HIGH PERFORMANCE DYNAMIC SHADING SOLUTIONS FOR ENERGY EFFICIENCY AND COMFORT IN BUILDINGS

Michael Hutchins

Sonnergy Limited,

PO Box 489, Abingdon OX14 4WY, United Kingdom

mhutchins@sonnergy.com

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EXECUTIVE SUMMARY

The energy saving and CO_2 reduction potential of solar shading in European buildings is very significant Effective use of solar shading can contribute to the reduction of overheating, space cooling demand and air conditioning use, improved thermal insulation of fenestration and thereby lower space heating loads.

In addition to improving the performance of the building envelope through greater envelope insulation, airtightness and ventilation heat recovery, solar shading measures are a necessary inclusion for solar gain control, daylight control, demand controlled ventilation, lighting control, and window opening.

Efficient and effective automated control of solar shading is of the highest importance and needed to be seen within the context of the entire building design. Synergies and integration of solar shading with other building technologies, e.g. dynamic shading, dimmable lighting and night cooling, is necessary to realise cost-optimal packages of energy saving measures. Highly glazed commercial buildings will not function effectively without intelligent use of automated shading.

Solar shading has a high potential to enable efficient cooling, heating and artificial lighting savings in new build. The drive towards reduced energy consumption in buildings can however have unwanted drawbacks. Highly insulated and airtight low and zero carbon homes, often designed with large glazing areas have the potential to overheat throughout the year and solar shading has been shown to be an effective strategy to combat such situations.

The International Energy Agency (2.4) identifies the importance of solar shading in realising the potential of energy efficiency in the advanced building envelope and recommends as necessary and of high priority that exterior shading with proper orientation and dynamic solar control should become standard features globally in new buildings and can also be applied to existing buildings. Pilot projects have demonstrated that such systems can enable energy savings up to 60% for lighting, 20% for cooling and 26% for peak electricity.

The potential for energy savings of solar shading solutions in the refurbishment of energy inefficient buildings, which represent the great majority of buildings in the EU-28 MS is extremely high. The impact of the shading system on the complex glazing thermal performance depends upon the choice of glazing and the largest improvements in thermal transmittance are observed when the shade is used in combination with energy inefficient glazing, e.g. single glazing, double clear glazing, which constitute some 86% of current glazing within the EU. Smaller reductions are observed when more advanced glazing with lower U-values is employed but solar shading is always found to produce a positive enhancement.

In our study we predict positive cooling and heating energy savings resulting from the effective use of solar shading systems. We investigated cooling and heating performance in 4 different European climates when using solar shading in combination with 6 reference glazing systems. In all cases positive results were found. Maximum cooling savings are always found for South / South-West orientations. For the buildings studied herein, assuming an energy end-use split of 50:50 between space heating and space cooling the impact of dynamic solar shading systems is estimated to be a

30% saving in cooling energy use of 39.8 Mtoe/yr and a 14% saving in heating energy use of 18.2 Mtoe/yr. Taken together the potential energy savings which can accrue from the use of dynamic shading systems are a 22% saving in heating and cooling energy use of 59 Mtoe/yr and a carbon emissions reduction of 22% equivalent to a saving of 137.5 $MtCO_2$/yr.

The use of external dynamic solar shading has been demonstrated to be a successful feature and a key strategy to be employed in overcoming problems of overheating and increasing occupant thermal comfort in low energy buildings. The market for refurbishment of window areas by integrating shading is very large and our results demonstrate that solar shading can be used to upgrade existing energy inefficient window systems when it is not possible to replace them. Improving the energy performance of energy inefficient glazing through the use of solar shading to achieve significant cooling and heating energy savings represents an attractive economic and cost-efficient refurbishment solution.

Exterior shading is the most effective form of solar gain control and the reduction of indoor temperatures. Interior shading is an effective form of thermal insulation and a means to control both daylight, avoid glare and provide visual comfort to the occupants. An integrated external and internal solar shading system is optimum for a combined solution addressing cooling, heating and visual comfort. Solar shading plays an important role in combatting overheating with accompanying benefits for occupant thermal comfort and health.

Smart glazing, such as the electrochromic window, is shown to have serious disadvantages in comparison to dynamic solar shading where performance is compromised in respect of glazing temperatures, colour rendering and dynamic range. Dynamic solar shading will compete with and outperform static glazing when reducing space heating demand, controlling excess solar gain and improving occupant thermal comfort.

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1. Introduction

1.1. Background and Context of the ES-SO 2014 Study

The European Union (EU) Climate and Energy Package (1.1) presents an integrated approach to climate and energy policy, addressing the central issues of climate change, energy security and economic competitiveness. Three key objectives for 2020 known as the "20-20-20" targets seek (i) a 20% reduction in EU greenhouse gas emissions (GHG) from 1990 levels, (ii) a raising of the share of EU energy consumption produced from renewable energy sources (RES) to 20% and (iii) a 20% improvement in the EU's energy efficiency. The necessary conditions to create a more competitive, low-carbon economy were further reinforced in 2014 by agreement amongst the EU Member States of higher targets for 2030 of a 40% GHG reduction, a 27% RES share and a 27% improvement in energy efficiency. The long term objective is a reduction in GHG emissions of 80% by 2050.

Buildings represent the largest single sector of energy use in the European Union and are responsible for some 40% of energy end use. The goals of the EU Climate and Energy Package can not be reached without significant improvements to the energy performance of the EU building stock. The Energy Performance of Buildings Directive (EPBD) (1.2) is a major driver for the achievement of better buildings and establishes clear and quantified targets for reduction in building energy consumption in all Member States. Through improving the energy performance of the building envelope, the use of smart control systems and the localised use of renewable energy sources, energy demand for heating, cooling and lighting can be substantially lowered and reliance on conventional fossil fuel energy sources reduced. Such improvements can be achieved without detriment to the quality of the indoor environment and the comfort of the occupants. In this respect solar shading technologies are a key component of the essential integrated measures which will need to be undertaken in order to improve building energy performance, promote energy efficiency and create conditions for a more sustainable future.

This ES-SO Study seeks to examine the recommended methodologies and tools emanating from the EPBD and its 2010 recast, to provide a firm scientific and economic demonstration of the many varied contributions that solar shading technologies can make to the realisation of high performance low energy buildings in the context of the"20-20-20" targets.

The study is oriented and shaped with reference and respect to (1.1, 1.2, 1.3, 1.4, 1.5)

- The EU Climate and Energy Package
- The EPBD-recast 2010
- The Ecodesign Directive 2010, Certification and Energy Labelling
- The ES-SO Position Paper, R+T 2012
- The ES-SO ESCORP EU-25 Scientific Study 2005.

The previous ES-SO ESCORP-EU-25 Scientific Study undertaken in 2005 (1.5) analysed, through building energy performance simulations, the beneficial energy and environmental impacts which can result from the intelligent use of solar shading in the Member States. The study predicted cooling energy and heating energy savings of 31 Mt/annum CO_2 reduction through a 12 Mtoe/annum reduction of heating demand and an 80 Mt/annum CO_2 reduction through reduction of 31 Mtoe/annum cooling demand. Taken together these savings represent an approximate 10% reduction in the energy end-use of the EU-25 building sector (455 Mtoe/annum in 2005) demonstrating this extremely high potential of solar shading technologies to serve as effective measures in both new-build and refurbishment building energy efficiency solutions.

1.2. Objectives of the ES-SO 2014 Study

The objectives of the ES-SO 2014 study are:

i. To evaluate the range of effective solar shading solutions as single measures and as a component of packages of energy saving measures.
ii. To demonstrate the relevance of solar shading for the realisation of high performance buildings arising from new EU energy regulations and thereby reinforce the ES-SO 2013 position paper (1.4).
iii. To determine the impact of the improvements that solar shading measures bring to the final and primary energy needs of high performance residential and commercial buildings in Europe.
iv. To demonstrate the added value of solar shading solutions (to include combined internal and external shading and automated control) in respect of overheating, improved building energy performance and climate change impact, e.g. carbon emissions.
v. To assess the cost efficiency of solar shading solutions and their contribution to the achievement of cost-optimal levels by applying the recommended methods of the EPBD recast and prEN 15603:2013 (1.6).

The scope of the ES-SO 2014 study encompasses the following activities

- A state-of-the-art assessment of solar shading research and implementation;
- Quantitative evaluation and demonstration of the benefits of a wide range of solar shading technologies and applications using building energy simulation;
- Calculated performance data for solar shading technologies and an evaluation of the effectiveness of the EPBD recast cost-optimal calculation methodology;
- Preparation of the Final Reporting and supporting documentation in formats which will assist widespread dissemination and presentation of results by ES-SO.

The study reviews modern glazing and shading solutions, selection tools, integration and control strategies and their impact on the internal environment and building energy performance.

2. Energy Use in EU Buildings

Buildings represent the largest energy consuming sector The International Energy Agency (IEA) identifies that more than one-third of all final energy, half of global electricity consumed and approximately one-third of all carbon emissions emanate from use in the built environment (2.1). With global population expected to increase by a further 2.5 billion by 2050, it is predicted that energy use in buildings will rise significantly. Within the 28 Member States of the European Union the built environment is responsible for more than 40% of total energy end-use (2.2). Space heating and cooling together with water heating account for 60% of global energy consumption in buildings. In the EU this proportion is much higher and is nearer to 80%. Furthermore the use of air conditioning reliant upon highly carbon-intensive electricity systems has become far more widespread and the proportion of end-use energy required for space cooling has steadily increased (2.3). Rising energy use which is dependent upon traditional fossil fuel energy sources will have adverse impacts on both CO_2 emissions and energy security. Integrated use of renewable energy sources together with improvements to the performance of the building envelope are high EU priorities and provide the essential opportunities for realising the potential of energy efficiency and the necessary transition to more sustainable buildings with reduced life-cycle material impacts (2.1). The International Energy Agency Technology Roadmap for energy efficient building envelopes predicts a rapid rise in energy consumption for cooling and identifies exterior shading as an effective technology for reducing cooling energy consumption (2.4). The recommendation is made that “exterior shading, proper orientation and dynamic solar control should become standard features globally in new buildings and can also be applied to existing buildings….Pilot projects have demonstrated that such systems can enable energy savings of up to 60% for lighting, 20% for cooling and 26% for peak electricity”.

2.1. The Energy Performance of Building Directive

The Energy Performance of Buildings Directive (EPBD) is a major driver in the achievement of better buildings throughout the Member States (1.2) underpinning the EU commitment to transform itself into a highly efficient, competitive, low-carbon economy. Since buildings offer the most promising potential for energy savings; the EPBD is central to realising these challenging objectives of the climate and energy policy. The Energy Performance of Buildings Directive (EPBD) 2010/31/EU (recast) was adopted by the EU Council and the European Parliament on 19 May 2010. It requires that from the year 2020 onwards all new buildings will have to be 'nearly-zero energy buildings' (nZEB), comply with high energy-performance standards and supply a significant share of their energy requirements from renewable sources (2018 for buildings occupied and owned by public authorities).

The recast of the EPBD requires MS to: “assure that minimum energy performance requirements for buildings or building units are set with a view to achieving cost-optimal levels”. (Cost-optimal level is defined as “the energy performance level which leads to the lowest cost during the estimated economic lifecycle”, i.e. the peak of the Net Present Value calculation).

The EPBD recast introduces a benchmarking mechanism for national energy performance requirements for the purpose of determining cost-optimal levels to be used by Member States for comparing and setting these requirements. MS shall also: “take the necessary measure(s) to ensure that minimum energy performance requirements are set for building elements that form part of the building envelope and that have a significant impact on the energy performance of the building envelope when they are replaced or retrofitted, with a view to achieving cost-optimal levels”.

MS are also required to develop a methodology to determine and permit certification of the energy performance of buildings. Such a requirement will inevitably lead to labelling and rating of the respective components, e.g. windows, doors, shading, solar protection devices etc, employed in the building (2.5).

2.2. The Energy Performance of European Buildings

The development of high performance low energy buildings and near-Zero Energy Buildings is a very high priority of EU research, development and demonstration actions. Indeed there is now encouragement for the construction of “plus-energy” buildings, i.e. buildings which produce more energy than they consume (2.6). The costs of highly energy performing buildings are often high and finding more affordable solutions will aid in overcoming barriers for investors in the construction industry.

The construction of new buildings offers the best opportunity to deploy passive heating and cooling designs which make use of energy efficient building materials to minimise energy required for heating and cooling.

The use of energy efficient materials in new buildings which integrate passive heating and cooling designs allows the energy required for heating and cooling to be dramatically reduced. However older buildings represent the great majority of the EU building stock and these are mostly of low energy performance. The Buildings Performance Institute Europe (BPIE) report “Europe’s buildings under the microscope” (2.7), identifies that annual growth rates in the residential sector of the EU28 MS is ~ 1%. Most countries have experienced a further decrease in the rate of new build in recent years in part as a consequence of the impact of the financial crisis on the construction sector.

The BPIE report states that “The actual rate of construction of new-build homes has been steadily in decline since the post-war boom times of the 1950s and 1960s. The most dramatic decline in new-homes building has been since 2000. (Of the existing European stock currently lived in, 53 per cent of it was built before 1971, 15-18 per cent between 1971 and 1980, 12-13 per cent up to 1990 and 12 per cent up to 2000). Only six per cent has been built since 2000”. It is estimated that non-residential buildings account for 25% of total stock in Europe and the residential stock comprises 64% Single family houses and 36% apartment blocks. The age profile of European residential building stock is summarised in Fig. 2.1.

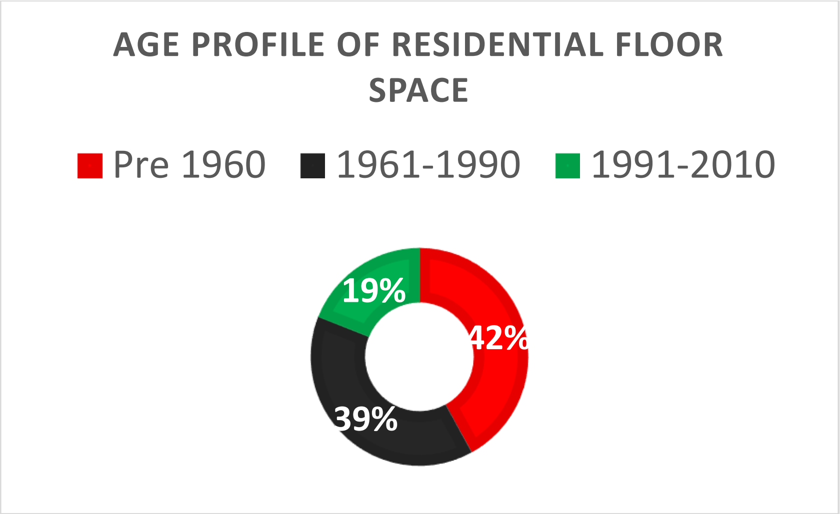


Figure 2.1 Age profile of European residential building stock within the EU28 Member States (from (2.7).

Europe has highest "building density" (building floor space wrt land area), followed by China and the USA. Energy use in EU buildings increased from 400 Mtoe in 1990 to 450 Mtoe in 2010 with a 50% increase in electricity and gas use and 27% and 75% decrease in the use of oil and solid fuels respectively.

In 2009 European households were responsible for 68% of total final energy use in buildings. Energy was mainly consumed by heating, cooling, hot water, cooking and appliances. The largest energy end-use in homes is for space heating ~ 70% and gas is the most commonly used fuel. Average annual specific energy consumption in the residential sector was ~ 200 kWh/m^2/annum for all end uses.

The breakdown of usage for the non-residential sector which makes up 25% of the building stock is wholesale and retail 28%, offices 23%, educational 17%, hotels and restaurants 11%, hospitals 7%, sports facilities 4%, other 11% (2.7). Average annual specific energy consumption in the non-residential sector was some 40% higher, ~ 280 kWh/m^2/annum, and non-residential electricity use has increased by 74% in the last 20 years.

Regional variations are also quantified. BPIE estimate that of the 25 billion m^2 of useful floor space in the EU28, Switzerland and Norway, 50% is located in the North and West region of Europe and 36% and 14% in the South and Central&East regions respectively.

A significant proportion of the building stock is older than 50 years and many buildings are hundreds of years old. More than 40% of residential buildings were constructed before 1960s when energy building regulations were very limited. The UK, Denmark, Sweden, France, Czech Republic, Bulgaria are countries with larger proportions of older buildings. Representative heating energy demand by building construction year is shown in Fig. 2.2 for Germany and Bulgaria respectively.

The age and performance of the EU building stock mitigate against the achievement of the energy and carbon emissions targets set out in the climate and energy strategy unless deep and ambitious renovations of existing buildings are undertaken. The challenge therefore is to find solutions which will lower carbon emission levels and produce buildings which consume very little energy. Through renovation and the integration of renewable energy sources, average energy consumption will need to improve by a factor of four or five (2.3). The means to improving energy efficiency without detriment to the quality of the indoor environment and the comfort of the occupants is through the improvement of the design, performance and control of the building envelope itself.

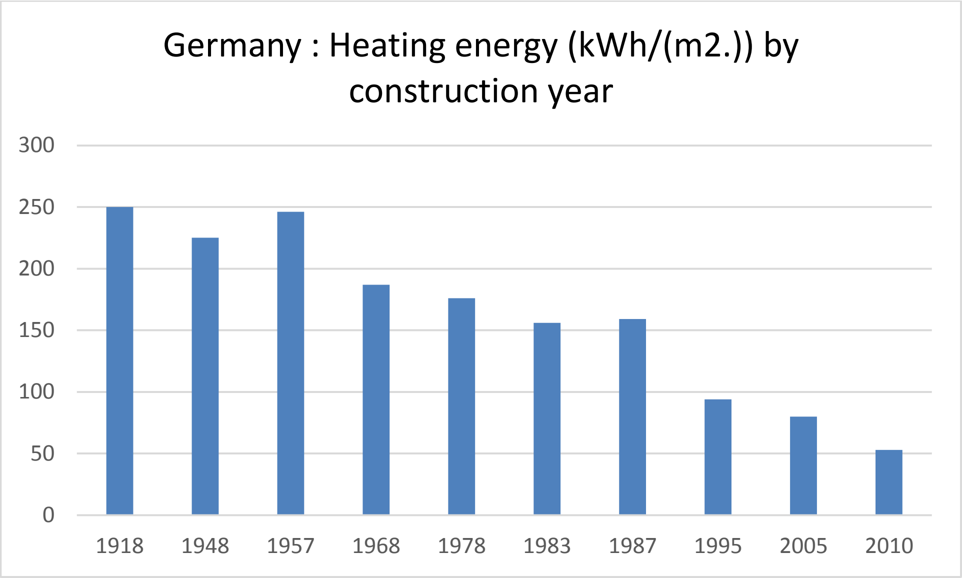


Figure 2.2a. Heating energy demand in kWh/m2 floor area by year of building construction – Germany (from (2.7)).

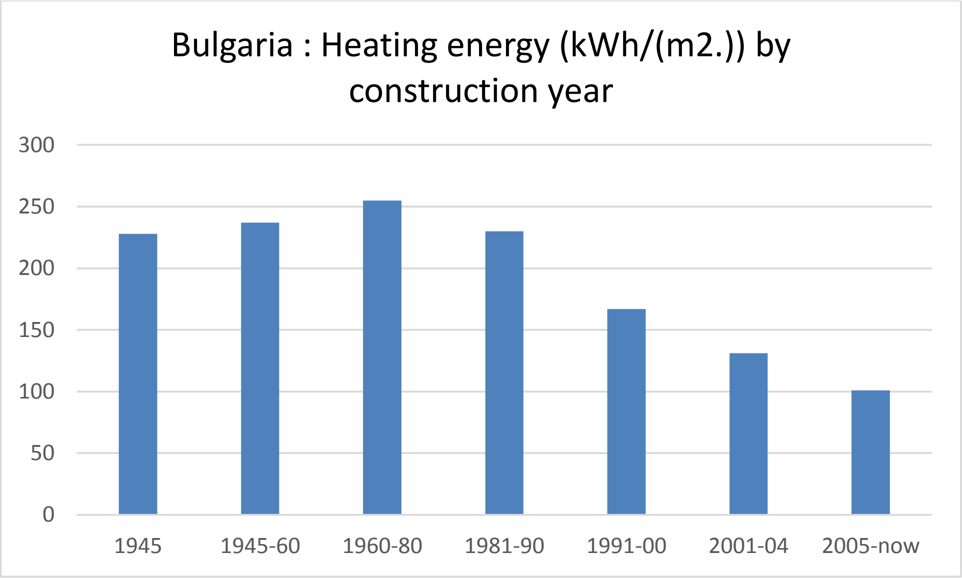


Figure 2.2b. Heating energy demand in kWh/m2 floor area by year of building construction – Bulgaria (from (2.7)).

2.3. Energy Efficiency and the Building Envelope: The Importance of Fenestration

The building envelope is the vital component of the building. It is required to perform many essential tasks, e.g. provide shelter from the weather, fire protection, security, privacy. In addition the envelope plays a key role in energy performance through the regulation and control of solar gain and thermal losses, of satisfying the needs for occupant comfort and ensuring the quality of the indoor environment through e.g. ventilation, views to the outside and the architectural design.

Since most heat is lost from a building by heat transfer through its walls, roofs, floors and windows improving the thermal insulation of the building envelope is of the highest priority. Effective insulation of the envelope will not only reduce heat losses during the cold season but also serve to protect the indoor environment from excessive heat gain during the hot season when overheating can be the major concern. Adequate sealing of the envelope is also necessary to prevent unnecessary air leakage and lower infiltration losses. However overheating of buildings and lowering of the quality of the indoor environment are recognised potential problem issues when buildings are too airtight. Detailed examination of the insulation and airtightness of the building envelope are not within the scope of the present study and are dealt with in much greater detail elsewhere (2.8).

Fenestration plays a key role in optimising building envelope performance, enabling control of solar gain and sustaining occupant comfort. Window energy performance is critical in reducing building energy consumption and the lessening of adverse environmental impacts. The core window industries comprise the glass and glazing industry and the shading and solar protection industry. They have undergone rapid technological change and is today represent a modern, vibrant set of businesses which can respond well to the building and climatic requirements to produce glazing systems with properties matching the desired end use. Windows are now perceived as an integral part of the building system functioning both as an energy source and an environmental solution. With the lowering of production costs advanced window technology can produce innovative products which can compete with other materials, e.g. opaque walls and result in high profit. A market advantage of high performance fenestration is that it provides natural light and the opportunity to increase glazing areas. In addition to energy performance issues of concern for high performance windows include daylight, comfort, view, privacy, aesthetics, acoustics, structure, security, weatherproofing, cleaning and maintenance (2.9).

The annual energy performance of buildings employing advanced glazing is highly climate-dependent and is a complex function of trade-offs between solar heat gain and thermal insulation. In heating-dominated climates the primary aim is reduce heat losses whilst admitting solar energy. In cooling climates the emphasis is on reducing solar gains to lower cooling loads. In climates requiring both heating and cooling there the need exists for some form of dynamic control, e.g. automated shading control, to regulate the solar gains.

The starting point for advanced glazing is the insulated glazing unit (IGU) which employs low-emissivity (low-e) coatings, low conductance gas fills, warm edge low conductance spacers and insulated frame systems. Low-emittance thin film coatings are manufactured by major glass and glazing companies worldwide and represent a widely available mature technology. Modern coatings can be produced with a flexible range of optical properties which permits the designer to select the level of visible light required, the fraction of unseen near infrared solar energy to be rejected or admitted and the amount of room heat retained (the glazing thermal transmittance or U-value). The choice to be made will be based upon climate, appearance and building type and design. The first cost investment required in advanced window technology may be greater than for conventional double glazing but can be off-set in other building systems, e.g. a reduced cooling load and hence chiller size; the lighting design strategy and desired internal daylight balance etc. Factors paramount in all advanced glazing are thermal performance, uniformity and appearance, reliability and durability.

However surprisingly, high performance glazing systems are not commonly employed throughout the EU28. The GlassforEurope “Competitive low carbon economy report”, 2012 (2.10) identifies that 86% of all installed glazing is energetically out-of-date ! The distribution of EU28 glazing is shown in Fig. 3. Across the European Union it is estimated that 44% of the installed glazing is single glazing, 42% is uncoated double glazingand only 14% is energy efficient glazing. Furthermore, Eurowindoor report based on Window market in Europe 2013 study (VFF-Verband Fenster+ Façade survey) (2.11) identifies that the market capacity for replacement of energy inefficient windows is limited and that it will take up to 50 years to replace this existing stock with energy efficient windows. It is estimated that nearly 2.000 million window units are energetically out of date in EU 27 and this figure rises to 3.090 for the whole of Europe.

To reach the EU energy efficiency targets of 2020 and beyond the need for replacement or refurbishment of this energy inefficient glazing stock is of the highest importance. It is shown in Section 5 of this report that dynamic solar shading solutions have a key role to play in improving the energy performance of Europe’s inefficient glazing stock by reducing both heating and cooling demands and that solar shading can be an important solution in any renovation strategy.

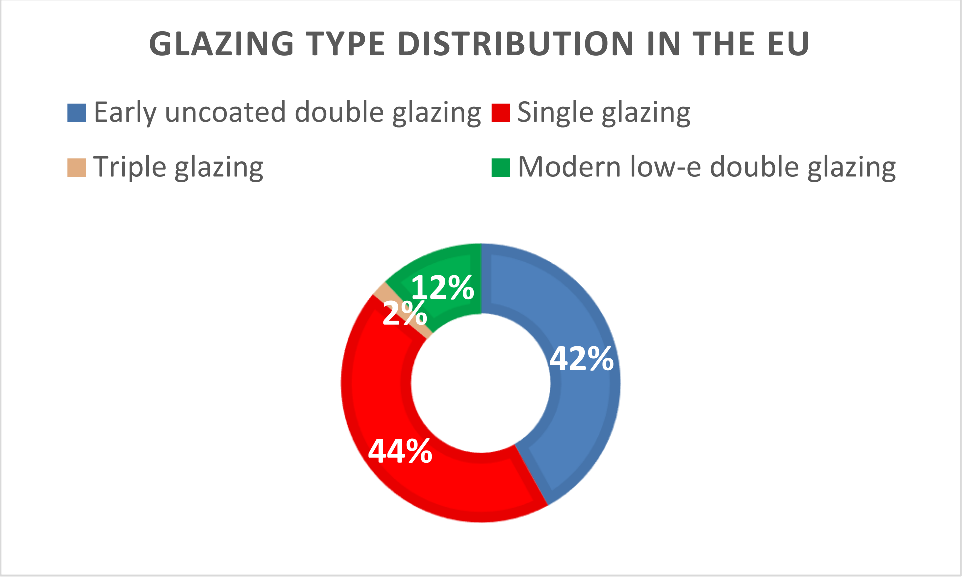


Figure 2.3 Distribution of Glazing Types in the EU Member States (from 2.11).

2.4. Energy Efficient Coated Glazing Products

Glass optical and thermal performance is modified through the application of coatings to the surface of the glass. Uniform coating of glass requires the glass surface to be very flat. The invention of the float process in the 1950's by Pilkington (2.9) allowed production of extremely flat sheets and the coated glass industry grew rapidly in the late 1970's and 1980's. Optical and thermal performance are modified through the application of coatings to the surface of the glass pane. Adding value to glass with coatings achieved a first major boost with energy conservation initiatives launched by the 1973 energy crisis. Coated glass products incorporated into double glazed units enable both the quantity of solar radiation entering a space (solar gain) and the thermal resistance of the window to be controlled (2.12).

Common glazing types are listed below:

- Clear Float Glass (uncoated)
- Soft-coated low-E panes
- Hard-coated low-E panes
- Absorbing solar control glass
- Reflecting solar control glass
- Anti-reflecting glazing
- Laminated combinations of the above

For the characterisation of the optical and thermal performance of a window the three main areas of interest are the determination of the thermal transmittance, the solar gain and the visible light transmittance of the window. The quantitative properties of interest are the overall heat loss coefficient (U-value in W/(m^2.K)), the total solar energy transmittance, termed the g-value, and the visible light transmittance (τ_v) . The centre-of-glass U-value is primarily driven by the emissivity of the coating(s) which determine the thermal radiative heat transfer. In conventional insulating glazing units (IGU) the U-value is also affected by the glass thickness, the distance between the respective glass panes (the gap width) and the gas which fills the gap. Air has the highest thermal conductivity of commonly used gases and argon is the most commonly used gas when windows with low U-values are constructed. The integrated optical properties of typical glazing combinations are illustrated in Table 1. A double glazed unit employing two sheets of uncoated clear float glass and an air gas fill will typically have a centre-of-glass U-value ~ 2.7 – 2.9 W/(m^2.K) which is half that of single glazing. In both cases however the solar gain is high.

The first generation of architectural solar control coatings were developed in the 1970's by depositing metal films on glass. Such coatings are often both highly absorbing and reflecting. These coatings attenuate solar transmittance at all incident wavelengths and are often dark in appearance with low values of visible transmittance requiring the need for artificial lighting. Infrared reflectance is moderate and hence the coating emissivity is relatively high, > 0.5, resulting in a window of relatively high U-value. Although far from optimum these simple solar control coatings continue to be manufactured today and are mostly used in commercial applications, e.g. offices, particularly in hot climates where air-conditioning also prevails. Such coatings are not the optimum choice for use in buildings where energy efficiency is a high priority. The spectral optical properties of such a coating (SS20) employed in a double glazed unit with the coating on the inside surface of the outer pane (Surface 2) is shown in Fig. 2.4.

2.4.1. Low-emissivity Solar Control Glass

Coated glass products with emissivity values less than 0.2 (low-e) are necessary to achieve unshaded glazing U-values below 2.0 W/(m^2.K). Two families of low-e products have been developed essentially based on the coating deposition process

1. Pyrolytic low-e, often termed “hard” coatings
2. Sputtered low-e, often termed “soft” coatings

The terms “hard” and “soft” refer to the relative durability and ease of handling of the coated product. Importantly the optical properties of the two families can be made to differ significantly and enable windows with low U-values to be manufactured with a wide range of solar gain and visible properties.

Glazing	**Gas Fill**	**τ_v**	**g_n**	**U (W/(m^2.K)**
Single	-	0.90	0.86	5.9
Double glazed unit (DGU)	Air	0.81	0.76	2.9
DGU, 1st generation solar control (SS20)	Air	0.18	0.25	2.5
DGU, low-e	Air	0.74-0.78	0.62-0.71	1.8 - 2.2
DGU, low-e pyrolytic heat mirror	Argon	0.75	0.72	1.9
DGU, low-e sputtered noble metal heat mirror	Argon	0.75	0.58	1.1
DGU, low-e sputtered noble metal heat mirror	Xenon	0.76	0.58	0.9
DGU, low-e sputtered solar control	Argon	0.66	0.34	1.2
Triple glazed unit, 2 low-e	Argon	0.62-0.67	0.49-0.58	0.8-1.1

Table 2.1 Thermal performance of unshaded insulating glazing units using low emissivity coatings. (τ_v = visible transmittance; g = total solar energy transmittance, U = thermal transmittance).

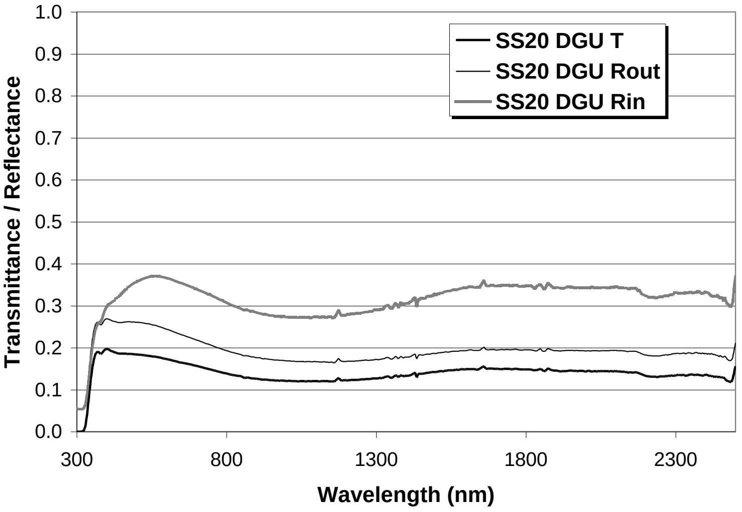


Figure 2.4 Spectral transmittance, T, outside reflectance, Rout, and inside reflectance, Rin, for SS20 : Clear 6-12-6 mm air-filled solar control DGU with coating on Position 2.

Approximately half of the incident solar energy is available in the visible spectral region and half in the near infrared. Modern low-e coatings are spectrally selective and provide the opportunity to design for the amounts of visible light required, the fraction of near infrared radiation in the incident solar energy to be rejected or admitted and the quantity of room heat to be retained.

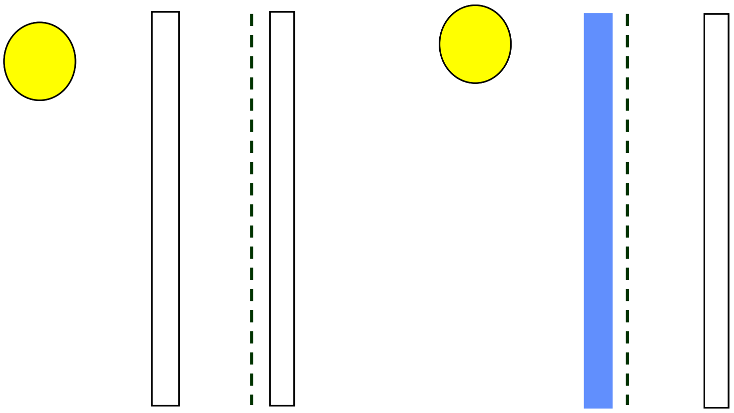
Pyrolytic low-e glazing is normally used where a low U-value is required in combination with high solar gain (passive solar design). The coating is normally located on Surface 3 of the double glazed unit (see Fig. 2.5.). This would often be the case in a heating dominated climate where solar gains can off-set some part of the heating demand. The high solar transmittance is however a disadvantage if it contributes to overheating the space and control through the use of a suitable shading strategy would need to be implemented.

In cooling dominated situations it is beneficial and desirable to reduce both the solar gain and the thermal loss. In a situation the ideal situation for limiting overheating is to use a glazing which is transparent in the visible region of the solar spectrum and reflective in the near infrared. This results in a glazing with moderate to good visible transmittance and low g (total solar energy transmittance). The coating is normally located on Surface 2 of the double glazed unit (see Fig. 2.5).

Such low-e solar control coatings are widely available in the modern market. The coatings employ thin silver films which form part of a multilayer coating. A “Single” silver coating has one silver film and a “Double” silver coating incorporates two layers of silver in the final coating. Triple silver coated glass products are now commercially available. The effect of increasing the number of silver coatings is to narrow the transmittance region of the product. The properties of single and double silver low-e solar control coatings and pyrolytic low-e are compared in Table 2.2 and Fig. 2.6 respectively (2.13).

Low-e Product	**Total solar energy gain** **g**	**Visible trans-mittance** **τ_v**	**τ_v:g ratio**	**U** **(W/(m^2.K))**
Pyrolytic low-e	High	High	≈1	1.6 – 1.9
Sputtered single silver	Moderate	High to Moderate	≥1 ≤1.5	1.4 – 1.5
Sputtered double silver	Lower	Moderate to Low	≈2	1.1 – 1.3

Table 2.2 Comparison of the relative total solar energy transmittance, visible transmittance and centre-of-glass U-value of glazings employing low emissivity coatings.



(a) High Solar Gain
(Coating on Surface 3)

(b) Low Solar Gain
(Coating on Surface 2)

Figure 2.5 Glazing configurations for (a) maximizing and (b) minimizing solar gain.

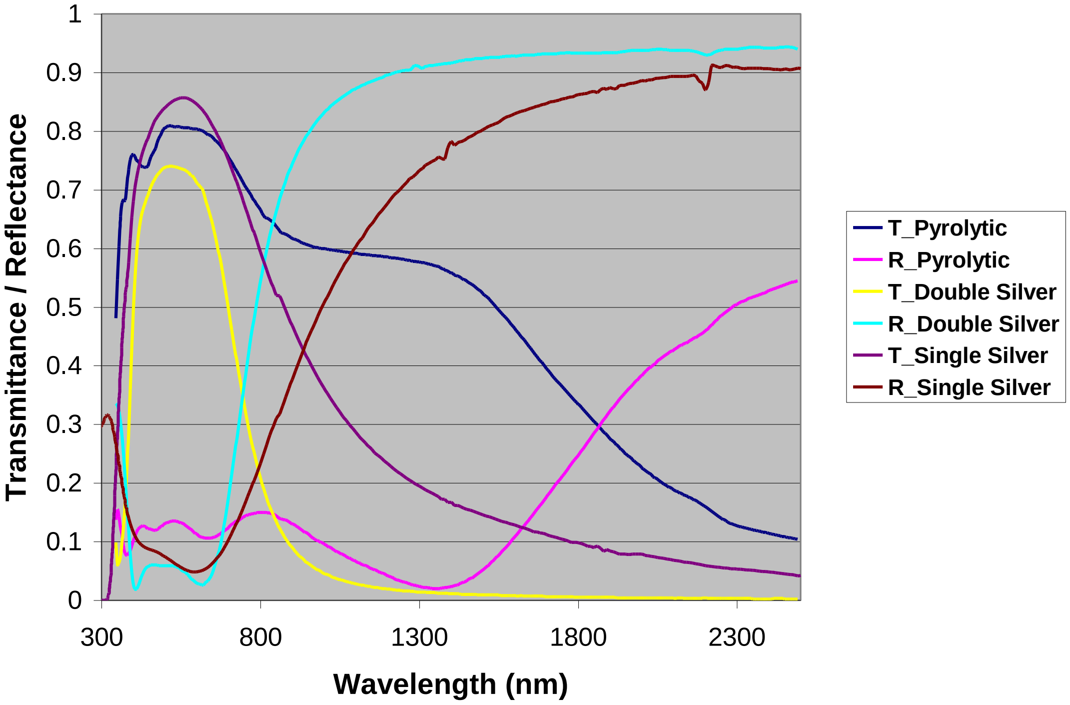


Figure 2.6 Comparison of the spectral transmittance and reflectance of pyrolytic, single silver and double silver low-emissivity coated glass showing the relative spectral selectivity for solar gain control (2.13).

3. Dynamic Solar Shading and Complex Glazing

"Complex Glazing" is defined herein as the combination and integration of a Glazing Unit together with a form of Solar Protection, e.g. shade, blind, curtain, shutter, overhang, awning etc.

Complex glazing permits dynamic control and the opportunity to significantly improve the energy performance and carbon footprint of buildings by contributing to the reduction of heating and cooling requirements with the resultant benefits of improved occupant comfort, reduced operating costs, energy use and greenhouse gas emissions. In addition, solar shading can promote improved thermal and visual comfort for building occupants.

The Complex Glazing challenge is to optimise heat flow depending on the season. In heating dominated periods or climates solar gain should be maximised whilst minimising thermal losses. In cooling dominated periods solar gains must be reduced and opportunities for the building to shed energy provided.

The solar shading industry offers a very wide range of products for external and internal shading options. The most common external products include roller blinds, drop arm awnings, Venetian slats and shutters. Roller blinds and Venetian slats are common internal shade products. Many other products can be employed as dynamic extendable and/or retractable solar protection or light directing devices. Other forms of shading may be static and non-retractable or permanently integrated, the latter includes sun protection foils. In addition to functional solar gain control, solar shading offers the potential for improved thermal insulation of the glazing system. Examples are low-emissivity shades, cellular shades which trap air in channels formed by the multilayers of shade material, and systems for ensuring more effective sealing of the shade to reduce air flow at the glazing interface can all improve the thermal resistance of the closed glazing system and reduce thermal losses. A comprehensive overview of solar shading system products which compares their relative performance is published by ES-SO (3.1).

The energy balance of the advanced facade is strongly dependent on the glazing and shade selection. Spectrally selective glazing integrated with solar shading affords efficient and dynamic control of energy gains and losses, whilst combating glare, maintaining visual comfort and the entry of daylight. Optimal use requires intelligent selection criteria embodying reliable methods to determine the energy performance of the dynamic façade and implementation by means of appropriate control (3.2). Solar shading is a smart component of the building envelope enabling control of energy from the outside to the inside or from the inside to the outside. Solar shading system control is challenging and sophisticated. Reliance on the user for traditional manual control efficiency can often be inefficient. The development of smart control strategies which reposition the solar shading system in response to the needs of the building is of the highest importance for effective operation of the dynamic façade (3.3).

4. The Energetic Performance of Shading Systems

For this ES-SO 2014 study all physical properties needed to determine the impact of shaded glazing systems on the energy performance of buildings are calculated in accordance with relevant current European norms and standards using prescribed methods and procedures.

The key physical properties necessary to characterise the energy performance of complex glazing employing dynamic solar shading systems and are determined from with regard to the relevant European standards. The EN standards relevant to solar shading are described below. Six unshaded reference glazings defined in these standards are identified. These reference glazings are used to benchmark potential energy savings for heating and cooling respectively in 4 different European cities, Rome, Brussels, Stockholm and Budapest which represent the climates of choice agreed with ES-SO for the purposes of this 2014 study.

A selection of shading product types is made based upon discussion and agreement with ES-SO. These shading types are representative of the market and exhibit the full range of performance which can presently be realised for both external and internal shading use. The optical and thermal characteristics of the complex glazing systems formed by combining these shading types with the 6 reference glazings are determined using the methods prescribed in the EN standards.

4.1. European Glazing and Shading Standards for Calculation of Energy Performance

The energetical performance of complex glazing is characterised from an understanding of the energy gains and energy losses, i.e. the energy balance at the window, in the presence of the glazing and its associated solar shading device.

The key performance parameters are

- The total solar energy transmittance, termed the g-value, which permits the determination of the solar energy gain through the window and includes any secondary gain arising from absorption;
- The thermal transmittance, or overall heat loss coefficient, termed the U-value (measured in W /(m^2.K)), which enables the calculation of the heat transfer through the window;

- The visible transmittance, τ_v, which provides information on the light distribution through and behind the window.

The total solar energy transmittance, g, and the visible light transmittance, τ_v, are fractions and hence dimensionless numbers in the range 0 – 1.

Other optical and thermal properties of interest include e.g. solar transmittance, solar reflectance, solar absorptance, visible reflectance, ultraviolet transmittance, colour rendering and emissivity. Such optical properties are most commonly determined from spectrophotometric measurements at the wavelengths of interest and detailed descriptions of the calculation methods employed to characterise the physical properties of such glazing and solar shading devices are given elsewhere (4.1, 4.2).

The relevant European Standards necessary to calculate the performance parameters of solar shading systems are listed below.

a) EN 410:2011 Glass in Building – Determination of luminous and solar characteristics of glazing (4.3).
b) EN 13363-1, Solar Energy and Light Transmittance through Glazing with Solar Protection Devices – Part 1, Simplified Calculation Method (4.4)
c) EN 13363-2, Solar Energy and Light Transmittance through Glazing with Solar Protection Devices – Part 2, Detailed Calculation Method (4.5)
d) EN 14500, Blinds and shutters – Thermal and visual comfort – Test and calculation methods (4.6)
e) EN 14501, Blinds and shutters – Thermal and visual comfort – Performance characteristics and classification (4.7)
f) EN 673:2011, Glass in Building. Determination of thermal transmittance (U-value). Calculation method (4.8)
g) EN ISO 10077-1:2006, Thermal performance of windows, doors and shutters – Calculation of thermal transmittance – Part 1: General. (4.9)
h) EN 13125 Shutters and blinds – Additional thermal resistance – Allocation of a class of air permeability to a product. (4.10)

A technical guidebook presenting the key elements of the relevant European solar shading standards has been published by ES-SO (4.11). A detailed comparative critique and appraisal of standards for solar optical properties of glazing materials has been made by Rubin (4.12).

EN 410 is an overarching standard which defines the calculation procedures required to determine all necessary ultraviolet, visible and solar optical properties of glazing systems. For a non-scattering insulated glazing unit which does not employ any form of shading device, the g value can be calculated precisely from the relevant integrated optical properties of the component panes using the methods prescribed. For scattering glazing systems the procedures of EN 410 do not directly apply although in many applications any necessary modifications or adaptations are commonly overlooked.

EN 14500 is a detailed measurement standard describing procedures for determining the necessary spectral total, diffuse and near-normal direct optical properties of shading materials.

The standards EN 14501, EN 13363-1 and EN 13363-2 enable the calculation of the total solar energy transmittance, g_{total}, of a complex glazing, i.e. a solar protection or shading system device, in combination with an unshaded glazing of known g- and U-values. The calculation procedures of the standards require knowledge of the integrated optical properties of the solar protection device, i.e. the blind, shading device etc. A weakness of these standards which remains to be rectified is that they claim to apply to diffuse materials as well as to specular materials and this is not yet the case.

EN 14501 addresses comfort-related parameters constructed from basic optical properties measured in accordance with EN 14500. These parameters include opacity, glare, privacy, visual contact, daylight, and colour rendition.

EN 13363-1 defines a simplified practical method for the calculation of total solar energy gain (g) which assumes that the optical properties of all components of the complex glazing system are known. Light and solar transmittance of combinations of glazing and shading are calculated with the specular glazing assumption which is not always reliable and accurate.

EN 13363-2 is a more complicated method than EN 13363-1 for determination of the g-value. derived directly from ISO 15099 (4.12). Calculations of the properties of slat shading systems from individual slat properties and combinations of glazing and shading-system layers are performed with an "energy balance" method .

EN 13125 permits calculation of the shaded glazing thermal transmittance, U, through the additional thermal resistance, ΔR, afforded by the shading device to the thermal resistance of the unshaded glazing. The additional thermal resistance, ΔR, accommodates material type and thermal conductivity, permeability and air tightness of the shade to glazing seal, and emissivity of the shading device. Classifications of air permeability are given for both external and internal shading positioning.

4.2. Complex Glazing Energy Performance Calculation Methods

In this study, and for the purpose of comparative methods only, the complex glazing g-value is calculated using the procedures of EN 13363-1 and the complex glazing thermal transmittance, U, is calculated using the recommended method of EN 13125.

4.2.1. Total solar energy transmittance, g, and Shading Coefficient

The total solar energy transmittance, g, is the measure of the total energy passing through the glazing when exposed to solar radiation, i.e. it is the direct measure of the solar gains. It is the sum of the solar transmittance, τ_s, and the secondary internal heat transfer factor q_i, i.e.

$$g = \tau_s + q_i$$

The solar transmittance, τ_s, is the fraction of the incident solar radiation that is directly transmitted by the glazing system, i.e. the solar radiation is transmitted without a change in wavelength. The solar transmittance may comprise both a direct component and a scattered, or diffuse, component.

The term q_i determines the inward flowing fraction which arises from absorption of solar radiation in the glazing and subsequent transfer to the inside of the enclosure by re-radiation at thermal wavelengths, conduction and convection.

In North America the g-value is termed the "Solar Heat Gain Coefficient" (SHGC) and in France it is referred to as the "Solar Factor" or the "Facteur Solaire".

The Shading Coefficient is derived by referencing the total solar energy transmittance of the glazing system to that of a clear float glass having a total solar energy transmittance of 0.87, which corresponds to float glass of thickness 3-4 mm. The Shading Coefficient is hence the total solar energy transmittance, g, of the fenestration system divided by 0.87.

In its simplest form one would seek to define the total solar energy transmittance of a glazing system, g_{system}, i.e. the combination of a glazing with total solar energy transmittance, $g_{glazing}$, and a shading device with total solar energy transmittance, $g_{shading}$ as the product of the two respective g values, i.e.

$$g_{system} = g_{glazing} \cdot g_{shading} \qquad [1]$$

This would enable the total solar energy transmittance of the shading device to be defined as

$$g_{shading} = \frac{g_{system}}{g_{glazing}} \qquad [2]$$

However this simple definition does not result in a unique value for the total solar energy transmittance of the shading device when used in combination with glazing units of different g values, $g_{glazing}$.

The matter is complicated since the glazing is essentially a static component whereas the shading device is a dynamic component which may at times be fully closed, fully open or at some intermediate position. Each position will result in a different value for g_{system}.

Under these circumstances it is necessary to specify the shading device performance in combination with the glazing with which it is to be used. It is neither sufficient nor correct to specify a unique value for the total solar energy transmittance of the shading device alone, i.e. we cannot define a unique value for $g_{shading}$.

The EN 13363-1 equations given below in the following sections are for the shade in the fully closed position. EN 13363-1 allows for a correction to be made to the near-normal shade optical properties to account for the use of Venetian slats when inclined at 45^0. These corrective equations based upon the near-normal optical properties of the shading device are also given. The solar and visible transmittance of combinations of glazing and shading are calculated assuming the specular glazing behaviour and this may not always be an accurate estimation.

4.2.2. Glazing with an internal shade

For a blind used internally, i.e. placed on the room side of the glazing, the total solar energy transmittance of the glazing / blind configuration, g_{system}, is calculated as

$$g_{system} = g(1 - g\rho_{SB} - \alpha_{SB}\ (\frac{\Lambda}{\Lambda_2})) \qquad [3]$$

where

g is the total solar energy transmittance of the glazing itself, i.e. without the blind
ρ_{sb} is the solar reflectance of the blind surface which faces the glazing
α_{sb} is the solar absorptance of the blind surface facing the glazing

$$\alpha_{SB} = 1 - \tau_{SB} - \rho_{SB} \quad [4]$$

Λ represents the effective heat transfer through the configuration defined as

$$\Lambda = (\frac{1}{U} + \frac{1}{\Lambda_2})^{-1} \quad [5]$$

where U is the thermal transmittance of the glazing without the blind and Λ_2 assumes the value 18 W/(m^2.K).

The space between the glazing and the internal blind is assumed to be open and ventilated.

It is evident that the optical property which enables incident solar radiation passing through the glazing to be rejected from the enclosure is the shade solar reflectance. Shades with high solar reflectance coupled with low solar transmittance and low solar absorptance will be most effective in limiting solar gain which has passed through the glazing.

Shade materials with high values of solar absorptance will experience a significant rise in temperature becoming a secondary source of thermal radiation and enhancing convective heat transfer.

Shades which have significant values of solar transmittance will be less effective at limiting solar gains as a proportion of the incident solar radiation transmitted by the glazing will pass through the blind.

4.2.3. Glazing with an external shade

For a blind used externally, i.e. located outside the glazing, the total solar energy transmittance of the glazing / blind configuration, g_{system}, is calculated as

$$g_{system} = \tau_{SB}\, g + \alpha_{SB} \frac{\Lambda}{\Lambda_2} + \tau_{SB}(1-g)\frac{\Lambda}{\Lambda_1} \quad [6]$$

where

$$\Lambda = (\frac{1}{U} + \frac{1}{\Lambda_1} + \frac{1}{\Lambda_2})^{-1} \quad [7]$$

and Λ_1 = 6 W/(m^2.K); Λ_2 = 18 W/(m^2.K).

4.2.4. Glazing with mid-pane blind

The total solar energy transmittance for the position of the blind between two glass panes is given by

$$g_{system} = g\tau_{SB} + g(\alpha_{SB} + (1-g)\rho_{SB}).\frac{\Lambda}{\Lambda_3} \quad [8]$$

where

$$\Lambda = (\frac{1}{U} + \frac{1}{\Lambda_3})^{-1} \quad [9]$$

and $\Lambda_3 = 3$ W/(m^2.K)

4.2.5. Optical properties correction for Venetian blinds

In the case of louver or Venetian blinds, the above material solar optical properties are used when the blind is in the closed position.

For blinds open to 45^0, the solar optical properties are corrected using the following

$$\tau_{SB}^{corr} = 0.65\tau_{SB} + 0.15\rho_{SB} \quad [10]$$

$$\rho_{SB}^{corr} = \rho_{SB}(0.75 + 0.70\tau_{SB}) \quad [11]$$

4.2.6. The thermal transmittance, U, and the EN 13125 calculation method

The U-value, or thermal transmittance, is defined as the (steady state) density of heat transfer rate per temperature difference between the environmental temperatures on each side of the glazing in the absence of solar radiation.

The U-value is measured using a hot-box, guarded hot plate or heat flow method but may be determined using the calculation method defined in EN 673. For the calculation for the transparent centre-of-glass part of the glazing, the U-value is defined as

$$\frac{1}{U} = \frac{1}{h_e} + \frac{1}{h_t} + \frac{1}{h_i} \quad [12]$$

where h_e and h_i are the external and internal heat transfer coefficients

The total thermal conductance h_t of the glazing is calculated as

$$\frac{1}{h_t} = \sum_{1}^{N} \frac{1}{h_s} + \sum_{1}^{M} d_j . r_j \quad [13]$$

where

h_s is the thermal conductance of each gas space
N is the number of spaces
d_j is the thickness of each material layer
r_j is the thermal resistivity of each material
M is the number of material layers

The thermal conductance of the gas space, h_s is given as

$$h_s = h_r + h_g \qquad [14]$$

where

h_r is the radiation conductance and h_g is the gas conductance
The radiation conductance is given by

$$h_r = 4\sigma\left(\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1\right)^{-1} T_m{}^3 \qquad [15]$$

σ is the Stefan-Boltzmann constant
T_m is the mean absolute temperature of the gas space
ε_1 and ε_2 are the corrected emissivities at T_m

To calculate the thermal transmittance, U, of a complex glazing employing an internal shade using the procedures of EN 13125 (16), an additional thermal resistance ΔR, which describes the air permeability, is added to the thermal resistance of the unshaded glazing determined in accordance with EN 673.

For external and internal blinds the air permeability, P_e, is determined as a function of the width of peripheral gaps, e_1 , e_2 and e_3 and the openness factor of the shade, p.

$P_e = e_{tot} + 10p$ [16]

where p is the openness factor, a measure of the direct-direct normal visible transmittance of the shade, and

$e_{tot} = e_1 + e_2 + e_3$ [17]

The EN 13125 classification of additional thermal resistance of shutters and blinds for the respective defined air permeability categories is presented in Table 4.1.

Air Permeability Class	Shutter Thermal Resistance (m^2.K/W)	External Blind Thermal Resistance (m^2.K/W)	Internal Blind Thermal Resistance (m^2.K/W)
1	$\Delta R = 0.08$ (Very high permeability)	$\Delta R = 0.08$ (Very high permeability)	$\Delta R = 0.08$ (Very high permeability)
2	$\Delta R = 0.25R_{sh} + 0.09$	$\Delta R = 0.11$ (Average)	$\Delta R = 0.11$ (Average)
3	$\Delta R = 0.55R_{sh} + 0.11$ (Average)	$\Delta R = 0.14$ (Low)	$\Delta R = 0.14$ (Low)
4	$\Delta R = 0.8R_{sh} + 0.14$		
5	$\Delta R = 0.95R_{sh} + 0.17$ (Air tight)		

Table 4.1. EN 13125 air permeability classification and additional thermal resistance of shutters and blinds (4.10).

The additional thermal resistance of the shade, ΔR, is multiplied by the term k, where

$$k = 1 + 1.54(1 - \frac{\varepsilon}{0.9})^2 \qquad [18]$$

and ε is the emissivity of the shade side facing the glazing.

The complex glazing U-value, U', is then calculated as

$$U^{'} = [(\frac{1}{U}) + \Delta R]^{-1} \qquad [19]$$

where U is the appropriate thermal transmittance of the unshaded reference glazing.

4.2.7. The visible transmittance, τ_v

The visible transmittance is calculated using the relative spectral power distribution D_λ of illuminant D_{65} (4.12) multiplied by the spectral sensitivity of the human eye V(λ) and the spectral bandwidth Δλ.

Measurements are made of the spectral transmittance, τ(λ), and the visible transmittance, τ_V, is then calculated using a weighted ordinate method according to EN 410 using the relationship:

$$\tau_\upsilon = \frac{\int\limits_{\lambda=380nm}^{780nm} D_\lambda \tau(\lambda) V(\lambda) d\lambda}{\int\limits_{\lambda=380nm}^{780nm} D_\lambda V(\lambda) d\lambda} = \frac{\sum\limits_{\lambda=380nm}^{780nm} D_\lambda \tau(\lambda) V(\lambda) \Delta\lambda}{\sum\limits_{\lambda=380nm}^{780nm} D_\lambda V(\lambda) \Delta\lambda} \qquad [20]$$

EN 13363-1 defines the following equations to determine the total light transmittance and the direct solar transmittance. Eqs. [21] and [22] can be used for both internal and external blinds when used in combination with a glazing.

$$\tau_{v,total} = \frac{\tau_v \cdot \tau_{vB}}{1 - \rho_v \cdot \rho_{vB}} \qquad [21]$$

$$\tau_{S,total} = \frac{\tau_S \cdot \tau_{SB}}{1 - \rho_S \cdot \rho_{SB}} \qquad [22]$$

where

τ_v is the visible transmittance of the glazing
τ_{vB} is the visible transmittance of the blind
ρ_v is the visible reflectance of the side of glazing facing the blind
ρ_{vB} is the visible reflectance of the side of the blind facing the glazing
τ_S is the solar transmittance of the glazing
τ_{SB} is the solar transmittance of the blind
ρ_S is the solar reflectance of the side of glazing facing the blind
ρ_{SB} is the solar reflectance of the side of the blind facing the glazing

For mid-pane blinds the methods for multiple glazing defined in EN 410 are to be used (4.3).

4.3. The unshaded reference glazings of EN 13363-1 and EN 14501

With respect to solar shading, the European Norms EN 14501 (4.7) and EN 13363-1 (4.4) define the physical properties of unshaded reference glazings intended to permit product comparisons of shutters, external blinds and internal blinds. The 6 relevant reference unshaded glazings taken from these EN standards are identified in Table 4.2.

Glazing ID	Glazing Type	European Standard	Total solar energy transmittance, g	Thermal transmittance U (W/(m^2.K))
A	Single clear glass	EN 14501	0.85	5.8
B	Double clear glass	EN 14501	0.76	2.9
C	Heat Control	EN 14501	0.59	1.2
D	Solar Control	EN 14501	0.32	1.1
E	Triple clear glass	EN 13363-1	0.65	2.0
F	Double clear glass with low-E coating	EN 13363-1	0.72	1.6

Table 4.2. Glazing identities and values of the total solar energy transmittance, g, and the thermal transmittance, U, of the unshaded reference glazings of EN 14501 (4.7) and EN-13363-1 (4.4).

The respective total solar energy transmittance, g, and thermal transmittance, U, of the 6 unshaded reference glazings of the European norms EN 14501 and EN 13363-1 are compared in Fig. 4.1.

4.4. Optical Properties of Representative Solar Shading Materials

Optical properties data are known for very many solar shading materials and can be obtained from different public domain databases (4.13., 4.14).

From these databases and using measurements made directly by Sonnergy Ltd, a selection was made to represent a meaningful range of the physical properties exhibited by current shading products. These products represent roller blinds, drop arm awnings, Venetian slats and shutters which may be employed either as external or internal shading attachments.

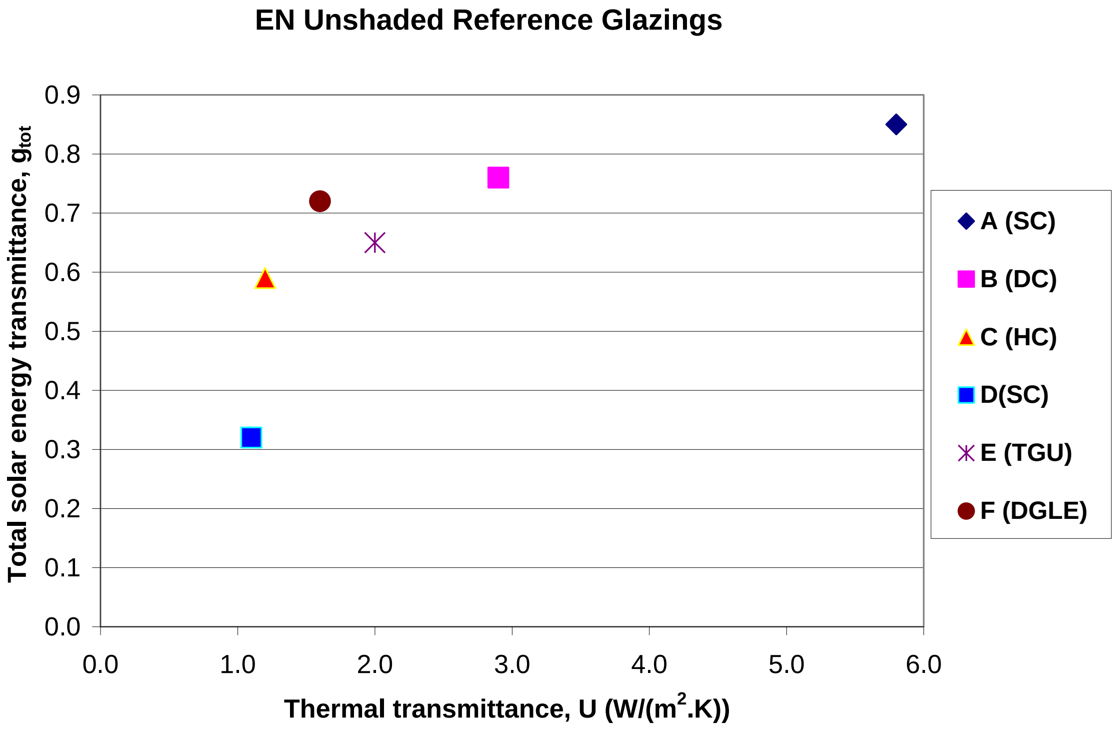


Figure 4.1. Total solar energy transmittance, g, and thermal transmittance, U, of the 6 reference glazings of the European norms EN 14501 and EN 13363-1.

4.4.1. External Shading: Dynamic Range of Total Solar Energy Transmittance, g_{total}

The dynamic range of the total solar energy transmittance of complex glazing systems formed by combining the representative external solar shading types with the reference glazings of EN 14501 and EN 13363-1 are shown in Fig 4.2. The g-values are calculated for the respective fully closed shaded glazing using the procedures of EN 14501 for the shades in combination with all 6 EN reference glazings.

4.4.2. Internal Shading: Dynamic Range of Total Solar Energy Transmittance, g_{total}

The dynamic range of the total solar energy transmittance of complex glazing systems formed by combining the representative internal solar shading types with the reference glazings of EN 14501 and EN 13363-1 are shown in Fig 4.3. Again the g-values are calculated for the respective fully closed shaded glazing using the procedures of EN 14501 for the shades in combination with all 6 of the EN 14501 and EN 13363-1 reference glazings.

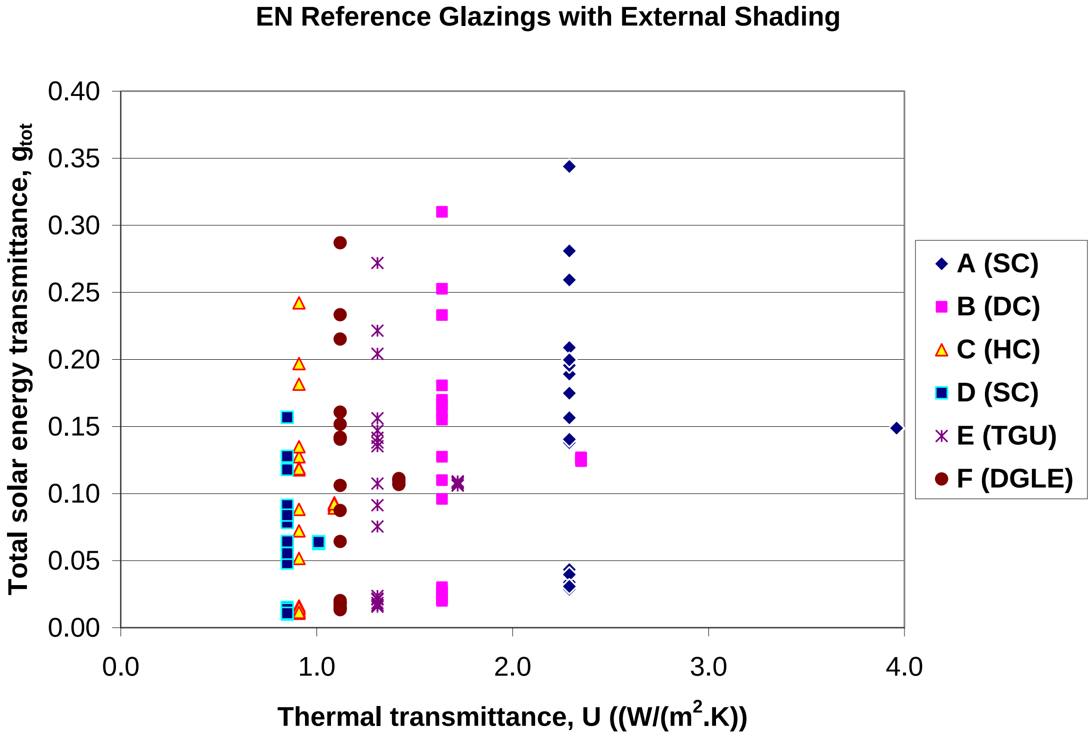


Figure 4.2. The impact of external shading products on the total solar energy transmittance of the 6 EN 14501 and EN 13363-1 reference glazings.

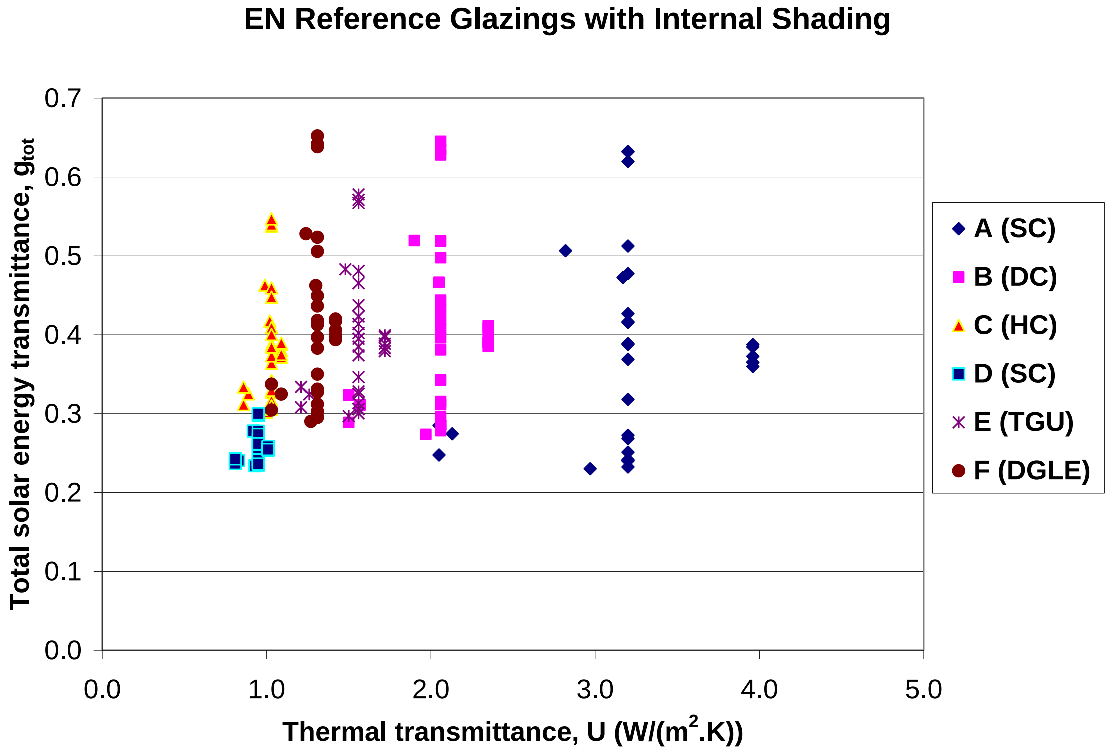


Figure 4.3. The impact of internal shading products on the total solar energy transmittance of the 6 6 EN 14501 and EN 13363-1 reference glazings.

4.4.3. Dynamic Range of Shaded Glazing Thermal Transmittance, U

The thermal transmittance, U, the shaded glazing is calculated using the procedures of EN 13125 which allows an allocation of different air permeability classes expressed from geometrical considerations of the total side of the air gap between the shade and the glazing, i.e. the tightness of the seal, the influence of shade emissivity and the openness factor, or the openness coefficient, C_o, as defined in EN 14500 (4.6).

The influence of the shade on the thermal transmittance of the double glazed low-e EN reference glazing F on shade emissivity for given categories of air permeability for an external shade is illustrated in Figure 4.4.

The influence of the shade on the thermal transmittance of the single clear, double clear and double glazed low-e EN reference glazings A, B and F on shade emissivity for given categories of air permeability for an internal shade is illustrated in Figure 4.5.

It is evident that the potential impact of the shade on the thermal transmittance of the complex glazing with the shade in the fully closed position can be very significant and is strongly dependent on air permeability, i.e. tightness of the seal, the thermal resistance of the shade product itself, the shade emissivity and the openness.

The impact on reduced thermal transmittance is greatest for those unshaded glazings which have the lowest thermal resistance, i.e. single clear (A) and double clear (B) glazing. For the shade incombination with insulated glazing units with low U-values, the relative impact of the shade is reduced.

Tables 4.3 and 4.4 illustrate the dependence of thermal transmittance, U, on air permeability and shade emissivity for externally shaded glazings for the respective cases of EN Reference Glazing C Heat Control and EN Reference Glazing B Double Clear respectively.

To investigate the impact of solar shading on the energy performance of buildings for both heating and cooling, highest and lowest values of total solar energy transmittance, g, and thermal transmittance, U, were chosen and four combinations of g and U generated for each reference glazing to create sets of shade quality. Each set of g and U define the range of energy related performance from “high” to “low” parameters. This approach mirrors that adopted in the recent “Energy Savings from Window Attachments” study undertaken by the Lawrence Berkeley National Laboratory in the USA (4.15). The total solar energy transmittance, g, and thermal transmittance, U, of the “high” and “low” sets of shade quality by reference glazing are shown in Table 4.5.

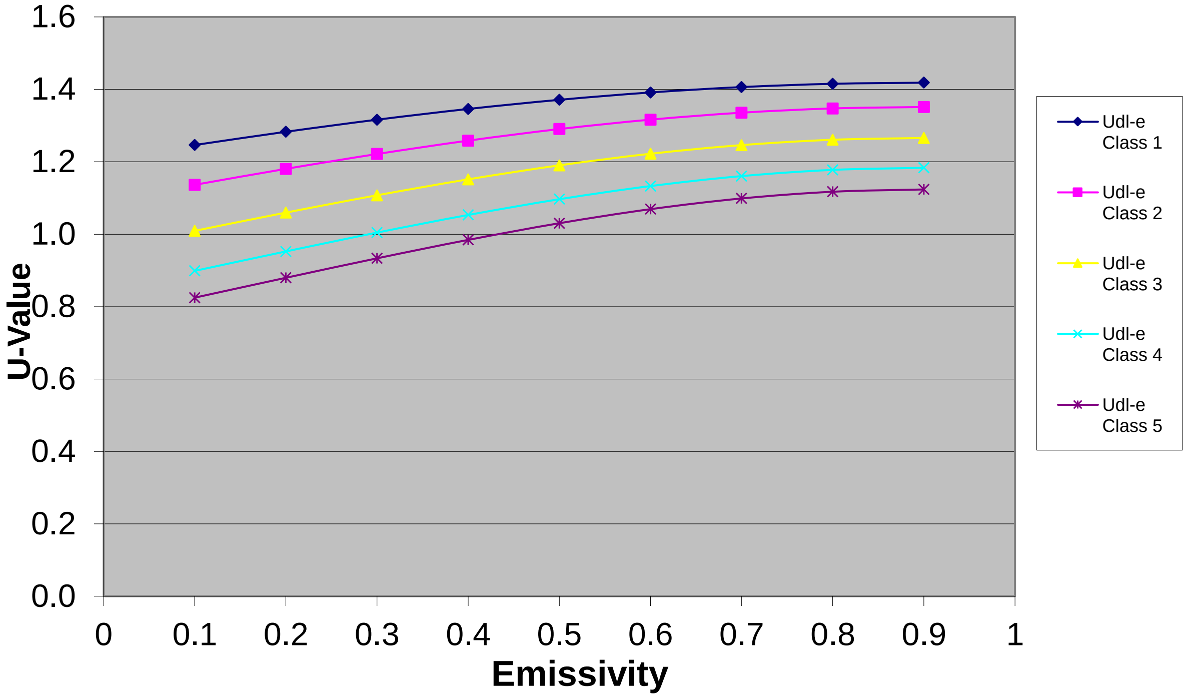


Figure 4.4 Influence on the thermal transmittance of the double glazed low-e EN reference glazing F on shade emissivity for given classes of air permeability for an external shade.

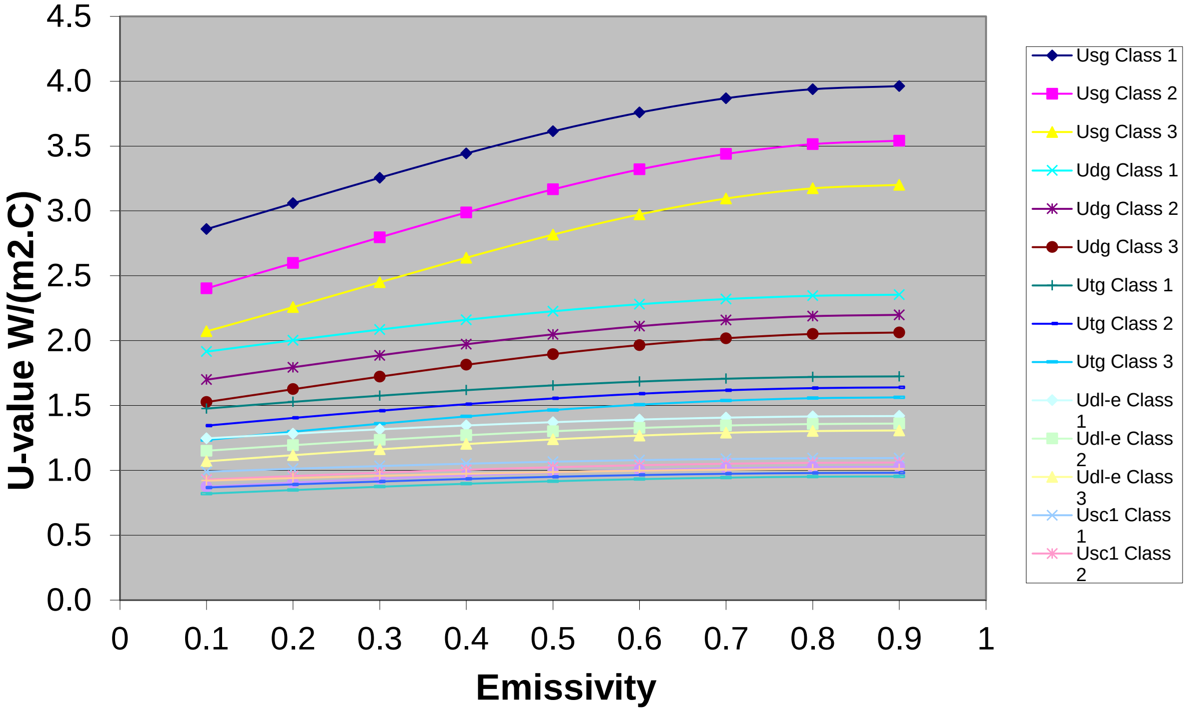


Figure 4.5 Influence on the thermal transmittance of single clear, double clear and double glazed low-e EN reference glazings A, B and F EN on shade emissivity for given classes of air permeability for an external shade.

F Double Clear Low-e				
Udl-e Class 1	Udl-e Class 2	Udl-e Class 3	Udl-e Class 4	Udl-e Class 5
1.25	1.14	1.01	0.90	0.82
1.28	1.18	1.06	0.95	0.88
1.32	1.22	1.11	1.00	0.93
1.35	1.26	1.15	1.05	0.98
1.37	1.29	1.19	1.10	1.03
1.39	1.32	1.22	1.13	1.07
1.41	1.34	1.25	1.16	1.10
1.42	1.35	1.26	1.18	1.12
1.42	1.35	1.27	1.18	1.12

Table 4.3. EN 13125 : Influence of shade permeability and emissivity on the U-value in W/(m2.K) of an externally shaded glazing – Glazing F Double Clear Low-e.

B Double Glazing				
Udg Class 1	Udg Class 2	Udg Class 3	Udg Class 4	Udg Class 5
1.92	1.67	1.41	1.20	1.07
2.00	1.76	1.51	1.30	1.17
2.09	1.86	1.61	1.40	1.26
2.16	1.94	1.70	1.49	1.36
2.23	2.02	1.79	1.58	1.45
2.28	2.09	1.86	1.66	1.53
2.32	2.13	1.91	1.72	1.59
2.35	2.16	1.95	1.76	1.63
2.35	2.17	1.96	1.77	1.64

Table 4.4. EN 13125 : Influence of shade permeability and emissivity on the U-value in W/(m2.K) of an externally shaded glazing – Glazing B Double Clear.

Reference Glazing	g Unshaded	U Unshaded W/(m^2.K)	g Shaded	U Shaded W/(m^2.K)	Run-Code
A: Single Clear	0.85	5.80	0.34	3.96	A-1-1
			0.34	1.32	A-1-5
			0.14	3.96	A-2-1
			0.14	1.32	A-2-5
B: Double Clear	0.76	2.90	0.32	2.35	B-1-1
			0.32	1.07	B-1-5
			0.02	2.35	B-2-1
			0.02	1.07	B-2-5
C: Heat Control	0.59	1.20	0.25	1.09	C-1-1
			0.25	0.70	C-1-5
			0.02	1.09	C-2-1
			0.02	0.70	C-2-5
D: Solar Control	0.32	1.10	0.16	1.01	D-1-1
			0.16	0.67	D-1-5
			0.01	1.01	D-2-1
			0.01	0.67	D-2-5
E: Triple Clear	0.65	2.00	0.27	1.72	E-1-1
			0.27	0.92	E-1-5
			0.02	1.72	E-2-1
			0.02	0.92	E-2-5
F: Double Clear Low-e	0.72	1.60	0.29	1.42	F-1-1
			0.29	0.82	F-1-5
			0.01	1.42	F-2-1
			0.01	0.82	F-2-5

Table 4.5 Total solar energy transmittance, g, and thermal transmittance, U, of the “high” and “low” sets of shade quality by reference glazing.

5. The Impact of Solar Shading on the Energy Performance of Buildings

5.1. The present study

In the present study both cooling energy and heating energy savings which are realisable through the efficient and effective deployment and control of dynamic solar shading systems are investigated.

Cooling energy savings are estimated using a modified window energy balance model validated by Karlsson et al (5.1). The model takes into account the U-value, g-value and angle dependent characteristics of the window. Hourly resolved climate data are used. The building type is considered through a balance temperature and there is the capability to model thermal mass through lightweight, medium weight and heavy weight buildings. The energy saving potential depends on both building and climate and there is not the scope here to investigate all possible relevant combinations for residential, commercial and other buildings. The energy balance approach represents a reasonable and meaningful compromise to benchmark potential savings and benefits that can accrue from differing dynamic shading solutions.

Heating energy savings are estimated using a steady-state monthly mean daily method validated by van Dijk et al, and incorporated into the ISO 13790 standard (5.2, 5.3). Calculation of the energy needs for heating in warm, moderate and cold European climates are demonstrated.

The estimation of cooling and heating energy savings is made for 4 European city climates previously used in an earlier ES-SO ESCORP study (1.5). The cities are Rome, Brussels, Stockholm and Budapest. Calculations are made for a medium weight building. Further simulations may be undertaken once European reference buildings, currently under development, are fully realised (5.4, 5.5).

For the present study, the benchmarks for the simulations are the 6 unshaded reference glazings of the respective EN Standards EN 14501 and EN 13363-1 as defined in Table 4.2.

The dynamic range of the total solar energy transmittance, g, and the thermal transmittance, U, of the complex glazing investigated for (i) external and (ii) internal deployment formed by combining the selected shadings of Section 4.4 and the reference glazings of Section 4.3 are determined by calculating complex glazing energy gain and energy loss coefficients using the defined procedures of EN 14501 and EN 13125 respectively as described in Section 4.2.

Calculations are made to predict maximum, minimum and mean potential cooling and heating energy savings in each of the 4 locations and in each case the associated control strategy employed is identified.

The base case house with the default glazing B, Double Clear, is defined in Table 5.1.

Dimension	10.0 x 2.7 x 10.0 m^3
Wall U-value	0.35 W/(m^2.K)
Glazing U-value	2.90 W/(m^2.K)
Glazing g	0.76
Frame U-value	2.2 W/(m^2.K)
Ventilation and infiltration	0.5 ach
Glazing to Wall Area	20%
Window orientation	Equal to all orientations
Internal gains	2000 kWh/yr
Heating set point	20 ^{0}C
Cooling set point	25 ^{0}C

Table 5.1 Default base case building parameters for cooling and heating calculations.

5.2. Space Cooling Energy

Cooling energy savings are estimated using a modified window energy balance model validated by Karlsson et al (5.1). Four combinations of g and U, selected as defined in Table 4.5 of the "high" and "low" sets of shade quality, represent the full range of performance of the dynamic shading system to be deployed with each of the 6 reference glazings. The combinations allow for the respective combinations of high and low total solar energy transmittance with high and low thermal transmittance, i.e. (i) low g, low U; (i) low g, high U; (i) high g, low U; (i) high g, high U, for the respective glazing/solar shading combinations. This approach is analogous to the categorisation of "product qualities" undertaken in the US study to estimate energy savings from window attachments (4.15).

5.2.1. Unshaded Glazing Benchmarks

With respect to glazing area, the mean annual cooling energy balance, P, in kWh/m^2/yr of the 6 unshaded EN reference glazings by each of the 4 city locations is shown in Table 5.2. These data are shown graphically in Figure 5.1. The dependence of the cooling energy balances on the orientation of the respective vertical façades for each of the 4 locations by reference glazing are shown in Figs 5.2 -5.5 inclusive. In all cases the largest cooling energy requirements are for the South-West and West orientations.

Unshaded glazing cooling energy demand is reference by comparison to the performance of unshaded clear double glazing (Glazing B). The mean cooling energy benefits, Psav, by location are shown in Table 5.3 and in Figure 5.6. The maximum and minimum cooling energy benefits, Psav, by location are shown in Tables 5.4 and 5.5 and the dependence for each of the 8 orientations are shown for Rome, Brussels, Stockholm and Budapest in Figures 5.7 - 5.10 respectively. The data clearly demonstrate the importance of glazing selection in lowering cooling demand which is dominated by the level of solar gain. The 2 reference glazings with the lower total solar energy transmittance, Glazing C Heat Control and Glazing D Solar Control, outperform the other 4 glazings and the best performance is seen for Glazing D which has the lowest unshaded g-value of 0.32.

Glazing ID	Glazing	Rome P (kWh/m²/yr)	Brussels P (kWh/m²/yr)	Stockholm P (kWh/m²/yr)	Budapest P (kWh/m²/yr)
A	Single Clear	-333.3	-113.3	-74.7	-181.4
B	Double Clear	-277.0	-97.7	-65.7	-153.2
C	Heat Control	-206.7	-74.3	-50.5	-115.2
D	Solar Control	-115.2	-40.7	-27.4	-63.8
E	Triple Clear	-227.7	-80.9	-54.7	-126.3
F	Double Clear Low-e	-253.2	-90.8	-61.6	-141.0

Table 5.2 Mean cooling energy balance, P, of the unshaded reference glazings by location.

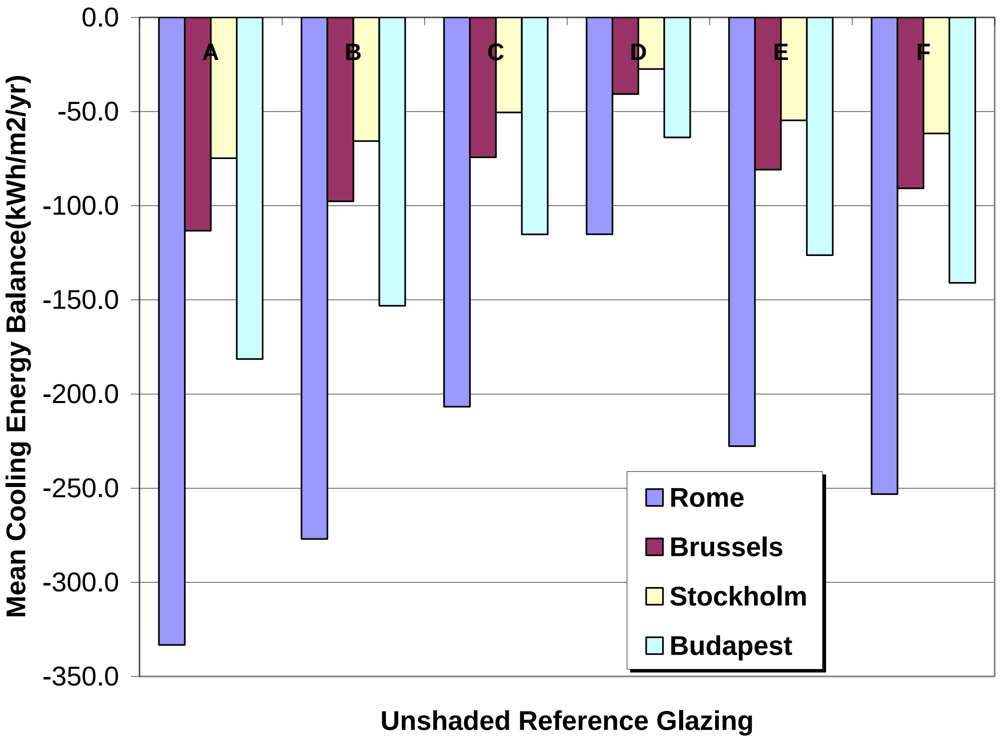


Figure 5.1 Mean cooling energy balance of the 6 unshaded EN reference glazings by location.

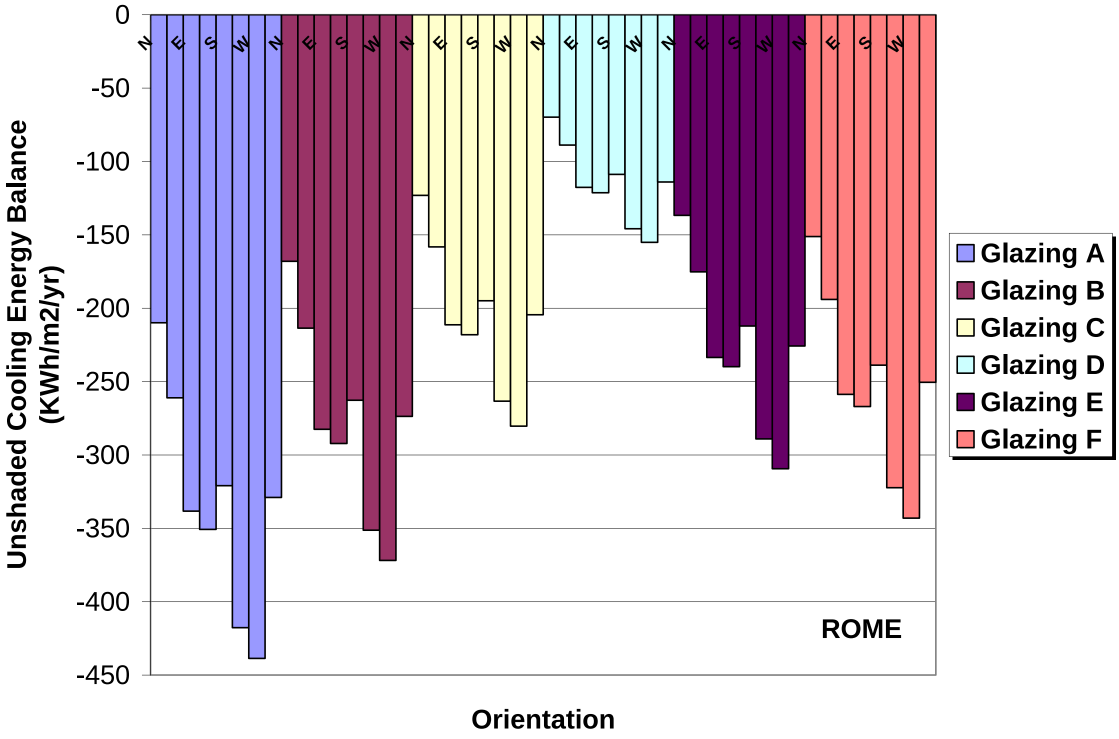


Figure 5.2 Unshaded cooling energy balance of the 6 EN reference glazings by orientation and location: Rome.

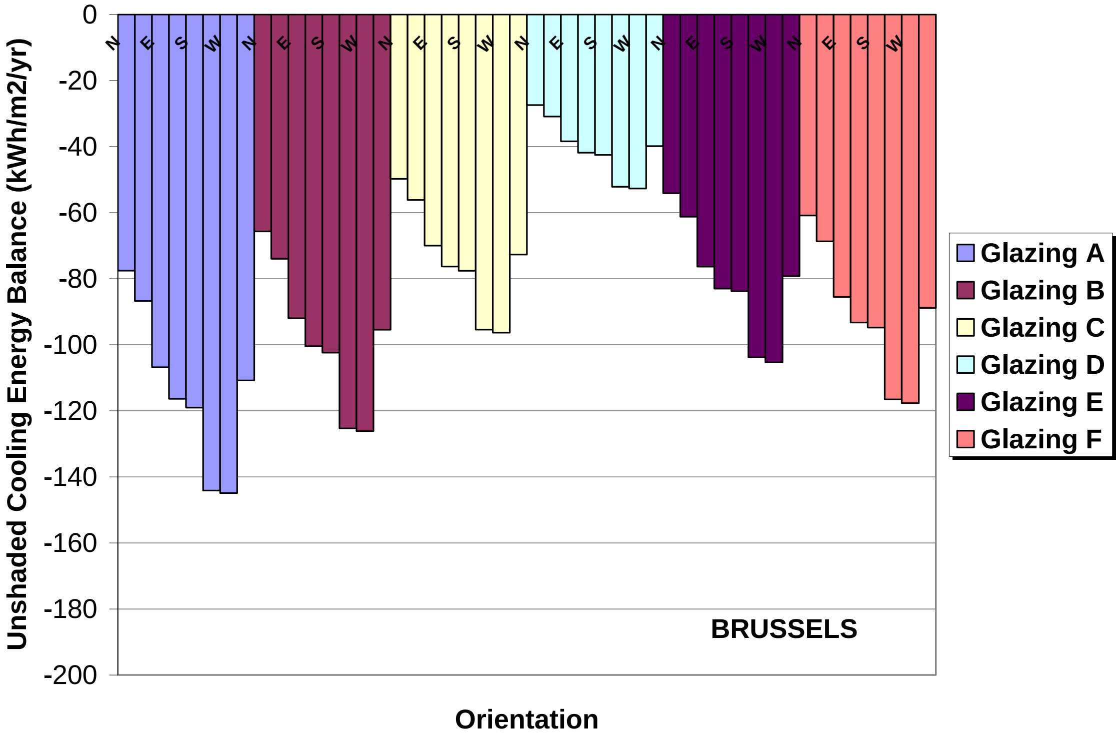


Figure 5.3 Unshaded cooling energy balance of the 6 EN reference glazings by orientation and location: Brussels.

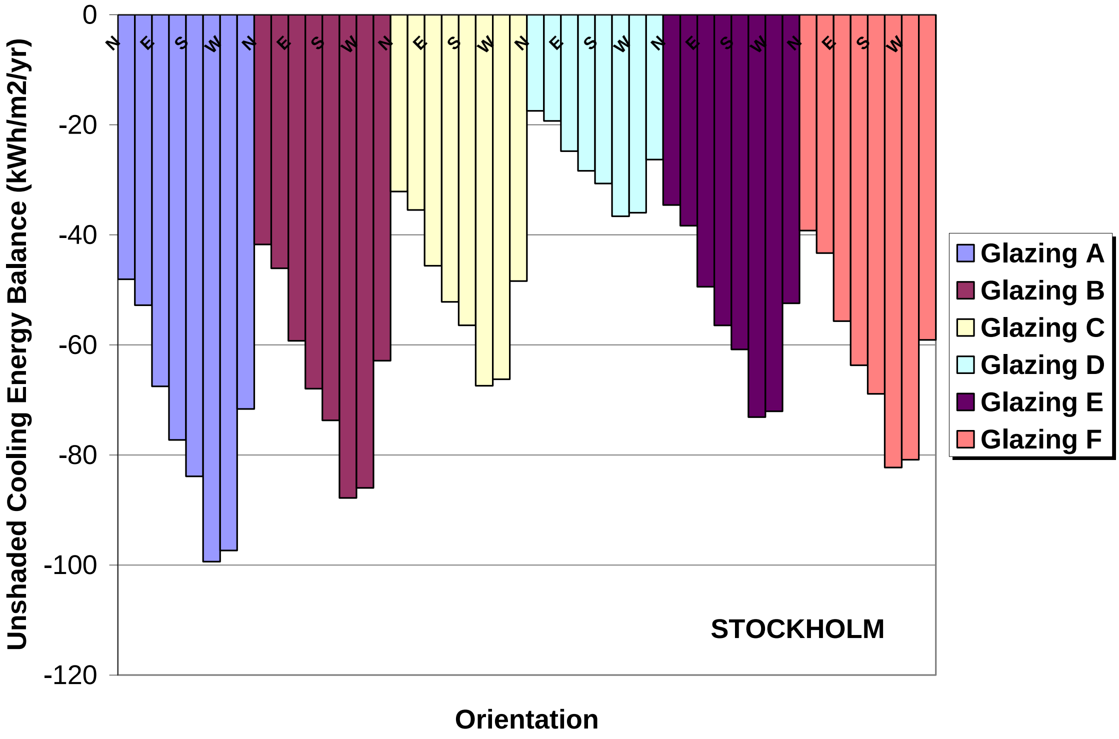


Figure 5.4 Unshaded cooling energy balance of the 6 EN reference glazings by orientation and location: Stockholm.

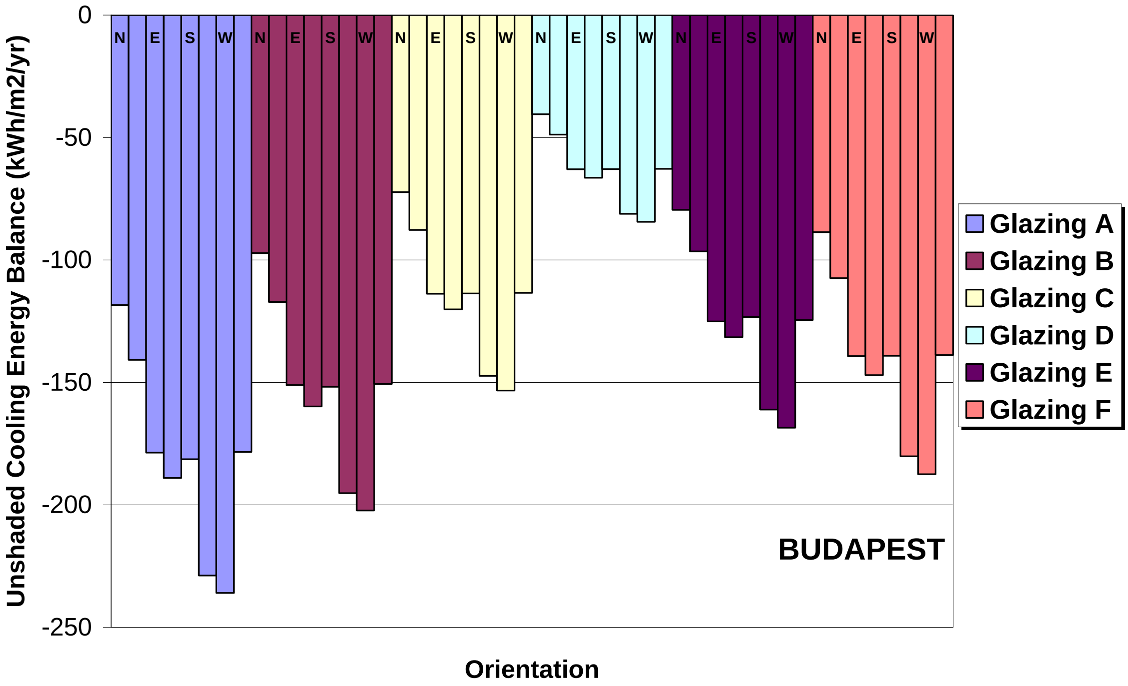


Figure 5.5 Unshaded cooling energy balance of the 6 EN reference glazings by orientation and location: Budapest.

Glazing ID	Glazing	Rome P (kWh/m²/yr)	Brussels P (kWh/m²/yr)	Stockholm P (kWh/m²/yr)	Budapest P (kWh/m²/yr)
A	Single Clear	-56.3	-15.6	-9.1	-28.3
B	Double Clear	0.0	0.0	0.0	0.0
C	Heat Control	70.3	23.4	15.2	37.9
D	Solar Control	161.8	57.0	38.2	89.4
E	Triple Clear	49.3	16.8	11.0	26.9
F	Double Clear Low-e	23.8	6.9	4.1	12.2

Table 5.3 Unshaded mean cooling energy benefit, Psav, of the reference glazings relative to clear double glazing (Glazing B) by location.

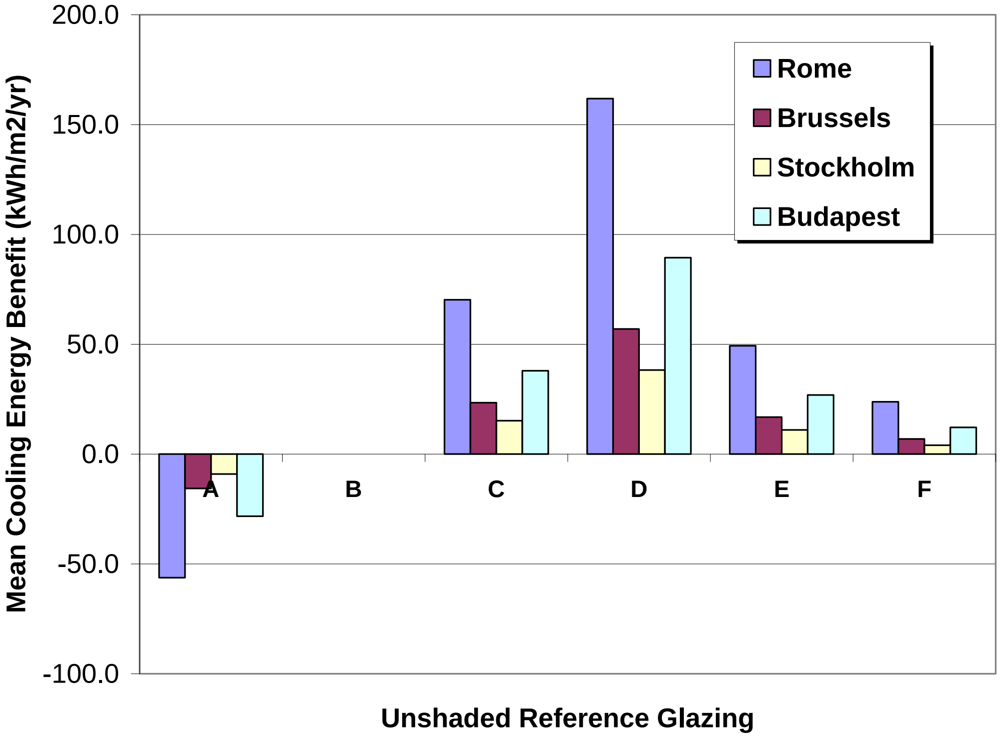


Figure 5.6 Unshaded mean cooling energy benefit, Psav, of the reference glazings relative to clear double glazing (Glazing B) by location

Glazing ID	Glazing	Rome P (kWh/m²/yr)	Brussels P (kWh/m²/yr)	Stockholm P (kWh/m²/yr)	Budapest P (kWh/m²/yr)
A	Single Clear	-66.7	-18.8	-11.6	-33.7
B	Double Clear	0.0	0.0	0.0	0.0
C	Heat Control	91.6	29.9	20.4	49.0
D	Solar Control	216.8	73.5	51.2	117.9
E	Triple Clear	62.5	20.8	14.7	34.1
F	Double Clear Low-e	29.0	8.8	5.5	15.1

Table 5.4 Maximum cooling energy benefit, Psav, of the unshaded reference glazings relative to clear double glazing (Glazing B) by location.

Glazing ID	Glazing	Rome P (kWh/m²/yr)	Brussels P (kWh/m²/yr)	Stockholm P (kWh/m²/yr)	Budapest P (kWh/m²/yr)
A	Single Clear	-41.9	-11.9	-6.3	-21.3
B	Double Clear	0.0	0.0	0.0	0.0
C	Heat Control	44.9	15.9	9.6	24.9
D	Solar Control	98.2	38.3	24.3	56.7
E	Triple Clear	31.3	11.6	7.2	17.7
F	Double Clear Low-e	16.8	4.8	2.5	8.6

Table 5.5 Minimum cooling energy benefit, Psav, of the unshaded reference glazings relative to clear double glazing (Glazing B) by location.

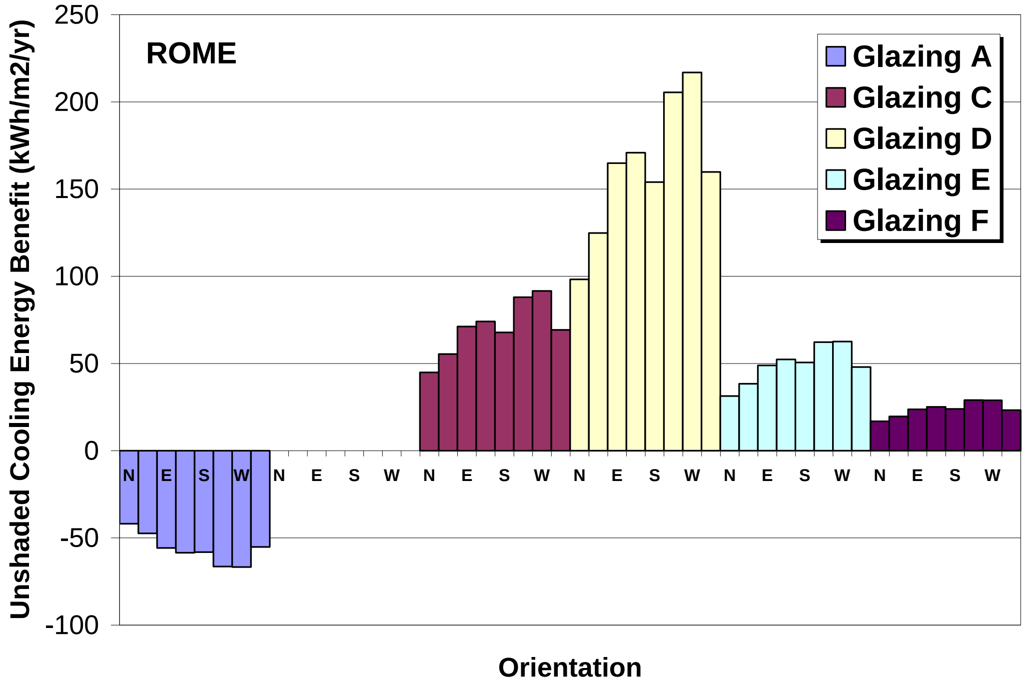


Figure 5.7. Unshaded cooling energy benefit, Psav, of the reference glazings relative to clear double glazing (Glazing B) by orientation : Rome.

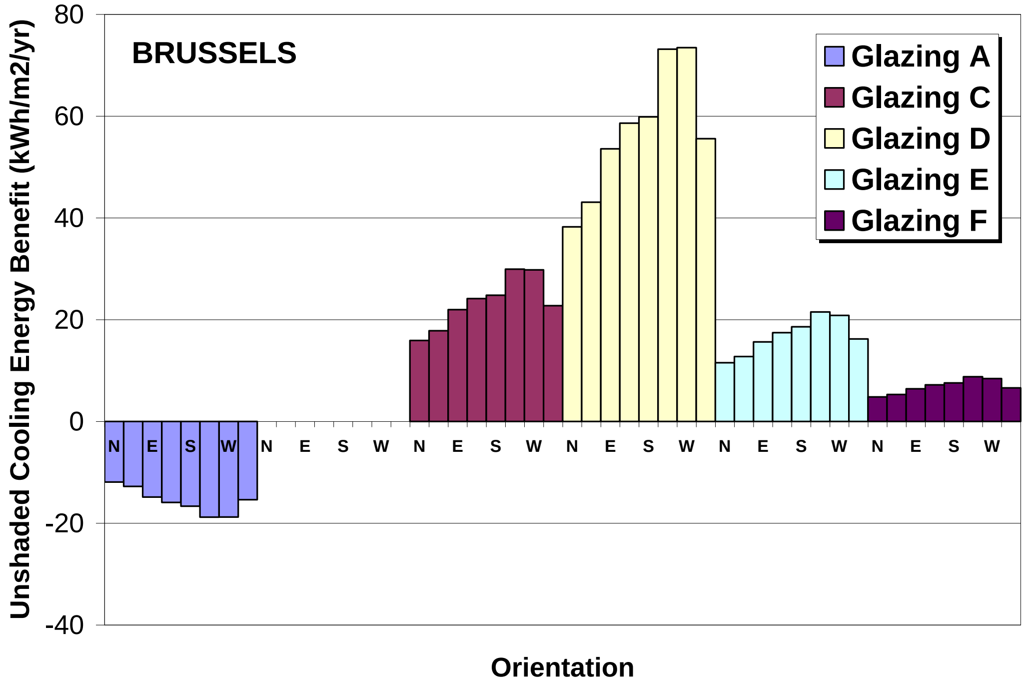


Figure 5.8 Unshaded cooling energy benefit, Psav, of the reference glazings relative to clear double glazing (Glazing B) by orientation : Brussels.

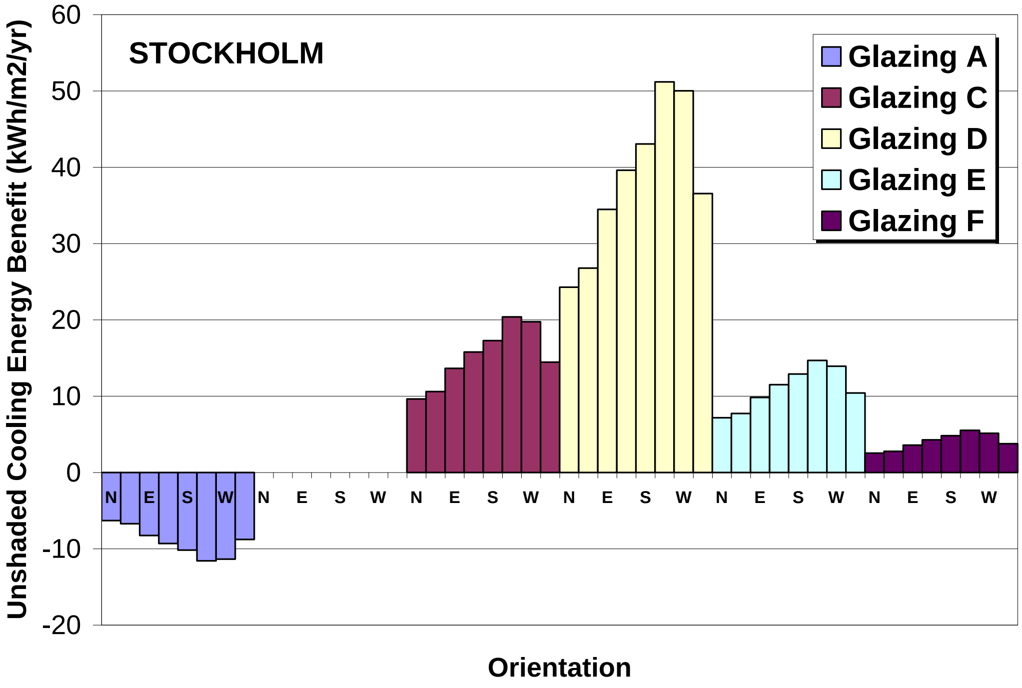


Figure 5.9 Unshaded cooling energy benefit, Psav, of the reference glazings relative to clear double glazing (Glazing B) by orientation : Stockholm.

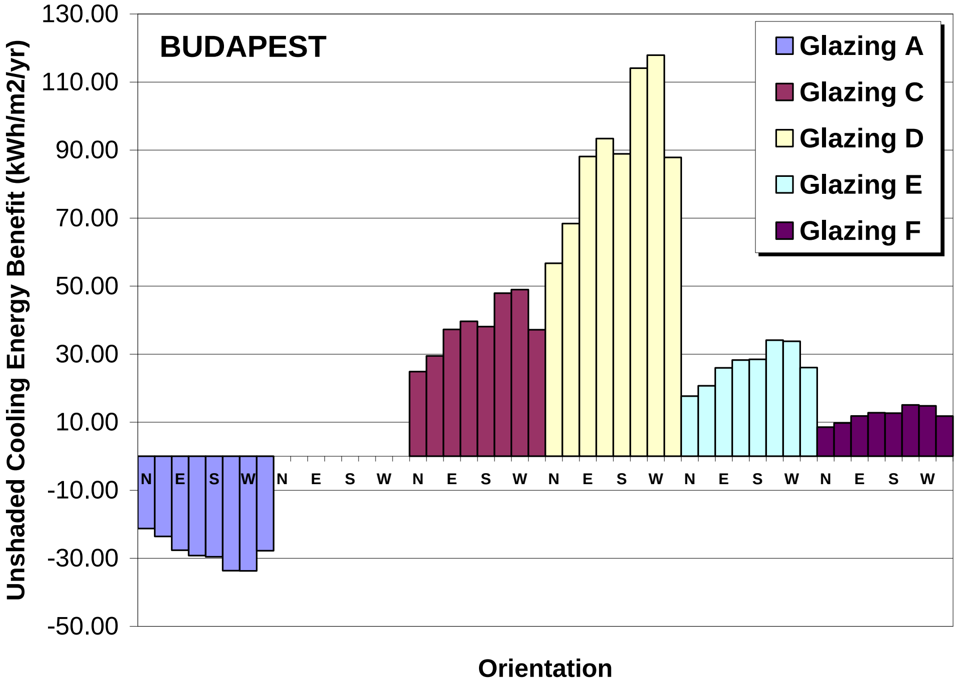


Figure 5.10 Unshaded cooling energy benefit, Psav, of the reference glazings relative to clear double glazing (Glazing B) by orientation : Budapest.

5.2.2. Optical and thermal properties of the shaded glazing systems

The 24 combinations of high and low total solar energy transmittance with high and low thermal transmittance enable the influence of dynamic shading on cooling energy savings to be determined. Shading materials were selected for deployment as either external or internal shades from the products examined in Sections 4. 4. As described above, g-values and U-values were calculated for the respective fully closed shaded glazing using the procedures of EN 14501 and EN 13125 for the shades in combination with all 6 EN reference glazings. The calculated values are shown in Table 5.6. which is a reproduction of Table 4.5. The g and U values are intended to represent the highest and lowest performance which can be expected of the shaded window system for the reference glazings as defined in the respective European standards. The Run-Code can be used to identify individual curves when examining the cooling energy savings. The shaded glazing with the lowest g-value and lowest U-value is identified as “2-5”; the shaded glazing with the highest g-value and highest U-value is identified as “1-1”.

Reference Glazing	g Unshaded	U Unshaded W/(m^2.K)	g Shaded	U Shaded W/(m^2.K)	Run-Code
A: Single Clear	0.85	5.80	0.34	3.96	A-1-1
			0.34	1.32	A-1-5
			0.14	3.96	A-2-1
			0.14	1.32	A-2-5
B: Double Clear	0.76	2.90	0.32	2.35	B-1-1
			0.32	1.07	B-1-5
			0.02	2.35	B-2-1
			0.02	1.07	B-2-5
C: Heat Control	0.59	1.20	0.25	1.09	C-1-1
			0.25	0.70	C-1-5
			0.02	1.09	C-2-1
			0.02	0.70	C-2-5
D: Solar Control	0.32	1.10	0.16	1.01	D-1-1
			0.16	0.67	D-1-5
			0.01	1.01	D-2-1
			0.01	0.67	D-2-5
E: Triple Clear	0.65	2.00	0.27	1.72	E-1-1
			0.27	0.92	E-1-5
			0.02	1.72	E-2-1
			0.02	0.92	E-2-5
F: Double Clear Low-e	0.72	1.60	0.29	1.42	F-1-1
			0.29	0.82	F-1-5
			0.01	1.42	F-2-1
			0.01	0.82	F-2-5

Table 5.6. Total solar energy transmittance, g, and thermal transmittance, U, of the shaded reference glazings used to determine cooling energy savings.

5.2.3. Control strategy

The control strategy employed to regulate the position of the shade with respect to the glazing for both external and internal shading situations is to raise and lower the shade in response to the level of the solar irradiance, G, incident on the outside surface of the glazing. Three conditions are allowed:

(i) Unshaded: $G < 200\ W/m^2$
(ii) Fully Shaded: $G > 400\ W/m^2$
(iii) Partially Shaded: $200 < G < 400\ W/m^2$

Condition (iii) Partially Shaded is a linear representation of the percentage of the glazing which is shaded against the incident irradiance G.

Under these conditions the percentage of time for which the glazing is either fully shaded, partially shaded or unshaded for each of the 4 locations is shown in Table 5.7.

The number of hours for which the glazing is either fully shaded, partially shaded or unshaded for Rome and for Stockholm are shown in Figure 5.11 and Figure 5.12 respectively.

For glazings located between South Eastern and Western orientations, the percentage of time for which the glazing is fully or partially shaded is high, in Rome ~ 45%, Brussels ~ 28%, Stockholm ~ 33%, Budapest ~ 44%, underlining the importance of reliable control of shade positioning.

Location	Orientation	Fully Shaded	Partially Shaded	Unshaded
Rome	N	0.0%	8.6%	91.4%
	NE	2.9%	17.4%	79.7%
	E	12.8%	22.1%	65.1%
	SE	21.5%	23.3%	55.2%
	S	24.7%	26.4%	48.9%
	SW	28.4%	19.8%	51.8%
	W	20.7%	17.9%	61.3%
	NW	6.8%	18.5%	74.7%
Brussels	N	0.0%	7.1%	92.9%
	NE	0.5%	12.9%	86.5%
	E	4.6%	16.6%	78.8%
	SE	8.9%	19.1%	72.0%
	S	10.9%	19.6%	69.5%
	SW	11.0%	18.5%	70.5%
	W	7.2%	17.2%	75.7%
	NW	1.7%	14.1%	84.3%
Stockholm	N	0.0%	4.5%	95.5%
	NE	1.2%	10.7%	88.1%
	E	7.5%	15.2%	77.3%
	SE	13.2%	18.5%	68.3%
	S	16.8%	21.4%	61.8%
	SW	16.0%	19.2%	64.8%
	W	10.6%	16.0%	73.4%
	NW	3.1%	12.5%	84.4%
Budapest	N	0.0%	7.6%	92.4%
	NE	1.3%	14.4%	84.3%
	E	7.2%	18.4%	74.4%
	SE	13.0%	20.4%	66.6%
	S	15.4%	21.8%	62.9%
	SW	16.6%	18.9%	64.5%
	W	11.5%	17.4%	71.1%
	NW	3.3%	15.5%	81.2%

Table 5.7 Percentage of time for which the glazing is fully shaded, partially shaded and unshaded for each of the 4 locations.

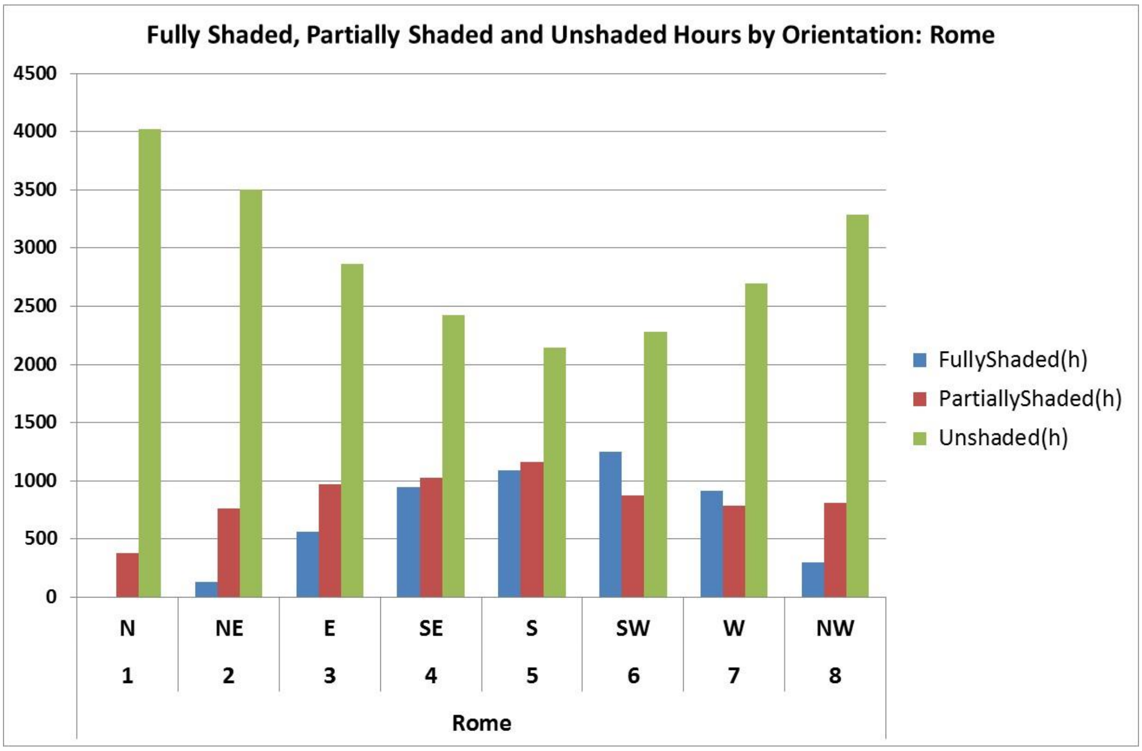


Figure 5.11 Number of shaded, partially shaded and unshaded cooling season hours by orientation: Rome.

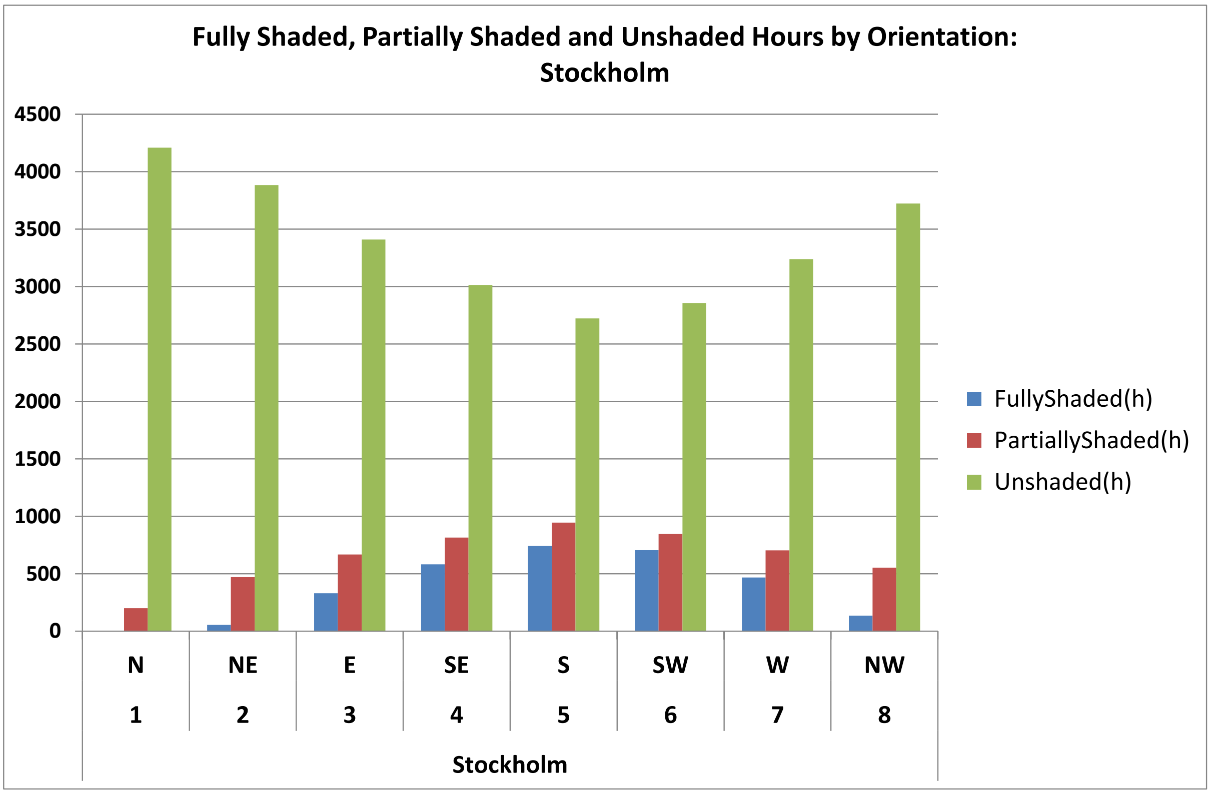


Figure 5.12 Number of shaded, partially shaded and unshaded cooling season hours by orientation: Stockholm.

5.2.4. Space Cooling Energy Savings

Cooling energy savings in kWh/m^2/year and as a percentage are determined per unit area of glazing by orientation and by location for each of the 6 EN reference glazings using the shaded glazing performance data given in Table 5.7. Savings are calculated for (i) external and (ii) internal dynamic solar shading systems.

5.2.5. Dynamic External Solar Shading

Figure 5.13 shows the reduction in cooling energy required for the Rome location for solar shading in combination with clear double glazing (Glazing B). Maximum savings are seen for the SW orientation and the savings are as high as 70% for the dynamic solar shading glazing system with the lowest g- and U-values. All orientations give a positive benefit. The solar shading system with the highest g- and U-values gives the lowest cooling energy savings but these still represent a 35% saving for SW orientation.

Figure 5.14 shows the reduction in cooling energy required for the Rome location for solar shading in combination with the highest performing solar control glazing (Glazing D). Maximum savings are once again seen for the SW orientation with savings of 63% for the dynamic solar shading glazing system with the lowest g- and U-values. Once again all orientations display a positive cooling energy saving. The solar shading system with the highest g- and U-values gives the lowest cooling energy savings but these are still above 30% for the SW orientation.

Similar findings are observed when dynamic external solar shading is combined with each of the EN 14501 and EN 13363-1 reference glazings of Section 4.7. Figure 5.15 presents the percentage cooling energy savings of the shaded glazings (B, C, D, E and F) for different shade performance by orientation (Glazing A Single Clear which shows a negative performance with respect to Glazing B is excluded; the improvement in both cooling and heating energy savings which can be realised when dynamic solar shading is employed as a refurbishment solution for energy inefficient glazing is analysed in detail in Section 5.3).

From these data the mean, maximum and minimum percentage cooling energy savings of dynamic externally shaded glazing by unshaded reference glazing are calculated. The results are shown in Table 5.8. Mean cooling energy savings are found by averaging over all possible orientations for all 4 solar shading systems; maximum and minimum savings are the mean of the maxima and minima for each of the 4 considered solar shading systems. The percentage savings are converted in cooling energy savings by reference glazing by multiplying with the cooling energy balance, P, of the unshaded benchmark reference glazings (Table 5.2). The results are shown in Table 5.9. For the Rome location, the percentage mean, maximum and minimum cooling energy savings and the mean, maximum and minimum cooling energy savings in kWh/m^2/year of Tables 5.8 and 5.9 are shown graphically in Figs 5.16 and 5.17 respectively.

This process is repeated for each of the 3 other locations, i.e. Brussels, Stockholm and Budapest.

Representative orientation dependent percentage cooling energy savings by glazing type for Brussels and Stockholm respectively are shown in Figs, 5.18, 5.19 and 5.20.

The percentage mean, maximum and minimum cooling energy savings and the mean, maximum and minimum cooling energy savings in kWh/m^2/year for Brussels are presented in Table 5.10 and Table 5.11 respectively and the results shown graphically in Figs5. 21 and 5.22.

The percentage mean, maximum and minimum cooling energy savings and the mean, maximum and minimum cooling energy savings in kWh/m^2/year for Stockholm are presented in Table 5.12 and Table 5.13 respectively and the results shown graphically in Figs 5.23 and 5.24.

The percentage mean, maximum and minimum cooling energy savings and the mean, maximum and minimum cooling energy savings in kWh/m^2/year for Budapest are presented in Table 5.14 and Table 5.15 respectively and the results shown graphically in Figs 5.25 and 5.26.

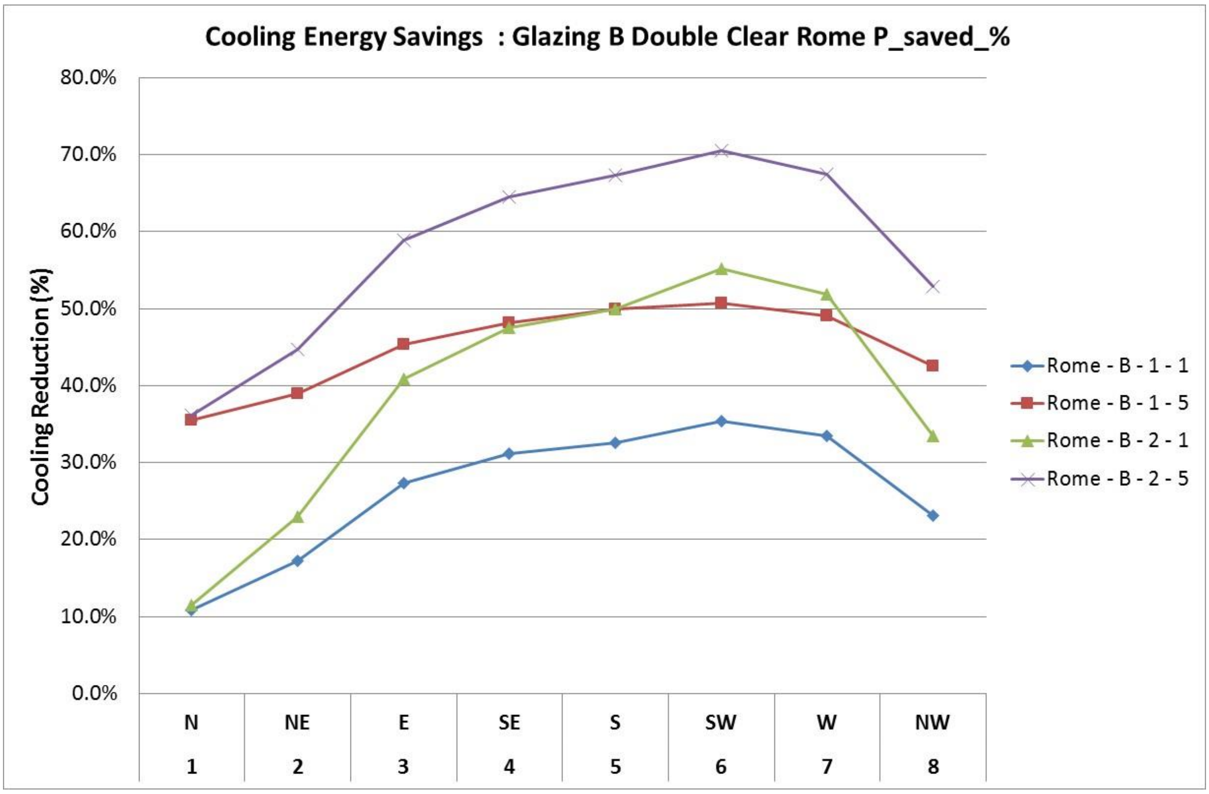


Figure 5.13 Percentage cooling energy savings of shaded double clear glazing (Glazing B) for different shade performance by orientation: Rome.

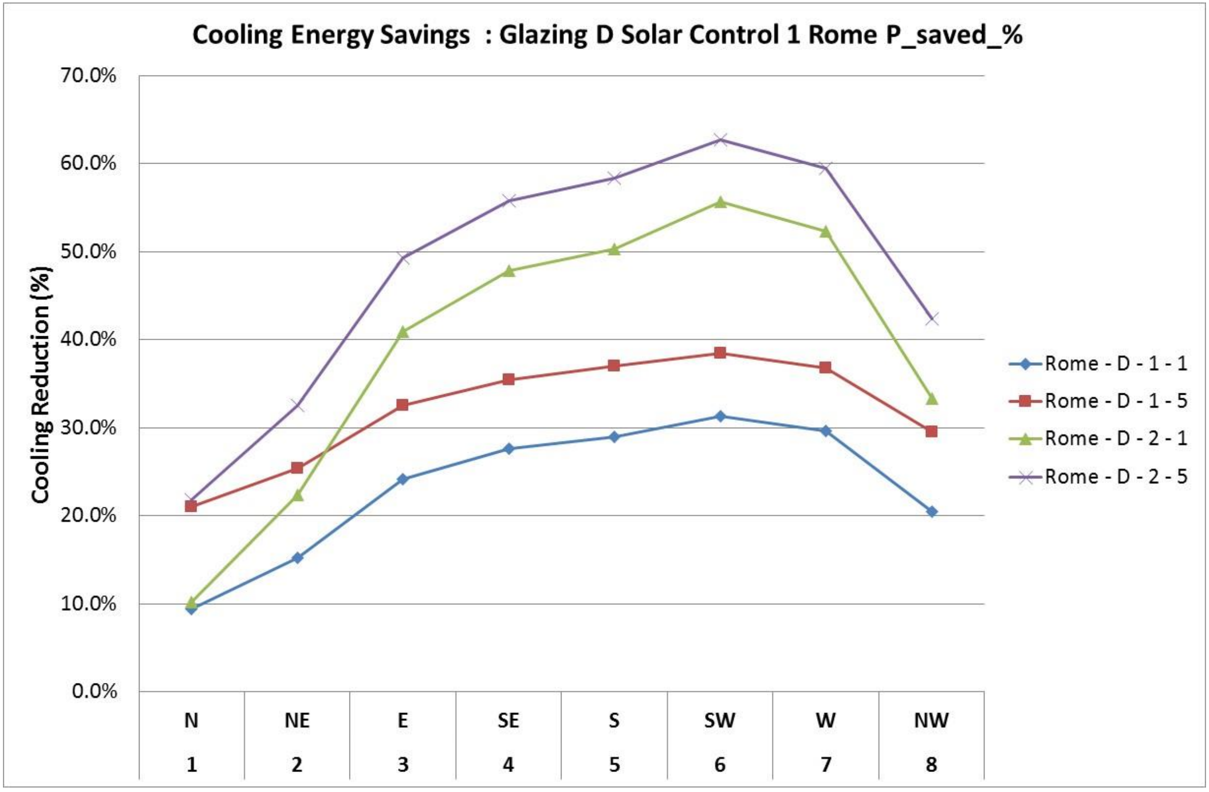


Figure 5.14 Percentage cooling energy savings of shaded solar control glazing (Glazing D) for different shade performance by orientation: Rome.

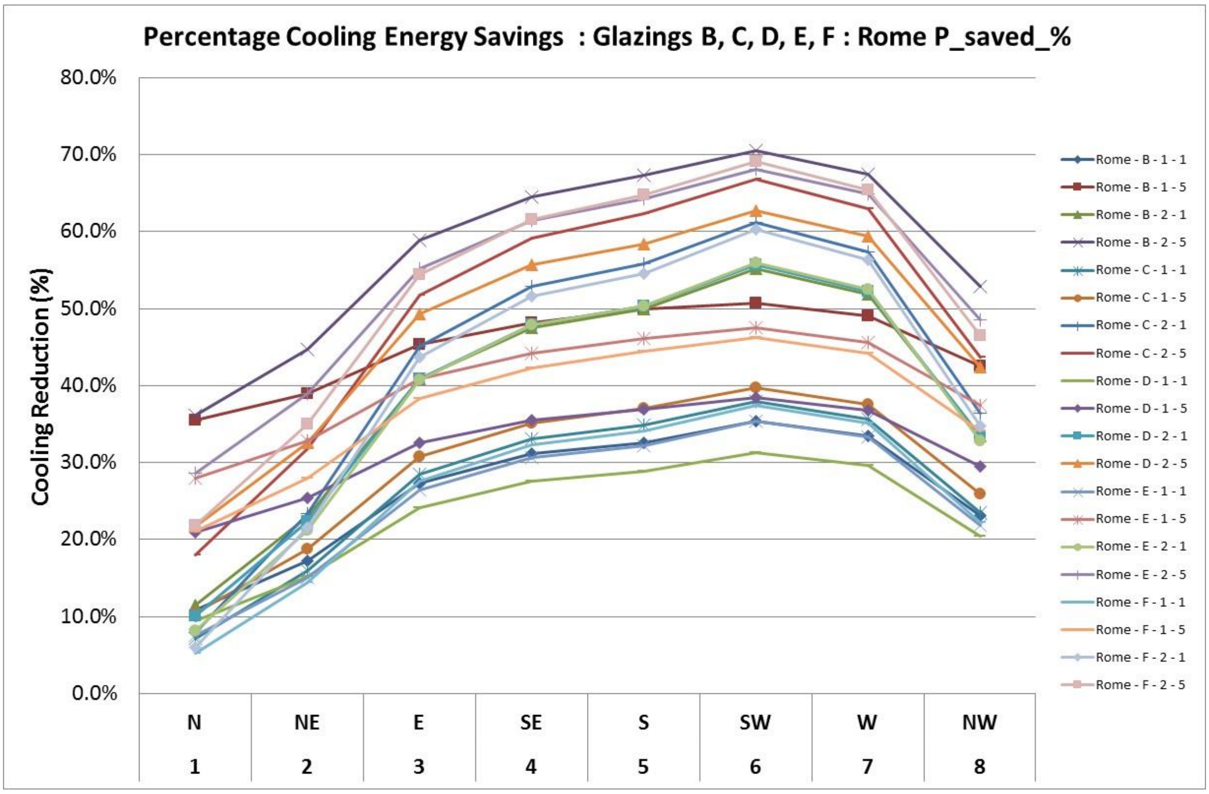


Figure 5.15 Percentage cooling energy savings of shaded glazings (B, C, D, E and F) for different shade performance by orientation: Rome.

Glazing ID	Glazing	Mean Cooling Savings (%)	Maximum Cooling Savings (%)	Minimum Cooling Savings (%)
A	Single Clear	49%	71%	23%
B	Double Clear	42%	70%	11%
C	Heat Control	37%	67%	7%
D	Solar Control	36%	63%	9%
E	Triple Clear	40%	68%	8%
F	Double Clear Low-e	39%	69%	5%

Table 5.8 Mean, maximum and minimum percentage cooling energy savings of dynamic externally shaded glazing across all orientations by unshaded reference glazing: Rome.

Glazing ID	Glazing	Mean Cooling Energy Savings ($kWh/m^2/yr$)	Maximum Cooling Energy Savings ($kWh/m^2/yr$)	Minimum Cooling Energy Savings ($kWh/m^2/yr$)
A	Single Clear	162.3	235.4	76.2
B	Double Clear	116.6	195.3	30.2
C	Heat Control	76.8	138.0	14.7
D	Solar Control	41.0	72.3	10.8
E	Triple Clear	90.0	155.1	17.1
F	Double Clear Low-e	99.3	174.9	13.2

Table 5.9 Mean, maximum and minimum cooling energy savings in kWh/m2/yr of dynamic externally shaded glazing by unshaded reference glazing: Rome.

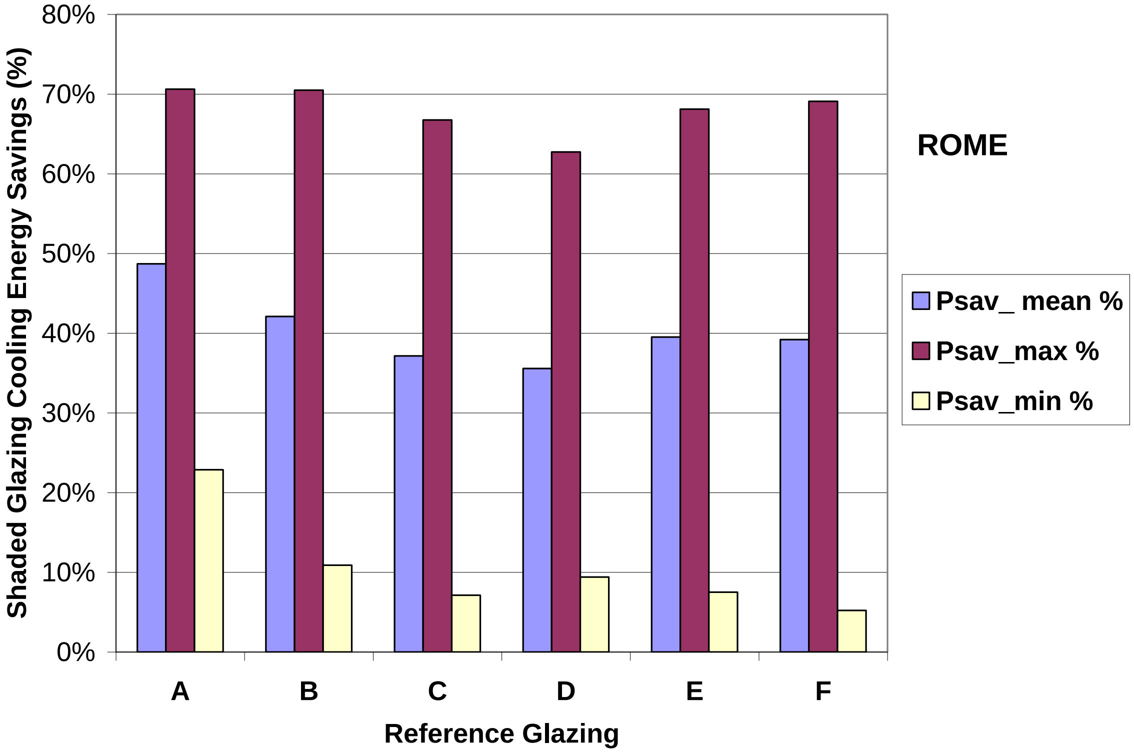


Figure 5.16 Mean, maximum and minimum percentage cooling energy savings of the dynamic externally shaded glazing by unshaded reference glazing: Rome.

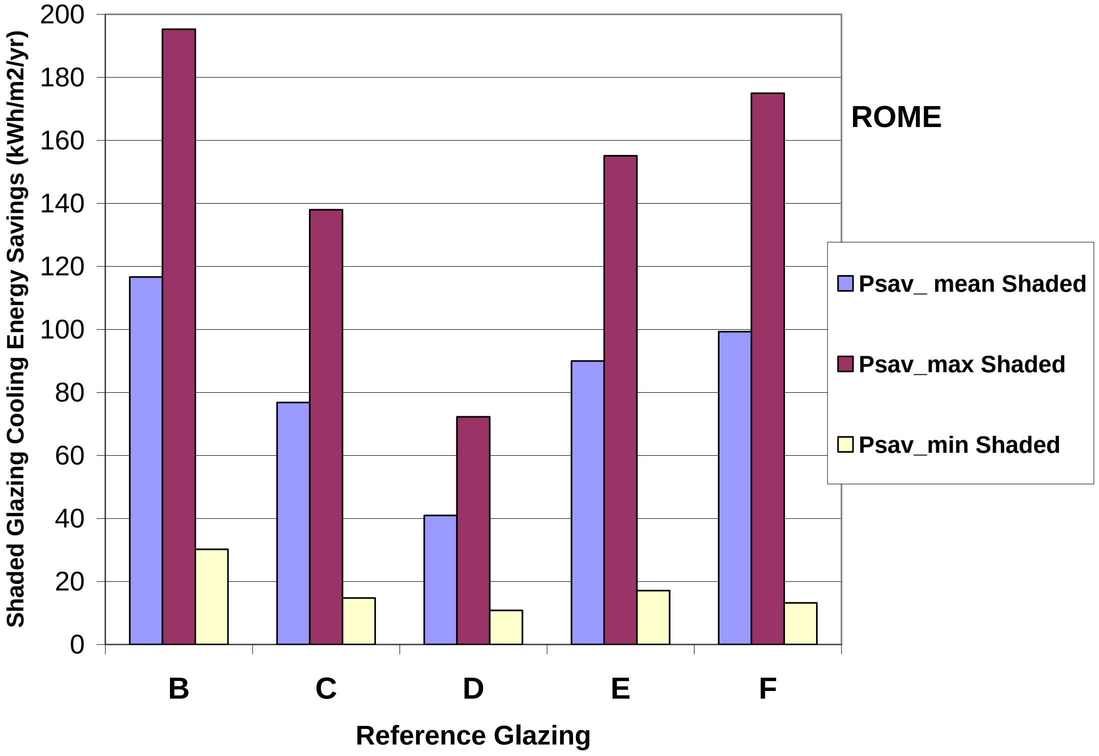


Figure 5.17 Mean, maximum and minimum cooling energy savings in kWh/m2/yr of the dynamic shaded glazing by unshaded reference glazing: Rome.

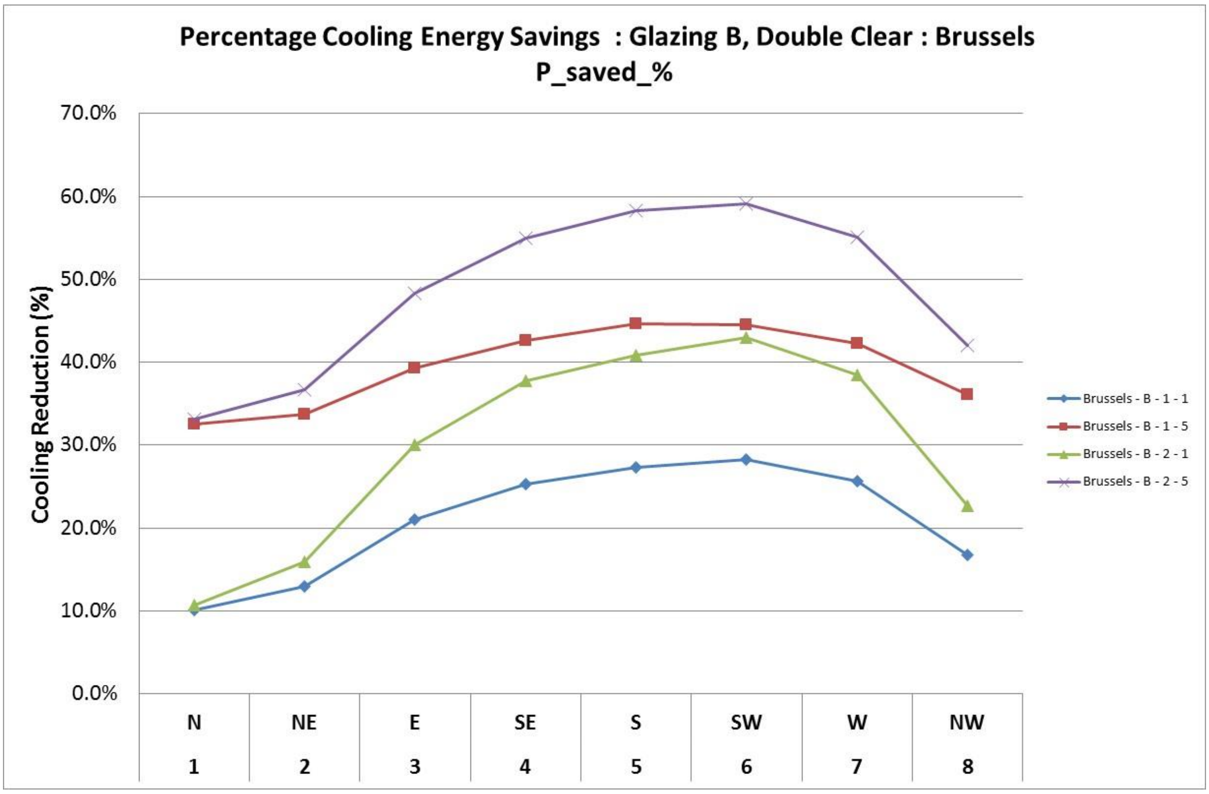


Figure 5.18 Percentage cooling energy savings of shaded double clear glazing (Glazing B) for different shade performance by orientation: Brussels.

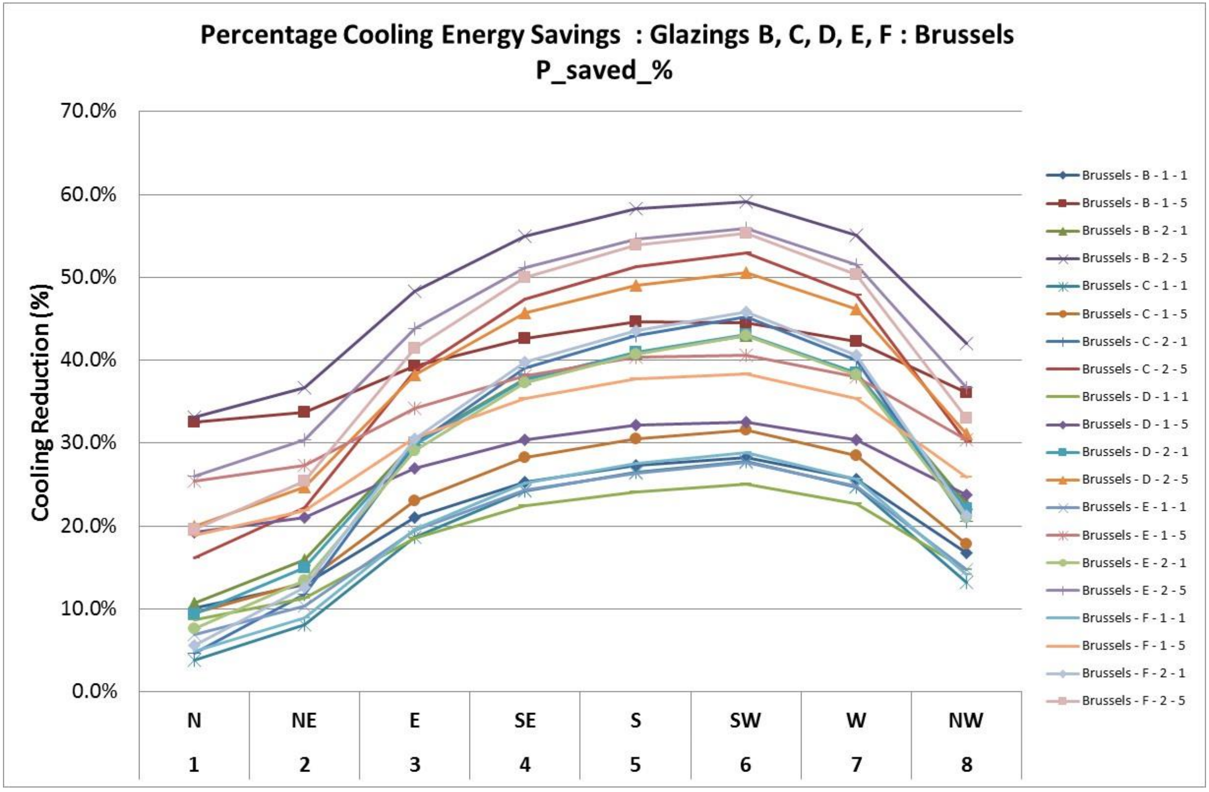


Figure 5.19 Percentage cooling energy savings of shaded glazings (B, C, D, E and F) for different shade performance by orientation: Brussels.

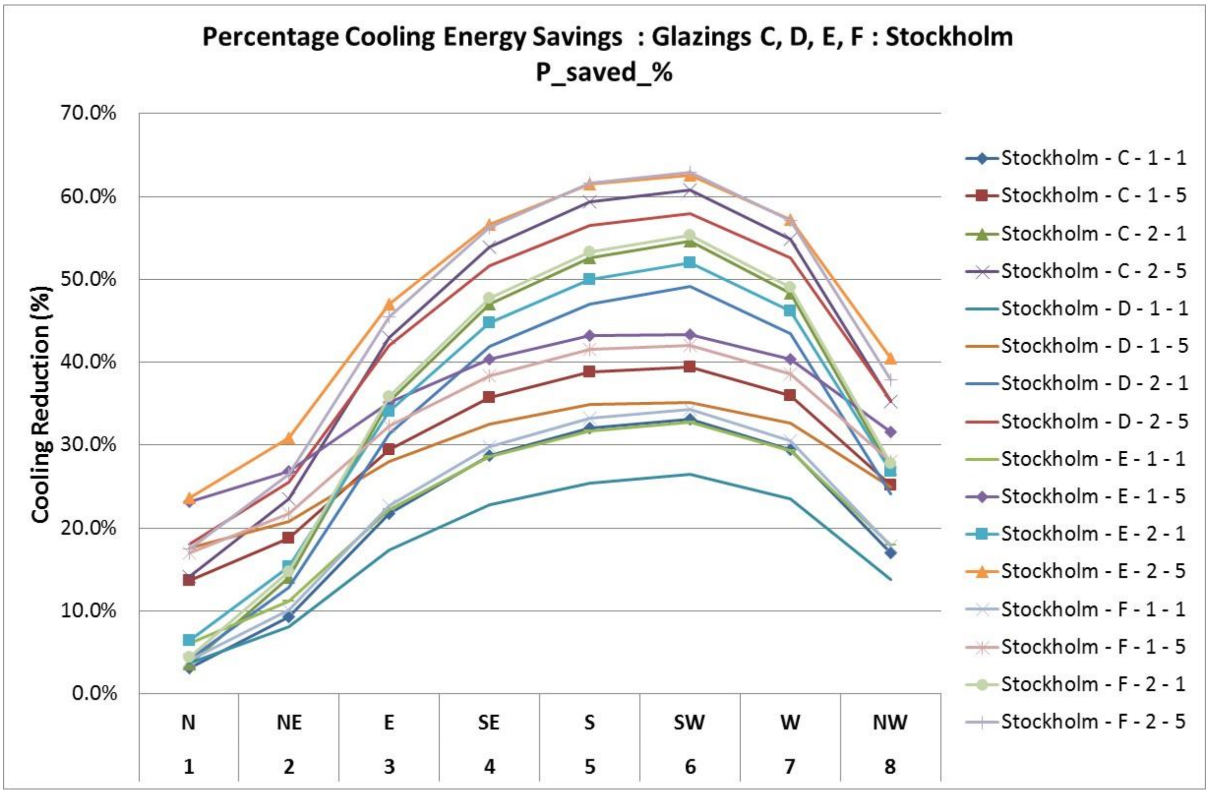


Figure 5.20 Percentage cooling energy savings of shaded glazings (C, D, E and F) for different shade performance by orientation: Stockholm.

Glazing ID	Glazing	Mean Cooling Savings (%)	Maximum Cooling Savings (%)	Minimum Cooling Savings (%)
A	Single Clear	43%	64%	22%
B	Double Clear	35%	59%	10%
C	Heat Control	27%	53%	4%
D	Solar Control	28%	51%	9%
E	Triple Clear	32%	56%	7%
F	Double Clear Low-e	30%	55%	5%

Table 5.10 Mean, maximum and minimum percentage cooling energy savings of dynamic externally shaded glazing by unshaded reference glazing: Brussels.

Glazing ID	Glazing	Mean Cooling Energy Savings ($kWh/m^2/yr$)	Maximum Cooling Energy Savings ($kWh/m^2/yr$)	Minimum Cooling Energy Savings ($kWh/m^2/yr$)
A	Single Clear	49.3	72.0	24.5
B	Double Clear	33.9	57.8	9.9
C	Heat Control	20.2	39.3	2.9
D	Solar Control	11.5	20.6	3.5
E	Triple Clear	25.5	45.2	5.6
F	Double Clear Low-e	27.5	50.2	4.4

Table 5.11 Mean, maximum and minimum cooling energy savings in kWh/m2/yr of dynamic externally shaded glazing by unshaded reference glazing: Brussels.

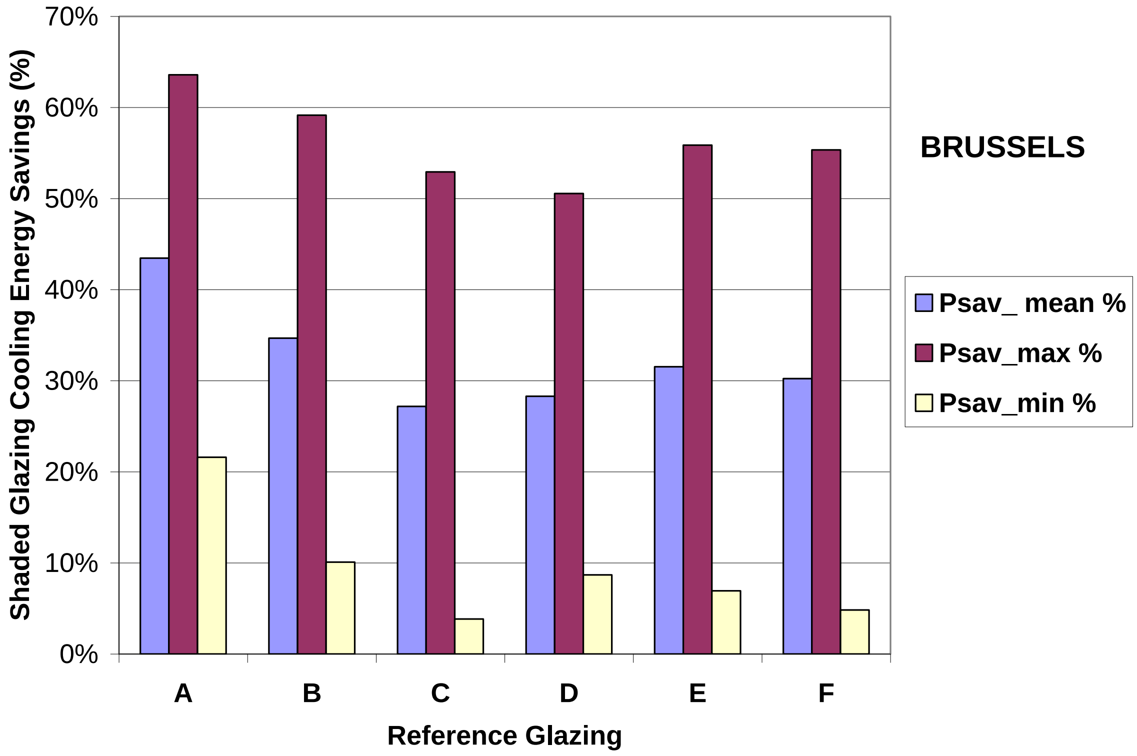


Figure 5.21 Mean, maximum and minimum percentage cooling energy savings of the dynamic shaded glazing by unshaded reference glazing: Brussels.

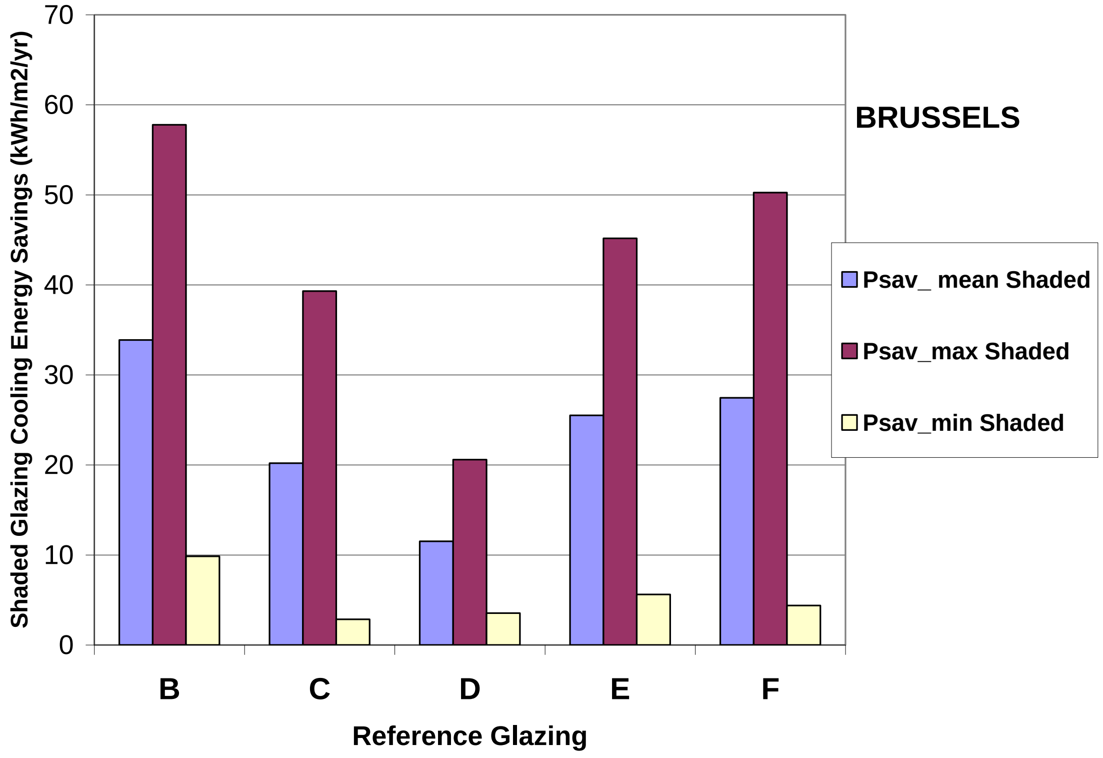


Figure 5.22 Mean, maximum and minimum cooling energy savings in kWh/m2/yr of the dynamic shaded glazing by unshaded reference glazing: Brussels.

Glazing ID	Glazing	Mean Cooling Savings (%)	Maximum Cooling Savings (%)	Minimum Cooling Savings (%)
A	Single Clear	45%	66%	20%
B	Double Clear	38%	65%	9%
C	Heat Control	32%	61%	3%
D	Solar Control	30%	58%	4%
E	Triple Clear	35%	63%	6%
F	Double Clear Low-e	34%	63%	4%

Table 5.12 Mean, maximum and minimum percentage cooling energy savings of dynamic externally shaded glazing by unshaded reference glazing: Stockholm.

Glazing ID	Glazing	Mean Cooling Energy Savings (kWh/m^2/yr)	Maximum Cooling Energy Savings (kWh/m^2/yr)	Minimum Cooling Energy Savings (kWh/m^2/yr)
A	Single Clear	33.3	49.2	15.3
B	Double Clear	24.6	42.6	6.0
C	Heat Control	16.4	30.7	1.5
D	Solar Control	8.2	15.9	1.0
E	Triple Clear	19.1	34.2	3.3
F	Double Clear Low-e	21.1	38.8	2.5

Table 5.13 Mean, maximum and minimum cooling energy savings in kWh/m2/yr of the dynamic externally shaded glazing by unshaded reference glazing: Stockholm.

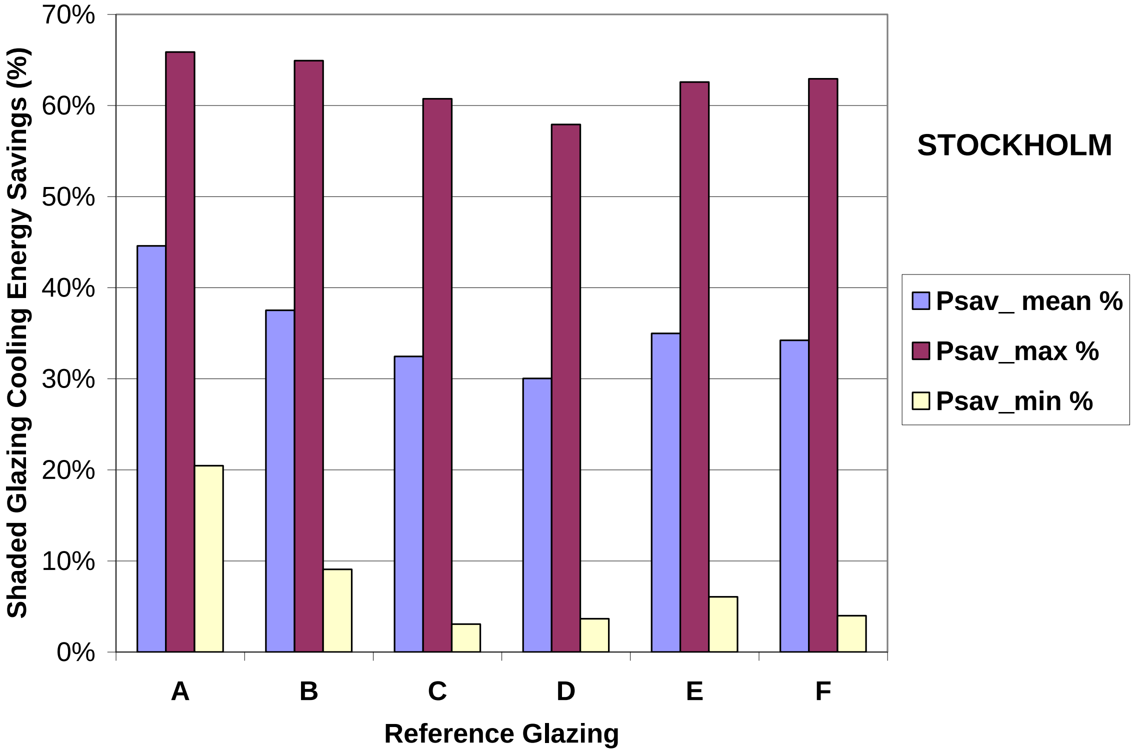


Figure 5.23 Mean, maximum and minimum percentage cooling energy savings of the dynamic shaded glazing by unshaded reference glazing: Stockholm.

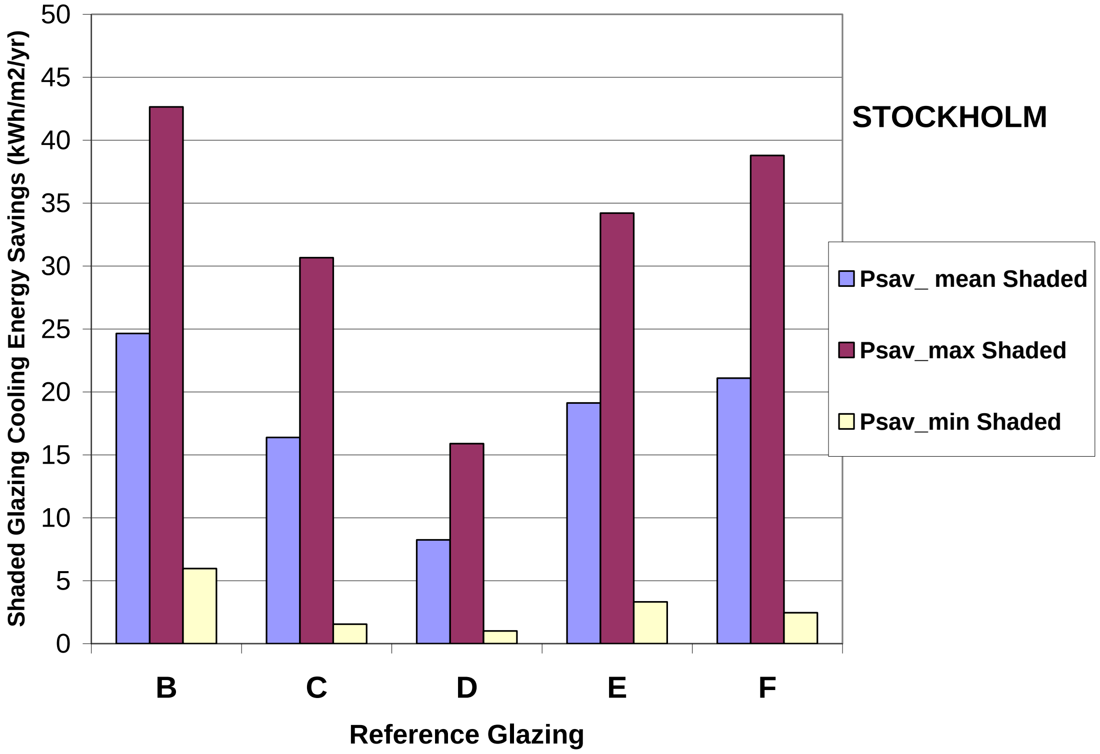


Figure 5.24 Mean, maximum and minimum cooling energy savings in kWh/m2/yr of the dynamic shaded glazing by unshaded reference glazing: Stockholm.

Glazing ID	Glazing	Mean Cooling Savings (%)	Maximum Cooling Savings (%)	Minimum Cooling Savings (%)
A	Single Clear	45%	65%	22%
B	Double Clear	37%	62%	10%
C	Heat Control	30%	57%	5%
D	Solar Control	30%	54%	9%
E	Triple Clear	34%	59%	7%
F	Double Clear Low-e	33%	59%	5%

Table 5.14 Mean, maximum and minimum percentage cooling energy savings of dynamic externally shaded glazing by unshaded reference glazing: Budapest.

Glazing ID	Glazing	Mean Cooling Energy Savings ($kWh/m^2/yr$)	Maximum Cooling Energy Savings ($kWh/m^2/yr$)	Minimum Cooling Energy Savings ($kWh/m^2/yr$)
A	Single Clear	80.8	117.8	39.4
B	Double Clear	56.0	94.9	15.6
C	Heat Control	34.5	65.2	5.6
D	Solar Control	19.3	34.3	5.6
E	Triple Clear	42.5	74.5	8.9
F	Double Clear Low-e	46.1	83.1	6.9

Table 5.15 Mean, maximum and minimum cooling energy savings in kWh/m2/yr of dynamic shaded externally glazing by unshaded reference glazing: Budapest.

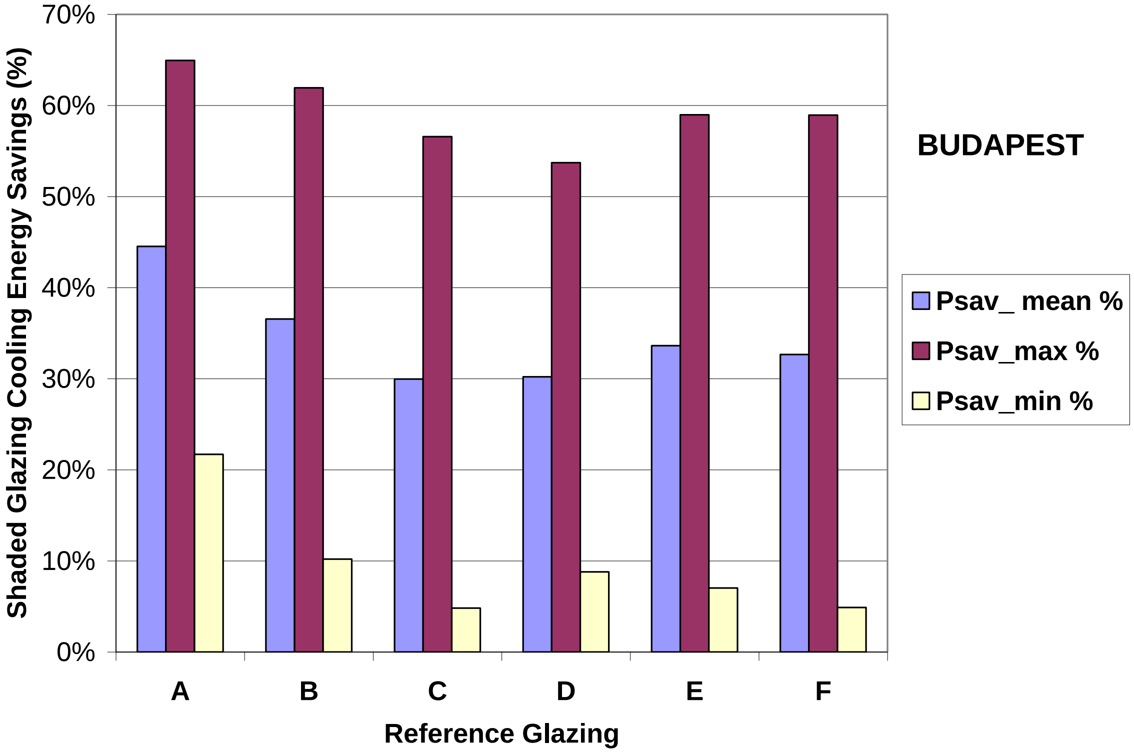


Figure 5.25 Mean, maximum and minimum percentage cooling energy savings of the dynamic shaded glazing by unshaded reference glazing: Budapest.

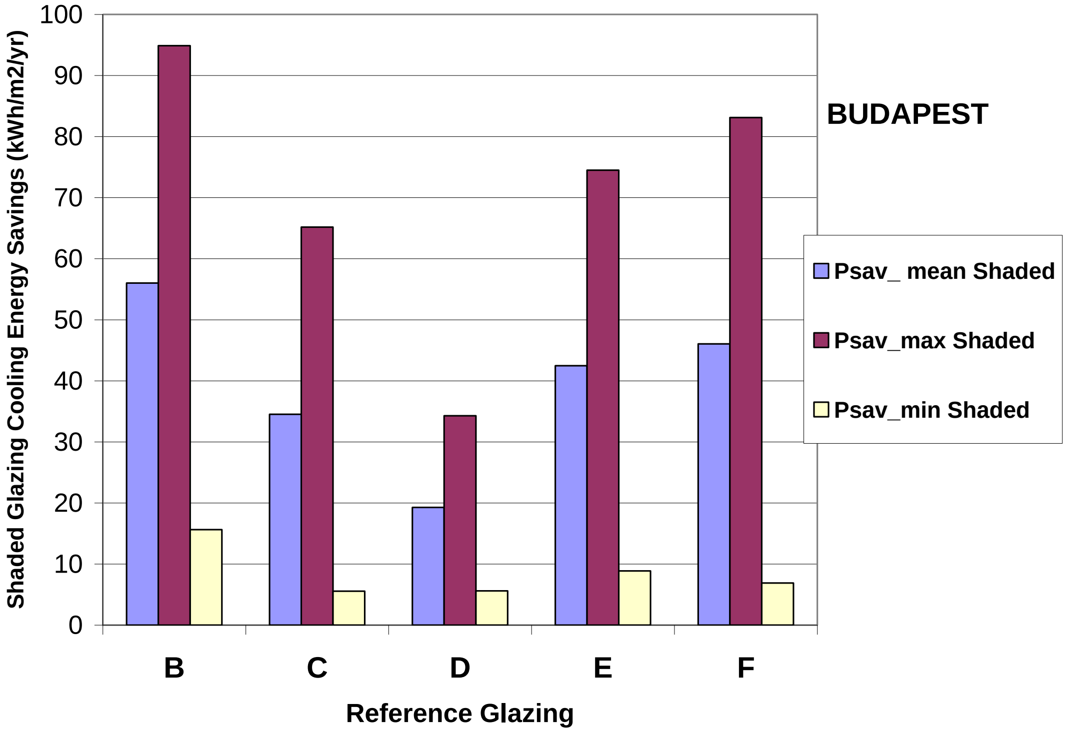


Figure 5.26 Mean, maximum and minimum cooling energy savings in kWh/m2/yr of the dynamic shaded glazing by unshaded reference glazing: Budapest.

5.2.6. Maximum cooling savings for SW orientation

Maximum cooling energy savings are exhibited for the SW orientation. Using the percentage maxima listed in Tables 5.7, 5.9, 5.11 and 5.13 and the maximum unshaded SW cooling demand of each reference glazing, Table 5.16 presents the maximum cooling energy saving in kWh/m^2/yr of the highest performing dynamic solar shading system (Ref Code 2-5) for the South-West orientation only for each of the 6 reference glazings for each of the 4 locations. The results are also presented graphically in Figure 5.27. The corresponding maximum percentage cooling energy savings are shown in Table 5.17.

		South West Orientation: **Maximum Cooling Energy Savings (kWh/m^2/yr)**			
Glazing ID	**Glazing**	**Rome**	**Brussels**	**Stockholm**	**Budapest**
A	Single Clear	295.0	144.2	99.4	228.9
B	Double Clear	247.7	125.4	87.8	195.2
C	Heat Control	175.8	95.4	67.4	147.3
D	Solar Control	91.5	52.2	36.6	81.2
E	Triple Clear	196.9	103.8	73.1	161.1
F	Double Clear Low-e	222.5	116.6	82.3	180.2

Table 5.16 Maximum cooling energy savings in kWh/m2/yr for South-West oriented dynamic externally shaded glazing with respect to the unshaded reference glazing: Rome., Brussels, Stockholm, Budapest.

		South West Orientation: Maximum % Cooling Energy Savings			
Glazing ID	**Glazing**	**Rome**	**Brussels**	**Stockholm**	**Budapest**
A	Single Clear	71%	64%	66%	65%
B	Double Clear	70%	59%	65%	62%
C	Heat Control	67%	53%	61%	57%
D	Solar Control	63%	51%	58%	54%
E	Triple Clear	68%	56%	63%	59%
F	Double Clear Low-e	69%	55%	63%	59%

Table 5.17 Maximum percentage annual cooling energy savings for South-West oriented dynamic externally shaded glazing with respect to the unshaded reference glazing: Rome., Brussels, Stockholm, Budapest.

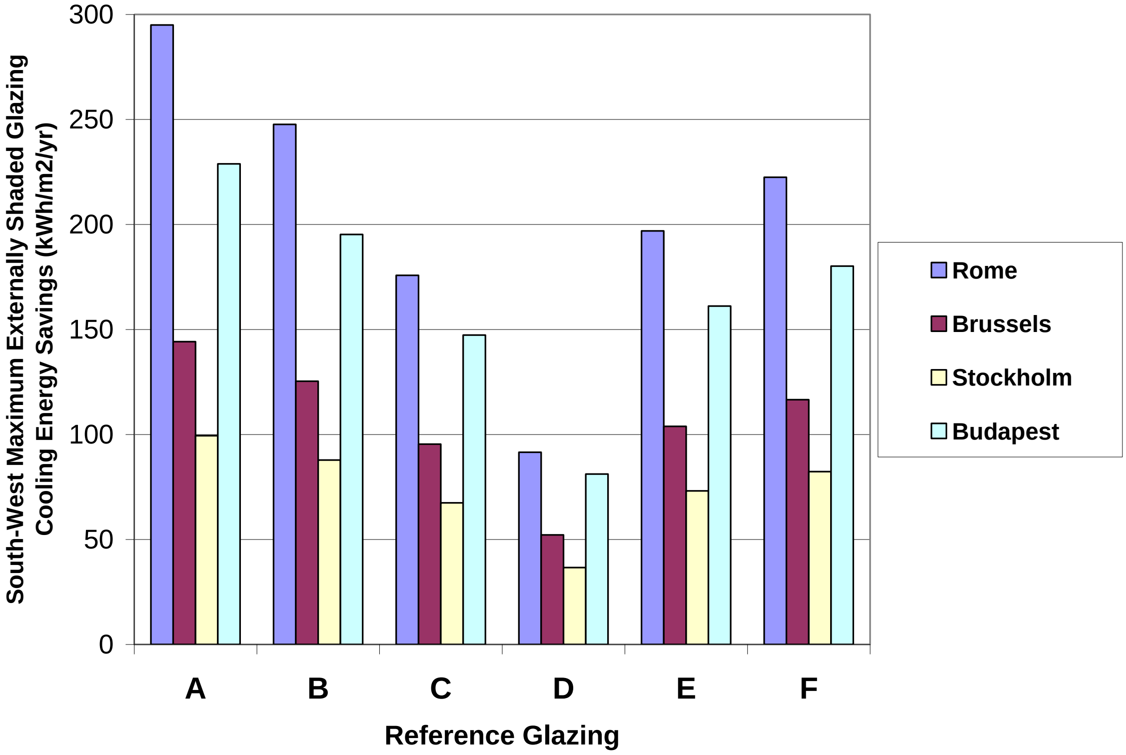


Figure 5.27 Maximum cooling energy savings for South-West oriented dynamic externally shaded glazing with respect to the unshaded reference glazing: Rome., Brussels, Stockholm, Budapest.

5.2.7. Dynamic Internal Solar Shading

For internal solar shading the minimum values of the total solar energy transmittance, g, are higher than those which can be achieved with external solar shading. Nevertheless, with smart control, significant cooling energy savings can still be achieved. This is important since internal shading can also provide significant heating energy savings as shown in Section 5.3 and because of the contribution that can be made towards providing increased thermal and visual comfort for the building occupier. Simulations of cooling energy savings for each of the 4 locations were undertaken using the higher g-value data pairs of Table 5.7.

The mean percentage cooling energy savings across all orientations for dynamic internally shaded glazing by unshaded reference glazing for Rome., Brussels, Stockholm and Budapest respectively are shown in Table 5.18 and the corresponding mean cooling energy savings in kWh/m^2/yr are shown in Table 5.19. The data are also presented graphically in Figs. 5.28 and 5.29 respectively.

5.2.8. Overall Mean Space Cooling Energy Savings

The data obtained for the best performing internal shading and are most fairly compared with the savings for the best performing external shading, e.g. the maximum cooling savings presented in Tables 5.8, 5.10, 5.12 and 5.14. The comparison is made in Table 5.20.

Comparison of relative percentage cooling energy savings of all dynamic internal and external shaded glazings by unshaded reference glazing: for (i) all orientations and (ii) 5 orientations (E, SE, S, SW, W) for all locations: Rome., Brussels, Stockholm, Budapest is shown in Table 5.21.

		Mean Cooling Energy Savings (%)			
Glazing ID	**Glazing**	**Rome**	**Brussels**	**Stockholm**	**Budapest**
A	Single Clear	36%	31%	33%	32%
B	Double Clear	33%	25%	29%	27%
C	Heat Control	35%	24%	29%	27%
D	Solar Control	31%	24%	25%	26%
E	Triple Clear	32%	24%	28%	26%
F	Double Clear Low-e	33%	25%	29%	27%

Table 5.18. Mean percentage cooling energy savings for dynamic internally shaded glazing by unshaded reference glazing: Rome., Brussels, Stockholm, Budapest.

		Mean Cooling Energy Savings (kWh/m^2/yr)			
Glazing ID	**Glazing**	**Rome**	**Brussels**	**Stockholm**	**Budapest**
A	Single Clear	120.0	34.9	24.7	58.0
B	Double Clear	90.8	24.8	19.3	42.0
C	Heat Control	71.9	17.7	14.4	31.1
D	Solar Control	36.0	9.8	6.8	16.6
E	Triple Clear	72.9	19.5	15.6	33.2
F	Double Clear Low-e	85.0	22.4	18.1	38.3

Table 5.19 Mean cooling energy savings for dynamic internally shaded glazing by unshaded reference glazing: Rome., Brussels, Stockholm, Budapest.

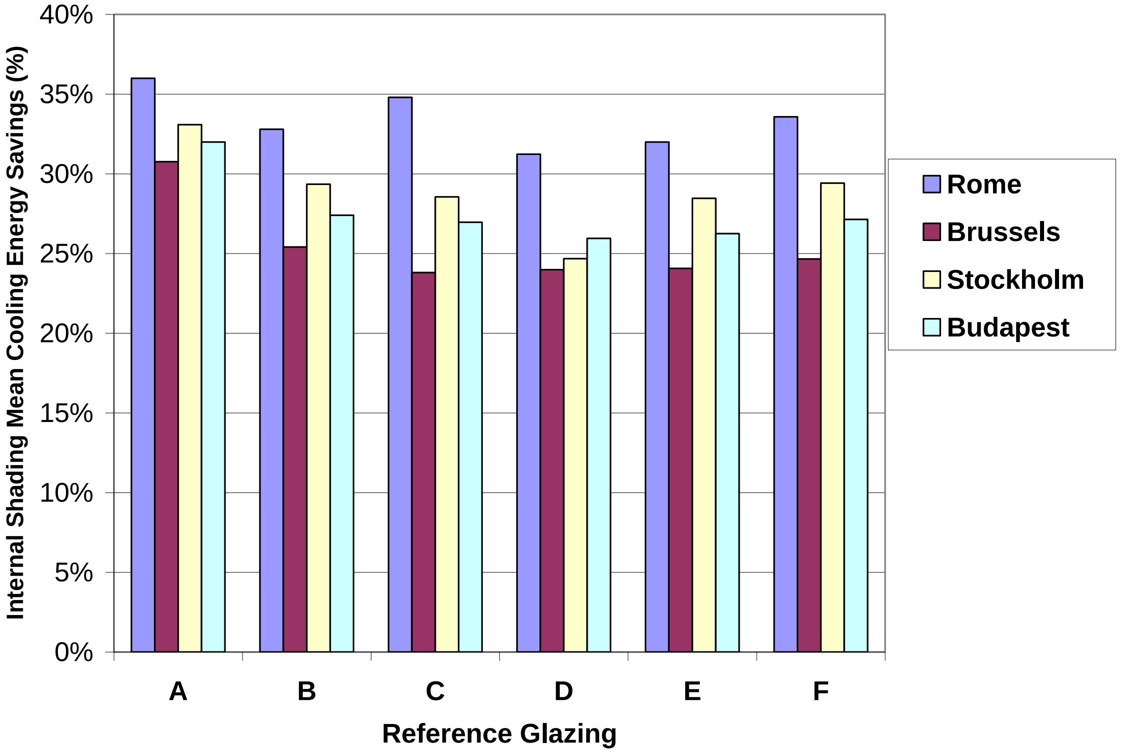


Figure 5.28 Mean percentage cooling energy savings for dynamic internally shaded glazing by unshaded reference glazing: Rome., Brussels, Stockholm, Budapest.

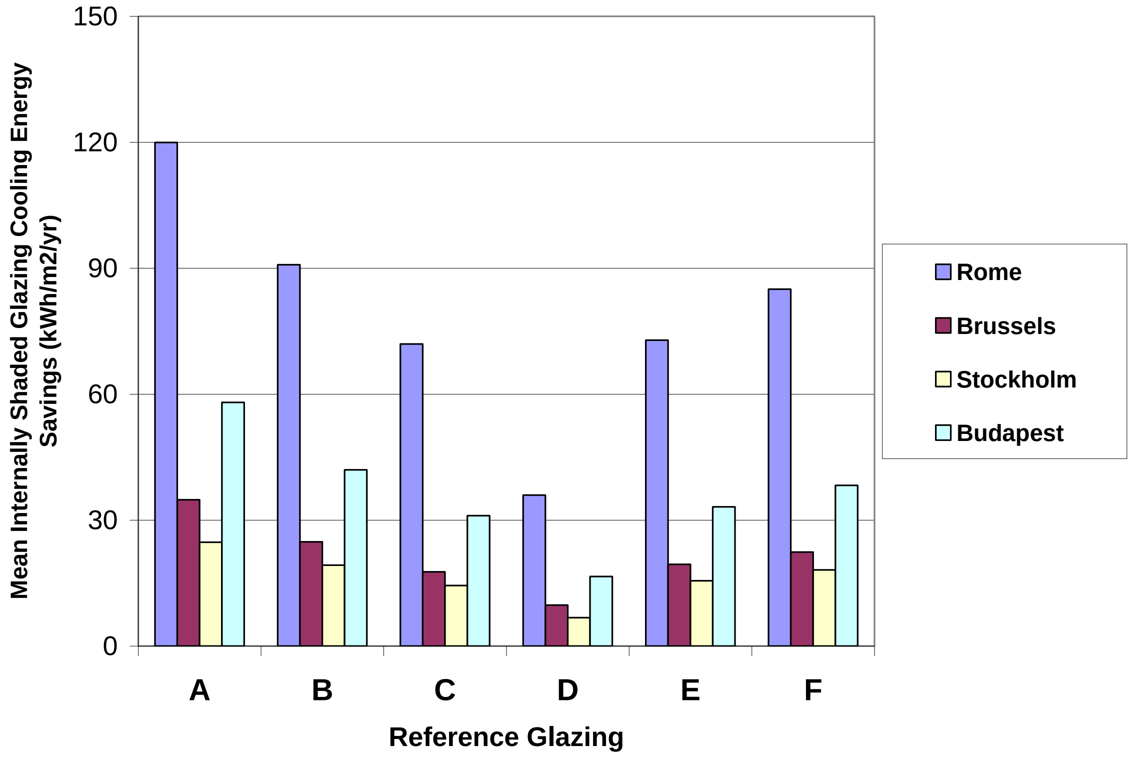


Figure 5.29 Mean cooling energy savings in kWh/m2/yr for dynamic internally shaded glazing by unshaded reference glazing: Rome., Brussels, Stockholm, Budapest.

Glazing ID	**Glazing**	**Rome**		**Brussels**		**Stockholm**		**Budapest**	
		Int	**Ext**	**Int**	**Ext**	**Int**	**Ext**	**Int**	**Ext**
A	Single Clear	36%	71%	31%	64%	33%	66%	32%	65%
B	Double Clear	33%	70%	25%	59%	29%	65%	27%	62%
C	Heat Control	35%	67%	24%	53%	29%	61%	27%	57%
D	Solar Control	31%	63%	24%	51%	25%	58%	26%	54%
E	Triple Clear	32%	68%	24%	56%	28%	63%	26%	59%
F	Double Clear Low-e	33%	69%	25%	55%	29%	63%	27%	59%

Table 5.20.Comparison of relative percentage cooling energy savings of best performing dynamic internal and external shaded glazings by unshaded reference glazing: Rome., Brussels, Stockholm, Budapest.

Glazing ID	Glazing	Mean % Cooling Saving All locations All 8 orientations	Mean % Cooling Saving All locations 5 orientations (E, SE, S, SW, W)
A	Single Clear	45%	65%
B	Double Clear	38%	61%
C	Heat Control	32%	56%
D	Solar Control	31%	53%
E	Triple Clear	35%	58%
F	Double Clear Low-e	34%	58%

Table 5.21. Comparison of relative percentage cooling energy savings of all dynamic internal and external shaded glazings by unshaded reference glazing: for (i) all orientations and (ii) 5 orientations (E, SE, S, SW, W) for all locations: Rome., Brussels, Stockholm, Budapest.

5.3. Space Heating Energy

A closed solar shading device provides additional thermal resistance and lowers the thermal transmittance of the window system. A control strategy which operates with the shade fully open during daylight hours and fully closed during the hours of darkness reduces space heating demand, combining passive solar gain by day with reduced thermal loss by night.

The potential impact of solar shading on the reduction of the space heating demand is estimated using a simple monthly mean daily method of van Dijk et al (5.2, 5.3). Validation has shown that the simplified method is well suited for calculation of the energy needs for heating and cooling of buildings in warm, moderate and cold European climates.

Calculations are made for the medium weight building described in 5.1 above located in each of the 4 cities, Rome, Brussels, Stockholm and Budapest.

The unshaded g-value and U-value of the 6 reference glazings of EN 14501 and EN 13363-1 were employed for simulation during daylight hours. A night-time U-value of the fully closed glazing, U_n, determined using the procedures defined in EN 13125, was used during the hours of darkness.

Night-time U-values were calculated to represent shutters ranging from air-tight (Class 5) to those with very high air permeability (Class 1) and external blinds and internal blinds ranging from Class 3 to Class 1. The emissivity of the blind was also accounted for in determining the additional thermal resistance provided by the shading device.

The fully closed night-time U-values for each of the 6 reference glazings are shown in Table 5.22.

	Single Clear	Double Clear	Heat Control	Solar Control	Triple Clear	Double Clear Low-e
	A_Un W/(m2.K)	B_Un W/(m2.K)	C_Un W/(m2.K)	D_Un W/(m2.K)	E_Un W/(m2.K)	F_Un W/(m2.K)
Unshaded	5.80	2.90	1.20	1.10	2.00	1.60
Class 1	3.96	2.35	1.09	1.01	1.72	1.42
Class 2	3.17	2.05	1.02	0.95	1.55	1.30
Class 3	2.64	1.81	0.96	0.90	1.42	1.20
Class 3/4	2.07	1.53	0.87	0.82	1.23	1.07
Class 5	1.32	1.07	0.67	0.70	0.92	0.82

Table 5.22.Night-time U-values, Un, of the fully shaded reference glazings by air permeability.

The lowest Un values occur for Class 5 air-tight shutters. The Class 3/4 values represent the external and internal blinds with low air permeability and low emissivity. The Class 2 and Class 3 values represent shutters and external and internal blinds with average air permeability and the Class 1 values shadings with very high air permeability.

The monthly average daylength in hours for each location is shown in Table 5.23.

	Monthly Mean Day-length (h)			
Month	Rome	Brussels	Stockholm	Budapest
Jan	9.5	9.2	6.1	9.6
Feb	10.5	10.7	8.0	10.8
Mar	11.9	12.5	10.4	12.5
Apr	13.3	14.5	13.2	14.2
May	14.5	16.3	15.8	15.8
June	15.2	17.2	18.0	16.6
July	14.9	16.7	18.4	16.1
Aug	13.8	15.1	16.6	14.7
Sept	12.4	13.1	14.1	13.0
Oct	11.0	11.2	11.5	11.3
Nov	9.8	9.5	8.8	9.9
Dec	9.2	8.7	6.6	9.1

Table 5.23 Monthly mean day-length (h) by location.

The building space heating requirement (SHR) is determined by calculating:

- The mean daily heat losses by transmission and ventilation
- The mean daily heat gains
- The useful heat gain
- The daily space heating requirement
- The monthly space heating requirement
- The annual space heating requirement

The solar gain, Qs, is calculated as

$$Q_s = G\ A\ g_{tot}\ m\ S \qquad [23]$$

where

Q_s is the solar gain in Watts (W)
G is the solar irradiance on a given façade in W/m^2
A is the window aperture area (including frames) in m^2
m is the ratio of glazed area to aperture area
g_{tot} is the total solar energy transmittance of the glazing including the blind where appropriate
S is a shading factor to account for e.g. obstruction by trees, buildings etc.

Internal heat gains, Q_{int}, from people, lighting, appliances etc. are added to the solar gains.

The building envelope thermal transmission heat loss, Q_t, is calculated as

$$Q_t = \Sigma (U_i A_i) \times (T_{in} - T_a) \qquad [24]$$

where

U_i is the U-value of the respective building element in $W.m^{-2}.K^{-1}$
A_i is the area of the respective building element in m^2
$\Sigma (U_i A_i)$ is the sum of the respective UA values for all elements of the building envelope in W/K
T_{in} is the internal temperature in ^0C
T_a is the external temperature in ^0C

The ventilation (infiltration) heat loss, Q_v, is calculated as

$$Q_v = \rho V c (T_{in} - T_a) \qquad [25]$$

where

the density of air, ρ, = 1.25 kg / m^3
the specific heat capacity of air, c is 1050 J / (kg ^0C)
V is the volume of heated space in m^3

The expression is evaluated by defining the mass flow rate in terms of the number of air changes, n, per hour and integrating over the required time period.

The total heat loss building heat losses, Q_L, are then summed as $Q_L = Q_t + Q_v$

In the steady state model employed in this study the gains and losses are evaluated as monthly mean daily values which are then summed to monthly values. The monthly values are then summed to give annual values.

Not all internal and solar gains contribute to reducing the space heating requirement. Some of the gains result in overheating or are available at times when heating is not required). A Utilisation Factor (UF) is introduced to calculate the useful heat gain. The Utilisation Factor is dependent on the ratio of the internal and solar gains to the heat losses. The Gain to Loss ratio (GLR) accounts for the thermal mass of the building, occupancy behaviour etc.

The Gain to Loss Ratio is found from

$$GLR = (Q_{int} + Q_s) / Q_L \qquad [26]$$

The Utilisation Factor, UF, is then calculated from

$$UF = (1 - GLR^{a}) / (1 - GLR^{a+1}) \qquad [27]$$

where “a” is a building dependent constant. Typical values for a are 0.8, 1.8 and 3.3 for buildings of low, medium and high utilisation factors respectively.

The useful heat gain, Q_u , is then calculated from

$$Q_u = UF \times (Q_s + Q_{int}) \qquad [28]$$

The Space Heating requirement (SHR) is then found as the difference $Q_L - Q_u$

The daily SHR is found and the monthly SHR calculated by multiplying by the number of days in the month. The monthly values for all months in the year for which a heating requirement exists are then summed to give the annual SHR.

5.3.1. Reduction of space heating energy requirement

The dependence of the monthly mean space heating requirement on the fully closed night-time thermal transmittance, Un, for Rome for each of the 6 EN reference glazings is shown in Figure 5.30.

The corresponding dependence of the monthly mean space heating requirement on the fully closed night-time thermal transmittance, Un, for Brussels is shown in Figure 5.31, for Stockholm in Figure 5.32 and for Budapest in Figure 5.33.

The lowering of the night-time U-value resulting from the closing of the shading device has a positive impact on the space heating requirement in all cases. Unsurprisingly the impact is greatest for the glazings with the highest thermal transmittance, i.e. A Single Clear and B Double Clear, and the impact is less for those glazings which have lower unshaded U-values.

The percentage space heating demand savings, SHS%, relative to the annual requirement for the unshaded reference glazing for Rome are shown in Figure 5.34 and for Brussels, Stockholm and Budapest in Figs. 5.35, 5.36 and 5.37 respectively.

Grouping the results for each location by glazing type, a regressive fit is made to give a linear expression for the percentage space heating demand savings as a function of the shaded night-time U-value, Un. The results for each glazing type are shown in Figure 5.38. The percentage annual space heating demand saving, SHS%, as a function of the shaded night-time thermal transmittance, Un, by reference glazing can be estimated from the following expressions:

Glazing A, Single Clear: $SHS\% = 100\,(0.4468 - 0.0769\,Un)$ [29]

Glazing B, Double Clear:$SHS\% = 100\,(0.3725 - 0.1283\,Un)$ [30]

Glazing C, Heat Control: $SHS\% = 100\,(0.2433 - 0.2026\,Un)$ [31]

Glazing D, Solar Control: $SHS\% = 100\,(0.2188 - 0.1989\,Un)$ [32]

Glazing E, Triple Clear: $SHS\% = 100\,(0.3182 - 0.1589\,Un)$ [33]

Glazing F, Double Clear Low-e: $SHS\% = 100\,(0.2901 - 0.1811\,Un)$ [34]

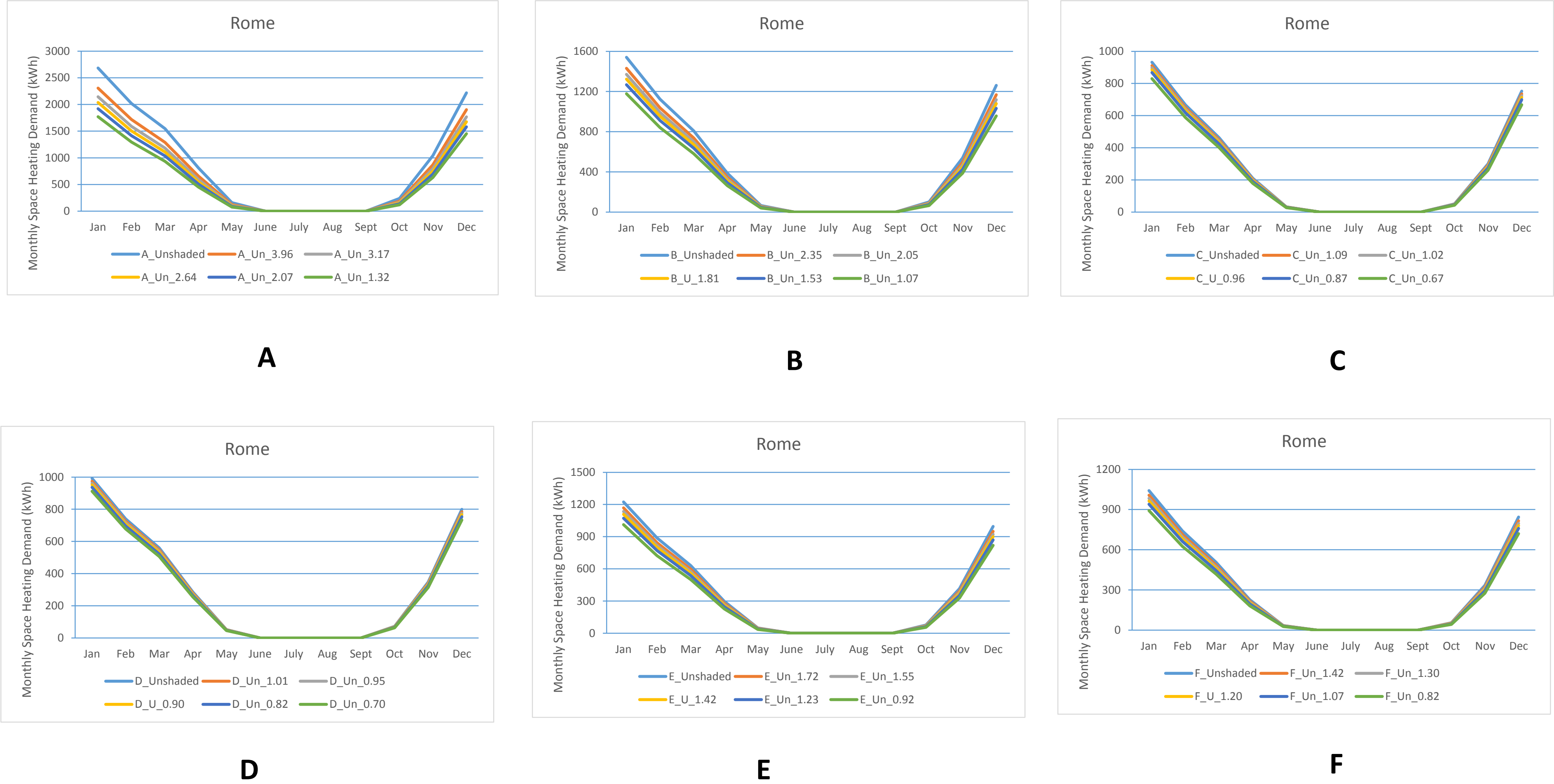


Figure 5.30. Dependence of monthly mean space heating demand on shaded night-time thermal transmittance, Un, by reference glazing: Rome.

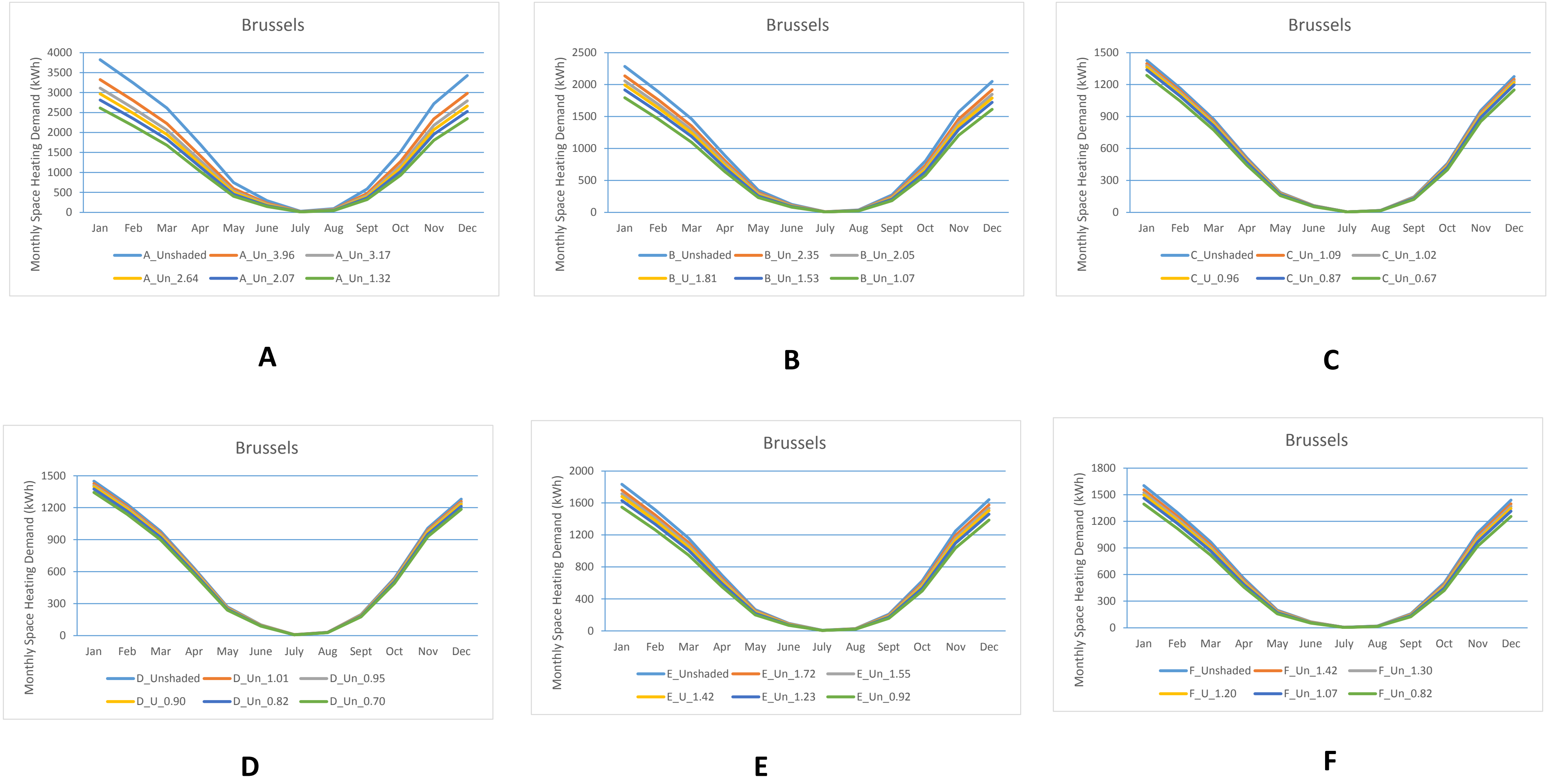
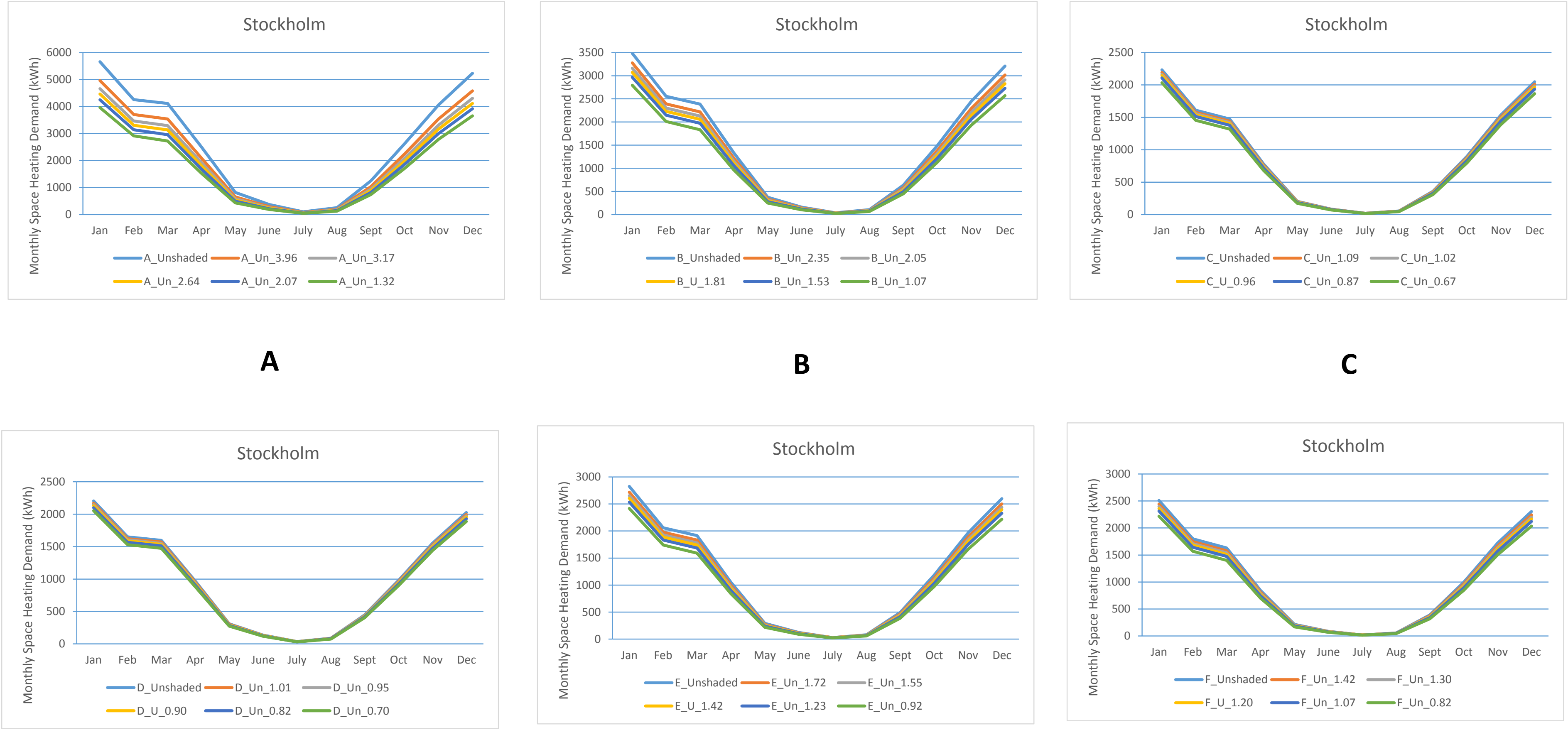


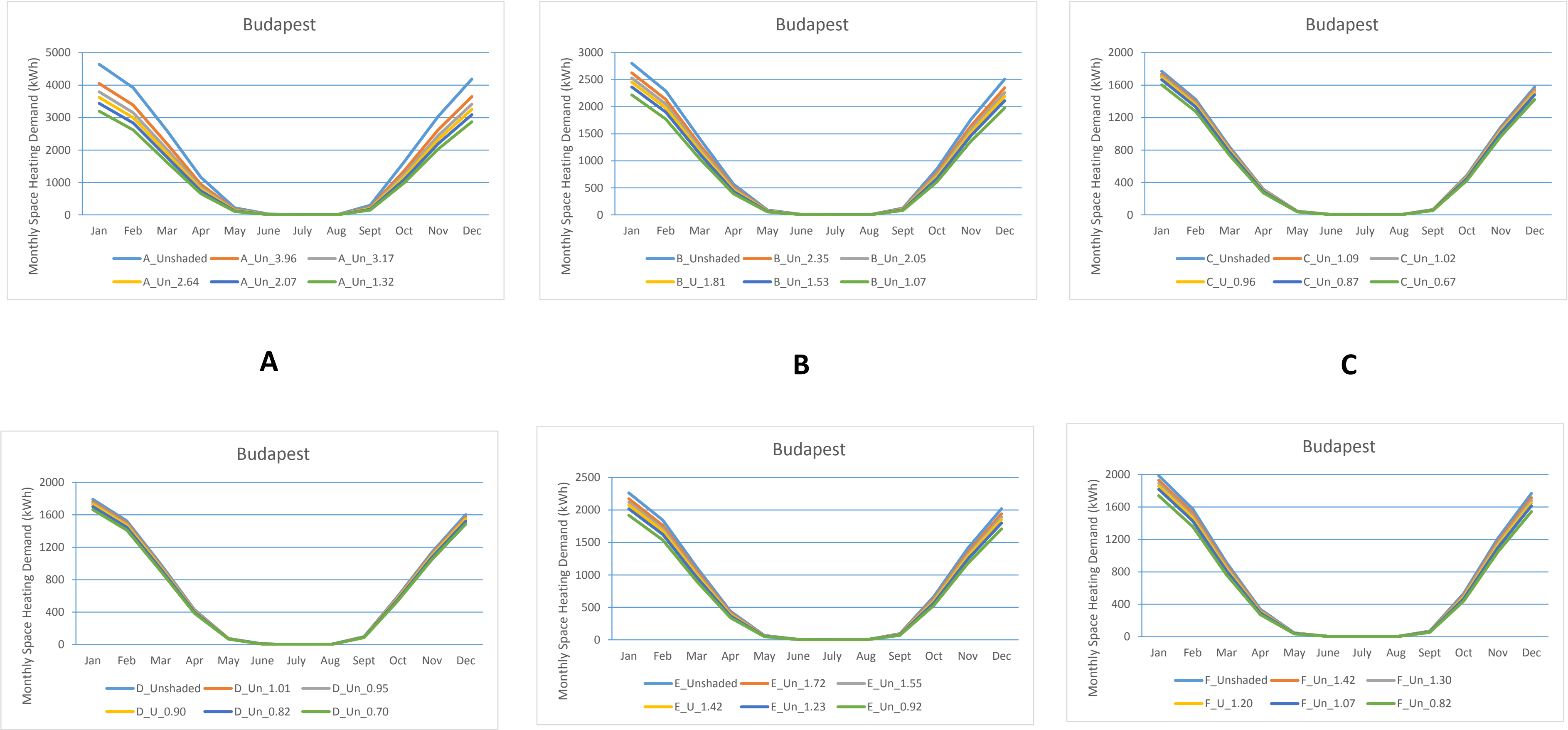
Figure 5.31 Dependence of monthly mean space heating demand on shaded night-time thermal transmittance, Un, by reference glazing: Brussels.



A **B** **C**

D **E** **F**

Figure 5.32 Dependence of monthly mean space heating demand on shaded night-time thermal transmittance, Un, by reference glazing: Stockholm.



A **B** **C**

D **E** **F**

Figure 5.33 Dependence of monthly mean space heating demand on shaded night-time thermal transmittance, Un, by reference glazing: Budapest.

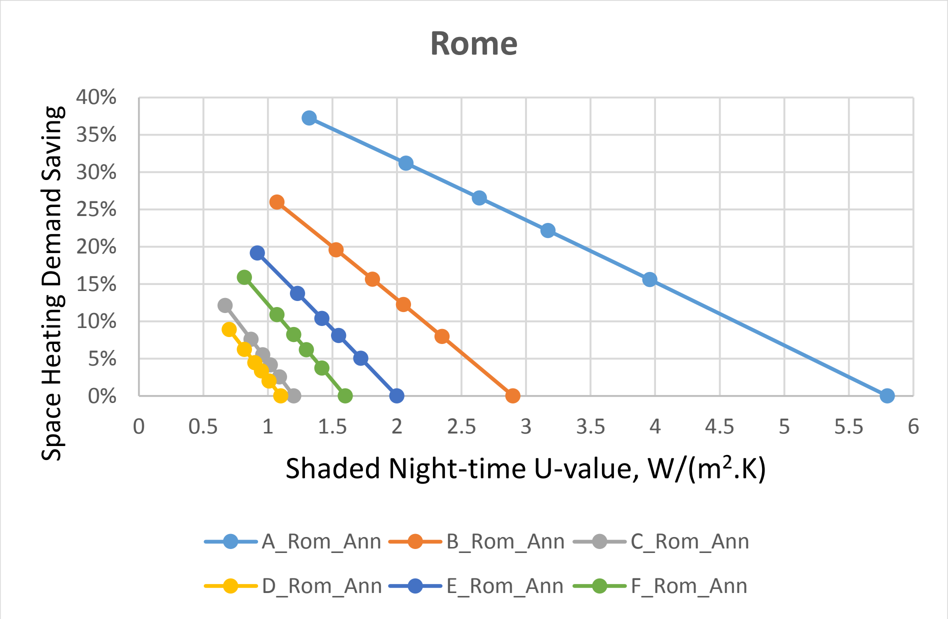


Figure 5.34 Percentage annual space heating demand saving on shaded night-time thermal transmittance, Un, by reference glazing: Rome.

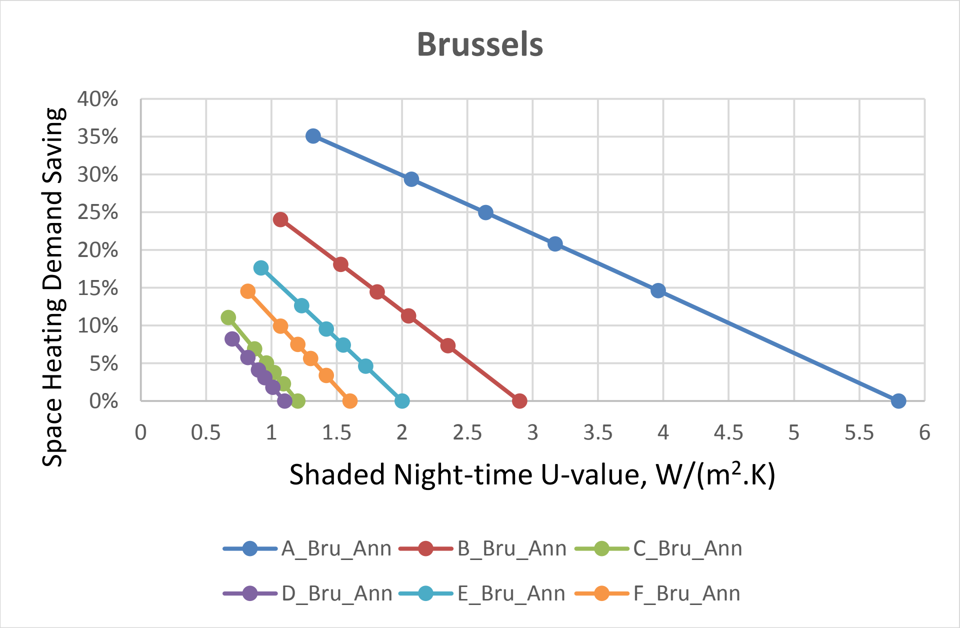


Figure 5.35 Percentage annual space heating demand saving on shaded night-time thermal transmittance, Un, by reference glazing: Brussels.

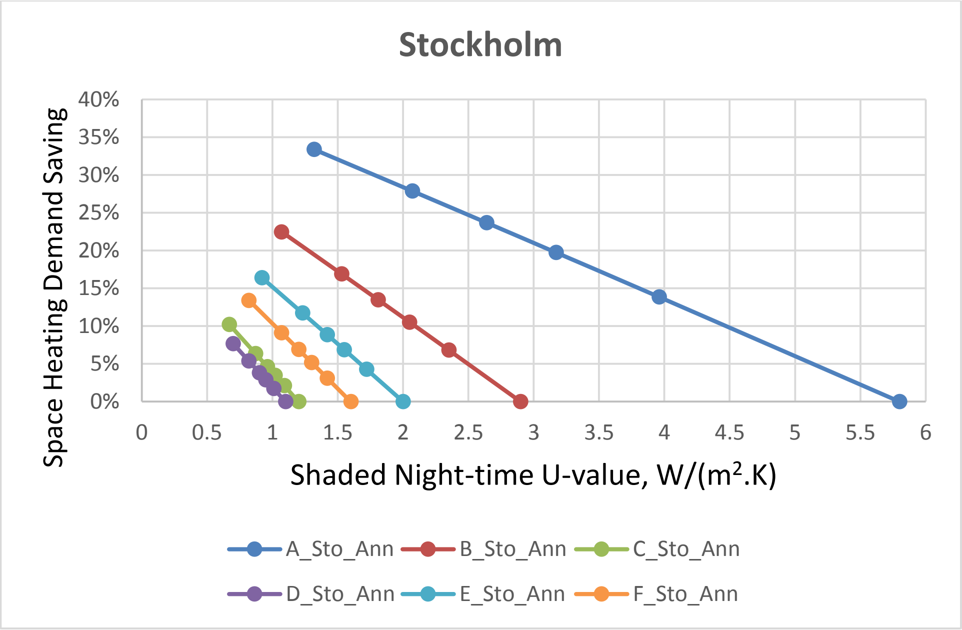


Figure 5.36 Percentage annual space heating demand saving on shaded night-time thermal transmittance, Un, by reference glazing: Stockholm.

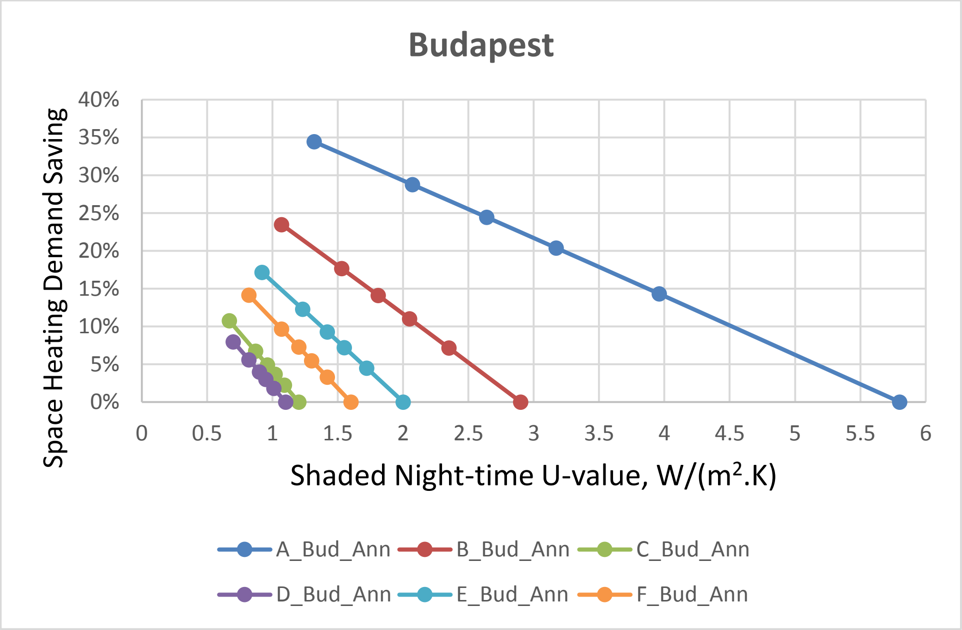


Figure 5.37 Percentage annual space heating demand saving on shaded night-time thermal transmittance, Un, by reference glazing: Budapest.

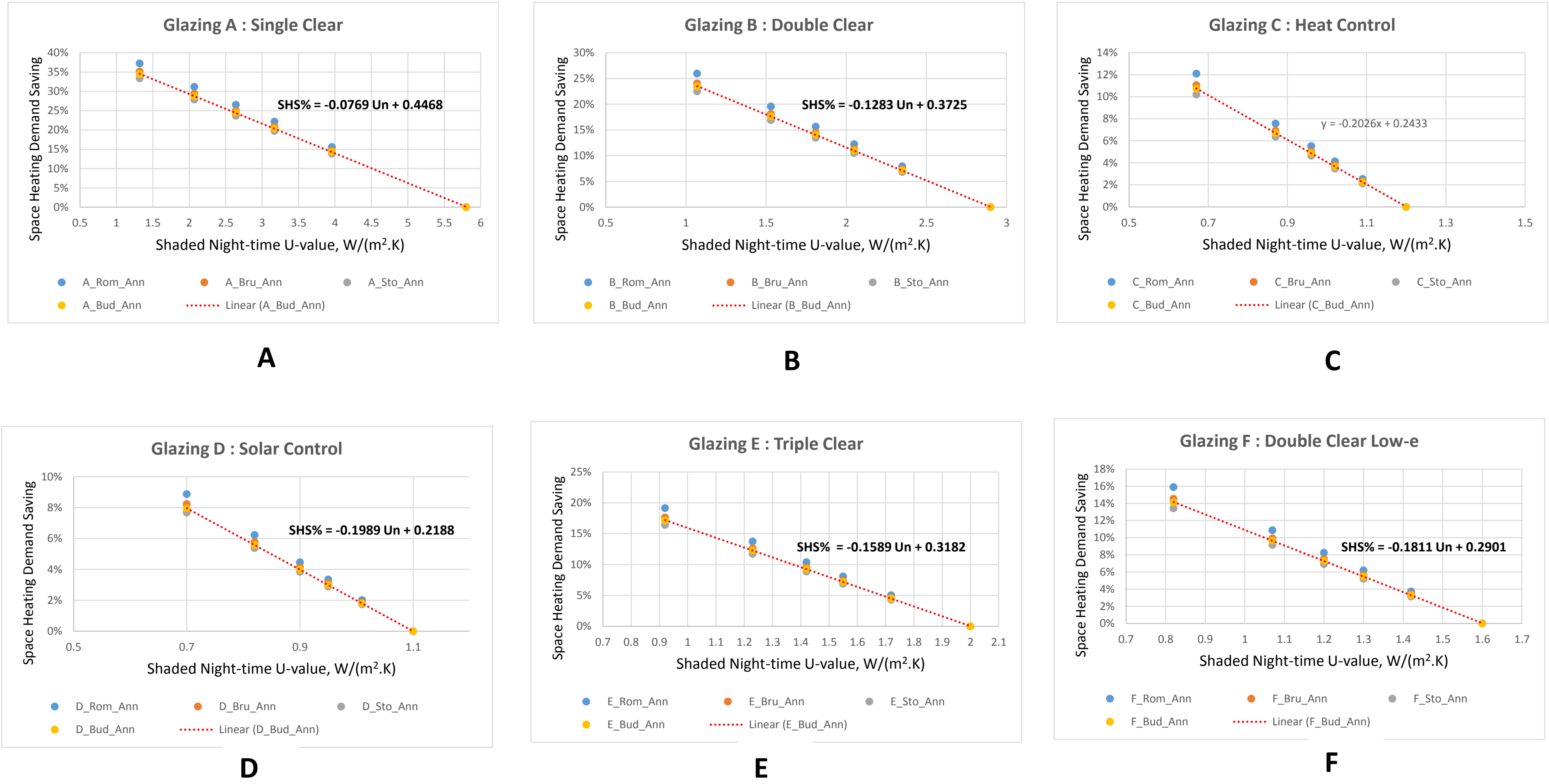


Figure 5.38 Percentage annual space heating demand saving on shaded night-time thermal transmittance, Un, by reference glazing.

5.4. Solar Shading as a Refurbishment Solution for Single and Double Glazing

Dynamic solar shading is an effective and efficient refurbishment solution for improving the thermal performance of energetically unfavourable windows. The EuroWindoor 2011 survey (2.11) estimates that 60% of existing window stock in the EU 27 Member States is energetically out of date, which corresponds to some 2.053 million window units of average area 1.3 m x 1.3 m. This number increases to 3.183 million window units for Europe as a whole. With present capacity and identifying 50% of marked volume as replacement windows, EuroWindoor estimate an average of 47 years to complete the replacement of non-energy efficient European windows. As stated earlier in Section 2.3, the Glass for Europe “Competitive low carbon economy report” (2.10) identifies that 86% of all installed glazing is energetically out-of-date and it is estimated that in the EU-28 44% of the installed glazing is single glazing and 42% is uncoated double glazing. Only 14% is high performance energy efficient glazing. The potential for dynamic solar shading to play a significant role in improving the performance of energy inefficient windows for the saving of both cooling and heating energy is hence very high.

5.4.1. Space cooling savings

The dependence of the cooling energy savings percentage on solar shading properties for single clear glazing (Glazing A) and for double clear glazing (Glazing B) by orientation and location for the locations of Brussels, Rome, Stockholm are shown in Figs. 5.39 and 5.40 respectively. The mean annual cooling energy balance in kWh/m^2/yr by each of the 4 locations for (i) single clear and (ii) double clear unshaded glazing is shown in Table 5.24 and the respective mean, maximum and minimum percentage cooling savings averaged over the 4 locations are shown in Table 5.25.

It is evident that, with sound engineering and installation of good quality products exhibiting appropriate and effective solar shading control, cooling energy savings in the order of 40% can readily be achieved by refurbishing existing energy inefficient glazing throughout Europe. This will represent an attractive economic and cost-efficient refurbishment solution. The extent of these potential cooling energy savings achievable by refurbishment are estimated and presented in Section 5.5.

Glazing ID	Glazing	Rome P (kWh/m²/yr)	Brussels P (kWh/m²/yr)	Stockholm P (kWh/m²/yr)	Budapest P (kWh/m²/yr)
A	Single Clear	-333.3	-113.3	-74.7	-181.4
B	Double Clear	-277.0	-97.7	-65.7	-153.2

Table 5.24 Mean cooling energy balance, P, of the unshaded single clear and double clear glazings by location.

Glazing ID	Glazing	Mean Cooling Savings (%)	Maximum Cooling Savings (%)	Minimum Cooling Savings (%)
A	Single Clear	46%	66%	22%
B	Double Clear	38%	64%	10%

Table 5.25. Mean, maximum and minimum percentage cooling energy savings of dynamic externally shaded glazing v. single clear and double clear glazing: All locations.

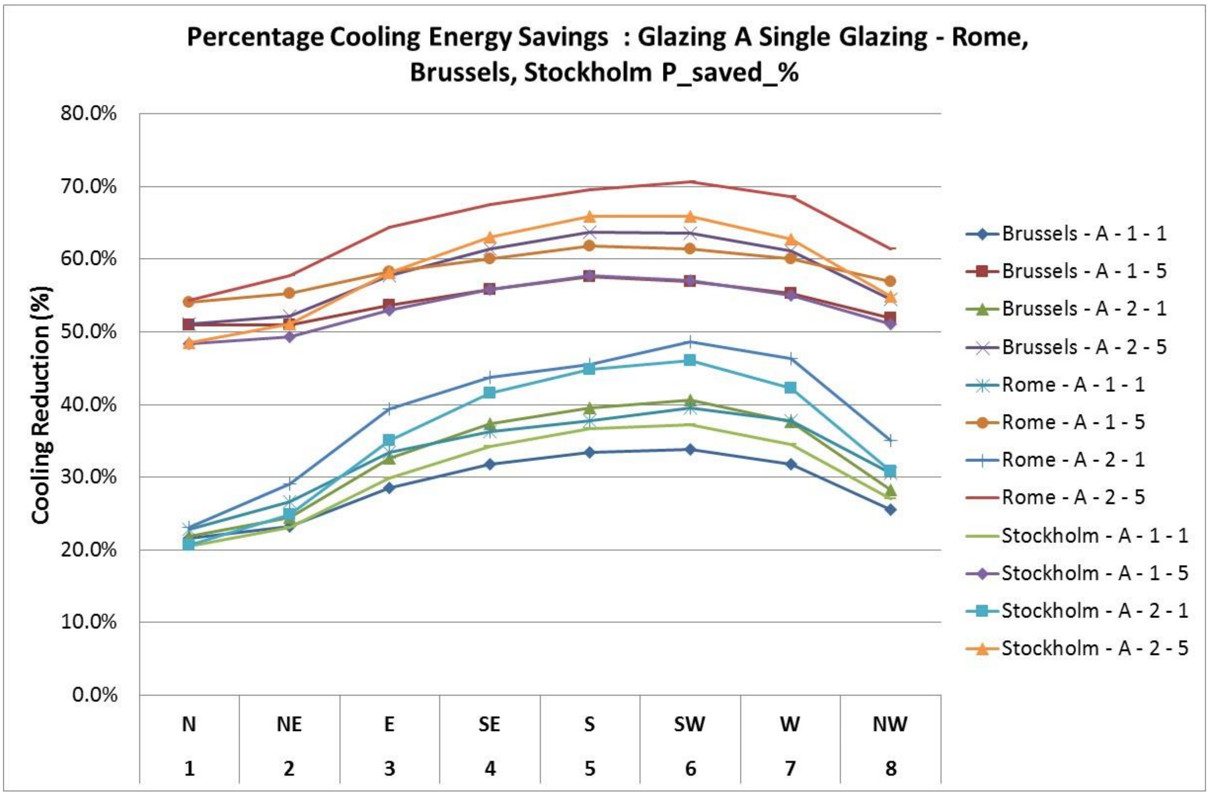


Figure 5.39. Influence of shade properties on percentage cooling energy savings of shaded single clear glazing (Glazing A) by orientation and location : Brussels, Rome, Stockholm.

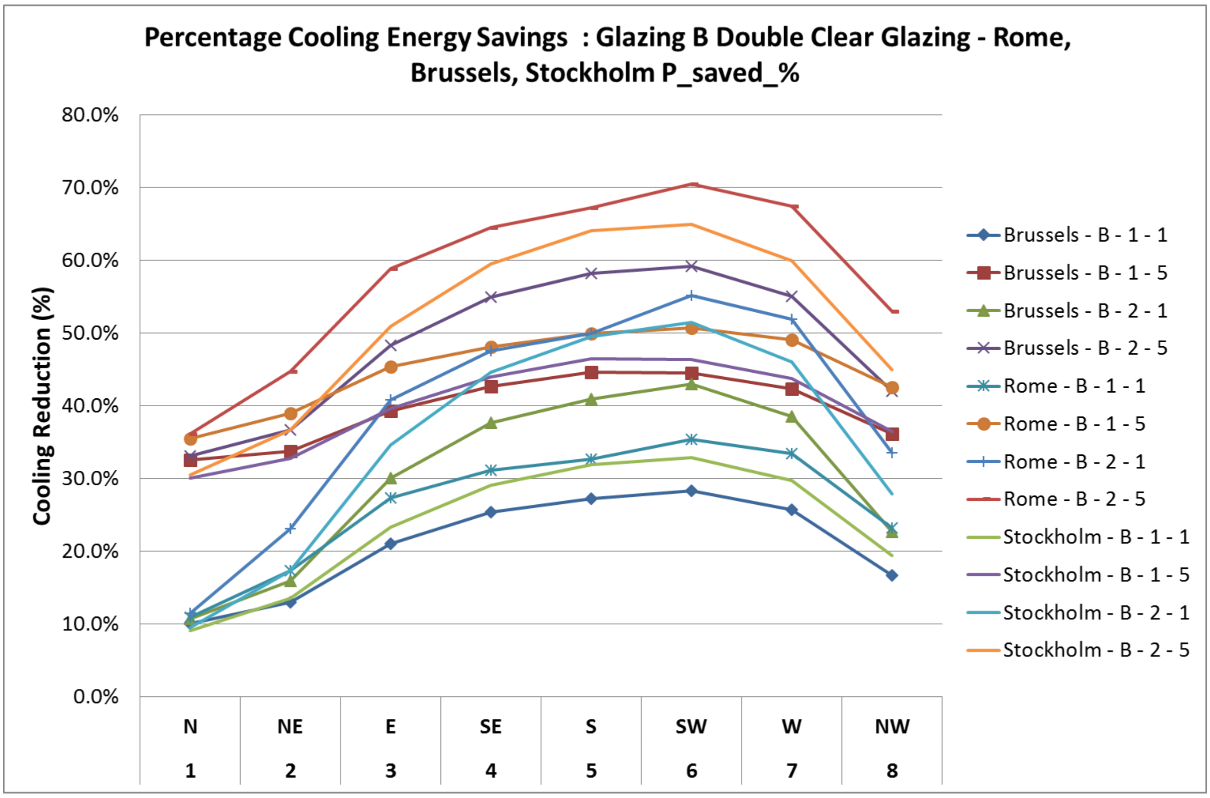


Figure 5.40. Influence of shade properties on percentage cooling energy savings of shaded double clear glazing (Glazing B) by orientation and location : Brussels, Rome, Stockholm.

5.4.2. Space heating savings

In addition to the substantial potential cooling energy savings that are realisable across Europe through the retrofitting of existing energy inefficient glazing with dynamic solar shading systems, there is a significant further energy improvement that can be attained by reducing space heating demand. As with space cooling, the refurbishment of the most poor performing energy inefficient single clear and double clear glazing results in the greatest percentage improvement of the window thermal performance. In providing enhanced thermal insulation through the closing of shutters, blinds and shading systems at night, thermal losses from the building can be significantly reduced and the energy performance of the building thereby improved.

The annual space heating demand percentage saving on the night-time thermal transmittance, Un, of the fully closed/shaded window for single clear glazing and double clear glazing are shown in Figs. 5.41 and 5.42 respectively.

As presented in Section 5.3.1, the annual space heating percentage savings, SHS%, for the unshaded single clear and double clear glazings can be estimated respectively from the expressions given in Eqns [29] and [30] :

Glazing A, Single Clear $\quad$ SHS% = 100 (0.4468 - 0.0769 Un)

Glazing B, Double Clear $\quad$ SHS% = 100 (0.3725 - 0.1283 Un)

The reasoning presented for the glazing refurbishment to achieve space cooling savings presented in 5.4.1 above are reiterated. Refurbishment of energy inefficient single clear and double clear glazing by installing good quality solar shading systems and controlling them appropriately, i.e. open by day and fully closed by night, will result in significant energy savings throughout the heating season. State-of-the-art of shading systems are more than capable of meeting heating energy savings in excess of 25% when used in combination with single clear glazing (Un ~ 2.6 W/(m^2.K), and more than 15% when used in combination with double clear glazing (Un ~ 1.8 W/(m^2.K). This again represents an attractive economic and cost-efficient refurbishment solution and energy performance figures will be improved further when dynamic shading systems are installed together with high efficiency glazings following replacement of the energy inefficient products.

The extent of these potential heating energy savings achievable by refurbishment are estimated and presented in Section 5.5.

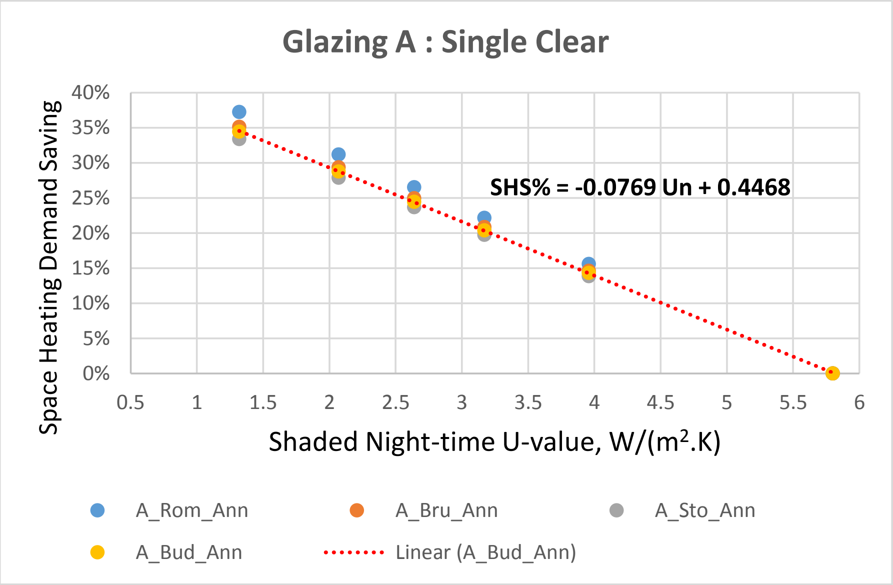


Figure 5.41. Percentage annual space heating demand saving on shaded night-time thermal transmittance, Un, for single clear glazing.

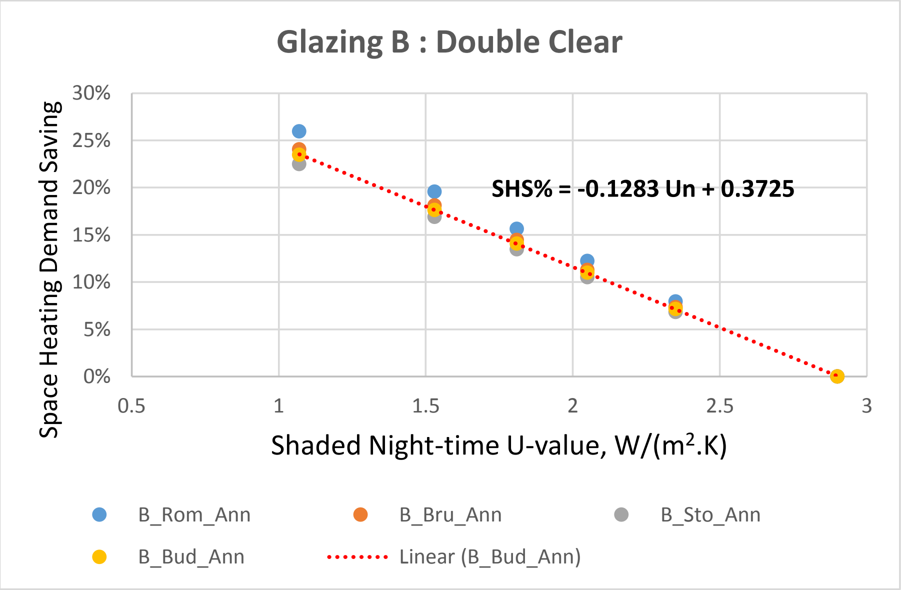


Figure 5.42. Percentage annual space heating demand saving on shaded night-time thermal transmittance, Un, for double clear glazing.

5.5. Impact of Solar Shading : Estimate of potential heating and cooling savings across the EU-28 Member States

To estimate the extent of potential cooling and heating energy savings that can result from the use of dynamic solar shading systems across the buildings of the EU-28 Member States, the energy consumption figures published in the EU 2014 pocket statistics handbook (2.1) have been assumed.

The percentage distribution of glazing type given in the Glass for Europe publication (2.9) are assumed and shown in Table 5.26. The respective glazing areas given in the EuroWindoor 2011 survey (2.10) are also assumed.

Single	Double	Energy Efficient
44	42	14

Table 5.26. The percentage distribution of glazing type in the EU-28 Member States (adapted from the Glass for Europe publication (2.9)).

The mean percentage heating energy and cooling energy savings by glazing type are taken from Tables 5.21 and 5.25 and the use of Equations (29] – [34] inclusive. The resultant savings are shown in Table 5.27 below.

Heating Saving by glazing %			Cooling Savings %		
Single	Double	Energy Efficient	Single	Double	Energy Efficient
25	15	8	46	38	30

Table 5.27. Mean percentage heating energy and cooling energy savings by glazing type.

The total EU energy consumption 2012 is taken as 1104.5 Mtoe of which 437.9 Mtoe is the energy consumption in EU residential and commercial buildings which represents 39.6% of the total (2.1).

Within the EU buildings it is assumed that 60% of the energy end-use is either for space heating or space cooling. The remainder is used for water heating, cooking, lighting and other electrical energy end-uses, e.g. appliances.

2 further assumptions are made to estimate:

- The penetration and uptake of dynamic solar shading systems
- The split of energy end-use between space heating and space cooling

We assume a 75% penetration and uptake of dynamic solar shading systems across all glazing types and apply the corresponding mean percentage heating energy and cooling energy savings by glazing type as in Table 5.27.

The calculations are performed for 2 relative splits of energy end-use between space heating and space cooling :

(i) An even split of 50% space heating 50% space cooling
(ii) A split of 70% space heating for and 30% for space cooling

The results obtained are presented in Table 5.28

EU Annual Energy and CO_2 figures	Assumed Energy End-Use Split 50% Heating; 50% Cooling		Assumed Energy End-Use Split 70% Heating; 30% Cooling	
		% Savings		% Savings
Total Heating Energy (Mtoe)	131.37		183.92	
Total Cooling Energy (Mtoe)	131.37		78.82	
Heating savings (Mtoe)	18.15	14%	25.41	14%
Heating CO2 savings ($MtCO_2$)	43.07		60.29	
Cooling savings (Mtoe)	39.81	30%	23.88	30%
Cooling CO2 savings ($MtCO_2$)	94.46		56.67	
Total Energy Saving (Mtoe)	57.95	22%	49.29	19%
Cooling CO2 savings ($MtCO_2$)	137.52	22%	116.97	19%

Table 5.28. Estimated heating energy and cooling EU buildings energy savings resulting from use of dynamic solar shading systems.

For an energy end-use split of 50:50 between space heating and space cooling the impact of dynamic solar shading systems is estimated to be a 30% saving in cooling energy use of 39.8 Mtoe/yr and a 14% saving in heating energy use of 18.2 Mtoe/yr. Taken together the potential energy savings which can accrue from the use of dynamic shading systems are a 22% saving in heating and cooling energy use of 59 Mtoe/yr and a carbon emissions reduction of 22% equivalent to a saving of 137.5 $MtCO_2$/yr.

For an energy end-use split of 70:30 between space heating and space cooling the impact of dynamic solar shading systems is estimated to be a 30% saving in cooling energy use of 23.9 Mtoe/yr and a 14% saving in heating energy use of 25.4 Mtoe/yr. Taken together the potential energy savings which can accrue from the use of dynamic shading systems are a 19% saving in heating and cooling energy use of 49.3 Mtoe/yr and a carbon emissions reduction of 19% equivalent to a saving of 117 $MtCO_2$/yr.

It should be noted that figures for the distribution of the primary energy sources, e.g. coal, gas, oil, electricity etc, used for heating and cooling across the EU Member States is not known by the authors. Hence the equivalent CO_2 emissions figures do not discriminate between respective energy sources employed for space heating and space cooling and have been set equal in all cases.

CO_2 emission figures will vary by MS but representative figures may resemble those reproduced in Table 5.29:

Primary Fuel Type	CO2 Emissions Equivalent
Coal:	0.382 $kgCO_2/kWh$
Mains gas:	0.206 $kgCO_2/kWh$
Electricity from grid:	0.591 $kgCO_2/kWh$
Oil:	0.284 $kgCO_2/kWh$
Biomass:	
Wood pellets:	0.037 $kgCO_2/kWh$
Wood chips:	0.015 $kgCO_2/kWh$
Wood logs:	0.018 $kgCO_2/kWh$

Table 5.29. Representative carbon dioxide equivalent emissions per kWh of primary energy source.

If the distribution between the relative need for heating and cooling is known accurately the above calculations can be refined and improved. Historically there has been a rapid growth in the demand for space cooling and this can be expected to continue to increase. Since the impact of dynamic solar solar on energy end-use is greater for cooling than for heating, and the demand for space cooling increases then the impact of the savings which will result from intelligent use of solar shading will be much greater.

Furthermore the overall energy performance figures for EU buildings will only be improved and final energy use demands decreased when more energy efficient replacement glazings are also installed and combined with appropriate dynamic shading systems for controlling both solar gain and thermal loss.

5.6. Summary of findings of previous studies

5.6.1. The ES-SO ESCORP EU-25 Study, Europe

The study commissioned by ES-SO in 2005 (1.5) investigated the potentials for energy saving and CO_2 emissions reductions in the existing building stock in the then EU-25 Member States through the use of solar shading. The study predicted feasible and significant cooling energy and heating energy savings of 31 Mt/annum CO_2 reduction through a 12 Mtoe/annum reduction of heating demand and an 80 Mt/annum CO_2 reduction through reduction of 31 Mtoe/annum cooling demand. Taken together these savings represent an approximate 10% reduction in the energy end-use of the EU-25 building sector (455 Mtoe/annum in 2005).

The savings predicted in this study are a little higher than those reported in the ESCORP report but are broadly in close agreement.

Additional simulations performed by ES-SO are reported (3.2) which analyse the annual energy requirement for heating, cooling and lighting for offices in Stockholm, Amsterdam and Madrid. The simulations were run for 3 glazing types which in performance are close to the reference glazings, B Double Clear, C Heat Control and D Solar Control, of the current study. Exterior Venetian blinds were employed as the dynamic shading component. Slat angles were continuously adjusted to block direct solar radiation. The control strategy employed avoided rejecting solar gain for passive heating purposes.

The results obtained are not presented in detail here but are consistent with the results presented in the present study. For Stockholm, the annual energy demand for cooling is predicted to be reduced by more than 70% for southerly orientations with small increases in energy demand for heating and lighting. The importance of glazing selection is evident; primary energy requirements are lowest for the low-e glazing (C Heat Control) which allows high solar gain in the heating period. The results for Amsterdam are similar to those reported for Stockholm. Solar shading is effective in reducing cooling loads by some 50% across all orientations between east through south to west. The Madrid results identify the solar control glazing (D) as the optimum glazing coice. Solar shading in combination with solar control glazing is predicted to reduce primary energy requirements of an office by some 30% when compared to the unshaded glazing of the same type.

5.6.2. Energy Savings from Window Attachments (LBNL, USA)

The Energy Savings from Window Attachments study published in 2014 (4.15) was undertaken by the Lawrence Berkeley National Laboratory (LBNL) to provide support for the “Certification and Rating of Attachments for Fenestration Technologies” CRAFT (5.6) currently in development.

The LBNL study is extensive and presents “energy-modelling results for a large number of window combinations with window attachments (shades) in typical residential buildings throughout the United States”. 4 types of typical houses in 12 climatic zones were analysed. A matrix of 16,486 energy analysis simulations in EnergyPlus (5.7) was generated.

3 baseline windows, respectively Clear single glazing and aluminium alloy frame, Clear double glazing and wood frame and Double glazed low-e and vinyl frame are combined with 11 window attachment product categories. Within each category 4 “product qualities” are defined and the shades are deployed in 3 different positions (Open, Half-open, Fully Closed). A selection of representative performance parameters for shaded double clear glazing is shown in Table 5.30.

Product	Emissivity		Transmittance		Reflectance		Angle	U-value (W/m2.K)		g- value (SHGC)	
	High	Low	High	Low	High	Low		Low	High	Low	High
Baseline window								2.78		0.59	
Horizontal blind	0.9	0.1	0.05	0	0.9	0.1	0	2.56	2.61	0.55	0.58
							45	2.44	2.56	0.33	0.51
							90	2.04	2.38	0.12	0.46
Vertical blind	0.9	0.1	0.05	0	0.9	0.1	0	2.61	2.61	0.59	0.59
							45	2.50	2.61	0.38	0.52
							90	2.04	2.38	0.12	0.46
Roller Shades	0.9	0.1	0.5	0	0.8	0.05	N/A	1.65	2.61	0.14	0.54
Cellular shades	0.9	0.1	0.5	0	0.8	0.1	N/A	1.14	2.44	0.15	0.48
Exterior solar screens	0.9	0.1	0.5	0.1	0.8	0.05	N/A	1.82	2.27	0.10	0.34

Table 5.30. Representative performance characteristics U-value / g-value (SHGC) by quality of shade category for Double Clear Glazing Combinations (from Energy Savings from Window Attachments (4.14).

The study finds that in the southern (cooling dominated) climates all window attachments save energy for all qualities. In the northern (heating dominated) climates interior panels and exterior storm panels consistently show the lowest energy use. Cellular shades with very good insulating properties show the lowest energy use. Some shades provide energy savings in specific climates but not all operable shades save energy in all climates. Mixed energy savings are predicted in northern and central climates due to either (i) variable insulation or (ii) reducing solar gain. Exterior shading is generally found to be more effective in saving cooling energy.

The study identifies the value and importance of improved manual operation or developing more cost-effective approaches to automating operation. Overall energy performance is found to be highly dependent on “use” or control of the shades. More intelligent and responsive use always improves energy performance. It is recommended to expand study to examine energy savings of sensor-controlled motorised shading systems where the expectation is that such operation would maximise energy savings.

The findings underline and confirm the extensive potential that solar shading systems have to reduce cooling and heating demands in buildings.

The US Department of Energy Buildings Technology Office prioritisation tool indicates that the use of insulating and reflective fenestration shading attachments is a cost-effective energy savings measure. An economic potential to save ~ 4500 TkWh by 2030 (800 TBTU) is estimated due to their low cost and rapid turnover of the installed base. The calculations assume that 50% of windows are covered with attachments.

The US DOE is exploring the opportunities to promote more extensive use of improved window attachments and is working with the shade industry to rate and certify the properties and performance of window attachments. The Window Covering Manufacturers Association (WCMA) has been awarded cost-shared DOE funding to launch the Attachments Energy Rating Council (AERC).

AERC will develop an energy efficiency rating and certification system for window attachments together with a public domain database of shading products. Over the next four years, AERC will develop a program that provides a consistent set of energy performance-based rating and certification standards and program procedures to assist consumers in realising the significant potential energy savings which can arise from the appropriate use of dynamic solar shading. An inaugural meeting of AERC was held a membership meeting in Alexandria, Virginia, USA on 8-9 April 2015 (5.8).

5.6.3. Benefits of shading and night cooling by vent windows (TU Delft)

A scientific feasibility study was undertaken by the Technical University of Delft, NL (5.9) to investigate the management of dynamic facades concept that combines the control of solar shading, vent windows and the Heating, Ventilating and Air Conditioning system (HVAC). In the majority of combinations investigated, solar shading systems result in lower energy consumption and allow reduced size of HVAC systems and thereby lower costs. When the use of dynamic solar shading is compared to a window with uncontrolled Venetian blinds, CO_2 emissions are predicted to be reduced by 18%. The CO_2 reductions can be increased to 28% if night cooling is applied in combination with motorised windows. Cost savings are optimised through the integrated design of the façade and the HVAC system. Integrated HVAC systems in combination with dynamically shaded window systems are shown to be cost-effective with pay back periods below one year.

5.6.4. Awnings and solar protective glazing for efficient energy use in cold climates / Solar shading for low energy use and daylight quality in offices (Lund University)

Annual energy use for heating and cooling of a single-occupant office room located in Sweden was analysed for 8 solar-protective glazing options and one shading system (5.10, 5.11). Shading devices are shown to reduce thermal losses through the window significantly, especially if the device is airtight, has a low emissivity and is multiple layered. Cooling energy savings in the range 23% - 89% are identified resulting from the use of solar shading. The studies identify a strong orientation dependence when considering energy efficiency and the need to employ flexible shading strategies which maximise solar gain during the heating season and a reduced solar gain during the cooling season.

5.6.5. Energy savings from controlling solar shading (BRE)

The energy and thermal comfort implications of installing solar shading with automatically controlled shading are examined (5.12). In addition to energy saving, the benefits in controlling overheating and glare are investigated. 4 cases identifying internal and external shading with either manual or automatic control are compared with a “no shading” base case. Buildings are modelled for 3 UK locations. Overall building energy cost savings of 10% are predicted for air-conditioned offices employing automatically controlled solar shading systems. In the case of a naturally ventilated hospital, automatically controlled external; saving significantly reduced summer overheating avoiding the need to install cooling in some cases. Some energy penalties are predicted if manually controlled shading is not optimised.

5.6.6. Estimation of the performance of sunshades using outdoor measurements and the software tool PARASOL V2.0 (Lund University)

External sunshades have a much greater potential to reduce cooling loads and unwanted solar gains than internal or mid-pane products since the absorbed heat is mainly dissipated to the outdoor air (5.13). The study indicates the importance of moveable shading. For an appropriately controlled dynamic solar shading system, cooling energy saving potentials which vary between 23% and 89% are predicted in south-facing offices. The importance of preserving acceptable levels of visible transmittance is emphasised to ensure that daylight transmission is sufficient. Minimising solar gain by reducing the window g-value to extremely low values can both decrease acceptable light levels within the building and obstruct the view to the outside.

5.6.7. Glazings in buildings – reducing energy use (NEF)

The National Energy Foundation (NEF) 2015 publication (5.14) examines the operational energy reduction potential driven by energy efficient glazing uptake in the UK existing building stock. NEF find that 8.7% of the overall energy used in UK homes (48,625 GWh/yr, 8.7 Mt CO_2/yr) can be saved if energy efficient glazing is installed. The study identifies an optimal solar control strategy designed to maximise solar gain in winter and heat rejection in summer through the use of dynamic (adaptable) solar shading systems with variable configuration under summer and winter conditions. Advancements in control are identified as likely to favour automated solar shading systems capable of offering versatile solutions to building occupants. Furthermore overheating in highly glazed facades, e.g. commercial office buildings, is recognised as a potential problem requiring the implementation of appropriate solar shading solutions.

6. Overheating, Health, Comfort and Productivity

6.1. Overheating in buildings

Overheating is a common problem in buildings and often occurs during periods of warm weather or exposure of the building and/or glazing to high levels of solar irradiance. Overheating can occur in all types of existing and new buildings. There has been rapid growth in the sales and use of air conditioning systems worldwide. Europe has witnessed substantial growth at all latitudes; in the developing economies of the Far East the growth in the use of air conditioning systems has been much faster. The effects of global climate change create more difficult conditions for achieving energy efficiency and thermal comfort in buildings.

Many factors can contribute to overheating, such as building orientation, glazed area, thermal occupant behaviour, internal gains etc. Natural ventilation and solar shading provide sustainable means to combat overheating but in many situations, in both commercial and residential buildings, indoor temperatures are commonly controlled by mechanical ventilation (6.1). Control of unwanted, excess solar gain is a vitally important factor in improving indoor environmental quality and increasing occupant thermal comfort. Dynamic solar shading is proven to be a highly effective and energy efficient means to combat overheating, simultaneously improving indoor quality and comfort whilst reducing cooling energy use and an overdependence and reliance on air conditioning (6.2).

The proportion of the world's population living in cities has been steadily increasing and since 2007, the majority of the world's population lives in urban areas. The United Nations 2014 Revision of World Urbanization Prospects (6.3) shows that urban population as a proportion of total population has risen from 47% in 2000 to 54% in 2014. The pace of growth of urbanisation has been rapid. The World Health Organisation (WHO) report that "a billion more people were added to urban areas within a span of 14 years. Global urban population increased from 2.86 billion in 2000 to 3.88 billion in 2014. The global urban population is expected to grow approximately 1.84% per year between 2015 and 2020, 1.63% per year between 2020 and 2025, and 1.44% per year between 2025 and 2030" (6.4). In 2014, the most urbanized regions include Northern America (82 %), Latin America and the Caribbean (80 %), and Europe (73 %). The impact of urbanisation on population health, health equity and the environment are key concerns for national and municipal authorities.

6.2. Health

The UK Housing Health and Safety Rating System (HHSRS) defines health effects of heat:

"As temperatures rise, the thermal stress increases, initially triggering the body's defence mechanisms such as sweating. High temperatures can increase cardiovascular strain and trauma, and where temperatures exceed 25 ^{0}C, mortality increases and there is an increase in strokes. Dehydration is a problem primarily for the elderly and the very young" (Office of the Deputy Prime Minister (ODPM) Housing Health and Safety Rating System (HHSRS): Operating Guidance, London, ODPM, 2006, (6.5)).

The effects of climate change are further exaggerated in urban environments. The phenomenon of localised temperature rises through the "urban heat island effect" is well documented (Ref). Temperature maxima are higher and more frequent. Heatwaves may persist for several days and hot spells have a longer duration. Major European cities, e.g. Athens, Lisbon, Madrid, Paris, Rome, face an important temperature increase. Heat Island intensity ranges between 1-10 ^{0}C Heat Island is present in low, mid and high latitude locations and observed during the day and the night periods. During the day period the heat island contributes to a high increase of discomfort hours, an increase in the cooling load of buildings and a very high increase of the peak electricity demand. By night the cooling potential of night ventilation techniques is reduced. High temperatures increase the vulnerability of citizens and in particular of low income people and those in vulnerable groups, e.g. the aged. Studies in Europe have shown that the greatest excess in mortality was registered in those with low socio-economic status living in buildings with improper heat protection and ventilation. Poor design and uncontrolled development of urban areas increase the heat island intensity. There is real concern that climate change will cause more frequent periods of extreme heat and increase the risk of serious health problems and lead to an increased number of deaths (6.6, 6.7).

In the United Kingdom the urban population has increased by 30% in the past 50 years (6.1). Throughout Europe people are living longer and the percentage of the ageing population is increasing. In addition a greater proportion of people are spending more of their time indoors.

There is increasing evidence that some existing dwellings are overheating for very significant periods of the year. High night-time temperatures adversely affect sleep and recovery from high day-time temperatures. The risk of overheating is increased in buildings which have limited opportunity for cross-ventilation. For reasons of security, pollution and noise, the opening of windows for night-time cooling particularly in urban locations is often not a favoured option. The problem can be worsened in small apartments and in airtight, lightweight houses with little or no solar shading.

6.3. Thermal Comfort

In this Section, it is shown that the use of dynamic solar shading to reduce cooling energy demand can also improve the quality of the indoor environment and raise the comfort category of the building.

The provision of comfort is a key concern for building designers. Mechanical cooling is energy intensive. Naturally ventilated (NV) buildings with fewer energy costs cannot control indoor conditions closely. Formally standards have used comfort models which favour close environmental control. ISO 7330 expresses thermal comfort in terms of predicted mean vote (PMV) based on an energy balance model and is appropriate for tightly controlled indoor environments (6.8).

ISO 7330 mitigates against free running, naturally ventilated buildings, where occupants have more control over their environment, e.g. openable windows more closely linking with external environment,. Free running buildings are the most common type of UK building where AC and MV are much less common than in continental Europe, e.g. Greece, Italy, Spain. Occupants may be more tolerant to temperature changes, change clothing, open windows, employ desk-top fans etc. to achieve greater comfort. This occupant driven adaptive means is now an accepted alternative means of measuring thermal comfort.

6.3.1. EN 15251 and the EU COMMONCENSE Project

The European Standard EN 15251 (6.9) defines acceptable indoor temperatures and light levels as the basis for energy calculation. EN 15251 requires indoor thermal comfort conditions to be assessed and to fall within a 4 category system for different levels of expectation and building purpose (see Table 6.1) and allows NV buildings more freedom for environmental variation in line with the findings of comfort theory.

For Naturally Ventilated (NV) buildings in free-running mode the comfort temperature (T_{comf}) is calculated according to the running mean of the outdoor temperature using the formula (6.10)

$$T_{comf} = 0.33\ T_{rm} + 18.8. \qquad [35]$$

The allowable maximum difference between this predicted comfort temperature and the actual indoor operative temperature (T_{diff}) is given in terms of the categories (T_{diff} ±2K for Category I, ±3K for II and ±4K for III see Table 1). This means that the limiting temperatures vary with the running mean of the outdoor temperature (Fig. 1). The limits of the range of acceptable operative temperature are shown in Figure 6.1 for each of the 'categories' of building. The categories are associated with limitations as to PMV (mechanically cooled buildings) or temperature deviation from the adaptive comfort temperature (free-running buildings) as definitions for thermal comfort. These limitations are introduced and described in the informative annexes. Because close control is costly in energy this categorisation is at variance with the aims of the EPBD.

For UK buildings which are mainly not air conditioned, maximum allowable difference from the comfort temperature is 3-4 ^{0}C. The maximum operating temperature in summer for Category II (normal expectation, used for new buildings and renovations) is 26 ^{0}C and for Category III (moderate expectation, existing buildings) is 27 ^{0}C. Figure 1 shows the upper and lower limits of comfort. The upper limit is referred to as "overheating".

The EU COMMONCENSE project (6.11) investigated the energy implications of EN15251 and in particular whether the standard encourages high-energy use buildings in the cases of new buildings and major rehabilitations.

The energy consumption of typical buildings in different climates necessary for compliance with the respective comfort categories of EN 15251 was determined against EPBD energy benchmarks. And made recommendations for a redefinition of the thermal comfort categories in order to minimise the energy consumption and improve the environmental quality of buildings. The new categorisation is recommended to take into account the real ventilation needs of the building as a function of the occupancy. Advanced control systems should operate intelligently to control the ventilation rates and solar gains, avoiding unnecessary ventilation losses and reducing the energy consumption for heating and cooling. The redefinition should take into account the variability of internal gains and advanced lighting systems should be properly integrated. Through these means energy consumption of buildings could be minimised, while the adaptive thermal comfort conditions are obtained.

COMMONCENSE showed that buildings do not behave as standards would like, in particular that different areas/zones of a single building can be in different "comfort categories" at any one time. A more flexible approach to comfort classification must be embodied by standards if they are to be widely employed and respected.

In addition, lighting standards developed to date fail to meet realistic practical levels and that far greater attention needs to be paid to ensuring lighting efficiency on buildings.

Of most relevance to the current study of the influence of high performance dynamic shading systems on the energy performance and comfort in buildings are the COMMONCENSE studies which investigated the energy cost of comfort (6.12). The required cooling and heating energy consumption of 28 buildings of different types (offices, hospitals, schools, residences) in 5 European countries (Greece, Austria, Italy, United Kingdom and Portugal). Simulations were performed assuming that the buildings belong to each of the EN 15251 thermal comfort categories I, II and III. The calculated energy consumption for each type of building was compared against existing national benchmarks. Example COMMONCENSE results are shown in Figs 6.2 - 6.5.

The percentage reductions predicted by COMMONCENSE in required energy for both cooling and heating are consistent with the savings that will accrue from the effective use of high performance dynamic shading systems as presented in Sections 5.2 and 5.3. Hence not only will dynamic shading systems reduce building energy consumption significantly but they will also produce greater thermal comfort and improve the quality of the internal environment. The data also indicate the enhanced benefits that will result from the integration of dynamic solar shading with demand side ventilation and advanced lighting systems through advanced control and building management systems.

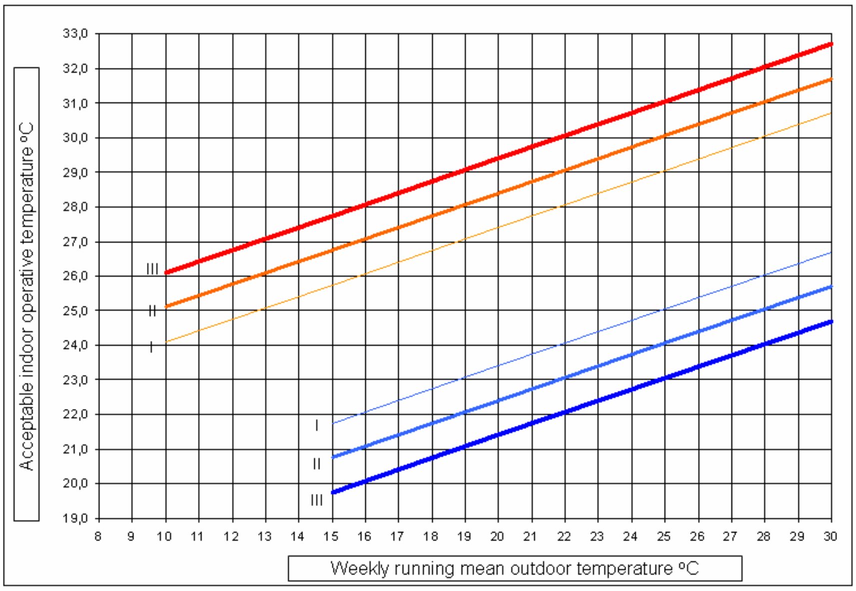


Figure 6.1 Temperature limits for NV buildings in free-running mode (after EN15251, (6.9))

Category	**Explanation**	**Temperature Limit (K)**	**Limit of the predicted mean vote (PMV)**
I	High level of expectation only used for spaces occupied by very sensitive and fragile persons	±2	±0.2
II	Normal expectation for new buildings and renovations	±3	±0.5
III	A moderate expectation (used for existing buildings)	±4	±0.7
IV	Values outside the criteria for the above categories (only acceptable for a limited periods)		

Table 6.1 The comfort categories of European Standard EN15251 and their associated acceptable ranges of operative temperature around the adaptive comfort temperature (free running buildings) or Predicted Mean Vote (mechanically cooled and heated buildings)(6.9).

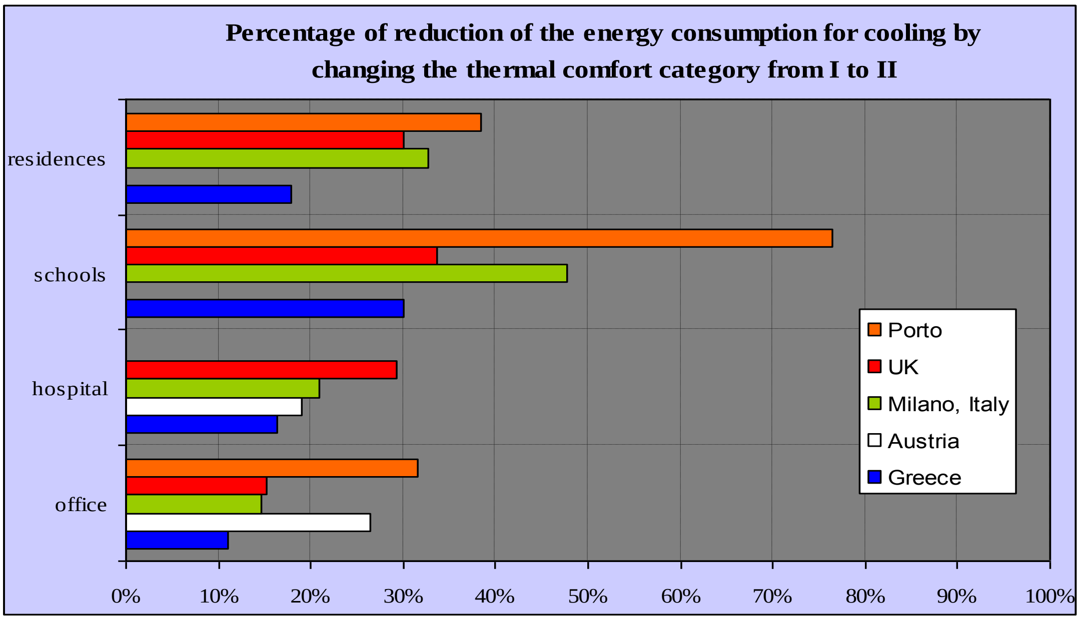


Figure 6.2. The percentage of reduction of the Final Energy Consumption for cooling by changing the thermal comfort category from I to II, in representative buildings, in various climates (6.12).

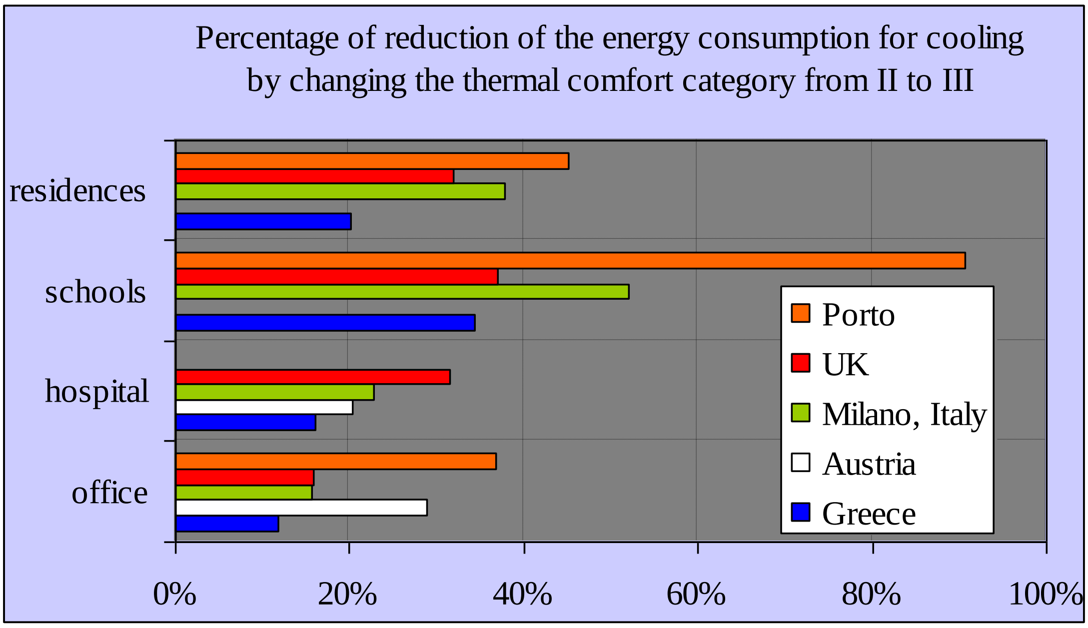


Figure 6.3. The percentage of reduction of the Final Energy Consumption for cooling by changing the thermal comfort category from II to III, in representative buildings, in various climates (6.12).

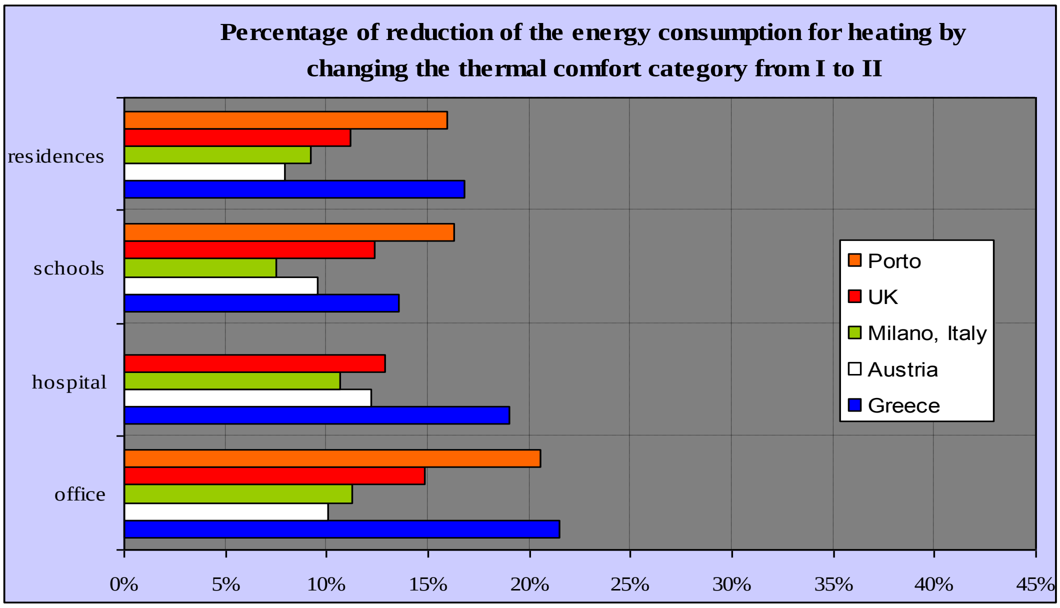


Figure 6.4 The percentage of reduction of the Final Energy Consumption for heating by changing the thermal comfort category from I to II, in representative buildings, in various climates (6.12).

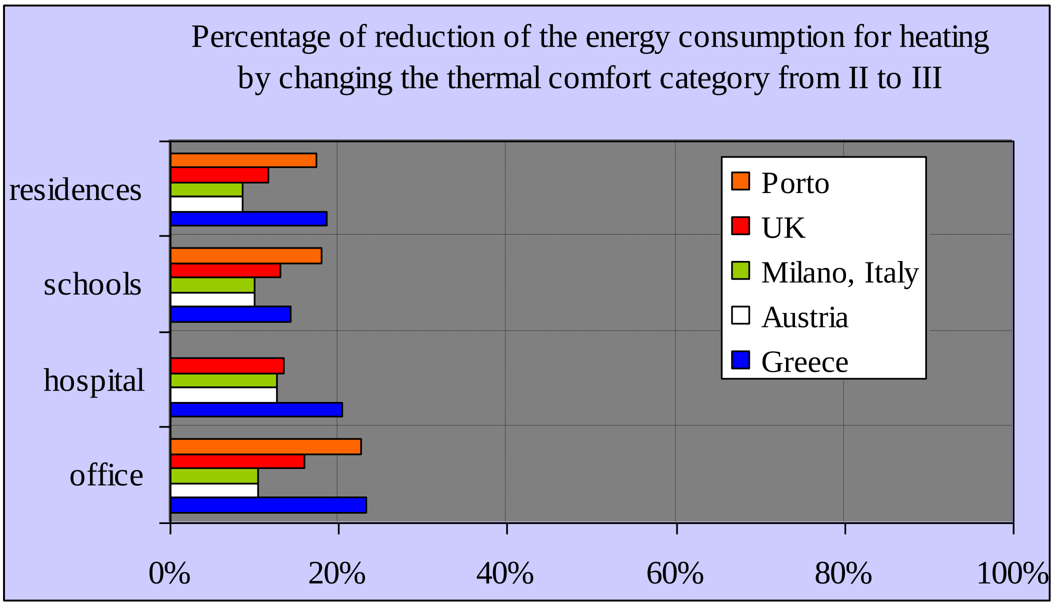


Figure 6.5 The percentage of reduction of the Final Energy Consumption for heating by changing the thermal comfort category from II to III, in representative buildings, in various climates (6.12).

6.4. Daylight, Visual Comfort and Glare

The use of solar shading devices is the most efficient means to reduce the cooling demand in buildings. Artificial lighting can be another significant component of the overall energy consumption of non-residential buildings. Innovative daylighting systems employing solar shading integrated with dimming lighting control systems can make very effective use of daylight, lower electricity consumption and reduce adverse environmental impacts.

The admission of daylight into buildings has been fundamental to architecture for centuries. Only in modern times, with the availability of relatively cheap energy and electric lighting, has artificial light become an option to daylight. This has led to the design of deep plan buildings often with sealed windows and the provision of light and ventilation from the natural outdoor environment is largely ignored. In such situations lighting and related mechanical cooling energy can represent as much as 40% of the total energy use of a commercial building (6.13).

High performance buildings must demonstrate energy efficiency and low operating costs whilst delivering comfort and satisfaction to the occupants and aid their productivity. Admission of daylight is in principle the most efficient way to light a building. The luminous efficacy, i.e. the useful visible light in relation to the total energy of the radiation is high. (The heating effect of daylight is about 1 W per 100 1m, which is between 1/2 and 1/10 of typical artificial lighting). Artificial lighting consumes electricity, usually on-peak electricity, whereas daylight is free. Interiors with good daylight will also provide visual contact to the outside and there is evidence that this can promote productivity and provide well-being for the occupants (6.14).

There are some disadvantages of daylight to be considered. Capital expenditure on the lighting system if artificial lighting has to be provided for occupation during the hours of darkness. The source of light, i.e. the sky varies in its brightness over a wide range. A window sized to provide sufficient daylight in dull sky conditions will admit too much light in bright conditions. Direct sun may also enter the space creating visual discomfort and glare. In buildings with large room depth, illumination levels close to the window will normally be much higher than those in the darker parts of the room (6.15).

Daylighting design can be complex. The quantitative parameter of importance is the Daylight Factor (DF)-defined as the ratio of the daylight illuminance in the building to that outside (6.13). In temperate climates daylight factors typically range between 0.5 and 5% according to building type. In tropical climates the sky brightness can be much higher and the direct component of the sun's radiation much greater than its diffuse component. Design seeks to reduce the daylight factor to combat over-illumination. The glare control, i.e. the capacity of the solar protection device to control the luminance level of openings and to reduce the luminance contrasts between different zones within the field of vision, is classified in Table 8 of EN 14501 (4.7) by the parameters normal-diffuse visible transmittance, $\tau_{v,\,n\text{-}dif}$, and the normal-normal direct visible transmittance,$\tau_{v,\,n\text{-}n}$. The ability of the shade to control glare is improved by reducing the direct transmittance and increasing the diffuse transmittance.

An integrated approach which views the building as a whole and assesses interactions between the components of the building façade, e.g. the fenestration and the electric lighting system may result in an automated window shading system working together with a dimming lighting control system. Buildings provided with fixed shading can reduce daylight transmission and produce semi-dark interiors. A smart control strategy which can alter the degree of shading present is key for achieving optimal performance.

Daylighting systems can be very varied in form and function. Some innovative examples include redirectional glazing, e.g. prismatic glass, lightshelves and reflectors, lightpipes and lightducts, transparent insulation. A detailed examination of these systems is outside of the scope of this work but is well documented elsewhere (6.16, 6.17). In this study the focus is on shading solutions for effective daylighting.

Shading selection, dimensioning and positioning will depend upon building form, use, climate and the daylight source itself. Solar shading devices of interest here which can provide both shading and daylighting include louvers and blind systems and may be positioned on the exterior or interior of any window or rooflight. The shading may be located between the glazing panes or within the cavity of the envelope of a double skin façade. They may continuous or slats which can be inclined to the horizontal or vertical.

Fig 6.6 shows details of the automated shading system employed in the Shard building in London, UK (6.18). The active facade-shading system which is deployed over more than 10,000 glazed modules. The façade comprises a triple-glazed system: single pane on the outside, ventilated inner cavity housing a motorised solar-control roller blind, and an insulated double-glazed unit (IGU) on the inside. The outer pane is a low-iron laminated glass. The IGU contains a solar control coated glass with high visible transmittance, τ_v, and low total solar energy transmittance, g (τ_v / g: 61/33). The Woven glass-fibre roller blinds constitute the solar shading material. Daylight penetration gives the building a clear and light appearance and reduces the time for which artificial lighting is needed. The control system tracks the sun’s intensity and position and the blinds are lowered when the solar irradiance exceeds 200 W/m^2. The glazing g-value is reduced from 0.33 to 0.12 when fully shaded. The unshaded façade U-value is 1.63 W/(m^{2}K). Some measured data showing the impact of the shading in reducing solar gain measured during a single day are shown in Fig. 6.7.

Shading devices for effective daylight use and the avoidance of glare reflect, redirect or scatter the beam component of the incident solar radiation light and admit diffuse light into the building. Exterior and/or interior Venetian blinds may be flat or curved and their orientation varied to reflect the incoming light. Shading which has very low visible transmittance may impair dayighting performance. A favoured strategy is the combination of an external solar shading device, with low g value to reduce cooling energy and/or overheating, with an interior shade of Venetian blind which can be manually controlled by the occupant to avoid problems of glare.

An example of a diffusing shade system which provides effective daylight and glare control is shown in Fig. 6.8. Exterior Venetian blind solar shading is illustrated in Fig. 6.9.

Estimations of overall energy savings and the reduction in energy use for artificial lighting achieved by effective daylighting of buildings vary but can be very significant. The survey of Dubois (5.11) found reports of reductions in the heating, cooling and lighting load of buildings attributable to the use of solar shading to vary between 23-89%. The investigation of moveable external shading to permit the controlled entry of daylight and solar gain (Littlefair and Baumik (5.12)) reports overall energy savings of as much as 12 kWh/m^2/annum. A 24% reduction in overall energy use is reported (6.19) for the New York Times Headquarters building in New York where an integrated shading and lighting dimming system allows the admission of daylight and automatically adjusts external roller shade position in response to the sun and sky conditions. The article reports that the analysis, by Selkowitz, LBNL, of the New York Times's investment finds that the shade/lighting system delivers roughly $13,000 in energy savings annually per floor and that the payback period was only three years. Thayer (6.20) reports a 75% reduction in the use of artificial lighting in the Lockheed Building 157 which is designed for daylighting. An investigation of dynamic highly reflecting coated glass lamellae (Laustsen et al (6.21)) shows the potential for reducing energy demand for cooling and ventilation whilst still maintaining good daylight conditions and a satisfactory view to the outside. Reduced energy consumption for lighting is calculated when the lamellae are oriented to redirect daylight deeper into the room. A 21% reduction in overall energy consumption is predicted. Colt (6.22) report a number of buildings which demonstrate the improved energy performance and optimization of daylight achievable with external solar shading.

Figure 6.6 The triple-glazed system of the Shard building, London: outside single pane, ventilated inner cavity housing a motorised solar-control roller blind, inside double-glazed unit (photographs courtesy of Arup, London (6.18).

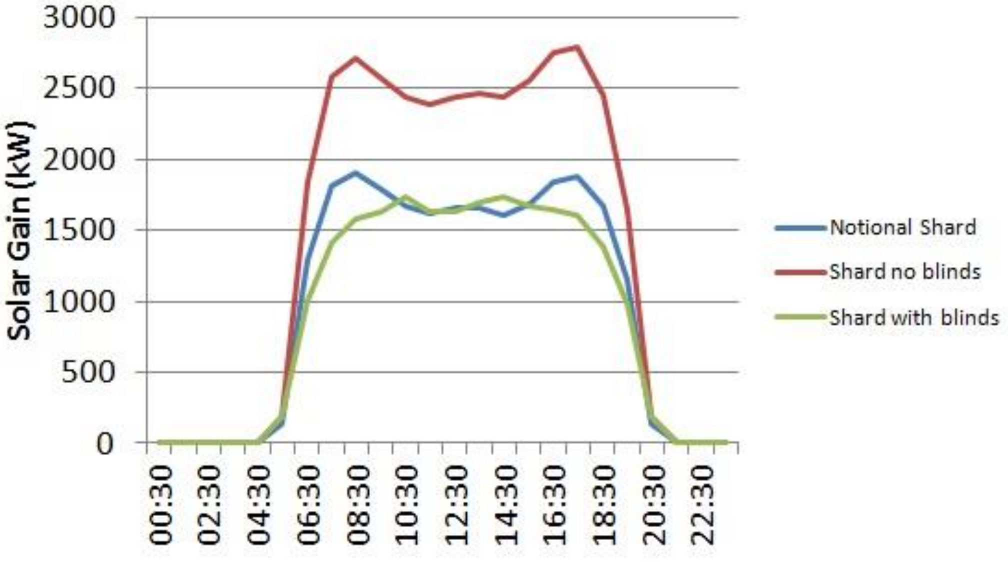


Figure 6.7 Measured reduction in solar gain of the Shard façade in unshaded and fully shaded conditions (results reproduced from Arup, London (6.18).

Figure 6.8 Roller shades in a double skin façade providing effective daylighting and glare control (Art Institute of Chicago, USA, photograph Wilson R (6.23)).

Figure 6.9 Exterior Venetian blinds (Lott Clearwater Alliance, USA, photograph Wilson R (6.23)).

6.5. Switchable glazing for solar control

When considering solar gain control it is of value to compare switchable glazing, such as electrochromic glazing, with dynamic solar shading. Spectrally selective solar control glazings possess fixed, or “static” optical properties. Switchable glazings, often termed “smart windows”, permit the optical properties of the glazing materials themselves to be varied and controlled in situ in a reversible way (6.24). Smart windows seek to avoid overheating, reduce glare and permit the use of greater glazed areas for increased solar gain and use of daylight. Integration with the building energy management system can reduce artificial lighting loads and diminish the size of HVAC systems.

Chromogenic materials form the basis of many switchable glazing designs. Photochromic materials darken as the intensity of light increases, thermochromic materials darken when the temperature exceeds a threshold value and the material undergoes an associated phase change. Electrochromic materials colour by charge injection. The optical properties of an electrochromic device (ECD) are controlled through the application of an external electric field enabling the control strategy to be independent of environmental conditions. There are many other switchable materials, e.g. liquid crystals, metal hydrides and suspended particle devices, but these are not discussed further here.

For building applications electrochromic tungsten oxide, WO_3, is commonly used as the active material. WO_3 is a transparent thin film. The application of a dc electric field drives the injection of ions and electrons into the lattice of the electrochromic material and creates the conditions necessary for a change of colour. ECDs for building applications commonly laminate two panes and employ a polymer or solid state electrolyte as the ion conducting medium. Such a device normally employs 2 glass or polymeric substrates and is assembled from the 2 respective halves: one employing the active electrochromic layer, e.g. WO_3, and the second the counter electrode, or ion storage layer. A schematic representation of the structure of a laminated electrochromic device using a polymeric electrolyte in a double glazed unit with low-e coating on Surface 3 for application as a variable transmission window is shown in Fig. 6.10 (6.25). Such a device in the transparent (clear) and dark (blue) states is shown in Fig 6.11.

Electrochromic glazing possesses a number of disadvantages in relation to dynamic solar shading. Typical ratios of transmitted, reflected and absorbed components of the incident solar radiation in an electrochromic glazing in the darkened (blue) state are shown in Fig. 6.12. The modulation of transmittance is by absorptance which can cause large temperature rises and hence unwanted thermal stress within the glazing system. Another serious disadvantage is the adverse effect of the strong colouring of the transmitted light. Electrochromic devices also do not diffuse the transmitted light and create scattering to reduce the potential for glare. A laminated ECD is effectively a single layer laminates with high thermal emittance and hence must be combined with a second low-e coated pane to produce an effective insulated glazing unit. This integration reduces the dynamic range between the clear and dark states.

In contrast the use of external solar shading has no adverse effect on the temperatures experienced within the glazing. Reduction of solar gain through solar shading will indeed reduce glazing temperatures. The impact of solar shading on the colour rendering of transmitted light can be controlled through the judicious selection of shading materials and their colour. Solar shading materials themselves can also exhibit low emissivity or include static air layers to improve further the thermal resistance of a glazing system.

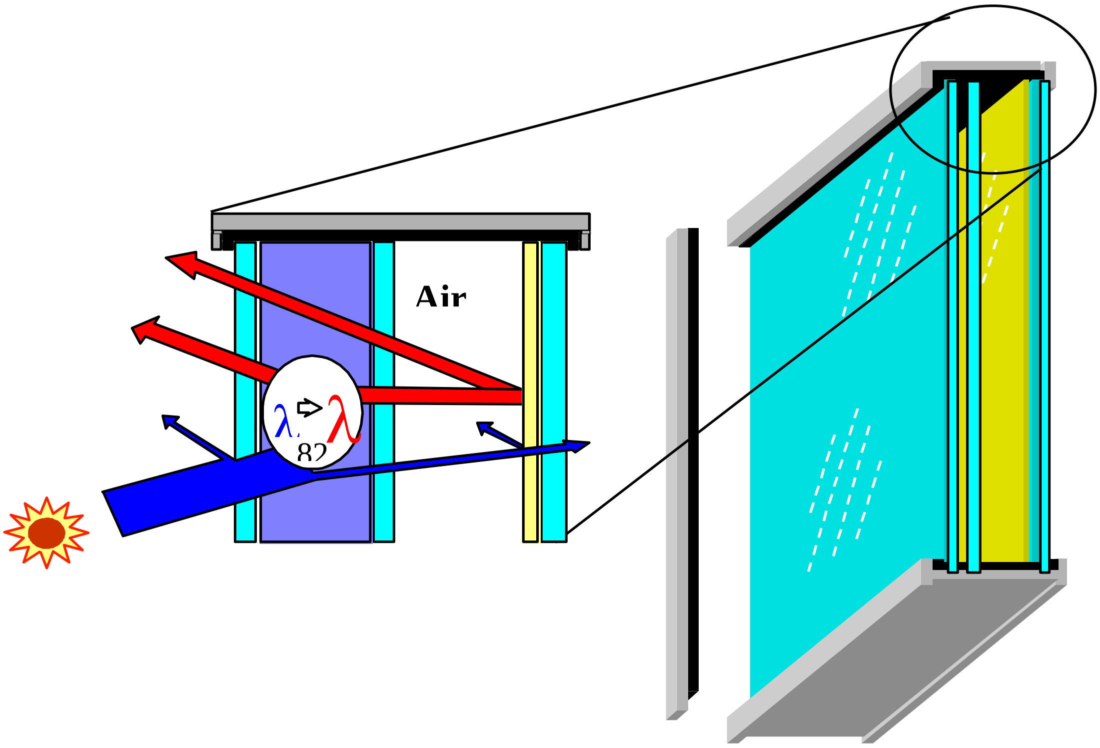


Figure 6.10. Schematic representation of the structure of a laminated electrochromic device using a polymeric electrolyte in a double glazed unit with low-e coating on Surface 3 for application as a variable transmission window (6.25).

Figure 6.11 Electrochromic glazing in the clear (transparent) and darkened (blue) states.

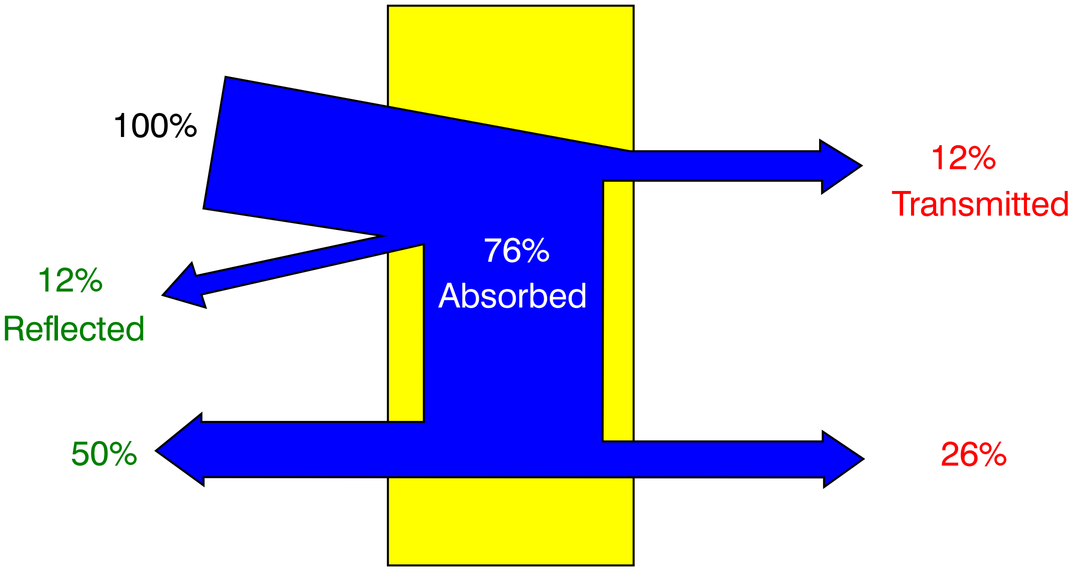


Figure 6.12 Transmitted, reflected and absorbed solar radiation of an electrochromic glazing in the darkened (blue) state (6.25).

7. Low Energy and Near Zero Energy Buildings

The Energy Performance of Buildings Directive (EPBD) has proven to be a powerful instrument for change throughout the European building sector (1.2). New buildings are required to meet 'nearly zero-energy' performance levels achieved through the use of innovative, cost-optimal technologies within the building envelope and the building services together with integration of renewable energy sources on site or nearby. Furthermore such buildings are intended to deliver appropriate indoor air quality and comfort in designs adapted to local climate and site.

7.1. Overheating in high performance buildings

The drive to reduce building energy consumption and lower carbon emissions significantly can inadvertently create new and unwanted problems. There is evidence to show that there is considerable risk of overheating in buildings which are more airtight and are highly insulated, e.g. new housing built to zero carbon standards, and that this overheating can occur at times which are outside of the normal cooling period. As an example, low energy buildings are often designed with large glazing areas to allow for passive solar heating. In winter when the sun is low in the sky, unshaded glazed areas may see a high proportion of direct solar radiation incident at near-normal angles where the glazing transmittance is highest. Overheating can result with high indoor temperatures reducing occupant thermal comfort. Experiences gained from 1st generation low-energy demonstration residential buildings have identified a serious gap between expected and actual energy use, an increased need for cooling at many times throughout the year and excessively high indoor temperatures even in the heating period (7.1, 7.2).

Overheating was a widely reported experience in the low-energy Passivhaus survey conducted by the Passivhaus Institüt, Darmstadt, Germany, 2012 (7.3). Since their inception in the late 1980s more than 37,000 Passivhaus buildings have been constructed worldwide. Passivhaus buildings are designed to minimise the requirements for both space heating and cooling. Key design features combine high levels of insulation and air tightness in combination with appropriate solar orientation of the building. Primary energy demand should be less than 120 $kWh/m^2/yr$ (referenced to floor area). Space heating demand must be reduced to 15 $kWh/m^2/yr$. When active cooling is included the additional energy demand must be no more than 15 $kWh/m^2/yr$. The air tightness should be no more than 0.6 air changes per hour (ach) (equivalent to 1.0 m^3/m^2h (absolute volume of air replaced in one hour divided by the total external envelope area); pressure differential 50 Pa). Mechanical ventilation and heat recovery (MVHR) is commonly included.

The Passivhaus Institüt carried out a survey of 736 dwellings in Germany (7.3, 7.4). Occupant satisfaction with internal comfort was found to be high. 92% of those responding to the survey indicated that their expectations had been met. However, 56% occupants reported that their dwelling had initially overheated in summer. To mitigate this problem 40% of households installed external blinds and 75% employed night-time ventilation to overcome these problems.

Overheating is already recognised to be a potential hazard in new and refurbished low energy buildings and a problem which will not be overcome by further increasing the building envelope insulation and air tightness. An increased need for cooling is found to occur at many times throughout the year and indoor temperatures can be too high even during the heating season.

Research work being undertaken in Denmark has achieved very positive results and is increasing understanding of the design and effective control of low energy buildings. Heiselberg (7.5, 7.6) identifies a number of necessary new measures which are needed to be included in the building design. These include demand controlled ventilation, shading for solar energy control, shading for daylighting control, lighting control and window opening. Implementation of smart operation through automatic control of an integrated set of energy efficiency measures is a new and challenging technology which must not only be able to be understood by the user but also be capable of satisfying the occupants' needs. Heiselberg identifies that it is difficult for users to understand control measures in low energy buildings and that automatic control should be better adapted to the fulfilment of user needs. Field studies identify that users avoid control measures to enjoy view or improve privacy and that such user driven actions may increase the risk of overheating and cause higher energy use. Occupants have been found to override automatic window opening at night to avoid noise or enhance security and to open windows in the winter season to get fresh air. The users aim to fulfil their personal needs often increases energy use.

However the research also finds that the impact of improved control together with the provision of operational guidance to the user can result in a significant decrease in energy consumption and an increase in occupant thermal comfort. Table 6.1 identifies the comfort category criteria of EN 15251. Measured comfort categories were determined for 2 successive years in the newly built "Home for Life" in Lystrup, Denmark (7.5). Category C conditions (moderate expectation) in living spaces reduced from 32% to 13% and the proportion of the higher comfort Category A and Category B conditions (normal and high expectation) increased from 56% to 84%. The research demonstrates clearly that solar shading and ventilative cooling are sustainable measures which when properly operated and controlled will reduce the risk of overheating and greatly improve levels of thermal comfort. The work is further substantiated in the research reported (7.6) on the impact of thermal mass and solar shading on overheating in the experiments performed at the Passivhaus, Vejle, and the Energiparcel renovation studies carried out in Tilst, Denmark. Traditional design methods which average heat loads in time and space and are unable to establish reliable correlations between cooling needs and the risk of overheating, are deemed to be oversimplified. Further work is ongoing which focuses on solutions that fulfil occupant needs and seeks to develop improved control strategies and user guidance to address overheating in new high performance low energy buildings and in buildings subject to deep renovation.

7.2. Cost effective and cost optimal solar shading solutions

The development of innovative smart control systems which will effectively regulate the operation of integrated air-conditioning, glazing, solar shading, ventilation and lighting systems within a common framework is a major challenge to be faced by the building sector if the EU targets of 40% CO_2 savings for 2030 and 80% CO_2 savings for 2050 are to be attainable. This challenge requires stakeholders in the buildings and construction industry to work in harmony to deliver a coherent and effective set of solutions.

The EPBD Recast 2010 (1.2) requires EU Member States (MS) to

"Take the necessary measures to ensure that minimum energy performance requirements are set for building elements that form part of the building envelope and that have a significant impact on the energy performance of the building envelope when they are replaced or retrofitted, with a view to achieving cost-optimal levels”.

Cost-optimal levels are defined as ”The energy performance level which leads to the lowest cost during the estimated economic lifecycle”. MS must determine this level taking into account a range of costs which include investments, maintenance, operating costs and energy savings.

Energy performance requirements using the cost-optimal methodology are required to be developed by each Member State and are widely discussed (7.7, 7.8, 7.9). Typologies to represent typical buildings in each of the EU-28 MS are the subject of intense research (7.10). Results of cost-optimal simulations of a wide range of packages of building energy saving measures within the Spanish context have been presented by Álvarez (7.11). Cost optimal calculations reported in the EPBD Concerted Action following the recommended methodology indicate good coherence across MS (7.12) which is very encouraging.

With the EPBD recast all new buildings are effectively defined as nearly zero-energy. For new-build, there is a need to deliver more affordable solutions with 'near zero-energy' performance levels and the relatively high costs of high energy performance buildings represent a barrier for investors (7.13). Research aims to reduce cost and accelerate market uptake of low energy buildings. Passive solutions which reduce the need for energy consuming building services together with active solutions which meet energy demand from renewable energies are recognised to be of very high priority. Smart and automated control systems are required if low energy buildings are to function effectively and this has a high impact on identifying the need for solar shading to work effectively. However, the great majority of buildings in the EU-28 are pre-1990 (Section 2.2), have poor energy performance and are in need of deep renovation to become energy efficient and meet the 2020 / 2050 criteria. It has been shown in Section 5.4 that the potential of solar shading as a cost-effective refurbishment solution meeting both space cooling and heating demands is extremely high and therefore represents a highly favourable cost-optimal solution contributing to the deep renovation of existing energy inefficient buildings.

Determination of cost-optimality requires that life cycle analyses (LCA) must be undertaken on all candidate measures (2.4). The energy balance should be calculated by means of a LCA approach, and consider embodied energy. The performance of LCA studies is beyond the scope of the present study. However, recent work which is focused on the optimisation of the energy balance and increased user comfort of transparent building components reports that external Venetian blind coverings may save some 8.5 tonnes CO_2 equivalent over its life cycle and only create 150 kg of CO_2 from production to disposal (7.14, 7.15). The positive impact of the window on daylight, heating, cooling and electric lighting energy is further confirmed by a recently published study from Estonia (7.16).

Life cycle analysis published to date and proven performance demonstrate that dynamic solar shading meets cost-optimal criteria either as a cost-effective single measure or as an integral component of a package of energy saving measures which aim to advance the energy efficiency of all buildings for both new-build and refurbishment solutions.

However it is of the highest importance to recognize that solar shading solutions cannot function to their full potential, be optimized and fulfil their role in cost-optimal building solutions in the absence of effective control. Operation of shading systems when left to manual control is known to be less than fully effective. The ESTIA study (7.17) shows that energy savings associated with automated blinds can reach several kWh/m^2 per room per year and that the implementation of automatic blinds can significantly increase the number of hours during which artificial lighting is unnecessary without detriment to the visual comfort of the occupants. The US residential windows study (7.18) finds that left to themselves people rarely move their shades. The study reports that between 75% and 84% of shades remain in the same position throughout the day and that 56% - 71% of households do not adjust shade position on a daily basis. Solar shading requires automated control to be truly effective.

8. Conclusions

The energy saving and CO_2 reduction potential of solar shading in European buildings is very significant Effective use of solar shading can contribute to the reduction of overheating, space cooling demand and air conditioning use, improved thermal insulation of fenestration and thereby lower space heating loads.

In addition to improving the performance of the building envelope through greater envelope insulation, airtightness and ventilation heat recovery, solar shading measures are a necessary inclusion for solar gain control, daylight control, demand controlled ventilation, lighting control, and window opening.

Efficient and effective automated control of solar shading is of the highest importance and needed to be seen within the context of the entire building design. Synergies and integration of solar shading with other building technologies, e.g. dynamic shading, dimmable lighting and night cooling, is necessary to realise cost-optimal packages of energy saving measures. Highly glazed commercial buildings will not function effectively without intelligent use of automated shading.

Solar shading has a high potential to enable efficient cooling, heating and artificial lighting savings in new build. The drive towards reduced energy consumption in buildings can however have unwanted drawbacks. Highly insulated and airtight low and zero carbon homes, often designed with large glazing areas have the potential to overheat throughout the year and solar shading has been shown to be an effective strategy to combat such situations.

The International Energy Agency (2.4) identifies the importance of solar shading in realising the potential of energy efficiency in the advanced building envelope and recommends as necessary and of high priority that exterior shading with proper orientation and dynamic solar control should become standard features globally in new buildings and can also be applied to existing buildings. Pilot projects have demonstrated that such systems can enable energy savings up to 60% for lighting, 20% for cooling and 26% for peak electricity.

The potential for energy savings of solar shading solutions in the refurbishment of energy inefficient buildings, which represent the great majority of buildings in the EU-28 MS is extremely high. The impact of the shading system on the complex glazing thermal performance depends upon the choice of glazing and the largest improvements in thermal transmittance are observed when the shade is used in combination with energy inefficient glazing, e.g. single glazing, double clear glazing, which constitute some 86% of current glazing within the EU. Smaller reductions are observed when more advanced glazing with lower U-values is employed but solar shading is always found to produce a positive enhancement.

In our study we predict positive cooling and heating energy savings resulting from the effective use of solar shading systems. We investigated cooling and heating performance in 4 different European climates when using solar shading in combination with 6 reference glazing systems. In all cases positive results were found. Maximum cooling savings are always found for South / South-West orientations. For the buildings studied herein, assuming an energy end-use split of 50:50 between space heating and space cooling the impact of dynamic solar shading systems is estimated to be a 30% saving in cooling energy use of 39.8 Mtoe/yr and a 14% saving in heating energy use of 18.2 Mtoe/yr. Taken together the potential energy savings which can accrue from the use of dynamic shading systems are a 22% saving in heating and cooling energy use of 59 Mtoe/yr and a carbon emissions reduction of 22% equivalent to a saving of 137.5 $MtCO_2$/yr.

The use of external dynamic solar shading has been demonstrated to be a successful feature and a key strategy to be employed in overcoming problems of overheating and increasing occupant thermal comfort in low energy buildings. The market for refurbishment of window areas by integrating shading is very large and our results demonstrate that solar shading can be used to upgrade existing energy inefficient window systems when it is not possible to replace them. Improving the energy performance of energy inefficient glazing through the use of solar shading to achieve significant cooling and heating energy savings represents an attractive economic and cost-efficient refurbishment solution.

Exterior shading is the most effective form of solar gain control and the reduction of indoor temperatures. Interior shading is an effective form of thermal insulation and a means to control both daylight, avoid glare and provide visual comfort to the occupants. An integrated external and internal solar shading system is optimum for a combined solution addressing cooling, heating and visual comfort. Solar shading plays an important role in combatting overheating with accompanying benefits for occupant thermal comfort and health.

Smart glazing, such as the electrochromic window, is shown to have serious disadvantages in comparison to dynamic solar shading where performance is compromised in respect of glazing temperatures, colour rendering and dynamic range. Dynamic solar shading will compete with and outperform static glazing when reducing space heating demand, controlling excess solar gain and improving occupant thermal comfort.

9. References

1.1 Analysis of options to move beyond 20% greenhouse gas emission reductions and assessing the risk of carbon leakage, COM(2010) 265 final, European Commission, 2010; http://ec.europa.eu/clima/policies/package/documentation_en.htm

1.2 Directive 2010/31/EU on the Energy Performance of Buildings (recast), European Parliament, 19 May 2010.

1.3 Ecodesign Directive 2009/125/EC establishing a framework for the setting of ecodesign requirements for energy-related products, 2009.

1.4 Solar shading is essential for low energy buildings, ES-SO Position Paper, European Solar Shading Organisation, May 2012

1.5 Energy saving and CO_2 reduction potential from solar shading systems and shutters in the EU-25, P. Standaert, PHYSIBEL, Report 2005_09A_ES-SO, December 2005.

1.6 prEN 15603:2013, Energy performance of buildings – Overarching standard EPBD, Draft, (will supercede EM 15603:2008), May 2013.

2.1 EU Energy in Figures, Statistical Pocketbook, ISBN 978-92-79 -29317-7, 2014.

2.2 Santamouris M. , Energy and climate in the urban built environment, ISBN 1 873936 907, James & James (Science Publishers) Ltd., 2001.

2.3 Transition to Sustainable Buildings, Strategies and opportunities to 2050, International Energy Agency, Paris, France, 2013.

2.4 Energy Efficient Building Envelopes Technology Roadmap, Energy Technology Perspectives, International Energy Agency, Paris, France, 2013.

2.5 Guidelines for establishing a comparative methodology framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and building elements, Directive 2012/C-115/01, European Commission, April 2012.

2.6 Buildings design for new highly energy performing buildings, European Commission Official Journal ref OJ C361, December 2013.

2.7 Europe's buildings under the microscope, Buildings Performance Institute Europe (BPIE), Marina Economidou, ISBN: 9789491143014, 2011.

2.8 Energy efficiency in buildings, CIBSE Guide, ISBN 0 900953 86 1, Chartered Institution of Building Service engineers London, 1998.

2.9 Glass in Building, A guide to modern architectural glass performance, Eds. Button D and Pye B, ISBN 0 7506 0590 1, Butterworth Architecture, 1993.

2.10 Europe's flat glass industry in a competitive low carbon economy, Glass for Europe, 2012.

2.11 The European window market evaluation of energy efficient modernisation (VFF-Verband Fenster+ Façade survey) EuroWindoor, 2013.

2.12 Hutchins M G, Glazing materials for advanced thermal performance and solar gain control, Proc. UK-ISES Conference C69 Using advanced glazing to improve daylighting and thermal performance in buildings, pp5-24, 1997; also published in Japan Journal of Solar Energy 23(5), 3-21, 1997.

2.13 Hutchins M G, Spectrally selective materials for efficient visible, solar and thermal radiation control, in Solar Thermal Technologies for Buildings, Ed. M Santamouris, pp37-64, James & James Ltd, 2003.

3.1 Energy-efficient buildings with sustainable comfort, Solar shading systems product sheets, European Solar Shading Organisation (ES-SO), Keep Cool 2, Intelligent Energy Europe, 2009.

3.2 Santamouris M, Tsangrassoulis A, Hutchins M G, Scheiring C, Pohl W, van Dijk H A, Spiekman M and Kenny P, Fenestration Handbook, ALTENER Contract No. 4.1030/Z/98-300, European Commission, September 2000.

3.3 Solar Shading, W Beck (ed.), D Dolmans, G Dutoo, A Hall and O. Seppänen, REHVA ES-SO Guidebook No. 12, European Solar Shading Organisation, 2010.

4.1 Workshop on optical property measurement techniques, Eds. Aranovitch E, Bassani C, Gillett W B and Bates J, Commission of the European Communities EUR 11607, May 1998.

4.2 Solar building components and integrated assemblies, Performance, durability and sustainability of advanced windows and solar components for building envelopes, Ed Köhl M, International Energy Agency Solar Heating & Cooling Task 27, 2006.

4.3 BS EN 410:2011 Glass in Building – Determination of luminous and solar characteristics of glazing, ISBN 978 0 580 71227 2, 2011.

4.4 EN 13363-1, Solar Energy and Light Transmittance through Glazing with Solar Protection Devices – Part 1, Simplified Calculation Method, BSI , Milton Keynes, 2003.

4.5 EN 13363-2, Solar Energy and Light Transmittance through Glazing with Solar Protection Devices – Part 2, Detailed Calculation Method, BSI , Milton Keynes, 2003.

4.6 EN 14500, Blinds and shutters – Thermal and visual comfort – Test and calculation methods, BSI, 2008.

4.7 EN 14501, Blinds and shutters – Thermal and visual comfort – Performance characteristics and classification, 2005

4.8 BS EN 673:2011, Glass in Building. Determination of thermal transmittance (U-value). Calculation method, ISBN 978 0 580 71226 5, 2011.

4.9 EN ISO 10077-1:2006, Thermal performance of windows, doors and shutters – Calculation of thermal transmittance – Part 1: General; ISO 15099: 2003, Thermal performance of windows, doors and shading devices – Detailed calculation.

4.10 BS EN 13125 Shutters and blinds – Additional thermal resistance – Allocation of a class of air permeability to a product, BSI, 2001.

4.11 Solar shading for low energy buildings, European Solar Shading Organisation, Edition 1, Ed. Lamy H, February 2012.

4.12 Rubin M, Standards for Solar Optical Properties of Specular Materials, Lawrence Berkeley National Laboratory, USA, http://windowoptics.lbl.gov/data/standards/solar.

4.13 International Glazing Database; Complex Glazing Database, Lawrence Berkeley National Laboratory, USA, http://windowoptics.lbl.gov/data/igdb.

4.14 Shade Specifier, , http://www.bbsa.org.uk/domestic/shade-specifier/27 . British Blind and Shutter Association, United Kingdom.

4.15 Curcija C, Yazdanian M, Kohler C, Hart R, Mitchell R and Vidanovic S, Energy Savings from Window Attachments, Lawrence Berkeley National Laboratory, USA, for the Building Technologies Office, U.S. Department of Energy, October 2013.

5.1 Karlsson J, Karlsson B and Roos A, A simple model for assessing the energy efficiency of windows, Energy and Buildings, 33, 7, 2001.

5.2 van Dijk H A L, Spiekman M E and DeWilde P, A monthly method for calculating energy performance in the context of European building regulations, Proceedings of the Ninth International IBPSA Building Simulation Conference, Montreal, Canada, August 2005.

5.3 EN ISO 13790:2008, Energy performance of buildings – Calculation of energy use for space heating and cooling, 2nd Edition, March 2008.

5.4 TABULA, Intelligent Energy Europe Contract IEE/08/495, http://webtool.building-typology.eu/ . 2009-2012.

5.5 ASIEPI : Assessment and Improvement of the EPBD Impact http://www.asiepi.eu/wp2-benchmarking/reports.html, Intelligent Energy Europe, 2011.

5.6 Certification and Rating of Attachments for Fenestration Technologies (CRAFT), EERE 105: Funding Opportunity Announcement, U.S. Department of Energy, Energy Efficiency & Renewable Energy, July 2013.

5.7 EnergyPlus, U.S. Department of Energy, Energy Efficiency & Renewable Energy, Office of Building Technologies, www.energyplus.gov , 2013.

5.8 http://energy.gov/eere/buildings/downloads/attachments-energy-ratings-council , 2015.

5.9 van Paassen A H C, Benerfits of various types of shading and night cooling by vent windows, Klima Delft, TU Delft, 2008.

5.10 Dubois M C, Awnings and solar-protective glazing for efficient energy use in cold climates, Proc Renewable Energy Technologies in Cold Climates, pp 380-385, Montreal, Canada, 1998.

5.11 Dubois M C, Solar shading for low energy use and daylight quality in offices, Simulations, measurements and design tools, Report No. TABK-01/1023, Dept of Construction and Architecture, Lund University, 2001.

5.12 Littlefair P, Ortiz E J and Das Bhaumik C, Energy savings from controlling solar shading, Blinds and Shutters, Issue 4, pp 21-24, 2006.

5.13 Bülow-Hübe H, Kvist H and Hellström, Estimation of the performance of sunshades using outdoor measurements and the software tool Parasol V 2.0, Proc. ISES Solar World Congress, Gothenburg, June 2003.

5.14 Glazing in buildings – reducing energy use, Operational energy reduction potential driven by energy efficient glazing uptake in the UK existing building stock, Eds Seguro F, John R and Smith L, National Energy Foundation, March 2015.

6.1 Overheating in new homes, A review of the evidence, NF 46, NHBC Foundation, November 2012, http://www.who.int/gho/urban_health/situation_trends/urban_population_growth_text/en/

6.2 Kuhn T E, Bühler C and Platzer W J, Evaluation of overheating protection with sun-shading systems, Solar Energy 69(Suppl.), Nos 1-6, pp 59-74, 2000.

6.3 World Urbanisation Prospects, Department of Economics and Social Affairs, United Nations, 2014.

6.4 World Health Organisation (WHO) Centre for Health Development, http://www.who.int/kobe_centre/measuring/WUP_2014/en/ .

6.5 Office of the Deputy Prime Minister (ODPM) Housing Health and Safety Rating System (HHSRS): Operating Guidance, London, ODPM, 2006.

6.6 Santamouris M, The impact of Climatic Change on the thermal comfort/energy performance of buildings, Proc EU COMMONCENSE Workshop, University of Porto, Portugal, November 2009.

6.7 Heat-waves: risks and responses, Health and Global Environmental Change Series No. 2, World Health Organisation, http://www.euro.who.int/__data/assets/pdf_file/0008/96965/E82629.pdf , 2004.

6.8 BS EN ISO 7730, Moderate thermal environments. Determination of the PMV and PPD indices and specification of the conditions for thermal comfort, 1995.

6.9 EN 15251 Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics, Bruxelles: European Committee for Standardisation, 2007.

6.10 Nicol F and Humphreys M, Environmental criteria for design, CIBSE Environmental Design Guide A, ISBN 1 903287 66 9, 2006.

6.11 Commoncense : Comfort monitoring for CEN standard EN 15251 linked to EPBD, Coordinator Sonnergy Ltd, Intelligent Energy Europe, EIE/07/190/SI2.467619, 2007-2010.

6.12 Energy consumption variation due to different thermal comfort categorisation introduced by European Standard EN 15251 for new building and major rehabilitations, A Sfakianaki, M Santamouris, M Hutchins, F Nicol, M Wilson, L Pagliano, W Pohl, J L Alexandre and A Freire, International Journal of Ventilation 10 (2), 195-204, 2011.

6.13 Daylighting: Architecture and Lighting Design, Tregenza P and Wilson M, Routledge, 2011.

6.14 Tips for daylighting with with windows, The integrated approach, O'Connor J, Lee E, Rubinstein F and Selkowitz S, Lawrence Berkeley National Laboratory report LBNL-39945, 1998.

6.15 Daylight and Shading, Comfortable Low Energy Architecture (CLEAR), http://www.new-learn.info/packages/clear/interactive/matrix/d/shading/index.html , London Metropolitan University.

6.16 Daylight in Buildings, A sourcebook on daylighting systems and components, Report LBNL-47493, International Energy Agency Solar Heating & Cooling Task 21, ECBCS Annex 29, 2000.

6.17 Innovative solar control devices, H Erhorn and H Erhorn-Kluttig, ASIEPI, Information Paper P186, Intelligent Energy Europe, 2010.

6.18 Spring M, The Shard, Solutions: Cladding, www.bdonline.co.uk , June 2010.

6.19 Biello D, Let the sunshine in, Scientific American 308, 26, 2013

6.20 Thayer B M, Daylighting and Productivity at Lockheed, Solar Today; Vol. 9, No. 3, 1995.

6.21 Lausten J B, Santos I D P, Svendsen S, Traberg-Borup S, Johnsen K, Solar shading system based on daylight redirecting lamellas, Proceedings of the 8th Symposium on Building Physics in the Nordic countries, 2008.

6.22 Maximising Energy Performance and Productivity with Solar Shading, Colt Solar Shading systems, http://www.coltgroup.com/files/pdf/Solar%20Shading/Maximising%20energy%20performance%20and%20productivity%20with%20solar%20shading.pdf , 2012.

6.23 Wilson R., *private communication*.

6.24 Handbook of Inorganic Electrochromic Materials, Granqvist C G, ISBN 0 444 89930 8, Elsevier Science B V, 1995.

6.25 Electrochromic variable transmission glazing, Pilkington, in European Solar Architecture, Eds. Fitzgerald E and Owen Lewis J, ISBN 1 898473 390, EUR 16855 of the European Commission, 1995.

7.1 Understanding Overheating – Where to Start. NF 44, NHBC Foundation, Milton Keynes, 2012.

7.2 Low and Zero Carbon Homes: Understanding the Performance Challenge, NF 41, NHBC Foundation, Milton Keynes, 2012.

7.3 Keul G and Salsmann R, Subjective/objective Temperatur/Feuchte im Wiener Passivwohnbau Kammelweg B, International Passivhaus Conference, Dresden 2010, http://passiv.de/en/05_service/05_literature_en.htm .

7.4 Lessons from Germany's Passivhaus experience, NF 47, NHBC Foundation, Milton Keynes, 2012.

7.5 Heiselberg P, Overheating in Low Energy Buildings; The Influence on Solar Shading, ES-SO Solar Shading Workshop, Brussels, http://www.es-so.com/images/downloads/Downloads%20presentations/Heiselberg_ESSO_Seminar_Brussels_April_2014.pdf , April 2014.

7.6 Heiselberg P, Overheating Energy Performant Buildings, ES-SO Seminar, R+T Stuttgart, http://www.es-so.com/images/downloads/Downloads%20presentations/Heiselberg_ESSO_Seminar_Stuttgart_February_2015.pdf , 26 February 2015.

7.7 Energy performance requirements using the cost-optimal methodology, Thomsen K E, www.buildup.eu ,BUILD UP, European Union, 2013.

7.8 Cost optimal building performance requirements, Calculation methodology for reporting on national energy performance requirements on the basis of cost optimality within the framework of EPBD, Boermans T, Bettgenhäuser K, Hermelink A, Schimschar S,. European Council for an Energy Efficient Economy, May 2011.

7.9 Cost optimal levels for energy performance requirements, Aggerholm S et al, Concerted Action Energy Performance of Buildings, Intelligent Energy Europe, July 2011.

7.10 Erhorn-Kluttig H, Erhorn H, Spiekman M and Westerlaken N, P158, A set of reference buildings for energy performance studies, ASIEPI : Assessment and Improvement of the EPBD Impact, 2011.

7.11 Álvarez S, How is solar shading positioned in the Spanish building code, implementing the EPBD, ES-SO Solar Shading Workshop, Barcelona, October 2013.

7.12 Kurnitski J, Buso T, Corgnati S P, Derjanecz A, Litiu A, nZEB definitions in Europe, REHVA Journal, 6-9, March 2014.

7.13 Sartori I, Noris F, Herkel S, Cost analysis of nZEB/Plus energy buildings, REHVA Journal, 40-45, May 2015.

7.14 Gerstmann J and Hall A, Optimise energy balance and increase user comfort of transparent building components,

7.15 Raffstore Carbon Footprint, ILA Institut für angewandte Logistik, Würzburg, WAREMA, 2013.

7.16 Thalfeldt M, Kurnitski J, Voll H, Pikas E, Total economy of windows and facades in low energy office buildings, REHVA Journal, 19-24, March 2014.

7.17 Paule B, Boutillier J, Pantet S, Performance globale en éclairage (Global lighting performance), Société Estia SA, Office federal de l’energie OFEN, Switzerland, 2014.

7.18 Bickel S, Phan-Gruber E, Christie S, Residential windows and window coverings, D&R International Ltd., for the Building Technologies Office, U.S. Department of Energy, September 2013.

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