THE CARBON NEGATIVE BUILDING FAÇADE

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ABSTRACT

Glass is a valuable building material: it is strong, durable, easily maintained, and most importantly, transparent. This transparency reduces artificial lighting loads and heating loads in the heating season, but results in undesirable solar heat gain in the cooling season. As a result a design compromise exists between high and low window-to-wall ratios, in terms of energy used in heating, cooling and lighting. Buildings with a high window-to-wall ratio are generally unable to maintain a comfortable and temperate internal environment in the cooling season without the use of energy-intensive HVAC systems; those with a low window-to-wall ratio do not exploit the potential solar hear gain in winter and require more artificial lighting. Smart glazing units, which can alter their optical properties through a reversible reaction, allow energy savings to be made, but typically have greater embodied energy than their static competitors.

This paper considers how current state-of-the-art glazing technologies might be used to create a carbon negative building envelope. Following a literature review, the decision is made to compare electrochromic (EC) glazing with a high performance static solar-control (SC) glazing. Figures for embodied energy of these technologies are quoted. The energy demand of a typical office room is assessed using building simulation software. This simulation is evaluated for an office facing north, south, east and west. The locations of London, Abu Dhabi and Singapore are considered to evaluate the effect of local climate. The window-to-wall ratio that delivers the lowest energy use is chosen for each location. The office is subsequently tested with each technology and the energy demand calculated. The sensitivity of the results to the size of the office is evaluated. The EC glazing is defined as carbon neutral if it delivers a greater reduction in carbon emissions through its use than are emitted in its production. The findings are considered in the context of a high profile highly glazed building to evaluate their relevance with regards façade design decisions. A façade life of 25 years is assumed.

It is found that EC glazing delivers net lifetime carbon savings of 13.0% in London, 10.8% in Abu Dhabi and 7.6% in Singapore, averaged across the four orientations, when compared to SC glazing. It is thus found that EC glazing is carbon negative. The maximum net carbon saving of 329 kgCO_2 per square metre of office floor space was realised for a south facing façade in Abu Dhabi. The greatest relative reduction is 20.5% for a south facing façade in London. It is found that potential savings reduce with room depth. When considered in the context of the construction of the Shard, London, the cash value of the savings at the current carbon price is found to be negligible.

INTRODUCTION

The building envelope is arguably the most important factor in determining the energy use of a building. The properties of a façade, for example the window-to-wall ratio or G-value, are variables in complex non-linear relationships that relate building energy use and occupant comfort to the transient external environment. This complexity is difficult to deal with in the early design stages. Aesthetic considerations tend to dominate the design of many façades, with occupant comfort provided through the extensive use of building services, often at the expense of energy efficiency.

Glass is a building material that has the potential to create a façade that satisfies the conflicting requirements of aesthetic demands, energy efficiency and occupant comfort. Its transparency is architecturally attractive and can be used to create dramatic spaces. The flow of radiation through a façade can be harnessed to reduce energy demand, but excessive solar gain will create energy demand through a need for cooling. Thus for a transient external environment, there is a set of optimum façades, as defined by their window-to-wall ratios, G-values, U-values and visible transmittances, which deliver the lowest building energy loads. The energy loads mainly depend on the type of building, its location, the geometry of the internal space, and the orientation of the façade in question. Energy savings are possible if a façade that can dynamically alter its properties to match the varying external boundary conditions to deliver the lowest energy loads. Several technologies exist to create this "Wall for all Seasons" [1]. They are evaluated below.

One tool that could be used to rationalise the design process is Life Cycle Analysis (LCA). It divides the life cycle of any product into four phases: raw materials, production, use and disposal [2]. For façade components, the use-phase can be evaluated using building energy simulation. LCAs are greatly simplified when used to compare two similar products, as the common aspects of each can be neglected.

Building energy simulation also represents a powerful tool for the designer. This paper uses a small, simple model of a typical office room to compare the energy loads placed on building services by façades comprising of the static and dynamic technologies.

Technology Review

Four dynamic glazing technologies were considered, as shown in Table 1.

Technology	Advantages	Disadvantages
Liquid Crystal	Proven technology widely used as privacy glass.	Consumes energy to maintain clear state.
Thermotropic	No energy input required.	No occupant control
Gasochromic	Can control large uninterrupted areas of glazed.	Liquid system give rise to a risk of leaks.
Electrochromic	Energy only consumed when changing state.	Effective only for limited size glazing.

Table 1: Summary of Technology Review [3].

Electrochromic (EC) glazing was chosen for this study. Research has found it capable of delivering significant energy reductions [4]. Papaefthimiou et al. [5] conducted an LCA to calculate the embodied energy of materials used in EC glazing manufacture. A market-leading static solar control (SC) glazing was chosen as the comparison.

METHOD

Building Energy Simulation

A typical rectangular office room was constructed using EnergyPlus Version 6.0.0. London, Abu Dhabi and Singapore were chosen as three locations spread over a range of latitudes with a high demand for commercial office space. A preliminary investigation was used to find the optimal window-to-wall ratio in a range from 50% to 99% for each location. 99% was considered the maximum feasible and 50% the minimum acceptable window area for a commercial office. The aim was to find a window-to-wall ratio that gave the lowest energy use, assuming that a designer would aim to use a geometry that minimised energy use before then deciding the glazing specification. The glazing units used in the simulation were uncoated double-glazing and the default switchable glazing defined within EnergyPlus. The results were the same for all four façade orientations. The window-to-wall ratio that resulted in the lowest office energy use was 99% in London and 50% in Abu Dhabi and Singapore.

The heating system was fuelled by natural gas with an overall system efficiency of 76.5%. The cooling system was an electrically powered heat pump with a seasonal energy efficiency ratio of 3. The heating and cooling setpoint temperatures were 19.9°C and 23.9°C respectively. The lighting and electrical equipment loads were set to be 15W/m^2 each, and the required work plane illumination was 500 lux. Occupation density was 10 m^2/person and ventilation provision was 8 litre/s/person [6]. Electricity for cooling, lighting and equipment was based on the UK National Grid [7], with average emissions of 0.125 kgCO_2 per MJ. The generation and transmission efficiency of the grid were assumed to be 40%.

The simulation was extended to consider offices of different sizes but each with the same floor plan aspect ratio. The offices considered are shown in Table 2.

	Width (m)	Depth (m)	Floor Area (m^2)	Façade Area (m^2)
Office 1	3	4.68	14.05	6.82
Office 2	6.65	10.38	69.07	15.14
Office 3	9.34	14.61	136.8	21.31
Office 4	12.47	19.46	242.7	28.36

Table 2: Offices considered in the study of room depth.

Life Cycle Analysis

It was assumed that the EC and the SC glazing units use the same amount of glass, sealants and frames, manufactured with the same processes. If the embodied energy due to the components is the same, then in a comparative study they can be neglected. The static SC glazing consisted of a double-glazed insulated glass unit (IGU), with a thin-film coating applied to surface two of the unit. The process energy of the coating process was the most significant component of the embodied energy of the SC glazing.

The EC glazing included materials and processes not found in the SC glazing. Papaefthimiou et al. [5] accounted for the production and preparation of the EC glazing polymer electrolyte. The manufacture of the EC film was counted, but the embodied energy of the material used in the layer is small and was therefore neglected. Values of 2.25 kgCO_2 and 120.1 kgCO_2 per square metre of façade are found for SC glazing and EC glazing respectively.

The values from the building energy simulation and life cycle analysis were combined as follows. The above-mentioned efficiencies for the office building services were used to convert the energy loads into kilograms of carbon dioxide emitted due to primary energy consumption each year. This is factored for an assumed 25-year service life, and then normalised per square metre of office floor space. This was added to the normalised embodied energy to find the total carbon footprint for each technology. The net carbon savings were then found by calculating the difference between EC glazing and SC glazing in total carbon footprint.

Case Study

The office room simulation was subsequently altered to match the floor to ceiling height and façade tilt of the Shard, which is currently under construction in London. This building has a complex façade shape formed of seven facets or "Shards". Offices 2, 3 and 4 have depths chosen to represent "Shards" 8, 1 and 3 respectively. The carbon savings due to an EC façade are calculated as before, and are converted into a cash value by adjusting the savings in kilograms into pounds sterling using a carbon price of £15.80/tonne [8].

RESULTS

Life Cycle Analysis

The highest magnitude net lifetime carbon saving of 329 kg CO_2 / m^2 was achieved for a south facing façade in Abu Dhabi. The greatest relative net saving was 20.5% for a south facing façade in London. Figures 1, 2, 3 and 4 show the results of the LCA.

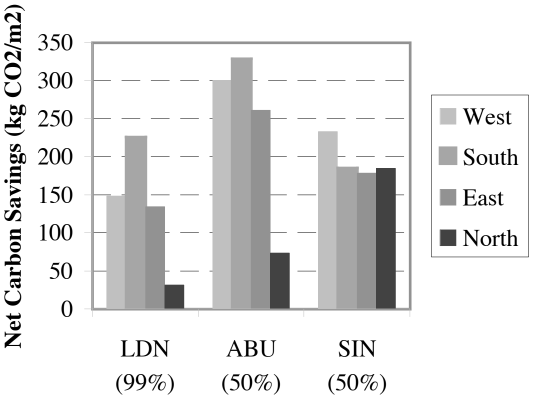

Figure 1: Net Lifetime Carbon Savings for EC Glazing with respect to SC Glazing for Office 1 at different orientations (window-to-wall ratios in parentheses).

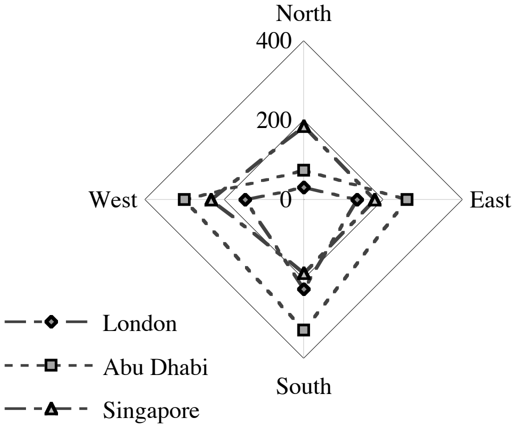

Figure 2: Geometric view of Net Lifetime Carbon Savings for EC Glazing with respect to SC Glazing for Office 1 at different orientations.

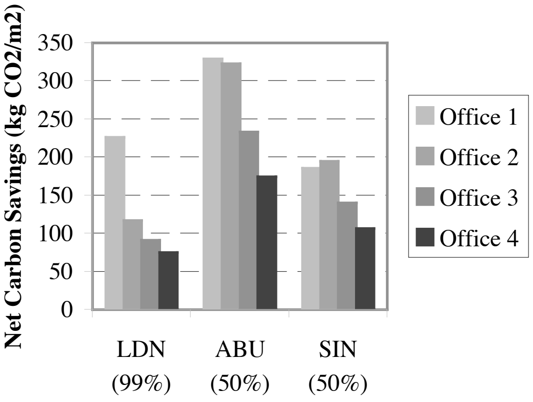

Figure 3: Net Lifetime Carbon Savings for EC Glazing over SC Glazing for Offices 1, 2, 3 and 4 facing south (window-to-wall ratios in parentheses).

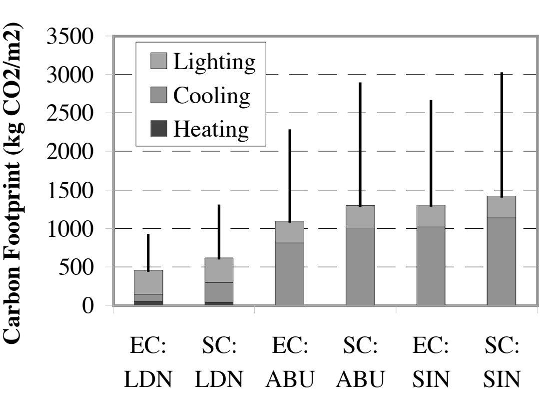

Figure 4: Carbon footprint, as the sum of lighting, cooling and heating, for the best-case window-to-wall ratios for office 1 facing south. Error bars represent carbon total for worst-case window-to-wall ratio.

Case Study

Shard Number:	**1**	**3**	**8**
Cash Value of Savings (£) per m^2	0.53	0.54	1.89

Table 3: Lifetime Cash Value of Carbon Savings per metre square of office floor space, based on a carbon price of £15.80 per tonne [8].

DISCUSSION

The carbon saving potential of EC glazing for different façade orientations in the three locations considered in this study is shown in Figure 1. This figure shows that EC glazing, despite its higher embodied energy, can deliver net carbon savings over its lifetime when compared with SC glazing. By the definition set out in this paper, EC glazing is carbon negative. The greatest potential carbon saving was achieved for a south facing façade in Abu Dhabi, showing that EC is particularly effective in locations with high peak temperatures and intermediate sun angles.

The change in potential savings with orientation shown in Figure 1 follows a similar pattern for London and Abu Dhabi, both of which lie in the Northern Hemisphere. The behaviour is different in Singapore, which lies on the Equator. The energy loads vary depending on east/west orientation rather than north/south, due to the high sun angle. The office is occupied for longer in the afternoon than in the morning, so the west facing office offers greater savings than the east facing one. For a location in the southern hemisphere, a reflection in the east/west plane of the pattern of behaviour for London and Abu Dhabi would be expected.

Referring again to Figure 1, it is perhaps surprising that the savings potential of EC glazing on a south facing façade in London exceeds that for all the orientation in Singapore other than west. In addition, from Figure 1 the average relative carbon saving of 13.0% achieved in London is the highest of the three locations. The high sun angle and consistent high air temperature throughout the year in Singapore means that the performance improvement of EC over SC glazing is less significant. This is reinforced by Figure 4, which shows that in Singapore EC glazing reduces total energy loads while maintaining the proportions of cooling and lighting energy. In contrast, EC glazing in London reduces the cooling load with respect to the total energy demand from 24.1% to 19.7%. These cooling loads are associated by high solar gains that occur at low sun angles.

Figure 3 shows the change in potential carbon savings with room depth for south facing façades. In London and Abu Dhabi the net benefit of EC glazing falls consistently with increased depth. The capacity of the façade to influence the internal conditions reduces with depth, and this is reflected in the reduced performance enhancement offered by EC glazing. The behaviour of offices 1 to 4 in Singapore is different, with the greatest savings achieved for Office 2. At this depth the proportion of the energy use due to lighting falls to a minimum of 16%. Artificial lighting is more carbon intensive than cooling, and so this minimum value for the proportion of energy use required for lighting coincides with greater carbon savings.

Table 3 shows the cash value of the net lifetime carbon savings per square metre of floor space for offices modelled with ceiling height, room depth and orientation to match three of the façade facets of the Shard, London Bridge. This assumes a carbon price of £15.80 per tonne [8], over a service life of twenty-five years. It is evident that at the current carbon price, the cash value of the carbon savings due to EC is negligible. The carbon price would need to be orders of magnitude higher to become pay back the capital cost of upgrading from SC glazing to EC glazing, based on the value of the carbon savings alone.

CONCLUSIONS AND FUTURE WORK

This study has shown how a simplified life-cycle analysis that includes the building energy simulation of a typical office can be used to calculate the net lifetime carbon savings of one glazing technology over another. Compared to SC glazing, EC glazing offers greater potential savings in locations and at orientations that experience the greatest variation in external boundary conditions, including specifically peak air temperatures and incident solar radiation from low sun angles. These conditions are found on south facing façades in Abu Dhabi and London respectively.

Offices with greater floor depths benefit less from the added performance of EC glazing. At the current carbon price, however, the cash value of even the greatest potential carbon savings is insignificant. The reduction in the operating energy costs resulting from the use of EC glazing and the potential increase in occupant comfort and performance would have a more significant impact on the whole life cost.

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