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1 **R** = Report, **P** = Prototype, **D** = Demonstrator, **O** = Other

2 **PU** = Public
PP = Restricted to other programme participants (including the Commission Services)
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EXECUTIVE SUMMARY

It appears that for commercial buildings, the total cost for glass in the facades is not mainly glass, but sunblind system related. This has to do with the fact that facades with a lot of glass lead to a significant cooling load, especially in hot, sunny climates like in California or the Middle East. Mitigation of this cooling load leads to sunblind systems. For high buildings, external systems cannot be applied because of wind speed related issues.

Smart windows combine the daylight transmission function with thermal management, either through controllable coatings or through microstructures. The commercially most advanced window type is that of electrochromic windows. This has proven durability and range of transmission and approaches the cost of traditional, automated, sun blinds.

The transmission controllable windows being developed in NEXT-Buildings are not yet commercial, but the fabrication technologies developed and several features as fast switching can lead to commercial products in a few years time.

1 INTRODUCTION

Intelligent windows can play an important role in the energy management of buildings. Windows may serve functions, like daylight access, insulation from heat and cold, sound barrier. However, as a static component, its performance is at best a compromise, depending on the use of a building, the time of day, the climatic conditions and other factors like sound levels outside. For that reason a large diversity of window types has emerged, in general optimizing a few factors like thermal insulation, Solar Heat Gain Coefficient (SHGC) or visible transmission. But even those are a compromise as there is no capability for dynamic behavior.

Modern technology, however, has produced a number of technologies that indeed make dynamic behavior possible. This report provides briefly an overview of the various technologies on the marker or under development, with a view to compare their properties in relation to energy management of buildings. (Other aspects will be mentioned but not treated extensively). Additionally, this overview serves as a background against which to compare the type of intelligent windows being developed in the NEXT-Buildings project, the Micro Electro Mechanical Systems (MEMS) type of transmission controllable glazing, employing the concept of micro lamella. It will provide an impression of the applicability of the technology in the future.

2 DYNAMIC WINDOWS

2.1 The concept

The emerging concept for the window of the future is more as a multifunctional "appliance-in-the-wall" rather than simply a static piece of coated glass. These facade systems include switchable windows and shading systems such as motorized shades, switchable electrochromic or gasochromic window coatings, and double-envelope window-wall systems that have variable optical and thermal properties that can be changed in response to climate, occupant preferences and building system requirements. By actively managing lighting and cooling, smart windows could reduce peak electric loads by 20–30% in many commercial buildings, increase daylighting benefits, improve comfort, and potentially enhance productivity in homes and offices. These technologies can provide maximum flexibility in aggressively managing demand and energy use in buildings in the emerging deregulated utility environment. They can also move the building community towards a goal of producing advanced buildings with minimal impact on the nation's energy resources.
The ideal window would be one with optical properties that could readily adapt in response to changing climatic conditions or occupant preferences. Researchers have been hard at work on new glazing technologies for the next generation of smart windows. After many years of development, various switchable window technologies are now in prototype testing phases and should be commercially available in the near future. As with other window technologies, the architect will need to understand these new systems in order to specify them properly.

There are two basic types of switchable windows—passive devices that respond directly to a single environmental variable such as light level or temperature, and active devices that can be directly controlled in response to any variable such as occupant preferences or heating and cooling system requirements. The main passive devices are photochromics and thermochromics; active devices include liquid crystal, suspended particle, and electrochromics.[3]
Apart from these, consideration will be given to blinding systems and, of course, the micro mirrors.

2.2 Definitions

In order to understand the different glass parameters right, the following definitions are provided:

Table 1 Window parameter definitions and description

Parameter	Description	Explanation
V_t	Visible transmission	The fraction of the visible light (400-800 nm) transmitted by a window system
SHGC	Solar Heat Gain Coefficient	Solar energy transmittance of a window or door as a whole, factoring in the glass, frame material (wood, aluminum, etc.), parameter value between 0 and 1
G	Solar energy transmittance	Coefficient commonly used in Europe to measure the solar energy transmittance of glass - called a Solar Factor on some window literature (%) i.e. 53% = 0.53; where 1.0 or 100% represents the maximum amount of solar energy passing through it and 0.0 or 0% represents a window with no solar energy transmittance.
LSG	Light to solar ratio	V_t/SHGC
Spectral selectivity	Different transmission for wavelength bands	A property of windows to preferentially transmit certain wavelength bands

3 PROPERTIES OF VARIOUS WINDOW TYPES

Appendix 1 contains a detailed overview of the parameters of the various window and shading types. This chapter contains a tabular summary to provide a quick impression of the application areas and performance. The economy column requires some explanation. In general, sun shading equipment is relatively expensive when compared to ordinary glass. For example automated sun blinds for offices require an investment of about EUR 250/m2 or even higher. Yet, many offices have such systems, especially on east, south and west facades. They do not only contribute to energy management, but also to well-being of people working in the offices and their productivity, which is very valuable but hard to measure. Apparently this is affordable, so for this comparison, such cost are defined as

[3] http://www.commercialwindows.org/

"moderate". Other systems are rated according to this level. Further, the technology of these sun blinds is relatively old, so prices will not drop significantly any more.

Table 2 Tabular summary of window properties

System	Subtype	Commer cial availa bility	Applicability for energy management	Operational energy consumption *	Glare control	Light steering	Economy for energy management
Micro mirrors		n.a.	+	+	+	+	-
Acrylic Lamellas		+	-	n.a.	+	+	n.a
Perforated foils		+	0	n.a.	0	-	+/0
Chromic devices	electrochromic	+	+	0	+	-	-
	gasochromic	-	+	+	+	-	?
	photochromic	+ (for sunglass es)	-	n.a.	n.a.	-	n.a.
	thermochromic	0	0	n.a.	0	-	0
Liquid crystal devices		+	-	-	0	Diffuses light	n.a.
Suspended particle devices		0	+	-	0	-	-
Light shelves		+	0	n.a.	0	-	+
Sun blinds	outdoor (motorized)	+	+	0	+	-	0
	indoor (motorized)	+	+	0	+	-	0
	slats in between dual pane windows	+	+	+	+	-	0

\+ Good performance

0 Moderate performance

\- Poor performance

n.a. Not applicable

* Per standard window of 1.24x1.48 m

+	<1 Wh/24 hours	< 2 EUR/lifetime of 30 years
0	1-10 Wh/24 hours	2-20 EUR/lifetime of 30 years
-	>10 Wh/24 hours	>20 EUR/lifetime of 30 year

This is exclusive of power consumption of the control electronics itself that must be on standby all the time.

Baetens (2010) published an extensive review of the technology of chromic "smart windows" in relation to a study on materials for buildings for the 21 century. Similarly, Klammt published a review of micro-structured windows for daylighting control in 2010, later followed by an article on a light redirecting system in 2012.

4 ENERGY MANAGEMENT APPLICABILITY IN RELATION TO BUILDING TYPE AND EXTERNAL CIRCUMSTANCES

4.1 General

Most extensive studies into the merits of dynamic glazing have taken place in the past in the United States. From these studies (Lee, 2004) it is clear that comprehensive energy modeling of buildings is needed to provide meaningful information on the energy benefits. Results depend among others on:

- Glazing and wall orientation
- Building use (office, dwelling, retail, etc.)
- Window to wall ratio
- Climatic conditions
- Latitude

Such extensive modeling is out of the scope of the present overview. It is however important to stress that applicability of the various products is not only dependent on the product, but indeed on where and how it is applied. This indicates that a "ranking" of the various types is an exercise of little use.

The overview given, however, provides useful insights.

Deliverable 2.6 led to the following analysis regarding the radiation heat load on a window (at 52 degrees latitude)

For a vertical, south-faced window, the heat load integrated over the day in March/April is about 4 kWh/m^2 *of window. Integrated over the entire year, it is about 1200 kWh/m*^{2}*.*

If we assume that all additional radiation needs to be cooled away by air conditioners with a COP of 3, we can find a maximum of the reduction of electricity consumption:
Air conditioner capacity: 600W/3=200W per m^2 *of window.*
Used electricity: 1200/3=400 kWh per m^2 *of window per year.*

At a consumer price of EUR 0.25/kWh this amounts to about EUR 100 /(m^2 **year), of course this is the absolute upper limit.*

A more realistic estimation can be made using a calculation tool of Microshade. This tool calculates the Energy Balance of windows without their products and including them.

For example, for Amsterdam, the (positive) heat gain for a vertical (double), south-faced window is about 220 kWh/m^2 year that possibly needs to be cooled away. This takes into account the local climatic conditions and weather data. Using the same calculation method as above, this results in an upper value of about EUR 20/(m^2 *year). By the way, this holds for most systems that effectively remove the solar heat gain.
In comparison, for a city like Abu Dhabi, the positive energy balance is more than 450 kWh/m^2year. This doubles the value of reduced solar gain (other conditions, like energy cost, being the same).

Four major systems of interest (commercial availability, of interest for energy management, or developed within NEXT-Buildings) will be discussed below.

4.2 Discussion of specific window systems

Electrochromic windows

This is the most advanced smart window type when it comes to commercial availability and active control. Its unobstructed view in the “dark” state is a major advantage. Besides this, the system is relative maintenance free and there are no restrictions as to the height of the building where this can be applied (as is the case for exterior blinding systems that are susceptible to heavy winds). Their application is most advantageous in warm, sunny circumstances. One of the disadvantages to sun blinds is the long switching times that can be minutes for larger windows. This makes the windows less applicable in climates in which sunny spells are changing with cloudy circumstances. Current price levels do not yet compete with automated sun blinds, but for e.g. board rooms with a luxury equipment level they compete.

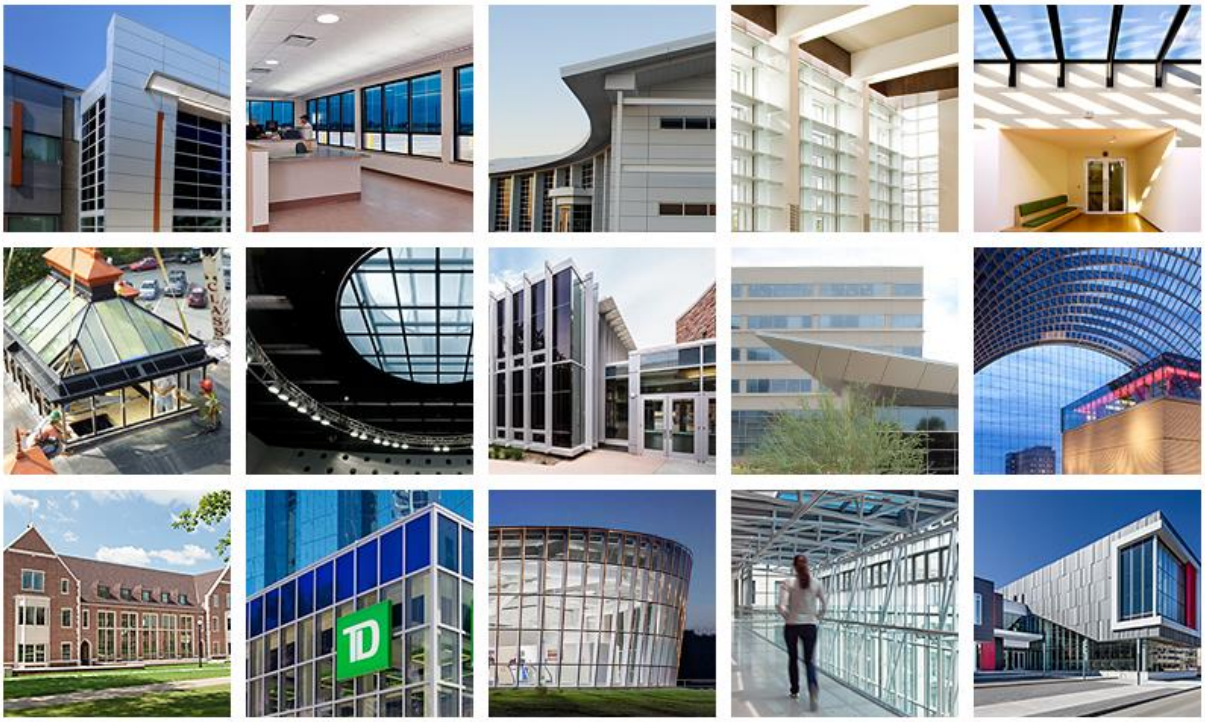

Figure 1 Overview of SAGE Electrochromic windows projects

Microshades

Microshades are perforated foils that are integrated in standard IGU (Integrated Glass Units). They are relatively cheap to install and require no maintenance, but cannot be removed. The amount of solar sunrays transmitted is depending on the angle of the sun versus the orientation of the foil/window. Therefore the system can be designed in such a way that it preferably blocks the sun when high south. Disadvantage is the reduced solar gain even in winter and the lack of active control. This system is thus best used in areas with stable and predictable weather conditions most of the year. Can be applied in high-rise buildings.

Sun blind systems

<u>Fixed</u>

Fixed sun blinds are the cheapest solution to control the solar heat gain from windows. They are effective when the sun is high –in summer-, and their they utilize solar gain when useful –in winter-. Drawback is the lack of control of glare at low sun heights, which often calls for additional measures in winter or at high latitudes.

Automated

Currently this is one of the reference systems in commercial buildings. It offers high degree of control, wide range of shading at a cost affordable for commercial buildings. Drawbacks are their esthetic appearance (disputable) and their required maintenance and application height limitations because of wind speeds. As a mature technology, its ball-park cost of about EUR 250/m^2 serves as a measure for other systems to judge competitiveness. It has been shown earlier that energy benefits could be of the order of EUR 20/m^2yr. Break-even would therefore be achieved in about 12 years.

Micro mirror systems (as developed in NEXT-Buildings)

Transmission controllable glazing based on MEMS offer a wide range of transmission. In addition, the micromirrors are able to "steer" the light towards the ceiling of a room. In this way the room can be better illuminated by natural daylight by bringing it "deeper" in the room. The system can be integrated in IGU's, securing low maintenance. It has very low operational energy use, that can be neglected in practice. The daylighting advantages compete with the fact that LED lighting becomes more and more common practice, reducing the energy consumption that is lighting related. Currently the system is non-commercial, but in the end the cost could be comparable with automated sun blinds.

Non energy related properties

As the MEMS system is likely composed of smaller units of 10x10 cm that can be individually controlled, it is possible to create patterns on windows, for example to transfer messages.

5 CONCLUSIONS

It appears that for commercial buildings, the total cost for glass in the facades is not mainly glass, but sunblind system related. This has to do with the fact that facades with a lot of glass lead to a significant cooling load, especially in hot, sunny climates like in California or the Middle East. Mitigation of this cooling load leads to sunblind systems. For high buildings, external systems cannot be applied because of wind speed related issues.

Smart windows combine the daylight transmission function with thermal management, either through controllable coatings or through microstructures. The commercially most advanced window type is that of electrochromic windows. This has proven durability and range of transmission and approaches the cost of traditional, automated, sun blinds.

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6 GLOSSARY

Abbreviation	Description
COP	Coefficient Of Performance
IGU	Integrated Glazing Unit
g	Solar energy transmittance
LED	Light Emitting Diode
LSG	Light to solar ratio
MEMS	Micro Electro Mechanical System
SHGC	Solar Heat Gain Coefficient
V_t	Visible transmission

7 REFERENCES

The Energy-Savings Potential of Electrochromic Windows in the US Commercial Buildings sector, Lee, E.S. et al, LBNL-54966, 2004,

Baetens et. Al., Properties,requirements and possibilities of smart windows for dynamic daylight and solar energy control in buildings: A state-of-the-art review. Elsevier, Solar Energy Materials & Solar Cells 94 (2010), 87- 105.

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http://www.kawneer.com/kawneer/north_america/en/product_category.asp?cat_id=1344&desc=sun-control-products

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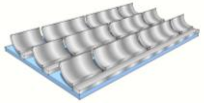
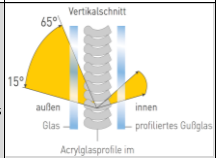
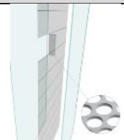
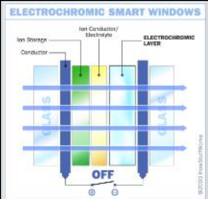
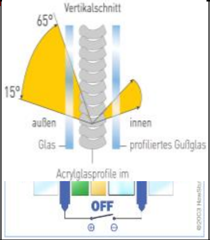
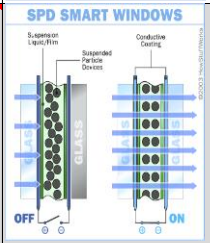
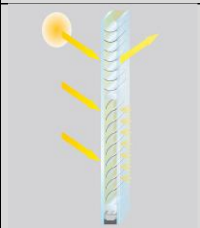
APPENDIX 1 Detailed overview of parameters of windows and shading systems

Daylight Control Device	Further Categorization	Function/benefits	Scheme	Disadvantages	Manufacturer/ Research Group	Operating Voltage	Operational Energy Consumption	Economics	Further Specifications (Visible Light Transmission, SHGC)
Micromirrors		Light-steering through reflection; adjustment of window transmittance by changing opening degree; electrostatic actuation; non-actuated state = opened state Fast switching			INA	**Design 1:** 80 V (DC) (record with 40 V DC) **Design 2:** 350 V (DC) 280V (AC)	**Design 1:** 2.5 mW/m^2 (record: 0.2 mW/m^2) **Design 2:** 1 mW/m^2 1.1 W/m2 at 1 kHz (real 2 kHz) Mean values for 12h usage (standard window W 1.24m x H 1,48m): 2x complete cycles (up/down) and 20 x repositioning = 1.05 mW/m^2 x 12h x 1.24m x 1.48m = **0.023 Wh per day**	Additional cost EUR 1000/m2 at market introduction, EUR 300/m2 at mass production Can avoid about 220 kWh/m2yr to be cooled away (Amsterdam south orientation , Abu Dhabi 450 kWh/m2yr). Value about EUR 20/m2year (if with heat pumps COP=3)	High freq. actuation of 3-6 kHz has been tested VL Transmission 1%-60%. SHGC similar as there is no wavelength selectivity >30 years lifetime extrapolated
Acrylic Lamellas		redirecting incident light from an solar altitude range between 15° and 65° to emergent angles larger than 0° (to the ceiling); macro structures: Acrylic (PMMA) profiles (~11 mm x 3 mm) fixed in glass gap and patterned inner glass pane (sinusoidal)		- static system - no complete shading - mostly suitable for skylights	GLASSOLUTIONS Sain-Gobain (LUMITOP)	----	----	Used for part of glass facades, mainly above eye level. Redirects light further in the spave behind. Not for thermal management	
Perforated foils		the light transmittance and g-value of the glazing changes with the incident angle of the solar radiation: At low radiation angles MicroShade® allows a high transmittance while the transmittance is low at higher angles		- static system - no complete shading	MicroShade	----	----	Can avoid about 189 kWh/m2yr to be cooled away (Amsterdam south orientation MS-A). Value about EUR 15/m2year (if with heat pumps COP=3)	
Chromic devices	electrochromic	changes its optical propertie reversibly by applying an external potential (oxidized and reduced form)		- most electrochromics are absorbing (problem of heating up) - no light steering - slow switching (5-10 min for 90 cm x 150 cm window) - no complete opaque state possible	SAGE Electrochromics, Econtrol-Glas, Gesimat (Saint Gobain Sekurit, ChromoGenics, Gentex -> small scale)	Ranging between 0.5-5 V (DC)	**2 types considered:** **1) Polymer laminated** status maintained for 3-5 days after switching **2) all-solid-state** **0.2 W/m^2** for switching and maintaining state Mean values for 12h usage (standard window W 1.24m x H 1.48m): 0.2 W/m^2 x 12h x 1.24m x 1.48m = **4.4 Wh per day**	2010: EUR 1000/m2, 2015: EUR 300-600/m2, at mass production EUR 250/m2 Energy savings possibilities through saving on cooling energy 6%-26% (1)	max size = 120 cm x220 cm (from Econtrol-Glas) VL Transmission: 2%-60% SHGC 0.09-0.41
	gasochromic	switch between bleached and coloured state by introducing diluted H_2 gas to film of tungsten oxide, O_2 returns window to transparent state		quick degradation	Fraunhofer Institute for Solar Energy Systems and Interpane (not yet commercial)		----		VL Transmission: 20%-70% Switching: 20 sec to colour; <1min to bleach
	photochromic	responds automatically to changes in light intensity		difficult to control (passive device)	e.g. in eyeglasses not yet commercially available for windows, Oakley, Rudy Project		----		VL Transmission 10-70% SHGC n.a.
	thermochromic	responds automatically to changes in tmeperature		difficult to control (passive device)	PLEOTINT L.C.C.		----		VL Transmission: 10%-50% SHGC 0.13-0.15

Daylight Control Device	Further Categorization	Function/benefits	Scheme	Disadvantages	Manufacturer/ Research Group	Operating Voltage	Operational Energy Consumption	Economics	Further Specifications (Visible Light Transmission, SHGC)
Liquid crystal devices		change in orientation of LC molecules between two conductive electrodes, by applying an electric field, changes transmittance. In use as privacy glass, not for energy management		- scattering in off-state - long-time UV stability is an issue - no light steering	Saint-Gobain glass, Innovative Glass Corporation, Nippon Sheet Glass, DreamGlass, SmartGlass International Ltd., Switchlite, etc.	Ranging between 60-230 V (AC)	Ranging between 3.5-15.5 W/m^2 Permanent voltage required Mean values for 12h usage (standard window W 1.24m x H 1.48m): (3.5-15.5) W/m^2 x 12h x 1.24m x 1.48m = **44-341 Wh per day**		max. size = 260cm x 488cm (from Innovative Glass Corpration) VL Transmission: 75% Haze 6%-94% (large means a lot of scattering, low is almost no scattering), SHGC comparable to Visible Light Transmission
Suspended particle devices		particles are random and light absorbing in off state, by applying an electric field they can be alligned to increase transmittance , fast switching (<1 s)		- absorbing (problem of heating up) - no light steering - low transmittance in off-state	Research Frontiers Inc. (NY, USA) -> Patent Innovative Glass Corpration, SmartGlass International Ltd., CRICURSA Cristales Curvados S.A.	Ranging between 65-220 V (AC)	Ranging between 1.9-16 W/m^2 Permanent voltage required Mean values for 12h usage (standard window W 1.24m x H 1.48m): (1.9-16) W/m^2 x 12h x 1.24m x 1.48m = **41-352 Wh per day**	Costly according to commercialwindows.org	max. size = 260cm x 488cm (from Innovative Glass Corpration) VL Transmission: 0.5%-22% and 12%-57% SHGC 0.41-0.56 and 0.5-0.7
Light shelfs		Interior shelf designed to reflect sunlight deep into building, variable angles and depth (motorized)		- high maintenance - esthetics	Kawneer			Kawneer tool estimates cost savings as all radiation to be cooled away, i.e 1200 kWh/m2yr. Shading dependent on blade length, angle and separation	

Daylight Control Device	Further Categorization	Function/benefits	Scheme	Disadvantages	Manufacturer/ Research Group	Operating Voltage	Operational Energy Consumption	Economics	Further Specifications (Visible Light Transmission, SHGC)
Sun blinds	outdoor (motorized)	blinds consisting of approx. 8 cm wide slats; blinds are seperated into 2 regions, where slats can be flipped independently in angle (Doppelbehang)		- high maintanance - esthetics - slow operation	WAREMA: model E 80 LD (Doppelbehang)	230V (AC) 2 types of motors: 1) for moving blinds up and down (Motor D339, 131W) 2) for flipping of slats (Motor D239, 108W)	Mean values for usage (standard window W 1.24m x H 1.48m): 2x complete cycles (up/down) = 4 x 131W x 24.3 s = 12733 Ws = 3.5 Wh 20 x flipping/repositioning of slats = 20 x 108W x 0.13 s = 281 Ws = 0,08 Wh Overall power consumption = **3.58 Wh per day**	Investment approx. EUR 250/m2, automated system, installed Manufacturer info: The light steering model E 80 LD with blind dimensions of 1.230 m (width) and 1.643 m (height), without any further special requests, would cost 1,237.65€ (613 EUR/m2)	
	indoor (motorized)	Comparable with outdoor sun blinds		-high maintanance -esthetics -slow operation	WAREMA	Motor 230V	Comparable with outdoor sun blinds	Investment approx. EUR 250/m2, automated system, installed	
	slats in between dual pane windows	electrical driven blinds, protected from dust and environmental influences through encapsulation		- Acts as a thermal bridge; problem reduced when applying triple or quadruple glazing - thermal distortion of window glass can cause jaming of slats	GLASSOLUTIONS Sain-Gobain, ScreenLine GmbH	24 V (DC) current consumption: 0.5 A	Mean value for usage (standard window W 1.24m x H 1.48m): 2-3 complete cycles (up/down): 5 x 24 V x 0.5 x 1 min = 60 Wmin = **1 Wh per day**		
		(1) The Energy-Savings Potential of Electrochromic Windows in the US Commercial Buildings sector, Lee, E.S. et al, LBNL-54966, 2004							