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Smart facades for existing, non-residential buildings

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SCHOOL OF SCIENCE & TECHNOLOGY

A thesis submitted for the degree of

Master of Science (MSc) in Energy Systems

NOVEMBER 2014

THESSALONIKI – GREECE

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Abstract

This dissertation was written as a part of the MSc in Energy Systems at the International Hellenic University. The aim of this paper is to assess the facade building technologies from the available literature, in order to investigate the possibility of designing a retrofit smart facade system, to be installed on existing buildings, with the ability of achieving "near zero energy building" status for any building it is installed upon. The assessment should focus on literature involving "smart" facade retrofits for energy performance upgrades on existing buildings and the benefits and challenges therein. It should also investigate the available technologies that can increase energy performance efficiency, taking into consideration advanced materials, hybrid system technologies, hi-end glazing as well as enhanced cooling technologies and other smart systems that can be mounted onto facades. There is a great amount of complexity in the field of modern building facade technologies and although they have been increasingly used by architects over the past few decades there are still many hurdles that have to be overcome in being able to fully predict their performance.

The knowledge acquired from the literature review will assist in the design of a prefabricated facade module to be used as a possible retrofit for implementation on existing office buildings. The scope of this retrofit scheme is the reduction of greenhouse gas emissions produced by building use, in correlation with environmental goals of many countries worldwide and the European Union. There are many design challenges in achieving this goal, including the difficulties of passive design in the hot Mediterranean climate and the increased difficulty of designing a retrofit facade with the ability to be compatible with multiple buildings of different shapes and sizes.

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1 Introduction

1.1 Buildings and environment

Over the past years there has been increasing interest in the connection buildings have with climate change. It is a known fact that buildings are responsible for a large part of global greenhouse gas emissions [1]. The energy performance of buildings has been a topic of increasing interest and has produced an abundance of articles on the matter. Since the signing of the Kyoto Protocol, the known connection of the energy consumption in buildings with their contribution to global warming has led many countries in the world to take some form of legislative action to mitigate the effect.

In 2002, in order to comply with the Kyoto Protocol and the United Nations Framework Convention on Climate Change (UNFCCC) the European parliament issued Directive 91/EC on the energy performance of buildings which was recast in 2010 by Directive 31/EU. The amended Energy Performance of Buildings Directive (EPBD) [2] sets new energy performance requirements for new buildings and provides guidelines for the refurbishments of existing buildings. All public authority buildings are to be nearly zero energy by 2019 and all new buildings by 2021. This means that a building's specific energy consumption at a "per square meter per year" value, should be "close" to zero.

With this directive a new generation of building construction is expected to become widespread across all EU countries. This construction trend is bound to affect all existing buildings as well, since the European Directive asserts that member states are to include measures and targets for near zero energy to stimulate higher refurbishment rates of existing buildings when the Directive is integrated into national law. If the global pursuit to reduce greenhouse gas emissions is to continue beyond 2020, a near zero energy level of performance is to be expected of all buildings in the near future. In this sense any new laws that will come into effect will enforce the renovation of existing buildings to fit the energy criteria needed in order to reach the intended climate change mitigation goal.

At a first degree, this will create a need for renovations of all of the existing public buildings in use, or at least those buildings that would have to be renovated in order to hold public functions. It would therefore be practical if there was a better understanding of the current building technologies available and a guideline as to how these renovations could be undertaken in order to reach the expected environmental goal.

One such approach would be the renovation of facades and the retrofitting of modern energy saving technologies on the existing buildings without interfering with the building interior. The construction industry has evolved during the last decades, and energy savings have become an important factor in building design. New technologies have emerged, with adaptability and automation finding a way to infiltrate traditional architectural building elements such as windows, walls and passive solar systems. There is a great interest in many forms of "smart" building technologies. Smart facade technologies are producing increasing interest as new integrated hybrid systems for dynamic control of solar radiation, shading, ventilation and energy production are evolving continuously. In this thesis we will investigate whether a near zero energy level of performance is achievable, by retrofitting existing buildings with smart facade technologies.

1.2 Dissertation goal

The question we investigate in this dissertation is whether there is a functional way to design a facade retrofit on an existing office building that would render the building's total energy consumption as that of a near zero energy building.

Building envelopes should no longer be considered as a means to shelter inhabitants from the elements, but be regarded as the simplest and most straightforward solar energy conversion devices that can be integrated into a building [3]. In this sense a retrofit procedure should not only pursue an upgrade in building insulation, but methods of harnessing heat from solar radiation with passive energy systems, protecting the building envelope from the sun during hot summer periods and generating energy directly through photovoltaic or other technologies.

One of the most substantial problems with solar radiation in building envelopes is the fact that it is beneficial in winter and detrimental in summer, especially in climates with large temperature discrepancies over the year as found in the Mediterranean. An ideal envelope would enable major solar energy utilization during winter and total solar gain avoidance during summer. That is why smart facades are advantageous. Adaptability to climatic conditions and regulation of solar radiation infiltration is one of the main objectives of "climate" or "smart" facades. By adapting to climate conditions, smart facades are able to enhance energy performance in buildings, lowering annual energy demand. In the next chapter we will review studies made on current technologies available for creating "smart" facade systems.

It is clear from what was analyzed in the previous section that the reduction of energy to practically zero in new buildings would not be enough on its own to reach the EU reduction target so measures have to be taken to increase the energy performance of existing buildings to sufficient standards. It is vital that Member States are able to cut-back on the energy consumption of their built environment and the only way that an overall positive impact can be achieved is if all buildings share a portion of the reduction. This initiative would need to be well planned and executed in orderly steps. It would need to be quick and repeatable in a "prefabricated" way. It would be useful if a differentiation in strategy between building types was followed, dividing buildings into groups depending on their usage. The design would have to take into consideration the available building types and investigate the methods available for a refurbishment. We examine whether a retrofit prefabricated facade could be designed to accommodate the energy needs of existing office buildings and make them of a higher energy standard.

One would argue that if energy conservation is such an important issue that it dwarfs any other concerns, such as financial or environmental, reconstruction of energy intensive buildings is a viable alternative. A *new* building, be it by form of complete renovation or by demolishing and rebuilding, would give the builder the option for advanced energy saving techniques, as well as cover the conditions set by energy law to the fullest. Most of the energy intensive buildings are old, nearing the end of their 60-year projected lifetime. Rebuilding would seem a beneficial choice, since apart from the new construction, modern building laws would enable a larger built area increasing property value [4]. It could also help reinvigorate the building construction industry.

Since the EPBD, an individual study would evaluate rebuilding as more beneficial, even regarding life cycle analysis for new materials and energy expenditure of reconstruction for many such examples. However, there will still be many building candidates where such an analysis would rule out reconstruction. It is these cases that a milder method of refurbishment, such as the one we are investigating, would be more appropriate.

1.3 Thesis structure

The goal of this dissertation is to assess the state of the art technologies for the refurbishment of facades in existing non-residential buildings, towards the nearly Zero Energy Building (ZEB) goal and to develop a methodological approach for the selection of appropriate, effective building elements. The type of non-residential building we will be investigating is the office building. And especially office buildings with "curtain-wall" facades of the late 60's to early 80's.

In the following chapters we will review the literature on smart facade technologies analyzing the characteristics and the proven energy savings calculated experimentally or via simulation. We will then evaluate these technologies on whether we believe they are suitable for upgrading the energy performance of existing office buildings. Moving to the next chapter we will examine what constitutes a near Zero Energy Building, and how office buildings fall into this category.

The fourth chapter deals with a proposal for a design of a composite retrofit facade module that will consist of different smart facade systems chosen from the literature as the most appropriate. In the next chapter, the results on energy performance of installing elements of this module on an existing building, are tested in a simplified simulation done with the Ecotect building simulation software. A cost benefit analysis as well as calculations on resulting energy savings and avoided CO_2 emissions are also performed.

We then analyze challenges that are expected to appear in implementation of this energy savings retrofit module, as well as some added benefits its use will have on buildings and occupants. Lastly we conclude in the final chapter with conclusions on our findings and propose further study on the matter.

Abbreviations

DSF	Double Skin Facades	AHU	Air Heating Unit
DGF	Double Glazed Facades	EU	European Union
DGU	Double Glazing Unit	CFD	Computational Fluid Dynamics
SHGC	Solar Heat Gain Coefficient	WWR	Window to Wall Ratio
CABS	Climate Adaptive Building Shells	PCM	Phase Change Materials
EC	Electrochromic	Low-e	Low Emissivity
HVAC	Heating, Ventilation and Air Conditioning		

2 Literary Review

In this chapter we gather information on the available smart technologies that could be used in a facade retrofit and comment on whether that can be considered as appropriate for our energy performance goal.

2.1 What we are looking for

Our goal is to search the literature for current technologies that are available for use in facade retrofits and are specifically targeted to upgrade energy performance. This will give us a scope of the currently available innovations in the field of energy upgrades, so that an assessment of the limits and possibilities of our design can be made.

When we talk about "smart building facades" we are usually referring to different types of climate adaptive technologies that incorporate an adaptive technology or system which can have a limited control on energy flows through the building shell. These include the different types of double skin facades, that can be integrated into the HVAC system of a building and are named Advanced Integrated Facades [5], mechanically or naturally ventilated double skin facades [6], non ventilated passive facade systems [M 13], building integrated photovoltaics for direct production of electricity [8] or thermal energy collectors [9], as well as different integrated advanced materials for energy storage and cooling, like PCMs [10], solar irradiance blocking technologies through tinting of glass like electrochromic windows [11], selective solar irradiance blocking mechanisms such as infrared radiation reflecting low-e coatings [12] or switchable liquid technologies [13].

2.2 Review

In order to achieve a general understanding of the specific challenges, and the technologies available to overcome them, when designing a multi-purpose facade system, literature on many different aspects of facade design and technologies available had to be reviewed.

Double skin Facades

DSFs are building envelopes comprising two glazed surfaces enclosing a ventilated air cavity with solar control devices within. The cavity has the combined properties of acting as a thermal buffer by reducing undesired heat during summer, providing thermal comfort due to asymmetric thermal radiation and protecting from heat loss during winter. Double skin facades also provide visual comfort by reducing glare and can maximize daylighting through the use of solar control devices. [6]

In their 2011 paper Jiru, Tao and Haghighat [6] studied the airflow and heat transfer in double skin facades. They conducted a set of simulations using computer fluid dynamics (CFD) for 3 different positions and 3 different blind angles of the venetian blinds system situated inside the DSF air cavity. Their findings were validated using experimental data collected from a mechanically ventilated double skin facade with venetian blinds.

The results showed that the presence of venetian blinds in the DSF influence the surface heat transfer coefficient as well as the temperature and the distribution of air in the DSF. In addition, positioning of the shading system inside the facade (distance from the boundary layer) is more important than the rotation angle of the blinds. The optimal position for the venetian blinds during winter was on the internal boundary, as it reduces heat transfer from indoors. However this can create thermal discomfort and increased cooling loads during summer. The lower temperature on the inner glass layer for middle positioning of the shading system along the air cavity width suggests that it is a favorable position for the cooling period.

During the research phase of this dissertation, a number of scientific papers were found on reviews of published emerging technologies in the field of facade "smart" design. One of these was by Quesada et al. [5] who conducted a survey in 2012 on studies carried out over the past decade on non opaque facade technologies.

The survey separates the reviewed technologies into passive, for non ventilated facades, and active, for mechanically ventilated and PV integrated facades. Ventilated facades have gained remarkable architectural recognition as elements of office building design. Apart from the aesthetic factor these facades protect the building from intensive weather phenomena, noise and reduce heat demand during winter and cooling loads during summer. Special attention is devoted to studying shading devices inside the ventilation cavity with the aim of solar gain reduction.

Semi-transparent building-integrated photovoltaic systems (BIPV) provide the added benefit of electricity generation apart from daylight and heat. Researchers however tend to neglect the techno-economical feasibility of the reviewed technologies. For most cases the performance is deducted from numerical predictions and efficiency is decided by a simple payback period.

In a 2014 paper Goia et al. [14] investigated the performance of two Advanced Integrated Facade designs by monitoring the performance of two scale models, one for each AIF, for a year. The experiment took place in Torino, Italy and was executed by taking measurements from sensors installed on a mockup of the test facade modules integrated on a real scale office room. As advanced integrated facades we define "smart" facade systems that are integrated into the buildings HVAC in some way. The AIFs in this example are climate facades meaning that they are double skin facades that regulate the interior air by extracting it through mechanical ventilation and flowing it through the air gap inside the double skin facade for ventilation purposes.

The design of these facades is the same in both modules and comprises an exterior shell of a selective laminated double glazed pane with 20mm total thickness, an air cavity of 16mm, a clear glass pane of 10mm, a mechanically ventilated air cavity of 240mm inside which is a retractable reflective roller screen and a final glass pane that separates the facade from the interior. The only difference between the two facades is in the final glass pane where module A has a single laminated clear glass and module B has a double glazed unit with low-e glass. This affects the transmitted energy of module B as well as its insulation properties, as expressed in the U-value, compared to module A. The calculated U-value for module A was 0.62 W/m^{2}K and 0.33 W/m^{2}K for module B. Cross sections of both facade modules design is illustrated in Figure 1 below.

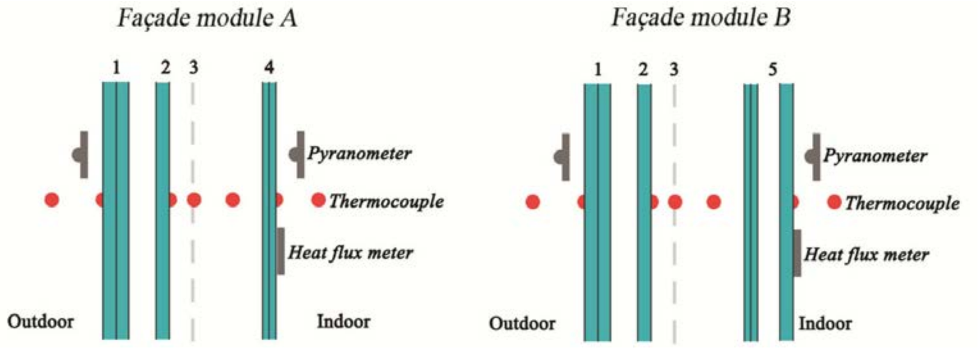

Figure 1: Cross section detail (not to scale) of both modules internal structure showing extra low-e glass layer in module B. [14]

Both modules are equipped with a reflective screen which can be rolled up to allow for the unobstructed solar radiation to penetrate the facade, or rolled down to minimize the amount of solar radiation transmittance, as well as reducing interior heat from escaping through the facade as infrared radiation during winter.

The year long measurements showed that module A had higher solar and light transmittance for summer and winter compared to module B. This was true in both shading instances, with the screen rolled up and down. The same result was observed for total energy transmittance throughout the year. For all seasons and shading instances the energy transmitted through module B is always lower than module A. The difference between the mean 24 hour energy transmittance of each module for each season was between 29% and 33% with a maximum measured difference of 41% during winter with the screen rolled down, because of the reduced solar gains.

Fallahi et al. [15] studied the integration of passive thermal mass in a DSF in order to decrease the risk of overheating during summer. It was witnessed that this contributes further to overall energy efficiency for both heating and cooling periods.

A building modeling simulation was run comparing a conventional DSF model with aluminum venetian blinds to a proposed DSF with thermal mass, in three different configurations. The simulation was run for mechanical and natural ventilation scenarios. For validation of the ventilation scenarios, measurements on existing DSFs were enacted for comparison and appeared to be in general agreement with the simulated results.

The calculations showed considerable reduction in energy loads in the thermal mass DSF, when mechanical ventilation was used instead of blinds, for both thermal periods. Energy savings were measured at 21% to 26% in summer and 41% to 59% in winter compared to conventional DSFs. Naturally ventilated DSFs with thermal mass were not found to be efficient.

In a 2013 paper Radhi, Sharples and Fikiry [16] studied the potential reduction of cooling loads in a fully glazed UAE building by use of multi skin facades. A comparison of climate interactive facade systems (CRFS) to classical single facade systems (CSFS) was made by simulation in a CFD program. The case studied was a three storey building housing the Architectural Engineering Department in UAE university in Al-Ain. The interactive facade was designed as a double skin facade with an air cavity of 1,2 m between building facade and exterior glazed layer, 3,4 m floor height and a 0,6 m opening on the glazed exterior at the start of every floor. Grills parted the CRFS between floors. The CFD model calculated natural airflow in the double skin through buoyancy and the effects of wind pressure on the facade exterior on airflow.

It was concluded that on a typical summer day, energy savings between 17% and 20% could be achieved on reduced cooling load demand. Further conclusions could be drawn from the CFD results including: the exploitation of optical properties, particularly SHGC, is the most effective way to reduce cooling loads; heat transfer rate decreases as the cavity depth is reduced while beam radiation received by the surface grows, optimal cavity size being between 0,7 and 1,2 meters; size and position of external layer openings have critical implication on the performance of the CRFS; heat transfer increases at higher levels because the airflow gets warmer as it rises; CRFS performance is subject to the level of irradiance received which is affected by incidence angle, making east and west orientations a better energy savings scenario.

H. Manz has released a number of papers on airflow and energy transmittance through Double Skin Facades in collaboration with others or on his own [17][18][19]. The goal of these studies was to investigate the calculation of expected thermal comfort during summer and solar energy transmittance for different ventilation modes using computer simulation software. A comparison of two types of mechanically ventilated Glass Double Facades was attempted by Manz et al. using CFD modeling. Facade A had a bottom supply of air while Facade B had a top supply. Both models consisted of a double glazed external module with low-e coating and argon filled cavity, an 18 cm air cavity with screen shading and a secondary low-e glass pane. The simulation calculated the complex fluid dynamics and energy flows that occur inside the double skin facade and produced the following results: Facade type A is superior to Facade type B in terms of thermal comfort during summer achieving a total solar energy transmittance of $g_A = 0.07$ compared to $g_B = 0.15$; Changing airflow orientation has a substantial impact on solar energy gain; Further decrease in solar energy transmission could have been achieved with external glazing of higher reflectivity. The validity of these results was tested in an outdoor facility for facade elements. He later proved that a cohesive thermal CFD model could be produced by the coupling of three different types of simulation models with a high level of accuracy.

Hashemi et al. [20] monitored an existing multi-storey building with a poorly ventilated double skin facade in Tehran, Iran during summer and winter in order to observe the DSF's behavior. The measurements showed an increase of 1°C to 10°C in the air cavity temperature compared to outside air temperature during summer. However, the western facade had a temperature difference of up to 12°C less than outside ambient temperature during the warmest part of the day due to shading from the dividing plates of the facade. During winter, internal air temperature for the double skin facade air cavity was 5°C to 12°C higher than the outside, depending on the floor. This had a positive effect on energy demand. The paper concludes that introduction of a shading system and night ventilation are necessary to increase summer performance. A calculation of optimal facade width to maintain proper ventilation could also reverse the negative effects of insufficient ventilation during summer.

Automation

To answer the question on what effect control systems have on smart facade efficiency and user satisfaction, we conducted a small research on the available literature for automation and control systems in facades and building elements.

A survey was executed by Shaikh et al. [21] on optimized "smart" building systems for energy and comfort management to evaluate the various control systems used and occupant satisfaction. The survey was mainly focused on control systems implemented in residential buildings and hotels.

There appears to be an increasing global interest in automated control systems for smart building energy efficiency and indoor environmental comfort. Many new control techniques have arisen and are being employed in control system frameworks. The implementation of intelligent systems can save a significant amount of energy which in turn leads to a reduction in CO_2 emissions. Furthermore, the sensor data collected facilitates the increased "know how" for enhanced performance in future buildings. The growing complexity however is a large challenge that will have to be faced in the future.

In their 2013 paper on local versus integrated control strategies for double skin systems, Park and Augenbroe [22] investigated if occupant responsive control of intelligent double skin facades was preferable to autonomous control for real-time performance of several facade features including energy, visual comfort and thermal comfort. The research treated the double skin facade as an isolated system but also extended the problem of local control of the facade to an integrated control problem which included the interior environment and the facade simultaneously. It was concluded that autonomous integrated control is preferable although only on a moderate scale.

The authors believe that further study is necessary on a whole building level of integration in order to test the effect of autonomous control as many features of the intelligent facade functions may impede on proper HVAC operation when both come into play. The lack of connection of the two autonomous control systems could lead to a decalibration of the HVAC system. For this reason a study on the techno-economical feasibility of building-scale control systems in collaboration with optimal configurations for double skin facade control is needed in this on-going research.

In a previous paper from 2004 by Park et al. [23] the authors test if fully integrated real-time optimization of a smart facade system performance through evaluation of weather data and user preference is possible. The system features dynamic reaction to environmental data input as well as web based user interaction for the optimization of energy, visual comfort and thermal comfort by means of motorized rotating louver slats that effect changes to the degree of shading and to the opening and closing of ventilation dampers at the top and bottom of the smart facade window.

The software model designed to control the optimization system turned out to be very successful in evaluating user and weather data input through laborious experiments. The model results were deemed accurate in predicting the most relevant state variables to achieve the required energy performance and visual and thermal comfort. The paper concludes that smart facade systems of this type are more advantageous in terms of achieving these goals.

As seen before, automated operation of dynamic facades is a proven method of reducing energy consumption in buildings while maintaining indoor environmental quality at a high standard. It is considered controversial however due to concerns for risk of occupant distraction and discomfort. To test this Bakker et al. [24] undertook an experiment in a real work environment with a group of test subjects. The results showed that when users were given the ability to manually override the automated facade control, they were satisfied with the end results on the most part as the inability to intervene was their greatest source of discomfort.

PV integrated smart facades

The integration of photovoltaics into facade systems provides the opportunity for a distinctive, visual character as well as contributing electricity to the building needs [25]. In his paper Pearsall gives an overview of current implementation of building integrated photovoltaics (BIPV) and estimates the future developments of this technology in buildings. He makes a brief case study of three different examples.

PV panels are usually integrated onto building roofs or building facades. For a maximum annual electricity generation, the roof system is favorable. However, facade integrated PV panels have their use on commercial buildings and for moderate or high latitude locations. The different design choices are a trade-off between factors of cost, electrical performance and compatibility with design and appearance. There are also the constraints of being overshadowed by nearby existing buildings and structural load issues.

There is an increased difficulty in integrating PV facades on existing buildings compared to new buildings as the PV functions may not be able to make use of their full range of building functions contribution like shading, ventilation, pre-heating of air for HVAC, passive solar gain reduction and glare control.

There are ways to make the BIPV more effective by having the PV facade serve several goals. This can include performing some protective function on the building envelope like shading, using the expelled heat by PV modules for assisted ventilation and added insulation. All these functions can offset the cost of integration. In commercial buildings PV facades can function as privately sponsored demonstration projects. The distinctiveness of an office building with a PV facade, especially one with a successfully integrated design, bestows the building with a certain prestige, a unique identity that, on top of the environmental and economic aspects, many tenants would be willing to pay a higher rent for.

The behavior of a full-scale prototype photovoltaic double skin facade was monitored by Gaillard et al. [8] under real conditions over the course of a year. The facade is characterized by an unconventional zigzag shape when viewed from above to account for its non-optimal westerly orientation. There was limited availability of primary thermal, optical and electrical data concerning building components, occupants and outdoor conditions. The objective was to test the assumption that simplified double-skin component behavior can be generalized to real multifunctional systems and to set up an analysis technique for this concept.

The system's performance was characterized as encouraging, despite the poor orientation, compared to building consumption. The system was found to behave in a predictable manner and could be fully described by simple system-environment relations.

Chow, He and Ji, [26] investigate the performance of a hybrid photovoltaic - water heating system (PV-T) for building integration in Hong Kong. The application of a hybrid system in buildings has the advantage of increasing the energy output per installed unit area. This wall mounted system serves as a photovoltaic collector panel that is cooled by a circulating water system. The heat absorbed by the water is used to pre-heat the domestic hot water system. It was found that natural circulation is preferable to mechanical circulation for the specific system. Thermal efficiency was measured at 38.9% and the electricity conversion efficiency was 8.56%. The space thermal loads were reduced in summer and winter, which led to substantial energy savings.

According to current literature review by the authors, crystalline silicon solar cell efficiency drops by about 0.0045%/°C of operating temperature rise. Most of the solar energy striking a PV panel is basically converted into heat. This waste heat can be recovered and utilized. In doing so, the reduction in electrical efficiency is prevented. An additional bonus to the heat removal is the prevention of heat accumulation after prolonged PV operation, which may lead to structural damage of the panels when they are not well vented or the heat is not recovered.

A solution to both of these problems is the introduction of a fluid coolant which can simultaneously be used to recover the solar thermal energy. The experiment conducted showed that through the use of electricity-and-heat co-generation, the overall output was higher for a given solar collector area than the outputs of two commercial photovoltaic and solar thermal collector units would have been, had they been placed side-by-side.

An experiment was conducted at the university of Hong Kong to test the liquid cooled building integrated photovoltaic system, by creating a test chamber and measuring its performance. The dimensions of the environmental test chamber were 7.3 m (L) · 4.0 m (W) · 3.7 m (H). The PVT module was installed on the south-west wall of the test chamber. Based on the experimental measurements during the late summer period in Hong Kong, the thermal efficiency found by statistical analysis was 38.9% at zero reduced temperature, and the corresponding average electricity conversion efficiency 8.56%.

Apart from these efficiencies, good thermal insulation performance during both summer and winter periods was observed, for the wall with the PVT system. Space cooling loads were reduced by up to 50% during the peak summer heat. There was no difference in collector performance between natural and mechanical circulation during summer. The thermal efficiency could have been higher had the volume of the water storage tank been larger. There were some discrepancies in the projected benefit mainly caused by shadows cast by neighboring buildings in the morning and afternoon, mostly during winter. The temperature diagrams for three consecutive days during summer and winter are shown in Figure 2 below.

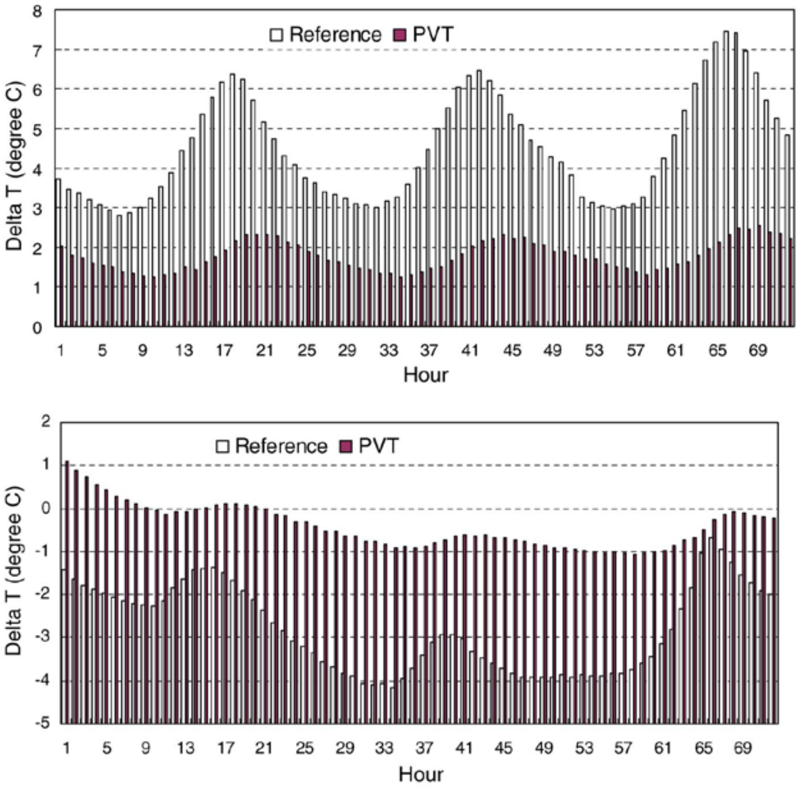

Figure 2: The graphs illustrate the variation of inside surface temperature of the wall behind the PVT in the test room and the reference room, as compared to the controlled (at 22°C) room temperature for three consecutive days. The top graph depicts 17-19 July (Summer), and the bottom 5-7 December (Winter). This proves the insulation improvement, as interior temperatures are lower in summer and higher in winter. [26]

The energy performance of a PVT collector array incorporated on a vertical wall is lower than a stand-alone single unit array positioned at the optimal tilt angle on the roof. This is mainly due to the higher incident angles of the incoming solar beam radiation most of the time and the higher flow resistance because of the lengthy and indirect interconnecting pipe work.

The PVT water cooled wall mounted system seems to have the best overall efficiency for a hybrid technology. However, it may not find use in a building that does not require domestic hot water, like an office building. It could work in the winter if there is a water distributed central heating system nonetheless. Its implementation in a large scale multi-storey facade may prove inefficient as well, due to the pull of gravity.

Peng, Lu and Yang, in their 2013 paper [9] investigate the performance of a novel double skin facade with integrated photovoltaic on an experimental building module. The experiments were tested with different methods of ventilation in Hong Kong, in order to identify the ideal operating configuration for that climate. They calculated the facade module's solar heat gain coefficient (SHGC) and U-values for the different modes of operation in order to evaluate the test results. After testing four different modes of operation they concluded that the ventilated mode produces the most favorable performance for the PV-DSF regarding SHGC. It was further concluded that even the non ventilated mode of this PV-DSF configuration, when compared to a tinted glass DSF with low-e coating, can still reduce the SHGC by up to 40%.

The authors attribute around 60% of electricity consumption in Hong Kong to buildings. Of this energy, 50% was for air-conditioning alone. The authors contend that curtain wall facades are the main cause of this increased consumption. According to the literature reviewed by the authors, clear glazed ventilated double skin facades can substantially reduce a building's solar heat gain. This is equal to a 26% cooling load reduction for Hong Kong, compared to a single-glazed curtain wall. This 26% gain is also true for reflective versus absorptive glazing double skin facades. Although a non-ventilated DSF is suitable for the winter period, since it reduces heat losses, ventilated double skin facades are more suitable for subtropical climates since the airflow reduces building cooling loads.

The integration of photovoltaic glazing on a ventilated double skin facade, such as the one mentioned above would further reduce energy needs for cooling, due to the partial absorption of solar energy and conversion to electricity, but also generate energy for the building. Due to this appealing characteristic of transparent PV double skin facades, a lot of research has been done in this field. Simulations on the Energy Plus building energy simulation software showed that a transparent amorphous silicon PV cell mounted inside a double glazed window and mounted on a building facade with a window to wall ratio (WWR) of 50% reduced total energy, including cooling heating and lighting, by 23% compared to a single glazed window and 16,4% compared to a double glazed window. Other research results showed that PV laminated glazing presented the best SHGC compared to clear and low-e glazing. However, low-e glass has a lower U-value that PV laminated glass because of its lower heat, in the form of infrared radiation and emissivity properties.

Sabry et al. [27] test the performance of a novel multi-paned smart window configuration incorporating water cooled solar cells with two axis tracking, using CFD modeling. They examine a new concept for smart windows, that aims at solving the problems of visual comfort and excessive heating caused by unobstructed solar radiation in conventional windows by using the solar energy instead of blocking it. This is accomplished by incorporating water cooled concentrator - PV cell units inside the double glazing window gap. Fresnel lens concentrators are used for solar ray concentration. A conceptual diagram of the smart window design is illustrated in Figure 3 below.

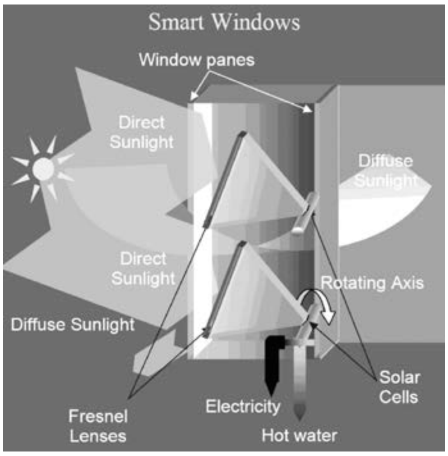

Figure 3: A conceptual arrangement of a the smart window illustrating its operation. [27]

The technical innovation of this design lies in the fact that Quantum Well square solar cells were used with an area of $16mm^2$ each. These cells are characterized by their ability to achieve up to 32% efficiency under a concentration ratio of 500, that can rise to over 34% when the ratio reaches 1000. The goal of the smart window design is to focus all incoming direct solar radiation onto the PV cells and allow for the passage of diffuse radiation to light the interior. This is to be accomplished by use of the appropriate Fresnel lens with properties tailored to achieving this goal. These windows will have several benefits including: electricity generation, reduction in cooling loads, visual comfort brought on by diffuse radiation and domestic hot water production.

Simulations were run with different configurations of the system variables in order to optimize the design for maximum performance. The CFD model results were promising but further testing with real scale prototypes to validate the simulation results is still pending.

On the negative side, Fresnel lenses blur visibility. This device would be very useful for buildings where natural lighting is vital, but visibility unnecessary. The presence of domestic hot water production is beneficial but most office buildings would have little use for it, not to mention the added complexity of handling a water pipe grid.

Zogou and Stapountzis [28] studied the integration of PV modules on the south facade of an office building in Athens, Greece. The calculations were carried out with TRNSYS building energy simulation software. An air cavity was used between the PV modules and the existing facade for air circulation. This functions to cool the modules, increasing efficiency, but can also be exploited by the buildings HVAC system. Optimal sizing of the PV panels and the duct design regulates economic viability of the system. Flowrate in the airduct is also critical to PV facade performance. A fair degree of adapting the design to different climatic conditions and building orientation is necessary.

The authors contend that since contemporary building construction implements expensive (1000 €/m^2) materials for facade design and construction, the integration of PVs on building facades can be utilized. However, results show that the proposed double skin PV facade can produce a significant contribution only if building energy demand is minimized by means of adequate energy upgrades. Only energy efficient buildings can profit from the proposed PV facade concept.

Kamthania and Tiwari [29] conducted a comparative study to distinguish the optimal connection combination for an array of semi-transparent double pass hybrid PV-T modules. Three different combinations of connection: in series, in parallel and combined, were calculated mathematically, using a matlab based computer program, for a twelve module PV-T array in Srinagar, India. The results showed that the parallel connection had the highest annual energy gain for both electrical energy generation and thermal energy production with values of 1291,26 kWh for electricity and 8013,44 kWh for heat.

The authors continued their investigation to find the optimal semi-transparent silicon and non-silicon based PV technologies, in terms of energy metrics, for the parallel connection configuration. The energy metrics investigated consist of the payback time for produced energy, the factor of electricity production and the life cycle conversion efficiency. The results showed that the maximum carbon dioxide emissions mitigation as well as energy metrics were achieved using the Heterojunction with Intrinsic Thin layer PV technology.

Facades that implement Smart Materials

As defined by Deb et al. "*A smart material, by its very definition, implies that it has the ability to sense or respond to an external stimulus in a predetermined and controllable manner.*" [30] We searched the available literature to find material technologies that would be suitable for our design.

Hi-End Glazing Technologies

In their 2012 paper Yasar and Kalfa [14] investigate the contribution to a building's energy consumption of 8 different types of glazing technologies by comparing their performance as windows in two types of apartment buildings in Turkey. Their study is based on numerical results from a simulation model and previous literature.

The 8 glazing types tested are listed in Table 1 below along with their thermal properties. The table lists the glazing types tested along with the abbreviations used for each one and a number of thermal properties: the heat transfer coefficient (U-Value), the solar heat gain coefficient (SHGC), the solar radiation transmittance (Tsol) and the visible light transmittance (Tvis). [14]

Table 1: glazing types tested

	Glass type	DGU	U (W/m^2K)	SHGC	T_{sol}	T_{vis}
S1	Clear glass	CLR	2,7	0,70	0,60	0,78
S2	Low-e glass (pyrolytic coated)	LECLR3	1,9	0,66	0,53	0,72
S3	Low-e glass (soft coated)	LECLR2	1,8	0,36	0,27	0,46
S4	Absorptive glass (blue)	HABLU	2,7	0,38	0,24	0,37
S5	Absorptive glass (green)	HAGRN	2,7	0,40	0,27	0,58
S6	Reflective glass (clear)	HRCLR	2,7	0,45	0,37	0,34
S7	Smart glass (blue)	HRBLULE2	2,7	0,32	0,19	0,34
S8	Smart glass (green)	HRGRNLE2	2,7	0,32	0,19	0,42

The simulation was run using the Design Builder software. Both apartments had building elements with the same thermal properties and frames of the same PVC. All windows consisted of two 6 mm thick panes with a 12 mm air gap.

The simulation results showed that the best energy efficiency performance in all cases was observed for the glazing type with the lowest U-value and SHGC (LECLR2). This meant that the specific window was able to shield the apartment effectively from intensive solar heat gains during the summer and provide sufficient insulation for energy savings during the winter. The overall energy savings over the CLR window type, for both apartments, was a mean of around 41%. The other low-e windows had very good summer cooling performance, but lacked in winter savings. The worst overall performance was that of the plain clear glass.

A life cycle cost study was also prepared to demonstrate the economic viability of each glazing type. The life cycle cost took into consideration initial window cost and annual energy savings over a 30 year time period (with a 15 % discount rate). The results showed that the blue tinted smart glass (HRBLULE2) has a 3,99% lower life cycle cost than the low-e window with the best energy performance. LECLR2 is 73% more economically efficient than the plain clear glass (CLR) however. In terms of payback period, the absorptive blue tinted glass (HABLU) is the best choice due to its low initial cost.

The study proves the importance of the correct use of low-e coatings. Since low-e coatings are either used to keep heat inside or keep outside heat from getting in, deciding which is most beneficial depending on the intensity of the heating and cooling periods, is crucial to the resulting annual energy balance. The right decision can make a world of difference or cause more harm than good.

The climate data of Trabzon, the Turkish city for which the simulation was run, are similar to that of a typical Greek city, so the results can be assumed to be similar for Greece.

A survey on the properties, requirements and possibilities of dynamic tinted windows was undertaken by Baetens et al. in 2010 [31]. The review consisted of electrochromic, gasochromic, liquid crystal and electrophoretic glazing technologies. The electrochromic windows seemed the most promising to reduce cooling loads, heating loads and lighting demands in buildings, with a measured regulation of the solar transmittance of up to 68%. For studies done in California, electrochromic windows were found to reduce up to 26% of lighting energy demand, compared to conventional blinds and up to 20% in peak cooling loads.

Electrochromic Glazing Technologies

According to Deb et al. "*an electrochromic (EC) smart window is a window in which the light transmission properties of the glass can be changed in a controlled and reversible manner when an electric current flows through the device.*" [30]

A. Piccolo [32] conducted experimental tests and ran a computer simulation in order to evaluate the performance of an electrochromic (EC) window. The study was carried out on a test-cell with an installed double glazed EC unit where one pain is an EC device and the other clear glass. The small scale experiment consisted of tests to examine control of global light transmittance, internal temperature, and solar heat gain under real environment conditions during summer.

In both cases experiments and numerical analysis showed that heat flow decrease is at its maximum point when EC double glazed unit is at its lowest transmitting state. This amounts to a 50% decrease in the western orientation and 60% in the south. The measured dynamic range of the heat gain was 4.4:1 for which heat load reductions were at 50%, when compared to the clear. In the south orientation, the dynamic control can effectively produce heat load benefits without producing thermal discomfort from radiated heat for the occupants. Real world examples are expected to produce useful information for estimating full capacity of summer overheat reduction.

Tavares et al. [11] evaluated the performance of electrochromic windows on energy performance of buildings in Mediterranean climates by comparing three glazing options: single glazing, double glazing and electrochromic glazing. The ESP-r building energy simulation program was used for the calculations. The results showed the advantages of the control properties offered by the EC window. The western facade had reduced annual energy needs by 62% compared to the eastern facade. For the south facade the use of double glazing produced the best results.

Implementation of the EC window was also advantageous for the cooling season and suggest that the glass may not be suitable for the heating season. However, these results are in regard to Mediterranean climates and may not be applicable for other regions. In conclusion, this technology is an energy efficient solution, it should however be utilized in western and eastern facades where it is most effective and after attentive study.

S.K. Deb et al. [30] present three different PV integrated electrochromic window technologies developed by their lab: A stand-alone, side-by-side PV-powered EC window; a monolithically integrated PV-EC device and a novel photoelectrochromic device based on dye-sensitized TiO_2 solar cells. The paper extends to elaborate on the physical and functional characteristics of these products, but does not supply any experimental or simulated data on their performance.

In his 2013 paper, M. Pittaluga [7] proposes an opaque ventilated thermal mass smart facade which he names "The Electrochromic Wall". His proposal is an innovative redesign of the Trombe wall equipped with an electrochromic glass exterior to be better adjusted to Mediterranean climates. He designed an experiment with three test cells located in Sardinia, Italy. Each one was equipped with a different facade system. The first had a traditional wall, the second a Trombe wall system and the third, his version of the Trombe wall with electrochromic glazing. For ease of control of the different variables (U-value, weather conditions, humidity) the experiment was simulated in Design Builder. Compared to the traditional Trombe wall where the only adaptability between summer and winter function is the closing of the ventilation hatches positioned at the top and bottom of the wall, the electrochromic wall possesses an extra degree of control due to its regulation of sunlight penetration.

The results showed that the electrochromic wall had annual energy savings of 17,6% compared to the traditional wall and 29,5% compared to the Trombe wall which had the worst energy performance of the three and is not suitable for hot Mediterranean climates.

Switchable Liquid Shielding

Water or liquid shielding is a technology used to reduce the solar gain passing through double glazed window facades. As already mentioned the glazed facade area of buildings is the part that produces the greatest energy losses and energy gains. In order to control the amount of solar energy passing through the double glazed facade, a thin layer of liquid is pumped through a gap in the exterior double window pane, that reduces the infrared radiation penetrating the glass, without impairing visibility. The technology is claimed to function similarly to low emissivity coatings, the benefit in this case being that it can be administered when useful and removed when larger solar infiltration is desired.

T. Gil-Lopez and C. Gimenez-Molina [33] contend that their proposed double glazing with a circulating water chamber is a less polluting and more efficient option than the systems currently used and that this system manages to reduce the energy losses and unwanted gains of the building through the glazed facade by 18.26% without impeding daylight infiltration.

Their liquid circulating window is compared to automated pigmented glazing technologies such as electrochromic and photochromic windows, though they assert that their technology is better. A number of disadvantages of the pigmented technologies is listed, including slow reaction times, reduction of visible light and high cost, causing a difficulty in user adaptation.

Using water as the working fluid in switchable liquid technology has the following benefits: low cost, ease of availability, high opacity to infrared radiation and high transparency. In order to prove these claims, Gil-Lopez and Gimenez-Molina conducted a number of experiments to compare a conventional double glazing system with another system containing a water chamber, the purpose of which was to check the system's energy efficiency, repercussion on the environment and economic feasibility.

A standard building industry glazing type was chosen consisting of a 6 mm thick double glazing with an 8 mm thick air chamber for the first, compared to two 6 mm thick glass panels with water circulation through an 8 mm thick chamber between the panels. The incorporated circulating water considerably reduces thermal transmittance (U value), increases the amount of blocked infrared radiation and preserves glass transparency. For the circulation of the water the building's existing installation was used which would also benefit from the excess energy supplied by the glazing, to preheat the building's hot water supply.

In order to conduct the experiment weather data was needed for the whole year which was supplied by AEMET (State Meteorological Agency, Ministry of the Environment, Rural and Marine Environment, Spanish Government). The experiment would then be mostly conducted through a computer simulation on the most part using measured data from the two test modules constructed as a validation of the simulated results.

The results showed that the water circulated window had a better result of retaining interior temperature during both winter and summer tests. The initial air temperature inside the models was set at 21°C at midnight during the winter solstice and at 25°C during the summer solstice, for thermal comfort reasons.

Gil-Lopez and Gimenez-Molina conclude that, with the temperature difference observed and bearing in mind that a standard building has 13% - 24% of its total energy losses from windows, the water circulated double windows require a mean energy of 0.09 kWh/m^3 to keep winter comfort temperature of 21°C compared to a 0.41 kWh/m^3 for the conventional double glazing leading to a 78.22% saving of energy for winter and a corresponding 90.45% energy saving for summer, since there the energy required to keep the comfort temperature of 25°C is 0.08 kWh/m^3 for the water circulated double window and 0.87 kWh/m^3 for the conventional one.

However these figures only reflect the savings correlated to window losses. If these savings are projected to the total building losses from all elements throughout the year then the savings produced by the water circulated double window in the text module is reduced to 18.26%. This on its own is not considered enough to render the building as a Passive building. The authors propose that additional measures need to be taken to reach the standard. On these grounds Gil-Lopez and Gimenez-Molina propose a scenario for the integration of the water circulating the windows with the domestic hot water production by means of solar panels.

Their second paper [34] describes the system in technical detail adjusted to residential buildings. A CO_2 emissions calculation is added. It is concluded that depending on the fuel type, a CO_2 reduction of up to 81.74% can be achieved with the use of a water circulated double glazed facade. There is also an expected payback time of 13 years for diesel fired boilers, 8 years for an electric boiler and 15 years for a natural gas condenser. Calculations were done for the city of Madrid, Spain.

Regarding the proposed water circulation system we can comment that in order for the system to function at maximum efficiency an integrated solar panel system for domestic hot water is necessary. This may be practical for a residential building but will highly increase the complexity and cost of a multi-storey office building.

Given the very brief testing period, the paper does not specify how they will overcome potential long term microbial growth in the water circulating the glazing as well as insoluble solids build-up that may impede water transparency and create potential circulation problems. If excess water that is not consumed within the building is not recycled but dumped into waste pipes and new water refilled from the mains, then it raises a serious question on sustainability and water conservation. In the case of multi-storey office buildings this renewal of water may greatly increase the buildings water needs and utility bills.

This technology is focused on domestic buildings with a built-in central water pumped heating system and the use of domestic hot water, something that may not be present in an existing office building. This however does not wholly rule out the use of this technology for existing office buildings. This system may work for a single storey building or single storey glazing, but in our multi-storey glazing approach the cost and pressure of pumping the water to multiple-storey heights may reduce the system's efficiency.

The experiments were undertaken in Italy. Since the Mediterranean climate of Italy is similar to that of Greece, the results should not be very different were the experiments held in Greece.

Carbonari et al. [13] propose a novel switchable liquid shielding technology, developed to solve passive house summer overheating. The goal of this system is to reduce solar loads and to serve as an alternative to existing shading technologies that doesn't affect visibility. This is accomplished by adjusting the solar factor of the glazing.

The authors compare this switchable liquid technology to other conventional shading technologies as well as more recent technological innovations such as glass coatings, electrochromic technologies, liquid crystal switchable glazing and silica aerogel granule coatings, stating drawbacks of each one that their prototype overcomes. They then proceed to highlight the innovative qualities of their liquid's design, which is characterized by high durability, solar properties similar to, and in some cases better than, low emissivity glazing and a triple glass solar transmittance drop to 15% from 50% when the liquid is introduced.

The concept of the switchable technology is the ability to automatically drain the liquid from the glass pane, storing it in a tank, and switch it with a gas when higher solar gains are needed, in cold weather. This is accomplished by internal and external temperature sensors. With this mechanism the internal temperature can be conditioned closer to the thermal comfort level.

The outdoor experiments conducted to measure the system's performance consisted of two window samples on two identical test cells. The first contained the liquid shading prototype while the second was a low-emission standard glass sample, which was used as the "benchmark". During the testing period the modules were oriented towards the south and tilted at various angles to minimize the incidence angle. The results determined considerable enhancement of the concept module in comparison to the reference window. This proved the concept window's high potential in dynamic behavior to actively control solar gains. The average incoming radiation, during the first part of the experiment where the test boxes were not tilted, was 56.1 W/m^2 for the liquid shading and 63.0 W/m^2 for the benchmark. The solar transmittance calculated for the liquid-shielded window gave a value of 0.38, which is a massive reduction in the transmitted solar radiation compared to the benchmark's 0.51.

The results support the claim that in using the liquid solution, a higher control of solar transmittance is attainable, thanks to its dynamic nature and its filtering capabilities, which are higher than those offered than the widespread low-e double glazing windows available in the market.

This solution offers a better perspective for implementation in office buildings. There is more promising evidence of liquid durability and the avoidance of microbial growth or solid accumulation. The prototype is however still in an experimental stage and not ready for large scale implementation.

These experiments were also undertaken in Italy, so the results should not be very different, were the experiments held in Greece.

Phase Change Materials

It is a known fact that energy can be stored as latent heat in materials and become available when needed, in the form of thermo-chemical bonds. A phase change material used for thermal storage in buildings is a substance, with these properties, that can be incorporated into construction materials and is capable of absorbing heat from the environment when it melts at a specific temperature cooling the air around it. This heat is later released to the environment when the PCM solidifies [35]. Most phase change materials are characterized by a high enthalpy of fusion which enables them to store large amounts of energy in a relatively small volume. It is practical for PCMs to function between temperatures than are within the operational temperature range of the required space to achieve optimal output [36].

In a 2013 paper, de Gracia et al. [10] study the thermal performance of a ventilated facade with a micro-encapsulated phase change material in its air channel, which is experimentally evaluated under summer conditions. A series of experiments were carried out in Puigverd de Lleida in Spain during the summer of 2012, to test the system in different day-night temperatures and ventilation calibrations.

The experimental set-up consisted of two identical cubicles with inner dimensions 2.4m x 2.4m x 5.1m. The only difference between them being that one of them has a ventilated facade with PCM installed inside the air chamber of its south wall, while the other cubicle keeps the basic constructive system. The ventilated facade has a 15cm thick air channel with an inner layer consisting of an Alveolar brick construction. The outer layer is made of glass which is covered during the summer by expanded polyurethane. There are 3 fans to provide mechanical ventilation at the base of the facade. The 4 different modes of operation can be seen in Figure 4 below.

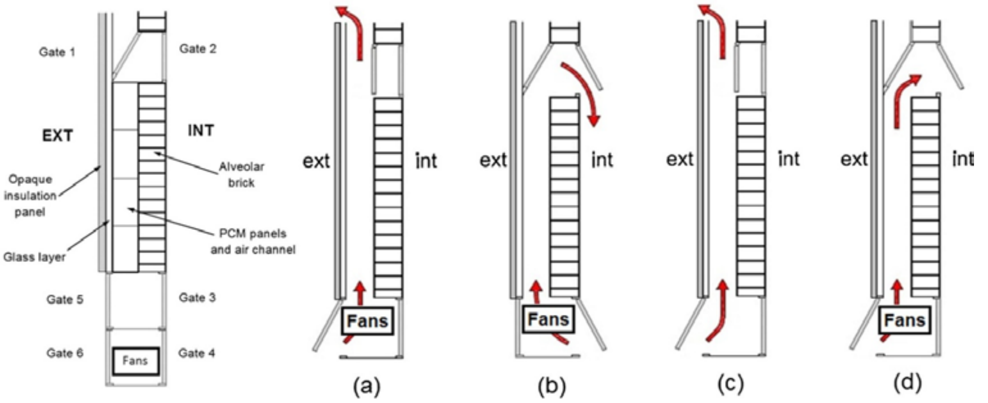

Figure 4: Diagram illustrating the automated gates and fan distribution along the facade, as well as the four modes of operation of the ventilated facade. [10]

The PCM used inside the facade was micro-encapsulated CSM panels of salt hydrate SP-22. The cubicles are also equipped with two heat pumps in order to stabilize the required inside air temperature.

The system is programmed to undergo 4 different functional periods:

- the PCM solidification period during the night, where the PCM expels heat into the environment and returns to its solid state
- the PCM melting period, where the PCM cools down the air pumped inside
- the overheating prevention period, when the PCM cooling process is over the system prevents hot air from getting inside
- the night ventilation, where the heat stored in the thermal mass of the Alveolar bricks is vented to the environment. This happens after the PCM solidification period.

The experiments carried out conveyed a number of results. The timing of the ventilation modes is crucial to the efficiency of the PCM cooling system since, if the timing is off, the ventilated facade may end up pumping hot air into the test cubicle and result in a higher energy consumption than the reference cubicle.

The PCM system manages to reduce electrical energy consumption in the heat pumps, in order to maintain inside temperature stable, however this is mostly due to the high efficiency of the nighttime ventilation. The cooling efficiency of the PCM is very low compared to its potential (about 6%). The overall system efficiency is also affected by thermal bridges in the construction. The cold storage system is almost useless unless the PCM has fully solidified during the night. This however requires that outside night-time temperatures drop below 18°C long enough for the PCM to solidify.

The overall thermal performance of the system was very sensitive to weather conditions and the final users cooling demands. This highlights the necessity of a programmable thermal control system in order to efficiently utilize the ventilated facade for cooling purposes.

The paper does not mention how the system works during winter conditions, or if the system can have a positive effect during the winter period as well (this is however done in another paper [37]). There is also no mention of the PCM system's durability and what measures need to be taken in order to ensure system maintenance. The conclusions derived by the experiments do not give a clear image of the benefit of PCMs and whether their implementation in the devised system is profitable.

The experimental conclusion that the PCM must be fully solidified overnight in order to function efficiently during the day gives little hope for its implementation in urban centers in Greece where for the majority of the summer the outside temperature does not drop lower than 25°C, not to mention the requested 18°C. This is mostly due to the heat island effect and would not serve the purpose of office building retrofits, since they are usually situated in city centers. This technology should either be disregarded in this case, or other PCMs with higher solidifying temperatures should be investigated.

The experiments were undertaken in Spain. Since the Mediterranean climate of Spain is similar to that of Greece, the results should not be very different, were the experiments held in Greece.

As mentioned previously, de Gracia et al. [37] have published another paper studying the thermal performance of a ventilated facade with a micro-encapsulated phase change material in its air channel, which in this case is experimentally evaluated under winter conditions in the same test cubicles as before. The ventilated facade with the PCM is located in the south cubicle wall. The PCM inside the wall increases the solar absorption capacity of the south wall and can, as seen before, also function as a cooling mechanism in warmer periods.

The experimental setup is the same as during the summer tests. The only difference is the absence of the polyurethane insulating panel to block the sun from penetrating the glass south facade. The appearance and layout of the seasonal test cubicles can be seen in Figure 5 below.

Figure 5: Summer (left) and winter (right) setup of the two test cubicles, showing the exposed glass facade with PCM on the right. [10][37]

The experiments were executed in three different motifs: severe or mild winter conditions, free floating or controlled temperature conditions and mechanically or naturally ventilated facade modes. In the first phase the ventilated facade acts as a solar collector by absorbing heat. Once the PCM is melted and the accumulated heat is needed inside, the heat discharge starts and hot air is driven through the openings to the interior of the cubicle. When no more energy can be delivered or is needed, the system closes up to reduce environmental losses. The operation of this facade is similar to that of a double skin facade with thermal mass.

During the experiments, a significant difference between the mechanically ventilated (19%) and the naturally ventilated (10.9%) operational mode was measured, which is justifiable since the use of fans supplies stored heat faster, limiting heat losses. It was observed however, that during low heating demands, the use of mechanical ventilation can produce higher electrical consumption than is saved by the PCM system. This proves the necessity of a proper control mechanism for mechanical ventilation, that will ensure maximum efficiency.

The overall performance of the ventilated PCM facade proved beneficial for the cubicle as even during severe winter conditions interior temperatures were held at a comfortable temperature. The measurements showed, however, that the PCM's contribution in the energy savings was negligible. This is probably due to the low melting temperature of the phase change material (SP-22) used. The results may prove more significant with the use of another PCM.

In their 2014 paper Goia et al. [3] deal with the development and use of an innovative glazing system that utilizes Phase Change Materials (PCM) to achieve dynamic and responsive thermal behavior. They introduce the coupling of a PCM and glass panes and investigate if this could be a way of improving the low thermal inertia of fenestrations and its effectiveness in collecting, storing and exploiting solar energy on a building scale.

The scope of the phase change material double glazing unit (PCM-DGU) is to overcome the gap in smart windows technology that is their lack of thermal mass potential. This system enables the window to store solar energy during the day, when it exceeds the heating demand, and release it during the night. Phase change materials exhibit properties that could potentially improve both thermal inertia and overall glazing performance since they allow relatively large amounts of solar energy to be stored during the day. Several PCMs seem to be fairly suitable for integration in transparent elements and transition temperatures can be easily tuned due to the wide range of available PCM values. There seems to be great potential in integrating them into Zero Energy Buildings as well.

The experiment was conditioned to focus on the test module's performance in a temperate climate, as well as throughout the different seasons of the year. The test module prototype was built to compare the PCM double glazed unit with a conventional clear glass double glazing window with air gap. The system was designed as simple as possible so that the components could be easily manufactured, to keep the cost low and so that the information gathered would benefit future more complex systems. An unnecessary high degree of complexity would have made the assessment of data and test output difficult to evaluate. The initial focus however was to optimize the PCM unit function for summer and mid-season performance, while at the same time trying not to compromise winter behavior.

The experimental setup consists of the PCM glazing prototype (DGU-PCM) which is a double glazed unit (8/15/6 mm) made of two clear glass panes and a 15 mm cavity filled with a commercial grade paraffin wax, whose nominal melting temperature is 35°C and heat storage capacity is 170J/g. The DGU-PCM has an area of around 1 m^2 with dimensions of 1,4m length and 0.72m height. The selected PCM does not have any compatibility problems with the other structural elements of the window.

The results show that the PCM glazing prototype is capable of providing significantly better performance in the summer than a traditional glazing system. The measured reduction is in the order of 20 - 55% of daily energy entering compared to a conventional double glazed window. A careful optimization of the mass of PCM used within the glazing is necessary in order to assure that the paraffin does not melt too quickly, to avoid significant heat flux increase that could compromise the performance of the window system. Another crucial aspect of the PCM system is the nighttime heat discharge of the paraffin. The thermal loads are undesirable during the cooling season and care must be taken that they are removed from the indoor environment before the next day.

It should be pointed out that the largest benefits were witnessed during the high solar irradiance periods. This is mainly caused by the shading and energy buffering effects provided by the paraffin layer. Nightly performance problems aside, this technology could be profitable in an office building environment as it is, given the considerable indoor thermal loads of offices during working hours.

While conventional windows function the same throughout the year, a PCM double glazing unit such as this has a dynamic performance not only towards seasons, but time of day as well. Building elements like this PCM glazing system cannot be simply installed in a building. Suitable integration strategy tailored for the building function is necessary. It is important that a preliminary study be undertaken to select the preferable PCM transition temperature as well, considering the local climatic conditions. The adoption of a PCM with a higher melting point is more suitable for warmer climates with milder winters.

Regarding the implementation of phase change materials in building facades, there are a few points that need to be observed. As expected the PCM is beneficial during the summer months but not so effective during winter. This could probably be solved by choosing a more suitable PCM with a different melting temperature. It is also important that a way be found for the PCM to solidify completely during the night without resending the heat of discharge into the building and increasing cooling loads. That was a large problem in this experiment and it brought the efficiency numbers down.

The paper does not analyze the visual comfort of using this glazing system. When in its solid state the PCM is translucent, totally blocking out visibility and allowing only a fraction of light to pass through. This may be beneficial during the hot summer months when sunlight is undesirable but it may cause an increase in electrical consumption for lighting during cooler periods, apart from the fact that it blocks visual communication with the outside world and that may not be satisfactory to building occupants.

In a different type of "smart" facade system, Chan [38] studied the effect of integrating PCMs into the walls (opaque facade elements) of a residence in Hong Kong and evaluates the effect they have on the building's thermal and energy performance. The findings were mostly based on literature review and computer simulation.

The literature review done by the author provided the following information. The application of PCM in building facades allows the storing of thermal energy during the daytime, can lower the interior surface temperature of external building walls, stabilizes indoor temperature within comfortable range and reduces the need for cooling energy from air conditioning. The use of PCM thermal storage can reduce the size of the required mechanical ventilation system and better thermal comfort is achievable. Double glazed facades combined with PCM were shown experimentally to achieve a 30% reduction in south facade heat losses. The visual effect of the homogenous appearance of solid PCM panels is however not appealing to designers and users alike. Reduction in maximum thermal loads ranged from 10 - 37%. By using PCM wallboards coupled with mechanical night ventilation in office buildings a peak cooling load reduction of 28% could be achieved.

For the validation of the PCM numerical model in EnergyPlus, the author used experimental data from published literature. Kuznik et al. conducted a set of experiments in their 2009 paper which were also run on computer simulations. The computer simulation results were in agreement with the experimental data, therefore, the representation given by the building energy computer simulation was reliable for the prediction of the PCM integrated facade's performance in this study.

Because of the occasional space heating demand in Hong Kong, due to temperate climate conditions, the study was focused on the investigation of building cooling over the summer months. The computer simulation modeling showed that the highest achieved daily decrease in interior surface temperature was in the west-facing PCM integrated external wall, with a value of 4.14%. Due to the diurnal variation of solar angles and position, the maximum decreases in indoor surface temperature occurred at different times for each wall. At night the PCM releases the stored energy into the surrounding environment.

The annual savings in cooling energy cost were achieved by the western facade overall to a total reduction of 2.9%. In the master bedroom alone, however, the PCM had a negative effect as heat discharged at night increased the cooling energy needs. PCM integration for bedrooms is therefore not recommended in subtropical climates.

Regarding the economic feasibility of the refurbishment proposal, the calculations indicate that the payback period is much longer than the average 60 year life span of a residential building in Hong Kong. This is mostly due to the high cost of PCM wall boards. On the other hand, regarding the embodied energy of manufacturing of the PCM, the calculation showed that the energy payback is 23.4 years. For an estimated building lifespan of 60 years, the net energy saving period is 36.6 years, which has a substantially positive effect on an environmental level . Taking an emission factor of 0.7 kg/kWh for CO_2 and the saving of electricity from A/C reduction gives us a calculated 1.84 tones of avoided CO_2 emissions. This shows that over the life time of a PCM wall-board the energy saved and greenhouse gas (GHG) mitigation is significant.

The paper has some interesting views on evaluating the life cycle analysis (LCA) of PCM integration, but the assumption that the PCM wallboards will continue functioning for 60 years and without a decrease in efficiency is a large step to take, especially since the technology hasn't been around for that long. On the other hand it proves that western facades usually have the largest stress from summer heat gains and because of this PCM integration can have its largest efficiency there, when it comes to negating direct solar gains.

In a similar investigation on PCM integration on building facades, a comparative case study on energy savings and cooling comfort provided by PCMs, was enacted by Ascione, Bianco, De Masi, de' Rossi and Vanoli [39]. In an initial review of the bibliography it was discovered that, although the benefits of PCMs on thermal comfort are evident, there seems to be little information available on annual energy savings that PCMs offer on space heating and cooling under tested building conditions. In this sense they set out to achieve a quantification of energy savings from use of PCMs in building envelopes in order to identify the most suitable PCM for application in buildings of Mediterranean climates. To accomplish this series of simulations with the accredited building simulation program "EnergyPlus 7.2.0" was undertaken.

A thermal building model was created of an office building with increased insulation of building envelope elements. Simulations were run for the climatic conditions of five different cities: Ankara, Athens, Marseille, Naples and Sevilla during the cooling season. Four different types of PCMs were used in three different envelope integrations and in four different quantities. The PCM used was tested for melting temperatures of 26, 27, 28 and 29° Celsius and a phase change enthalpy of 110 kJ/kg.

The results showed that the integrated PCM did not produce the same benefits for all cases and throughout all the months of the cooling period. Warmer cities, like Athens and Seville, had longer thermal comfort periods with the high melting PCM, while the others had longer thermal comfort with the lower melting PCM. Likewise, higher PCM thickness on the building envelope led to lower energy demands. Integration of PCMs reduced indoor air temperature peaks. This delay in the onset of overheating helped to retain thermal comfort for longer periods. Optimization of phase change materials for the entire cooling season is difficult. It is strictly constrained by climate location and building use.

This paper had an interesting comparison of how PCMs would react on the same building in different climatic conditions. Thermal building modeling simulations with comparison of PCM integration is not so common in older literature, that is why this paper was quite interesting, despite not being fully on topic.

Panels

In the spirit or researching facade systems, smart materials with innovative capabilities regulating and adapting energy flows for energy performance enhancement were also regarded.

Moretti, Zinzi and Belloni [40] consider polycarbonate panels as an alternative envelope system for buildings that increases daylighting, where direct visual contact is not necessary, while retaining a thermal insulation standard and a low cost. Polycarbonate panels (PC) can be used to replace the more expensive transparent insulation walls, as both are characterized by similar light diffusion abilities. An example of a PC clad facade can be seen in Figure 6 below.

Figure 6: Example of a building clad in PC panels (DAP Studio in Bergamo, Italy). [40]

Polycarbonate plastic is characterized by the following abilities that render it superior to glass. It is moldable, durable, lightweight, flame resistant and has an over 200 times greater impact resistance to shattering than glass. Building PC panels are also weather resistant and UV protected.

Depending on the use, polycarbonate sheets can be clear, translucent or opaque. The panels can be rigid, flexible, corrugated, flat, thick or thin and in a variety of colors. They also come in different cell geometric characteristics. The paper considers the evaluation of different types of polycarbonate panels of higher or lower geometric complexity for possible use in non-residential buildings as a cheaper alternative to standard glazing facades.

Experiments for light transmittance and reflectance properties were carried out using a large diameter integrating sphere facility for optical measurements, as well as for thermal performance by use of a Hot Box apparatus. The PC layers showed high transmittance in the solar spectrum and particularly in the visible range. The angular transmittance, however, was lower in respect to conventional glazing units. The U-values displayed by the PC panels are well inside the regulation U-Value range for most European regions, so it can be concluded that the investigated polycarbonate systems are a viable candidate for replacing conventional window systems in non-residential buildings. The results for both experimental procedures can be summarized in Table 2 below.

Table 2: correlation between light and solar transmittance of PC panels compared to Double glazing units, as well as their respective U-Values. It is clear that PC panels have generally higher U-Values and solar transmittance than the glass units, while maintaining a slightly lower light transmittance. [40]

	PC S3	PC S5	PC S9	DGU	DG low-e	DG low-e (megatronic)	DG low-e Argon fill
Light Transmittance	0,72	0,52	0,48	0,81	0,74	0,74	0,74
Solar Transmittance	0,69	0,54	0,47	0,72	0,52	0,43	0,43
U-value (W/m^{2}K)	1,84	1,45	1,20	2,70	1,70	1,40	1,10

Polycarbonate panels are a cheap alternative to traditional multiple glazing systems. They present a higher insulation to conduction heat loses but lower resistance to radiated heat loses and gains. This can be easily overcome, however, by implementing innovative transparent materials such as aerogels in the structure, if the need arises.

PC panels present an interesting alternative to using glass for transparent facades. They add an architectural quality to the design through the wide variety of panel types and their diffusion of light reduces interior glare increasing visual comfort inside, but also reduces harsh reflective glares outside the building. However, their diffusive nature can have major drawbacks on visibility creating a sense of isolation from the outside world which may not always be welcome.

Other Material Technologies

Suresh et al. [35] compiled a review of passive energy savings technologies for buildings. They list a wide range of available materials and systems for various building components such as: walls, roofs, windows, insulation as well as guidance for air infiltration, simulation software and envelope diagnostics and maintenance. We limited our interest to the technologies that we found would be most useful in our facade retrofit design.

There is a mention of PCM imbedded in building elements and its correlation to thermal mass storage. The authors report sources that denote a 4°C maximum room temperature reduction in buildings with walls lined with PCM and an experimental maximum decrease of 4,2°C for composite PCM wallboards. Experimental testing of a new class of organic based PCM showed a maximum energy saving of up to 30% and a peak load shift of up to 60 minutes, as well as a 30% cost reduction over conventional PCMs. The specific BioPCM is also less flammable than the usual organic PCMs, making it safer to use.

State of the art glazing technologies are aimed at providing a combination of high performance insulation, solar gain control or daylighting solutions. It is observed that annual window energy savings are dependent on orientation, climate and building parameters such as insulation, floor area and height, apart from the usual parameters of thermal conductivity and solar heat gain coefficient.

Spectrally selective low emissivity coatings allow visible light to pass through the glass unobstructed, while infrared radiation, which is mainly responsible for solar heat gains, is reflected. This allows the window to minimize solar heat gains without affecting daylighting inside the building. There are hard and soft types of low-e coatings. Soft silver based coatings exhibit a lower solar transmittance and higher infrared reflectance compared to hard tin oxide coatings. When treated with silicon dioxide, low-e hard based coatings have increased antireflection properties that increase solar transmittance to a value of 0.915. This allows the use of low-e coatings in triple glazing construction, producing high U-Value windows without hindering visibility.

Aerogel glazing entered the market in 2006. It consists of a granular mesoporous solid encapsulated between polycarbonate panels that weigh less than 20% of their glass equivalent. They have very high impact strength and high energy performance. They diffuse light, however, which greatly impedes visibility although they are transparent.

Vacuum glazing is a widely used form of glazing insulation where a vacuum space is created between two panes of clear glass. This eliminates conductive and convective heat transfers between the glass panes reducing the mean glass U-Value to as low as 1 W/m^2K. A low-e coating is usually applied to reduce re-radiation of thermal energy indoors. The heat transfer of evacuated triple glazing was investigated with numerical finite element modeling and the results showed that a U-Value of 0,2 W/m^2K was achievable.

The switchable reflective technologies mentioned by the authors include electrochromics and gasochromics. These basically change the tint of the window to reduce cooling loads during summer. A life cycle energy analysis performed on EC windows in Greece showed that for a life time of 25 years, 6388 MJ were saved, which is the equivalent of a 54% reduction in energy. The payback period would be 9 years with a total estimated energy cost saving of 569 $€/m^2$ for 25 years of operation.

Suspended particle devices are films laminated between two clear glass panes that contain light absorbing particles that form an opaque barrier when randomly aligned. With the application of voltage, the particles align perpendicular to the glazing plane creating transparent glass. The switching speed is higher than that of electrochromic windows but there are a number of drawbacks to the technology including radiant temperature, glare, color rendering, clarity and lifetime.

Regarding insulation materials, vacuum insulation panels are high performance thermal insulators that contain evacuated foil-encapsulated material. They have a very low conductivity values in the range of 0.020 W/mK at dry conditions in ambient pressure, which is half the thermal conductivity of most conventional insulation materials.

Ventilation and cooling technologies

Night ventilation can be considered as a "smart" facade technology when facade systems are designed around the optimization of this mechanism (with integrated automation, mechanical or other ventilation, PCMs etc)

Perez et al. [41] review the effect reflective materials have on the thermal performance of buildings when applied to exterior building components. The paper studies the use of reflective materials on mostly opaque building elements, their main characteristic being enhanced reflectivity of solar radiation that leads to a lower absorption of heat, which results in maintaining them at a lower temperature than standard materials. That is why these materials are also known as "cool materials". The paper goes on to investigate the effect on thermal performance these materials have when applied on building roof elements, through the use of experimentation and CFD analysis for various examples. It however only focuses on roof applications and not building facades in general.

According to Perez et al. roofs can contribute up to 50% of a building's heat loads during summer, especially in hot climates. This is the main reason cool materials are so important in roof cladding. An alternative method of cooling roofs is through an accumulated layer of water or through water spraying. These are known as wetted roofs. These water sprinkling mechanisms cool the roof elements through evaporative cooling.

The paper concludes that reflective materials can have a positive effect during the summer but minimize beneficial solar heat gains during the winter as well, this is however negligible compared to the energy savings during the cooling period. Experimental data through the use of test cells indicated that indoor air temperature can be reduced between 2 and 14°C. This is however dependent on the size and thermal mass of the elements. CFD analysis showed an indoor air temperature decrease of 3 to 7°C owing to the difference in test building nature.

This methodology is favorable for warm climates, displaying an increasing positive outcome the hotter the weather and the poorer the building insulation. Indoor thermal comfort also increases as discomfort hours are minimized by up to 63%. Energy saved by cool material implementation was calculated up to 20%, depending on the climate, building type and roof condition. This also effects the reduction of greenhouse gas emissions.

2.3 Conclusions

Building envelopes are one of the main sources responsible for a building's heating and cooling loads. Proper insulation can reduce the heating loads in winter by retarding the heat flows from the building interior to the outside environment and reduce the cooling loads in the summer by retarding the penetration of heat from the exterior to the cooler interior. Apart from acting like a boundary to the exterior environment, a building's envelope is its connection to the energy flows to and from the outside world. In this sense, building envelopes need not be considered merely as a protective shelter from the elements, but as a device for harnessing the radiation reaching the building from the sun to benefit the energy performance of the building.

It is generally referenced in the reviewed literature that mechanical ventilation has better results than natural ventilation on most occasions, including the electrical energy consumed by ventilation fans. Implementation of phase change materials requires careful design and proper selection of the appropriate material with properties that will serve the specific climatic conditions the building is found in, primarily regarding PCM melting and solidifying temperatures. Automated control will enhance PCM efficiency since the materials are sensitive to changing weather conditions. Western facades receive higher heat loads, and for longer durations, due to smaller solar incidence angle, especially during summer.

Double skin facades can be beneficial to building energy performance even in hot arid climates if designed properly. Vital for an efficient double skin facade design is the dimensioning of the air cavity width compared to the ventilation openings, the provision for effective night-time ventilation and a compatible to the airflow shading system. Night-time ventilation is very important in removing heat from a building between working hours. If executed properly, night-time ventilation can effectively reduce cooling demand for the building.

Before proceeding on an energy upgrade some groundwork needs to be set to ensure appropriate measures are being taken. A better investigation of each building's energy performance is necessary in order for the designed energy upgrade to reach the highest possible efficiency. Some systems may have a very positive effect during one season, but have a negative effect during another season. Careful consideration is necessary to insure the right materials and systems are used for the specific target.

In the next chapter we will investigate if the technologies reviewed are capable of granting a near zero energy level of demand on an existing office building in the Mediterranean region.

3 Retrofitting for near Zero Energy

As stated in the introduction chapter, we will attempt to determine whether an office building upgraded with smart technology retrofits on its facade is capable of achieving near zero energy building status. In this chapter we discuss the nature of a near ZEB and its application on office buildings.

3.1 What is near ZEB

According to article 2 of the EPBD [2] a "near zero energy building" is one that has a very high energy performance. This is determined from calculated actual annual energy consumption to meet heating and cooling energy demands needed to maintain the prefered temperature conditions of the building and for domestic hot water. The very low energy demand should be covered significantly by renewable energy sources, including energy from renewable sources on-site or nearby. For an office building this would translate as a building that manages to retain its internal air temperature at a level necessary to achieve thermal comfort during the hours of occupancy throughout the year, with an annual energy demand per square metre of building area (in kWh/m^2) being close to zero.

Since the EU Directive specifies that Member States are expected to layout the criteria that define a near ZEB in their country, no single near ZEB definition can exist. There is quite a large number of different definitions by government or private entities. Definitions vary depending on building primary demand, use of renewable energy or CO_2 emissions. Most countries have not yet integrated the 2002 EPBD into national law [42, pg 32]. Depending on each country's climate, energy needs and environmental protection target, the minimum amount of energy consumption that will characterize a building as near zero energy may differ. Apart from that, there is of yet no official near ZEB definition for any type of office building.

Defining the conditions for characterization of an office building as a near ZEB is not an easy task. There is no official standard for near ZEB office buildings. This is to be expected since offices are very energy intensive and have a much different energy balance than residential buildings. Considering that the first type of near zero energy buildging, the Passivhaus [43], is a residential building prototype, designed for few occupants and without many excessive energy needs, retaining a stable internal temperature is mostly achieved by heavy insulation and controlled ventilation. Office buildings have a number of problems on this level as they are highly glazed, consume an immense amount of energy for lighting and appliances, have far more occupants per square metre that are expending more energy due to their vigorous activity and have different hours of occupancy compared to houses.

This article legally binds member states in that all public authorities need to reside in near zero energy buildings by 31 December 2018. This means that public authorities are obligated to either refurbish the buildings they operate from to near zero energy status, or move to near zero energy buildings by the end of 2018. Since in many cases the most viable option would be to renovate their existing buildings, it is to be expected that many near zero energy refurbishments are going to occur. The Directive [2] then suggests that member states should take measures to increase refurbishment of existing building stock, plan an outline to increase near zero energy buildings for different building types and create energy guidelines expressed in kWh/m^2/year. In the light of these expected changes in building energy performance, the scope of this thesis is to investigate if measures in facade retrofitting could fulfil these goals.

One of the main differences in energy performance that an office building has compared to a residential building when it comes to near Zero Energy Building classifications is the increased energy consumed for lighting and appliances as mentioned above. Office buildings have higher needs for lighting than residential buildings as stated in the Greek Technical Chamber Technical Instruction [44]. The increased energy needs for lighting and appliances takes up a large part of the overall energy demands of the building. In addition, part of the energy consumed by lighting and appliances is released as heat into the interior environment (plug load) of the office building, decreasing the need for heating but increasing cooling loads. Furthermore, heat expelled by the people working inside the office adds to the internal gains of the building, which in combination to the heat gains from lighting and appliances have a high impact on cooling needs. For these reasons, office buildings have a higher cooling demand compared to other building types, which may become higher than the heating demand [45].

3.2 Intervention characteristics

The characteristics of the proposed interventions mentioned above are further explained in this section. As we have mentioned before, in this thesis we will try to answer the question: Is near zero energy building status achievable in an existing office building, solely by means of a sophisticated facade retrofit?

The reason we ask this question is because, as we have shown earlier, in order to increase energy efficiency in the building stock, it is not enough to enforce only new buildings to be net Zero Energy Buildings. The higher difficulty is in reducing the energy demand of existing buildings, which by today's standards and especially in Greece can be considered as extremely energy intensive. Since constructing new energy efficient buildings will not effectively increase overall energy efficiency and because this is done mostly for environmental reasons, waiting for old buildings to be replaced by new will take too long, an efficient and rapid method of massively refurbishing existing buildings is needed. Following this logic, we derive upon the question whether an industrial grade retrofit solution can bring sufficient results, when implementing current state of the art energy saving technologies for facades, using climate adaptive and other "smart" features.

Retrofit Strategies

From information gathered in their literature review Juan, Gao and Wang [46] affirm that buildings account for 37% of all total energy in the EU, which is a larger percentage than that consumed by the industrial sector in Europe. It is calculated that during a building's life cycle, energy consumed on HVAC, lighting and appliances can accumulate to 80% of total building energy consumption. The authors proceed to suggest that improving the energy efficiency of existing buildings is considered one of the most sustainable and easily accomplished measures in reducing greenhouse gases and achieving energy savings.

According to Juan, Gao and Wang, office buildings have the highest energy consumption of all building types by comparison, with annual energy demands reaching 1000kWh/m^2, depending on location, type of office equipment, operational schedule, building envelope, HVAC use and lighting. Sources reviewed by the authors predict an increase in energy consumption in the next 15 years for the EU, of up to approximately 50%. This trend will continue increasing for buildings due to the expansion of built area and new uses of energy. It is therefore clear that improvement of energy efficiency in buildings is of critical importance for global sustainability.

There are different types of retrofit strategies available for converting existing buildings into near ZEB or carbon neutral buildings. Jones et al. [45] investigate a method of upgrading existing office buildings to Carbon Neutral by means of upgrading the building envelope, replacing the HVAC system with a more efficient one, implementing passive design-smart facade systems and reducing internal heat gains by increasing appliance and lighting eficiency. This does however still leave the building with a reduced energy demand which is covered by integrating renewable energy sources on site. A simulation is run comparing the results of the proposed upgrades in 3 different cities around the world.

The paper concludes that since use of the local electricity is necessary to cover demands at intervals where generated power from the renewable sources does not suffice, carbon neutrality is dependent on the location of the office building, since the amount of carbon emissions porduced by kWh of generated power from the grid, depends on the carbon content of the country's fuel mix for electricity generation.

In their papers published on a nZEB building design in Estonia, Pikas et al. [47] produce a design methodology on how to upgrade the building elements in terms of insulation, optimal window to wall ratios and on-site renewable energy production to reach their near ZEB goal. Calculations were run via building simulation model on a typical office floor plan. Hi-end window glazing technologies were also compared to demonstrate specific glazing cost as a function of energy performance. The optimal solution was decided with regard to energy savings for a 20 year payback period. The paper concludes that near-zero energy buildings were not cost optimal.

Statistical data on the Greek building stock showed that for non-residential buildings of different types, including office buildings, annual specific energy demand is 115 - 170 kWh/m^2 [48] or 130 - 180 kWh/m^2 [49]. According to the empirical specific energy In order to achieve a near Zero Energy level of performance, a decrease in energy demand in the order of 80 - 95% must be achieved. According to the literature reviewed, no smart technology could produce such a high performance upgrade. It is therefore doubtful whether the implementation of a smart facade system alone could achieve an increase in energy performance of near Zero Energy magnitude, and under what existing building circumstances.

Since our design approach is limited to facade retrofits only, we cannot address energy consumed for lighting or other needs unrelated to heating or cooling. Therefore we will attempt to establish a near zero energy level of energy demand solely for heating and cooling loads from energy savings accomplished by the retrofit smart facade module.

In absence of a specific energy demand standard we will adopt the Passivhaus standard but only for heating and cooling loads. That means 15 kWh/m^{2}yr for heating, 15 kWh/m^{2}yr for cooling and a specific primary energy demand of 120 kWh/m^{2}yr. There is however a problem with posing a constraint on specific primary energy demand because as we will see in Chapter 5, it is dependent on the carbon content of a country's local grid [45].

In the next chapter we will attempt at proposing a composite retrofit smart facade module. This design will integrate multiple smart facade systems aimed at optimization of solar energy management, ventilation, cooling and electricity production in order to maximize the attainable energy performance benefits. We will then test this design, to see if a composite smart facade can combine different smart system benefits to reach higher levels of efficiency.

4 Design Proposal

In this chapter we propose a design for a composite smart facade module to be retrofitted on existing office building facades in order to increase energy performance.

Design goals

The objective goal of our retrofit design is to increase an existing office building's energy savings and attempt to bring the building's energy performance status to that of a near zero energy building, without drastically effecting the existing building's natural lighting and visibility through the existing windows.

In order to achieve this we expect to design a building element that will be easily installed on any candidate existing office building. The facade retrofit design depends on the needs of the building in question. In doing so it must solve a number of points that are vital to minimizing the existing building's annual energy consumption.

- it must absorb heat from the sun during winter
- it must protect the building from penetration of solar rays in the summer without impeding on visibility and natural light
- it must offer insulation for the building, decreasing heat flows and increasing the mean U-Value
- it must harvest energy from the sun (through PV) to offset the energy consumed during the year and reduce the overall annual consumption
- it must offer other energy saving services like hot water (if required), ventilation, cooling, heating, lighting. All these energy intensive functions contribute to the building's annual energy consumption per area unit (kW/m2)

Our design should provide an efficient solar energy absorption system for the heating period, an effective means of warding off solar heat gains during the cooling period without hindering visibility and visual comfort and a functional way of discarding accumulated heat loads in the summer through a ventilation/cooling system, as well as a practical method of preheating fresh air introduced into the building during winter. The design should also avoid overheating during the summer months which are prone to heat waves .

4.1 Existing building prototype

In an attempt to designate the "mean office building prototype" that we are designing the retrofit facade for, we need to investigate some common characteristics of office buildings in Greece.

According to the National Hellenic Statistical Service, in 2001 74,6% of all buildings in Greece had been constructed until 1980 [48]. The reason we make this distinction is because the first ever Greek law enforcing energy saving measures in building construction was introduced in 1979 with the Hellenic Building Insulation Regulation [50]. This regulation set the minimum requirements for building envelope thermal conductivity depending on the climatic zone. All buildings built before the enactment of this law, and quite a few after it, can be safely assumed as not containing any form of structural insulation in the building elements. This is quite surprising since the majority of buildings in northern Greece reach above 2600 heating degree days [48]. According to an empirical assessment realized in 2006 by A.G. Gaglia et al. [48] the majority of office or commercial buildings in Greece constructed before 1980 have inadequate or no roof and wall insulation, only one in six have central heating and less than 10% have full air conditioning. The review also calculated mean annual energy demands for electricity and thermal energy based on statistical analysis of energy consumption measurements in each of four climate zones. The aggregated total annual demand for Zone A is 115 kWh/m^2, which is the warmest zone, and 170 kWh/m^2 for Zone D which is the coldest. These numbers are fairly low considering they characterize non insulated buildings, but as mentioned before, there are few buildings before 1980 with central heating and even fewer with air conditioning that may find other means of heating and cooling that were not documented by the national statistical service.

There is scarce statistical data available on non-residential building typologies, structural characteristics or other factors of contemporary office buildings in Greece. That is why we will rely mostly on observation to build our prototype. There are two predominant architectural styles present in public office buildings in Greece. One is the modernist era repetitive concrete facade with window ribbons. The other is the all glass "curtain wall" of the international style. There is a third group that we are intentionally avoiding. Many listed buildings which function as office buildings for government or private enterprises have facades which are protected by law and it would be impossible to install any retrofit facade device on them, regardless that such a task would entail very little, if any, benefit. Most of these buildings are characterized by intricate decoration and extravagant architectural motifs that would make any form of retrofitting very difficult and presumably extraneous.

In the two more common styles however a retrofit would appear easier to implement since both have a similar architectural austerity. The modernistic concrete facade is on par with the strictness of a prefabricated modules and to the curtain wall, a glazed modulated retrofit would seem like a newer version of the existing facade design. Examples of typical office buildings found in the central business district of Thessaloniki are found in Figure 7 below.

Figure 7: In this figure we see photos of the two types of buildings mentioned above. Buildings 1-3 are of curtain wall facade buildings, while buildings 4-6 are the more modernist repetitive windows type. The photographs were taken in the Central Business District (CBD) of Thessaloniki by the author.

Given the plethora of buildings built before 1980, it would be convenient to choose a typical 70's style curtain wall facade office building as our retrofit prototype. The effects on energy performance would be more apparent in an uninsulated building, plus the simplicity of their facade construction would make retrofitting easier.

For all these reasons we designed a "best case scenario" retrofit-receiving building prototype based on measurements of an existing office building. The logic of this being that if we can prove that our goal cannot be accomplished in the most favorable case, then it is not possible.

The characteristics of this building are:

- south facing orientation
- attached on both sides to other buildings of the same height
- its south facade receives no shading all year round

Typical urban office buildings in Greek city CBDs are attached, making our best case scenario very close to a typical example. The orientation of office building facades depends on the street direction since all buildings in city centers are built directly on the property boundary facing the street. It is therefore quite possible that a large number of buildings would be facing south, as well as that the buildings on the opposite side of the street would be facing north. We cannot contribute to north facades however since the majority of the smart systems available depend on direct sunlight in order to function properly. This is also the reason we assume a non shaded facade, since it will give us the maximum available solar heat gains.

Figure 8: The typical floor plan of the building we chose in order to investigate our retrofit proposal. The building is attached on both sides to other buildings making these surfaces adiabatic in our energy performance calculation.

The building chosen is a seven storey office building built in the 60's, with a south facing curtain wall facade. In has a facade width of 14 meters and a building depth of 14,5 meters, making it almost square in floor plan shape as seen in Figure 8 above. Since we are only interested in interfering with the building's facade, an ideal building would have a narrow depth allowing for a larger facade to floor area ratio. Figure 9 below shows the buildings cross section. The office building extends on seven floors with the ground floor occupied by other commercial enterprises. These can be assumed as using their own HVAC systems making energy flows between the ground floor ceiling and the office building floor negligible. This further enhances our example's energy performance. The presence of other uses on the ground floor of office buildings is the norm in most office buildings situated in city centers, since the real estate value is higher for ground floor space and these are usually rented out to shop owners. This is convenient for our proposal since the retrofit can only be installed in levels above the ground floor.

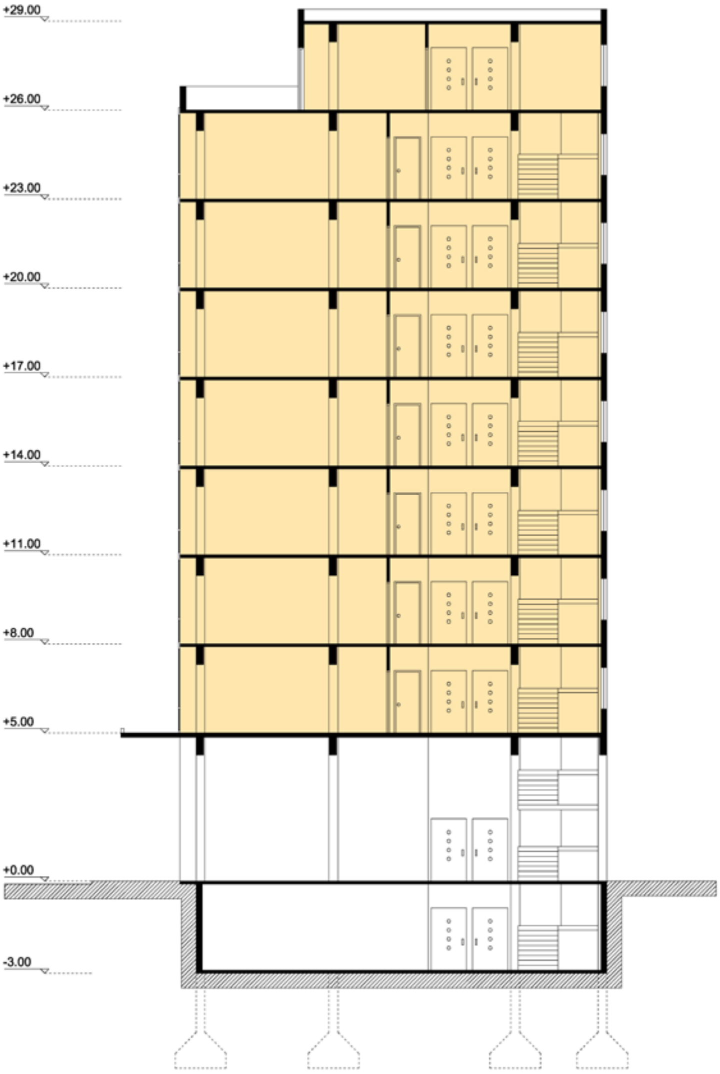

Figure 9: Cross section of our existing building example. We can see the commercial uses on the ground floor. The office space stretches out from the first to the 7th floor.

The building is attached on both sides to other existing buildings of the same height. This ensures that there will be no energy flow from these surfaces during the energy performance calculation, effectively reducing energy demand, compared to a corner building with more facade area exposed to the elements. The building's final important characteristic is that we assume it to be situated in a way that no other building, landscape or foliage casts shadows on its surface throughout the year. This simplifies our energy calculation, but also gives us the maximum available solar radiation gains for our building. This ensures that our best case scenario will effectively harness all available solar energy giving us the maximum achievable output.

General methodology for energy renovation of buildings asserts that once a building has been selected to be refurbished, its energy performance has to be calculated. The building's compulsory energy certificate is a good place to start. There are however some limitations to the amount of information derived from an energy certificate, although it does state the annual energy demand of the building which is our main concern. The energy demand calculation of our building example will be conducted in chapter 5.

4.2 Design proposal

Before we analyze the characteristics of our retrofit facade module, it would be appropriate to discuss some general issues of retrofit modules.

Architectural characteristics

When attempting to design a non-customizable facade module for multiple buildings, a considerable issue is how to overcome the variation of storey height and the size and position of openings in the existing buildings. Since our goal is to produce a prefabricated mass produced prototype, multiple variations and customizable panels will greatly increase the cost. An ideal scenario would be to only design a single compound facade module that would be able to produce multiple variations of complete facade designs by its own repetition in an array.

A module design that was symmetrical on the horizontal axis but not on the vertical and was still compatible to be connected to the other modules even if rotated 180°, could create a form of customization depending on the size of the facade module array. This design method, if predicted properly, could help overcome the difficulties of integrating the same prefabricated module to buildings of varied building envelope characteristics. By designing a module that is capable of connection to the array even when rotated 90° we can get an even greater number of facade possibilities. Figure 10 displays the different connection types below.

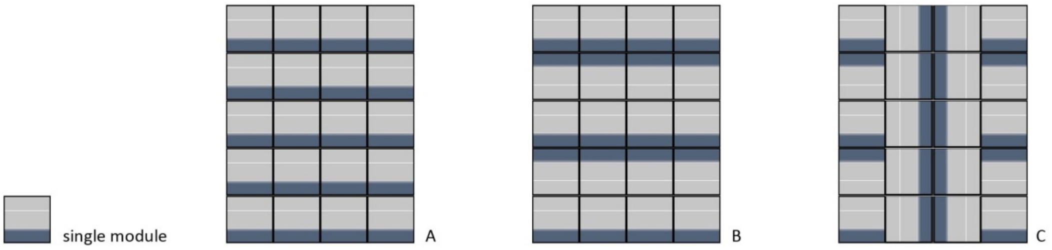

Figure 10: The image illustrates the possible array variations for (A) a module that cannot be rotated, (B) a module that can be rotated 180° and (C) a module that can be rotated at 90° intervals.

If we take this logic of tessellation further, we might envision a facade where each module carries out a specific function enabling the facade functions to become tailored to each building's needs. This would unfortunately mean the existence of more than one prefabricated module type and would inevitably increase the manufacturing cost. Keeping the module dimensions at a single storey height would be ideal for integration on a typical office building, retaining the ability to differentiate the array for special building examples.

When designing a mass produced prototype module for building facades, especially in cases where the implementation of such a design is to be integrated on a large number of existing buildings, it is expected that some sort of aesthetic standards have to be addressed, not only to convince property owners but to accommodate town planning restrictions as well. Fully glazed building facades have always been associated with contemporary architecture, austerity, modernity and status quo [51]. It is not incidental that most existing office buildings have highly glazed facades, as in our curtain wall example. Every owner however, wants their building to differ, and a large problem with prefabricated design is its constant repetitive motif. If all eligible buildings in a region decided to refurbish their facades with our design, they would all end up looking the same. There should in this case be some provision for aesthetic differentiation, by means of color options or pigmentation, in a way that does not conflict with the energy performance of the system.

Design features

After considering the technologies presented in the literature review, a composite design was drafted that implemented a number of different smart facade technologies into a single retrofit facade module.

As mentioned in the introduction to this chapter, the goals of a successful smart facade design are the optimal management of solar energy, the increase of building insulation, controlled ventilation, generation of energy, effective regulation of air temperature entering the building, visual comfort and the effective removal of heat for cooling of building elements when possible. Hot water provision is optional but highly unlikely to be useful, at least in our example, in an office building.

In order to accommodate these needs and according to the literature reviewed in previous chapters, the smart facade systems that would be useful to us in achieving these goals are:

- "smart" windows capable of protecting from increased solar gains during the summer but at the same time able to absorb the maximum possible energy gains from the sun during the heating period.
- PV cells integrated in the facade for electricity generation.
- Some form of controllable shading system that could adjust solar gains and natural lighting.
- A double skin that would serve as a means of facade ventilation to either remove excess heat during the summer or preheat air channeled into the office interior during the winter.
- A system that would regulate mechanical ventilation to achieve optimal cooling in summer and energy savings in winter.
- Integrated phase change materials to cool incoming air or delay heat onset during peak hours.

These features appear as incompatible and there was no literature found that studied such a complex system. We will attempt to analyze each feature separately and predict what the outcome of each system will be and what effect it will have on overall building performance. It is essential that the systems are integrated in a compact prefabricated module that will be easily assembled and installed on the existing building facade. A cross section of the proposed retrofit smart facade module can be seen in Figure 11. The module has a designed depth of 0.65 m. This means that it will offset the existing building facade by 65 cm outward.

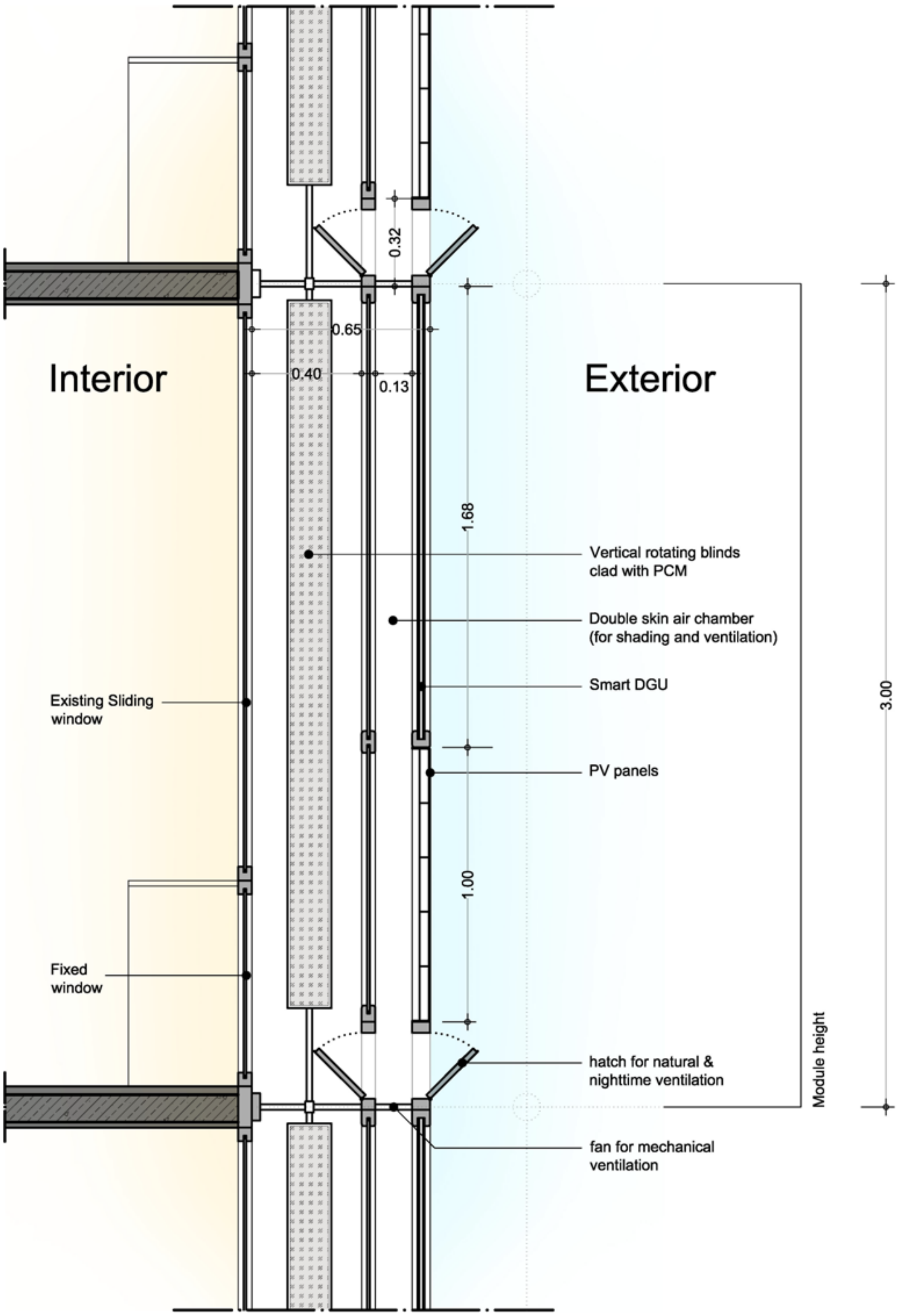

Figure 11: Cross section of the proposed retrofit module installed on a curtain wall facade.

Module dimensions

Module dimensions are 3.0 x 0.9 m. This covers the typical storey height of 3 meters and offers flexibility on facade widths variation as a fairly short module width of 90 cm is easier to retrofit to an existing building of any size, compared to a rigid 2 of 3 meter width module. This will of course lead to an increase in air infiltration and decline in insulation but this is a problem solvable through technology unlike the restrictions imposed by existing building geometry. A floor plan of a retrofit module array can be seen in Figure 12 below.

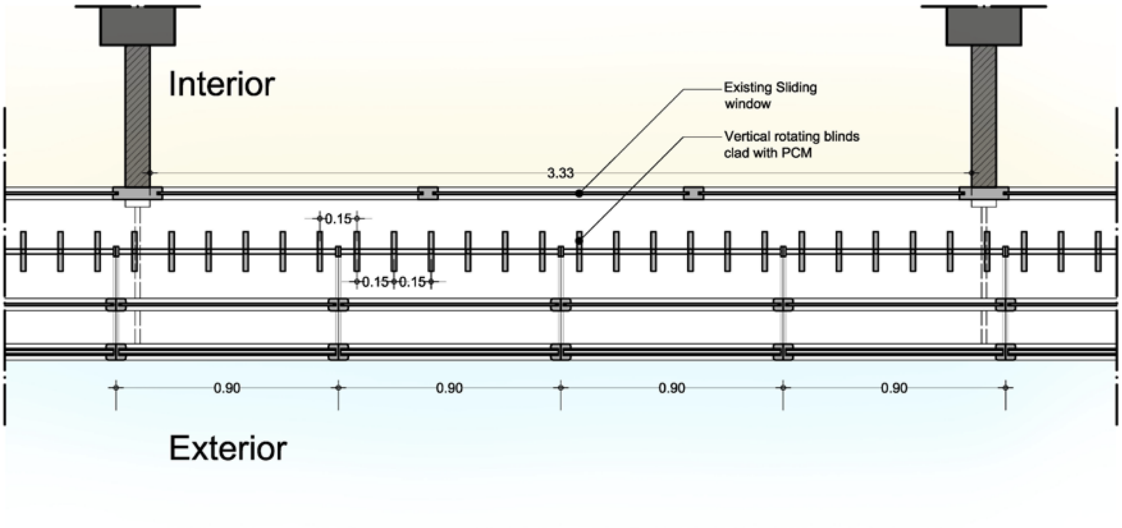

Figure 12: Floor plan of the proposed retrofit module installed on a curtain wall facade.

It is assumed that capping modules will also be available to bridge the gap left at the sides and at the top and bottom of the final facade matrix. These capping modules will regulate air infiltration and retain the same level of insulation and solar absorption.

Facade Design

The external layer of the retrofit smart facade will be a "smart" glazing technology. A hi-end glazed prototype should be the first surface incident radiation comes into contact with. This "window" will contain the main retrofit facade features involving solar heat absorption, reflection of solar radiation, control of solar infiltration and high insulation capacity. It can consist of a double or triple glazed window pane with air or gas filled cavities, low emissivity coatings and an electrochromic glazing technology. These features will ensure increased climate adaptability for the facade. This retrofit facade layer will regulate the bulk of solar radiation reaching the building facade and grant the highest insulating upgrade for the existing building out of all the retrofit facade features.

Double skin facade

Our design could be characterized as a "detached" double skin facade, since the main structure is essentially a double facade that when erected on the existing facade creates an air gap of about 40cm from the existing windows. Due to this characteristic installing it on an existing building facade would effectively create a "triple skin" facade with the existing envelope comprising the role of the first "skin" as we count from the interior to the exterior. This will produce two voids inside the facade that can be mechanically ventilated to accommodate the needs of the building depending on the season. Vertical rotating blinds are integrated into this void in order to produce a dynamic shading device and to facilitate vertical shaft ventilation. Phase change materials are installed on these vertical blinds. As mentioned above, the external layer of the DSF contains the hi-end smart glazing prototype that regulates the incident solar radiation. The second glass layer need not be so sophisticated. It serves mostly as a barrier that defines the double skin facade.

Phase change materials

PCMs are usually known to be integrated in building elements such as in dry walls, ceiling panels or even beneath floor boards. The integration of PCM materials on the vertical rotating blinds has a number of positive characteristics: The rotating blinds enable the facade module to be adaptable to westerly and easterly facade orientations where horizontal blinds are not so practical, giving the facade a limited adaptability to different inclination on a southerly orientation. The blinds function as a structural element for the mounting of PCM boards, the easily accessible blinds are more practical for maintenance or replacement purposes, because of the PCM's variable lifespan, integrating the PCM boards on replaceable elements is practical for PCM maintenance as well. Due to the stack effect acting on the air inside the PCM void, offices on lower floors will have cooler air coming in through open windows than those higher up [16].

The application of a PCM layer in the vertical louvers assists in regulating the temperature of air entering the building through the windows. By selecting an appropriate PCM based on melting temperature for the specific climate, we enable the dynamic ability of the facade to regulate heat flows throughout the year. During the heat of the cooling period, the PCM boards store heat which is rejected after office hours at night when the temperature drops and is removed by means of controlled night ventilation. During winter, the boards store heat which can be rejected after sunset in the afternoon working hours since the daytime is shorter, in order to reduce heating loads [52].

It should be noted that the PCM integration on the vertical blinds may not necessarily reduce the ambient air temperature of the interior. It will however retain thermal comfort and delay the increase of the interior air temperature, which will in turn delay the onset of the daily cooling with air condition to retain thermal comfort for the inhabitants. This is an important feature of PCMs as it offsets the electricity demand of the building for cooling during summer to an off peak period, creating an added benefit to the use of this system, releasing strain from the grid and helping reduce the risk of blackouts, especially in the high electricity demand periods during hot summer months [10].

Ventilation Characteristics

As mentioned in the literary review, DSFs are frequently used for the benefit they have on implementation of a movable shading device inside the facade cavity. This can be a roller shade, louvered blinds, vertical fins or other retractable shading device. The positioning inside the facade cavity protects the shading system and reduces maintenance costs. This is also very effective in ventilated DSFs since the heat accumulated when the shading device is operational, is vented outside, or inside depending on the season, effectively reducing the buildings energy demands, either from avoiding unwanted heat gains in the summer or increasing heat gains in the winter.

A controlled ventilation double skin facade has the ability of preheating the air in its cavity for ventilation of interior air during winter. Poirazis claims that thinner air cavities are more efficient in this aspect because thinner cavities have higher air velocity and thus higher heat transfer coefficients [53, pg 62]. This can also function during summer when heat absorbed by the glass is radiated into the air cavity increasing its temperature. The resulting stack effect causes the air to rise, naturally venting the heat accumulated.

In terms of proper summer ventilation and night ventilation, it is vital to research the ideal dimensions for optimal ventilation in combination with the other moving systems involved (blinds, vents) as well as the dimensioning of the mechanical ventilation fans and the air ducts. This constitutes an interesting topic for further research into the current subject.

The retrofit module is equipped with ventilation hatches on each glazing layer. These hatches serve to regulate heat flows to and away from the building interior depending on the thermal period. During the cooling period the external hatches are open while the internal hatches are closed. Hot air is accumulated in the first air gap of the facade, from the dissipation of heat absorbed by the glazing and by means of a greenhouse effect. In order to protect the building from the accumulated heat, the aforementioned ventilation hatch formation vents the excess hot air back into the outside environment protecting the interior from the heat dissipation of the glazing and keeping it cooler than the exterior temperature.

During winter the exterior hatches are closed and the interior layer hatches are open. As in the previous case, hot air accumulates inside the double skin but is this time vented into the interior air gap. If windows in the existing building are open, this air will find its way inside, effectively carrying heat to the building interior. Figure 13 illustrates the two forms of ventilation introduced in the facade design.

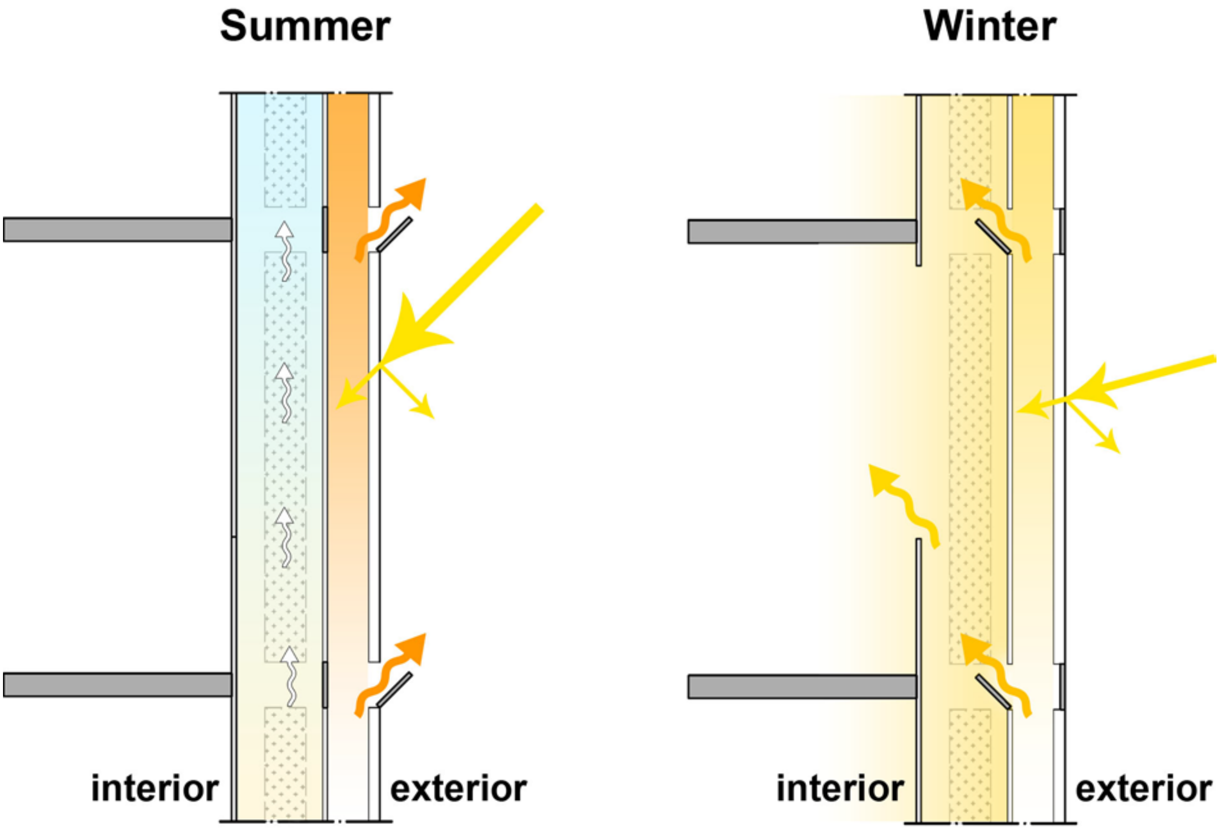

Figure 13: The image illustrates a simplified section of the retrofit facade describing the function of the two air gaps during summer and winter.

The interior air gap can function as a chiller of incoming air during summer, by absorbing the heat of the outside air through the phase change materials installed on the vertical blinds. Outside air enters the facade from the bottom and is led upward by mechanical ventilation through the vertical blinds, while the integrated PCM absorbs heat from it. It can then enter the building interior when widows are open and if occupant thermal comfort allows it.

The same effect can be used in winter, only this time the air is pre-heated in the external double skin facade. However, the incoming air should not be cooled as it flows through the vertical blinds. This can be achieved by selecting the ideal PCM with a melting temperature above that of the incoming air but capable of melting during summer. Because of the difference in thermal comfort temperature during summer and winter, an appropriate design temperature for the PCM is possible.

In order for the system to function properly, mechanical ventilation is vital. It may still be able to work properly with natural ventilation due to buoyancy, but as was concluded from the literature review, mechanical ventilation definitely increases efficiency and avoids negative effects due to changes in the wind. This mechanical ventilation is made possible by integrated fans in the retrofit facade module.

Photovoltaic integration

On the external surface and below the "smart" glazing surface, will be the position of the PV module. PV cells are naturally translucent because they are very thin. This permits a portion of light to pass through. This however has a negative effect on efficiency. There are many transparent PV technologies found in the literature that could be used in order to minimize shading of the existing building. In our design we propose a 1,0 m high PV module to be installed below our external "smart-glass" layer. This will ensure unobstructed absorption of sunlight and optimal electricity generation for the PV module's position. Whether the PV module is transparent or not does not conflict with proper smart facade function. Therefore we shall assume that it is a typical PV module for ease of calculations.

Automated control system

As we saw in the literature review, control systems are proven to enable the optimal thermal performance of a smart facade system. Since weather conditions are unstable in many cases, the proper sensors should be installed on the facade system and control the appropriate functions of the embedded systems to achieve the maximum efficiency of the system. The centralized control mechanism should manage electrocromic window opacity, ventilation hatch position, vertical blind rotation and mechanical ventilation. In an ideal scenario it would also assume control of the existing building windows for full integration.

Night-time ventilation

Although not directly incorporated into the design, the retrofit smart facade allows the employment of night-time ventilation. This basically permits the building to vent heat accumulated during the day and absorbed by the interior elements when the building is not functioning. Night ventilation takes advantage of the lower ambient temperature during the night to cool the building interior. The purging of heat absorbed during the day will delay the increase of internal temperature to uncomfortable levels when the office opens again on the next day, reducing the duration of cooling and overall cooling demand. The ventilating ability of the smart facade allows for the efficient changing of air while the existing windows are left open overnight. The protection supplied by the double facade protects the building interior from wind and rain as well from break-ins.

Load Bearing structure

As may be evident, a facade module matrix of this size needs the appropriate structural system to bear its structural loads. This needs to be designed in such a way that it accommodates the facade retrofit and does not impede the smart facade's functions. As we will demonstrate in the final section of the next chapter, we will assume that such a structural system is applicable and does not affect our proposal, without analyzing it further.

5 Calculations

In this chapter we run a simple simulation in order to obtain some workable values to assist in our assessment and to quantify gains.

5.1 Hypothetical case study

As mentioned in the previous chapter, in our effort to calculate the effects our design will have on an existing building example we will try to simulate it on a "best case scenario". This will give us a representative indication on the achievability of our goal, since if the best case scenario fails to achieve our goal, it is unlikely that a real life example will.

We need to calculate the building's annual energy needs before the installation of the retrofit facade. Then we must test the applicability of such an installation and if there are any conflicting parameters that will impede on the current building's function. If the design fits onto the building without creating any problems in doing so, then we calculate the new energy performance of the building and compare the results.

Apart from the assumptions on building orientation, shading and position regarding neighboring structures we should also make some assumptions for the function of the building and it's HVAC system. As discussed, the building is an office building with a continual use from level 1 to level 7. There is a small foyer on the 8th floor that serves as the landing of the staircase, provides access to the roof and houses the machine room for the elevators. There is no specific ventilation or heating system installed. That is why our simulation will be used only to cover the energy loads, for heating and cooling, needed to retain air internal temperature at the standards dictated by building codes [44]. This direction was chosen because it is apparent from the statistical data available that not all existing office buildings employ central heating, air-conditioning or central ventilation systems. Apart from that, there are different heating systems present in existing buildings utilizing different fuel types and with different efficiencies. This may give us a generalized image of final consumption but it will also allow us to compare fuel prices in the end.

5.2 Simulation

In this section we use energy modeling software to calculate energy demand values for our existing building before and after application of a smart facade system. We also calculate the maximum attainable output of the building integrated photovoltaics.

5.2.1 Thermal simulation

The use of simulation software is a very common practice for investigating the effects different technologies have on energy performance of buildings. In most of the literature reviewed, the core measurements were made using simulation software and experiments were used to validate the simulation results. A simulation can never be considered a precise means of performance prediction, mainly because of the very large number of variables contributing to the final result, weather being a large factor. It can however be considered a very methodical approximation and is accepted as scientific evidence in many cases lacking experimental measurements.

In our case, we will use "Ecotect Analysis" for our thermal simulation. It is a software package commonly used by building designers and architects for thermal analysis, daylighting, sound insulation and shading calculations of their designs. It is however quite simplified in that it does not take any consideration of dynamic systems like, double skin facades, phase change materials, electrochromic windows, moving shading systems and, of course, photovoltaics.

Since the direction of this dissertation is mostly a review of the available smart facade technologies and an evaluation on their documented results, we will rely mostly on the literature for validation of our design proposal and the support of our claims. In order to fully simulate our design we would require a fluid dynamics analysis to calculate the effects of ventilation and air movement in the double skin facade. This may still not be enough to fully simulate our design. In any case, experimental measurements on scale or real size models is the best choice in order to achieve results that validate our predictions.

The steps we took to calculate the thermal analysis of the existing building as it is today were the following:

- We designed the office space volume as one thermal zone for simplicity. This is a reasonable simplification, since interior energy flows are negligible.

- We added the two attached buildings and the ground floor as separate thermal zones that are not included in the thermal simulation. The program will consider their common surfaces with the office space as adiabatic and not consider energy transfer through them.
- We design the south curtain wall facade as a series of large windows with a U-value of 6.0 W/m^{2}K which is in agreement with the Greek Technical Chamber's Technical Instruction 20701-2/2010 [44]. This value is used for all other windows on the building as well.
- We add a fixed-window ribbon below the line of windows on the south facade with adjusted transmittance to simulate the tinted glass band that rises from the floor to +0.75 m on each floor. The same U-value as the other windows is retained.
- The U-value adopted for the brick wall on the north facade was 2.20 W/m^{2}K and for concrete walls in contact with the external air U = 3.40 W/m^{2}K [44].
- The roof is a concrete slab with U = 3.05 W/m^{2}K [44]

The geographic location selected is Athens, Greece and the orientation is south facing for the curtain wall facade. We run a thermal simulation to calculate space loads for heating and cooling if thermal comfort for summer is at 26° Celsius and 20° C for winter. We set the internal heat gains from appliances at 15 W/m^2 [44] and the air infiltration rate at the default of 0.5 changes per hour. Finally we set the working hours from 9:00 to 21:00 on weekdays and to 0 hours over the weekend for the whole year. We did not select an HVAC system type as we are only interested in thermal load calculation regardless of HVAC system efficiency. Figure 14 below illustrates the visualized building model in Ecotect.

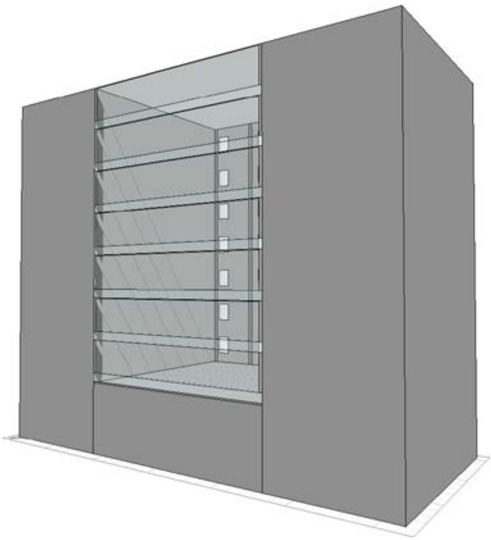

Figure 14: Visualization of existing building model in Ecotect with neighboring buildings.

After running the simulation, a table containing monthly heating and cooling loads is produced by the program. The final annual energy demand for the building is 108 729 kWh, which can be analyzed as 76,5 kWh/m^2, for an office building area of 1421 m^2. This corresponds to 44,4 kWh/m^2 for heating and 32,1 kWh/m^2 for cooling. These values are fairly low considering the mean office building of this type has almost double the energy demand as mentioned in the previous chapter [48]. Low values were anticipated as we have chosen few annual working hours as well as a best case scenario. If the energy demands for 24-hours 7-days a week use are calculated then the energy demand for the same building would rise up to 214,16 kWh/m^2, which is much higher than the statistical mean for this climate zone. The assumption we make here is that the building is never used outside of office hours and that a strict program is followed.

If we proceed to examine the effects of changing the thermal properties of the existing facade, by means of a window upgrade, we can increase thermal insulation on the window properties to U = 1.60 W/m^{2}K, as given by a high quality low-e double glazed window from the literature [12], with a SHGC of 0.4 and run another simulation. The results show that final annual energy demand has dropped to 61,4 kWh/m^2. That is a 20% decrease which agrees with the literature. By looking at the monthly demand we can see that this upgrade has a positive effect on heating and cooling for every month of the year. However it is not enough to drop the demand to a near zero energy building.

If we attempt using an even more sophisticated glazing technology as advertised in the state of the art smart windows for dynamic daylighting review by Baetens et al. [31]

we can use an electrochromic window with triple glazing and gas filled voids with a U-value of 0.50 W/m^{2}K and a SHGC of 0.3-0.1 depending on window transmissivity. Since Ecotect does not support dynamic window properties we will attempt to run two separate simulations and select the most convenient data for each case. The initial results show a definite improvement from the previous glazing type but as expected the higher SHGC glass has a better performance in winter while the lower SHGC glass has a better performance in summer. Since this is an adaptive "smart" glazing technology it is to be expected that it will function in the best interests of energy performance in each case so we can create a new monthly chart with the favorable values for each month and draw an optimized annual demand. The results are 37,5 kWh/m^2 for annual heating loads and 17,9 kWh/m^2 for annual cooling loads for a combined 55,5 kWh/m^2 annual energy demand. This is a 27,5 % reduction from our buildings initial energy demand, however it still doesn't qualify for near ZEB.

We shall attempt one final simulation in which we will try using fictitious thermal properties to prove that window properties are not enough to solve the energy performance of a building. If we change the previous window SHGC to 0.85 for winter, in order to utilize maximum solar heat gain, and to 0.01 in summer, in order to minimize solar heat gains, then our resulting demand will be marginally below 50 kWh/m^2 (49,9 kWh/m^2). It is a slight improvement from our previous plausible result and still not good enough for near zero energy.

In order to have a representative notion on the effect of smart facades on overall building performance, we re-ran the simulation on the previous model, this time using as U-values for all existing building elements the minimum required by the Greek Regulation for Energy Performance in Buildings [54] for thermal Zone B. These values are 0.45 W/m^{2}K for the roof, 0,50 W/m^{2}K for all external walls and 3,00 W/m^{2}K for windows. The resulting annual energy demand was 47,0 kWh/m^2. As we can see, application of regulation limits on insulation for all building elements on top of implementation of a smart facade system was not enough to bring energy demand down to a near zero energy building level. It does however illustrate the effect the smart facade has on the building's energy performance. For comparison, if all the existing building elements were all upgraded to the regulation limits, the annual energy demand would be 55,4 kWh/m^2 without the integration of a smart facade. As we can see the resulting energy savings are similar in both cases. The retrofitting of a smart facade on the existing building would have almost the same energy savings as a total refurbishment of the entire building envelope to regulation standards. If the overall building shell refurbishment is a more economical solution than the smart facade retrofit, then there seems to be no reason to proceed in such an upgrade.

Concluding remarks on building performance simulation

It is worth mentioning that by regarding the building only functioning from 9am to 9pm, there are a few hours in the morning where sunlight penetrates the building facade and heats up the interior air. This is especially true during summer since the heat build-up can become quite intensive [53, pg 63]. By enacting night-time ventilation on the building, from closing time to opening time, this heat build-up is avoided and substantially reduce cooling loads. Ecotect does take this heat build-up into consideration in its calculations but cannot calculate ventilation reductions. Therefore, with night-time ventilation it can be expected that cooling loads will be less. This was found to function when working hours were set to earlier in the day.

In an effort to further improve our findings, another simulation was conducted in which a retrofit facade was hypothetically installed on the north building facade as well. The reasoning for this was to see what benefits the increase in thermal insulation would have on the only other exposed facade of the office building. The results showed energy demand dropping to marginally below 50 kWh/m^2. This shows the importance of air infiltration and ventilation, because for lower levels of air infiltration and controlled ventilation the above model's energy demand drops to almost half. We cannot however manipulate air infiltration and ventilation, because our interest is only in upgrading the building facade without interfering with the building interior, and air infiltration won't change on the rest of the building envelope, nor can we upgrade the building HVAC system.

The validation of results produced by Ecotect and its integrity in comparison with real-life results was tested in the proceedings of the 2012 Winter simulation Conference [55]. Ecotect results were determined to closely resemble the actual monthly energy usage curve. In comparison with the other three Building Energy Modeling tools used, Ecotect simulations appeared to be the most precise. We can therefore assume that these results are fairly accurate for the building in question.

5.2.2 PV simulation

A separate calculation was conducted for the annual electrical energy produced by the PV panels on the facade module. The program used was "System Advisory Model". Geographic location was again set to Athens, Greece.

Following the "best case" scenario we initiated in the previous chapter, we will choose a PV module with high capacity in order to generate as much electrical energy as possible for the facade surface we have available. We pick a 440 W module by SunPower with a high efficiency (21%) in order to maximize our output. This can definitely be considered as overkill since such an efficient PV module will be quite expensive and the difference in production at such an inefficient angle does not justify such an investment.

There are a few inconsistencies in our assumptions regarding the selection of a PV module, mostly on the part of module size. The PV panel area on a single retrofit facade module has dimensions of 0,9 x 1,0 m making it 0,9 m^2. The PV module we selected has different dimensions and is almost double in area. Nevertheless we will assume for the sake of simplicity that in the case of the mass production of our retrofit facade design, the same PV technology will be used in producing its PV surface.

Since our example existing building has a facade width of 14 m and a height of seven floors, the total PV area will be equal to 14 m x 1m, which is the height of the PV module area, times 7 floors. This equals 98 m^2. This is our only constraint in calculating annual energy production. Running the simulation with these variables on SAM we come up with an estimated production of 11 386,7 kWh of electrical energy per year, for the first year. This is effectively the highest achievable output we can hope to achieve in Athens, with 98 m^2 of PVs on a south facing building facade. A chart with the monthly output is available in the Appendix.

It should be mentioned that if the same PV module was mounted on the roof of the building, assuming sufficient space was available, and at the optimal angle for Athens, which according to SAM would be 20°, then the annual output would be 13 402,7 kWh electricity.

On PV efficiency and slope

The decrease in output experienced by positioning the PV module vertically in comparison to its optimal angle is in the order of 15%. In order to avoid this decrease we could attempt to alter the retrofit facade module's planar shape to a non-planar irregular one giving the installed PV panels a better slope of 80° or even 70° for example. Even at this low inclination the overall volume of the facade would change disproportionally. The uneven result would create a lot of technical problems and complications in installation, increase difficulty of transportation and manufacturing costs. It would also cause a number of structural weaknesses on the module, increasing the risk of failure. The inclination would facilitate the accumulation of dust reducing cell efficiency and increasing maintenance costs. The non-vertical design would also have unpredictable results on air flow patterns possibly affecting ventilation efficiency. The overall payback of the increased PV efficiency, in terms of energy, would probably not be enough to attest to the increase in risk amounting from the altered module form. In this logic, a simpler rectangular planar form is favored.

5.3 Measured benefits

In this section we will perform some simple calculations on the energy benefits from the energy performance upgrade of the facade retrofit.

On Energy performance

By installing the retrofit smart facade module on the existing building's facade we successfully managed to reduce energy demand from 76,515 kWh/m^2 per year to 55,470 kWh/m^2 per year. That is a reduction of 21,045 kWh/m^2. For a building of 1421 m^2 that would equal an estimated annual energy saving of 29 904,95 kWh.

In order to perform energy savings calculations per fuel type, we need to calculate the energy savings for cooling and heating separately. The energy demand for our existing building was calculated at 44,411 kWh/m^2 for heating and 32,104 kWh/m^2 for cooling, while the annual demand after refurbishment was calculated at 37,535 kWh/m^2 for heating and 17,935 kWh/m^2 for cooling. That gives us savings of 6,876 kWh/m^2 for heating and 14,169 kWh/m^2 for cooling, which is translated as 9770,796 kWh per year for heating and 20 134,149 kWh for cooling.

In order to calculate final energy demand, we have to multiply these values with the efficiency coefficients of the HVAC systems used.

Avoided Greenhouse gas emissions

Apart from the building's energy use and the heat loads produced by its functions we have the environmental benefit which as described in the introductory chapter is the driving goal behind all the legislative attempts made for energy saving.

We can calculate the avoided greenhouse gas emissions by multiplying the total amount of primary demand kWh saved, by the amount of emissions produced in generating this amount of energy and delivering it to the building. This depends on the type of fuel used for the production of energy. The primary energy coefficient allocated to each fuel type depends on the fuel conversion or energy production process in that country. For Greece the primary energy coefficients as well as the GHG emissions per fuel type appear on the Table 3 below.

Table 3: Primary Energy coefficients and GHG emissions, in the form of kgs of CO_2 per kWh of energy consumed. [44]

Fuel	Primary Energy coefficient	GHG emissions per energy unit ($kgCO_2/kWh$)
Natural Gas	1,05	0,196
Heating Diesel	1,10	0,264
Electricity	2,90	0,989
Biomass	1,00	---
District Heating	0,70	0,347

The actual final demand for heating and cooling will be eventually altered by the HVAC system's efficiency. This will probably lead to an increase in heating demand if central heating is used because central heating systems usually have efficiencies of less than 1,0. It may also lead to a decrease in final demand for cooling or both if air-conditioning or heat pumps are used in the buildings HVAC system, since air pumps have efficiencies of 2,0 - 3,0 or even more depending on the type. In the absence of an HVAC system, we will assume an efficiency of 1,0 for heating and cooling.

By substituting the numbers in table 1 above, the avoided GHG emissions per year will be:

- 2,01 tons of CO_2 if Natural gas is used for heating
- 2,837 tons of CO_2 if Diesel is used for heating
- 28,024 tons of CO_2 if electricity is used for heating
- 2,373 tons of CO_2 if District Heating is used for heating
- 57,747 tons of CO_2 from electricity used for cooling

It should be noted that the real amount of avoided GHG from cooling demand will be less once the air-conditioning Energy Efficiency Ratio is used in the calculation, but it will still be in this order of magnitude. The reason electricity produces such a large amount of GHG emissions is because Greece's energy fuel mix comprises mainly of lignite fired powered plants [56] and lignite carbon to energy ratio is higher than other qualities of coal [57].

Biomass is assumed to produce no GHG emissions by definition.

Energy balance

Our energy balance can be calculated by offsetting overall cooling load demand with produced electricity on a yearly basis. This does not imply that all energy produced is used on the cooling loads. It only functions as a means of calculating "net" building energy demand.

According to our SAM calculation we can theoretically generate 11 386,7 kWh of electricity per year on the facade of our example building. If this amount is added to the annual energy savings our retrofit has on the building's cooling demand we have:

$$20\ 134{,}149 + 11\ 386{,}7 = 31520{,}849 \text{ kWh}$$

In terms of avoided GHG emissions, this would increase the amount to 90 404,9 tons of CO_2. Again without correcting for HVAC efficiency. This is a substantial decrease and an interesting point to be made on the effectiveness of using renewable energy for environmental reasons, apart from the financial benefit of energy production.

5.4 Simple cost - benefit analysis

In order to calculate the economic feasibility of our proposed smart facade upgrade, we need to calculate the financial benefits deriving from the energy savings we have calculated so far. We will estimate the maximum cost per meter square of retrofit facade in €/m^2 in order to make a straight line payback in 10, 20 and 40 years. This will help us form an opinion on whether the proposed design is economically feasible in today's energy prices.

According to Eurostat, the price for domestic electricity of high (above 5000 kWh) consumption in the first half of 2014 for Greece was around 0,19 €/kWh including all taxes and levies [58]. That results in a total annual savings of 3825,49 € from cooling. If we apply net-metering with the electricity produced from the PV modules then our total savings are 5988,96 € per year.

If the electricity produced by the PV cells was sold to the Power Company at the feed-in tariff rate of 0,115 €/kWh [59] we would have an added annual income of

1309,47 € from the sale of electricity. This would lead to annual savings of 5134,96 €. Since these savings are lower, it is not in our financial interest to sell generated electricity for a Feed-in Tariff. This was obvious, since the sell price of 0,115 € is lower than the buying price of 0,19 €. Therefore our preferred annual savings from reduced cooling loads is 5988,96 €.

From our heating demand we have an annual saving of 9770.796 kWh which if applied to natural gas fuelled heating, at a buying price of 0,075 €/kWh [58] would bring a total of 732,81 €. This is a fairly small sum, but our design didn't produce a large energy saving to the existing building's demand.

If our fuel is heating oil (diesel) with an estimated energy value of 10 kWh/lt [60] and a price of 1,05 €/lt [61] then our annual savings would be 1025,93 €. This is slightly higher, because oil prices are higher than natural gas prices, for the same heating value, at the moment.

If we take our worst case from the two (oil), we will have a total annual energy savings of 7014,89 €. This is our best case scenario because we have not taken HVAC efficiency into consideration yet and although oil fired boilers have efficiencies of below 1,0 there are heat pumps and air-conditioning systems with rated efficiencies above 1,0 [62]. It is therefore to be expected that actual savings would be less in reality.

The total facade area of our existing building example is 14 x 21 = 294 m^2. This means that for a 10 year payback on a 7014,89 €/year savings we would need a retrofit facade that would not cost more than 238,60 €/m^2. For a 20 year payback the maximum cost is 477,20 €/m^2 and 954,40 €/m^2 for 40 years.

According to Pikas, Thalfeldt and Kurnitski [47], the specific price of a hi-end triple glazed window of 2 m^2 is about 120 €/m^2 making the final cost of a 2 m^2 unit 240 €. The PV panels we chose cost around \$1000/m^2 [68] making them highly unprofitable. We had commented on this during our electricity generation calculation. A cheaper PV module would have a minor reduction in output at such an inefficient angle. That is why we will follow the previous example and use their calculations of 250 €/m^2 as our guideline. This gives us a total of 370 €/m^2 for the external layer of the smart facade module alone. That already leads us to a payback period longer than 10 years. If we add the cost of the second glass layer, the blinds, the PCM, the control mechanisms for the mechanical ventilation and blind rotation as well as peripheral structures (frames, hatches, fans) the cost is bound to climb above the 20 year payback mark.

This ascertainment makes the affordability of the retrofit debatable. The EPBD calls for energy upgrading refurbishment to be cost effective [2]. A 20+ year payback does not seem like a good value for money investment, especially when inflation and price changes are not taken into consideration. In this case a traditional refurbishment of the entire building envelope may even prove to be a cheaper alternative.

The principal reason for designing a single module type is production economy. Mass production of prefabricated modules that only need to be installed on an existing building greatly minimize the cost of the final product. We cannot predict the decrease in production costs, but depending on the size of production it may lead to a substantial percentage. Another factor in a modular approach that has an economic benefit is the brief and non-invasive installation. Traditional envelope refurbishment would hinder smooth office functions and could even cause building operations to halt. That would create an economic strain on the commercial aspect of the work done by the occupants of the building.

Financial incentives are expected to develop in order to aid energy upgrade retrofits for existing buildings. According to the EPBD [2] these can be either in the form of financial incentives or energy certificates. Economic incentives of this type already exist in Greece [63].

The results of our calculations, though they may have been indicative, have a distinct conclusion on the non financial feasibility of our design. However the substantial reduction of calculated avoided greenhouse gas emissions indicate the potential in environmental benefits of this proposal. The weighing of environmental over financial benefits is an issue that needs to be addressed. At the moment there seem to be different schools of thought on the matter since LCA of smart technologies and costs of retrofits may tip the scale in either direction. In the end it is up to every person involved to decide what the true benefits are and to decide accordingly.

5.5 Assumptions

In this section we list the factors of executing a retrofit of this scale, that we did not take into consideration. Although these factors are crucial in the event that such a proposed mass scale retrofit is to be enacted, they do not hinder the outcome of the objectives we chose to investigate regarding the integration of smart facade systems and the effects on the energy performance of the selected existing building.

Structural integrity

A large scale retrofit such as a new facade has a substantial structural impact on a building and in most cases the building's existing structural elements may not be enough to withhold the added weight. A study is necessary in every major building renovation. Apart from that, the subject matter of structural reinforcing for building renovations as a study field on its own, has a plethora of published papers. This dissertation will not go in that direction. It will be presumed that such studies will take place in each case a retrofit is made and the structural design will not interfere with the performance of the facade upgrade. A viable solution is generally possible for every type of existing building and every type of refurbishment, so it will be presumed that every design proposed is structurally applicable.

Surrounding obstacles

As mentioned before in our paragraph on existing building selection, it is assumed that the existing office building to be upgraded will be free of obstacles that would block the sun's rays throughout the duration of the year. This is to ensure that maximum solar efficiency is achieved. All calculations made in this chapter were under these circumstances. This has indeed an adverse effect during summer, but neighboring obstructions are usually less helpful in producing shading during summer when the sun has a higher altitude and more impeding during winter when solar gains are useful but the solar altitude is low. In our case it is also a helpful method for testing our design's capacity for energy conservation and to ensure maximum solar cell output.

Architectural and urban planning constraints

There are constraints when it comes to altering building facades in an urban environment even for non-listed buildings, especially when that entails increasing building volume. That is however not something entirely outside current legislation and there are possibilities in gaining approval for special circumstances. However, it is pretty obvious that since the entire operation is bound to be executed on a national level, the corresponding legislation will be provided to accompany all legal matters that will occur.

6 Challenges and qualitative benefits

In this chapter we will analyze the different types of added bonuses that the implementation of our retrofit facade design would have, when installed on an existing office building. These are the benefits that cannot be quantified into calculated energy or financial savings, but that nevertheless contribute to some form of increase in work efficiency, real estate value, occupant comfort or safety. On the other hand we also describe the adverse effects this retrofit will have on a building that could negate some of its benefits if not addressed carefully.

6.1 Qualitative benefits

Apart from the initial goal of increasing energy performance for financial and environmental reasons there are a number of added benefits that installing a retrofit facade module will have on many features of the existing building. The facade retrofit will function as a second skin and thus represent a near manifestation of one with very similar characteristics to a double skin facade. There is a number of unintentional benefits that will derive from this, as well as some due to characteristics of the facade design. These benefits may prove more important for achieving the acceptance of the facade retrofit by the occupants, as they are easier to experience than energy savings [64].

Benefits derived from implementation of retrofit facade module:

Other benefits, apart from energy performance, that can be achieved by installation of a retrofit facade are listed below.

Sound insulation

Acoustics can be one of the main reasons for applying a facade retrofit apart from the upgrade in energy performance. This is very beneficial for a working environment since outside noise, especially at a CBD level, is a negative factor for work efficiency. The additional external layer on the facade can considerably improve the sound insulation of the building, effectively screening off external noise like a protective barrier. The external layer reflects sound off its surface and towards the direction it came from. This effect allows for the existing windows of the building to be opened without an increase in outside noise penetrating, so sound insulation in the building is improved even when the windows are open.

It is however possible, that sounds from the interior will be partially reflected back in certain situations where sound or information may be transmitted to other rooms. This undesirable effect may create problems mentioned later. Many extensive studies have been done on this matter to measure the sound insulation achieved. Oesterle [51] showed in one such example, that the sound insulation value from the outside to the inside is 15 dB.

Apart from the calculated factor of sound insulation, there is also the psychological function. Windows in office rooms tend to be of great importance to the person working there, as it helps that person define their space and is a manually operated connection to the outside world and a regulator of comfort. The ability to retain these benefits with less exterior disturbance will be liberating for the person and will positively impact their mood [51, pg47].

Natural ventilation

Another main advantage of double skin facades is their ability to allow natural ventilation. The natural flow of air through the facade due to stack effects and difference in pressure will serve to replenish the air of the office interior providing fresh air before and during office hours and effectively increasing comfort and satisfaction for the occupants. During the heating period the preheating of air inside the double skin void allows for natural ventilation with pre-heated air with natural means and without the expenditure of energy. By simply opening the windows occupants can naturally ventilate their office space while retaining thermal comfort.

During the cooling period, the PCM installed in the vertical blinds will absorb heat when incoming air flowing up through the void is too hot. This will again ensure natural ventilation that retains thermal comfort even in the hot summer climate.

Daylight control - visual comfort

The retrofit facade system possesses a number of solar radiation adjusting systems that also regulate glare from intense sunlight. The automation of these systems offers comfortable working conditions for the occupants at various office depths from the facade. The shading systems along with the increased facade thickness reduce incoming sunlight to comfort levels for occupants next to the windows during summer, while the white non glaring reflective material of the vertical blinds allows for the even distribution of diffuse light to greater office depths during the winter.

Fireproofing

The extra layers integrated onto the building facade enhance the building's resilience to fire by increasing the structural elements integrity under flame and delaying their fail time. This is also foreseen by the Greek building fire code [65]. However the true effects of this cannot be fully predicted and there is dispute on whether double skin facades protect or endanger the building in the case of fire.

Wind load adjustment

Double skin facades on the exterior of tall buildings can serve to reduce the negative effects of sudden changes in wind pressure. Gusts of wind may often press upon the building facade, a phenomenon which is more likely in tall unobstructed buildings, which can result in slamming of open windows and general disruption of working of occupants. Similarly to sound proofing, the external layer of the retrofit facade and especially the internal void of the double skin, act as a wind pressure barrier, protecting from sudden bursts of wind and allowing for the users to work unobstructed, even with the windows open.

Night time ventilation

Although night time ventilation is directly linked to energy savings, it is a non-quantifiable benefit since its affect on annual energy demand cannot be directly calculated. The process of night time ventilation is an effective way of easily removing heat loads absorbed by the materials in the building, be they structural elements, furniture, or finishes, to pre-cool the inside environment to its lowest possible temperature before the beginning of the next day. When absorbed heat is successfully discharged, night time ventilation provides a great improvement on thermal comfort and air quality for the occupants. Double skin facades are able to facilitate this due to their ability of providing natural night ventilation while being both burglar proof and protecting from weather phenomena [53, pg 63].

Thermal comfort

The regulation of daylight that an automated glass facade entails has a positive outcome on user satisfaction due to thermal comfort as well. The retrofit module is designed to pre-heat incoming air during the winter, and pre-cool the air during the summer. The presence of natural ventilation at an air temperature that is regulated to be closer to thermal comfort standards will definitely have a positive effect the occupants level of thermal comfort [64]. Another important factor than increases thermal comfort is the fact that due to the greenhouse effect acting on the double skin, existing building envelope temperatures will be closer to indoor air temperatures. This minimizes radiated heat from occupants to the building elements of the envelope, effectively increasing thermal comfort.

Insulation

The extra layers of materials will inevitably increase the buildings loss of energy, or heat gain, through radiation. That is, besides, one of the main goals of installing the retrofit facade in the first place. The pockets of air and solid mass of the retrofit facade layers will also delay transmission of heat through convection and conduction, increasing insulation.

Elimination of existing thermal bridges

Since the retrofit facade will cover the entire facade, it will create a new insulation layer and also a barrier with the external air minimizing or totally eliminating infiltration of external air. Because of this the effects of thermal bridges will be drastically reduced if the retrofit facade is air-tight.

Increased burglary protection

As already mentioned above, it is highly unlikely that any break-ins will occur through the facade openings after the retrofit facade has been installed. [64]

Aesthetic upgrade of building's image - refurbishment of building envelope

The "all glass" exterior of the retrofit facade will change the Architectural character of the building, to one of "futuristic modernity", at least in the eyes of most people, since fully glazed facades always have a luxurious yet sophisticated outlook to them. The building's image will be upgraded to an impressive and austere modern business complex. It will instantly achieve an avant-garde status through the self-advertising of its handling of sunlight, renewable energies and care for the environment. It will differentiate itself from surrounding buildings because of its innovative facade refurbishment automatically drawing attention and publicity. This will undoubtedly have positive effects on any form of business residing inside. This will inevitably lead to:

Increase of real estate value

With an investment of this size that will revitalize the image of the building and is a definite upgrade to its previous form, the worth of the building will undoubtedly go up. Its office space demand is sure to increase making potential tenants more willing to pay a higher rent [25]. If the increase in real estate value per square meter of office space ends up being higher than the corresponding charge of the upgrade cost, the retrofit facade will end up paying for itself and being profitable as well.

6.2 Drawbacks

Apart from the benefits, there are however, some negative factors brought on by a glazed double skin facade.

danger of overheating during summer.

Special care has to be taken during summer since, if system functions are not synchronized to accommodate solar path to building work schedule, solar heat gains may have inverse effect causing major indoor overheating and system failure. When double skin facade systems are not properly designed with the appropriate distances between glass layers and size of ventilation openings, the above problems may occur. During prolonged heat wave periods during summer when the diurnal temperature does not drop below the solidification temperature of the PCM, the retrofit facade will not function properly as efficiency will drop and there is a possibility that this may have inverse effects that may cause overheating of the office building.

Expensive to install and costly to maintain.

Given the market value of the hi-end industrial materials used and the low, in comparison, price of energy, installing double skin facades solely for energy purposes is seldom cost effective. On top of that the extra cost of maintenance is mandatory in order to keep smart facade system functioning properly, while routine monitoring of system efficiency is also needed. The increased amount and complexity of systems installed in the retrofit facade increase the chance of one of them malfunctioning and needing repair. Exposure to the elements and the polluted city atmosphere will increase frequency of cleaning, while multitude of facade surfaces increases areas where dust could set.

User skepticism

In many cases of existing buildings that had window openings, the retrofitting of a second skin with non opening windows bestows a sense of stuffiness and isolation from the outside world on the inhabitants, decreasing user satisfaction. This will not affect curtain wall facade buildings where windows could not be opened and ventilation was fully mechanized. [51, pg 198]

Automation of dynamic facade systems may increase user discomfort as occupants tend to feel displeased with control settings. Automatic adjusting of moving systems at apparently random intervals may also cause distraction in many building occupants [24]. Allowing for manual override of the controls will restore user satisfaction on the most part.

Limited knowledge on facade durability

Since double skin facades have not been around for very long, there are limited examples that can guarantee lifetime functionality of the system and durability of the materials. It is impossible to predict a system's lifetime and the curve the gradual reduction in efficiency will have.

Poorer cross ventilation

In the absence of an integrated building HVAC system, when office ventilation is dependent on natural ventilation by opening of wind, an effect which is highly efficient in a building where cross ventilation is possible by opening windows on two opposite sides, the presence of a double skin facade immediately negates the current driven ventilation of cross ventilation in the building. This can also render natural ventilation almost impossible in windless periods as the exterior facade effectively blocks exterior wind pressure effects [53] making unlikely the creation of a negative pressure inside the double skin void, which is capable of ventilating the inside air.

Noise transmission

As mentioned before, the double skin facade effectively reduces outside noise transmission. However, the smooth hard surface of the glass may carry sound through the void of the double skin from other rooms or floors when the windows are open. This can be overcome by using a proper partitioning system in the facade design, or by implementing acoustical absorbing materials.

Fire safety

Double skin facades are effective in fireproofing a building envelope but at the same time seal off access to the building from the windows for fire fighters, as well as block potential points of escape or rescue for people trapped inside the building in the event of a fire. There is also the possible problem of room to room transmission through the double skin facade. The literature is divided on whether double skin buildings are actually safer against fires or not. Oesterle pointed out in 2001 [51, pg 83] that no information on DSF behavior during fire really exists.

Fitting inconsistencies

Although designed to accommodate the mean Greek office building design and incorporated with versatility, there will be problems in the retrofitting process. The retrofit facade module will have fitting inconsistencies with building height and width. It is impossible to have a single module suitable for every possible building shape and size. Although edge adjusting panels will be available, to compensate for facade air tightness as well, it is still to be expected that performance of the facade in these cases will be suboptimal.

6.3 Challenges for Greek and Mediterranean cities

Insulation is the largest contributor to energy performance enhancement and increased energy savings. This is logical since the goal of a controlled thermal environment inside a building is to retain thermal comfort throughout the year. In climatic conditions with high outside air temperature fluctuations like the Mediterranean, insulation is responsible for keeping heat trapped inside or keeping heat from getting inside. As it turns out, the latter is the more difficult of the two.

Buildings in the Mediterranean are unable to guarantee adequate comfort conditions during both summer and winter periods. The climate conditions are becoming all the more polarized towards hotter summers and colder winters [7]. This causes needs for heating and air-conditioning to gradually increase.

Mediterranean cities are notorious for having an increasing onset of the heat island effect. This will obstruct the double skin facades ventilating abilities and may even have adverse effects causing the building to overheat in hot summer days. In 2013, Kapsomenakis et al. [66] released a paper presenting 40 years of data from Greek meteorological stations. The data proves the increasing air temperatures in urban areas due to the heat island phenomenon and the undeniable effects of global warming. An analysis using a typical office building model showed that during this period, heating demand decreased by 1 kWh/m^2 per decade, while cooling demand increased by about 5 kWh/m^2 per decade. This portends an increasing energy demand from cooling loads for the region.

In a paper released in 2012 by Asimakopoulos et al. [67] three different scenarios were predicted for the change in building energy demand for heating and cooling up to the year 2100. The results showed that in the most favorable scenario, heating demand could drop by up to 50%. However cooling demands are expected to rise substantially as the most conservative scenario gives an estimated 148% increase in cooling energy needs while the most pessimistic predicts an increase of 248%.

There is a prevailing notion that mean ambient air temperature will rise drastically in Mediterranean cities, making thermal comfort the largest obstacle for buildings, especially in cities. Cooling energy demands will become the prevailing problem in energy consumption as well as the GHG emissions from buildings. This makes the implementation of smart facades on buildings all the more fundamental.

7 Conclusions

In the final chapter of this dissertation we draw our conclusions and remark on our findings as well as predict what future study on the subject matter can produce.

7.1 What we have learned

This thesis started with the question of whether a Zero Energy office building was possible with retrofitted smart facades on an existing office building. The resulting investigation proved that such an outcome is highly unlikely, without a combination of interventions on the building envelope, on ventilation and on building heating systems. The thesis also presented the increased difficulty of defining near zero energy building performance since many different conditions need to be fulfilled and a large number of variables, including building location, contribute to the "official" definition. This may be the reason that there are so many different types of near ZEB prototypes. Nevertheless, in our effort to design the ideal smart facade retrofit we ended up with an interesting retrofit module design.

In our investigation on whether smart facade retrofits were enough to bring an existing office building to near zero energy status, we learned that apart from the mandatory energy performance goals instructed by law, there are other benefits that effect performance in general be it from occupant work performance or non energy related performance, that cannot be measured directly.

With the implementation of the proposed facade retrofits examined above the overall building performance will be upgraded. The expected results will affect:

- reduction of the energy needed to retain thermal comfort inside the building during the summer months by mechanical means (Air Conditioning)
- reduction of the energy needed to retain thermal comfort inside the building during the winter months through central heating
- an increase in the comfort level (thermal comfort, visual comfort) and quality of working conditions (outside noise reduction) for the people inside the building
- the improvement of the buildings image and real estate value

- reduction in overall energy consumption for the building
- reduction in GHG emissions
- our understanding in the importance of renewable energy sources for the reduction in GHG emissions (as seen in chapter 5)

The results from our simulation model assisted in proving the importance of ventilation and air infiltration in building energy demand. As proposed by the Passivhaus standard [43] and implemented in near zero energy office building solutions by Pikas, Thalfeldt and Kurnitski [47], controlled ventilation with heat recovery is very important in achieving near Zero Energy performance. Strict measures are taken to ensure low air infiltration measures compared to wall insulation standards [43].

There is no simple solution for the energy and environmental problem in existing buildings. Especially in Greece, building architecture varies depending on year of construction, region, function and inhabitants. Building trends change every few years as do construction laws and regulations. Building usage also plays a major role in the overall energy balance. All these factors constitute the search for simple solutions an impossible, and at times unsuitable, objective.

This major reason renders the grouping of existing buildings into categories and the finding of common solutions for building types an appealing task. The ideal path to follow, to achieve maximum efficiency, would be a unique study and design for each building. However this would require the largest investment in time and money and would end up being unsustainable in itself. A modular approach would serve as the most practical solution.

Our research helped us understand the importance of non measurable benefits that result from implementation of different smart facade technologies. Many of these have been standardized to function as design guidelines, such as inside air-temperature and humidity levels depending on building function and occupant activity [44] but the benefits on occupant wellbeing and business profitability cannot be directly calculated. Buildings are built to accommodate human activities and in doing so need to offer more than just a suitable air temperature.

The results of our study showed that achieving near zero energy building status for an existing office building by means of retrofitting of the building facade is not possible. The simulations run did not include the entirety of the energy systems implemented in our design and this cannot be determined as conclusive evidence. This does however indicate that such a goal is not possible, considering we worked upon a "best case" scenario. Further study into the matter could produce more reliable results through a more sophisticated simulation that would include airflow, mechanical ventilation and PCMs in the calculations. In absence of such a building energy simulation the only indicative experiment that could produce admissible results would be a scale model of the facade prototype.

The proposed modular facade retrofit may prove to be more expensive, as an initial investment, than a renovation of the building facade with installation of an outer layer of insulation and window replacement would cost. We should not however neglect to take into consideration the time needed for such a renovation. In the modular case the retrofit facade installation would be carried out in very little time and with minor office work hindrance for the occupants of the building. In the second case, the renovation procedure could last for months and building functions would be greatly restricted if not utterly shut down. This is a cost that is avoided in the modular facade retrofit. On the other hand since the modular facade produces energy apart from supplying insulation, it could have a faster payback time than a building envelope upgrade would have.

7.2 Future work

In this dissertation we had the opportunity of investigating a retrofit scenario in which prefabricated facade modules were installed onto office buildings in Greece in order to improve energy performance and a number of other accompanying factors. The main reasons for choosing this path was to achieve a beneficial manufacturing price from mass production, to invigorate the industry, to attempt to solve a customized problem with a common solution, to improve the building stock quickly and with minimal obstructions of building functions.

The results have given us an image of a possible outcome should the government, or any other governing body attempt to follow this method of refurbishment of the existing building stock. The data provided could also be used as an argument for choosing another method of approach. This thesis serves as a theoretical investigation on how current smart facade technologies could be implemented to overcome a growing environmental and financial problem. It provides an image of what results this direction of study could produce.

The next step in this line of study is to continue research on the module design, run simulations with a higher level of detail to get more detailed and trustworthy results in order to proceed to a first modeled prototype for field testing. Despite the failure to produce the expected outcome, our design manages to gather a number of positive features for energy performance, occupant comfort and other spatial qualities discussed in previous chapters. The research initiated here could assist in future investigations on multi-layer facades, adaptive building envelopes or modular retrofits for energy performance upgrades.

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Figure 1: Francesco Goia, Lorenza Bianco, Marco Perino, Valentina Serra, Energy performance assessment of and advanced integrated façade through experimental data analysis, Energy Procedia 48, 2014

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Figure 2: T.T. Chow, W. He, J. Ji, An experimental study of facade-integrated photovoltaic/water-heating system, Applied Thermal Engineering 27, 2007

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Figure 3: M. Sabry, P.C. Eames, H. Singh, Yupeng Wu, Smart windows: Thermal modelling and evaluation, Solar Energy 103, 2014

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Table 1: Yalcin Yasar, Sibel Macka Kalfa, The effects of window alternatives on energy efficiency and building economy in high-rise residential buildings in moderate to humid climates, Energy Conversion and Management 64, 2012

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Figure 4: Alvaro de Gracia, Lidia Navarro, Albert Castell, Alvaro Ruiz-Pardo, Servando Alvarez, Luisa F. Cabeza, Thermal analysis of a ventilated facade with PCM for cooling applications, Energy and Buildings 65, 2013

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Figure 6: Elisa Moretti, Michele Zinzi, Elisa Belloni, Polycarbonate panels for buildings: Experimental investigation of thermal and optical performance, Energy and Buildings 70, 2014

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Table 2: Elisa Moretti, Michele Zinzi, Elisa Belloni, Polycarbonate panels for buildings: Experimental investigation of thermal and optical performance, Energy and Buildings 70, 2014

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Table 3: Greek Technical Chamber Technical Instruction 20701-2/2010

Appendix

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MONTH	HEATING (Wh)	COOLING (Wh)	TOTAL
Jan	16307937	0	16307937
Feb	15577152	0	15577152
Mar	11583763	0	11583763
Apr	2681048	352522	3033569
May	317353	2942662	3260015
Jun	0	7817222	7817222
Jul	0	12085722	12085722
Aug	0	15241908	15241908
Sep	58122	6729156	6787278
Oct	4281612	451030	4732642
Nov	3870958	0	3870958
Dec	8430457	0	8430457
TOTAL	**63108404**	**45620220**	**108728624**
PER M^2	**44411**	**32104**	**76515**
Single Floor Area:	**203.000 m2**		
Total Floor Area:	**1421.000 m2**		

Monthly heating and cooling demand in Wh for existing building example before retrofit.

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MONTH	HEATING (Wh)	COOLING (Wh)	TOTAL
Jan	13877211	0	13877211
Feb	13229817	0	13229817
Mar	9994876	0	9994876
Apr	2194618	0	2194618
May	176472	895193	1071665
Jun	0	4427167	4427167
Jul	0	7578058	7578058
Aug	0	9394962	9394962
Sep	0	3190780	3190780
Oct	3572442	0	3572442
Nov	3151654	0	3151654
Dec	7140114	0	7140114
TOTAL	**53337204**	**25486160**	**78823364**
PER M^2	**37535**	**17935**	**55470**
Single Floor Area:	**203.000 m2**		
Total Floor Area:	**1421.000 m2**		

Monthly heating and cooling demand in Wh for retrofitted building using smart glazing with varying SHGC (between 0.1 - 0.3) and U = 0,50 W/m^{2}K.

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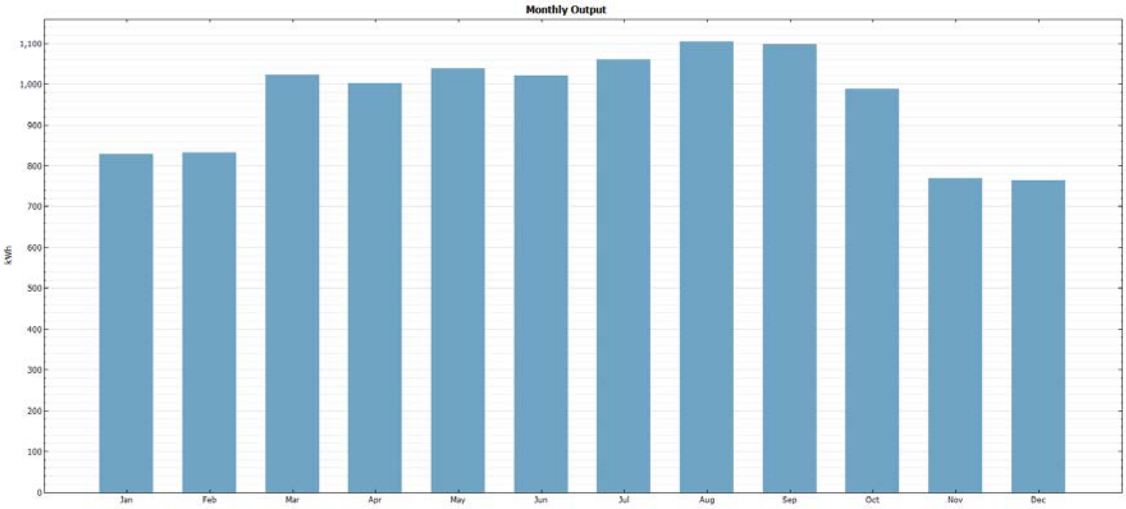

Monthly PV output for 98 m^2 of PV modules with selected SunPower 440 module.