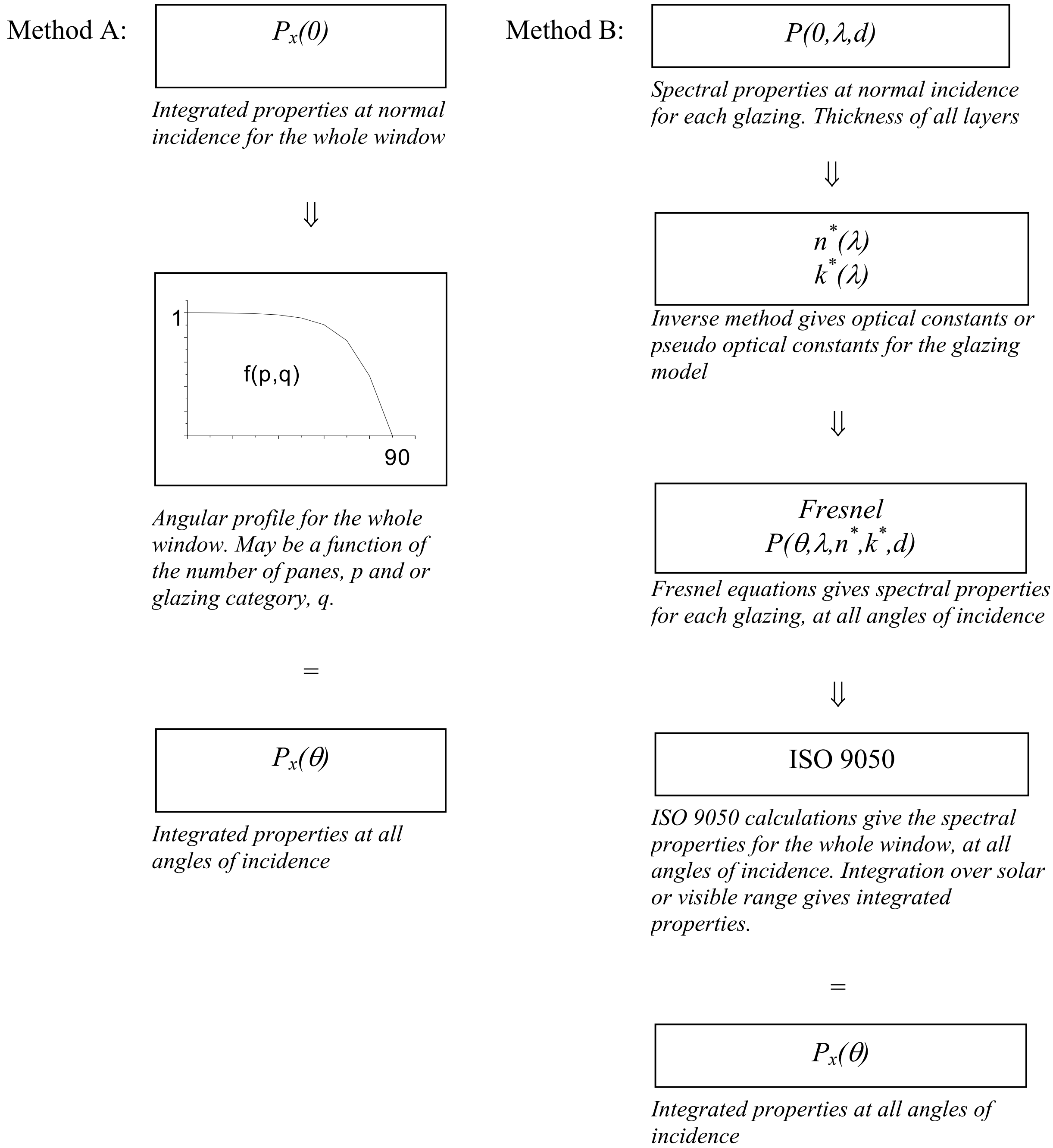

Figure 14: Schematic block diagram of two different methods to obtain angle resolved optical properties of windows. The star in n^* and k^* is to note that the optical constants may be "pseudo" physical.

In paper I a new model (of method A, above) for predicting the angle dependence of the g-factor is presented. This is an empirical model that takes the number of panes, *p*, and the type of glazing, *q*, into consideration. These two parameters then determine an angular profile by a polynomial expression that is multiplied with the g-factor at normal incidence of the whole window giving the g-factor at all angles (g(θ)=g(0)f(q,p), see paper I). The parameter *q* is an empirical parameter that can vary from 1 to 10 indicating the type of glazing as described in paper I and III. A normal float glass has a q-value of about 4 (dashed curve in figure 15). Glazing that have lower or higher q-values correspond to glazings having lower (solid curve in figure 15) or higher (dotted curve in figure 15) angular profiles, respectively.

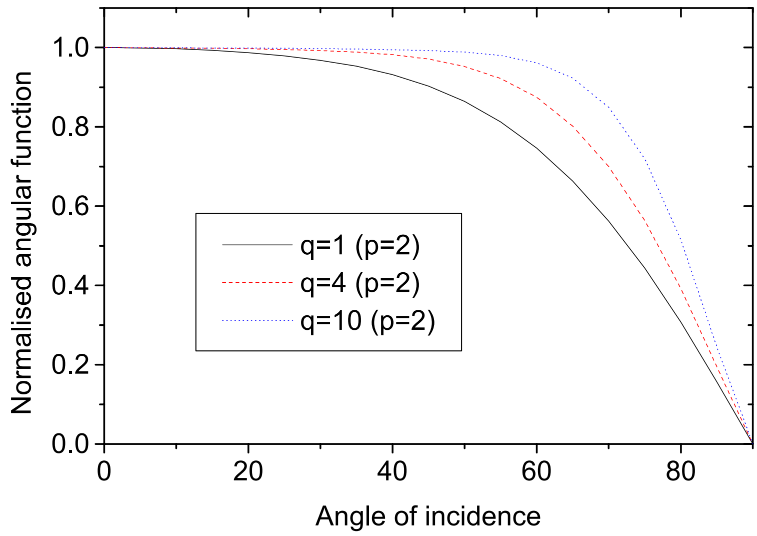

Figure 15: Angular profiles as given by the polynomial in paper I for coating category, q equal to 1, 4 and 10, respectively. p represents the number of panes.

A glazing having a low q-value is generally an absorbing glazing or a glazing that is coated with an absorbing layer (with a high extinction coefficient, k). A glazing having a high q-value is generally a glazing that is coated with a layer having a high refractive index, n. This model has shown very good fits to both Fresnel calculated glazings and measured glazings[I,III]. The implication is that the q-value, which represents the type of coating, needs to be catalogued for several types of coatings.

When it comes to the angle dependence of the g-factor we have found that the number of panes and the type of coating are the critical parameters[I,III]. It seems that knowing the type of coating is more important than knowing the thickness of the coatings in most cases. This is exemplified in figure 16 where the solar transmittances of measured commercial silver coated glazings are illustrated. The polynomial model, having $q = 2$ and $q = 1$, and a theoretical silver based coated glazing ("Fresnel") are also plotted for comparison. In this case the normalised angle dependence hardly change with silver thickness. The only difference occurs between the double layered silver coating and the single layered ones. These are reproduced with a q-value of about 1 and 2, respectively. If the glass substrate is absorbing, as in the case of green or grey glass[26], the thickness of the glass is important[I].

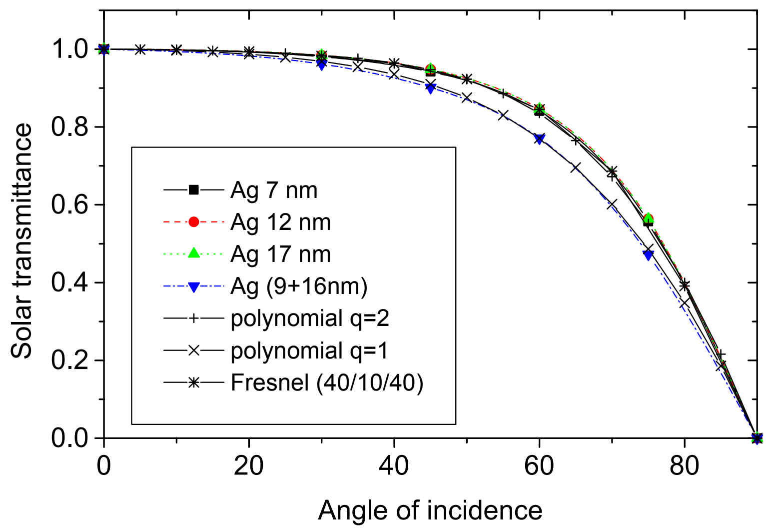

Figure 16: Measured angle dependence of T_{sol} for commercial, single glazings with different silver thickness. Results from the polynomial model with q-value 2 fit well for all the single silver layer coatings and the polynomial with q-value 1 fits well to the double silver layer coating. A calculated glazing with one single 10 nm thick silver layer between tin-oxide layers fits very well to all the measured real single coated glazings. Commercial samples are supplied from Pilkington, (Paper III).

In paper III some approximate proposed models for predicting the angle dependence are compared. It is found that the angle dependence of the g-factor for many glazings is described within in low error limits by simply using the angular profile of a glazing containing clear glass panes (the same number as for the studied glazing). Other simple models, such as the "bulk" and "tangens" models showed higher errors on the test set in paper III. If the glazing type is known, the model proposed in paper I might reduce the errors by about half, compared to using the clear glass profiles[III]. An additional new solution to the problem may be the equivalent models (EM:s) presented by Montecchi et al.[62], but they require the spectral *R* and *T* data to be known at normal incidence.

The importance of correct angle dependence may be disputed, especially when considering the number of approximations that are made in building simulation programs. Furthermore, it is very difficult to measure transmittance and reflectance accurately at oblique incidence[64]. In paper III, extreme angular profiles are examined with the window selection tool in paper II. Figure 17 and 18 illustrate how the energy balance[II] of the window varies with different extreme angle dependence profiles. The windows with extreme angle dependence functions are always solar control windows, which commonly have lower g-factors at normal incidence than what has been used in the simulation in figure 17 and 18. The differences could therefore be slightly overestimated in the graphs. Furthermore the simulations were performed for unshaded windows. If shading factors are included, the importance of the angle dependence of the window itself is reduced. The influence of different angle dependence transmission models on the predicted energy performance of commercial buildings has been previously studied by Pfrommer et al.[65]. See also: Purdy and Beausoleil-Morrison[66] and Maccari and Zinzi[67]

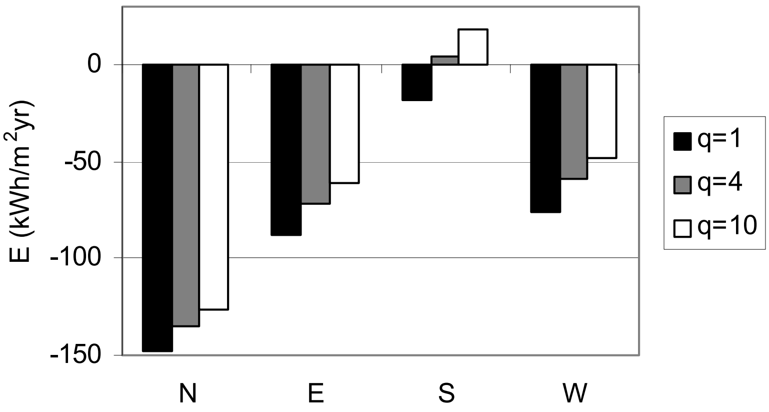

Figure 17: Heating energy balance, E, for a residential building in Stockholm with T_b=15°C and τ=14h, E_{conv}=1, P_{conv}=1 (see paper II). The category parameter, q, is varied between 1 and 10, representing a low and high indexed coating respectively. The window is a double glazed unit with g(0)=50% and U=2 W/m^{2}K. (See paper III).

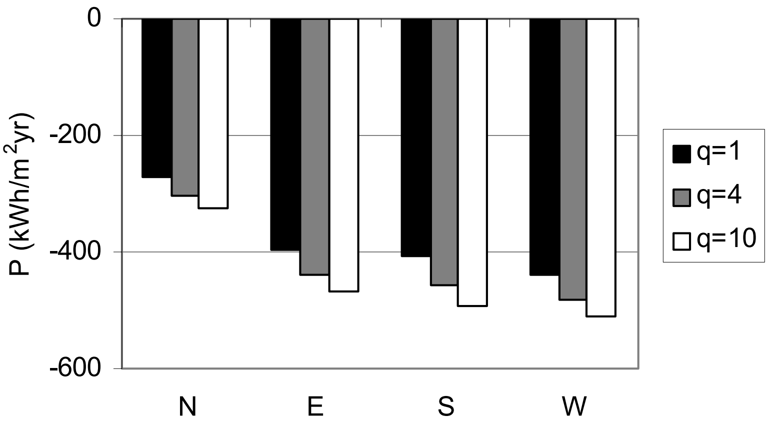

Figure 18: Cooling energy balance, P, for a residential building in Miami with T_b=15°C and τ=14h, E_{conv}=1, P_{conv}=1. The category parameter, q, is varied between 1 and 10, representing a low and high indexed coating respectively. The window is a double glazed unit with g(0)=50% and U=2 W/m^{2}K.

In paper VIII, angular resolved measurements were performed on an electrochromic device, i.e. with electrically controlled variable transmittance properties[68]. It was found that the optical memory of this particular device was limited with an increase in transmittance of about 1.5 %/h[VIII]. The angle dependence of this electrochromic device was found to be within the "extreme" limits as described by the polynomial in paper I. In the dark state the angle dependence is reproduced by using a q-value of about 1, and in the bleached state the angle dependence is reproduced with a q-value of about 2, figure 19. This is consistent with the discussion in paper I that the q-value decreases with the absorptance. It seemed as if the angle dependence does not change drastically between the dark and the bleached state.

Measurement difficulties increased the errors in these measurements, in particular, the problem to find a stable transmittance level with time and applied voltage.

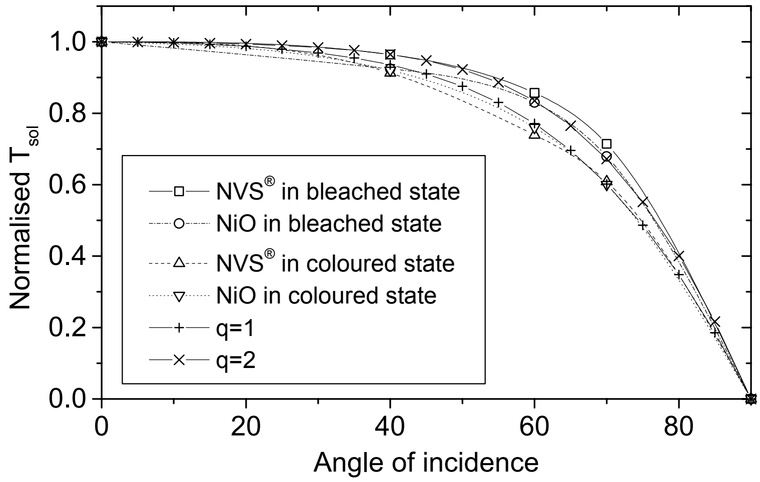

Figure 19: Angle dependence of T_{sol} for NVS® and a NiO/WO_3-prototype in their bleached and coloured states (paper VIII) and the angle dependence as assessed by the polynomial approach (paper I). The "+" marked curve is the angle dependence as assessed by the polynomial with a q-value of 1. The "x" marked curve is the angle dependence as assessed by the polynomial with a q-value of 2. NVS® is a commercial device (by Gentex corp.) and NiO/WO_3 is a lab device.

6.2. A simple model for the energy performance of windows

The energy efficiency of a window does not depend only on the physical performance of the window itself but also on in which climate and type of building it is used. Thus it is difficult to say whether a window is good or not, without knowing where it is supposed to be situated. On the other hand, if there is no access to detailed building data, it may still be interesting to know which window that saves the most energy for an approximate location and type of building. In paper II we present a model, based on the work by B. Karlsson et al.[69,70,71], that assess the energy performance of a window having only limited knowledge of the building (see also: AHSRAE[5]). The model utilises the fact that the outside temperature roughly determines whether heating or cooling is needed. Figure 20 illustrates how heating and cooling is required for an office module with a south-facing window, situated in Lund, Sweden. The hourly heating power is plotted on the positive y-axis and the hourly cooling power is plotted on the negative y-axis, all versus the outside temperature. The data is obtained by a simulation using DEROB-LTH[41]. It is seen that one can identify a certain outdoor temperature below which heating is needed and above which cooling is needed. The balance temperature is thus defined as the outdoor, average temperature above which no auxiliary heating is required.

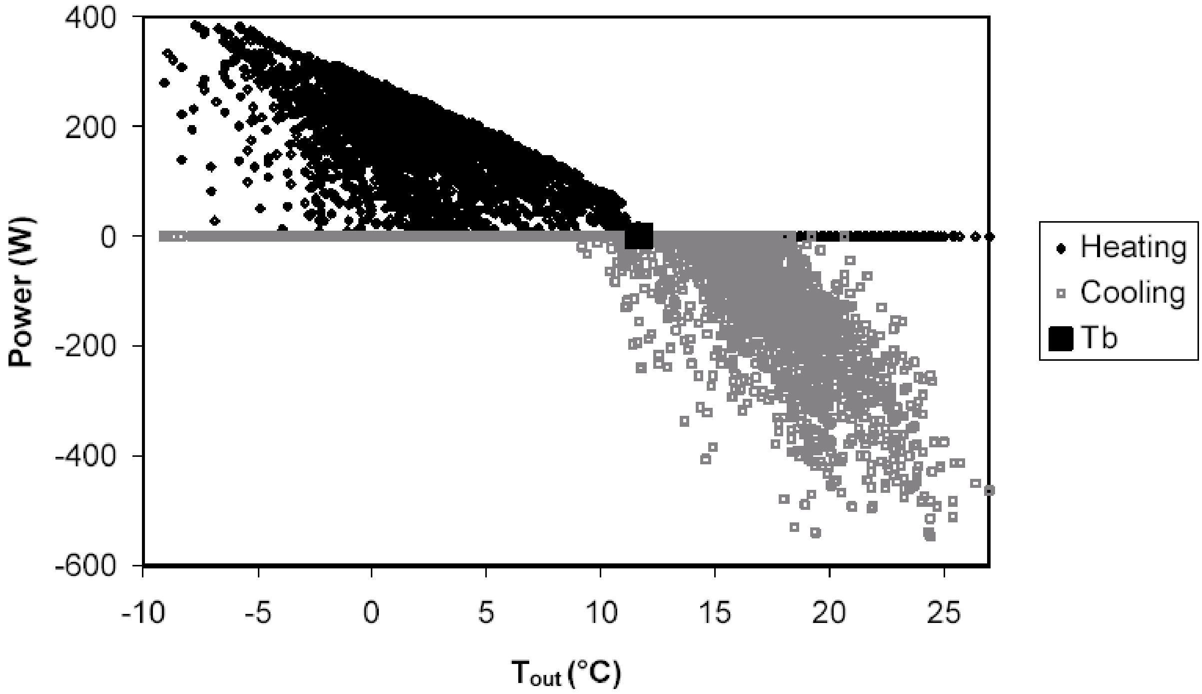

Figure 20: Heating and cooling power for an office module with a south-facing window in a Lund climate versus outside temperature. The heating power is plotted on the positive side of the y-axis and the cooling power is plotted on the negative side of the y-axis. The solid square indicates the balance temperature, T_b, for this office module[II,IV].

Once T_b is set, it characterises the building and the algorithm takes solar energy that enters the building at outside temperatures below T_b as useful for the building energy system and solar energy that enters the building at outside temperatures above T_b as negative for the building energy system. In this way, hourly energy balance for the window can be accumulated to an annual energy balance of the window. This is clearly a simplified description of a building and it is inherently not a good description for buildings with high window to wall ratios, since it assumes that a temperature change is more important than a change in solar irradiation (for buildings with large glazed areas see Wall[72]). However, it can be a very simple way to compare the energy efficiency off different windows in different types of buildings, without knowing the details of the building.

In paper II the theoretical framework of the model is presented and it is tested on a large number of low-e, and solar control windows, mainly for a Stockholm climate. Furthermore, a sensitivity analysis of varying T_b and time interval, τ, is performed. By varying the balance temperature it is seen how different types of windows fits in different types of buildings, figure 21[II]. A low-e window is suitable for buildings with high balance temperatures and a solar control window is suitable for buildings with low balance temperatures.

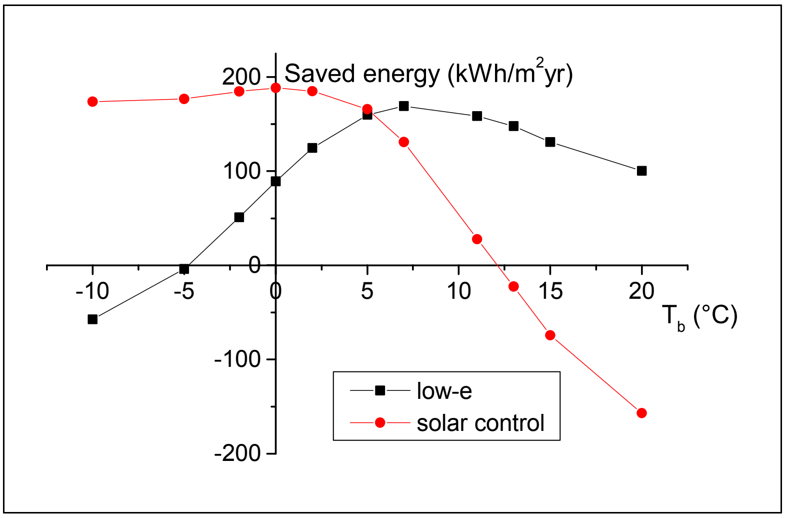

Figure 21: Saved heating plus cooling (per square meter glazed area) compared to an uncoated DGU, versus balance temperature for low-e and solar control window in a south-facing direction[II].

In paper IV, it is described how the balance temperature can be explicitly calculated from building data, and how it varies with various different building parameters. This paper evolves the degree-day method by the inclusion of hourly useful solar energy. This requires accumulated solar irradiation versus temperature interval. The degree-day method is used all over the world for simple building energy considerations. The problem is that solar energy is often not included, and especially not useful solar energy. Furthermore, the balance temperature is often set to a fixed value for all types of buildings. This leads to very high errors, since the balance temperature depend on the type of building. Paper IV clarifies this by illustrating how the balance temperature varies for different building components. For instance a passive solar house with high insulation levels, large windows to the south and low infiltration will have a lower balance temperature than an old, leaky house[IV]. In paper IV, the balance temperature model is also compared with a dynamic building simulation program. The comparisons show that it is important to include useful solar energy, but that the simplicity of the model still leads to limited accuracy.

If building data is accessible the model can be used as in paper IV. If no building data is accessible the balance temperature needs to be assessed, and then the procedure described in paper II and XI can be used to assess the window energy efficiency. A user-friendly program implementation of the model has been presented[XI,73].

6.3. Energy efficiency of different types of windows

Paper II exemplifies several results from the window selection tool. For a Stockholm climate, possible energy savings are typically of the order of 100-150 kWh/m^{2}yr depending on window, climate, building type and direction of the window. Figure 22 compares the heating energy balance (denoted *E* in paper II) for a standard DGU and a “super” insulated TGU with U = 0.9 W/m^{2}K and g = 56 %, both unshaded, in a residential building in Stockholm. The standard window has a negative heating energy balance for all directions, which means that it “looses” energy annually for all directions. The “super” window has a positive *E* for all orientations except for the north facing orientations, which means that it is an annual "collector" of energy for these orientations. If the window has some shading, as it basically always has, *E* would be reduced. However, the g-factor of a super window can also be increased by the use of low-iron glass and AR-coatings, which would increase *E*[VII]. Results from northern US have also proven that advanced windows can outperform well-insulated walls, even for north-facing windows[52].

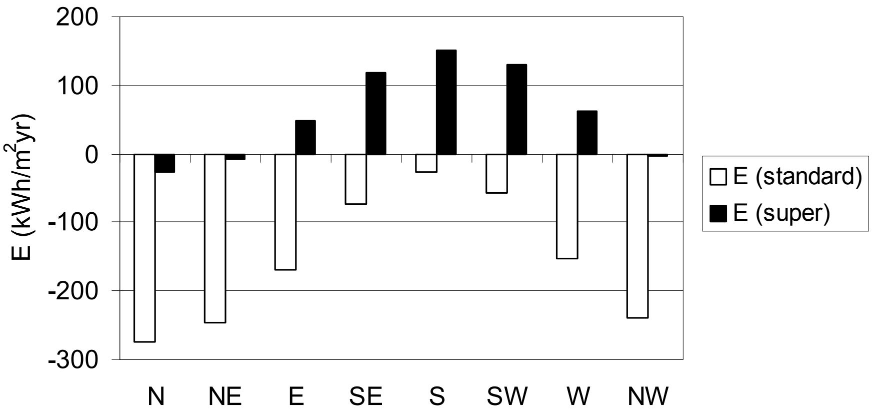

Figure 22: Heating energy balance for a standard DGU (g=76 %, U=2.9 W/m²K, q=4, p = 2) and a super window (g=56 %, U=0.9 W/m²K, q=3.5, p=3). T_b *= 13 °C,* τ*=14,* E_{conv}*=0.75,* P_{conv}*=2.9 (see paper II), Stockholm climate. Positive E-values means that the window is a "heat source", it gains more energy than it looses.*

Figure 23 illustrates the saved heating, cooling and total energy (denoted E_{saved}, P_{saved} and $E_{totsaved}$ as in paper II) when changing from a standard window to a window with both considerably lowered g-factor and U-value in a residential building with a balance temperature of 15°C. It is seen that for north facing windows the saving potential is considerable due to the low U-value of the coated window. However, the decreased solar transmittance reduces useful solar heat gain and for a south facing window no energy saving is accomplished. If the building has a lower balance temperature, the same change of window results in a different saving, as illustrated in figure 24. For this case the saved heating energy is somewhat reduced but the window also saves cooling energy, especially for south facing windows. The total energy saving is almost constant of about 80-90 kWh/m²yr for all directions.

In extremely sunny and hot climates it is only the cooling energy balance that is of importance, as is the case for buildings with very low balance temperatures. In figure 25 the saved energies are given for Miami[74], where it is seen that the reduced solar transmittance from 76 to 40 %, save in round figures 100 kWh/m²yr. The negative E_{saved} has its origin in the fact that there is some irradiation at outdoor temperatures below the balance temperature of 15°C in this example, and that the standard window transmits more of this "useful" energy than the window with the low g-factor. Thus, the figures below illustrate the energy performance of the windows in three different situations: when heating is of prime importance (figure 23), when cooling is of prime importance (figure 25), and a mix of these two mentioned cases (figure 24).

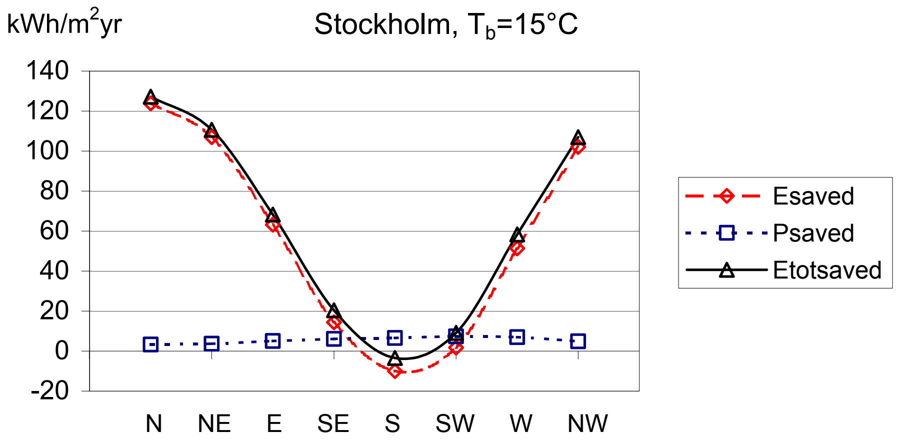

Figure 23: Saved energy when changing from a standard DGU to a solar control window with g=40 %, U=1.5 W/m²K, q=4, p =2, E_{conv}=0.75, P_{conv}=2.9 in a building with T_b =15°C, medium thermal mass, Stockholm climate.

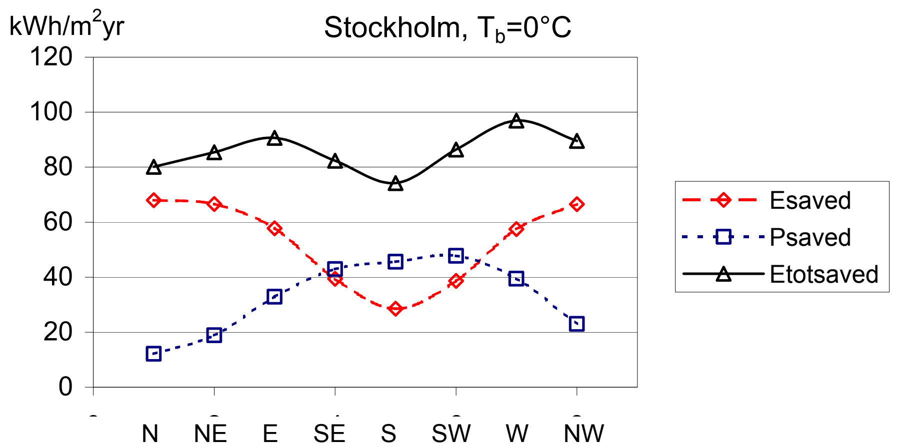

Figure 24: Saved energy when changing from a standard DGU to a solar control window with g=40 %, U=1.5 W/m²K, q=4, p=2, E_{conv}=0.75, P_{conv}=2.9 in a building with T_b =0°C, medium thermal mass, Stockholm climate.

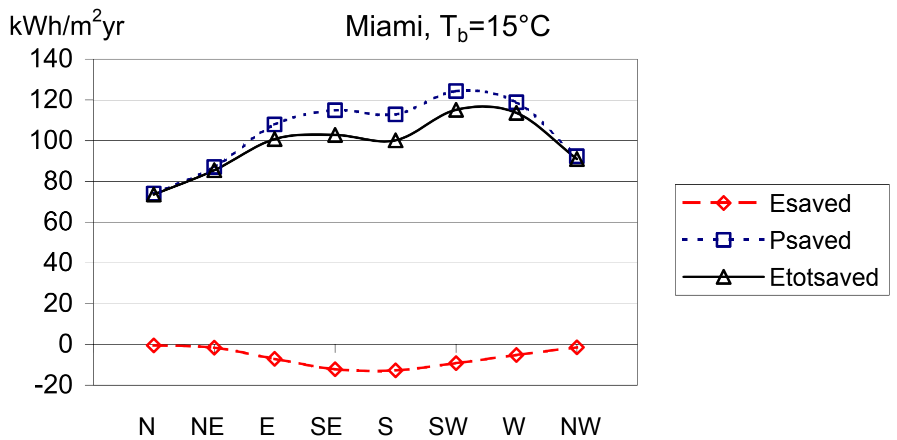

Figure 25: Saved energy when changing from a standard DGU to a solar control window with g=40 %, U=1.5 W/m²K, q=4, p=2, E_{conv}=0.75, P_{conv}=2.9 in a building with T_b =15°C, medium thermal mass, Miami climate.

Low-e windows are clearly beneficial in residential buildings in cold climates. However, during the nineties it has become a kind of "manufacturers race" towards zero emittance[VI]. The thermal emittance has been used as a measure of how "good" a glazing is. In paper VI we investigate how important small changes in emittance is. It is seen that it is clearly an improvement to go from a thermal emittance of 84% down to of the order of 10%. But it is also seen that small changes in the emittance does not necessarily lead to a better window, especially if the solar or light transmittance is reduced at the same rate as the thermal emittance[VI]. The coatings with the lowest values of thermal emittance are solar control coatings. For these coatings the light and solar transmittance values are more important than the U-value. This is exemplified in figure 26. Figure 26a gives the reduced cooling demand in a Miami house, and figure 26b gives the reduced heating demand in a Stockholm house when the thermal emittance and the g-factor are changed. The change in energy performance when the thermal emittance is changed by 0.05 is small compared to the change in energy performance when the g-factor is changed by 0.05, figure 26a. In a cold climate the influence of the emittance is obviously more pronounced. However, the transmittance is still (equally) important and, in fact, for a south-facing window it is the dominating parameter for this case, figure 26b.

It is also necessary to recognize the difficulties to measure very small emittance values. The emittance is obtained as $\varepsilon_{th} = 1-R$ and an error of 1 % at $R = 0.95 \pm 0.01$ becomes an error of 20 % in the emittance value $\varepsilon_{th} = 0.05 \pm 0.01$. In order to achieve an emittance value with a two-digit precision, the reflectance must be measured with an accuracy of 0.1%. Furthermore, the U-value for the whole window can normally only be measured within an accuracy of about 6%[75].

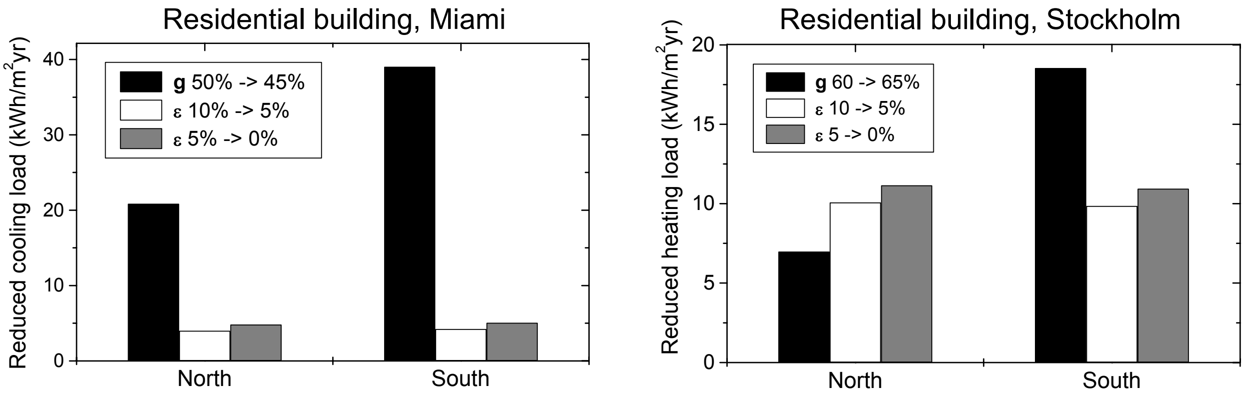

Figure 26: Reduced cooling demand in a Miami house (figure 26a) and reduced heating demand in a Stockholm house (figure 26b) when the thermal emittance and g-factor is changed by 0.05, respectively.

As discussed above, neither the thermal emittance nor the U-value of a window determines the energy efficiency of a window, but also the solar and light transmittance. In paper VII we analyze the potential to use AR-coatings and low-iron glass in order to increase the energy and visual performance of windows. Normal float glass has become standardized to contain a certain amount of iron-oxide, which gives rise to a transmittance dip in the near infrared zone (see figure 8 above). This comes from the raw material that is used to produce the glass. It is however possible to get low-iron glass, without this transmittance dip. Furthermore AR-treatment can be applied in order to reduce the reflectance from the air/glass and glass/air surfaces, which sums up to about 8%. In figure 27 two different low-iron, and AR treated glazings are illustrated, one single film broadband AR and one commercial narrowband AR treated glazing. It is seen that the reflectance can become very low after this treatment.

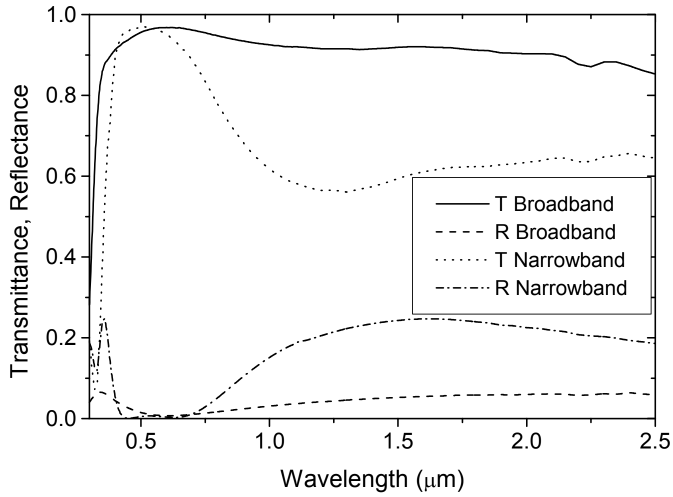

Figure 27: Spectral transmittance and reflectance curves for the broadband[76] *and narrowband AR-coated (Amiran*[TM] *by Schott) glazing, respectively. The spectra were measured at near normal incidence.*

In paper VII, low-iron glass and AR treatment is applied for a triple glazed low-e window and a double glazed solar control window, respectively. For the low-e window it is shown that the light transmittance can increase by almost 0.09, if all three panes are low-iron and if the central pane is AR-treated on both sides. This will actually result in a window with a very low center-of-glass U-value and at the same time a light transmittance that is higher than for a normal, uncoated DGU. The g-factor will increase about 0.1 by this treatment, see figures 28 and 29. For the solar control window the light transmittance can increase by about 0.06 if both panes are low-iron and if one pane is AR treated[VII].

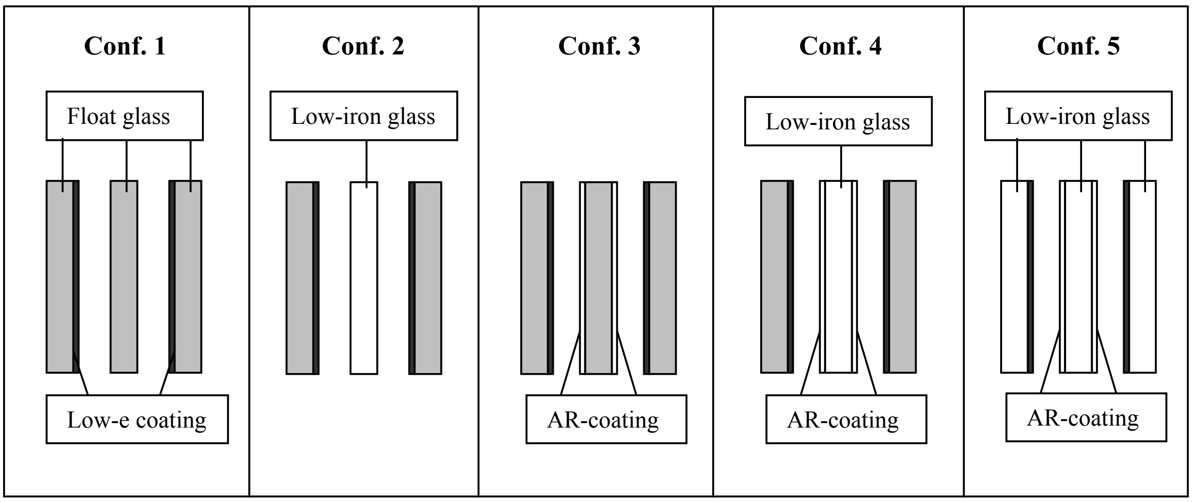

Figure 28: The five different low-e window configurations from paper VII. The first is a triple glazed unit with two low-e coatings on the inside of the outer panes and argon gas fill. For the rest of the configurations the following changes are made; 2: center glazing is low-iron, 3: center glazing is AR coated (double sided), 4: center glazing is low-iron and AR-coated, and for the 5th configuration all glazings are low-iron and the center glazing is AR-coated.

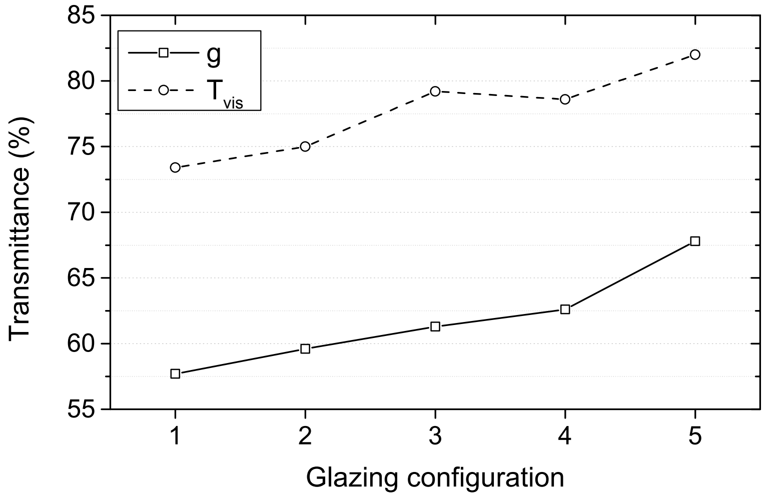

Figure 29: g-factor and light transmittance, at normal incidence, for the five different low-e configurations (figure 28), calculated according to ISO 9050.

Papers IX and X assess the energy efficiency of switchable windows. The energy efficiency of switchable windows is very difficult to evaluate, since it depends strongly on the control strategy, location, type of building, orientation, lighting and comfort demands, and also the choice of reference window[77,78,79,80,81,82,IX,X]. In paper IX the window selection tool in paper II is used and a simple solar control strategy of the smart windows is applied. The solar control is a linear regulator, which darkens the window if the impinging solar irradiation power is higher than a certain set point, I_{gmin}, and bleaches the window if the impinging solar irradiation power is lower than another set point, I_{gmax}, figure 30.

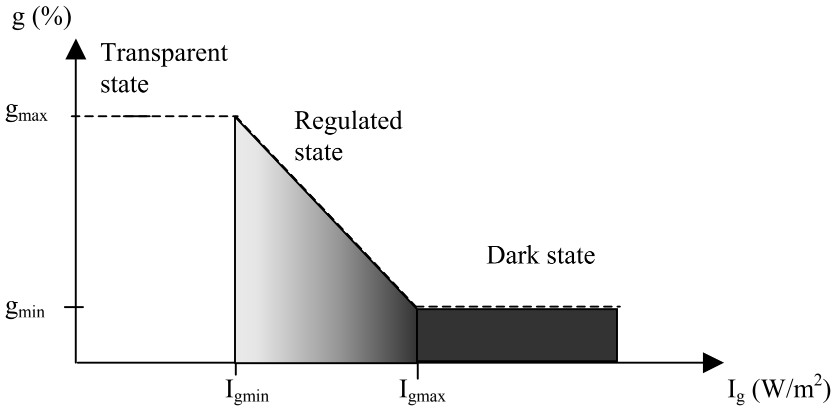

Figure 30: Linear regulator for controlling solar transmittance. I_g is total irradiation impinging on the window surface and g is the total solar energy transmittance. g_{max} and g_{min} is transmittance at the transparent and dark state respectively and I_{gmin} and I_{gmax} are the regulation set-points (paper IX).

From paper IX it is concluded that switchable glazings do not save energy in residential buildings in cold climates, figure 31. This is because of the same reason that solar control windows do not save energy in residential buildings in cold climates – almost all solar energy is useful. However, in commercial buildings with a cooling demand switchable windows can compete with solar control windows, figure 32 (from paper X). The sunnier and the warmer the climate, the better the smart windows perform from the energy perspective[X]. However, there is a trade-off situation between cooling and lighting performance of the switchable window[IX].

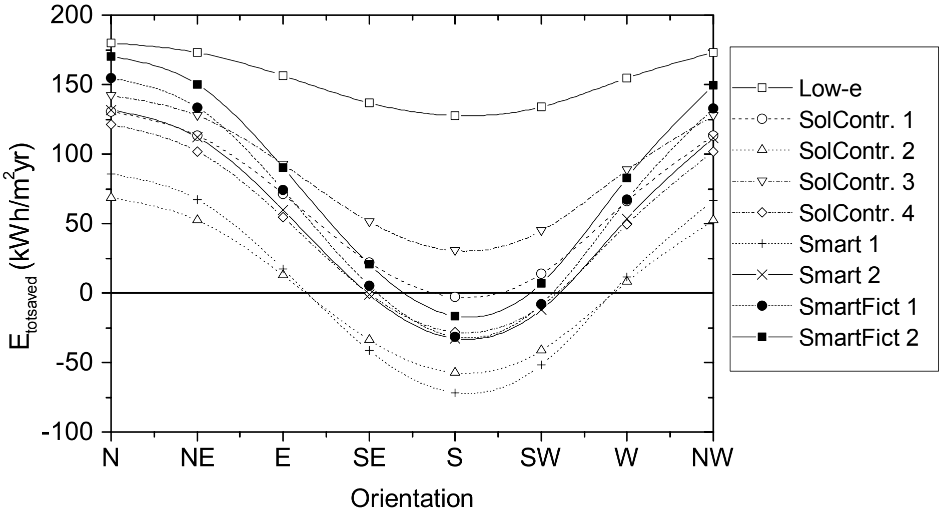

Figure 31:Total (heating plus cooling) saved energy versus the direction of the windows for different window alternatives[IX] compared to an uncoated double glazed window in a residential building with T_b = 15°C in Stockholm. The solar control strategy is used with setpoints 200 to 400 W/m² (see paper IX).

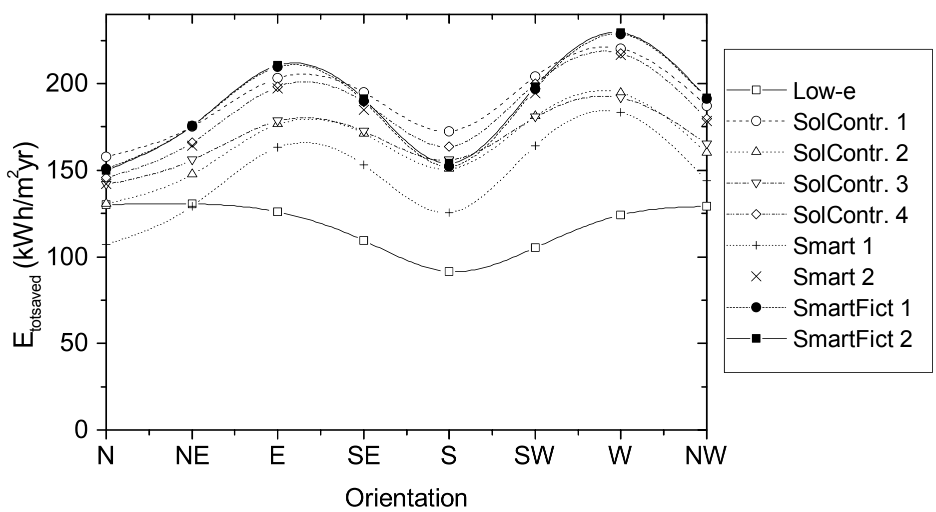

Figure 32:Total (heating plus cooling) saved energy versus the orientation of the windows for the different window alternatives compared to an uncoated double glazed window for the base case (paper X) in a Stockholm climate. Setpoints: 50 to 300 W/m²

In paper X, another building model is applied on a very simple, “shoe box” office module. In this paper an adaptive system is used in order to see whether such a system can improve the switchable window performance. The adaptive system detects occupancy, indoor temperature and solar irradiation, and based on those data it changes heating, cooling, lighting, ventilation, and transmittance of the windows[X]. In figure 33 it is seen that the choice of window is very important for the energy performance, but that a possibility to switch the window is important only in very sunny climates. Furthermore it is seen that heat recovery of the exhaust air is important in cold locations and that occupancy control is beneficial in warm countries. The occupancy control also saves electricity, not illustrated in this figure.

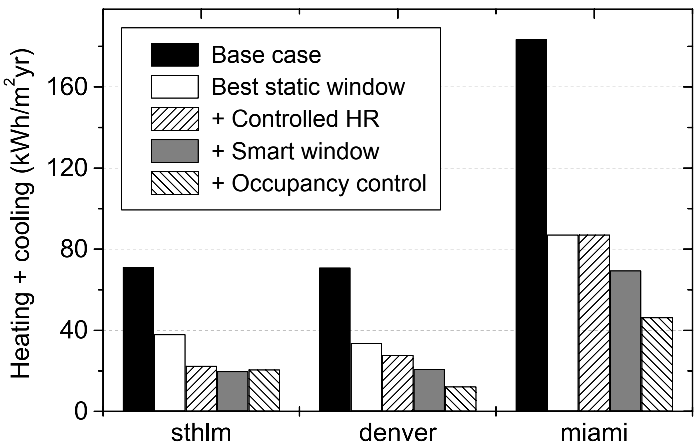

Figure 33: Heating plus cooling demand per square meter floor area for the base case in three different climates, paper X. The leftmost bar gives the demand for the base case and the bars to the right gives the demand when changing to the best static window, plus controlled heat recovery, plus best smart window, plus occupancy control with 25% randomly distributed absence. For simplicity the heating and cooling energy are equally treated here, i.e. 1 kWh heating = 1 kWh cooling, but normally they are associated with two distinct energy systems.

One of the reasons that the switchable glazings do not clearly outperform the static glazings is that the static solar control glazings are highly developed. Today it is possible to get glazings that transmit basically only within the visible spectral region, figure 34. This type of glazing rejects a large part of the solar irradiation, still having a high light transmittance. The ratio between the light and the solar transmittance is about 2, which is the physical limit[VII]. Such a window can thus have a T_{vis}/T_{sol} of about 0.70/0.35, 0.40/0.20 depending on the need for solar protection and allowed lowest light transmittance.

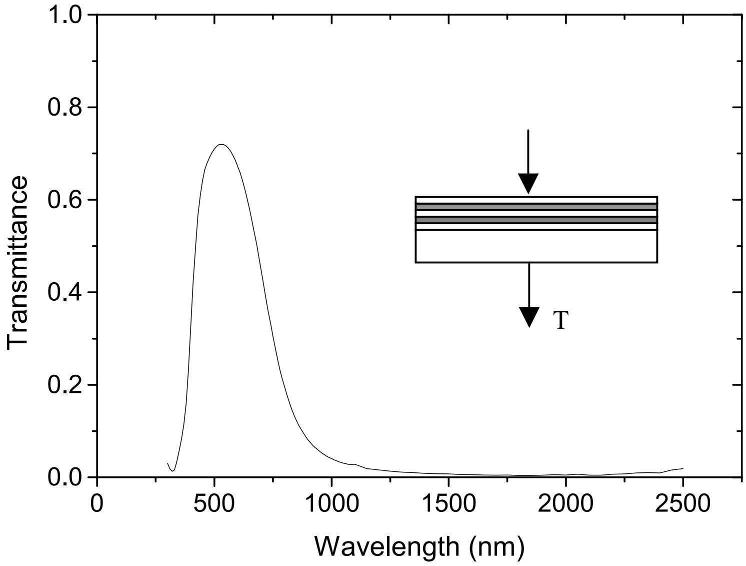

Figure 34: Measured transmittance of a double silver (oxide/silver/oxide/silver/oxide, Pilkington "Brilliant") coated glazing.

Paper II briefly discusses the cost efficiency of energy efficient windows. It is not always the case that the most energy efficient window is the most cost efficient window, depending on the costs involved. In paper II the saved costs are given on an annual basis with the installation cost discarded, which is valid for new construction and in cases were the windows should be changed anyway. To clarify, figure 35 show the present value of the annually saved energy with different technical lifetimes and interest rates. The average annual energy price is set to 1 SEK/kWh (1 SEK was about 1/10 USD in September 2001). The present value of the given saved energy thus represents how much more the energy efficient window can cost than the window with which it is being compared, in order to break even. For instance, if a window saves 150 kWh/m^{2}yr and the assumed lifetime, interest rate and energy price are 30 years, 5 % and 1 SEK/kWh, respectively, the window may have an additional cost of 2300 SEK/m^2 to break even. Present production cost of sophisticated multilayer coatings of below 50 SEK/m^2 is considerably lower than this allowed extra cost[52]. However, changing functioning windows is mostly not cost effective from a pure energy cost point of view since the total cost (installation + new window) exceeds the present value of the total energy saving. But in new constructions and if the windows are to be changed for some other reason, the energy efficient alternatives are cost effective in basically all cases. The costs can be reduced further if, for instance, a smaller or no air conditioning system needs to be installed because of the energy efficient windows. Comfort problems, such as glare and cold draughts are in practically all cases reduced by installing suitable energy efficient windows. This is not seen at all in the energy or cost efficiency assessment but they are very important factors.

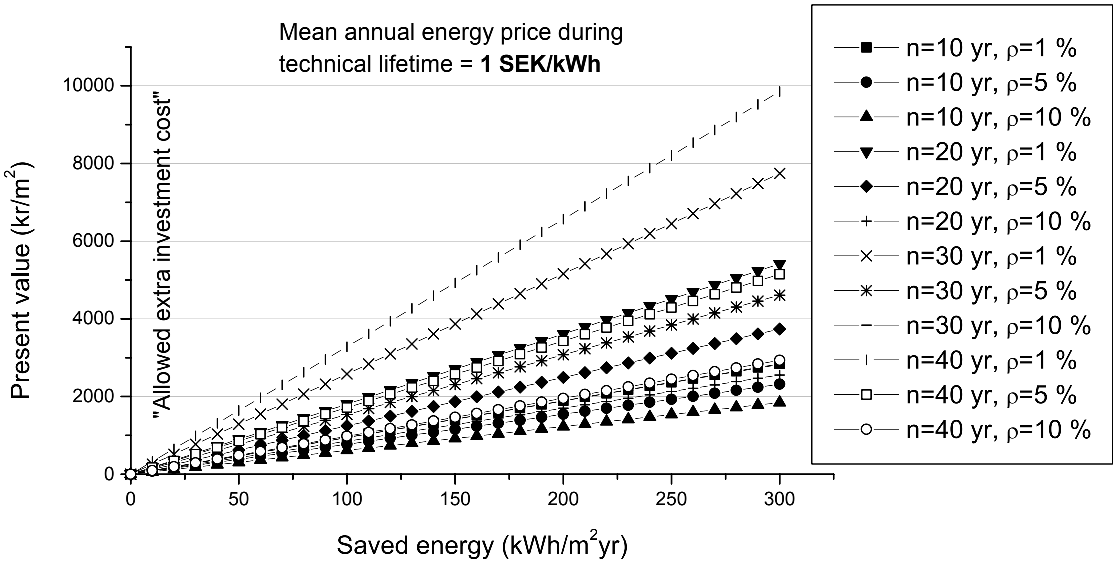

Figure 35: Present value of a saved amount of energy per square meter for different technical lifetime, n, interest rates, ρ, and for an average energy price of 1 SEK/kWh.

6.4. Energy rating of windows

The energy efficiency of a window is not immediately obvious, which makes the choice of window difficult for a consumer. There is ongoing work in several countries[83,84,85,86,87,88,89,90], with the purpose of establishing a system for energy labelling, or energy rating, of windows, which would indicate the possible savings of an advanced window, compared to a standard window. There are several ways of establishing a window energy rating system (WERS). However, many problems are also involved. The most striking problems, as discussed in sections 6.2 and 6.3 above, are that the energy efficiency of a window depends on in which climate it is used, in which type of building it is used, and which direction it is facing. Paper V evaluates the different ways to create a WERS for European climates and categorize the different approaches. The following steps are discussed:

1. <u>Include physical properties</u>: Compare windows based on their physical data, such as the heat loss (U-value), total solar energy transmittance (g) and the light transmittance, (T_{vis}).
2. <u>Include climate</u>: Make a simple energy balance of the window of the type: Ag-BU, where the empirical coefficients A and B depend on annual or seasonal solar irradiation and temperature (degree-days) within the climate zone. Different orientations of the window can also be considered by varying A.
3. <u>Include building properties</u>: Identify simplified building parameters in order to distinguish between different building types.
4. <u>Full scale building simulation:</u> Perform full-scale simulations within a certain climate zone, in which the investigated windows are placed in a certain category.

Paper V indicates that a linear model of the 2nd type above seems possible to use with some restrictions. The coefficients A and B vary for different buildings and climates. Coefficient A decreases with "better" buildings and with higher glazing fraction to the north. Coefficient B is basically equal to the number of degree-days for the climate zone and thus decreases for warmer climates. Using the same A and B coefficients, within the same climate but for different types of buildings does not seem to yield very high errors[V], figure 36. The difference when using the same energy rating coefficients for the base-case house (A=370) on the low energy house (A=300) or the house with high south facing glazed area (A=450) is of the order of 20 kWh/m^{2}yr when comparing a glazing with g=50% and g=75%, figure 36. This indicates that it may be possible to use the same linear rating equation for different type of houses.

The difference between the climate zones (figure 37), illustrates a maximum difference of about 40 kWh/m^{2}yr between Stockholm and Berlin, and a very large difference between the Stockholm and the Madrid climate. This means that the division into climate zones is important. The different A and B coefficients are fitted to data from building simulations in paper V.

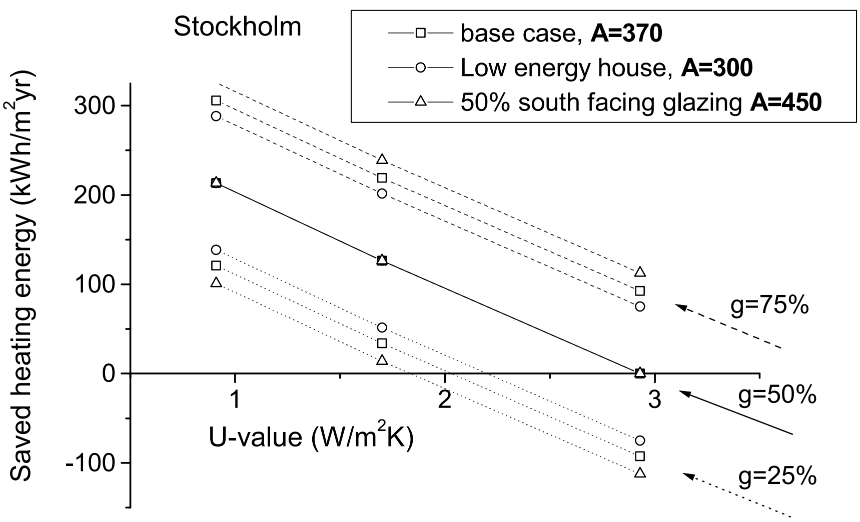

Figure 36: Errors, using the base case linear heating energy rating model (A=370, from paper V) for different types of houses. The reference window have U=2.9 W/m^{2}K and g=50%.

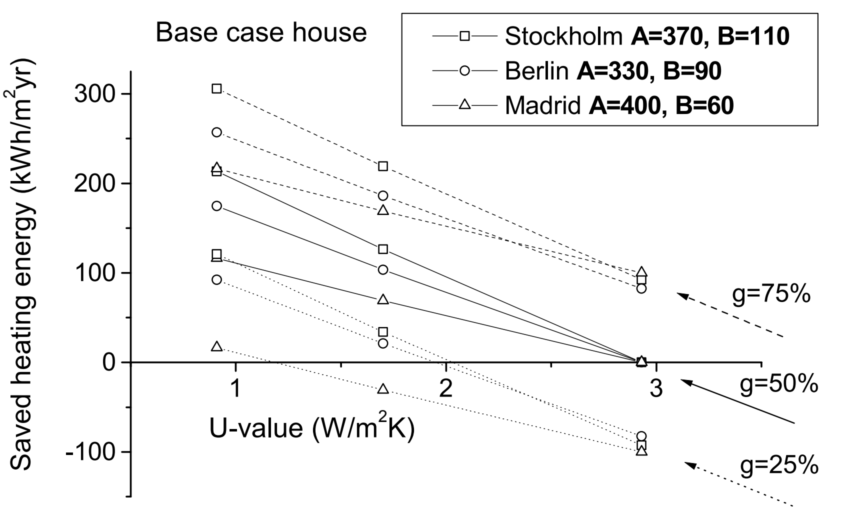

Figure 37: Differences using a linear model in the three different climates from paper V. The coefficient are extracted from building simulations

7. CONCLUSIONS AND FUTURE WORK

This thesis deals with four different problems related to window energy efficiency: angular dependent transmittance, simple modelling of the energy efficiency of windows, the energy efficiency of different advanced windows and energy rating of windows. Other important issues for windows, such as daylighting and comfort (glare, draught, etc.) are not treated.

At present, practically no building simulation tool takes the different angular dependencies of coated glazings correctly into account. The outcome from papers I and III illustrates that categorisation of the glazings may be a possible solution to this problem. However, for programs that need surface temperatures of each pane this is not a good solution. In this case the work of Rubin et al.[61] and Polato et al.[62] may be a solution.

When the correct angle dependence of the g-factor is vital, a choice could be made depending on what is known about the window:

- If all properties are known, such as thickness and optical constants, the correct Fresnel equations can be applied. This requires advanced programs and knowledge.
- If the reflectance for both sides of the glazing and the transmittance are known at all wavelengths the model such as the one presented by Montecchi[62] can be used.
- If the g-factor is known for normal incidence and one oblique angle of incidence, the angle dependency can be extracted from the model in paper I, by fitting.
- If the g-factor at normal incidence and information about the type of coating are known but not the R and T spectra, the model in paper I can be used.
- Finally, if only the g-factor at normal incidence is known, the profiles of uncoated glazings should be used[III].

For uncoated glazings the bulk model (see definition in section 6.1 above) render exact solutions, provided the data for normal incidence are correct. The bulk model should not be used for glazings coated with thin metal films[III].

I believe that the angle dependent issue is, in most cases, not of dramatic importance for energy assessment purposes. Unfortunately, for some cases when, for instance, titanium-nitride coated glazings and silver coated glazing are compared or for buildings with very large glazed areas it is of considerable importance[65,III]. The categorisation does not necessarily have to be as detailed as demonstrated in papers I and III. Maybe it is sufficient to separate the extreme cases such as the Ag-coated glazings from the TiN coated glazings and from the uncoated glazings, giving three basic types of angle dependency.

Further work on the angle dependence subject should be related to the development of similar predictive algorithms as for the g-factor but for T_{vis} and R_{vis}, which are also of interest in building simulations. Initial tests have shown that a polynomial very similar to that for the g-factor works equally well for T_{vis}. More measurements and calculations should be performed in order to test the generality of the formulation. If the model holds, it could easily be included as an appendix to the ISO 9050 or EN 410 standards for improving the accuracy of angular dependent transmittance. The categorisation of glazings, with the q-value[I,III], could be done by the glazing manufacturer.

The balance temperature model offers a possibility to compare the energy efficiency of different glazings, without knowing the details of the building, but still taking different type of buildings into account. The model shows acceptable results when compared with building simulation programs[IV,V]. A model of this form makes studies of different parameter changes of the window such as, for instance, angle dependent transmittance[III], thermal emittance[VI], g-factor[VII], etc. effortless. The tool can be used as a window selection tool by architects, energy consultants and within education. In paper IV it is shown that useful solar energy needs to be included in degree-day methods and it is illustrated how the balance temperature varies with the different properties of the building. The variation of the balance temperature when changing the U-value or the g-factor of the window is moderate, which means that the window energy model described in paper II is consistent even when such changes occur.

It is shown that modern energy efficient windows can be energy collectors, rather than energy losers, in cold countries. Low-e windows, with U-values below 1 W/m^2K are capable of highly reducing the heating demand in residential buildings. A "super" insulating window of this type does not have to be dark but can have a light transmittance higher than a normal uncoated DGU, as shown in paper VII. Furthermore, since the U-value is decreased, larger window areas can be allowed, without getting cold draughts, and more light can be collected than for standard window. It should be noted that neither the thermal emittance nor the U-value is the only measure of the energy efficiency of a window, but also the transmitting properties. Paper VI illustrates that low emittance is of course beneficial but it is not necessary to argue about small differences in the emittance value. Solar control windows with, basically, only transmittance within the visible spectral region are effective filters for buildings with cooling demand.

For buildings where heating is of prime importance the U-value should be as low as possible and the g-factor as high as possible. For buildings where cooling is of prime importance the g-factor should be as low as possible (with maintained light transmittance). For buildings requiring both heating and cooling, a low U-value and a low g-factor saves heating and cooling. For some cases it is optimal to have different windows in different directions. In cold climates it is beneficial to focus on low U-values for north directions and high g-factors for south directions.

Future switchable windows can perform at least as well as today's high performing static solar control windows when it comes to heating and cooling. Furthermore, they have the advantage of automatic glare-, thermal comfort- and lighting-control. The control of switchable windows is a tricky question. If the control is optimized for energy they may not be comfortable, if optimized for comfort they may save less energy. Furthermore, different occupants normally want different settings and thus require manual override. The best option may be to optimize for energy when no one is present and for comfort when someone is present in the room[X]. Although there are already switchable windows on the market there is room for improvement. Reflective switchable glazings can be very interesting for energy management of buildings and for privacy control[77,91,92]. Present smart windows switch mostly over the whole solar spectrum[93], it could be interesting to see a smart window that can have a spectral profile like in figure 34, but with switchable properties. Further studies need to be made on control strategies of switchable windows and more comparisons with other types of windows and shadings, such as controllable blinds. The comparisons should be made from energy, lighting and occupancy acceptance aspects.

When it comes to energy rating of windows, many countries have proposals of how this should be done. However, I have seen few systematic studies on how accurate this would be for different buildings and climates. Paper V is an attempt to investigate this in some detail. However, many more building variations should be investigated. Results from paper V indicate that a linear model (category 2 in paper V) may be accurate enough, but the heating and cooling coefficients need to be evaluated for the building types and climate zones. The model from paper II (category 3) seems to give a correct rating but requires the balance temperature for the building, hourly climate files and software. Furthermore, this model gives the possibility to compare glazings with different angle dependent transmittance properties, something that is difficult to do with category 2. This can be of importance since a glazing with a normal transmittance of 75% does not, normally, have the same angle dependence profile of the transmittance as a glazing with a normal transmittance of 25%. Category 4 can of course be used but requires all building and climate data and thus some kind of systematisation or categorization of buildings in order to be applicable[55]. It is essential to divide the world into appropriate climate zones for proper rating.

Within the scientific community, everybody agrees that energy efficient windows do save energy, but that the technology of these coated glazings is not as widespread as it should be. However, further knowledge about them, developed building regulations and window energy rating are contributing to a constant increase of these products[94]. The question always remains of how to select the optimal window for a given building. The choice of window highly affects the energy demand in buildings. It is therefore recommended to use building simulation tools, simplified window selection tools or at least consult some energy-rating scheme before the windows are selected. On a large (regional, national, global) scale the energy saving potential with energy efficient windows is huge.

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