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MSc Built Environment

ENVIRONMENTAL DESIGN AND ENGINEERING

IMPROVED FACADES FOR OFFICE BUILDINGS

CASE STUDY: WATES HOUSE

THALEIA KONSTANTINOU

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Abstract

In the context of climate change and the need to decarbonise the building sector, the present thesis sets off to investigate the potential of cutting down on the carbon footprint of buildings, particularly office and commercial, by applying improved façade systems. Moreover, facade options are compared, in order to examine the effect they have on building performance and appearance.

Various facade options were researched in literature, and the findings were applied and tested in re-cladding a case study building. The re-cladding options can be divided in three groups according to the strategies applied; improved thermal conductivity of the envelop, use of sola shading devices and responsive solar transmittance of glazing, by applying electrochromic technology. They were tested through building simulation software TAS. The key issues of the building performance evaluated are the heating loads and the potential of overheating- which is connected with the use of air-conditioning. Analysis of BIPVs and cost analysis cover additional issues related with the facade options.

After the research and evaluation of the facade options, the preferable option for re-cladding the case study building was found the use of electrochromic glazing. This conclusion covers not only the environmental performance but also the value of this option on the image of the building.

The study concluded that improved facades can significantly reduce- about 90%- carbon footprint of the aging office building stock. It is also indicated the energy demand is not the only criterion when evaluating a facade performance, since a much wider range of issues are related, such as cost, payback period, health and comfort of the occupants and architectural appeal of the building.

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Chapter 1 – Introduction

In the context of climate change, there has been an increasing concern about the causes and remedies of this phenomenon. It is generally accepted that greenhouse gas emissions related to human activity are the main factor responsible for recent global warming. In 1997, the world's leading countries met in Kyoto and worked out a method to try and address climate change. The Kyoto protocol, by legally setting commitments for industrialized countries to limit their CO2 emissions, was the outcome. Eleven years on from that date, carbon emissions are still rising and the effects of climate change are clearer. In terms of overall CO2 emissions the building sector is a major source and so has an essential role to play in achieving these targets.

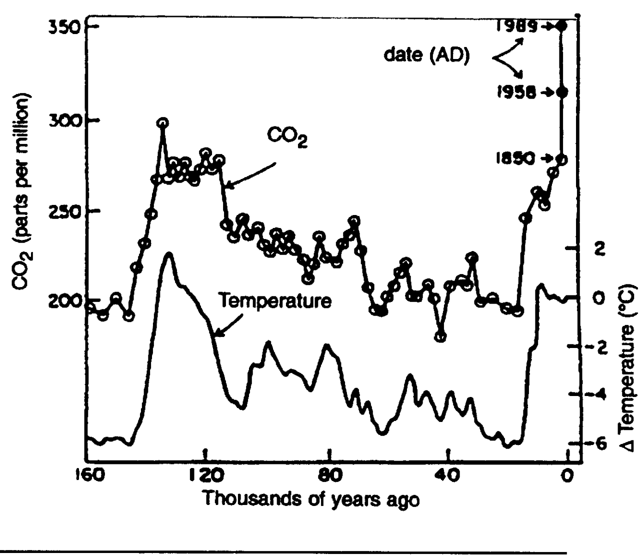
The present study will investigate the potential of cutting down on the carbon footprint of buildings, particularly office and commercial, by applying improved façade systems. In order to realize the significance of such a potential it is important to understand the correlation between the energy use and the climate change.

Climate change

'Climate change' encapsulates the wide variety of accompanying impacts on temperature, weather patterns and other natural systems *[Grubb, 2005, p.2]*. The list of evidence that the climate is changing is long, from increase in average surface temperature, sea level rise, melting of glacier ice etc *[Smith 2005, p.7-10]*.

The fundamentals of climate change have been well understood, because they involve the same basic physics that keeps the earth habitable. It is related to the 'greenhouse gases' in the atmosphere, the two most important of which are water vapour and CO2. The production of energy through the burning of fossil fuels, and long-term deforestation has been increasing the concentration of CO2 and other greenhouse gases in the atmosphere since the industrial revolution began, thickening the greenhouse blanket *[Grubb, 2005, p.2]* and inducing an enhanced greenhouse effect.

Figure 1 : Correspondence between historic temperature and CO2



Thus, there is a strong relation between the energy used and the climate change. Figure 1, presented in June 1990 in the journal "Nature", supports this conclusion. It demonstrates a remarkably close correlation between temperature and concentrations of CO2 in the atmosphere from 160,000 years ago until 1989. It also reveals that present concentrations of CO2 are higher than at any time over that period.

Climate change has been addressed as an issue since the 80s. After scientific consensus, governments established the

Intergovernmental Panel on Climate Change (IPCC) to help them understand and build some international consensus on the nature of the problem. This defined the context and principles upon which governments subsequently negotiated the 1997 Kyoto Protocol *(Grubb, 2005, p.14)*

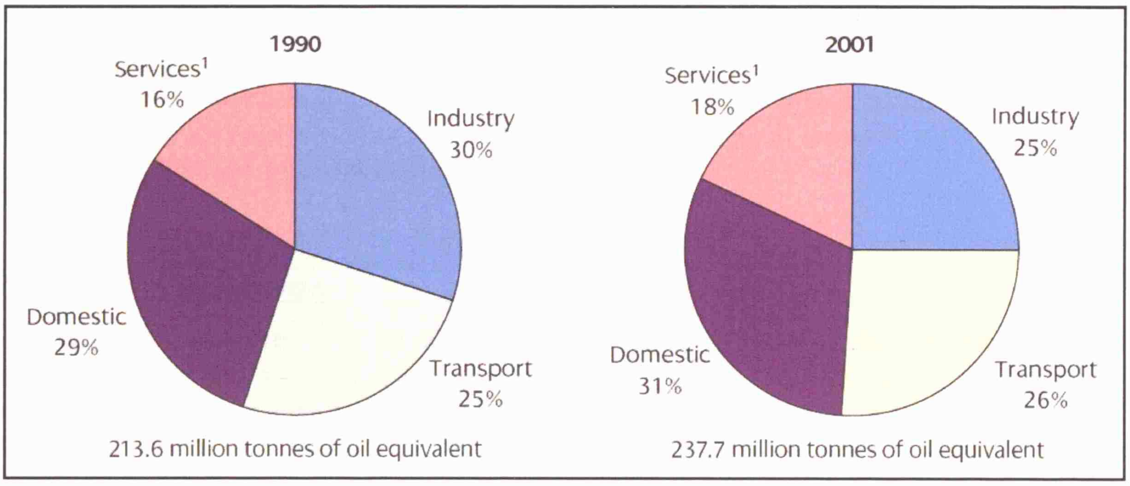
The Kyoto protocol to the UN Framework Convention on Climate Change (UN FCCC) represents a top of trends towards globalization in economic and environmental policy and sets the underpinning elements of global efforts to tackle climate change in the twentieth first century *(Grubb et al. 1999, p.xxxiii-iv)*. In practice the protocol impose a 5% global cut in CO2 emissions based on 1990 levels, come into action for 2008/2012. Yet the UN IPCC scientists stated that a 60% cut world-wide would be necessary to halt global warming (*Smith, 2005, p.19)*, a numerical target that now UK has adopted for 2050 *(DTI, 2003, p.8)*.

Building energy use

Since the connection between energy use and greenhouse gases is evident and given the limitations required by the international legal framework, the role of the built environment for cutting down on greenhouse emissions needs to be established.

According to figure 2, the building sector accounts for almost half the energy consumption of the UK. It refers to both domestic and services sector. The service sector can be split into two main components: public administration and private commercial *(DTI, 2002, p.36)*

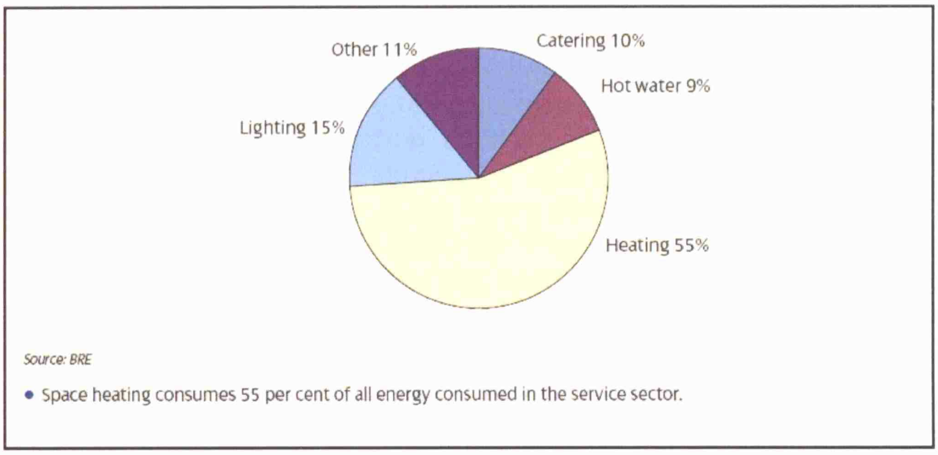
Figure 2 : Final energy consumption, by sector, in primary energy equivalents, 1990 and 2001 (Source: DTI, 2002, p.9, chart 13)



Approximately one third of the building related energy is consumed by the service sector, which is the subject of the present study. Thus, the service sector building, which can be generally characterized as offices, consist an important part of the energy consumed.

More than half of this energy is due to space heating (fig. 3). Moreover, according to DTI, since 1990 electricity consumption has more than doubled. The growth in the use of air conditioning in offices is largely responsible for it *(ECON 19, 2000 p.6)*.

Figure 3 : Service sector energy consumption, 2000 (Source: DTI, 2002, p.9, chart 13)



Building Facades

The facade of a building is the main element of its architectural expression and the key feature of its existence, as it characterises the building and make it conceivable both from inside and outside. What is more, the façade plays a key role not only in the form and appearance of the building, but also in its performance, in terms of optimized energy use and indoor climate. If the building can be resembled to the human body, then the façade represent the human skin, which performs an important function in the body's reaction to weather variations and regulating the heat emission. The façade can also be perceived as the body's clothing, serving to protect of the weather and other external influences and can be flexible according to these.

The facade constitutes undeniably an important part of how the building is perceived and performs. Thus, in the attempt of improving a building the facade has an integral role to play, in terms of architectural appeal and aesthetics, internal conditions and environmental impact.

Aims and Objectives

As already discussed, it is obviously important to reduce carbon emissions from offices. This thesis aims to investigate whether re-cladding using improved facade options can be an effective method of reducing offices carbon footprint. The reason why re-cladding is on the focus is the impact the façade has on the internal conditions.

As we already discussed, the larger area of potential improvements in the energy consumption is space heating, as it accounts for half the energy consumed. Air conditioning is also a growing issue for offices, and it should also be a key concern. The building skin can have a major impact in both aspects through design, construction and function, as it acts as condition regulator. This impact has been recognized and as a consequence UK Building Regulation set specific limiting requirement for the building envelop, including thermal conductivity, air permeability etc *(Approved Document Part L2, 2006)*. These regulations manage to set a minimum standard for the façade quality and the consequent environmental performance for the new buildings.

However, even though improved facade can be fairly easily incorporated in the new buildings, the vast majority of building stock is already existing. In the concern of decarbonising the building sector, the importance of improving the energy performance of the existing building stock has been generally admitted *(Lowe, 2007 and Clift, 2007)*. Improving the building skin is one of the main paths to upgrading the building stock and re-cladding the way through it. Apart from boosting the energy efficiency of the building it can also add to its architectural appeal. According to the Architectural Record, practices design re-cladding project more and more, and the number seems to grow. "Re-cladding is going to be a big focus of attention as cities try to reduce carbon output," *(Appelbaum, 2008)*.

In the process of investigating the potential of reducing offices carbon footprint through re-cladding, the first step is to analyse the function of the facade and determine the issues the facade should answer to. Before proceeding with the design, improved facade options are researched and evaluated. Finally, the options are tested in order to estimate their environmental performance and balanced according to parameters of cost, energy consumption and comfort.

Chapter 2 - Facade options

In this chapter, facade requirements and performance for the different conditions are explained. Subsequently, advanced facade options are researched in the literature. Research and understanding the facade is an essential step before the proposal and evaluation of the re-cladding options in the following chapters.

Façade requirements

The preliminary role of building envelop is to protect the occupants from environmental conditions. The design of the facade should address all the related issues like thermal comfort, indoor air quality, lighting, local control over conditions and view to outside. Not only does it provide comfortable condition, but also aims to reduce heating, cooling, ventilation and lighting energy consumption.

The present thesis' main concern is heating load of the building, as they comprise almost half of the energy consumed by buildings. Additionally the effect the façade has on the internal temperatures and particularly overheating is important in order to reduce the use of air conditioning.

Design for comfort

According to the ISO 7730 standard, thermal comfort is described as being "That condition of mind which expresses satisfaction with the thermal environment". This is a definition most people can agree on, but not easily converted into physical parameters *(INOVA, 2002)*. It is generally accepted that for indoor temperature between 19-24 °C and relative humidity 40-70% most people are likely to feel comfortable.

In order for the temperatures to be achieved, extra energy in needed to balance the heat losses with the heat gains. A general expression of *energy balance*, that is true for summer and winter, is *(McMullan Randall, 2002, p.82)*:

Fabric Heat Losses	+	Ventilation heat losses	=	Solar heat gains	+	Casual heat gains	+	Energy for Heating or cooling

The design and the operation of the façade have obviously a significant contribution to the energy balance, as the fabric and ventilation heat losses are mostly determined by it.

Under summertime operation the maintenance of comfort is not always applicable to buildings without cooling or air conditioning systems. The overheating risk has to be measured against some benchmark temperatures. According to CIBSE A p. 1-12, 25 °C as an acceptable summer indoor design operative temperature for non-air conditioned office buildings, while recommends limiting the expected occurrence of operative temperatures above 28 ºC to 1% of the annual occupied period (e.g. around 25-30 hours). Nonetheless, the adaptive approach to thermal comfort suggests that people tend to feel comfortable in higher temperatures, if they have the opportunity to adapt to conditions and control their thermal environment *(CIBSE A p. 1-16)*.

The importance of the perception of local control of the working environment, particularly for temperature, air flow and lighting, has been recognized by a great number of authors and the lack of control has been correlated with Sick Building Syndrome (*Wilson & Hedge, 1987, p 2; Raw, 1992, p 62; Palmer & Rawlings, 2002, p. 30)*. Such adaptive possibilities are mainly provided by the façade, for instance through opening windows or ventilators and shading systems.

Façade performance

In order to meet the needs for occupants comfort and reduced energy use, the function of the façade must be adaptive to the environment. It doesn't necessarily suggest that the façade must change in appearance, though it is also possible, but mostly that it must perform according to the external conditions, which vary dramatically.

Winter /summer

In winter the objective is to reduce the heating loads while providing adequate levels of indoor air quality. To achieve that heat losses must be minimised. The characteristics that need to be integrated are:

- High thermal mass by terms of heavyweight construction and mostly insulation, in order to reduce conductive fabric heat losses. Thermal bridging and glazing type and proportion must be also considered *(McMullan R, 2002 and Hausladen et al., 2006)*.
- Ventilation heat losses control. Low levels of ventilation are necessary in winter to maintain good levels of indoor air quality. The façade is the main supply of fresh air for ventilation. However, it can be a great source of heat losses, thus it must be controlled. Air tightness of the building and the adjustability of openings for ventilation can help to limit air change to minimum required. Other strategies to be integrated in the facade could be to preheat the air supply and heat recovery systems *(Hausladen et al., 2006, p. 32)*
- Solar gains. The sun is a major source of heat gains for the buildings. In winter heating energy demands can be considerably reduced by taking advantage of solar heat gains. Orientation, openings layout, type and proportion of glazing play a key role *(Persson et al., 2006)*

In summer, on the other hand, the target is to reduce cooling loads, which is an issue gaining increasing concern due to climate change and global warming. The façade mostly determines the cooling demands, since it is the receiver of the high solar gains and air temperatures. Its performance can be improved by:

- Solar control. The proportion of window area has a considerable influence on a room climate, particularly in summer. In general terms, large windows areas exposed to direct sunlight are only acceptable with exterior solar shading *(Hausladen et al., 2006, p. 44)*. This may come in form of movable or fixed louvers, projections and overhangs etc. Advanced technology glazing may also help in solar control. The effect of the shading systems as architectural features need to be carefully considered.

- Ventilation. The need for ventilation is crucial in summer. Much higher rates of air chance are required, to provide a cooling effect. The potential on natural ventilation depends on the permissible room temperature, in correlation with the external temperature. As long as the temperature outside are lower than the inside and between 23-25°C, the façade must be opened as wide as possible. If outside temperature exceeds these values, windows may only be opened a small amount during the day and nightcooling may be necessary to maintain comfortable inside temperatures with minimum cooling loads *(Hausladen et al., 2006, p. 53)*.
- Thermal mass. Thermal mass is still important to control heat transfer between higher to lower temperatures. It is also used in nightcooling as "cooling" storage.

Facade design

The facade of a building forms the interface between the environment outside and the user inside. A comfortable interior climate in the winter must be ensured while preventing the entry of too much solar radiation in the summer. Daylight and natural ventilation must also be provided. These requirements lead to conflict of objectives *(Hausladen et al., 2006, p. 94)*. A balance between the needs must be provided through a combination of strategies, including an innovative, bioclimatic design and the implementation of advanced technology materials. Subsequently, a critical overview of various facade options is presented, in order to understand their function and how they may interact with the climate and the occupants.

Facade concepts

A principal differentiation between facade concepts is whether the façade is single or double-skinned *(Hausladen et al., 2006, p. 96)*. Attributes such as insolation, sound insulation and ventilation characteristics are determined by this differentiation. Further classification is whether the façade is perforated of elemental, box window or unsegmented etc (Appendix A, Figure A1)

Double Facades

Recently, building designers have begun to use double-skin facades (DSF), attempting to improve the thermal energy performance of facades of buildings with high glazing fractions *(Roth et al. 2007, p. 70)*. Compared to a single-skin facade, a DSF consists of an external glazing offset from an internal glazing integrated into a curtain wall, often with a controllable shading system located in the cavity between the two glazing systems. This structure may have various effects on building performance.

According to Eicker et al. (2008, p. 601) most authors agree that DSF may reduce winter demand, due to reduced transmission heat loss and preheating the air in double façade. During the cooling season air can flow through the cavity via natural or mechanical ventilation and is used to help moderate building thermal loads *(Roth et al. 2007, p. 70)*. However, most authors state that overheating problems are not dramatically improved by the double skin *(Eicker et al. 2008, p. 601)*

DSFs have the potential to reduce building heating and cooling energy consumption in several ways. It is also admitted that a major benefit of DSF the possibility to enhance the organization image through a technologically forward looking and sustainable image. This is, to some extent, where they owe much of their deployment *(Roth et al. 2007, p. 70)*.

In practice, though, it is not clear that DSFs realize appreciable energy savings. Due to the number of variables affecting DSF performance, effective control is crucial to realizing the full energy-saving potential of DSFs *(Roth et al. 2007, p. 70)*. An important drawback of DSF is cost related. Designing and constructing is currently very expensive, resulting to a long payback period *(Roth et al. 2007, p. 70-71)*. Other drawbacks of DSF are the complexity of detailed assessment of the performance and difficulty to demonstrate code compliance, as code officials are often not familiar with DSF.

Facade Technologies

Glazing systems

Glass is a key element in the architectural expression of the building. It provides visual connection with outdoors and daylight indoors, enhancing the quality of the interior work environment (*Selkowitz, 2005, p.1)*. A lot of hope and effort has been put in the development of coatings, laminates and various specialized types of glass to solve the inherent problems of poor thermal performance and fragility that glass as a material brings.

- *Insulated glazing*

One of the shortcomings of glass is its relatively poor insulating qualities. Multiple panes of glass with air space between improve the insulation value considerably. *(Carmody et al., 2004, p.81)*. Another improvement to the thermal performance of glazing units involve reducing the conductance of the air space between layers by filling the space with a less conductive, more viscous or slow-moving gas. Manufacturers generally use argon or krypton gas fills *(Carmody et al., 2004, p.83)*.

- *Low- E coating*

Low-emissivity coatings, called Low-E for short, act to reduce the surface emissivity of glass. Such coating materials are mainly transparent over the visible wavelengths of light, but reduce the amount of long-wave infrared thermal radiation both absorbed and emitted by the glass pane. This way, heat loss is greatly reduced with almost all re-emission taking place towards the interior of the building in cold climates (if the coating is on the outside face) or back out into the environment in a hot climate (if the coating is on the inside face) (Square One).

Table 1 : Comparison of typical heat transfer through different glazing options (Source: Smith, 2005, p. 65, table 5.1)

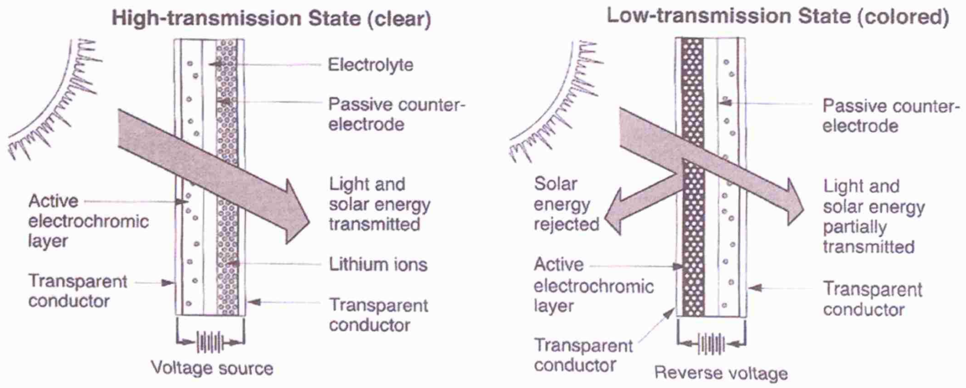
Glazing	U Value (W/m2 K)
Single glazing	5.6
Double glazing	3.0
Triple glazing	2.4
Double with Low E	2.4
Double with Low E and Argon	2.2
Triple with 2 Low E and 2 Argon	1.0

- *Chromogenic glasses*

The term refers to glazing in which transmission properties are variables. This means the glass is able to undergo a reversible change form darker or lighter or transparent to translucent on demand.

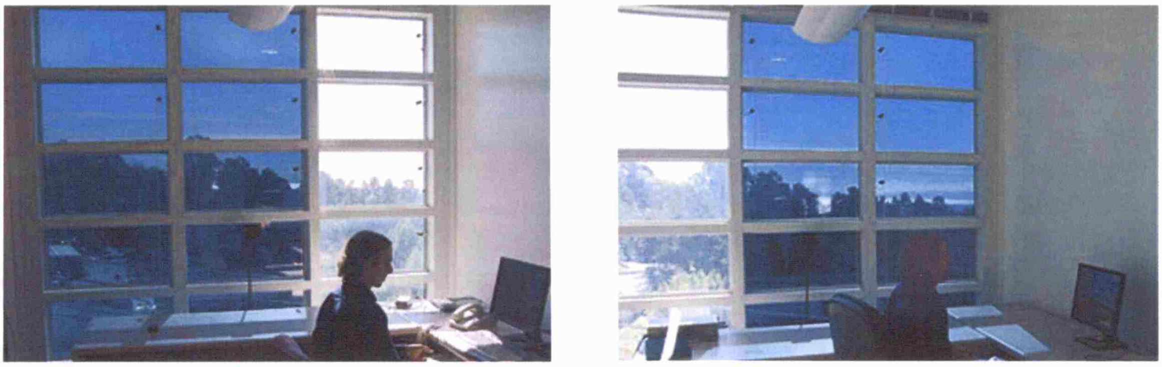
Such technologies are photochromic glass that contains a coating of silver halide which changes form clear to dark due to sunlight and thermochromic has a coating of vanadium dioxide which changes when temperature rises from between 25°C to 40°C *(Noble, 1996, p. 8)*. Thermochromic glass turns to opaque at around 30°C, reducing insolation by about 70%. It is more suitable for external solar shading, as if it is used for window it could react to internal temperature *(Smith, 2005, p. 67)*

Figure 4 : Schematic diagram of a five layer electrochromic glass (source: Carmody et al., 2004, fig. 3-30, p.97)



Electrochromic glazing is the most promising technology of switchable glazing *(Carmody et al., 2004, p.96)* as it is the more controllable *(Smith, 2005, p. 67)*. Electrochromic glass has a coating of tungsten trioxide which changes from clear to dark when current is applied *(Noble, 1996, p. 8)*. Their construction consists of a thin metallic coating sandwiched between two transparent electrical conductors. When a voltage is applied between the transparent electrical conductors, a distributed electrical field is set up. This field moves various coloration ions (most commonly lithium or hydrogen) reversibly between the ion storage film through the ion conductor (electrolyte) and into the electrochromic film. The effect is that the glazing switches between a clear and transparent blue-tinted state with no degradation in view *(Carmody et al., 2004, p.96)*. Typical EC windows have an upper visible transmittance range of 0,50-0.70 and a lower range of 0.02-0.25.

Figure 5 : Electrochromic glass example (source: SAGE Electrochromics)



The electrical signal reduces the transmission capacity of the electromagnetic layer, affecting not only daylight but also solar heat gain. Research has shown *(Mardaljevic and Nabil, 2008)* that the potential energy benefit of electrochromic glazing comes from reducing the cooling load along with the effective use of daylight, as it would offer a much greater degree of control over the luminous environment

Photovoltaic panels

Photovoltaic (PV) installations are technical systems that transform radiation directly into electricity. At the core of the installation there are solar cells, combined into modules that produce DC voltage *(Schittich C, 2006, p.50)*.

The main drawback of PV technology is cost related. It is still expensive although it is potentially advantageous in reducing the environmental impacts caused by human activities. Therefore achieving to as large an extent as possible optimum PV module efficiency and thus improving the overall environmental performance of the building are of importance *(Yun et al., 2006)*.

The annual output of the PV system is also determined by the orientation and the angle of the module surface. For northern Europe, the highest annual radiation is for south-facing systems on an angle of 30°. The performance diminishes in vertical facades surfaces *(Schittich C, 2006, p.52)*.

However, the building façade area available, at rough calculations, is a considerable amount compared with the roof space. In terms of the entire building skin, higher potential toward true solar architecture are given *(Schittich C, 2006, p.53)*. Thus, incorporating PVs in façade design results in reducing energy demands by producing electricity as well as enhance the performance of the façade. What is more, the payback period is improved as the PV panels replace the normal cladding of the building *(Schittich C, 2006, p.53)*.

The task of integrating the PVs into the building skin is integral. The visual and constructional integration must guarantee that the installation does not conflict, but complements the requirements and characteristics of the building skin.

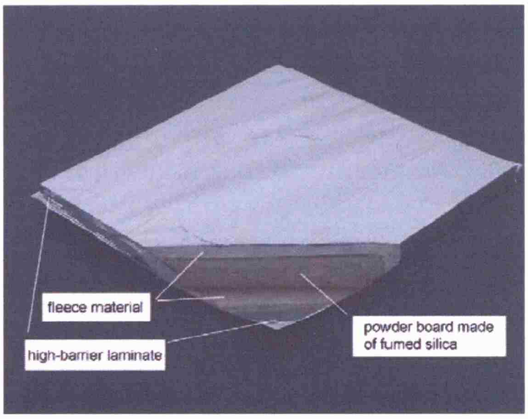
Insulation

An insulator is a material with high thermal resistance that opposes the transfer of heat between areas at different temperature *(McMullan, 2002, p.37)*. The insulating effect of a material is based on the low thermal conductivity of enclosed air. Insulating materials are classified into inorganic/mineral or organic types according to their raw materials. Depending on their make-up they are subdivided into fibre, foamed and granulate or loose fill insulation *(Hausladen et al., 2006, p. 122)*.

- *Vacuum insulation*

The evacuation of air increases the insulating effect of the material because heat transport by convection and conduction is almost completely suppressed. Vacuum insulation panels (VIPs) have a thermal resistance about a factor of 10 higher than that of equally thick conventional polystyrene boards. In principle, a VIP is composed of a core of microporous material and an envelope (Fig. 5). The core material is a load-bearing material that is inserted between the evacuated walls of flat panels in order to prevent them from collapsing (J. Fricke et al, 2008, p. 683).

Figure 6. Construction of a VIP: the nanostructured kernel is sealed into a PE-coated Al-foil or a high-barrier laminate. (Source: J. Fricke et al, 2008, p. 683, p.683, fig 5)



Vacuum insulation panels (VIP) are very thin. A centre U-value of 0.2 Wm2K1 can be achieved for a VIP thickness of only 2 cm (J. Fricke et al, 2008, p. 680). They are particularly advantageous in refurbishment projects, due to their minimal space requirements. From an economic point of view, even though they combine very good insulation values with modest layer thickness, they are expensive. *(Hausladen et al., 2006, p. 129)*. "Vacuum insulation panels (VIPs) are currently quite expensive-in the order of 320 euro/m2 for panels with a U-value of 0.15 W/(m2.K) compared to 32 euro/m2 for fibre or solid-foam insulation (Erb, 2005). However the VIP is 8cm thick, compared with 30cm for the alternative." *(Harvey, 2006)*. Thus, the additional cost needs to be balanced against a considerable gain in space

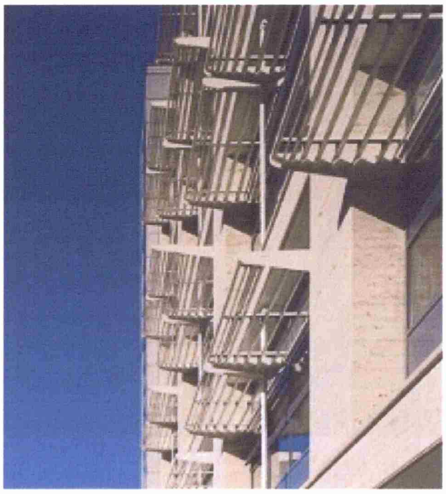
Solar control

- *Shading devices*

As already discussed, solar shading is a crucial aspect of the facade design. There is a wide range of shading systems available, to suit the aesthetic and environmental demands. The final decision on the shading system comes down to a number of factors, such as the orientation, the weather conditions and the efficiency of the system.

The shading systems can be external or internal. External solar shading is the most efficient, because the solar radiation is blocked before it reaches the façade. However, construction and maintenance costs are higher as the system is exposed to the weather conditions. Internal systems on the other hand are protected from the weather but the solar shading effect is lower. An indicator of the system efficiency is the shading factor F_c, where $F_c=1$ for no shading at all . For external blinds the shading factor can be as low as 0.1 and for internal systems 0,3. A point that needs consideration is the impact of the shading devices, mostly the external ones, as architectural elements of the building *(Hausladen et al., 2006, p. 134-135)*.

Figure 7: External shading examples, respectively: Solar fins- Cambourne Business Park, Cambridge, Membrane Louvre-Baader Bank, Germany, Brise Soleil- Addison, Wesley Longmans, Harlow (source: The Colt Group)



Another important distinction of shading systems is whether they are fixed or movable. Overhangs are a case of fixed solar control, while blinds and drapes can allow the user to move in demand. The effectiveness of sun control elements is increased when they are adjustable, to better account for the inherent daily and seasonable variability of the sun and sky *(Carmody et al., 2004, p.112)*. The systems are possible to be used in conjunction. For instance, fixed external fins can be combined with adjustable internal blinds for additional glare protection. In movable systems controls are either manual and/or motorised by users or automatic by more sophisticated systems.

A drawback of shading devices is that even though they control light and heat gain, yet they also can reduce the amount of light in a space and increase electric lighting loads, along with cut off solar gain in winter and increase heating loads. What is more, when daylight is ample, there is often too much light and glare neat the window and not enough light further back *(Carmody et al., 2004, p.118)*. These are additional issues to be considered when decisions on solar shading are taken.

Dynamic Façade controls

Facade typologies are mostly incapable of lowering the heating and the cooling demand simultaneously. Only by combining typologies or by changing system settings according to the particular situation, a substantial overall improvement over the traditional solutions is possible. This implies that control mechanisms are inevitable to make facades work efficiently throughout the entire year (*Saelens* et al., 2008, p.642).

Balancing the need for view, glare control, thermal comfort with solar load control and daylighting energy savings is a complex challenge. In order for these designs to meet often contradictory performance objectives they will need to have a degree of active, reliable management of solar/optical properties of the building envelope that has rarely been consistently and economically achieved in buildings.

When comes to controls, some of these passive strategies are very dependent on occupant, assuming that they will "appropriately" use them. However, the way occupants interact with passive control features is poorly understood and they are often not used to maximise environmental benefits *(Foster and Oreszczyn, 2001, p. 149)* and it must be considered when the technical design decisions are taken. Automated and motorised systems can provide a solution. Some of the technologies to provide active control of fenestration transmittance and associated control of electric lighting in building interiors are now available and have been shown to be capable of good performance. To fully realize the potentials of these emerging technologies, it needs additional exploration of systems integration solutions, new sensors and adaptive controls, and most importantly, a good understanding of occupant needs and preferences (Selkowitz, 2005).

Figure 8: Smart controls on the automated blind systems (left photo) keep direct sun out of the space, reducing glare and cooling loads. The same hardware system with different control strategies (right photo) admits sunlight to offset heating loads but creates excessive glare. (Source Selkowitz, 2005)


Summary

The literature review of facades has brought out a number of options that can be applied to improve and make the façade meet the requirements for comfort and efficient use of energy. In order to achieve it, the façade must be adaptive, not necessarily in appearance but mostly in performance.

The following table summarises the options researched. It also provides an overview of how the different technologies function according to the conditions. The research and understanding of the different facade option was an integral step before proceeding with the re-cladding design and advanced facade options implementation and testing, which is going to be presented in the next chapter.

Table 2 : Summary of Façade Technologies

Façade Technologies - Materials		Adaptive appearance	Controls	Adaptive performance	
				winter	summer
Glass	Insulated glazing	No	No	Prevents heat losses, allow solar heat gains daylight	Minimises conductive heat gains, allow solar heat gains (solar control needed)
	Chromogenic glasses-electrochromic	Yes (form clear to dark)	Automatic and/or manual	Maximise solar gain, control glare. Effective use of daylight	Minimise solar heat gains. Effective use of daylight
Photovoltaic panels	Building Integrated PVs (BIPV)	Yes (only for movable panels to adjust to sun angles)	Motorized (only for movable panels to adjust to sun angles)	Generate electricity Functions as a pre-heating device	Generate electricity. A natural ventilation system reduces PV module temperatures
Shading devices and/or natural light redirection systems	Fixed	No	No	If designed properly, allow solar heat gains	Prevent solar heat gains,
	Movable	Yes	Motorized and/or manual	allow solar heat gains, control glare	Prevent solar heat gains, control daylight and glare
Insulation	Insulating materials	No	No	Minimise heat losses	Minimises conductive heat gains,
	Vacuum insulation	No	No	Minimise heat losses	Minimises conductive heat gains,

Chapter 3 – Re-cladding Evaluation Methodology

After the review of the facade options in chapter 2, we would like to investigate how they perform and how the various options affect the energy consumption and the environmental performance of a building. For this purpose, a case study building is going to be re-clad and the proposed facades are going to be modelled and tested through a building simulation software.

Methodology

The thesis considers a case study building, Wates House, and applies several different improved facade options to investigate relative performance differences between them.

The first step would be to investigate the current condition of the case study building and more importantly to evaluate the present environmental and energy performance. A model of the building in its current situation is also set up and simulated. This model serves to further estimate the current environmental performance along with setting the inputs, such as schedules and internal conditions that will be used for the following simulations.

The next step is to evaluate the different cladding options, for this purpose, different facades are going to be developed. Those facades are going to have the same basic design, so as the comparison will be more accurate. The main differentiation will be in the materials and any additional features or strategies they may require. The different options are grouped in three broad categories, briefly described as:

i. The SAP Model: In that model, elements' minimum U-values are going to be applied the facade, such as insulated glazing and vacuum insulation panels. We shall call it SAP model based on the positive effect that the improved U-values and airtightness of the fabric have on the building rating of the Standard Assessment Procedure. Additionally, PV panels are going to be incorporated in the facade.

ii. The Solar Control Model: In that model, solar shading will be integrated in the design and its effect on the energy performance will be assessed.

iii. Electrochromic facade: For that model, electrochromic glazing, responsive to solar heat gains, will be applied.

Each of the three broad groups of facades includes a number of sub-options, presented in Table 3. The facade option selected and evaluated arrived following the research presented in the literature review. Through iterative design, they are the ones that are considered to be more applicable to the case study re-cladding and more interesting to be evaluated and compared, according to the author's views.

The options are developed and modelled and the results of the different models are compared. The purpose of the models is not only to examine the efficiency of each facade, but also to provide a creative way of simulating the different facade technologies. In that way, we will also be able to understand how the facade functions and meets the requirement for adaptive performance.

Table 3 : Overview of re-cladding options examined

Group	options	description
current	current leaky	Close to real energy consumption, current building elements, very leaky (infiltration rate=0,8)
SAP model	Part L U-values	U-values required in Part L
	best U-values	minimised U-values, argon filled glazing, vacuum insulation panels
	improved U-values	U-values improved form Part L, not minimised
Solar Shading	internal blinds	internal blinds
	overhang50	500mm overhang above all windows
	horizontal louvres	improved U-values, 100mm louvres every 200mm
	vertical louvres	200mm wide vertical fixed louvres every 400mm
	movable vertical louvres	200mm wide vertical louvres every 400mm, applied only in summer+hourly schedule
electrochromic	Electrochr800	Electrochromic glazing tinted for surface solar gain >800 kWh
	Electrochr-Gradual	transmittance 0,20 when solar gain >800 and 0,06 when > 1200
	Electrochr-Seasonal	transmittance 0,06,when surface solar gain >700 kWh summer >1200kWh winter

An additional analysis of the Building Integrated Photovoltaic Panels (BIPVs) proposed in the design will provide an estimation of their cost and output. Finally, a cost analysis of the different options will be performed.

The aim of the proposed methodology is not just to come up with an efficient facade design in terms of energy consumptions but compare and find a balance between the key issues regarding the facade of a building. The key issues on which the different option will be evaluated are energy, comfort, cost and aesthetics. The balance between these factors is the question of the present thesis

Chapter 4 – The Case study building

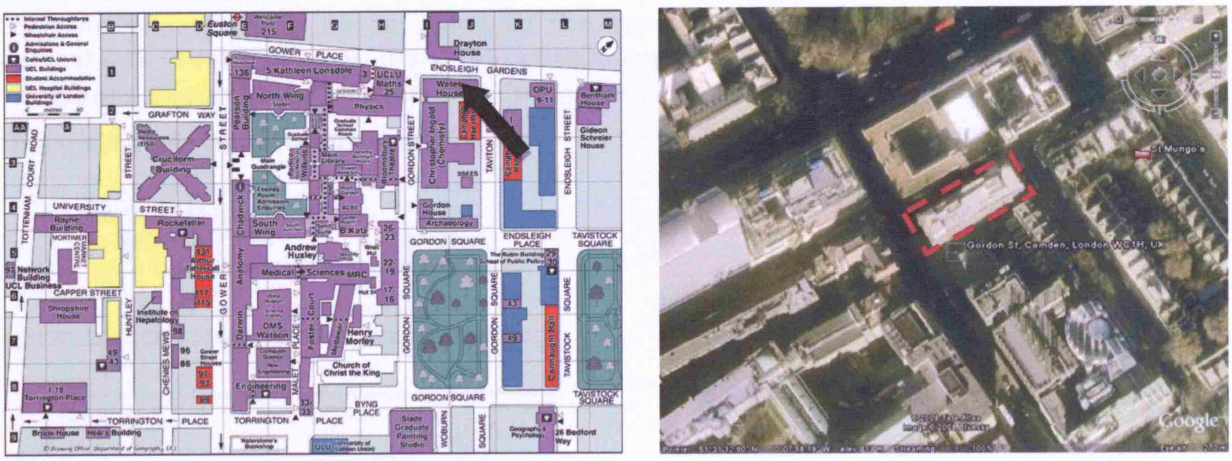
Before proceeding with the new facade design and modelling, it is important to analyse the current situation of the case study building, so as to understand the problems the re-cladding should aim to solve.

Figure 9 : Wates House

General information

Wates House is part of the University College London Campus, located in central London, at the corner of Gordon Street and Endsleigh Gardens (Fig.). It was build in 1974 (Nick Ayres, Senior Estates Surveyor, UCL Estates & Facilities Division) and currently houses The Bartlett School of Architecture.

Figure 10 : Wates House on the Map of UCL Campus



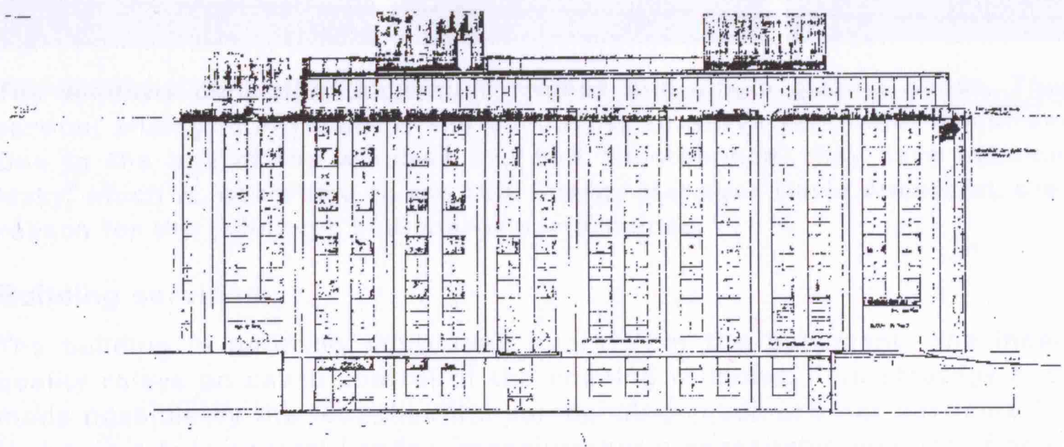
It is a rectangular shaped building, as shown in Figure 2, and it is oriented parallel to the NW-SE axis. Thus, the Gordon Street façade's orientation is South-West, while the southeast long facade overlooks the interior backyard between Wates House and Christopher Ingold Building, which allows a significant amount of daylight to reach Wates House.

The plan building is relatively narrow, measuring approximately 15 x 51 m (source: UCL Estates & Facilities Division, building plan, Appendix B, fig. B1). It has 7 floors, including the basement, and a total area of 5262m² (UCL Estates & Facilities Division), which lead to the assumption that approximately 500 people are using the building, for an occupancy density 10m²/person (CIBSE Guide A, p.6-3, table 6.2, offices in city centre) .

Fabric

The most striking feature of Wates house elevation are the repeated pattern of vertical zones, interchanging from dark red brick to window-opaque surface zone. Approximately 35% of the building is glazed, 20% covered by the dark opaque material and 45% brick

Figure 11 : Original elevations of Wates House (Source: UCL Estates & Facilities Division)



The construction of the building is heavyweight. The structural system is reinforced concrete, as revealed by the columns visible in the internal layout and the facade. Based on individual observation, the construction of the external walls are assumed to be as shown in figure 12,

Figure 12 : External wall detail

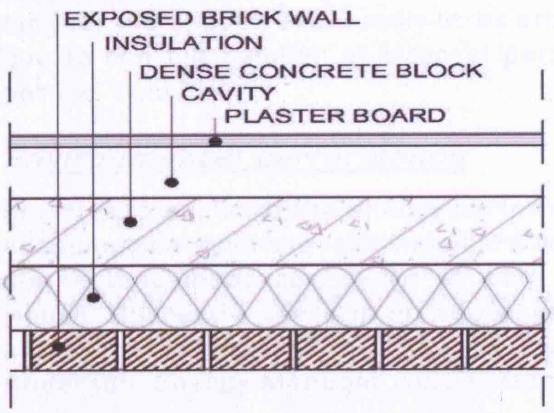
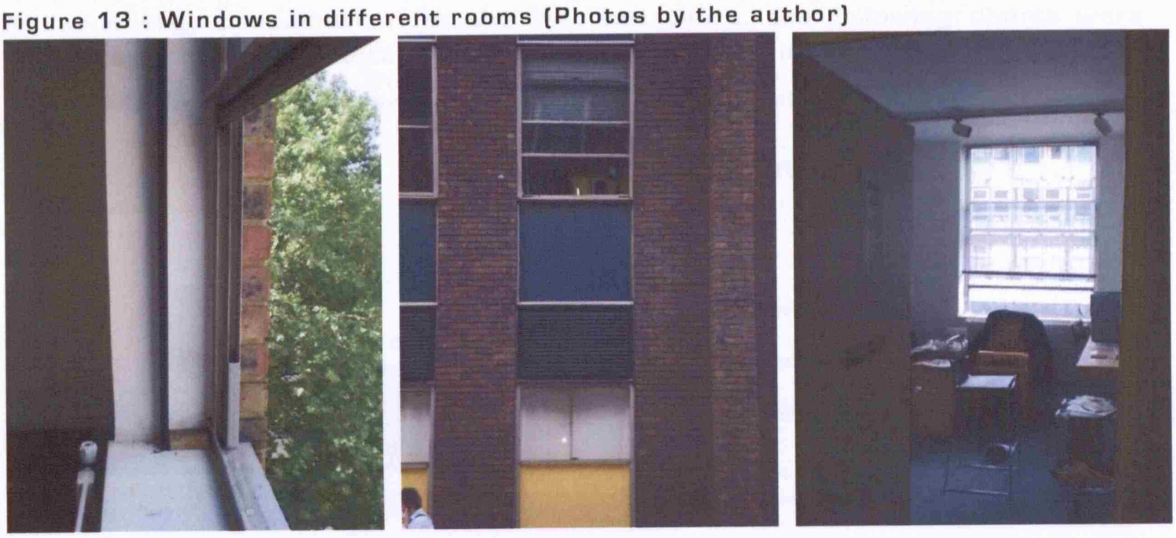


Figure 13 : Windows in different rooms (Photos by the author)



The windows consist of aluminium frames and single glazing panes. They are vertical sliding, controlled by the occupants to serve ventilation requirements. Due to the age of the windows and bad maintenance, they have become very leaky, which is, according to the UCL Energy Manager David Anderson, the main reason for the building's bad energy performance.

Building services

The building is naturally ventilated, apart from the basement. The indoor air quality relays on users control of the opening windows. This strategy has been made possible by the fact that the surrounding roads are not particularly busy. However it is in central London, meaning that a reasonable amount of noise and dust may enter through the windows.

As far as heating is concerned, there is no boiler plant installed in Wates House. The radiators, located mostly on the perimeter of the Wates House, are supplied with hot water by the three gas fired boilers of the neighbouring Christopher Ingold building.

The artificial lighting in the internal spaces of the building is fluorescent lamps luminaires in linear layout. Even though the big proportion of openings in the facade, the spaces are mostly lit by artificial lighting, especially in the corridors, due to the big number of internal partitions or the inadequate management of natural light.

Environmental performance

In order to evaluate the energy performance of Wates House, data of the energy consumption from the last two years were gathered. The data came from a heat meter that measures usage in both Christopher Ingold Building and Wates House. Currently, there is no separate meter for Wates House. Based on floor area, the percentage of the total relating to Wates House is 31% (David Anderson, Energy Manager, UCL Estates & Facilities Division)

According to the ventilation type and the size of the building, Wates House can be classified as naturally ventilated open-plan (Econ19, 2000, p.7). Using ECON19 figures for typical and good practice and the figures about Wates

House energy consumption for the last two years, the following charts were composed. More detailed tables can be found in Appendix C.

Figure 14 : Comparative chart of annual energy consumption

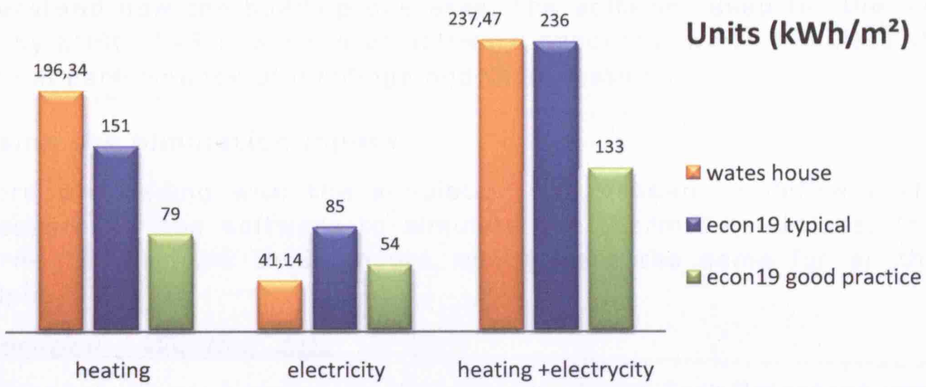
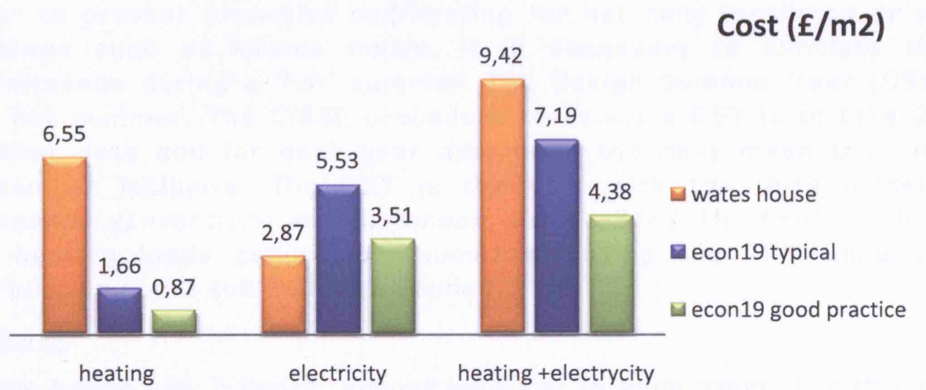


Figure 15 : Comparative chart of annual energy cost



The fact that there is not separate meter for Wates House and the energy consumption distribution is only based to the area proportion make the figures less accurate, as the 31% of the energy assumed to be consumed by Wates House may not be precise. The simulation of the current condition will help to check the figures. However, it is still pinpointing that the energy demand for heating is way above the good practice suggested by ECON19.

Taken into account the age of the building, the fabric performance is expected to have declined during the years. The thermal conductivity of the external walls has probably increased through the years due to insulation faults, causing reduced thermal mass effect. Thermal bridging is also very probable to occur and must be considered. The main reason, though, for the high heating loads are the heating losses through the windows which do not close properly and are very leaky.

On the other hand, the electricity energy consumption is very satisfactory, even lower than ECON19 good practice guide. This is another indication why the present study will focus on the heating loads of the building.

Simulation

As described in the methodology chapter, the current situation was simulated, in order not only to act as benchmark for the improved options, but also to understand how the building operates. The software used for the simulation is TAS by EDSL. TAS is a suite of software products, which simulate the dynamic thermal performance of buildings and their systems.

Setting the simulation inputs

Before proceeding with the simulation, we needed to define certain inputs, necessary for the software to simulate the thermal conditions. The following information explains those inputs, which were the same for all the different models.

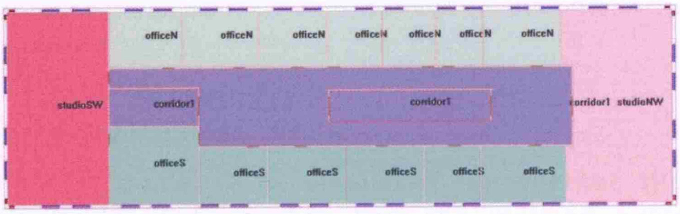
- *Location – Weather data*

The site location is central London. Initially, CIBSE Test Reference year (TRY) for Heathrow was used. The TRY is composed of the most average months from the 20 or so years of data (*Levermore* and Parkinson, 2006, 311). However, in order to prevent excessive overheating for naturally ventilated or mixed-mode buildings such as Wates house, it is necessary to simulate the thermal performance during a 'hot' summer. The Design Summer Year (DSY) contains this hot summer. The CIBSE procedure to select a DSY is to take 20 years of weather data and for each year determine the daily mean DryT for April to September inclusive. The DSY is the year with the third hottest April to September *(Levermore and Parkinson, 2006, 316)*. The final results regarding the heating loads come from simulation using the TRY while to find the overheating hours the DSY was applied.

- *Zones*

Wates house has 7 floors, almost identical to each other. For this reason, the thermal performance of only one "typical" floor was analysed in more detail.

Figure 16 : Typical floor plan of the existing building.



The typical floor was divided in 5 zones. More details about the area of each zone and can be found in Appendix D Table D1.

- *Construction*

Given that the present study deals with re-cladding, the proposed improvements concern only the skin of the building, Hence, certain building elements, such as the floors and ceiling and internal partitions are assumed not to change when modelling both the current condition and the future possible building. Table D4, Appendix D these elements.

- *Internal conditions – Casual gains*

The building is naturally ventilated through the opening windows, controlled by the occupants. The refurbished building will be still naturally ventilated though openable ventilators. Thus the ventilation rate will be 0 in both cases. The infiltration rates, however, will be different. The existing building, as already discussed, is considerably leaky and based on the age of the building an infiltration rate of at least 0,8 ACH can be assumed. The new cladding compiles with the requirements of Part L for air permeability which is $10m^3/h.m^2$ (*Approved Document Part L2, 2006, p.18)*. Given the building type and size and according to CIBSE A, p. 4-13 (see table D 2 Appendix D) the infiltration rate should be 0.5 ACH.

To estimate the casual gains we need to refer to CIBSE A, p. 6-3, table 6.2, considering an office building in city centre with occupancy density 1 person per $10m^2$. More detailed calculations are presented in Table D 1, Appendix D. Since all the zones have similar use, the gains are very similar, thus the same conditions - presented in the following table- were applied to all of them. The only differentiation occurs in the corridor, which is modelled as a utility zone, with no internal gains, apart from lighting.

- *Schedules*

Even though it is an office building, the nature of the activities as a school of architecture dictates operational hours other than the regular office hours. In order to be as close to reality as possible the schedule applied was based on the information from the UCL Estates & Facilities Division. Thus, the building is occupied every day, including weekends, from 9am to 8pm. The same schedule is applied for the casual gains. The heating system operates for the occupied hours plus one hour, from 8am to 9am to preheat the building. The thermostat is set at 20° C

- *Design Targets*

The design targets refer to the issues to be considered when evaluating the environmental performance of each option, including the current condition. The heating loads are compared with ECON19 good practice (see fig. 14).Since the building is naturally ventilated the risk of overheating needs to be considered. Thus, the design target is the inside temperature not to exceed 25°C for more than 5% of the occupied time and 28°C 1% of the occupied time (CIBSE A, p.1-9).

Current situation model

The first model to be simulated represented the current situation. The aim of this model is to realise how the building currently performs and check the figures for real energy consumption. Hence, it can be further compared with the proposed re-clad building. What is more, it will help to determine the way the building functions, e.g. the aperture types, which can be used for the following models.

The building elements used for the simulation was based on the observations about the current construction, as it was described before. Table 4 presents those elements and the resulting U-values.

Table 4 : Building elements used in the model of the current situation

Building Elements:	U-Value (W/m^2 C)	Thickness (mm)	Description	Materials:
External Walls	0,42	350	Brick wall	Plaster / concrete block/ cavity/ expanded polystyrene/ brick
Windows	3,00	100	single glazed windows with blinds	aluminum frame/ 6 mm clear float glass/ medium blind
opaque surface	0,6	120	opaque pane	plasterboard/ cavity/ expanded pvc board/ plastic

For the internal venetian blinds, an hourly schedule was assumed, based on variations according to the time of the day and average insolation. The rest of the inputs were described in the simulation section.

The building current energy consumption for heating is 196 kWh/m². After a number of simulations, where certain parameters varied, we came up with a model having energy consumption similar to the real one. The parameters with the greater impact were the aperture types and the infiltration rate. The aperture types finally applied was the windows to open for inside temperature 21°C and 23°C. Infiltration rates from 0,7ach to 1ach were tested and finally 0,8ach was found to be the more representative, as originally estimated.

The simulation indicated that the inside conditions are satisfactory, with the inside temperature to rise above 28°C for 1,05% of the occupied time. The delivered heating energy demand is 130,9 kWh/m² and the primary, assuming a boiler efficiency 70%, 187kWh/m², very close to real energy figures and considerably higher than ECON19 good practice, which would be 79kWh/m² (see fig.14)

Chapter 5 - Re-cladding options evaluation

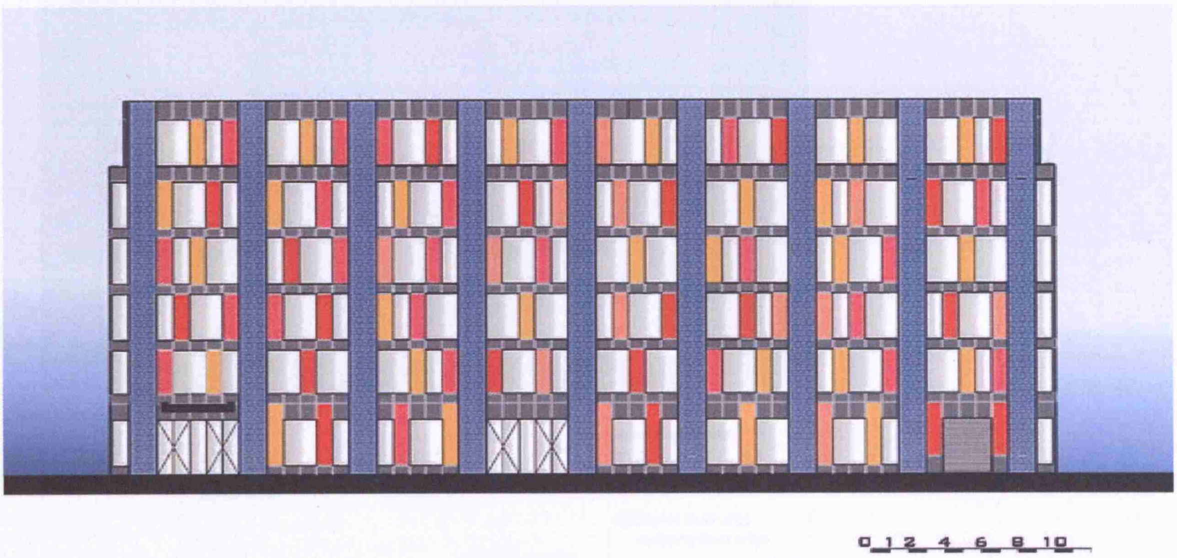
According to the figures on Wates House energy performance, it becomes obvious that measures need to be taken. It is believed that re-cladding will solve a number of the reported problems and improve the energy performance. Additionally, an innovative facade could give a fresh, modern air to the building of the Bartlett School of Architecture, which would act as a statement for the faculty in the UCL campus.

Proposed design

The re-cladding suggests that the building will be stripped of any external element, walls, windows etc, left with only its structure, where the new facade is going to be supported. The new cladding will be single skinned. The double skin facade option was rejected due to cost and space requirements. Moreover, the height and location of the building did not make a second skin particularly advantageous for the facade function. On the other hand, by removing the brick exterior walls and aligning the final surface with the existing structural columns more space was saved, both for building serviced and occupied space, more than 60m² in each floor and 200 m² in total (Appendix B, figure B2).

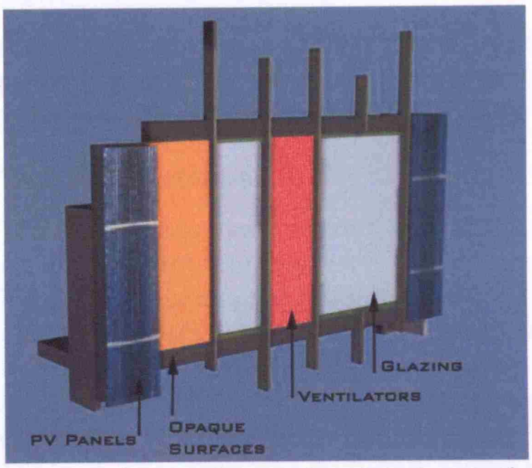
The predominant feature of the proposed facade is the vertical zones, referring to the old facade. A facade module was developed and repeated with certain modifications between the vertical zones along the structural columns of the building. In that way a more creative and "playful" facade was composed.

Figure 17 : Proposed design of the SE façade of Wates house



The module consists of three distinct parts: the glazing, the opaque surfaces and the ventilators. The glazing is divided in two window units, 0,85m and 1,78m wide. With a height of 2,60m, they occupy most of the floor height. The repetition of the module results in a 42% of the facade to be glazed, against 35% that it is currently.

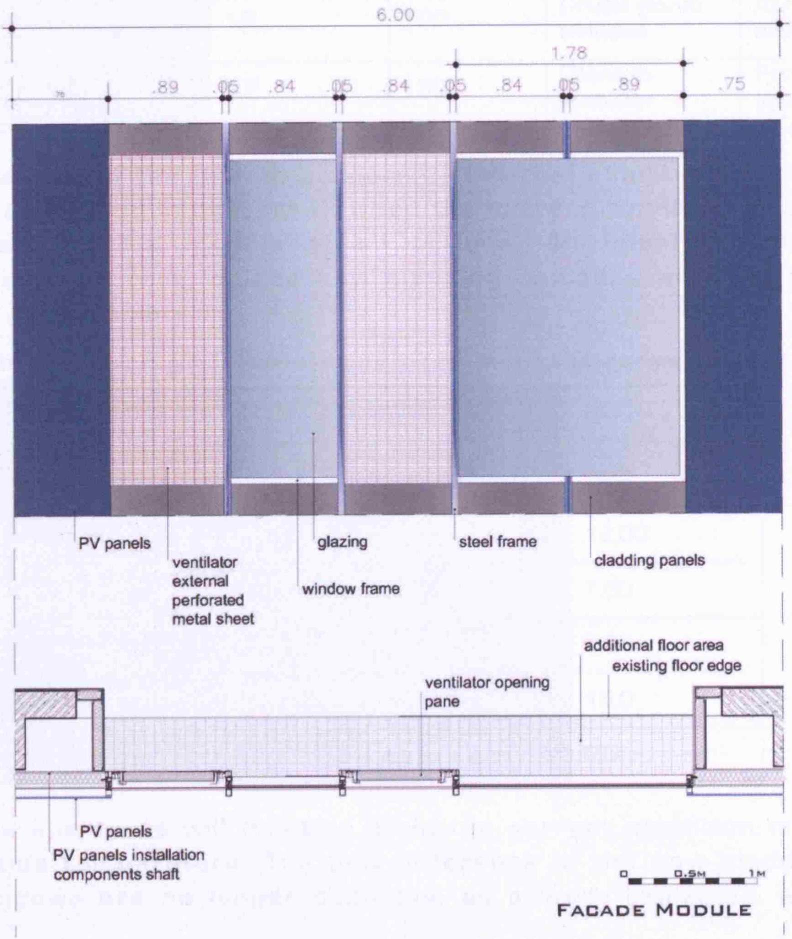
Figure 18 : representation of façade module



The opaque surfaces form the space between the glazed parts and the ventilators and, most importantly the vertical zones, measuring 1,50m of width. They will be of metal cladding panels; more details on the construction and elements will be given when the different options are discussed. In the SE and SW facades the vertical zones are additionally covered by PV panes arrays.

The ventilator is a new feature of the facade, introduced to cover the need for ventilation. The outer skin of the ventilator consists of a perforated metal grid, while an openable-on-request pane will be placed in the inside. The advantage of these ventilators against the current opening windows is the enhanced control of dust and noise, while the fixed windows are preferable in terms of cost and operation. Besides, the external metal surface, painted in lively colours, is a striking architectural element of the facade.

Figure 19 : Façade module (for lower scale see Appendix B)



Options and Results

After the design of the new cladding has been developed, the thermal performance of the different options, as they were described in the methodology, needs to be tested. The basic design is the same for all options

The SAP options

The first improved model was based on the proposed design, using building elements that comply with the design limits for envelop standards, required in Part L2 (Approved Document Part L2, 2006, p.16). The limiting U-values applied can be found in the Appendix D, table D3. The purpose of this simulation was to find out the effect on the building performance with the minimum possible improvements in compliance with building regulations, regarding the thermal conductivity of the envelop. For this reason this option will be called *SAP min*. Table 5 presents the building elements applied to the new cladding design and the resulting U-values, in compliance with the building regulations.

Table 5 : Building elements used in the model of the SAP min option

Building Elements:	U-Value (W/m^2 C)	Thickness (mm)	Description	Materials:
External Walls	0,33	150	Metal panel cladding	Steel coating/ mineral wool insulation 130mm
Windows	1,8	100	Double glazed windows	Aluminum frame, pane clear 6-12-6 double glazing low E
Ventilator	0,7	150	Operable ventilator	Perforated metal sheet/ cavity/ plywood openable door

The rest of the inputs, concerning internal conditions, schedules, apertures etc were defined in chapter 4, when the current condition model was set up and are fixed for the models of all options. An important improvement is in the infiltration rate, as the new cladding compiles with the building regulation for air permeability.

Table 6 : Average internal conditions in all the zones

Infiltration ACH	0,50
Ventilation ACH	0,00
Lighting gain W/m²	12,00
Occupancy Sensible Gain W/m²	7,50
Occupancy Latent Gain W/m²	5,80
Equipment Sensible Gain W/m²	15,0
Equipment Latent Gain W/m²	0,0

The apertures will function as in the current condition model, according to the inside temperature. The only difference in the new cladding design is that the windows are no longer openable, as already explained, and the ventilation will occur through openable ventilators. Particularly the ventilators will open for inside temperature 21°C and 23 °C.

The results (see tab.9, p.29) indicate a significant reduction in heating loads from the current conditions, about 95%. This reduction can be explained by the replacement of the external cladding with a new, more airtight and with improved U-values. What is more, the new design includes a bigger proportion of windows. On the other hand the percentage of overheating hours has risen well above the acceptable limits.

The purpose of the thesis is not simply to reach a specific design target but to investigate the various façade options though the iterative modelling of the various options. According to that concept, the next façade option attempts to further improve the previous model, by applying material with higher thermal resistance. The U-values are significant low, achieved with technologically advanced materials, such as vacuum insulation panels. Table 7 presents the material used.

Table 7 : Building elements used in the model of the SAP best option

Building Elements:	U-Value (W/m^2 C)	Thickness (mm)	Description	Materials:
External Walls	0,15	150	Vacuum insulated panel	Steel coating/ core material
Windows	1,4	100	Double glazed windows , argon filled	Aluminum frame, pane clear 6-12-6 double glazing low E/ argon filled cavity
Ventilator	0,42	150	Operable ventilator	Perforated metal sheet/cavity/ plywood insulated openable door

The simulation of this model resulted in a heating load reduction around 60% from the previous model, which is justified by the reduction in fabric heat losses. However, the hours of overheating increased (see tab.9).

The third and final model of the first broad group is a compromise between the previous two and will be referred as SAP-improved option.

Table 8 : Building elements used in the model of the SAP-improved option

Building Elements:	U-Value (W/m^2 C)	Thickness (mm)	Description	Materials:
External Walls	0,25	200	Metal panel cladding	Steel coating/ mineral wool insulation 180mm
Windows	1,8	100	Double glazed windows	Aluminum frame, pane clear 6-12-6 double glazing low E
Ventilator	0,42	150	Operable ventilator	Perforated metal sheet/cavity/ plywood insulated openable door

If compared with SAP best model, the heating load increased by 30%, while the hours of overheating improved. The heating load reduction from SAP min is 42% and the overheating increased by 5% (see tab.9).

The third model performance was in the middle between the previous two, accordingly with the thermal conductivity of the materials used. To further evaluate which option is preferable the cost also need to be taken into account.

The Solar shading options

The next broad category of options tested concerns the use of solar shading devises. The models consist of the SAP improved model, as described before, with the addition of shading devises. The SAP-improved model will be further referred as base option.

The first option to be tested is the most common in offices to control solar gain and glare; the internal venetian blinds. A number of schedules for the blinds operation were tested and finally an hourly schedule for the different orientation windows was applied (Appendix D, Table D5).

The simulation results were disappointing (see tab.9), given that, compared with the base option, both the heating loads and the overheating hours increased. This lead to the conclusion that the internal blinds do not manage to make effective use of the solar gains in the winter, while, in the summer, they increase the surface temperature (Appendix D, table D6)

Figure 20 : Example of window shading with fixed overhang

The next option refers to external shading. The simplest form of external shading would be an overhang. Given the height of the windows and the sun angles, an overhang of 0,5m shades half of the window in the summer, while allow the sun to penetrate in the winter, when solar gains are wanted.

Both the overheating hours and the heating loads decreased, in comparison with the internal blinds option, suggesting that the façade performs better, in terms of solar gains and the solar protection (see tab.9).

Figure 21 : Example of window shading with fixed horizontal louvres

Following the overhang, fixed external fins were applied. Since the orientation of the main façade is SE, both horizontal and vertical fins are tested. After a number of horizontal fins layouts were tried, the one finally applied are horizontal louvres 100mm wide, every 200mm in front of the glazing pars of the façade.

The horizontal fins addition to the base model resulted in improved overheating conditions, while the heating loads didn't rise significantly. If compared with the overhang option, there is a noticeable reduction to the heating loads (see tab.9).

Figure 22 : Example of window shading with vertical louvres

The Vertical louvres option is to be applied next. 200mm wide vertical louvres every 400mm were applied in front of the glazing, perpendicular to the glazing surface. The distance between the louvres is relatively long, but the view outside must be allowed.

The results of the fixed vertical louvres option are considered similar to the previous option, the horizontal louvres, with the overheating a little increased and the heating loads slightly improved (see tab.9). Thus, additional features will be applied. The next and final model of the Solar shading group simulates movable vertical louvres. Particularly, they will be applied only during summer, while form 11h-18h they will turn 45° to the glazing surface.

The movable louvres option did not affect much the overheating hour (see tab.9). The heating loads improved, though, due to lack of shading during winter.

Electrochromic glazing

The last board group of option refer to electrochromic glazing application. The reason why this technology was selected has to do with the potential of better controllable light transmittance according the solar gain and temperature.

Since the Simulation software TAS does not have a material for electrochromic glazing, we created a transparent material with similar solar transmittance which is the variable property in electrochromic glazing. A typical electrochromic glazing has a transmittance from 0,60 in clear state to 0,035 in tinted state *(SAGE Electrochromics, Inc.)*. These changes in transmittance were simulated with a double glazed unit with movable blinds between the panes, conjuncted with a schedule for every time of the year. When the blinds are down- 0 value in the schedule- the transmittance is 0,04, when they are up -1 value in the schedule- it is 0,5.

In order to form the yearly schedule, we were based on the surface solar gain and the corresponding internal gain of our base option, the SAP improved. The correlation of the data for summer reveal that the temperature rises after the surface solar gain exceeds the 800 Wh. Table D7 in Appendix D presents this condition for the hottest day (203). Thus the first option to be tested was for the glazing to turn to tinted state when the solar gain of the surface exceeds 800Wh. The schedule was composed in a spreadsheet using as reference surface the South windows, which receive the higher isolation. If the solar gain is higher than 800W the value is 0, if lower than 800W it is 1. This first option is therefore referred as Electrochr800

The results indicate that the overheating was reduced (see tab.9). However the heating loads increased significantly from the base option, suggesting that too much of the solar gain, especially in winter, was cut off.

The next option improves the Electrochr800, by simulating a more gradual reduction of the solar transmittance. The simulation method was the same but the yearly schedule changed. For solar gain higher than 800W the value is 0,5, suggesting that the glazing transmittance will be about 0,2, while the transmittance is minimum, 0,06 for solar gain above 1200W, when the schedule value is 0. If solar gains are lower than 800W the value is 1 again.

According to the simulation result (see tab.9), the use of solar gain is more effective, since the heating loads decreased. However, we still need to consider the blockage of the solar gain in winter, when they are needed. For this purpose, a third and final option is examined, called Electrochr-Seasonal.

The results are considered satisfactory, since the heating loads reduced 25% from the previous option. The overheating hours also reduced significantly (see tab.9).

Energy Consumption and Internal Conditions

After all the results are collected and evaluated, it is necessary to draw some conclusions from the correlation between the different option performance. The following table presents an overview of the environmental performance for the different option.

Table 9 : Overview of the simulation results for the re-cladding options

The first striking figure is the enormous reduction in heating loads between the

Group	options	description	T>25°C (% hours of year)	T>28°C(% hours of year)	heating loads (kWh/m² annual)	primary heating loads (kWh/m²)*	CO2 emissions kgCO2/m² **
current	current leaky	Close to real energy consumption, current building elements, very leaky	5,29	1,05	130,88	186,97	36,27
SAP model	Part L U-values	U-values required in Part L	10,37	2,90	9,35	13,36	2,59
	best U-values	minimised U-values, argon filled glazing, vacuum insulation panels	11,30	3,09	3,65	5,21	1,01
	improved U-values	U-values improved form Part L, not minimised	10,80	3,10	5,47	7,82	1,52
Solar shading	internal blinds	internal blinds	12,01	3,92	8,79	12,56	2,44
	overhang 50	500mm overhang above all windows	9,76	2,58	7,12	10,17	1,97
	horizontal louvres	improved U-values, 100mm louvres every 200mm	10,10	2,55	6,00	8,58	1,66
	vertical louvres	200mm wide vertical fixed louvres every 400mm	10,52	2,86	5,77	8,24	1,60
	movable vertical louvres	200mm wide vertical louvres every 400mm, applied only in summer+hourly schedule	10,34	2,83	5,48	7,82	1,52
electrochromic	Electrochr 800	electrochromic tinted for surface solar gain >800 kWh	10,32	2,69	7,34	10,49	2,03
	Electrochr -Gradual	transmittance 0,20 when solar gain >800 and 0,06 when > 1200	10,35	2,71	5,93	8,47	1,64
	Electrochr -Seasonal	transmittance 0,06,when surface solar gain >700 kWh summer >1200kWh winter	7,37	1,19	5,53	7,90	1,53

*assuming a boiler efficiency 70%

**CO2 emission factor for natural gas 0,194 kg/kWh (source: Part L, p. 15, tab. 2) current building and the re-clad. There can be some possible explanations, probably all of them true. The first one is that the data about the energy consumption are not accurate. There is no meter for Wates house and the energy consumption is assumed to be distributed according to the area proportion between Wates house and the neighbouring building where the meter is located. Another explanation is that the current building performs significantly bad and it is mainly due to the bad thermal performance of the fabric and the lack of air tightness, as we already realized when analyzing the current condition. Given the above, it is reasonable for the energy consumption to improve dramatically with the new, improved cladding.

The following charts present the heating loads and the percentage of overheating hours. The correlation is not concrete. There is a tendency the overheating to reduce when the heating loads increase. This is mostly explained by the relation between heating loads and solar gain. The greater the solar gain, the lower the energy demand for heating, though, the greater the overheating potential. However there are options where this relationship is not so obvious, due to the specific characteristics of the façade, such as in the internal blinds option, where both heating loads and overheating are high.

Figure 23 : Chart of heating loads for all facade options

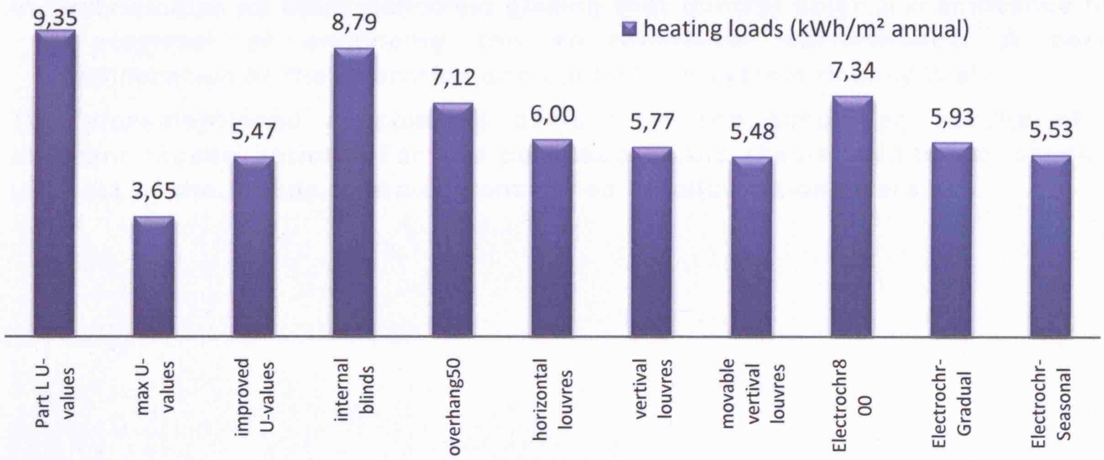
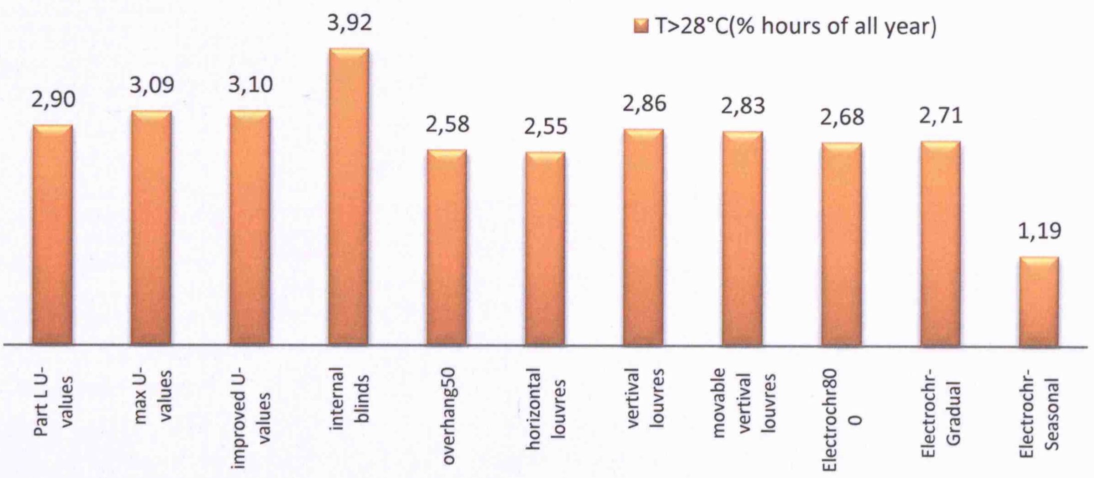


Figure 24 : Chart of overheating for all facade options



Summary

Subsequently, the main key conclusions are presented. Even though they were drawn from the simulation of the case study building, they can be generalised as they endorse issues that can be addressed to any re-cladding or new-built project.

i. Re cladding can significantly improve the energy demand of an existing badly performing building

ii. Improved U-values and air-tightness are important to reduce heat loss and the consequent heating loads. According to the options tested, the energy demand reduced linearly with the thermal conductivity (SAP group).

iii. External shading devices perform better than internal.

iv. Shading devices can help reduce overheating, by blocking solar gain. However, this also results in increase in energy demand for heating

v. An appropriate design and elaboration of the shading device operation, e.g. to be moveable and not cut off solar gains when wanted, is necessary for an effective use of solar gain. It is possible to control overheating without increase in energy demand, as in the movable vertical louvres option.

vi. Technologies as electrochromic glazing that control solar transmittance have a potential of enhancing the environmental performance. A careful consideration of the operation and control the system is essential.

The aforementioned conclusions come from the simulation results of the different façade options. For the purposes of the thesis, additional issues, as the cost of the façade, are also considered in following chapters.

Building Integrated Photovoltaic Panels (BIPV's)

As described in the proposed design chapter, Photovoltaic panels will be integrated in the façade, particularly in the SE and SW elevations. They will be suspended in vertical zoned 1,5m wide and 20m high, along the existing structural columns. The zones refer to the vertical zones of the existing façade, constituting a connection between the past and the future façade. Apart from its value as an architectural element, the BIPV main task is the energy generation, which can be subtracted from the total energy demand.

For the analysis of the photovoltaic panels the RET Screen software was used. "The RETScreen Clean Energy Project Analysis Software is a unique decision support tool developed with the contribution of numerous experts from government, industry, and academia. The software, provided free-of-charge, can be used worldwide to evaluate the energy production and savings, costs, emission reductions, financial viability for various types of Renewable-energy and Energy-efficient Technologies (RETs)" *(RETScreen International)*.

The PV panels are located in the SE and SW façade, in vertical zones as described. Particularly, in the SE façade, there will be 9 zones, accounting for 9x20x1,5= 270m^2 of PV panels, and 3 zones in the SW facade, accounting for 3x20x1,5=90m^2 of PV panels. Overall, **360m^2** of PVs will be integrated in the facade. The analysis of the two facades needed to be in separate spreadsheets, due to the different azimuth angles (30° for SE and 120° for SW). Table 10 presents the sum of both facades. More detailed spreadsheets can be found in Appendix D.

Table 10 : PV array information (Source: RETScreen International)

PV Array		SE Façade	SW Façade
PV module type	-	poly-Si	poly-Si
PV module manufacturer / model #		Sharp/ ND-L3EJE	Sharp/ ND-L3EJE
Nominal PV module efficiency	%	12,4%	12,4%
NOCT	°C	45	45
PV temperature coefficient	% / °C	0,40%	0,40%
PV array controller	-	MPPT	MPPT
Miscellaneous PV array losses	%	5,0%	5,0%
Nominal PV array power	kWp	33,21	11,07
PV array area	m^2	267,8	89,3

The panel model was selected from the software product database and it is the Sharp/ ND-L3EJE. The specific model has an efficiency of 12,4% which was found satisfactory compared with the other models. The dimensions of the panel (Width (mm): 662, Length(mm): 1.499) are also convenient for the proposed layout.

Table 11 presents the energy output, Green House Gases estimated reduction and initial installation cost. These figures came from the RETScreen software, having as inputs location, PV array orientation and slope and the electricity generation fuel mix for UK *(National Statistics)*. More detailed tables can be found in Appendix E. The annual savings and the payback period were calculated for UK tariffs. Particularly, the price for electricity in the UK was found to be

£0,1093/kWh *(BERR, tab.5.5.1.)*. The annual savings would be: Renewable energy delivered x unit price, and the payback period: Initial costs/Annual savings

Table 11 : PV application output

Renewable energy delivered	(kWh/yr):	24.393
Net average GHG reduction	(tCO2/yr):	/2,52
Total Initial Costs:	(£)	534.586
Annual Savings	£/yr	2666
Simple Payback	yr	200

To sum up, the previously described PV array, measuring 360m² of the SE and SW facades, delivers **24.393kWh/year**. The energy output is considered satisfactory as it accounts for more than 10% of the current energy demand for electricity *(Appendix B, tab. B2)*, reducing the building carbon footprint. However, the payback period is tremendously long, making this option probably inapplicable. Still we need to consider that the payback period maybe in fact shorter, as the electricity prices rises, and the environmental benefit of cutting down on CO_2 emissions. What is more, the energy generation can potentially increase, if a bigger area of PVs is installed or in a different tilt. In that case, the integration in the façade design and the effect on the internal conditions need to be balanced against the energy generated.

Cost analysis

Apart from the effect the various façade systems have on the energy consumption and internal conditions, cost and the resulting payback period are important factors to consider when evaluating the options. In the present study, the cost of Wates house re-cladding is estimated and correlated with the respective savings in energy.

The cost analysis is based on the module prices for the different options previously described. It refers mainly to the cladding components, ignoring the fitting systems, building services and maintenance costs, since they are assumed to be very similar to all options. The PV panels are also not considered, seeing that they will be integrated in all the options

As presented in figure 18, the module area is 3,12x6= 18,72m². According to Langdon, 2008, p.66, an average price for external cladding for central London offices would be £ 433/m² *[Langdon, 2008, p.66]*; hence an average cost for the façade module would be £ 8330. Although it is an approximation and a more detailed cost accounting is necessary, it could act as a benchmark for the Wates House cladding cost.

Following tables present an estimation of the façade module cost. More detailed costing is presented in Appendix F. The prices were found after research in literature for costs and specifications along with contact with manufacturers and suppliers.

Table 12 : Façade module cost for the SAP options group

	external wall		ventilators		windows				
	description	cost [£]	description	cost [£]	description	Cost [£]	façade module price[£]	plus fitting [£]	**Final module cost[£]**
Part L U-values	coated steel insulated composited cladding panels	381	Perforated metal/ plywood pane	1171	Double glazed windows	2186	3738	4486	6728
best U-values	vacuum insulation panels	1733	Perforated metal/plywood insulated pane	1198	Double glazed windows , argon filled	2273	5204	6245	9367
improved U-values	coated steel insulated composited cladding panels	437	Perforated metal/plywood insulated pane	1198	Double glazed windows	2186	3820	4585	6877

The final module cost derives by assuming an additional 20% for detailing and 50% more for labour *[Langdon, 2008]*. The costs are comparable with the average façade price. The "Best U-values" option cost is noticeably high, which is due to the high price of vacuum insulation panels.

As far as the Solar Shading group is concerned, the cost of the module will be the SAP-improved module price, adding the cost of the shading device.

Table 13 : Façade module cost for the solar control options group

shading device	amount	unit	cost £ per unit		total cost	original module cost, base option	final module cost	additional cost % from base option
internal blinds	7,285	m²	60	*	437,1	6877	7314	6,35
overhang40	2,65	m	250	**	662,5	6877	7539	9,63
louvres	7,285	m²	350	**	2549,75	6877	9427	37,07
vertical louvres	7,285	m²	380	**	2768,3	6877	9645	40,25
vertical louvres movable	7,285	m²	450	**	3278,25	6877	10155	47,67

*Click for Blinds **Buck R.

Finally, the module cost is the same for all the tree sub-option of the Electrochromic group, as the difference between them is only in the operation schedule and not the materials. The cost of the module is shown in Table 24 (see also tab.F4, Appendix F). The elements are the same as in the SAP-improved module apart from the glazing, which resulted in a 38% increase in the module cost.

Table 14 : Façade module cost for the Electrochromic group

	external wall		ventilators		windows				
	description	cost (£)	description	cost (£)	description	Cost (£)	façade module price(£)	plus fitting (£)	Final module cost(£)
Elecrtochromic glazing	coated steel insulated composited cladding panels	381	Perforated metal/ plywood pane	1171	Electrochromic double glazed windows	3642	5277	6333	9499

Nevertheless, the cost of each module as a number is hard to evaluate. In order to better assess and compare, the concept of the payback period is introduced. The payback period of each facade option depends on the financial savings, resulting from the reduction in energy demand due to re-cladding, and the initial re-cladding cost. Overall, the facade options can be further compared according to the savings in energy in relation with their initial cost.

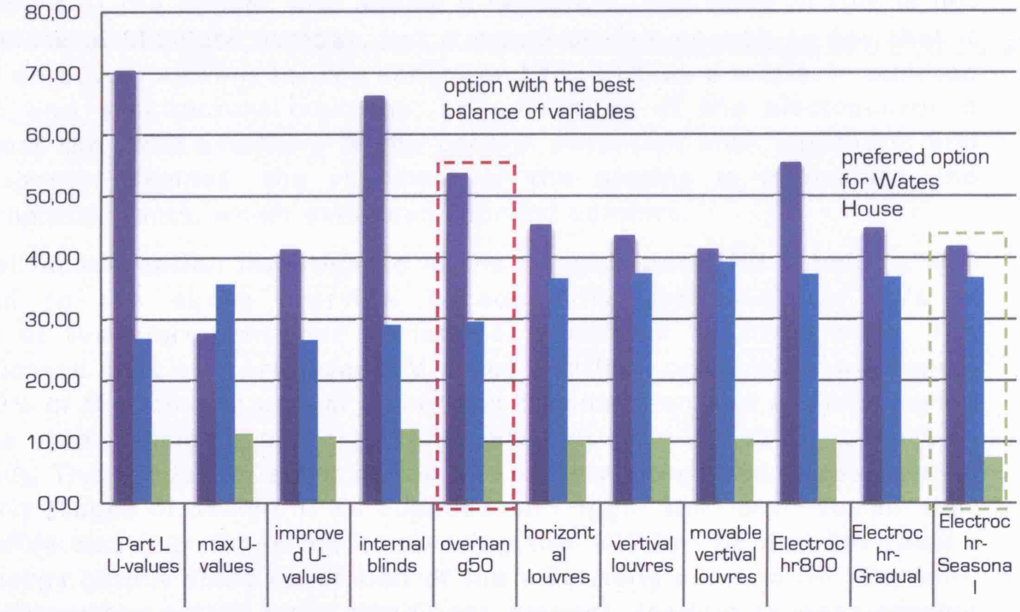
Table 15 : Facade options payback period (see also tab G1, Appendix G)

	Part L U-values	max U-values	improved U-values	internal blinds	Overhang 50	horizontal louvres	vertival louvres	movable vertival louvres	Electrochr 800	Electrochr -Gradual	Electrochr -Seasonal
energy offset (kWh/yr)	913553	956402	942705	917752	930325	938704	940473	942671	928638	939289	942244
cost offset (£/yr)	30147	31561	31109	30285	30700	30977	31035	31108	30645	30996	31094
overall recladding cost (£)	807397	1124010	825211	877663	904711	1131181	1157407	1218601	1139923	1139923	1139923
Payback period (yr)	27	36	27	29	29	37	37	39	37	37	37

Chapter 6 – Discussion and Conclusion

In chapter 5, various facade options for re-cladding a case study building were proposed, tested and evaluated. The appraisal of the options was based on three axes: internal conditions-mostly in terms of overheating-, heating energy demand and cost. The following figure summarises the performance of each option on these key issues. The heating loads presented are the annual primary energy demand of the whole building and the overheating is the percentage of occupied time when the inside temperature exceed 25°C. The issue of cost is addressed with the payback period (see Appendix G for detailed data). In order to understand the correlations, the relative changes of each parameter, compared with the other options, needs to be observed.

Figure 25 : Chart of heating loads, overheating and payback period



	Part L U-values	max U-values	improved U-values	internal blinds	overhang50	horizontal louvres	vertival louvres	movable vertival louvres	Electrochr800	Electrochr-Gradual	Electrochr-Seasonal
primary heating loads kWh x10³	70,28	27,43	41,13	66,09	53,51	45,13	43,36	41,17	55,20	44,55	41,59
Payback period (yr)	26,78	35,61	26,53	28,98	29,47	36,52	37,29	39,17	37,20	36,78	36,66
T>25°C (% hours of all year)	10,37	11,30	10,80	12,01	9,76	10,10	10,52	10,34	10,32	10,35	7,37

The relation between the variables is not the same for all the option. Thus, we shouldn't be looking for linear correlations but rather for a balance between the variables for the different options. In the SAP option group, a relation can be stated; the minimum U-values have lower price but higher energy consumption, while it is the exact opposite for the best U-values model. The third model balances the three parameters in question, as it provides savings in energy and has low price, resulting in short payback period, the shortest of all the options examined.

As far as the shading group is concerned, a different relation is observed. As heating loads decrease the payback period increases. It can be explained by the fact that in order to control solar gain more efficiently, the systems are more sophisticated, hence more expensive and have a greater payback period. The overhang option seems to offer a better balance between the variables. Last but not least, in the electrochromic option group, the third option is obviously the best, as it has the best environmental performance and the lower payback period.

Overall, according to the author's view, the best balance of key parameters is provided by the overhang option. Compared with the other options, it provides an average energy demand with good overheating percentage and relatively short payback time.

However, if we need to choose one option for Wates House, that would be the Electrochromic-Seasonal option. This decision includes more aspects than the key issues previously discussed. Even though its price is high, the option has the best environmental performance, both in terms of internal temperatures and energy consumption. Still, cost can be overcome, if other issues, apart from environmental performance, are considered. First of all, the use of emerging technology, as the electrochromic glazing, combined with an innovative design can add to the image of the building and, thus of the Bartlett, reflecting the pioneering spirit of the school, and act as a landmark. The value of this is not easy to estimate in absolute number, but it would be fair enough to say that it could act as an advertisement for the school and the UCL as a whole. In addition to aesthetic and architectural reasons, an advantage of the electrochromic glazing against the fixed overhang is the control potential, both automatic and by the occupants. Besides, the response of the glazing is immediate and realised by the occupants, which enhances thermal comfort.

An additional facade option investigated is the integration of PV panels. It was not included to the above overview because the application of PVs is independent of the aforementioned variations, additional to all of them. The analysis indicated that the proposed PV array, 360m^2, could have an annual output of 10% of the current annual electricity consumption and payback period 14years. The area, efficiency and orientation are the main variables accounting for the output. The proposed layout of the PVs is fully integrated in the facade, from the early stages of design. If we suppose- to trigger the conversation- that the area of PVs was four times more, covering the 1320m^2 SE and SW facade area, the energy output could cover half of the electricity demand (RETScreen). The energy generated would be a significant amount, leading to considerable CO_2 emission offset. However, it would also lead to a monotonous facade that would not meet the basic requirements for comfort, view or solar gain.

Although the opinions expressed were drawn from the comparative design and testing of re-cladding option for Wates House, they have a general value and can be applied in an extend variety of office building projects, providing a guideline for designer. To see the bigger picture, a facade design is a complicated task and there cannot be black or white decisions, as a number of issues –energy, comfort, cost, aesthetics- are addressed and a balance needs to be found. The procedure followed in the present thesis was a proper designing and decision-making process that is suggested to be followed when facades and re-cladding are in question. The options needs to be stated, tested and evaluated before the one that compromises the variables with the best possible way for the project is selected. As the case study indicated, it is possible that the cheapest solution is not always the most preferable as the additional cost can be overcome by the improved environmental performance and, moreover, the benefit of an architecturally appealing office building to the image of the corporate.

Conclusion

After realising the importance of decarbonising the building sector and the effect energy consumed by office buildings, the present thesis sets off to investigate the potential of advanced facade re-cladding to reduce offices carbon footprint. Moreover, facade options were compared, in order to examine the effect they have on building performance.

Various facade options were researched in literature, and the findings were applied and tested in re-cladding a case study building. It is a 35-year-old building with poor energy performance, currently owned be a university and houses the faculty of architecture, which makes the demand of an innovative re-cladding, in terms of design, material and sustainability, even more imperative.

The re-cladding options can be divided in three groups according to the strategies applied; improved thermal conductivity and airtightness of the envelope, use of solar shading devices and responsive solar transmittance of glazing, by applying electrochromic technology. They were tested through building simulation software TAS. The key issues of the building performance evaluated were the heating loads and the potential of overheating- which is connected with the use of air-conditioning. Analysis of BIPVs and cost analysis cover additional issues related with the facade options.

The thesis managed to answer the initial question. The conclusion is that re-cladding using improved facades can significantly reduce office building carbon footprint. However, the energy demand cannot be the only criterion when evaluating a facade performance, as a much wider range of issues are related, such as cost, payback period, health and comfort of the occupants and architectural appeal of the building. The procedure of iterative design and evaluation followed in this study pointed out how the related issues can be correlated and balanced, according to the requirements of each individual building.

As stated in the beginning of the study, the motive is to reduce the overall CO2 emissions. Our research indicated that an appreciable reduction, about 90%, on the heating energy demand can be achieved by re-cladding the existing, poorly performing stock of offices building. Given that the energy consumed by offices accounts for 18% of the total UK energy consumption and half of it is consumed for heating, re-cladding the aging offices building stock results in a substantial overall reduction in energy consumed and the respective CO2 emissions. Such a reduction can make a significant proportion of the attempt to achieving the Kyoto protocol target of 5%, However, it is not enough to halt the climate change process, which is estimated to requires 60% reduction on CO2 emissions. Still, it is a first step and it is indicative of actions that need to be taken in order enhance the human effect on the environment. What is more, sustainable re-cladding adds to the building architectural appeal, promoting not only the corporate image, but also the sustainability as way to improve the aesthetics of the built environment.

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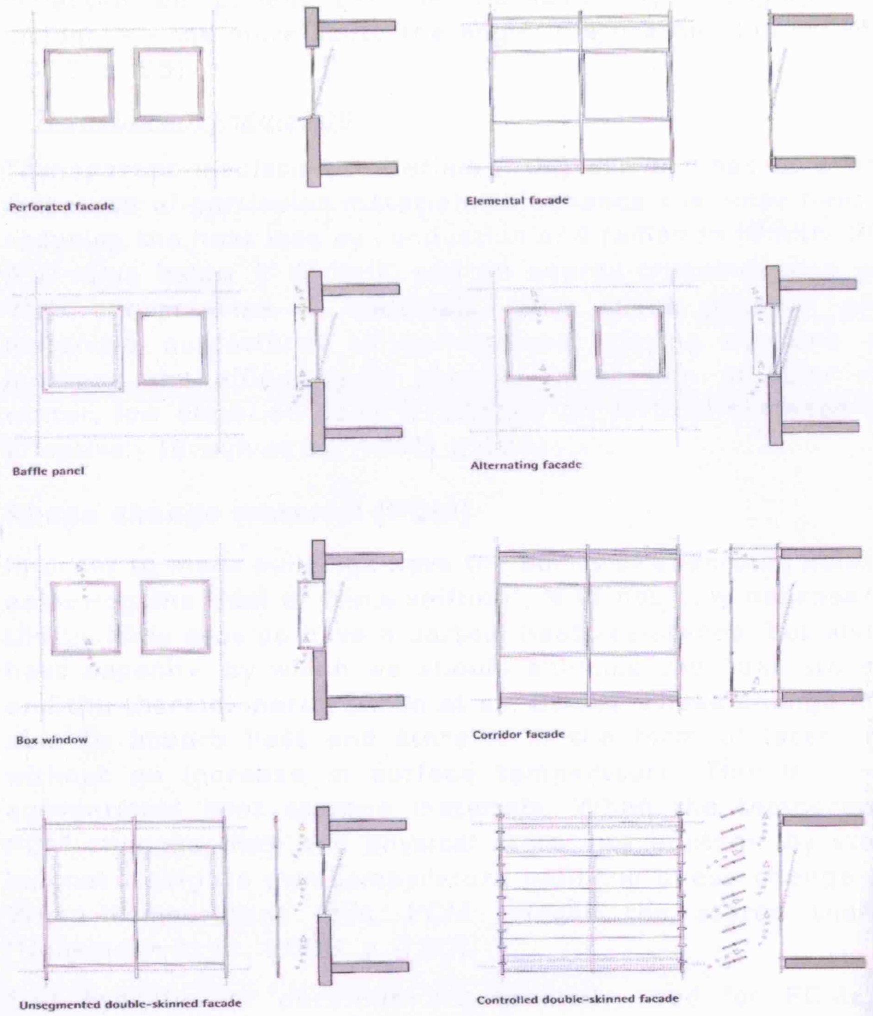
Appendix A- Literature review Addition

Figure A1 : Facades concepts (source: Hausladen et al., 2006, p. 96, fig. 3.1)



Heat reflective and heat absorbing glazing

These products are usually considered for application in situations where overheating poses a risk. Visible light and solar heat gain are both parts of the electromagnetic spectrum of energy emitted by the sun. The interaction of glazing with light and solar heat has three components: reflection, absorption and transmission.

Modifications in the proportions of reflected, absorbed and transmitted radiation could be engineered by changing the glazing system properties. There are several ways of achieving this:

- using 'body tinted' glass which increases absorption
- using reflective coatings, which increase the reflected component and usually the absorbed component too

• using combinations of body tinted and reflective coatings.

It must be remembered that a reduction in solar heat gain can only be achieved at the cost of reducing daylight transmission, though some tinting and reflective products are more selective than others. The reflected component can be increased by changing the angle of incidence —the more acute the angle, the greater the reflection (Smith, 2005, p. 65).

Transparent insulation

Transparent insulation materials (TIM) are a class of products which make use of particular materials to enhance the solar heat gain, whilst reducing the heat loss by conduction and radiation (Smith, 2005, p. 77). A U-value below 1 W/m^2K and an energy transmittance greater than 70% characterize TI materials. With these physical properties TI materials outperform all conventional glazing systems and further increase the efficiency of thermal conversion of solar radiation. In winter, low elevation solar irradiance on vertical surfaces can be used effectively (Braun et al., 1992, p.431)

Phase change material (PCM)

In order to make buildings have the ability of absorbing solar energy and achieving the goal of "time-shifting", it is not only necessary to ensure the building envelop have a certain heat resistance, but also have a big heat capacity, by which we should enhance the heat storage capacity and the thermal inertia (Chen et al., 2008). Phase change materials are able to absorb heat and store it in the form of latent heat energy without an increase in surface temperature. This is in contrast to conventional heat storage materials. When the temperature rises a PCM changes from one physical state into another, by storing energy but not rising its own temperature until the phase change is complete. When temperature falls, PCM release the stored thermal energy (Hausladen et al., 2006, p. 130).

Salt hydrates or paraffins are normally used for PCMs, which are integrated into the materials used to construct internal features or facades components. PCM can be encapsulated into building material (Hausladen et al., 2006, p. 130).

Figure 1: Encapsulated PCM in facade elements (Source: Hausladen et al., 2006, p. 132)

Natural light redirection systems

Shading devices control light and heat gain, yet they also can reduce the amount of light in a space and increase electic lighting loads. On the other hand, a problem with providing daylight is that there is often too much light and glare neat the window and not enough light further back (Carmody et al., 2004, p.118). Natural light redirection systems produce uniform illumination and improve lighting conditions particularly in the depth of the room, while controlling the light levels near the window (Hausladen et al., 2006, p. 138). They work by changing the course of direct or indirect outside light into the upper part of the room. The ceiling then distributes the light over the whole area of the room. Such systems are light selves, reflective louvers, prismatic panels etc.

Appendix B – Wates House existing and proposed design

Figure B 2 : Wates House, Ground plan and typical floor plan

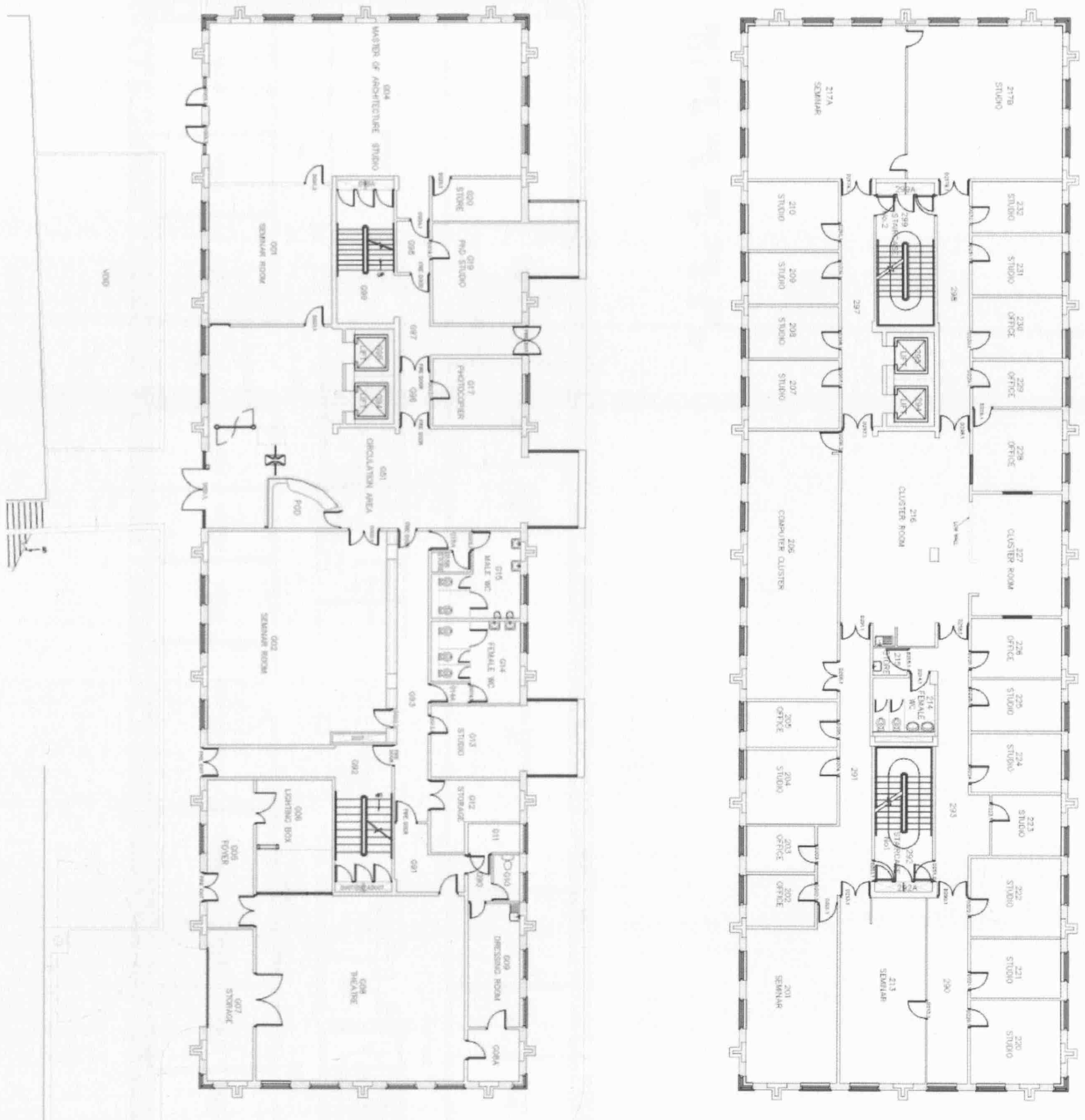


Figure B2 : Wates House, typical floor plan of the proposed design

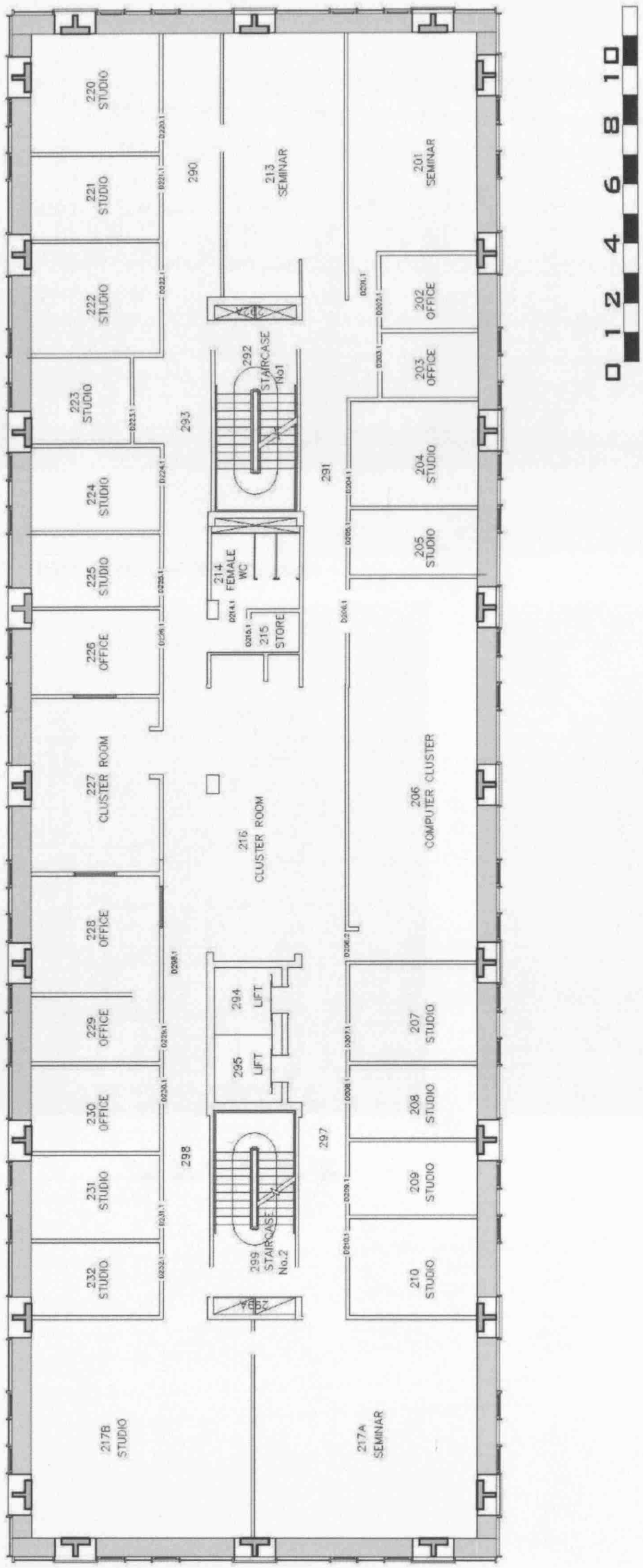


Figure B3 : SE elevation. The façade module is indicated (for details Fig. B5)

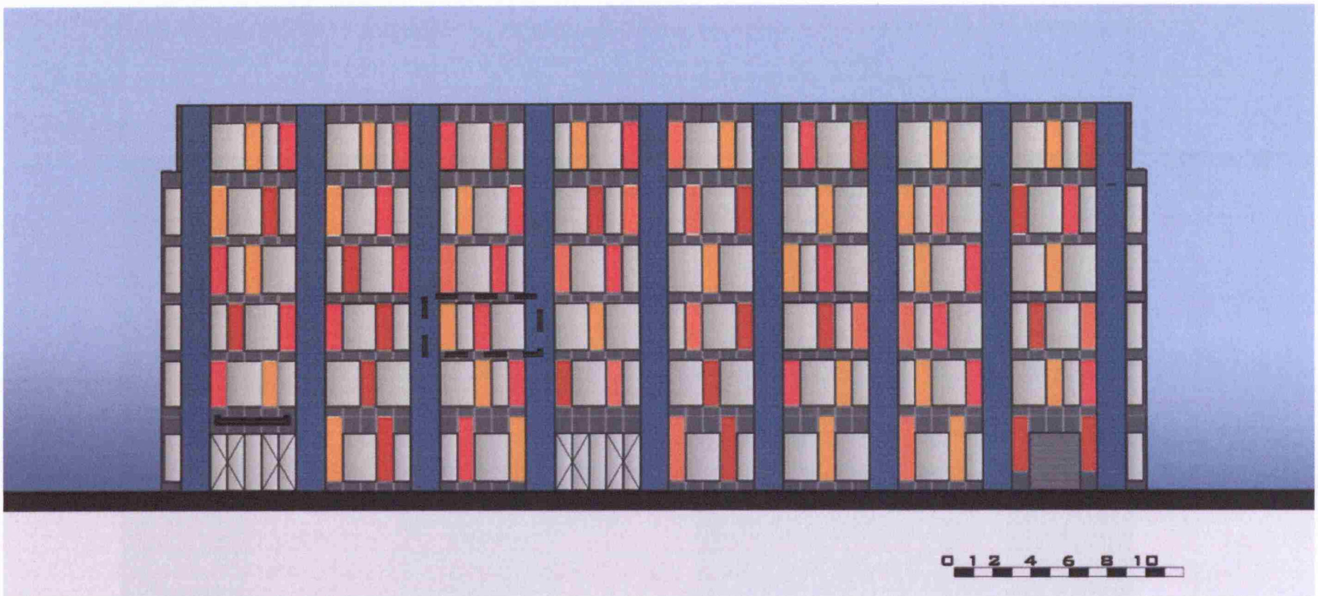
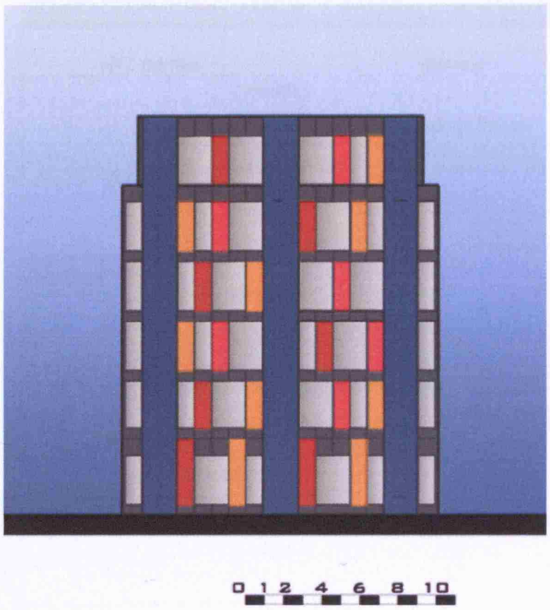


Figure B4 : SW façade and NE elevation



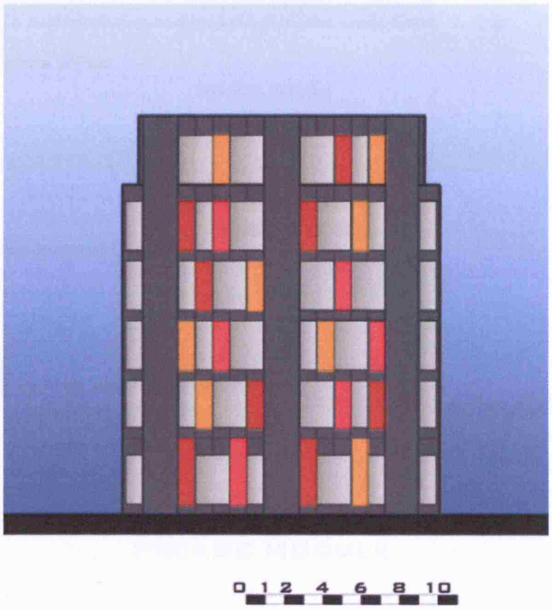
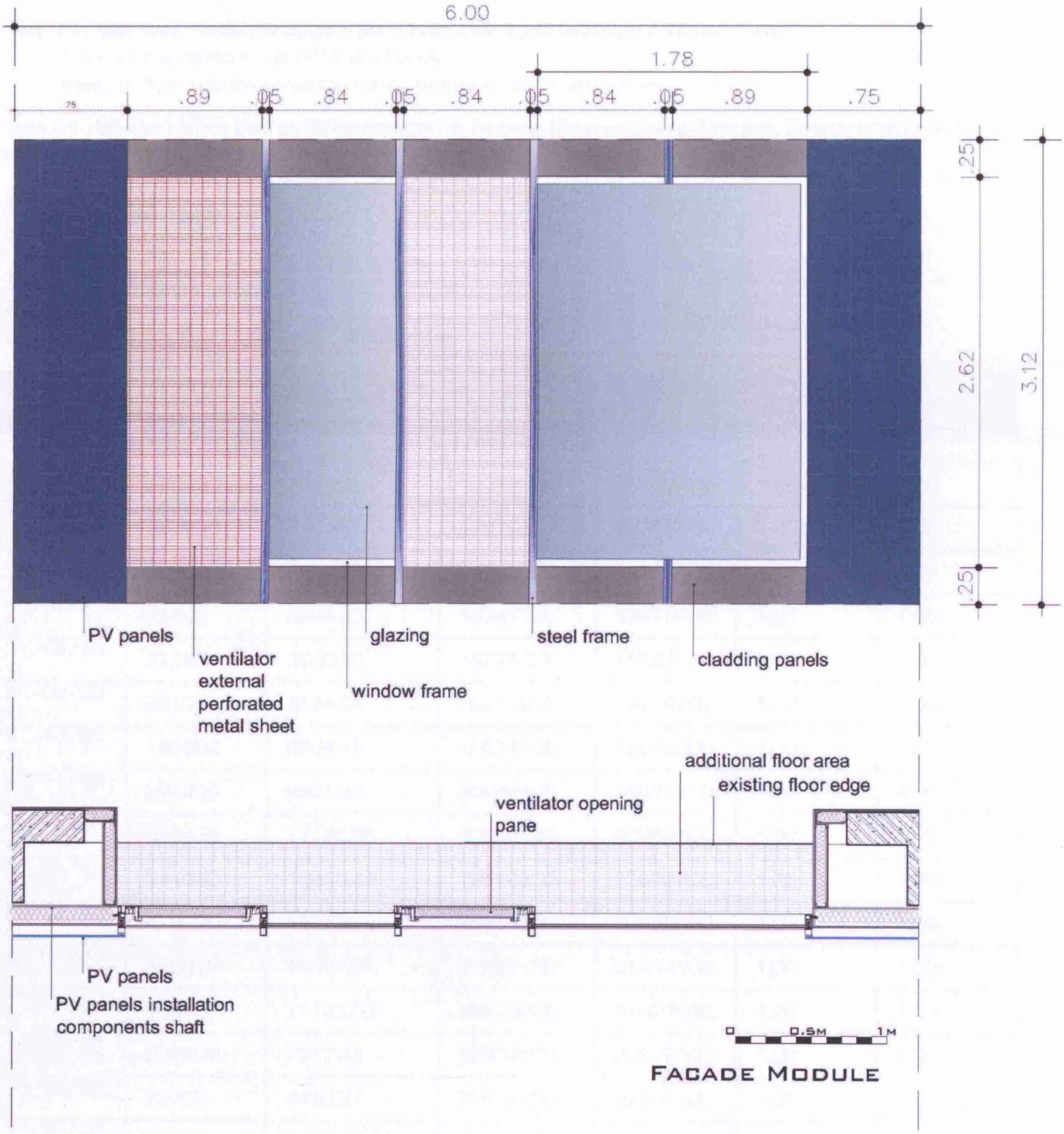


Figure B5 : New cladding module



Appendix C - Wates House Energy Consumption

Note: This heat meter measures usage in both Christopher Ingold Building and Wates House.
There is no separate meter for Wates House
Based on floor area the percentage of the total relating to Wates House is 31%

Table C1 : Wates House Energy Consumption for heating (Source: David Aderson, Energy Manager, UCL Estates & Facilities Division)

Site	Christopher Ingold Laboratories / Wates House
Code	067 / 082
Type	Heat
Number	M28
Location	Christopher Ingold Labs / Wates House

Date	Units (kWh)	Cost (£)	Meter Reading	Previous Reading	Cor Fac	Cal Val
30/04/2006	295000	7910,95	19382600	19087600	1,00	1,00
31/05/2006	237000	6464,57	19619600	19382600	1,00	1,00
30/06/2006	90400	3928,53	19710000	19619600	1,00	1,00
31/07/2006	31180	3095,93	19741180	19710000	1,00	1,00
31/08/2006	37520	3220,86	19778700	19741180	1,00	1,00
30/09/2006	35100	3134,99	19813800	19778700	1,00	1,00
31/10/2006	160900	5904,18	19974700	19813800	1,00	1,00
30/11/2006	294400	9321,30	20269100	19974700	1,00	1,00
31/12/2006	367200	11160,35	20636300	20269100	1,00	1,00
31/01/2007	344000	10630,45	20980300	20636300	1,00	1,00
28/02/2007	473800	12943,48	21454100	20980300	1,00	1,00
31/03/2007	453000	12557,61	21907100	21454100	1,00	1,00
30/04/2007	368900	11123,05	22276000	21907100	1,00	1,00
31/05/2007	228500	7977,43	22504500	22276000	1,00	1,00
30/06/2007	73700	4450,27	22578200	22504500	1,00	1,00
31/07/2007	31700	3493,65	22609900	22578200	1,00	1,00
31/08/2007	34900	3516,44	22644800	22609900	1,00	1,00
30/09/2007	28200	3374,35	22673000	22644800	1,00	1,00
31/10/2007	273300	8793,54	22946300	22673000	1,00	1,00
30/11/2007	407700	11730,20	23354000	22946300	1,00	1,00
31/12/2007	564500	15304,84	23918500	23354000	1,00	1,00
31/01/2008	588700	15922,63	24507200	23918500	1,00	1,00
29/02/20	502200	14005,44	25009400	24507200	1,00	1,00

08						
31/03/2008	558900	15455,77	25568300	25009400	1,00	1,00
30/04/2008	477100	13670,92	26045400	25568300	1,00	1,00

	Units (kWh)	Cost (£)
sum/year	3331400	105590
wates	1032734	32733,02
kWh/m2	196,3372624	6,546604

Table C 2 : Wates House Energy Consumption for heating (Source: David Aderson, Energy Manager, UCL Estates & Facilities Division)

Site	Wates House
Code	082
Type	Electricity
Number	12343726
Location	Wates House
S Number	12 0001 0036 761

Date	Units (kWh)	Cost (£)	Meter (D)	Meter (N)	kWh (Night)	kWh (Day)	kW	kVA
30/04/2006	53090	3816,53	0	0	12610	40480	136,00	150,00
31/05/2006	63912	4573,18	0	0	14108	49804	151,00	150,00
30/06/2006	59083	4228,98	0	0	13694	45389	151,00	150,00
31/07/2006	52071	3749,58	0	0	12302	39769	118,00	150,00
31/08/2006	52830	3805,13	0	0	12311	40519	114,00	150,00
30/09/2006	50325	3639,02	0	0	11614	38711	123,00	150,00
31/10/2006	59732	4313,23	0	0	12277	47455	123,00	150,00
30/11/2006	59833	4332,06	0	0	11835	47998	152,00	150,00
31/12/2006	50662	3682,37	0	0	11370	39292	159,00	150,00
31/01/2007	56497	4074,18	0	0	12328	44169	134,00	150,00
28/02/2007	57656	4158,79	0	0	12350	45306	157,00	150,00
31/03/2007	63910	4580,38	0	0	13823	50087	147,00	150,00
30/04/2007	53337	3834,82	0	0	12604	40733	147,00	150,00
31/05/2007	65719	4734,15	0	0	14269	51450	147,00	177,00
30/06/2007	56382	4082,21	0	0	12942	43440	147,00	177,00
31/07/2007	50983	3710,64	0	0	11965	39018	147,00	177,00
31/08/2007	57365	3460,68	0	0	13700	43665	119,00	150,00
30/09/2007	55620	3371,61	0	0	13243	42377	125,00	150,00
31/10/2007	64434	4017,80	0	0	13488	50946	177,00	150,00

30/11/ 2007	66536	3974,41	0	0	13405	53131	174,00	150,00
31/12/ 2007	51984	3189,03	0	0	11387	40597	162,00	150,00
31/01/ 2008	63679	3865,53	0	0	13597	50082	165,00	150,00
29/02/ 2008	65000	3936,88	0	0	14012	50988	170,00	150,00
31/03/ 2008	60123	4365,45	0	0	13408	46715	171,00	194,00
30/04/ 2008	58287	3616,15	0	0	12044	46243	152,00	194,00

	Units (kWh/year)	**Cost (£)**
sum	697980	46325
wates	216373,8	14360,61
kWh/m2	41,1357	2,872121

Table C 3 : Wates House Energy Consumption Overview and comparison to ECON 19

	heating		electricity		heating +electrycity	
	Units (kWh/m²)	**Cost (£/m²)**	**Units (kWh/m²)**	**Cost (£/m²)**	**Units (kWh/m²)**	**Cost (£/m²)**
wates house	196,34	6,55	41,14	2,87	237,47	9,42
econ19 typical	151	1,66	85	5,53	236	7,19
econ19 good practice	79	0,87	54	3,51	133	4,38

Appendix D – Simulation additional information

Table D 1 : Internal conditions estimation

Zone	Floor Area [m²]	Occupancy [10m²/person]	Activity	Total	Sensible	Latent	Sensible Gain [W/m²]	Latent Gain W/m²]
office north	148	15	Moderate office work	130	75	55	7,60135	5,57432
office south	162	16	Moderate office work	130	75	55	7,40741	5,4321
studio SW	115	11	Moderate office work	130	75	55	7,17391	6,69565
studio NE	119	12	Moderate office work	130	75	55	7,56303	5,54622
corridor	200	20	Walking/Standing	145	75	70	7,5	7
				Source: CIBSE A, p. 4-13, table 4.14				

Table D2 : Limiting U-value Standards (W/m²K). (Source: CIBSE A, p. 4-13, table 4.14)

Table 4.14 Empirical values for air infiltration rate due to air infiltration for rooms in buildings on normally-exposed sites in winter — office type 2: naturally ventilated up to 10 storeys (500–4000 m²); partial exposure

Air permeability / (m³/m²·h at 50 Pa)	Infiltration rate (ACH) for given building size / h⁻¹							
	2 storeys: 500 m² (20 m × 12.5 m × 3 m)*		2 storeys: 1000 m² (25 m × 20 m × 3 m)*		4 storeys: 2000 m² (25 m × 20 m × 3 m)*		8 storeys: 4000 m² (25 m × 20 m × 3 m)*	
	Peak	Ave	Peak	Ave	Peak	Ave	Peak	Ave
20.0 (leaky)	0.95	0.70	0.80	0.60	0.75	0.55	0.80	0.55
10.0 (Part L (2002))	0.50	0.35	0.40	0.30	0.40	0.30	0.40	0.30
7.0 (Part L (2005))	0.35	0.25	0.30	0.25	0.25	0.20	0.30	0.20
5.0	0.25	0.20	0.20	0.15	0.20	0.15	0.20	0.15
3.0	0.15	0.10	0.15	0.10	0.15	0.10	0.15	0.10
Air change rate at 50 Pa (/ h⁻¹)		5.95		5.15		3.50		2.65
ACR_{50} divisor		16.9		17.1		13.3		9.7

* (Length × width × height) for each storey

Note: tabulated values should be adjusted for local conditions of exposure

Table D3 : Limiting U-value Standards (W/m²K). (Source: Approved Document Part L2 A, 2006, p.17, table 4)

Element	(a) Area-weighted average	(b) For any individual element
Wall	0.35	0.70
Floor	0.25	0.70
Roof	0.25	0.35
Windows[1], roof windows, rooflights[2] and curtain walling	2.2	3.3
Pedestrian doors	2.2	3.0
Vehicle access and similar large doors	1.5	4.0
High usage entrance doors	6.0	6.0
Roof ventilators (inc. smoke vents)	6.0	6.0

Table D4 : Fixed Building elements in all models

Building Elements:	U-Value (W/m² C)	Thickness (mm)	Description	Materials
Upper floor/Ceiling	2,5	160	concrete internal	concret slab/ carpet
Ground Floor	0,3	300	Ground floor no false floor	carpet/Expanded polystyrene /Concrete screed /Concrete/Crushed Brick aggregate /Soil
Ceiling	0,29	275	flat concrete roof	Concrete/ expanded polystyrene/ asfalt Roofing Felt (5mm)
Internal Walls	0,82	150	plastered block internal wall	Plaster /Foamed concrete partition block/Plaster
Internal doors	1,8	50	wooden frame and pane	Pine

Table D5 : Internal Blinds hourly schedule

For value 0 the blinds are closed, for value 1 blinds are open

Hour	South windows	East windows	West windows	North windows
1	0,000	0,000	0,000	1,000
2	0,000	0,000	0,000	1,000
3	0,000	0,000	0,000	1,000
4	0,000	0,000	0,000	1,000
5	0,000	0,000	0,000	1,000
6	0,000	0,000	0,000	1,000
7	1,000	0,000	1,000	1,000
8	1,000	0,000	1,000	1,000
9	1,000	0,000	1,000	1,000
10	1,000	0,000	1,000	1,000
11	0,500	1,000	1,000	1,000
12	0,800	1,000	1,000	1,000
13	0,000	1,000	1,000	1,000
14	0,000	1,000	0,500	1,000
15	0,000	1,000	0,000	1,000
16	0,800	1,000	0,000	1,000
17	0,500	1,000	0,000	1,000
18	0,500	1,000	0,000	1,000
19	1,000	1,000	0,000	1,000
20	1,000	1,000	0,000	1,000
21	0,000	0,000	0,000	1,000
22	0,000	0,000	0,000	1,000
23	0,000	0,000	0,000	1,000
24	0,000	0,000	0,000	1,000

Table D6 : South window internal surface temperature with and without internal blinds

Hour	NO INTERNAL BLINDS officeS Surface 9 Internal Temp (deg.C)	WITH INTERNAL BLINDS officeS Surface 9 Internal Temp (deg.C)
203, 1	23,34591	24,04233
203, 2	23,37601	23,69015
203, 3	22,72046	23,27332
203, 4	22,94139	23,16629
203, 5	23,00005	23,39678
203, 6	24,11063	25,55039
203, 7	26,3371	29,15803
203, 8	28,90197	33,09464
203, 9	32,97741	39,14046
203, 10	36,44154	43,44913
203, 11	39,63256	47,98114
203, 12	40,28419	47,83517
203, 13	39,256	46,01036
203, 14	38,24196	42,43055
203, 15	37,11077	40,85958
203, 16	37,00496	40,72292
203, 17	35,815	38,68861
203, 18	34,62504	37,00526
203, 19	33,30433	35,17646
203, 20	30,77987	32,25695
203, 21	29,39489	30,01954
203, 22	28,52201	29,33454
203, 23	25,82462	27,52512
203, 24	24,88101	26,35718

Table D7 : South window surface solar gain and room internal temperature on the hottest day

Hour	officeS Surface 9 External Solar Gain (W)	officeS Dry Bulb (deg.C)	Solar Gain >800	T>25
203, 1	0	22,24735	FALSE	FALSE
203, 2	0	23,35021	FALSE	FALSE
203, 3	0	21,69056	FALSE	FALSE
203, 4	0	22,92747	FALSE	FALSE
203, 5	24,72118	22,81188	FALSE	FALSE
203, 6	241,4158	22,50808	FALSE	FALSE
203, 7	550,1763	23,46083	FALSE	FALSE
203, 8	**837,4664**	**24,69301**	TRUE	FALSE
203, 9	**1327,036**	**26,76804**	TRUE	TRUE
203, 10	1522,569	30,18432	TRUE	TRUE
203, 11	1921,247	32,0433	TRUE	TRUE
203, 12	1769,751	33,15535	TRUE	TRUE
203, 13	1449,87	32,95958	TRUE	TRUE
203, 14	955,9257	34,48671	TRUE	TRUE
203, 15	714,3674	33,88019	FALSE	TRUE
203, 16	624,6151	34,18694	FALSE	TRUE
203, 17	469,5899	33,18879	FALSE	TRUE
203, 18	350,1121	32,1548	FALSE	TRUE
203, 19	203,392	31,46015	FALSE	TRUE
203, 20	44,49813	29,05769	FALSE	TRUE
203, 21	0	28,21381	FALSE	TRUE
203, 22	0	27,03714	FALSE	TRUE
203, 23	0	23,47151	FALSE	FALSE
203, 24	0	22,72834	FALSE	FALSE

Appendix E– PV Analysis

Table E1 : Energy model for the SE facade (Source: RETScreen)

RETScreen® Energy Model - Photovoltaic Project

Training & Support

Site Conditions		Estimate		Notes/Range
Project name		Wates House		See Online Manual
Project location		London UK		
Nearest location for weather data	-	London	Complete SR&SL sheet	
Latitude of project location	°N	51,5		-90.0 to 90.0
Annual solar radiation (tilted surface)	MWh/m²	0,70		
Annual average temperature	°C	9,8		-20.0 to 30.0

System Characteristics		Estimate	Notes/Range
Application type	-	On-grid	
Grid type	-	Central-grid	
PV energy absorption rate	%	100,0%	
PV Array			
PV module type	-	poly-Si	
PV module manufacturer / model #		Sharp/ ND-L3EJE	See Product Database
Nominal PV module efficiency	%	12,4%	4.0% to 15.0%
NOCT	°C	45	40 to 55
PV temperature coefficient	% / °C	0,40%	0.10% to 0.50%
Miscellaneous PV array losses	%	5,0%	0.0% to 20.0%
Nominal PV array power	kWp	33,21	
PV array area	m²	267,8	
Power Conditioning			
Average inverter efficiency	%	90%	80% to 95%
Suggested inverter (DC to AC) capacity	kW (AC)	29,9	
Inverter capacity	kW (AC)	72,0	
Miscellaneous power conditioning losses	%	0%	0% to 10%

Site Latitude and PV Array Orientation		Estimate	Notes/Range
Nearest location for weather data		London	*See Weather Database*
Latitude of project location	°N	51,5	-90.0 to 90.0
PV array tracking mode	-	Fixed	
Slope of PV array	°	90,0	0.0 to 90.0
Azimuth of PV array	°	30,0	0.0 to 180.0

Annual Energy Production (12,00 months analysed)		Estimate	Notes/Range
Specific yield	kWh/m²	74,5	
Overall PV system efficiency	%	10,7%	
PV system capacity factor	%	6,9%	
Renewable energy collected	MWh	22,173	
Renewable energy delivered	MWh	19,956	
	kWh	19.956	
Excess RE available	MWh	0,000	

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Table E2 : Energy model for the SE facade (Source: RETScreen)

RETScreen® Energy Model - Photovoltaic Project

Training & Support

Site Conditions		Estimate	Notes/Range
Project name		Wates House	See Online Manual
Project location		London UK	
Nearest location for weather data	-	London	Complete SR&SL sheet
Latitude of project location	°N	51,5	-90.0 to 90.0
Annual solar radiation (tilted surface)	MWh/m2	0,47	
Annual average temperature	°C	9,8	-20.0 to 30.0

System Characteristics		Estimate	Notes/Range
Application type	-	On-grid	
Grid type	-	Central-grid	
PV energy absorption rate	%	100,0%	
PV Array			
PV module type	-	poly-Si	
PV module manufacturer / model #		Sharp/ ND-L3EJE	See Product Database
Nominal PV module efficiency	%	12,4%	4.0% to 15.0%
NOCT	°C	45	40 to 55
PV temperature coefficient	% / °C	0,40%	0.10% to 0.50%
Miscellaneous PV array losses	%	5,0%	0.0% to 20.0%
Nominal PV array power	kWp	11,07	
PV array area	m²	89,3	
Power Conditioning			
Average inverter efficiency	%	90%	80% to 95%
Suggested inverter (DC to AC) capacity	kW (AC)	10,0	
Inverter capacity	kW (AC)	72,0	
Miscellaneous power conditioning losses	%	0%	0% to 10%

Site Latitude and PV Array Orientation		Estimate	Notes/Range
Nearest location for weather data		London	*See Weather Database*
Latitude of project location	°N	51,5	-90.0 to 90.0
PV array tracking mode	-	Fixed	
Slope of PV array	°	90,0	0.0 to 90.0
Azimuth of PV array	°	120,0	0.0 to 180.0

Annual Energy Production (12,00 months analysed)		Estimate	Notes/Range
Specific yield	kWh/m²	49,7	
Overall PV system efficiency	%	10,7%	
PV system capacity factor	%	4,6%	
Renewable energy collected	MWh	4,931	
Renewable energy delivered	MWh	4,438	
	kWh	4.438	
Excess RE available	MWh	0,000	
			Complete Cost Analysis sheet

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Table E3 : Cost Analysis - Photovoltaic Project (Source: RETScreen)

	Type of analysis:		Pre-feasibility		Currency:	£
Initial Costs (Credits)			Unit	Quantity	Unit Cost	Amount
£Feasibility Study						
	Other - Feasibility study	Cost	1	£ 10.000	£ 10.000	
	Sub-total :				£ 10.000	2,3%
Development						
	Other - Development	Cost	1	£ 15.000	£ 15.000	
	Sub-total :				£ 15.000	3,4%
Engineering						
	Other - Engineering	Cost	1	£ 55.000	£ 55.000	
	Sub-total :				£ 55.000	12,5%
Energy Equipment						
	PV module(s)	kWp	44,28	£ 5.750	£ 254.610	
	Transportation	project	0	£ -	£ -	
	Other - Energy equipment	Cost	0	£ -	£ -	
	Credit - Energy equipment	Credit	0	£ -	£ -	
	Sub-total :				£ 254.610	47,6%
Balance of Equipment						
	Module support structure	m²	357,1	£ 100	£35.710	
	Inverter	kW AC	72,0	£ 1.000	£ 72.000	
	Other electrical equipment	kWp	33,21	£ -	£ -	
	System installation	kWp	33,21	£ 1.500	£ 49.815	
	Transportation	project	0	£ -	£ -	
	Other - Balance of equipment	Cost	0	£ -	£ -	
	Credit - Balance of equipment	Credit	0	£ -	£ -	
	Sub-total :				£ 174.130	32,6%
Miscellaneous						
	Training	p-h	6	£ 65	£ 390	
	Contingencies	%	5%	£509.130	£ 25.456	
	Sub-total :				£ 25.846	4,8%
Initial Costs - Total					**£534.586**	**100,0%**
Annual Costs (Credits)			Unit	Quantity	Unit Cost	Amount
O&M						
	Property taxes/Insurance	project	0	£ -	£ -	
	O&M labour	p-h	16	£ 55	£ 880	
	Other - O&M	Cost	0	£ -	£ -	
	Credit - O&M	Credit	0	£ -	£ -	
	Contingencies	%	0%	£ 880	£ -	
	Sub-total :				£ 880	100,0%
Annual Costs - Total					£ 880	100,0%
Periodic Costs (Credits)				Period	Unit Cost	Amount

	Inverter Repair/Replacement	Cost	12 yr	£ 50.000	£ 50.000	
				£ -	£ -	
				£ -	£ -	
	End of project life		-	£ -	£ -	

Table E4 : Greenhouse Gas (GHG) Emission Reduction Analysis (Source: RETScreen)

Background Information					
Project Information		Global Warming Potential of GHG			
Project name	Wates House	1 tonne CH_4 =	21	tonnes CO_2	(IPCC 1996)
Project location	London UK	1 tonne N_2O =	310	tonnes CO_2	(IPCC 1996)

Base Case Electricity System (Baseline)

Fuel type	Fuel mix	CO_2 emission factor	CH_4 emission factor	N_2O emission factor	Fuel conversion efficiency	T & D losses	GHG emission factor
	(%)	(kg/GJ)	(kg/GJ)	(kg/GJ)	(%)	(%)	(t_{CO2}/MWh)
*Natural gas	37,0%	56,1	0,0030	0,0010	45,0%	8,0%	0,491
*Nuclear	23,0%	0,0	0,0000	0,0000	30,0%		0,000
*Coal	34,0%	94,6	0,0020	0,0030	35,0%		0,983
*#6 oil	2,0%	77,4	0,0030	0,0020	30,0%		0,937
*Wind	2,0%	0,0	0,0000	0,0000	100,0 %		0,000
*Geothermal	1,0%	0,0	0,0000	0,0000	30,0%		0,000
*Solar	1,0%	0,0	0,0000	0,0000	100,0 %		0,000
Electricity mix	100,0 %	147,2	0,0048	0,0039			3,0%

GHG Emission Reduction Summary

	Base case GHG emission factor	Proposed case GHG emission factor	End-use annual energy delivered	Annual GHG
	[t_{CO2}/MWh]	[t_{CO2}/MWh]	(MWh)	(t_{CO2})
Electricity system	0,535	0,000	23,415	12,52

Net GHG emission reduction t_{CO2}/yr	12,52

*The Fuel mix was found in: Electricity generation: by fuel used, EU comparison, 2001 , Table 11.13
Source: Eurostat (National Statistics, http://www.statistics.gov.uk/STATBASE/ssdataset.asp?vlnk=7286)

Appendix F – Cost Analysis

Table F1 : Cost analysis for the SAP min option

		SAP min	Limiting U-values required in Part L		
Building element	area[m²]	u-values	description	cost £/ m²	cost
externam wall	6,93	0,34	coated steel insulated composited cladding panels insulation 130mm	55,00 [Anderson et al, 2002, p.36]	381,15
ventilators	4,505	0,7	Perforated metal sheet	180,00 Buck, the Colt Group	810,9
			plywood internal pane	80,00 [Anderson et al, 2002, p.64]	360,4
					1171,3
glazing	7,285	1,8	standard double glazed unit	300,00 [Anderson et al, 2002, p.54]	2185,5
TOTAL	18,72				3737,95

Table F2 : Cost analysis for the SAP max option

		SAP max	Limiting U-values required in Part L		
Building element	area[m²]	u-values	description	cost £/ m²	cost
externam wall	6,93	0,15	vacuum insulation panel	250,00 [Harvey, 2006, p.54]	1732,5
ventilators	4,505	0,42	Perforated metal sheet	180,00 Buck, the Colt Group	810,9
			insulation 50mm	6,00 Anderson et al, 2002, p.60]	27,03
			plywood internal pane	80,00 [Anderson et al, 2002, p.64]	360,4
					1198,33
glazing	7,285	1,4	double glazed unit argon filled	312,00 [Anderson et al, 2002, p.54]	2272,92
TOTAL	18,72				5203,75

Table F3 : Cost analysis for the SAP improved option

		SAP max	Limiting U-values required in Part L		
Building element	area(m²)	u-values	description	cost £/ m²	cost
externam wall	6,93	0,25	coated steel insulated composited cladding panels insulation 180mm Assuming 8 £/ m² for the increase in insulation compared with SAP min (Anderson et al, 2002, p.60)	63,00 (Harvey, 2006, p.54)	436,59
ventilators	4,505	0,42	Perforated metal sheet	180,00 Buck, the Colt Group	810,9
			insulation 50mm	6,00 Anderson et al, 2002, p.60)	27,03
			plywood internal pane	80,00 (Anderson et al, 2002, p.64)	360,4
					1198,33
glazing	7,285	1,8	standard double glazed unit	300,00 (Anderson et al, 2002, p.54)	2185,5
TOTAL	18,72				3820,42

Table F4 : Cost analysis for the Electrochromic glazing option

		SAP max	Limiting U-values required in Part L		
Building element	area(m²)	u-values	description	cost £/ m²	cost
externam wall	6,93	0,25	coated steel insulated composited cladding panels insulation 180mm Assuming 8 £/ m² for the increase in insulation compared with SAP min (Anderson et al, 2002, p.60)	63,00 (Harvey, 2006, p.54)	436,59
ventilators	4,505	0,42	Perforated metal sheet	180,00 Buck, the Colt Group	810,9
			insulation 50mm	6,00 Anderson et al, 2002, p.60)	27,03
			plywood internal pane	80,00 (Anderson et al, 2002, p.64)	360,4
					1198,33
glazing	7,285	1,8	double glazed unit with electrochromic glazing	500,00 (Sanders H.)	3642,5
TOTAL	18,72				5277,42

Appendix G– Options overview

Table G1 : Overview of energy, cost and payback period for the re-cladding options

Group	Options	primary heating loads kWh/m²	primary heating loads kWh for the whole building *1	energy offset	cost offset (£)* 2	reclad module cost (£)	overall recladding cost (£) *3	Payback time (yr)
SAP model	Part L U-values	13,36	70283,49	913553,44	30147,26	6728	807397	26,78
SAP model	max U-values	5,21	27434,72	956402,21	31561,27	9367	1124010	35,61
SAP model	improved U-values	7,82	41131,32	942705,61	31109,29	6877	825210	26,53
Solar Shading	internal blinds	12,56	66085,09	917751,84	30285,81	7314	877662	28,98
Solar Shading	overhang50	10,17	53511,73	930325,19	30700,73	7539	904710	29,47
Solar Shading	horizontal louvres	8,58	45133,13	938703,80	30977,23	9427	1131180	36,52
Solar Shading	vertival louvres	8,24	43363,67	940473,26	31035,62	9645	1157406	37,29
Solar Shading	movable vertival louvres	7,82	41165,84	942671,09	31108,15	10155	1218600	39,17
electrochromic	Electrochr800	10,49	55198,38	928638,55	30645,07	9499	1139922	37,20
electrochromic	Electrochr-Gradual	8,47	44547,61	939289,32	30996,55	9499	1139922,72	36,78
electrochromic	Electrochr-Seasonal	7,90	41592,89	942244,04	31094,05	9499	1139922,72	36,66

*1.Area of the building is 5262m²

*2.According to current figures from energy consumption and cost (UCL Estates & Facilities Division) the price of heating unit is 3p/kWh

*3. module number for the whole facade is 120.