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CONTROL SYSTEM AND ENERGY SAVING POTENTIAL FOR SWITCHABLE WINDOWS

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ABSTRACT

The energy efficiency of switchable (variable transmittance) windows having a control system based on occupancy, temperature and impinging solar radiation is evaluated. The heating and cooling performance of the switchable windows are compared with the performance of several conventional glazings. The study indicates that the energy efficiency of switchable windows depends highly on several different parameters, such as location, type of building, orientation, occupancy, etc., but that there is a potential to use a "intelligent" control system for the switchable window in order to reduce the need for external energy and potentially also improve the comfort. The energy efficiency of switchable windows increases with internal heat production and is more beneficial the sunnier and the warmer the location is.

INTRODUCTION

Static state-of-the-art glazings for architectural window applications are reaching their physical limits when it comes to improving the energy efficiency of the building. Using thin film technology it is possible to achieve close to zero thermal emittance leading to "low-e" windows with low U-values. Furthermore, "solar control" windows having twice as high light transmittance (T_{vis}) as solar transmittance (T_{sol}) leading to solar heat rejection with maintained high visual transmittance is manufactured on a regular basis. A subsequent possible step towards improved glazing energy efficiency may be through the use of switchable (variable transmittance) windows, or smart windows. As the material science behind these types of windows is reaching maturity, the question arises of how to control these windows in order to maximise energy efficiency and comfort.

Previous work at Lawrence Berkeley Laboratory has dealt with different ways of controlling the smart windows such as by incident solar radiation, indoor light level, the presence of a cooling load, etc. (see for instance: Sullivan et al., 1995, Sullivan et al., 1996). Furthermore, this group has investigated smart windows in several different locations, type of buildings (ibid.) and studied energy efficiency as well as comfort issues (Moeck et al., 1996). The group demonstrates that idealised smart windows (i.e. not available today) outperform conventional glazings, but that savings depend highly on which control strategy that is chosen.

In Karlsson et al. (2000) a solar control strategy was used to compare the heating and cooling performance between available and future smart windows with a set of different solar control windows and also a low-e window. The results indicated that switchable windows mostly compete with high performance solar control windows with high light transmittance and low total solar energy transmittance (g-value). In that study (ibid.) the results indicated that smart windows are, from a pure energy point of view, mostly interesting in commercial buildings, with a relatively high internal load, and/or in hot and sunny climates. Consequently, the present report is limited to the study of commercial office modules in three very different climate zones.

This paper study a complex control system with the purpose to investigate if a switchable window can be beneficially controlled, not only by load parameters (cooling, heating, lighting) but also by occupancy (patent application, SE0003112-0) as has been demonstrated before in the case of lighting and ventilation (see for instance: Garg and Bansal, 2000, and Brandemuehl and Braun, 1999). For example, if there is a high cooling load in the office and there happens to be no one present, the window can be allowed to become dark (low transmitting) and thus reduce unnecessary influx of heat.

A very simple physical description of an office module is used in which different high performance static and variable windows are compared. Some features of the office module and the climates are also varied.

PREREQUISITES

As a building simulation tool the simple hourly dynamic model presented by Keller et al. (2000) (see also: Burmeister and Keller, 1998) is used with TRY weather data as input. The anisotropic Hay and Davies (see for instance: Duffy and Beckman, 1991) model is used for the solar radiation on vertical surfaces and the angle dependence of the transmittance of the glazings is calculated according to Karlsson and Roos (2000). All U-values are assumed to be constant. A "base-case" was defined as a commercial office module of a very simple “shoe box” form, described in table 1. The office module was assumed to have adiabatic surfaces in all orientations except for the front facing surface. The “free” internal heat was assumed to be 330W during office hours, which corresponds to about 1 person, one computer and energy efficient lighting, and 0W after working hours. Heating and cooling set points were different during working hours and non-working hours and the ventilation was reduced during non-working hours as described in table 1.

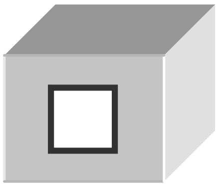
<table>
<tr><td colspan="3">BASE CASE <i>(south facing, no shading)</i></td><td rowspan="12"></td></tr>
<tr><td>Front wall U-value</td><td colspan="2">0.3 W/m^2K</td></tr>
<tr><td>Glazing U-value</td><td colspan="2">2.9 W/m^2K</td></tr>
<tr><td>Frame U-value</td><td colspan="2">2.2 W/m^2K</td></tr>
<tr><td><i>GWAR</i></td><td colspan="2">30 %</td></tr>
<tr><td>Glazing g-value</td><td colspan="2">76 %</td></tr>
<tr><td>Time constant[1]</td><td colspan="2">180 h</td></tr>
<tr><td></td><td><i>Working hours (8-17)</i></td><td><i>else</i></td></tr>
<tr><td>“Free” internal heat</td><td>330 W</td><td>0</td></tr>
<tr><td>Heating set point</td><td>20</td><td>17</td></tr>
<tr><td>Cooling set point</td><td>25</td><td>28</td></tr>
<tr><td>Ventilation + infiltration</td><td>1.1 + 0.1 ach</td><td>1.1*0.25 + 0.1 ach</td></tr>
</table>

Table 1: Data for the office module base-case. GWAR denotes glazing to wall area ratio. Heating and cooling plant efficiency is set to unity. [1] See: Keller et al.(2000). The base case window is uncoated and double-glazed.

Three different locations (same as in Karlsson et al., 2000) were chosen for the simulations: Stockholm (Sweden), Denver (USA) and Miami (USA), all having highly different annual average temperatures and annual solar radiation as illustrated in table 2. A test set of glazings containing one uncoated, one low-e, four solar control and four smart windows as described in table 3 were used. Smart 1 and 2 are data from currently available smart windows, and SmartFict 1 and 2 are variable windows that may be available in the future.

Location	**Annual average temperature** (°C)	**Annual average solar radiation** (kWh/m^2yr, horizontal surface)
Stockholm (TRY)	Low (6.9)	Low (920)
Denver (TMY2)	Low (9.9)	High (1700)
Miami (TMY2)	High (24)	High (1800)

Table 2: The three locations chosen for the simulations and their annual average temperature and solar radiation. TMY means Typical Meteorological year and TRY means Test Reference Year.

Identity	**Type**	***g* (%)**	***U* (W/m^2K)**	**Category**	**Panes**	**T_{vis} (%)**
Clear	Clear floatglass	76	2.9	4	2	82
Low-e	Low-e	56	0.9	3.5	3	64
SolContr. 1	Solar control	24	0.8	2.5	3	36
SolContr. 2	Solar control	27	1.2	2.5	2	42
SolContr. 3	Solar control	34	1	1.5	2	67
SolContr. 4	Solar control	18	1	1.5	2	32
Smart 1	Smart (existing)	44/15	1.6	1	2+1	50/15
Smart 2	Smart (existing)	36/12	1.1	1	2+1	50/15
SmartFict 1	Smart (fictitious)	44/3	1	1	2	55/0
SmartFict 2	Smart (fictitious)	56/3	1	1	2	65/0

Table 3:Parameters for static and variable glazings. All the static glazings are commercially available, but data for the last solar control alternative was simulated, to get a static alternative with a very low g and reasonably high T_{vis} (double silver layer coating on grey glass). Smart 1 and 2 are data from recently released smart windows (E-Control by Pilkington Flabeg GmbH) and SmartFict 1 and 2 are data for idealised smart windows that might be available in the future. The U-value is given for the centre of glass. The “Category” parameter accounts for proper angle dependence of the transmittance according to Karlsson and Roos (2000).

RESULTS

Figures 1-3 illustrate the results in the three different locations for the base case. The y-axis in the figures gives the saved heating plus cooling in kWh per square meter glazed area and year compared to an uncoated double glazed unit. For the base case, the smart windows were controlled linearly by the impinging radiation with the low and high set points put to 50 and 300 W/m^2 (as in Karlsson et al., 2000), respectively. It is seen that in the Stockholm and Denver climates the future smart windows performed about the same as the best static alternatives. For the Miami climate the future smart windows outperformed the best static windows by about 60-80 kWh/m^{2}yr for the southeast to the southwest orientations. Even the available smart windows outperformed the best static windows, except for the north facing windows. Note that the heating and cooling plant efficiencies are both set to unity in all simulations.

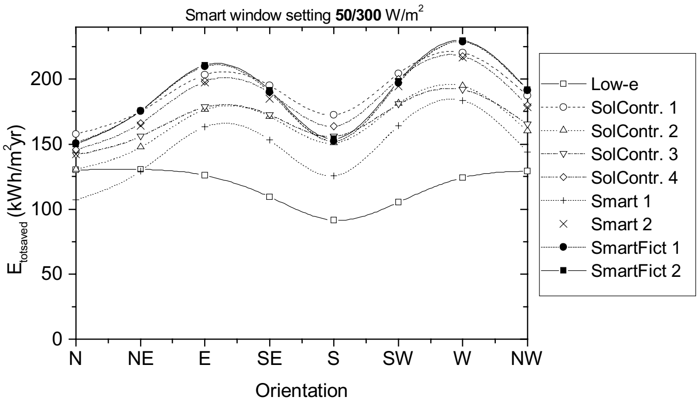


Figure 1:Total (heating plus cooling) saved energy versus the orientation of the windows for the different window alternatives compared to an uncoated double glazed window for the base case in a Stockholm climate.

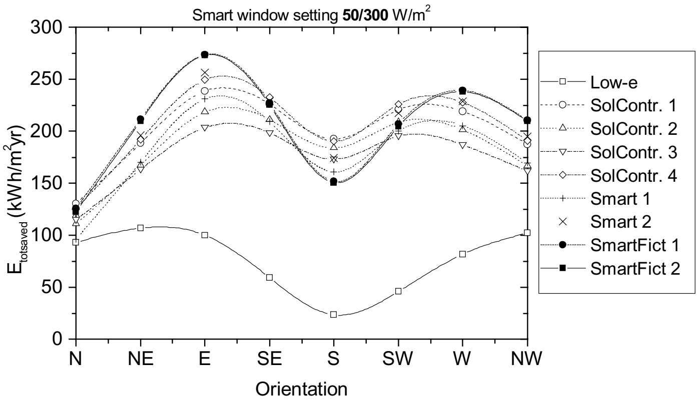


Figure 2: Total (heating plus cooling) saved energy versus the orientation of the windows for the different window alternatives compared to an uncoated double glazed window for the base case in a Denver climate.

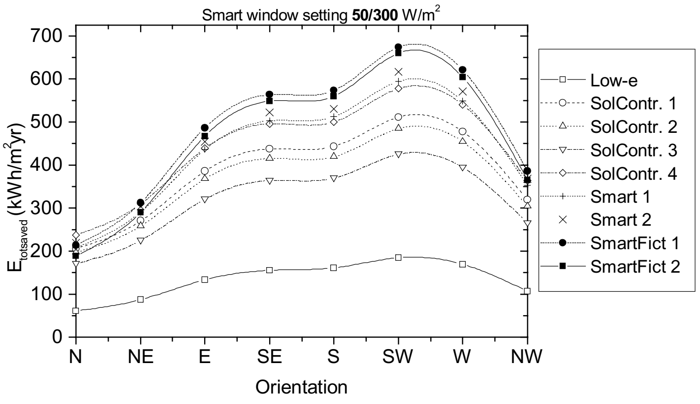
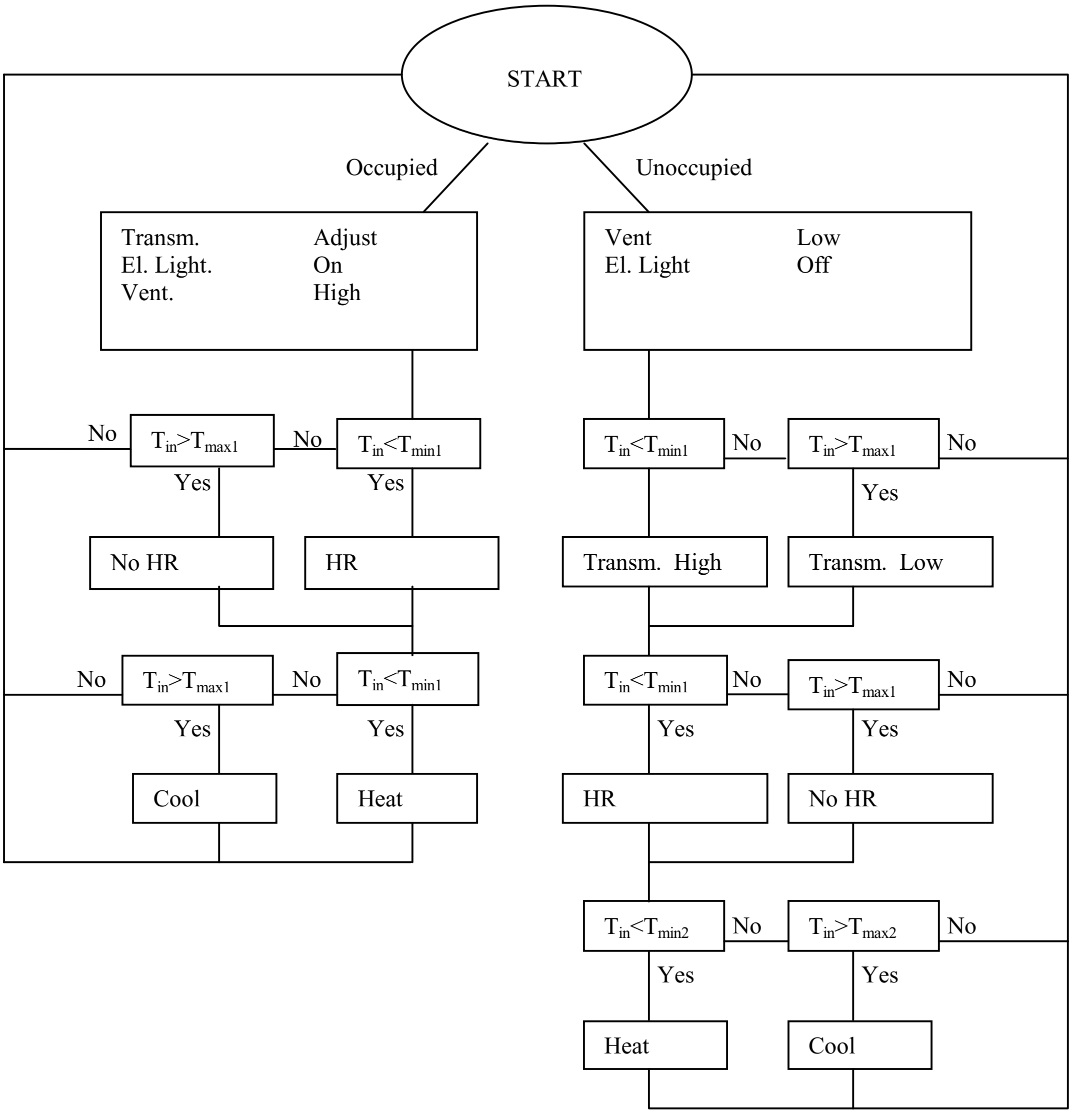


Figure 3: Total (heating plus cooling) saved energy versus the orientation of the windows for the different window alternatives compared to an uncoated double glazed window for the base case in a Miami climate.

The results above are quite similar to the ones in Karlsson et al. (2000), except that the office module in that investigation had higher internal energy production, and somewhat higher savings for the variable windows in the Denver and Stockholm climates. In order to investigate possible synergies of different "intelligent" envelope designs the control system as described in figure 4 was simulated. This control system requires controllable HVAC (Heating, Ventilation, and Air Conditioning), lighting and switchable windows. Furthermore this would require temperature, light and occupancy sensors. In the following cases it was assumed that the occupant in the room was out of the room 25%, randomly distributed, of the office hours. Lighting was set to full when the office was occupied and zero when unoccupied.



Nomenclature:

Transm. = Transmittance of smart window

El. Light. = Electric lighting

Vent. = Ventilation

HR = Heat recovery of exhaust air

T_{in} = Indoor temperature

T_{min1} = Low temperature set point (e.g. 20 degrees)

T_{max1} = High temperature set point (e.g. 25 degrees)

T_{min2} = Low temperature set point for heating when no presence (e.g. 18 degrees)

T_{max2} = High temperature set point for cooling when no presence (e.g. 27 degrees)

Adjust = Natural lighting level adjusted according to automatic settings

Figure 4: Flow chart of the tested "Intelligent" control system including heat recovery and smart window.

In figure 5 below it is illustrated that with the advanced control system in Stockholm the future smart windows can, just barely, outperform the best static alternatives and the present smart windows cannot. However, in the Denver climate the saving was noticeably increased by the intelligent control system, figure 6. In this climate, the future smart windows illustrate savings of the order of about 50 kWh/m^{2}yr and the best present smart window outperforms the best static by about 0-30 kWh/m^{2}yr, depending on the orientation. Finally, for the Miami climate the intelligent control system increased the saving to about 100 kWh/m^{2}yr and 50 kWh/m^{2}yr for the future and the present smart window alternatives, respectively, and for south facing orientations and compared to the best static window (figure 7). Note that the y-axis in figures 5-7 represents saving compared to the base case windows and that the total energy demand of the office module is affected by the control system for all types of windows.

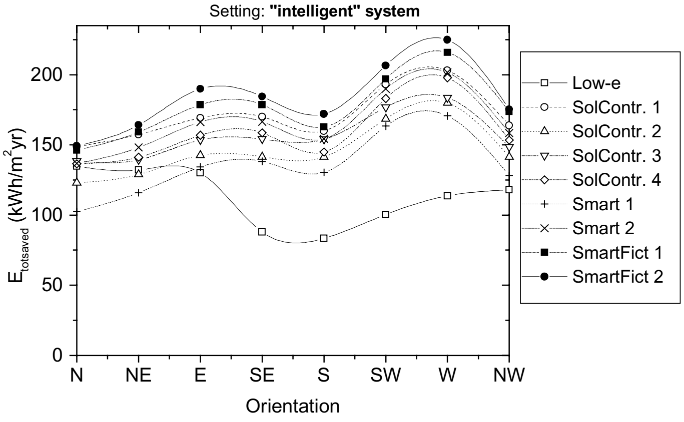


Figure 5: Total (heating plus cooling) saved energy versus the orientation of the windows for the different window alternatives with the intelligent HVAC/lighting/occupancy control system compared to an uncoated double glazed window for the base case in a Stockholm climate. For comparison of best switchable window versus best static window see difference between "Smartfict 2" and "Solcontr. 1"

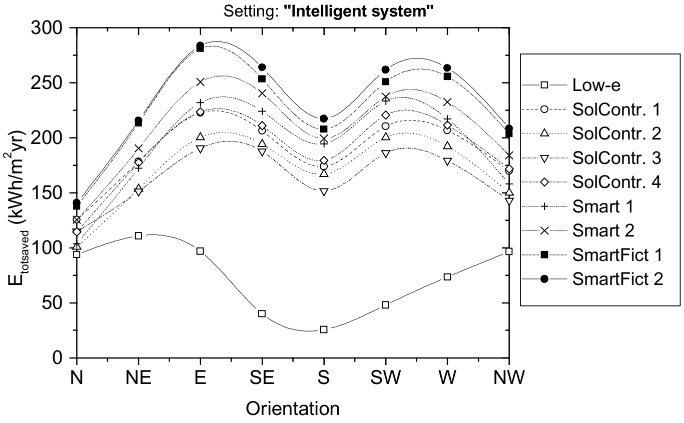


Figure 6: Total (heating plus cooling) saved energy versus the orientation of the windows for the different window alternatives with the intelligent HVAC/lighting/occupancy control system compared to an uncoated double glazed window for the base case in a Denver climate. For comparison of best switchable window versus best static window see difference between "Smartfict 2" and "Solcontr. 4"

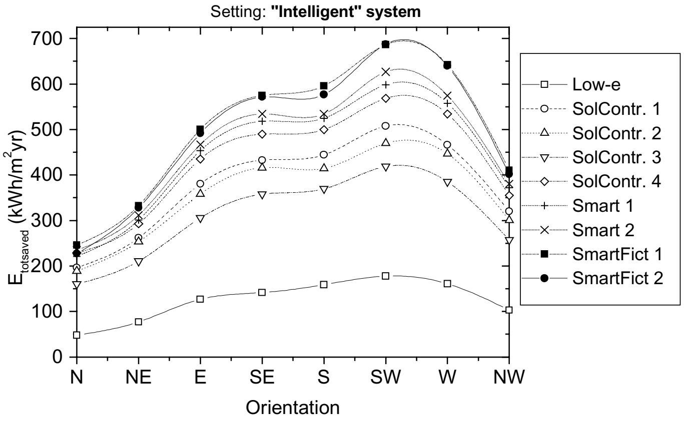


Figure 7: Total (heating plus cooling) saved energy versus the orientation of the windows for the different window alternatives with the intelligent HVAC/lighting/occupancy control system compared to an uncoated double glazed window for the base case in a Miami climate. For comparison of best switchable window versus best static window see difference between "Smartfict 2" and "Solcontr. 4"

As in Karlsson et al. (2000) the saving caused by the smart window increased with increased internal heat load, as illustrated in figure 8, for the Stockholm climate. In this case the internal heat production was doubled to 660W, which would correspond to about two persons, two computers and inefficient lighting, and it is seen that the saving with the switchable window increased to of the order of 50 kWh/m^{2}yr compared to the best solar control window. The saving also increased for the Denver climate (to about 75 kWh/m^{2}yr) when the internal heat was increased but that illustration is left out here because lack of space.

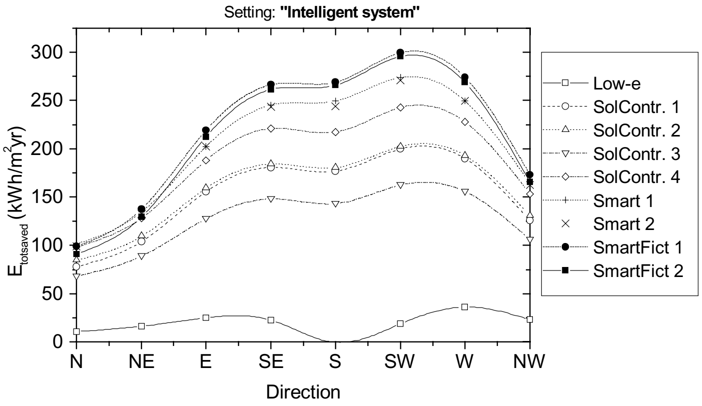


Figure 8: Same figure as in figure 5 but with twice the internal heat production. For comparison of best switchable window versus best static window see difference between "Smartfict 2" and "Solcontr. 4"

To summarise and compare, the different changes are plotted in figure 9 where each measure is added to the base case. Note that the energy in figure 9 is given per square meter floor area as opposed to the figures above were the saving is given per square meter glazed area. For all locations it is clearly important to choose the appropriate window (and/or shading) from the beginning. Controlled heat recovery of the exhaust air is of importance in heating dominated (cold) climates and of no importance in cooling dominated climates. The ability to vary the transmittance can be of importance in sunny climates, and the saving seems to be higher the warmer and the sunnier the climate is. Furthermore, figure 8 demonstrates that smart windows can be beneficial in less sunnier climates if it is an office with a high internal heat production. Occupancy control as described above increases the savings, especially in hot climates.

The occupancy control also leads to electricity savings, not seen in figure 9, since the lighting and ventilation can be reduced when no one is present. Furthermore, when the office is occupied, automatically regulated light can reduce the electricity need, and if the smart window has a higher light transmittance in the transparent state than the window that it is compared with, this saving can be enhanced. In the Stockholm case (figure 9), the occupancy control leads to an increased heating need since "free" useful energy from persons and lighting were reduced during the 25% of time of absence. This is balanced by increased electricity savings from the reduced lighting and ventilation (not seen in figure 9). For the Miami case, the occupancy control leads to high cooling savings because of the reduced solar throughput and reduced internal energy from persons and lighting.

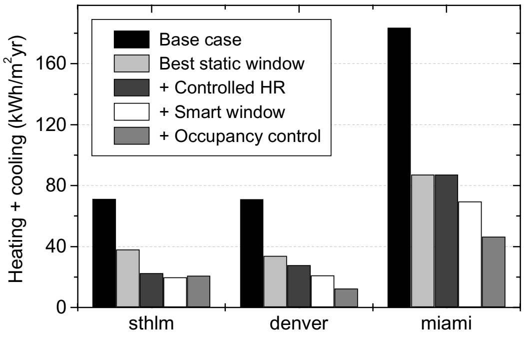


Figure 9: Heating plus cooling demand per square meter floor area for the base case in three different climates. The leftmost bar gives the demand for the base case and the staples to the right gives the demand when changing to the best static window, plus controlled heat recovery, plus best smart window, plus occupancy control with 25% randomly distributed absence.

DISCUSSION & CONCLUSIONS

- The energy saving potential of smart windows depends strongly on various different parameters, such as location, type of building, orientation, lighting and comfort demands, and also the choice of reference window.

- When it comes to energy performance the smart windows "compete" with high performance solar control windows.

- An "intelligent" HVAC/lighting/occupancy control system has the potential of increasing the energy saving potential of the smart windows as compared to a "simple" control strategy (figures 1-3).

- A switchable window does not seem interesting in a north facing orientation (for the northern hemisphere; and south facing for the southern hemisphere).

- Approximate savings versus the best static window in an office module (as defined above) are of the order of: 0-50 kWh/m^{2}yr in a Stockholm-like climate, 25-75 kWh/m^{2}yr in a Denver-like climate, 50-150 kWh/m^{2}yr in a Miami-like climate (all given per square meter glazed area).

These results will in a real situation also be affected by occupant behavior, but it is clear that the smart windows can have an equal or better energy performance than static windows and on top of this give an increased comfort with, for instance, automatic glare control.

From figure 9 it can be further concluded that it is important to choose correct window (and/or shading). Controlled heat recovery is important in cold climates. Switchable windows are beneficial in sunny climates and offices with high internal heat generation. Occupancy control saves cooling energy in the Denver-like, and even more in the Miami-like, climates. Furthermore, occupancy control, regulated lighting and ventilation also save electricity, which is not illustrated in this study (see for instance: Garg and Bansal, 2000, and Brandemuehl and Braun, 1999).

It should be noted that the future smart windows had a high cooling performance, but this is related to the fact that they were in their darkest state for several of the occupant hours. This may not be accepted by the occupants, but the darkest state should be possible to regulate. If the darkest state were set to, for instance T_{vis}=15% the saving would correspond to the same as the available "Smart –2" alternative. There seems to be a "trade off" situation between natural lighting and cooling, i.e. higher fraction of natural light gives higher cooling demand and if the cooling demand is reduced by lower transmittance, less natural light is available. The static windows, on the other hand, may need additional shading to avoid glare, while the smart window can automatically reduce such problems.

When the office was occupied, the transmittance was controlled linearly by the impinging radiation as descried above. Further work should be devoted to a control system similar to the one in figure 4 but where the transmittance is regulated by light sensors in the room (e.g. on the work plane) and where the artificial lighting is used to control the light level. (Moeck et al., 1998, Sullivan et al., 1995, Sullivan et al., 1996). Further work is needed to compare of smart windows with static windows in combination with shadings, such as blinds.

From a purely "energy-economical" point of view and if a lifetime of 30 years, interest rate of 5% and energy cost of 0.1 Euro are expected, a saving of about 100 kWh/m^{2}yr means that the extra cost for the smart window is allowed to be about 150 Euros/m^2, including control system. This "allowed cost" can be increased if the smart windows can replace other shading systems.

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