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

EXECUTIVE SUMMARY

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1. Introduction

An in-depth study is made to evaluate the impact of solar shading technologies on the performance of buildings. The investigation is undertaken within the context of European policy addressing the issues of climate change, energy security and economic competitiveness. Recommended methodologies and tools emanating from the Energy Performance of Buildings Directive (EPBD) and its 2010 recast (1) are employed 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. The study examines the energy saving and CO_2 reduction potential of solar shading in European buildings in both new-build and refurbishment and the consequent impacts on reduced space cooling demand and air conditioning use, the lowering of space heating loads and overcoming risks of overheating whilst maintaining comfort for the building occupants and maintenance of the quality of the indoor environment.

The state-of-the-art of solar shading research which aims to quantify and demonstrate the benefits of a wide range of solar shading technologies and applications in Europe and globally is assessed. The present study builds upon the previous ES-SO ESCORP-EU-25 Scientific Study undertaken in 2005 (2) which used building energy performance simulations to estimate the beneficial energy and environmental impacts which can result from the intelligent use of solar shading in the EU Member States. The ESCORP 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 were predicted to represent an approximate 10% reduction in the energy end-use of the EU-25 building sector (455 Mtoe/annum in 2005) demonstrating the extremely high potential of solar shading technologies to serve as effective measures in both new-build and refurbishment building energy efficiency solutions.

The energy savings predicted in this study are a little higher than those reported in the previous ES-SO ESCORP report but are broadly in close agreement. The impact of solar shading on the energy saving and CO_2 reduction potential in European buildings across the EU28 MS is estimated. 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.

The trends observed are also consistent with those found in the energy savings from window attachments study published in 2014 by the Lawrence Berkeley National Laboratory, USA (3).

2. Energy Use in EU Buildings

Buildings represent the largest energy consuming sector. Space heating and cooling together with water heating account for 60% of global energy consumption in buildings. In the EU this proportion is nearer to 80% and the built environment is responsible for more than 40% of total energy end-use. 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 (4). With global population increases and increased urbanisation, it is predicted that energy use in buildings will rise significantly. Use of air conditioning reliant upon highly carbon-intensive electricity systems is more widespread and the proportion of end-use energy required for space cooling has steadily increased. 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.

The EPBD (1) is a major driver in the achievement of better buildings throughout the Member States underpinning the EU commitment to transform itself into a highly efficient, competitive, low-carbon economy. The 2010 recast of the EPBD requires each MS to: “assure that minimum energy performance requirements for buildings or building units are set with a view to achieving cost-optimal levels”. The EPBD further requires that from the year 2020 onwards all new buildings will have to be 'nearly-zero energy buildings' (nZEB). However, the costs of high performance low energy buildings are often high and finding more affordable solutions is necessary to overcome barriers for investors in the construction industry.

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. However older buildings represent the great majority of the EU building stock and these are mostly of low energy performance and have energetically poor glazing systems. The Buildings Performance Institute Europe (BPIE) report “Europe’s buildings under the microscope” (5) identifies that annual growth rates in the residential sector of the EU28 MS is ~ 1% and that the rate of construction of new-build homes has been steadily in decline since the post-war boom times of the 1950s and 1960s. 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. 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 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.

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 building envelope is the vital component of the building and is required to perform many essential tasks, e.g. provide shelter from the weather, fire protection, security, privacy. 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. Window energy performance is critical in reducing building energy consumption and the lessening of adverse environmental impacts. Advanced glazing solutions, integrating insulated glazing units with solar shading technology, can deliver high thermal insulation and selective control of solar gain acting to reduce heat losses, to protect the indoor environment from excessive heat gain and mitigate against overheating. High performance fenestration also provides opportunities to admit natural light to the interior and to increase glazed areas.

Surprisingly, high performance glazing systems are not commonly employed throughout the EU28. The GlassforEurope "Competitive low carbon economy report" (6) identifies that 86% of all installed glazing in the MS is energetically out-of-date. It is estimated that 44% of the installed glazing is single glazing, 42% is uncoated double glazing and only 14% is energy efficient glazing. The Eurowindoor report based on the VFF Window market in Europe 2013 study (7) estimates that nearly 2.000 million window units are energetically out of date in the EU 27 and this figure rises to 3.090 for the whole of Europe. In addition, market capacity for renewal of these windows is limited and replacement of existing stock with energy efficient windows will take up to 50 years.

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. The IEA Technology Roadmap for energy efficient building envelopes (4) predicts a rapid rise in energy consumption for cooling and identifies exterior shading as an effective technology for reducing cooling energy consumption. 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". The present study demonstrates that dynamic solar shading solutions have a key role to play in improving the energy performance of Europe's inefficient glazing stock, not only by reducing cooling demands but also by reducing heating demand through increased night time insulation. Solar shading solutions are shown to be an important component of any building renovation strategy aiming to lower carbon emission levels and produce buildings which consume very little energy.

3. Dynamic Solar Shading and Complex Glazing

Integration of a glazing unit together with a form of solar protection, e.g. shade, blind, curtain, shutter, overhang, awning etc, produces complex glazing permitting dynamic control and the opportunity to significantly improve the energy performance and carbon footprint of buildings with improved occupant comfort, reduced operating costs, energy use and greenhouse gas emissions

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 (8).

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 (9). 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 (10).

4. The Energetic Performance of Shading Systems

In this study all physical properties of shaded glazing systems are calculated in accordance with relevant current European norms and standards using prescribed methods and procedures. The relevant European Standards are EN 410:2011, EN 13363-1, EN 13363-2, EN 14500, EN 14501, EN 673:2011,EN ISO 10077-1:2006 and EN 13125 respectively (11, 12, 13, 14, 15, 16, 17, 18).

The key performance parameters are

- The total solar energy transmittance, termed the g-value, which permits the determination of the solar energy gain;
- The thermal transmittance, 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.

Six unshaded reference glazings defined in these standards are used to benchmark potential energy savings for heating and cooling respectively in 4 different European cities, Rome, Brussels, Stockholm and Budapest.

The 6 unshaded reference glazings taken from EN 14501 and EN 13363-1 are identified in Table 1.

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 1. Glazing identities and values of the total solar energy transmittance, g, and the thermal transmittance, U, of the unshaded reference glazings of EN 14501 and EN-13363-1.

The selection of shading product types made is representative of the market and exhibits 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 (Single clear glass, Double clear glass, Heat Control, Solar Control, Triple clear glass and Double clear glass with low-E coating) are also determined using the methods prescribed in the EN standards. For the purpose of comparative methods only, the complex glazing g-value is calculated using the procedures of EN 13363-1. 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 are shown in Figure 1 and for the representative internal solar shading types in Figure 2. The g-values are calculated for the respective fully closed shaded glazing. Lowest values of solar gain, $g < 0.05$, are seen when employing fully closed external shading.

Thermal transmittance, U, is calculated using the recommended methods of EN 13125 which allow for 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. The impact of shading on reducing complex glazing thermal transmittance is greatest for those unshaded glazings which themselves have the lowest thermal resistance, i.e. single clear and double clear glazing.

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. 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 2.

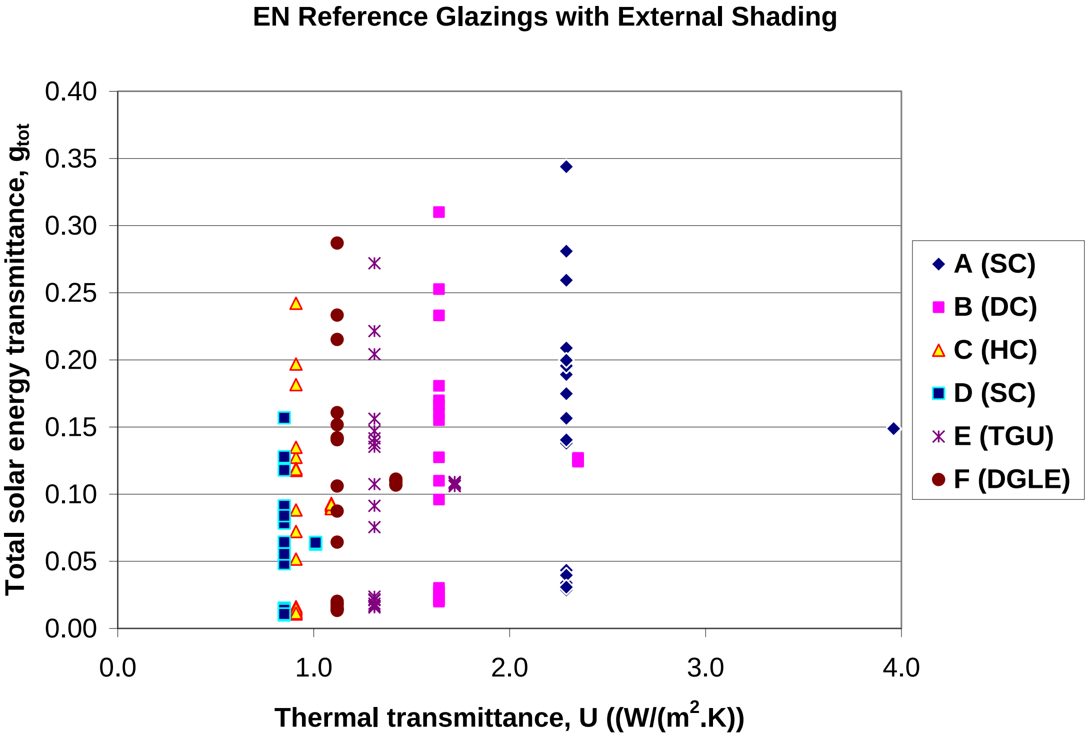

Figure 1. The impact of external shading products on the total solar energy transmittance of the 6 EN 14501 and EN 13363-1 reference glazings.

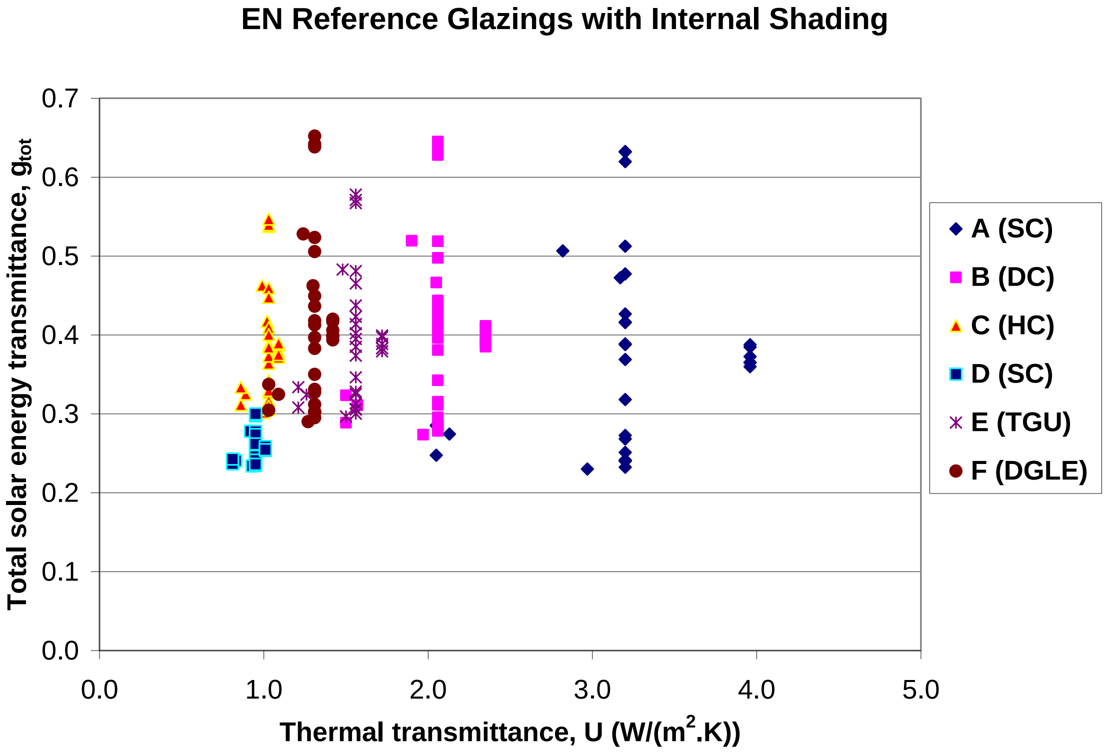

Figure 2. The impact of internal shading products on the total solar energy transmittance of the 6 6 EN 14501 and EN 13363-1 reference glazings.

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

Table 2. 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

Cooling energy savings are estimated using a modified window energy balance model which takes into account the U-value, g-value and angle dependent characteristics of the window. Hourly resolved climate data are used (11). The building type is considered through a balance temperature and simulations performed for lightweight, medium weight and heavy weight buildings. It was not possible to investigate all possible residential, commercial and other buildings typologies. However, the energy balance approach represents a meaningful compromise to benchmark potential savings and benefits that can accrue from differing dynamic solar shading solutions. Heating energy savings are estimated using a steady-state monthly mean daily method validated and incorporated into the ISO 13790 standard (12). The estimation of cooling and heating energy savings is made for 4 European city climates : Rome, Brussels, Stockholm and Budapest. For each reference glazing, the dynamic range of the total solar energy transmittance, g, and the thermal transmittance, U, of the complex glazings investigated for (i) external and (ii) internal shading are four combinations of g and U, selected to represent “high” and “low” shade quality sets. 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. 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.

For space cooling simulations, 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

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

External solar shading produces a positive impact on space cooling in all cases investigated. As example, Figure 3 presents the percentage cooling energy savings when dynamic external solar shading is combined with the EN 14501 and EN 13363-1 reference glazings (B, C, D, E and F) by orientation. 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 represent more than a 30% saving for the SW orientation. 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. Figure 4 presents the percentage of time for which the glazing is fully or partially shaded for Rome.

The mean, maximum and minimum percentage cooling energy savings and cooling energy savings in kWh/m2/yr of dynamic externally shaded glazing by unshaded reference glazing were determined for each location. The results obtained for Rome and Brussels respectively are shown in Tables 3, 4, 5 and 6 respectively.

Maximum cooling energy savings are exhibited for the SW orientation. Table 7 presents the maximum cooling energy saving in kWh/m^2/yr of the highest performing dynamic solar shading system averaged for each of the 4 locations. The corresponding maximum percentage cooling energy savings are shown in Table 8.

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. The mean, maximum and minimum percentage cooling energy savings and cooling energy savings in kWh/m2/yr of dynamic internally shaded glazing by unshaded reference glazing are shown in Tables 9and 10.

Cooling energy savings when averaged across all possible orientations for both external and internal shaded glazings can vary between 30% - 45% dependent on the reference glazing and this can rise to 50% - 65% if only orientations between East, South and West are considered. For the climates investigated, solar shading realises mean percentage cooling energy savings of 46% for single glazing, 38% for double glazing and 30% for energy efficient glazing.

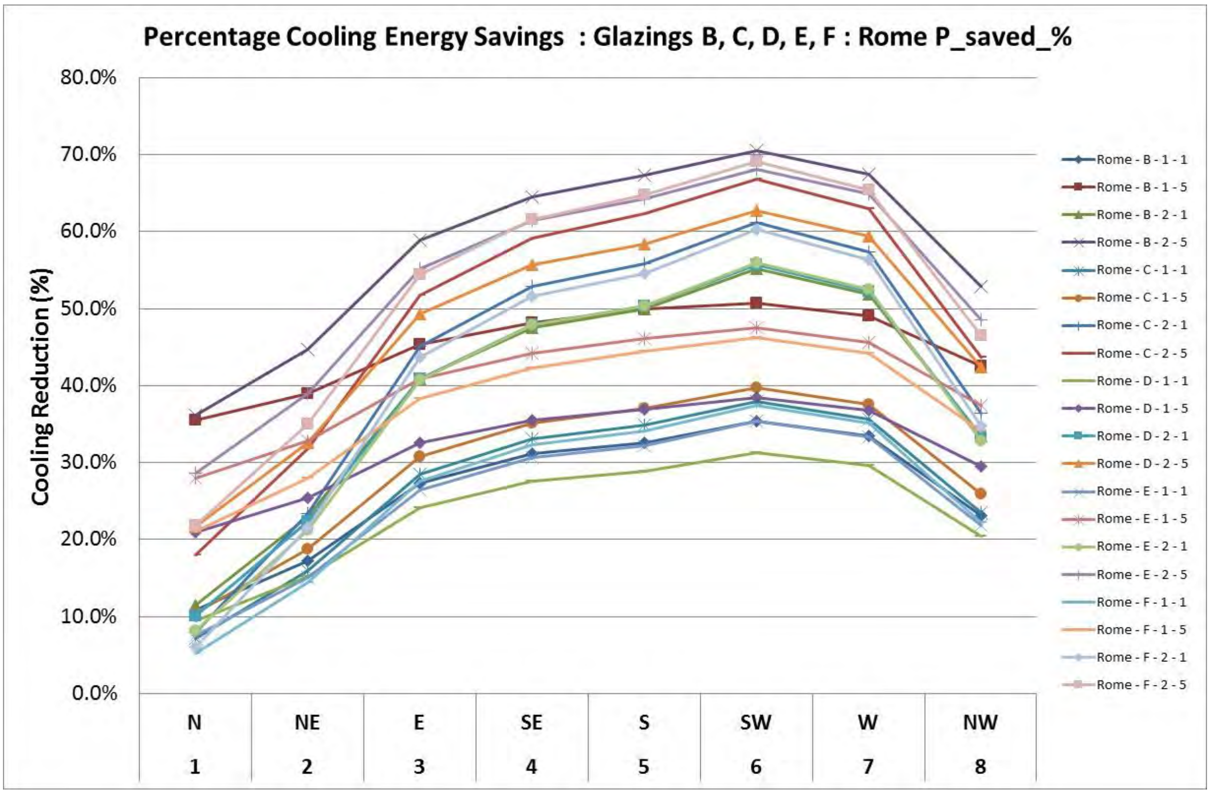

Figure 3. Percentage cooling energy savings of shaded glazings (B, C, D, E and F) for different shade performance by orientation: Rome.

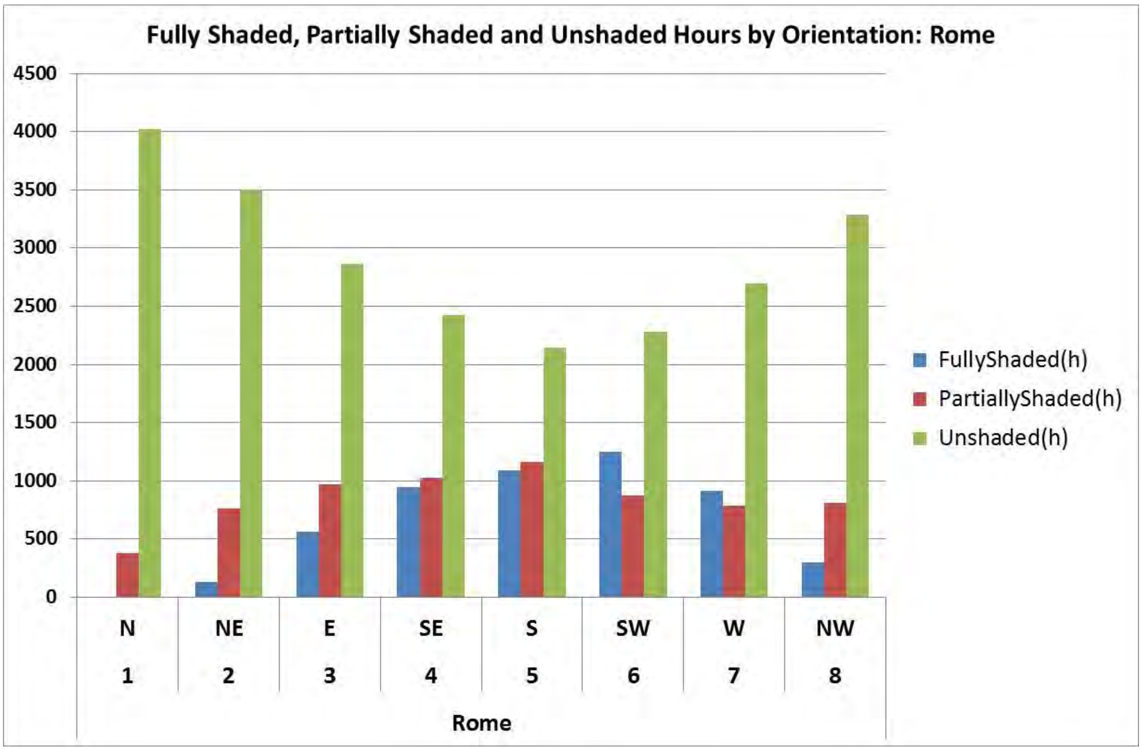

Figure 4. Number of shaded, partially shaded and unshaded cooling season hours by orientation: Rome.

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

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

		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 7. 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 8. 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.

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

In addition to the contributions that can be made towards providing increased thermal and visual comfort for the building occupier, internal shading can also provide significant heating energy savings because of increased night time insulation. 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. Monthly mean space heating requirements are hence strongly dependent on the fully closed night-time thermal transmittance. 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 those glazings with the highest thermal transmittance, i.e. Single Clear and Double Clear, and the impact is reduced for glazings which have lower unshaded U-values. For the climates investigated, night time shading realises mean percentage space heating energy savings of 25% for single glazing, 15% for double glazing and 8% for energy efficient glazing.

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 11. 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.

As example, the percentage space heating demand savings, SHS%, relative to the annual requirement for the unshaded reference glazing for Rome and for Brussels are shown in Figures 5 and 6 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) [1]

Glazing B, Double Clear:SHS% = 100 (0.3725 - 0.1283 Un) [2]

Glazing C, Heat Control: SHS% = 100 (0.2433 - 0.2026 Un) [3]

Glazing D, Solar Control: SHS% = 100 (0.2188 - 0.1989 Un) [4]

Glazing E, Triple Clear: SHS% = 100 (0.3182 - 0.1589 Un) [5]

Glazing F, Double Clear Low-e: SHS% = 100 (0.2901 - 0.1811 Un) [6]

	Single Clear A_Un W/(m2.K)	Double Clear B_Un W/(m2.K)	Heat Control C_Un W/(m2.K)	Solar Control D_Un W/(m2.K)	Triple Clear E_Un W/(m2.K)	Double Clear Low-e 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 11. Night-time U-values, Un, of the fully shaded reference glazings by air permeability.

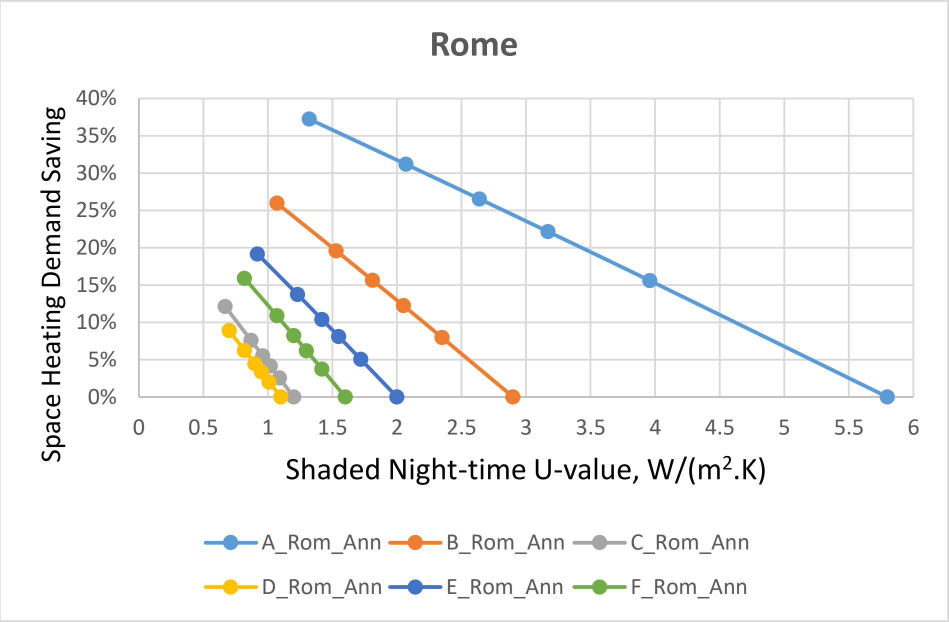

Figure 5. Percentage annual space heating demand saving on shaded night-time thermal transmittance, Un, by reference glazing: Rome.

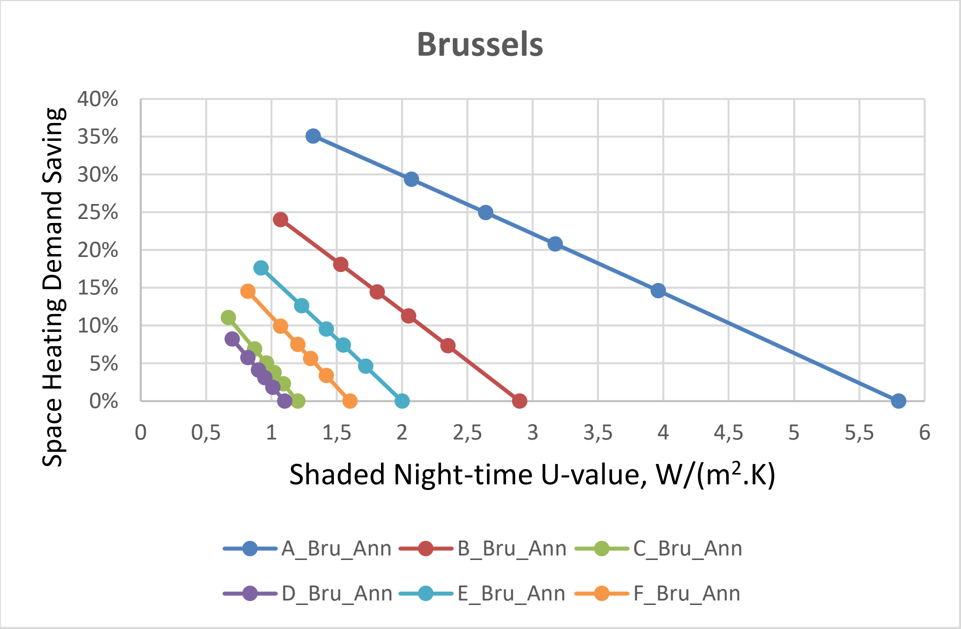

Figure 6. Percentage annual space heating demand saving on shaded night-time thermal transmittance, Un, by reference glazing: Brussels.

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 (13) have been assumed.

The percentage distribution of glazing type given in the Glass for Europe publication (6) are assumed and shown in Table 12. The respective glazing areas given in the EuroWindoor 2011 survey (7) are also assumed.

Single	Double	Energy Efficient
44	42	14

Table 12. 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 and the resultant savings are shown in Table 13 below.

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

Table 13. 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 (13).

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 12.

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 14.

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 14. 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 are 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.

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.

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The savings predicted in this study are a little higher than those reported in the previous ES-SO ESCORP report but are broadly in close agreement. The trends are also consistent with those found in the energy savings from window attachments study published in 2014 by the Lawrence Berkeley National Laboratory, USA. The USA study confirms the extensive potential that solar shading systems have to reduce cooling and heating demands in buildings and identifies the value and importance of improved manual operation or developing more cost-effective approaches to automating operation. The US Department of Energy Buildings Technology Office indicate 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.

6. Overheating, Health, Comfort and Productivity

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. 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.

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 impact of urbanisation on population health, health equity and the environment are key concerns for national and municipal authorities (14, 15). The effects of climate change are further exaggerated in urban environments. Temperature maxima are higher and more frequent. Heatwaves may persist for several days and hot spells have a longer duration. 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.

Dynamic solar shading can improve the quality of the indoor environment and raise the comfort category of the building. Mechanical cooling is energy intensive. The energy cost of comfort was investigated in the EU COMMONCENSE project (16). The required cooling and heating energy consumption buildings belonging to each of the EN 15251 (17) thermal comfort categories I, II and III (Table 15; Figure 16) was calculated and compared against existing national benchmarks. 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 demonstrating not only that dynamic shading systems will reduce building energy consumption significantly but will also produce greater thermal comfort and improve the quality of the internal environment (18).

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. Shading selection, dimensioning and positioning will depend upon building form, use, climate and the daylight source itself. 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. Reductions in the heating, cooling and lighting load of buildings attributable to the use of solar shading which vary between 23-89% have been reported. These studies demonstrate the efficacy of external solar shading in combining improved energy performance and optimization of daylight.

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 15. The comfort categories of European Standard EN15251 (17) 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).

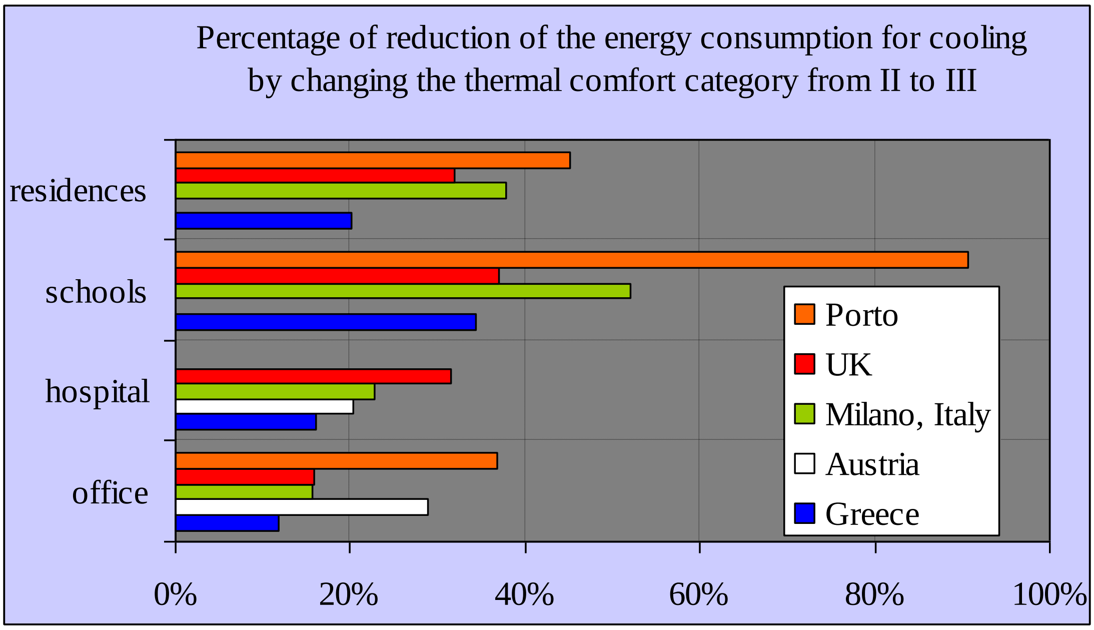

Figure 16. The percentage of reduction of the Final Energy Consumption for cooling by changing the thermal comfort category from II to III, in representative buildings, in various climates (18).

7. Low Energy and Nearly Zero Energy Buildings

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, deliver appropriate indoor air quality and comfort and be adapted to local climate and site. 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. Overheating was a widely reported experience in the low-energy Passivhaus survey conducted by the Passivhaus Institüt, Darmstadt, Germany (19). Recent research in Denmark (20) 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. The research 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.

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. 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, reduce cost and accelerate market uptake. Further solar shading is shown to be a cost-effective refurbishment solution meeting both space cooling and heating demands and therefore represents a highly favourable cost-optimal solution contributing to the deep renovation of existing energy inefficient buildings. 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 (21).

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 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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