Analysis of Life Cycle Costs and Energy Savings of

Electrochromic Glazing for an Office Building

by

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A Thesis Presented in Partial Fulfillment
of the Requirements for the Degree
Master of Science

Approved April 2012 by the
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ARIZONA STATE UNIVERSITY

May 2012

ABSTRACT

Building Envelope includes walls, roofs and openings, which react to the outdoor environmental condition. Today, with the increasing use of glass in building envelope, the energy usage of the buildings is increasing, especially in the offices and commercial buildings. Use of right glass type and control triggers helps to optimize the energy use, by tradeoff between optical and thermal properties. The part of the research looks at the different control triggers and its range that governs the use of electrochromic glass to regulate the energy usage in building. All different control trigger that can be possibly used for regulating the clear and tint state of glass were analyzed with most appropriate range. Its range was triggered such that 80% time of the glass is trigger between the ranges. The other building parameters like window wall ratio and orientations were also investigated. The other half of the research study looks into the feasibility of using the Electrochromic windows, as it is ought to be the main factor governing the market usage of Electrochromic windows and to investigate the possible ways to make it feasible. Different LCC parameters were studied to make it market feasible product. This study shows that installing this technology with most appropriate trigger range can reduce annual building energy consumption from 6-8% but still cost of the technology is 3 times the ASHRAE glass, which results in 70-90 years of payback. This study concludes that south orientation saves up to 3-5% of energy and 4-6% of cooling tons while north orientation gives negligible saving using EC glass. LCC parameters show that there is relative change in increasing the net saving for different parameters but none except 50% of the present glass cost is the possible option where significant change is observed.

ACKNOWLEDGMENTS

I would like to express my deep gratitude to Professor Harvey Bryan, my academic advisor and committee chair, for his support and guidance in thesis and throughout my course work. His mentorship and assistance played an important role in developing my skills and knowledge in the concerned field. I shall remain grateful for his constant encouragement and help.

I greatly appreciate the constant advice, encouragement and support from my committee members, Professor Marlin Addison and Professor Agami Reddy, for all the help and cooperation. I would like to thank Professor Muthu Ramalingam, for all his help and constant discussion throughout my thesis.

I would like to express deep gratitude to Professor Addison and Professor Muthu, for his help and continuous guidance during my course work and especially during my thesis research. It helped me a lot in developing deep insight in energy simulations and data analysis.

I thank all my colleagues at Arizona State University, especially Kurtis, Supriya, Vipul, Steve, Shreya, Sandeep, Shaily, Marcus, Vishal, Karla and Nasim for their friendship, assistance and numerous simulation discussions during my course work.

I am grateful to my parents, my sister, brother-in-law and relatives for their constant encouragement and financial support during all my course work and accomplishments. Finally I am grateful to my friends.

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Chapter 1

INTRODUCTION

Today commercial buildings consume 18% of the total energy in the United States.[1] More specifically, commercial building consume a significant amount of electricity, typically for lighting and space cooling, as well as natural gas typically for space heating.[2] Among the commercial building in United States, 19% of the building activity is office, with glazing as the outer skin.[1] With the increase in energy consumption and in the associated utility cost to operate office building, serious thought needs to be given for controlling energy usage. The design of building envelope can significantly affect perimeter space thermal loads, lighting loads and visibility. Previous research on energy transmission by building envelope components indicate that windows accounts for 50% of thermal energy transmission through building enevelope followed by infiltration, roof, and floor. [3] As architects and building designer incorporate more glass in envelope for aesthetics and occupants comfort, the energy benefits of interactive glass, which changes thermal and optical properties according to climate response, are becoming prevalent.

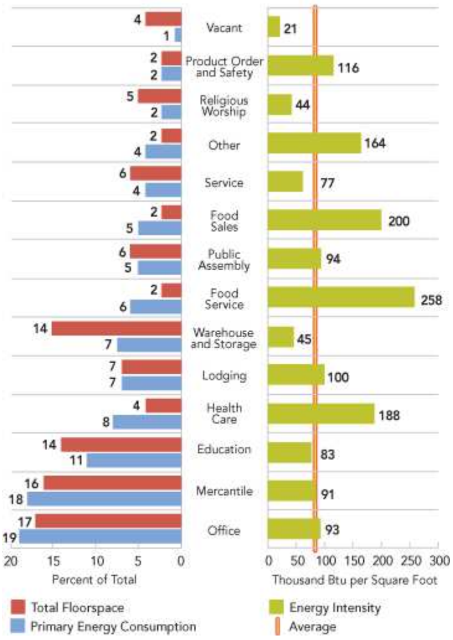

Figure 1: Commercial building energy consumption percentages (Energy Information Agency).

An experimental simulation made for an prototype medium sized office building indicate that building envelope accounts for 16.5% of the total building energy consumption, which includes annual energy due to windows/glazing. The annual energy consumption solely due to glazing is about 14.5 % of total building energy end use.

"Advanced Glazing" is the term used by glass industry for this type of interactive glass, which changes it's thermal and optical properties to create a more comfortable work space and a more energy efficient building. Advanced glazing can reduce the peak thermal load by 10- 20%, when compared to ASHRAE prototype glass, and can increase the natural daylighting illumination level in the building.[4] It is an emerging technology which can reduce the building energy loads as well as overall carbon footprint of the building.

1.1 Background

Since office building typically features a significant area of glazing as building envelope, it can be feasible to introduce smart glazing in order to mitigate both the space thermal and the lighting loads. Furthermore, as office buildings are occupied strictly during daytime hours, investigating smart glazing can be justified. Thus reducing the overall energy usage, accounting for tradeoffs between thermal loads and lighting loads, can be done by implementing smart glazing.

Energy related performance of the glazing depends on various parameters, such as orientation, Window to- wall ratio, climate, building type and operational hours of building. To decrease the total energy usage of the building, all these parameters should be taken into consideration.

Chapter 2

BACKGROUND LITERATURE

2.1 Advanced Glazing

In the past, there has been much research done to develop new and advanced glazing, which reduces adverse thermal transfer with outdoor environment. This research has resulted in the development of both Low Emissivity (Low E) glass as well as dynamic glazing. Dynamic glazing which is commonly known as smart glazing is a new generation technology which alters thermal and optical properties, such as shading coefficients and visible transmittances in response to either an electric charge or an environmental signal. Depending on the chemical composition used for manufacturing this glass, the dynamic behavior of the glass varies.

Thermochromic

Thermochromic is one of the oldest technologies used for advanced glazing. Chromic technology is known since 1870's and used in several applications. Thermochromic materials demonstrate change in optical property as a function of temperature, thus as outdoor temperature increases, the visible light transparency decreases and vice a versa. The thermochromic glazing which are currently under development feature gels sandwiched between glass and plastic. The gels switch from a clear state when cold to a more diffuse, white, reflective state when hot. In their switched-on state, less visible light is transmitted through the glazing. Although the thermochromic operational principles seem promising, there are some prohibitive disadvantages associated with the technology. These glazing are prone to chemical leakage around the edges and optical properties are demonstrated to degrade over time. Prototype windows have been tested but are not commercially available. [3]

Photochromic

Photochromic material is one of the oldest technologies in chromogenic glazing. The tint of the material slowly changes in response to the incident light intensity. In essence, this glass automatically adjusts its visible transmittance according to exterior light exposure. However, this glass is not largely used as window glazing due to the fact that it dims when exposed to winter sun and therefore increasing heating loads. Large Photochromic windows are not commercially available. (Compagno, Andrea.1995)

Figure 2: Photochromic glass adjacent to static glazing.

Liquid Crystal

Liquid crystal display technology, which is widely used in wrist watches, is now being developed and modified for use in windows and interior partition. This technology is comprised of a very thin layer of liquid crystals which is sandwiched between two transparent electrical conductors. This electrical conductors are deposited on thin plastic films and the entire emulsion or package (called a PDLC or polymer dispersed liquid crystal device) is laminated between two layers of glass. When the power is off, the liquid crystals are in a random and unaligned state which scatters light and causes the translucent appearance of glass appears. The material transmits most of the incident sunlight in a diffuse mode, thus for perimeter zones the solar heat gain coefficient remains high. Unlike thermochromic glazing technology, liquid crystal requires continuous power supply for the glass to remain clear (24-100 V AC or 0.5 W/ft^2 of glass).

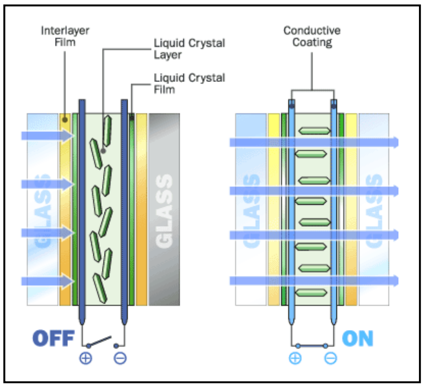

Figure 3: Schematic of Liquid Crystal Glass

Exterior Window Interior Partition

Figure 4: Application of Liquid Crystal Glass

Electrochromic

Electrochromic (EC) technology has been actively researched for over thirty years, and examples of EC window prototypes have been installed in a number of buildings in Japan and more recently in Europe and the United States (Carmody, et al., 2004). Lee, et al. (2000) determined that EC windows would be a next major advance in energy efficient window technology; helping to transform windows and skylights from an energy liability to an energy source for the nation's building stock. In accordance, Pacific Gas & Electric identified daylighting as the single largest new opportunity for saving energy in commercial lighting today (Koti, et al., 2006).

A typical EC window cross-section and functionality is shown in figure 5. EC windows are capable of automatically altering their state to a shaded mode based on available light. This reduces the heat gain generally experienced during the peak cooling demand times throughout the day. They are also manually controllable to shade the perimeter spaces according to the building occupant's desire; preventing the solar heat gain during hot summer months and transmitting solar radiation to occupied space during cold winter months. Electrochromic coatings are switchable thin-film coatings applied to a glass or plastic that can change optical and thermal properties of glass when a small voltage is applied. This EC glazing is composed of transparent conductors as an outer layer, an active electrochromic and passive counter-electrode layer as the middle layers, and an ion-conducting electrolyte layer as center portion of the configuration. When small voltage is applied to this chemical configuration, ions migrate to the counter electrode on the opposite side causing the glass to tint. Reversing the process causes the ions to migrate back, causing the glass to return its transparency.

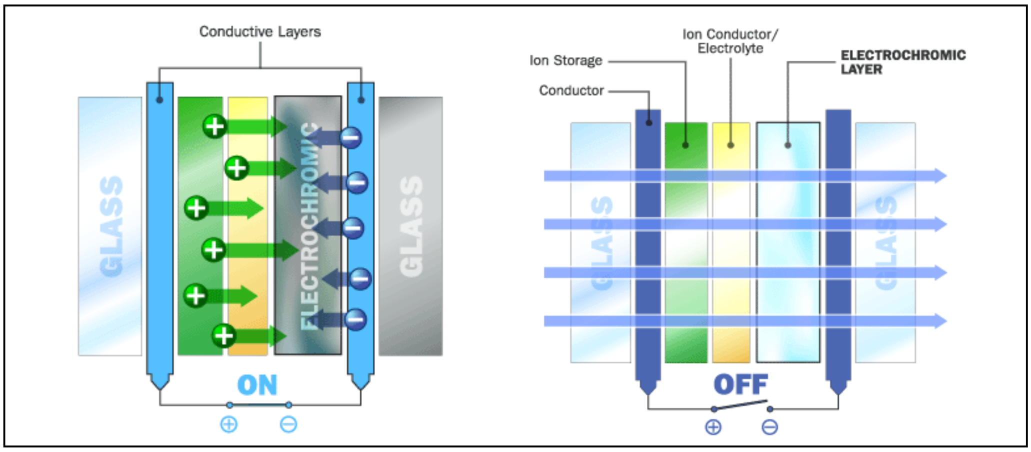

Figure 5: Schematic of Electrochromic Glass

Based upon the material and physical composition of EC window, the dynamic behavior of the glazing may vary. In particular the unique material and physical properties of EC windows can define the switching range in terms of visible transmittance, speed versus temperature characteristics, power consumption when being switched, durability and color.

Relative to preciously mentioned chromogenic glazing, Electrochromic glass can be the most reliable and effective glazing technology, as it has the most appropriate trade-off between lighting loads and space thermal loads, i.e. cooling and heating load of the building. EC window is not controlled by outdoor light or temperature but it is controlled by the electric power applied to the electrochromic layer. This can be calibrated and operated by the preset controller.

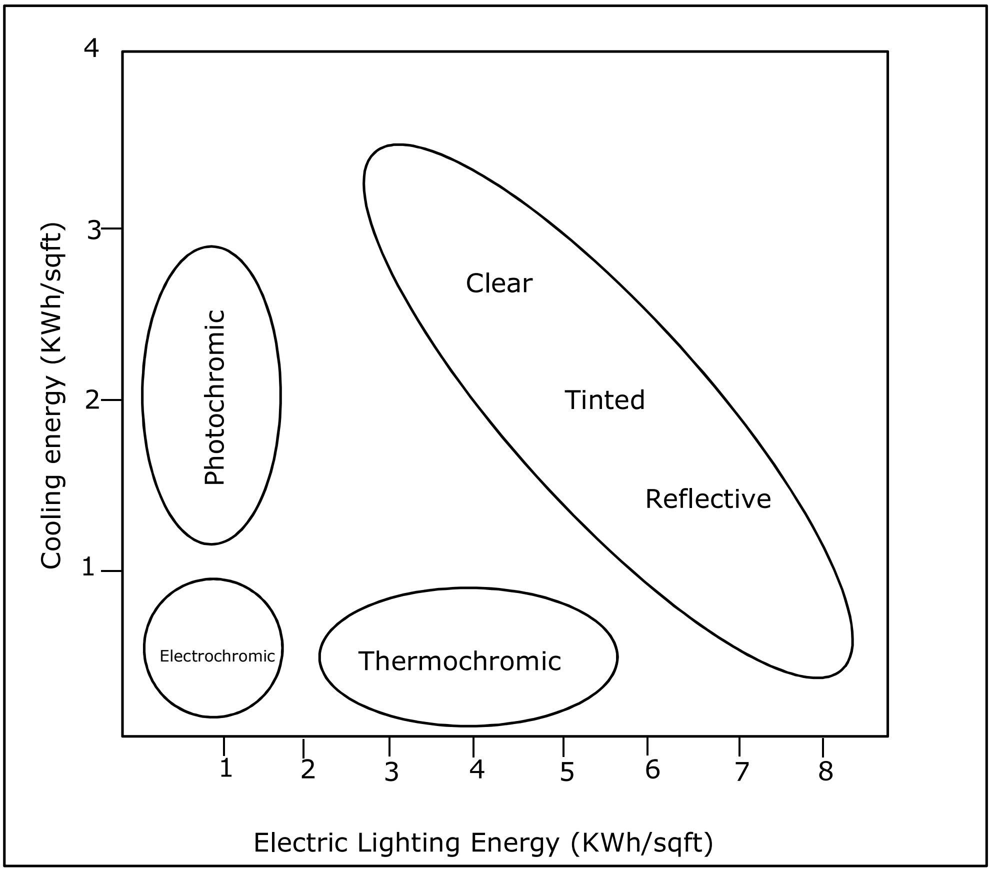

Figure 6: Conceptual comparison of different types of smart glazing with respect to cooling energy and electric lighting energy requirements. (Selkowitz, 1986)

As mentioned above, electrochromic technology proves to be efficient and most promising technologies among advanced glazing. The majority of passed research focuses on material science behind electrochromic glazing. These studies describe the development of new chemical compound and processes which improves the thermal and optical properties of electrochromic glass. The below study is about the multilayer structure of electrochromic windows.

2.2Electrochromic Structure

Due to its wide range of optical properties, transition metal oxide EC window like Tungsten Oxide (WO_3) is proven tested and is commercially available.

The reaction that takes place can be grossly simplified (Grandqvist, 2000) as follows:

$$WO_3 + xM^+ + xe^- \leftrightarrow M_xWO_3$$

with M+ = H+, Li+, Na+ or K+, and e- denoting electrons.

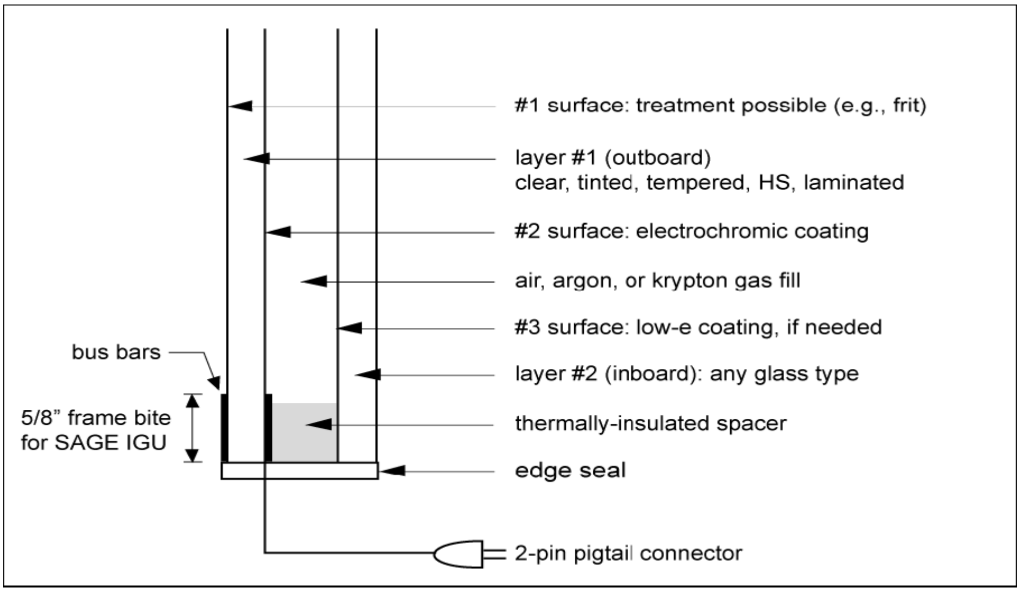

Figure 7: Cross sectional view of Electrochromic glass (SAGE Electrochromic)

Usually electrochromic glass is a five layered structure, consisting of two layers of insulated glass unit (IGU), electrochromic coating and gas fill. The EC insulating glass unit is composed of two panes or layers of glass assembled with a spacer, then sealed on all four edges, where the exterior glass layer has the EC coating on the second, #2 interior-facing surface (glass surfaces of a window are numbered from exterior to interior). The gas between two glass panes is supposedly air or inert gas such as argon or krypton. Typically, spacers are insulated to prevent thermal conductance and condensation. EC coatings degrade rapidly if water vapor is allowed to enter into the intra-pane air gap, consequently proper edge seal is required. The EC window functions when voltage is passed through bus bars attached to the external pane, which has 2 pin pigtail connector. (SAGE electrochromic)

EC glass s only commercial available in limited number of shapes and sizes. Unlike other glass, it is available only in flat rectangular shapes. Typically EC glass is available in standard 42.5 by 60 inch units (SAGE Electrochromic, Inc.). Flat organic shapes can be prefabricated however the custom fabrication introduces an additional cost to the unit. Due to sealed nature of Electrochromic chemicals, the glass cannot be cut and installed in window frames at the building site. As a result, its size and shapes should be pre-determined prior to shipment and installation.

At the time of installation, proper wiring and connection of electrical components is critical for the operation of EC window. For small residential projects, prefabricated window system is shipped to field and installed to single control unit. On the other hand, commercial building which feature a curtain wall of EC windows, require a complex wiring network and necessitate an array of control unit. The wiring should be passed through hollow framework to its assigned control unit. There can be an on/off switch for both the cases. If switchable glazing needs to be automated, controller unit should be programmed with possible switching range depending on the control trigger such as daylighting level, incident radiance, outside air temperature or space loads.

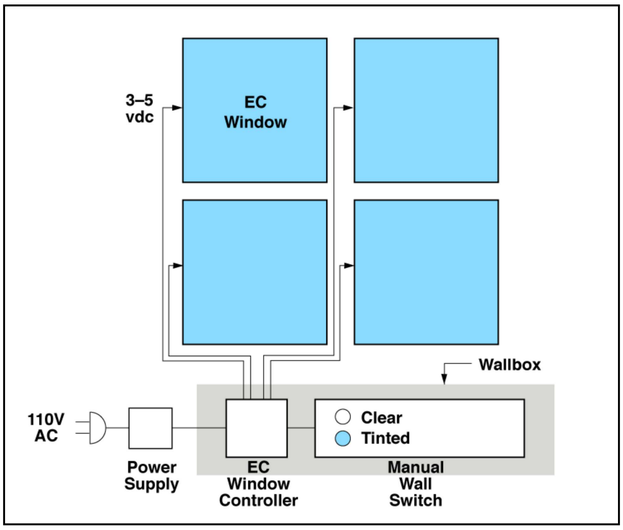

Figure 8: Small-scale EC window installation diagram.

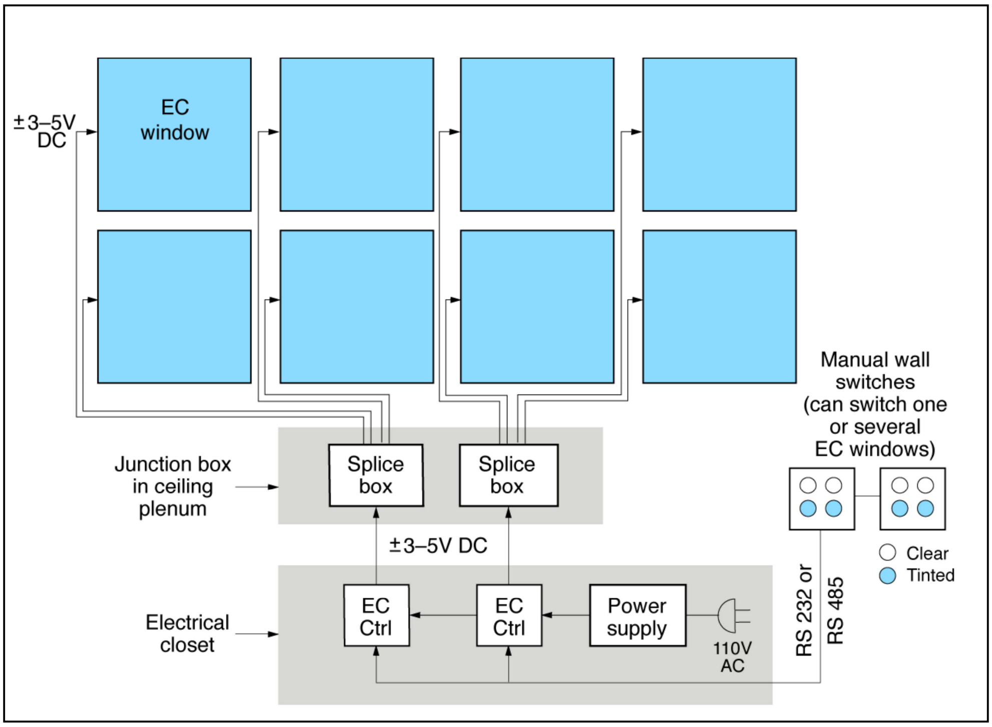

Figure 9: Large-scale EC window installation diagram.

2.3 Thermal and Optical Properties of EC windows

Electrochromic glass has a unique character of changing optical and thermal properties due to its chemical composition. Solar Heat Gain Co-efficient (SHGC) is a thermal property of glass and indirectly affects space temperature, while visible transmittance (VT) is optical property and controls daylighting level inside the building

Electrochromic glass demonstrates a wide range of visible transmittance. It may vary from 0.70 - 0.50 as upper range to 0.02 - 0.25 as lower range. Optical property of this glass reacts to a change in light intensity, spectral composition, heat, electric field or voltage passed.

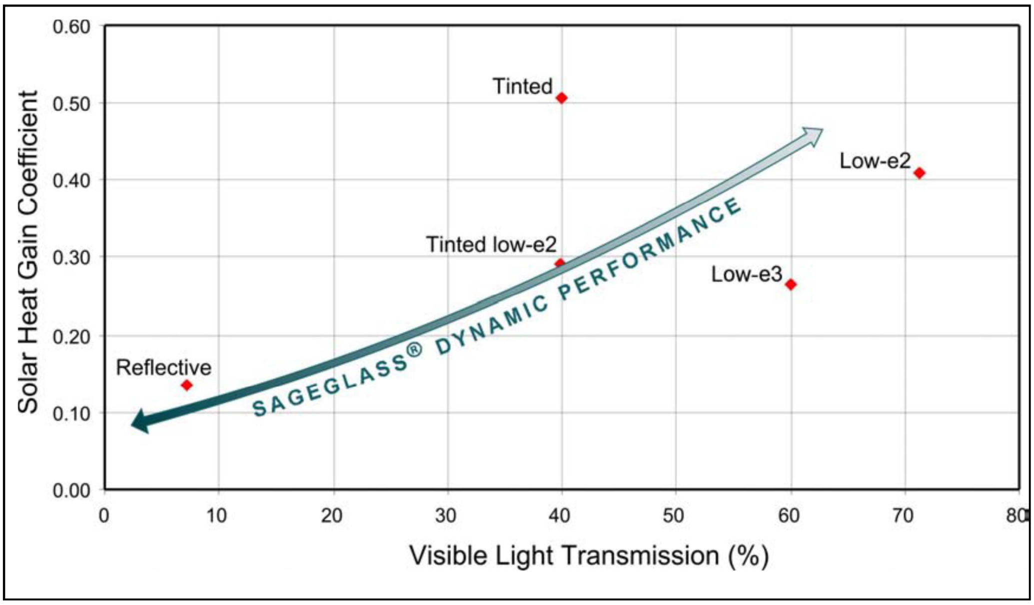

Figure 10: Correlation between SHGC and VT for electrochromic glass.

Figure 10 demonstrates SAGE glazing which can be tinted from a highly transmitting state to a very dark state to adapt to a wide range of sunlight conditions. Today's static glazing (the individual points on the chart) is specific to one condition and cannot be changed. [5]

It demonstrates a wide range of Solar Heat Gain Co-efficient which may vary from 0.10 – 0.8. SHGC governs the heat transmittance via solar radiation through the glass. Based upon a given set of control triggers, EC glass which features a wider range of thermal (SHGC) and optical (Vt) properties can result in more optimal operation of glass and thus results into more overall energy savings. [5]

Unlike, other types of smart glazing which can only alter thermal or optical properties but not both simultaneously, electrochromic can modulate both the properties accordingly, which optimize the energy load by tradeoff between lighting load and space thermal load. Figure 10 shows the relationship between SHGC and VT for electrochromic glass when compared to conventional static glazing.

To achieve ideal reduction in building energy consumption, the chemical composition of the EC windows can be altered and/or innovative controlling strategies can be developed. Control strategies are directly related to the physical and visual comfort for a given space. For an office building, were occupant productivity is important, the selection of control strategies which maintains occupant’s comfort is critical.

2.4 Control Trigger and its range

Electrochromic Window is composed of electro powered glasses, which alters transparency as electricity is passed through them. This can be managed manually or automatically. The manual mode only allows the electrical power to be switched on/off, corresponding to a tinted/clear state of glass. Since there is no intermediate tinting of glass, there is no tradeoff between thermal and optical properties, thus it is less preferable. To automate operation of EC window, control mechanism must be programmed to monitor and respond to specified triggers. Control trigger can be defined by a wide range of variables, which describe either exterior or interior condition of the given space. Exterior triggers include solar incidence on glazing, total horizontal radiation and outdoor temperature while the interior triggers can include space temperature, daylighting level, space load and VAV damper position. The switched/unswitched state of glass is defined by Low/High Setting point. Between low and high control trigger set points, the thermal and optical properties of the glass are interpolated as the proportion of switched/unswitched conditions. This triggers function as explained below:

1. Solar control: Solar controls can often result in ineffective operation of EC windows. Based on sky condition, solar radiation can be highly unpredictable and drastically fluctuates throughout the day. This weather behavior can disrupt the switching process of the glass thus preventing ideal indoor conditions. AS a result, this control trigger cannot be used for commercial building.
2. Daylighting level: Daylighting illumination can also be considered as a valid control trigger for EC glass. Daylighting sensors take care of the lighting parameter inside the building. However, daylighting does not directly correlate to the space thermal loads inside the building.
3. Space loads: Space loads directly account for temperature within the work space, which can correspond to occupant productivity. VAV damper position reflects the load in the space by recording the temperature of the return duct and interpolating the optical and thermal properties of glass.

Refer above given diagram (figure 8 and 9) for installing Window and control trigger.

After selection of control trigger range, establishing an appropriate trigger range is important. The control trigger low and high set points indicate the thresholds at which the glazing undergoes switching. At control trigger values between low and high set points, the switching factor can be interpolated and applied to the glass at the specific control trigger condition. Window wall ratio, orientation, location are some of the other important parameters to understand for the use of electrochromic glass.

2.5 Life Cycle Costing:

Life Cycle Costing (LCC) is an economic analysis method widely accepted to identify cost optimal building design options. The Federal Energy Management Program (FEMP) of US Department of Energy (DOE) has codified the rules for performing LCC analysis of investments for energy and water conservation and renewable energy resource projects.

All LCC programs are designed to follow three step procedures:

1. Collection of relevant user input describing the parameters of the analysis, including inflation rate, fuel price escalation rate, utility costs, and acquisition costs etc. 2. Allowing the LCC program to 'go away' to calculate results and 3. To post the results to one or more reports for user review. This process is like a black box, which has all algorithms and formulae and calculates results in the form of Life Cycle Cost and Simple Payback.

Life Cycle Cost Analysis (LCCA) should not be confused with Life Cycle Assessment (LCA). Life Cycle Assessment is analysis more of environmental aspects and potential impacts associated with a product or service. It also includes the energy and material used, and potential environmental impacts associated with identified inputs and releases to help the designer to identify more sustainable design solutions. [6]

LCC Analysis is conducted to prove whether or not the product is economically stable and market feasible. It accounts for the time value of the money by calculating the payback period and net saving at the end of time span.

In the context of electrochromic window products, the life cycle analysis depends upon the durability of EC window. Durability can be defined as the reproducibility of the switching range as a function of extended operation. Testing for the durability was done by accelerating age testing procedure where small area of electro chemical decomposition (ECD) was made to run for high temperature and continuous cycling. It was seen that there was minor change in transmittance level after 20,000 cycles. According to US department of energy standards, an average life of windows is considered to be 20 years that is equivalent to 15,000 full cycles i.e. 2 full cycles for day for 20 years. [6] Thus durability test for electrochromic glazing shows that the life span of EC glazing is more than 25 years.

2.6 Validation Method:

For an emerging technology, validation is the most important process. Validation method helps in rating the product for a specific purpose and application. Any research can be validated on the basis of three different commonly used methods as listed below:

1. Full Scale Modeling.
2. Test Cell.

3. Software simulation.

Use of the above methods solely depends on type of research.

Full scale Validation of glazing glass type is only possible when the glass type is under manufacturing and full scale model is under operation. This gives the accurate results from all the above methods as it is experimented on real climatic conditions. This method limits the flexibility to modify the building on the later stages of experiment and thus this method is more applicable for retrofit situation.

Scale model is another useful method to analyze the product. In some cases, this method fails when many different parameters affect the variable of interest and sometimes observed behavior cannot be scaled to actual conditions. Thus the actual conditions cannot be accurately estimated by the scaled model and often results in significant error.

Software simulation, especially in integrated building systems can be the most preferable method, if software used to analyze the product is well-validated. Unlike previously mentioned modeling techniques, it allows for modification and experimentation of various design alternatives. This is particularly advantageous for preliminary feasibility and conceptual studies, saving both money and time.

Hence, in order to investigate the energy consumption and Life Cycle Costing of Electrochromic glass, software simulation is the most appropriate validation method as it allows for flexibility using multiple variables in numerous different combinations. This widens the scope and quality of the project.

2.7 Tools Used

Computer simulation proves to be an important tool when analyzing a technology in research phase, such as electrochromic glass. Several tools and simulation programs are commercially available in the market, which evaluate energy related performances and various design parameters. Lawrence Berkley National Lab (LBNL) is one of the most active labs which develop the software for energy analysis. LBNL develops different tools for analyzing the different elements of the buildings. WINDOW 5, daylighting software developed by LBNL is used to create glass type used for dynamic window, while energy simulation software e-QUEST for Department of Energy (DOE-2) is most commonly used to quantify the performance of glazing constructed in WINDOW 5.

WINDOW 5

WINDOW5 is a Microsoft Windows based computer program developed at Lawrence Berkeley National Laboratory (LBNL) for use by manufacturers, engineers, educators, students, architects, and others to determine the thermal and solar optical properties of glazing and window systems. WINDOW5 is used to create new and dynamic windows used for energy efficient buildings. The window type created by this tool can be used by other energy simulations software to analyze. All LBNL developed software as well as DOE2 can import the window type created by this tool and use for further analysis. [7]

DOE 2 (eQUEST)

DOE-2 is energy simulation software used to analyze the energy performance of the building. It is one of the most developed tools used for building energy simulations and features a user interface which facilitates easy input of building parameters. eQUEST was designed to allow you to perform detailed analysis of today's state-of-the-art building design technologies using today's most sophisticated building energy usage simulation techniques but without requiring extensive experience in the "art" of building performance modeling. (eQUEST, DOE-2). DOE-2 has been developed for use by architects, engineers and other energy agencies to analyze the building energy performance before starting the project. This tool helps to analyze the complex algorithms related to building energy performance by yielding output in the form of simple statistical data, which can be interpreted by non-technical individual.

As mentioned above eQUEST is the most sophisticated tool which has various capabilities such as analysis of daylighting, usage of dynamic glazing using various controls, importing elements (window) from other supportive software. Along with all this capabilities, it also has limitation to some analysis. Daylighting can be performed in eQUEST and calculate energy loads, but daylighting levels and related analysis should be performed in specific software.

Life Cycle Costing is also facilitated by eQUEST which helps in analyzing the energy efficient product economically. It is a Microsoft excel based spreadsheet which requires relevant user input including first cost, replacement cost, utility rates, fuel escalation rate. This spreadsheet has preset formulae and multiplier known as crystal ball multiplier which helps to escalate utility data which provides result in the form of simple payback and Life Cycle Costing which gives general idea of tradeoff between energy and cost. [7]

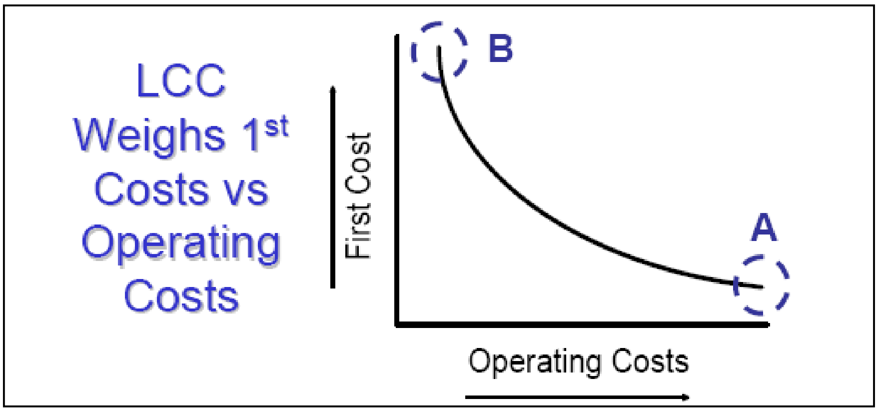

Figure 11: Ideal trend for Life Cycle Costing.

Chapter 3

CONTEXT OF THIS RESEARCH

3.1 Problem Statement

Energy efficiency and intelligent environmental control are crucial in decreasing building energy usage and minimizing carbon foot print. There are plenty of opportunities to design the building envelope to reduce energy consumption. Smart windows can effectively reduce space thermal loads and maintain favorable daylighting condition.

Static window are defined by fixed solar heat gain co-efficient and visible transmittance. Often, static window must be installed with external or internal shading device which adds to the cost of the system. This shading devices are typically manually operated, which can negatively affect occupant's behavior. Unlike static window, electrochromic glazing can assume a wide range of solar heat gain coefficient and visible transmittance properties, which allows for the control of thermal loads and daylighting level without compromising the visibility. This type of glass can control the quality and quantity of light, both visible and ultra violet radiation being transmitted to the space.

Much of past research studies in electrochromic technology addresses the fundamental material science. However, not much work has been done to understand the automated control of this dynamic glazing system. More specifically, additional work should be done to investigate the energy tradeoff between both thermal and optical properties of electrochromic glass. This energy tradeoff is directly related to the system control trigger which modulates the properties of electrochromic glass. In particular, type and range of the control trigger which defines the switching behavior of the electrochromic windows should be further studied.

Relative to static windows, electrochromic windows can reduce the building energy consumption associated with both space conditioning and lighting. However, since the electrochromic industry has not entered into mass production, and manufacturing cost is still too expensive, the electrochromic windows are not economically competitive with conventional glazing. However, in order to make transition of this technology from laboratory testing to commercial product, lot of financial investment needs to be done by manufacturers in engineering industry. This transition is only possible if manufacturers can see profitable equation which includes flexibility of material properties, performance factors, manufacturing cost, and interest of owner to accept this technology. This equation is complex in terms of energy and utility cost, sizing of heating and cooling equipment, thermal and visual comfort, installation and maintenance cost, market feasibility and many more. The complexity of the equation is made more difficult as it does not address "engineering optimization" of the technology but also includes real time tradeoff between energy savings, human comfort and market economics. To make this technology a commercial product, one needs to have better understanding of the present and future market economics associated with this product. Scope and limitations to this research are discussed in next section.

3.4 Research Objective

Based upon the deficiencies of past research (as outlined in previous section), this paper is meant to investigate the control algorithms and market economics associated with electrochromic glass system. In particular, the objectives of this paper are as follows:

- Develop predictive control algorithms which can be incorporated in operation of electrochromic glass.
    - Select appropriate control trigger
    - Define the range for the control trigger
        - Establish orientation-specific control trigger range.
- Compare the energy consumption with ASHRAE 90.1 compliant base case.
- Determine the life cycle cost of electrochromic glass, utilizing the control algorithms previously defined.
    - Conduct a parametric analysis on influential economic variables (i.e. Glass cost, fuel escalation rate, discount rate, utility cost)

3.5 Scope and Limitations

The scope of the study is constraint to office building located in Phoenix as maximum benefit of electrochromic can be observed in hot and sunny climate.

Limitations

- This study has ASHRAE 90.1 2007 prototype building as its base case and all building parameters are defined accordingly.
- This research strictly analyzes the energy reduction due to installing electrochromic glazing, and thus all other building parameters (i.e. building area, aspect ratio, window wall ratio, HVAC system etc.) are kept constant.

- The electrochromic switching hours span from 7:00 AM to 6:00 PM, which reflects the building operational hours.
- The study is based upon software simulation. However though the simulated glass type has realistic configuration, as manufactured by SAGE Electrochromic.
- Life Cycle Cost Analysis is carried on the present energy rates of Phoenix, Arizona and can be changed accordingly. For high electric rate Southern California Edison (SCE TOU8) rates are considered.

Chapter 4

METHODOLOGY

4.1 Approach Methodology

A methodology is developed to select an appropriate control trigger and define the upper/lower set-point for the trigger range. This can be done by following the steps mentioned below:

1. Build Base case: ASHRAE 90.1 compliant office prototype building
2. Introduce market available electrochromic windows
    - Selection of Control trigger
    - Definition of control trigger range
        - Sensitivity check for trigger range with respect to each orientation.
3. Simulate the building energy performance:
    - Specify daylighting and non-daylighting
    - Specify 20% and 40% Window Wall ratio
    - Specify Orientation with electrochromic glazing
4. Calculate Life cycle cost of electrochromic windows.
    - Input glass investment cost
    - Input Fuel Price Escalation (Electricity and Natural Gas)
    - Input Utility Cost (medium and High utility rates)
    - Input Discount Rate

4.2 Models in eQUEST

4.2.1: Base Case: ASHRAE 90.1-2007, office building

Model used as base case is compliant with prototype commercial office building according to ASHRAE 90.1, 2007. All the variables are as per ASHRAE 90.1, 2007 code. Window-wall ratio is taken from prototype building i.e. 40%. Glass type used in base case has similar properties as ASHRAE glass. All other remaining parameters including the HVAC systems are taken from appendix G of ASHRAE 90.1, 2007. Refer Table1. for design parameters assumed for base case simulation run.

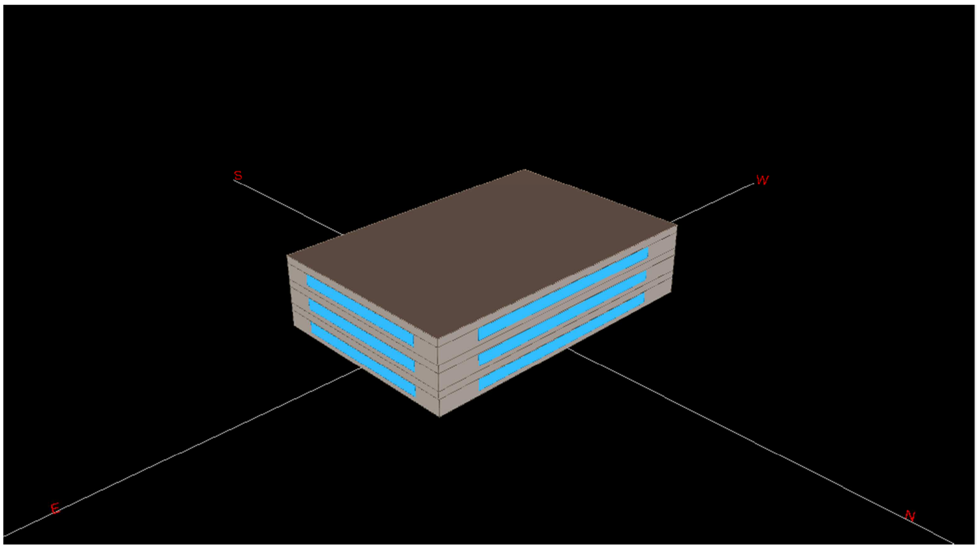

Figure 12: simulated eQUEST model for medium office building.

General	
Building Prototype	Medium Office
Total Floor Area	53,600 sf
Building Shape	Rectangular (163.8 X 109.2 ft)
Aspect Ratio	1.5
Number of floors	3
window wall ratio	40%
Shading geometry	None
Thermal Zoning	Perimeter zone depth: 15 ft. Each Floor has Four perimeter and one core zone. Percentage of floor area: Perimeter 40%, Core 60%
Floor to floor height	13ft.
Floor to ceiling height	9 ft. (4ft. Above ceiling plenum)
Glazing sill height	3.35 ft
Exterior walls	Steel Framed Wall
Roof	Insulation entirely above deck, metal deck roof
Foundation	8 inch concrete slab-on-grade floors (unheated)
Interior partitions	2 X 4 uninsulated stud wall
Internal mass	6 inches standard wood (16.6 lb/ft^2)
Infiltration	Peak: 0.2016 cfm/sf of above grade exterior wall surface area (when fans turn off) off Peak: 25% of peak infiltration rate (when fans turn on)
Internal Loads & Schedules	
Lighting power density (W/ft^2)	Building average, 1.00
Plug load power density (W/ft^2)	Building average, all zones 0.75
Occupancy	268 Total (5 person/ 1000 sf)

HVAC	
System Type	
Heating type	Gas furnace inside the packaged air controlling unit
Cooling type	Packaged air controlling unit
Distribution and terminal units	VAV terminal box with damper and electrical reheating coil. Zone control type: minimum supply air at 30% of the zone design peak supply air.
HVAC Control	
Thermostat set point	74^0F Cooling/ 72^0F Heating
Thermostat setback	80^0F Cooling/ 60^0F Heating
Supply air temperature	Maximum 110^0F, Minimum 52^0F
Ventilation	20 cfm/person
Demand control ventilation	No
Energy recovery	No
Supply Fan	
Fan type	Variable air volume
Supply fan total efficiency (%)	57% to 60% depending on the fan motor size
Supply fan pressure drop	3.5" water
Service Water Heating	
SWH type	storage tank
Fuel type	Natural gas
Thermal efficiency (%)	80%
Tank volume (gal)	260
Water temperature set point	120^0F
Misc.	
Exterior Lighting	
Peak power	2730 W

Table 1: Energy parameters assumed for base case simulation.[8] (Analysis of IECC and ASHRAE 90.1-2007 Commercial Energy Code Requirements, by Y Haung and K Gowri, February 2011)

4.2.2: Proposed Case: Electrochromic Glass

After simulating the ASHRAE 90.1, 2007 prototype office building in e-QUEST, the ASHRAE prototype glass was replaced by market available SAGE electrochromic glass. The electrochromic configuration was designed using WINDIW 5 software. The procedure to create electrochromic window can be seen in appendix A.

Case 4.2.2.1 Selection of Control Trigger

e-QUEST, DOE-2 software was used to studying the behavior of electrochromic glass and to determine the most appropriate control trigger. e-QUEST does not have any default control trigger for electrochromic windows. The available control triggers options in e-QUEST are total solar radiation, solar transmittance, outdoor temperature, space loads and daylighting level. e-QUEST has the limitation of analyzing a single control trigger during each simulation. To understand the behavior of each trigger, all the control trigger with defined range where applied to office building to understand the relative magnitude of energy savings attributed trigger.

The control trigger range can be decided on the bases of the thermal and optical properties of available glass type. Unlike all other control trigger space load trigger in e-QUEST fails to simulate the theoretical relationship for shading co-efficient (SC) and visible transmittance (Vt) for a given sensible load per square feet of glass. To solve this error, SC and VT schedule were created to overwrite the defective thermal and optical properties demonstrated in e-QUEST. The process of editing and overwriting was done by following steps:

- Hourly reports of sensible space load for a simplified glass were generated at SC intervals of 0.10 from 0.2 to 0.6. The range of SC values directly reflects the values specified by SAGE electrochromic manufacturer. This
- process was carried out to see the difference of space load for each SC interval.

- The simulated space load (btu/hr/sqft) for each SC interval was plotted against energy consumption (Kwh/sqft).
- The percentile method was used to justify the range of control trigger. 10% of the points on either end of the range were ignored. This means 20% of the plotted points indicate clear and darken state. In this case, 80% of simulated space load data represent the switching phase of glass.
- The space load values that bounded 80% of total simulated data set were defined as the low and high set points of the control trigger. During the switching phase the value for SC and VT were interpolated between switched and unswitched state.
- This process was repeated for each orientation, as the solar radiation incident on each orientation differ.

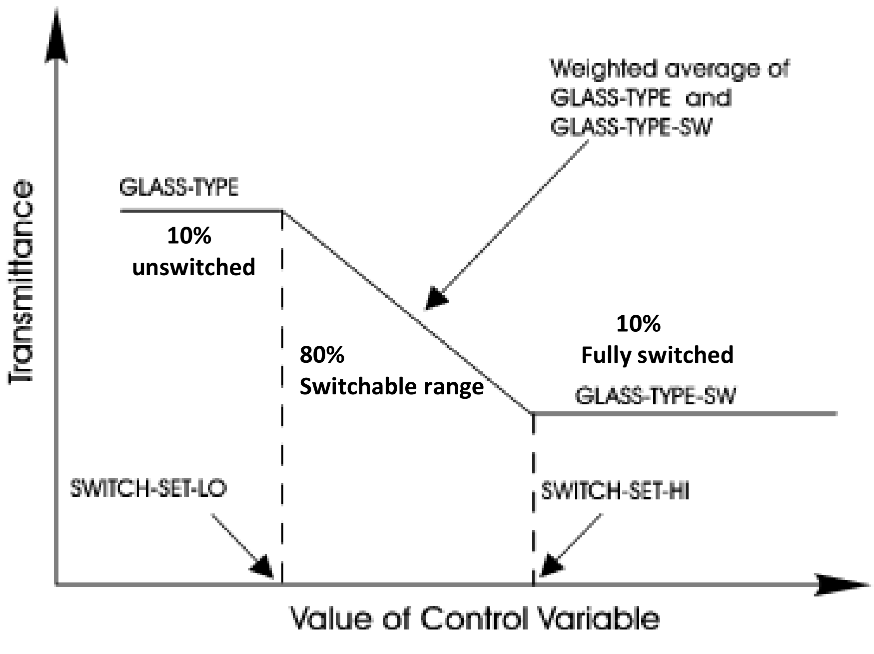

Figure 13: Percentile method used for establishing control trigger set points and trigger range.

This part of the process was performed to understand the behavior of thermal and optical properties i.e. shading co-efficient (SC) and Visible Transmittance (Vt) of control trigger with respect to electrochromic glass. The behavior of all the triggers used for this part of experiment is discussed in next chapter. Space load proves to be the most appropriate trigger to control the comfort level within the work space. Since, daylighting sensors were installed during schematic wizard phase, the minimum daylighting level was implicitly included in the building model. Thus both space and visual comfort have been accounted for in the model.

Space load trigger is useful to understand the behavior of electrochromic glass in building simulation program. In actual, office building with electrochromic glazing installed, terminal damper position directly reflects the thermal load in the space. Thermostat set points for the space modulate the damper position as a direct response to the thermal load in the space and send the signal to controller to switch the electrochromic glass. For simulation based study, space load trigger was directly addressed to modulate the behavior of electrochromic glass. For this research study, the switching factor of the glass responds to the thermal load recorded for the previous hour. Thus there is a time lag of one hour in switching of electrochromic glass.

Case 4.2.2.2 Control Trigger Range

Selecting the most appropriate control trigger range for a given trigger is as important as selecting the control trigger. Recall that the control trigger range is the governing factor for interpolating the fraction of shading co-efficient and visible transmittance at the given time of day. Experimental run explained in previous section helps us to understand the behavior of control trigger while this section helps to derive the most appropriate range of the selected trigger.

To justify the selection of range for space load, a sensitivity analysis was conducted. There are two types of sensitivity analysis as follows:

1. The upper and lower limits of space load range (which bound the switching phase) were shifted 10%, 20% and 30% in either direction relative to initial switching set points. This alters the control trigger set points yet increases the switching range.
2. The switching range was shifted 10%, 20% and 30% on either direction relative to initial switching range. This set of analysis was conducted to observe the magnitude of change in energy consumption.

If the change was negligible, the selected range for space load was justified. Results are presented in next chapter.

4.2.3: Results for Energy Savings

After selecting the most appropriate control trigger and establishing an ideal trigger range, several other relevant building parameters including window wall ratio (WWR), specialized orientation design, and with & without daylighting were studied. The parameter study was conducted as follows:

1. Recall that base case prototype building featured 40% WWR. Simulation was then performed for 20% WWR, to observe the relative influence of WWR on energy consumption.
2. Initially EC glass was specified on all orientation. Simulation was then performed for design that featured electrochromic glass on each

orientation individually with the remaining orientation with ASHRAE standard glass.

Both the above feature were introduced in excel based spreadsheet, used for energy analysis and life cycle cost analysis. The energy consumption for the energy model in eQUEST is dynamic, so to create the relation of window wall ratio to energy consumption and sizing of HVAC system, use of energy consumption to WWR were plotted to generate polynomial and linear equation. This dynamic relation was established by simulating following run:

1. Initially, a model with no windows on all four orientations was simulated to establish a case which has the energy consumption irrespective of the change in WWR.
2. Simulations with WWR from 5% - 40% at interval of 5% were simulated to generate the linear/polynomial equation to estimate the energy consumption and sizing of HVAC for a given WWR.
3. This process was repeated for base case glass (ASHRAE glass) as well as proposed case glass (SAGE electrochromic glass) for each orientation individually as the effect of WWR for each orientation would be different.

The results are discussed in next chapter. Thus, this method gives benefit to study the relative effect of WWR and orientation.

4.3 Life Cycle Cost Analysis

Compiling the annual energy consumption figures for fore-mentioned design configuration, Life Cycle Cost (LCC) analysis was then conducted. LCC analysis is composed of initial cost and operational (energy) cost. The costs are outlined as follows:

- Initial Cost:
  - Cost of Glass:

    Base case uses ASHRAE glass in all orientation

    Proposed case uses EC glass on orientation mentioned in proposed case, and all other orientation features ASHRAE glass
  - Cost of Sensor:

    If the base case and proposed case have daylighting in the building, cost of sensor is considered for LCC analysis
  - Cost of HVAC System:

    The cost of HVAC is calculated per tonnage. In this type of LCC study per tonnage multiplier is multiplied to cooling tons simulated in base case and proposed case.

In addition to the initial cost incurred, LCC also accounts for maintenance cost which occurs once in 25 years' time period. All other costs are neglected as they remain same in both the base case and the proposed case, independent of type of glazing installed.

- Energy Cost:
  - Cost of electricity:

    This cost is derived from the utility tariffs from the local utility company supplying services to the building. This cost may differ by company offering the electricity.
  - Cost of Natural Gas:

    This cost is derived from the utility tariff offering the natural gas to the building.

4.3.1 Initial Cost:

The cost of ASHRAE glass and SAGE electrochromic glass used for this study are as follows:

Specification	ASHRAE glass	SAGE EC glass
Glass Cost	$25	$75
Controls and Wirings	--	$12
"Occupant override" wall switches:	--	$0.75
Total:	**$25.00/ sq.ft**	**$87.75/sq.ft**

Table 2: Cost of glazing system per square foot.

Cost of daylighting sensor is estimated to be $300 per sensor, as reflected by market price. For the modeled building which includes three stories, each perimeter zone has 1 sensor, which equates to 12 sensors for the entire building. Thus the total cost of daylighting sensor is $3600, and it requires no replacement during 25 period of analysis.

In case of HVAC system, VAV Hermetic water cooled chiller with cooling tower system is simulated and system type is consistent for all building models. The cost of HVAC system is calculated using graph shown below. These curves are for water cooled chiller cost which includes chiller and local piping, pumping assembly; one base mounted pump, cooling tower and its piping and chemical treatment assembly.

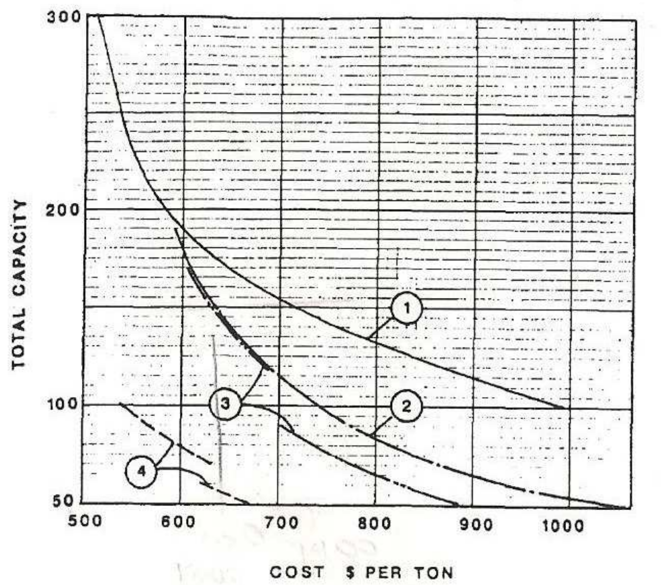

Figure 14: Cost Comparison curves for chilled water plants, (1) Hermetic centrifugal, water-cooled with tower; (2) hermetic reciprocating water-cooled with tower; (3) hermetic reciprocating condenser less with remote air-cooled condenser; (4) hermetic reciprocating air-cooled. Note: all this rates are from 1987 so to inflate these cost to 2011 cost, multiply each cost by 2.03 (assume 3% annual inflation rate of 24 years)

Peak Cooling tons are used to size a HVAC system. From the above graph it is shown that the HVAC system cost approximately $2500 per cooling tons. [9]

4.3.2 Energy Cost:

Building energy cost is composed of primary and secondary fuel energy source, where electricity is a primary source and natural gas is a secondary source. For the simulated building model, space cooling and lighting energy demand are both accommodated by electricity from the grid, while space heating energy demand is accommodated by combustion of natural gas. The simulated energy data also includes domestic hot water, pumps and auxiliary, ventilation fans and other miscellaneous equipment.

Total electricity and natural gas site energy consumption is considered for LCC analysis. The present cost of electricity reflects the current rates from Arizona Public service (local electricity energy provider for Phoenix) utility tariff, plan E32 medium. Appendix C shows the details for E32 medium and E32 medium- time of use plan. The cost of Natural gas utility rates is established based upon the data provided by Energy Information Administration database, June 2011. However this rates change frequently and often unpredictable.

All the building parameters including initial Glass cost, annual Electric and Natural Gas utility cost and HVAC cost per tonnage (all for each orientation) were calculated per square feet of glass. This data tables were attached to the LCC spreadsheet created by Prof. Addison for department of energy.

To further explore relative influence of aforementioned parameters on market economics, several LCC cases were studied. Specifically, alteration in glass cost, fuel escalation rate, utility cost and Discount rate were analyzed. The alteration in this parameters were identical in both the base case and the proposed model, thus there were equivalent number of base case as proposed case. By compiling both the base case and proposed case with same parameters, this isolated the effects of electrochromic windows, relative to windows prescribed by ASHRAE, in terms of energy consumption and sizing of HVAC. The parametric study was conducted as follows:

- Glass Cost: Initially, present market value of electrochromic glass was considered. However to account for future implementation of this technology, a reduction in initial cost of 50% was analyze. This assumption considers a more wide spread penetration of new technology in past.

- Fuel Escalation Cost: Escalation is the rate at which the prices increase, also known as inflation. The current projected US-DOE fuel escalation rate for electricity and natural gas are accounted for in life cycle costing. According to EIA, the maximum fuel escalation rate for both electricity and natural gas is considered to be 3%. This maximum rate was incorporated in the life cycle costing for electrochromic windows.
- Utility Cost: Utility Cost is location specific and depends on the local utility rates. For an office building in Phoenix, APS E32 and E32 Time of Utility were studied. Based upon the APS tariff structure, a preliminary simulation was conducted to generate the virtual rate which was used for Life Cycle Costing. To explore the payback period in the location with higher utility rates, Southern California Edison TOU8 plan was evaluated.
- Discount Rate: A real discount rate is the discount rate expressed relative to general inflation, i.e. discount rate that has been adjusted to express the 'net opportunity cost. Typically, both discount rate and inflation rate are positive values, this adjustment results in a reduction in magnitude of discount rate. The discount rate not adjusted to express net opportunity cost is said to nominal rate. [7] According the US standard, 3% real discount rate was considered in this analysis. In addition 6% real discount rate was also considered to account for future market economics.

Simple Payback Method:

Simple payback considers the initial costs, i.e. incremental initial investment cost and incremental first year utility savings. It is calculated using the following equation:

$$SPB = \frac{\text{Incremental First Cost (\$)}}{\text{First Year Annual Savings (\$)}}$$

Where:

SPB = Simple Payback

Incremental First Cost = Alternative First Cost - Baseline First Cost

First Year Annual Savings = Baseline First Year Utility Cost - Alternative First Year Utility Cost

Net Saving:

Net Saving is defined as the total project cost at the end year of LCC analysis. It is the difference between the sum of resultant initial cost and energy cost for the base case and that of the proposed case for the LCC time span. It is calculated using the following equation:

Net Saving = total cost of base case - total cost of proposed case

Where:

Total cost of base case = Sum of initial, discounted escalated energy cost of base case

Total cost of proposed case = Sum of initial, discounted escalated energy cost of proposed case

For the purpose of this research study, several Window wall ratio and orientation schemes were analyzed from both simple payback and net savings perspectives.

Chapter 5

ENERGY RESULTS AND ANALYSIS

5.1 Energy analyses for an electrochromic glass:

The chapter discusses the quantifiable benefits of saving in energy consumption due to electrochromic windows. The simulated energy consumption reductions, relative to an equivalent ASHRAE base case model, allowed for the selection of most appropriate control trigger and trigger range. The simulation is conducted by configuring the base case which is ASHRAE 90.1 2007 prototype office building. For the proposed case, the ASHRAE glass type for windows was replaced by SAGE electrochromic glass. As electrochromic windows are operated by control trigger and trigger range, the subsequent analysis illustrates the operation of SAGE electrochromic glass as a function of a particular control trigger and control trigger range.

Next section of this chapter discusses the effects of different control trigger for a market available SAGE electrochromic glass for an office building.

5.1.1 Selection of Control Trigger

To reduce the energy consumption, several possible control triggers, which modulate the property of electrochromic glass, were studied. As mentioned in previous chapter effects of exterior as well as interior control trigger that dictate the internal thermal space load and lighting level were studied. During the process of selecting the most appropriate control trigger, and associated trigger range was established using simplified glass method. Specifically, the space load, outdoor temperature, Total horizontal radiation and daylighting were studied as possible control triggers. Table 3 indicates the relative magnitude of energy saving for each control triggers, in comparison with base case. See table 3 below.

Sr No	Specification	Space Cooling	Lighting	Space Heating	Electricity mKwh	Natural Gas M Btu	Energy Bills	Energy Savings (%)
0	Base Case	161.52	113.4	114.11	596.52	226.19	$80,434	
1	Space Load	141.4	119.9	128.33	569.26	240.57	$77,002	4.27%
2	Outdoor Temperature	164.3	116.97	136.26	602.36	248.38	$81,418	-1.22%
3	Total Horizontal Radiation	167.89	115.71	155.51	606.95	267.57	$82,209	-2.21%
4	Daylighting	154.92	112.44	154.17	582.41	266.37	$78,980	1.81%

Table 3: Energy Savings for different control triggers.

The evaluated trigger ranges which were used in the selection of most appropriate control trigger were not specified arbitrarily. The definition of trigger range established for each trigger is described in next section.

As seen in Table 3 that internal control trigger which includes space load and daylighting responds positively to electrochromic glass while external trigger which includes outdoor temperature and total horizontal radiation responds negatively to electrochromic glass. The results presented in table 3 indicates that space load control trigger reduces the overall energy consumption by 4%, where proposed case features SAGE electrochromic glass on all orientation as compared to base case which features ASHRAE defined glass on all orientation. On the other hand, implementation of daylighting control triggers results in 2% saving of overall energy consumption with respect to base case. The external control triggers which include outdoor temperature and total horizontal radiation indicate increase energy consumption relative to base case. This increase in energy consumption was not expected. To ensure the EC windows were operating properly, such that the shading coefficient and visible transmittance properties of the glass were switching as defined by control trigger range.

Based upon the hourly sensible space load data and associated trigger range, the shading co-efficient and visible transmittance was calculated. As seen in plot below the SC and VT properties were interpolated in between the upper and lower control trigger set points. The process was repeated for other control trigger including outdoor temperature (global temperature); total horizontal solar (total horizontal radiation) and daylighting trigger (illumination level at 10 feet of perimeter space where there is a daylight sensor). Furthermore, same procedure was repeated for all orientation.

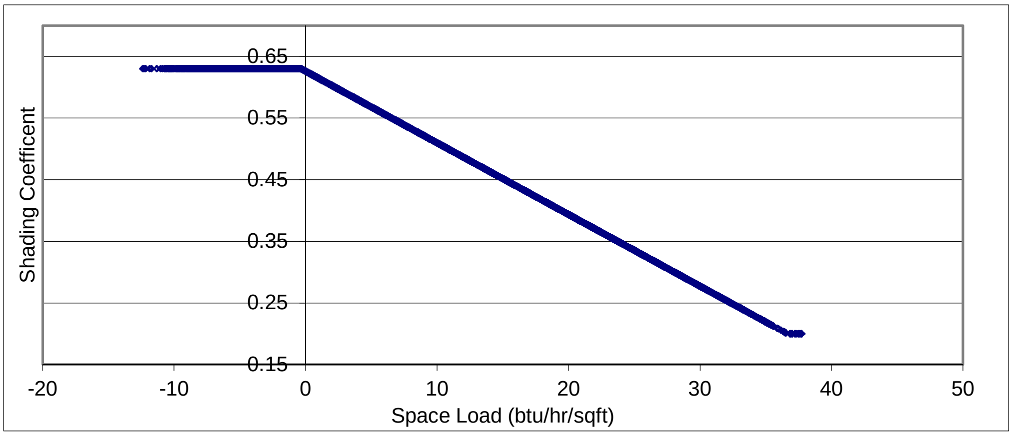

Figure 15: Ideal shading coefficient switching behavior for space load trigger.

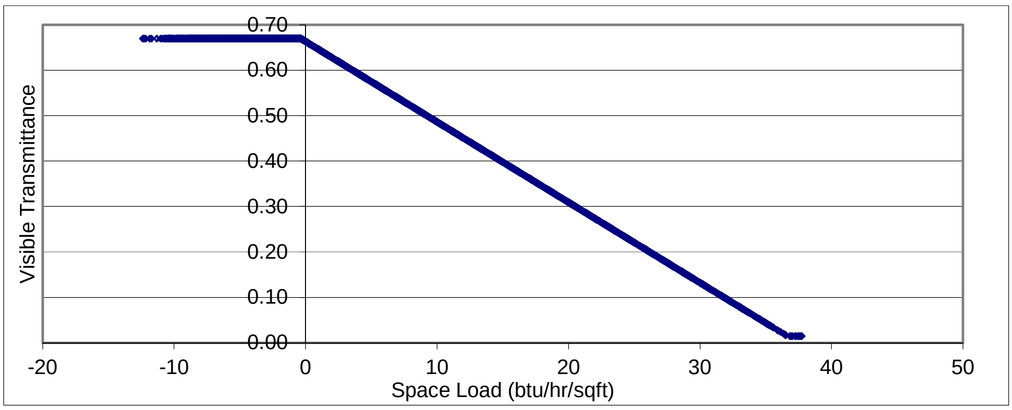

Figure 16: Ideal visible transmittance switching behavior for space load trigger.

Both the graphs shown above are only for south orientation; however identical graphs were generated for all other orientation.

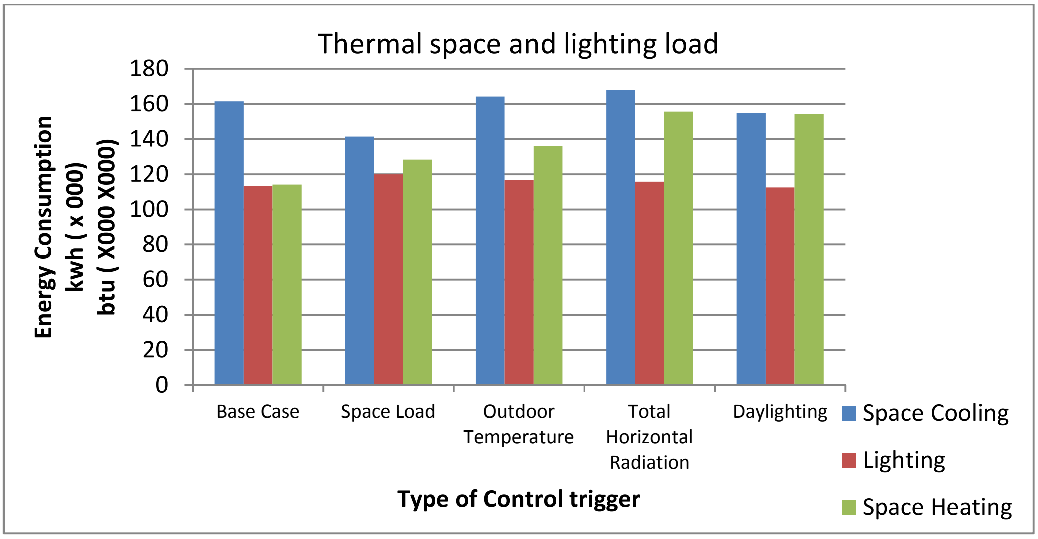

Figure 17: Comparison of space conditioning and lighting energy consumption for different control triggers.

In terms of overall energy consumption, space load trigger results in most significant savings in energy consumption. More specifically while using the space load trigger, the space cooling and space heating energy consumption are the least of all other trigger analyzed. However as seen in figure 15, the lighting energy consumption for the space load trigger is greater than all other trigger analyzed. The switching of electrochromic glass transmits less daylight into the space, and thus more artificial lighting is needed to satisfy a minimum threshold illumination level for workspace.

The hourly data for daylighting is reviewed for space load control trigger to analyze the impact of space load trigger for daylighting inside the work space. It is observed that daylighting illumination level drops below 50fc switching hours and as a result the lighting requirement is supplemented by artificial lighting. Although the lighting level consumption increases, there is a favorable tradeoff in terms of thermal space loads.

5.1.2 Control Trigger Range

While selecting the type of control trigger in the previous section trigger range was established for individual orientation. This particular range was defined using simplified glass method, mentioned in section 4.2.2.1. Table 4 indicates the specified range of each control trigger used to analyze the energy consumption associated with each control trigger.

Sr. No.	Specification	South	East	North	West
1	Space Load	-0.37--36.63	-1.61--35.25	-4.80--21.24	-3.82 --36.29
2	Outdoor Temperature	53 -- 93	54 -- 93	55 -- 93	56 -- 93
3	Total Horizontal Radiation	42 -- 287	42 -- 287	42 -- 287	42 -- 287
4	Daylighting	43 -- 604	27 -- 596	16 -- 169	21 -- 576

Table 4: Control trigger with defined trigger ranges for each orientation. (units = btu/hr/sqft)

Space load control trigger was not uniform for all orientation. As indicated by table 4, solar geometry has a significant effect on the function of trigger range. As expected north direction receives mostly diffuse sunlight which reflects the lower value in upper limit of trigger range while the south direction has higher value in upper limit due to fact the south façade receives the highest amount of solar radiation during the day. Outdoor temperature and Total horizontal radiation uses the global TMY3 data to generate the hourly report, therefore no change in the control trigger range is observed for individual orientation. Similar to space load trigger, solar geometry influence the amount of daylighting transmitted through each façade orientation. Thus each façade demonstrates its own unique trigger range. Daylighting trigger in eQUEST allows for maximum 500 foot candles.

To justify the selection of control trigger range for space load trigger, a sensitivity analysis was conducted as described in section 4.2.2.2 of chapter 4. There are two types of sensitivity analysis as follows:

1. As mentioned in methodology, this sensitivity analysis was performed to analyze the magnitude of reduction of energy consumption when the lower and the upper limits of the range were either increased or decreased by 10%, 20% and 30% respectively.

Sr. No	Specification	South	East	North	West
0	Trigger Range	-0.37 -- 36.63	-1.61 --35.25	-4.80 -- 21.24	-3.82 -- 36.29
1	10% decrease on lower end	-4.07 -- 36.63	-5.31 -- 35.25	-7.40 -- 21.24	-7.82 -- 36.29
2	20% decrease on lower end	-7.77 -- 36.63	-9.01 -- 35.25	-10.00--21.24	-11.82 --36.29
3	30% decrease on lower end	-11.47--36.63	-12.71 --35.25	-12.36 -21.24	-15.82 --36.29
4	10% increase on higher end	-0.37 -- 40.33	-1.61 -- 38.95	-4.80 -- 23.84	-3.82 -- 40.29
5	20% increase on higher end	-0.37 -- 44.03	-1.61 -- 42.65	-4.80 -- 26.44	-3.82 -- 44.29
6	30% increase on higher end	-0.37 -- 47.73	-1.61 -- 46.35	-4.80 -- 29.04	-3.82 -- 48.29

Table 5: Values for increased space load trigger range. (units = btu/hr/sqft)

The change in trigger range as mentioned above were simulated in eQUEST to determine relative magnitude of annual energy consumption for each case. The results are given in table below.

Sr. No.	Specification	Electricity (Kwh X000)	Natural Gas (Btu X 000000)	Energy Bills
0	Trigger Range	569.26	240.57	$77,002
1	10% decrease on lower end	569.31	242.8	$77,031
2	20% decrease on lower end	569.43	244.72	$77,065
3	30% decrease on lower end	569.58	246.54	$77,103
4	10% increase on higher end	568.88	239.38	$76,940
5	20% increase on higher end	568.71	238.18	$76,906
6	30% increase on higher end	568.66	237.59	$76,894

Table 6: Energy consumption for increased space load trigger ranges.

The percent change in energy consumption of above cases, relative to the initially defined trigger range, was negligible. Thus, the initially defined space load trigger range for space load trigger is most appropriate.

2. This sensitivity analyses was conducted to determine the change in energy consumption when shifting the trigger range towards either upper or lower limit by 10%, 20% and 30%.

Sr No	Specification	South	East	North	West
0	Trigger Range	-0.37 -- 36.63	-1.61 --35.25	-4.80 -- 21.24	-3.82 -- 36.29
1	10% shift towards lower end	-4.07 -- 32.93	-5.31 -- 31.55	-7.40 -- 18.64	-7.82 -- 32.29
2	20% shift towards lower end	-7.77 -- 29.23	-9.01 -- 27.85	-10.00 -- 16.04	-11.82 -- 28.29
3	30% shift towards lower end	-11.47 --25.53	-12.71 -- 24.15	-12.36 -- 13.44	-15.82 -- 24.29
4	10% shift towards higher end	3.33 -- 40.33	2.09 -- 38.95	-2.22 -- 23.84	0.18 -- 40.29
5	20% shift towards higher end	7.03 -- 44.03	5.79 -- 42.65	0.4 -- 26.44	4.18 -- 44.29
6	30% shift towards higher end	10.73 -- 47.73	9.49 -- 46.35	3.00-- 29.04	8.18 -- 48.29

Table 7 Shifting of space load trigger set points. (units= btu/hr/sqft)

Sr. No.	Specification	Electricity (Kwh X 000)	Natural Gas (Btu X000000)	Energy Bills
0	Trigger Range	569.26	240.57	$77,002
1	10% shift on lower end	570.12	244.16	$77,150
2	20% shift on lower end	571.55	247.23	$77,368
3	30% shift on lower end	573.6	250.39	$77,668
4	10% on shift higher end	568.99	237.16	$76,933
5	20% on shift higher end	569.16	234.41	$76,928
6	30% on shift higher end	569.67	232.05	$76,972

Table 8: Energy consumption for shifted space load trigger set points.

The percent change in energy consumption of above cases, relative to the initially defined trigger range, was negligible. Thus, the initially defined space load trigger range for space load trigger is most appropriate.

Thus, the sensitivity analysis supports the trigger range established by simplified glass method is most appropriate to derive the reduction in energy consumption by electrochromic glass.

5.1.3 Results for energy analysis for electrochromic glass:

After selecting space load trigger as the most appropriate trigger and establishing its range, some other building parameters which include window wall ratio and orientation were then explored.

Initially, a building model with no window was simulated to provide some reference case for annual energy consumption. As described in methodology, series of ASHRAE building model which featured a wide range of window wall ratio were then simulated to determine the incremental annual energy consumption per square feet of glass. The same range of window wall ratio was simulated on all orientation. See table 9 below for energy consumption for south orientation.

Specification	Electricity (kwh X000)				Natural Gas (Btu X000000)			
		%	Δ Kwh	Kwh/ sqft		%	Δ Kwh	Kwh/ Sqft
No window	548.48				125.77			
40% ASHRAE	579.84	40	31.36	0.78	138.57	40	12.8	0.32
35% ASHRAE	574.57	35	26.09	0.74	134.59	35	8.82	0.25
30% ASHRAE	570.92	30	22.44	0.74	131.97	30	6.2	0.20
25% ASHRAE	567.26	25	18.78	0.75	130.47	25	4.7	0.18
20% ASHRAE	563.78	20	15.3	0.76	128.98	20	3.21	0.16
15% ASHRAE	560.41	15	11.93	0.79	127.82	15	2.05	0.13
10% ASHRAE	559.71	10	11.23	1.12	126.97	10	1.2	0.12
5% ASHRAE	555.78	5	7.3	1.46	126.37	5	0.6	0.12

Table 9: Energy consumption (electricity and natural gas) for south façade with ASHRAE glass.

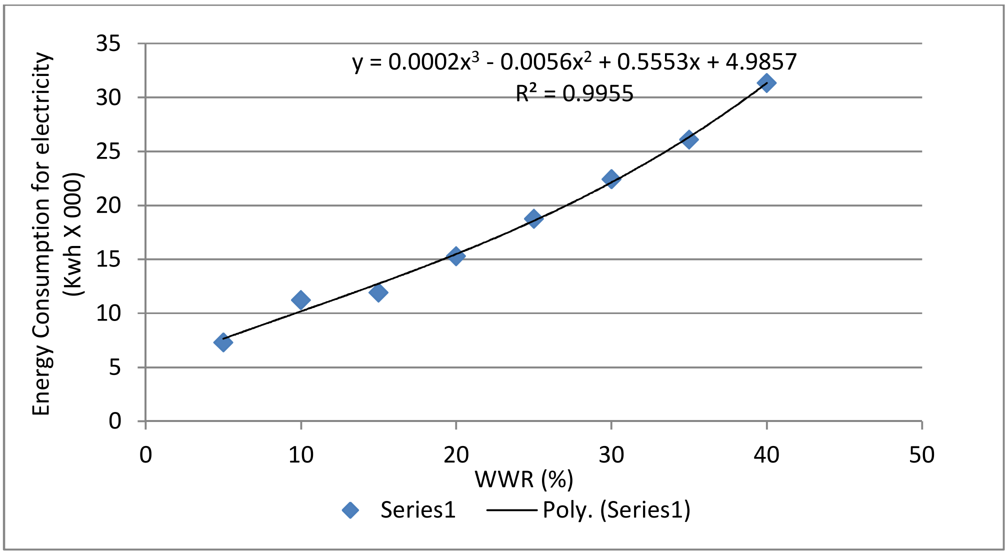

Figure 18: Electric Energy consumption vs. Window Wall ratio for ASHRAE glass on South facade

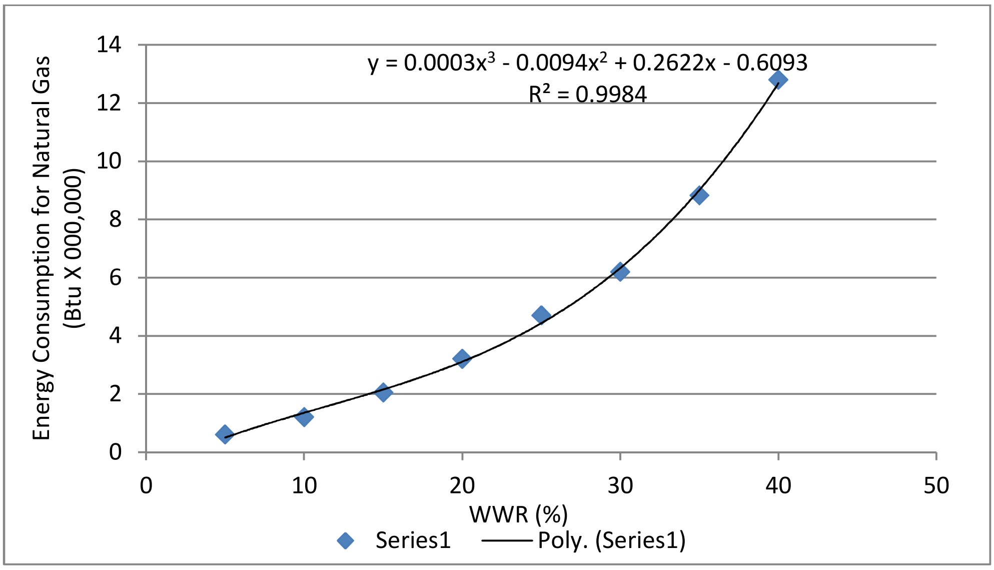

Figure 19: Natural Gas Energy consumption vs. Window Wall ratio for ASHRAE glass on South facade

Similar study for SAGE electrochromic glass was conducted where wide range of window wall ratio were simulated to determine the incremental annual energy consumption per square feet of glass for specified window wall ratio and orientation. Same procedure was repeated for all orientation. See table 10 for wide range of change in annual electric and natural gas with wide range of window wall ratio for south façade.

Specification	Electricity				Natural Gas			
		%	Δ Kwh	Kwh/ sqft		%	Δ Kwh	Kwh/ sqft
No window	548.48				125.77			
40% ASHRAE	565.68	40	17.2	0.43	140.48	40	14.71	0.36
35% ASHRAE	563.92	35	15.44	0.44	137.95	35	12.18	0.34
30% ASHRAE	562.1	30	13.62	0.45	135.51	30	9.74	0.32
25% ASHRAE	560.49	25	12.01	0.48	133.52	25	7.75	0.31
20% ASHRAE	558.48	20	10	0.5	131.48	20	5.71	0.28
15% ASHRAE	556.37	15	7.89	0.52	129.71	15	3.94	0.26
10% ASHRAE	554.15	10	5.67	0.56	128.17	10	2.4	0.24
5% ASHRAE	552.42	5	3.94	0.78	126.94	5	1.17	0.234

Table 10: Energy Consumption (electric and Natural Gas) for south façade SAGE electrochromic glass.

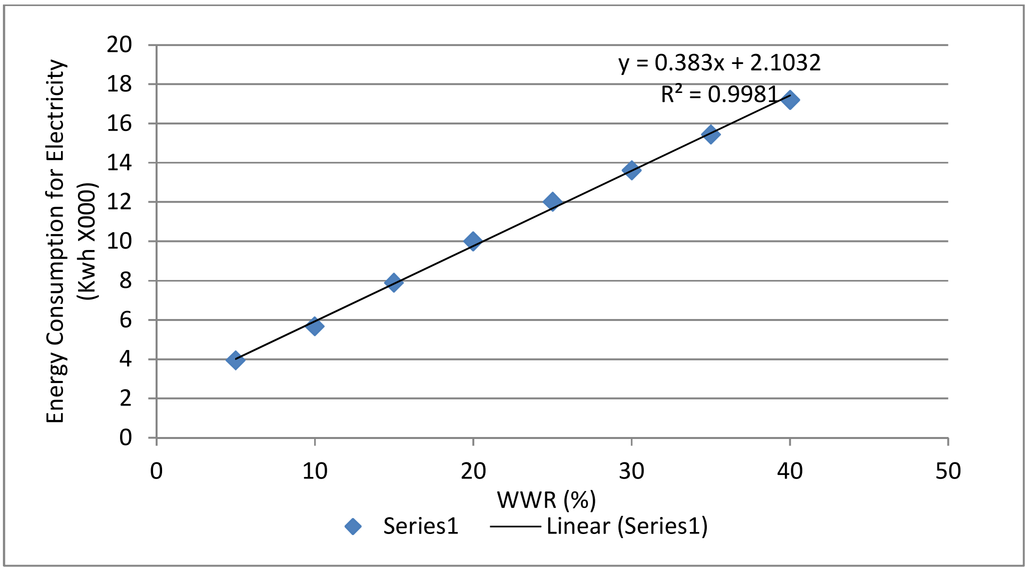

Figure 20: Electric Energy consumption vs. Window Wall ratio for SAGE glass on South facade

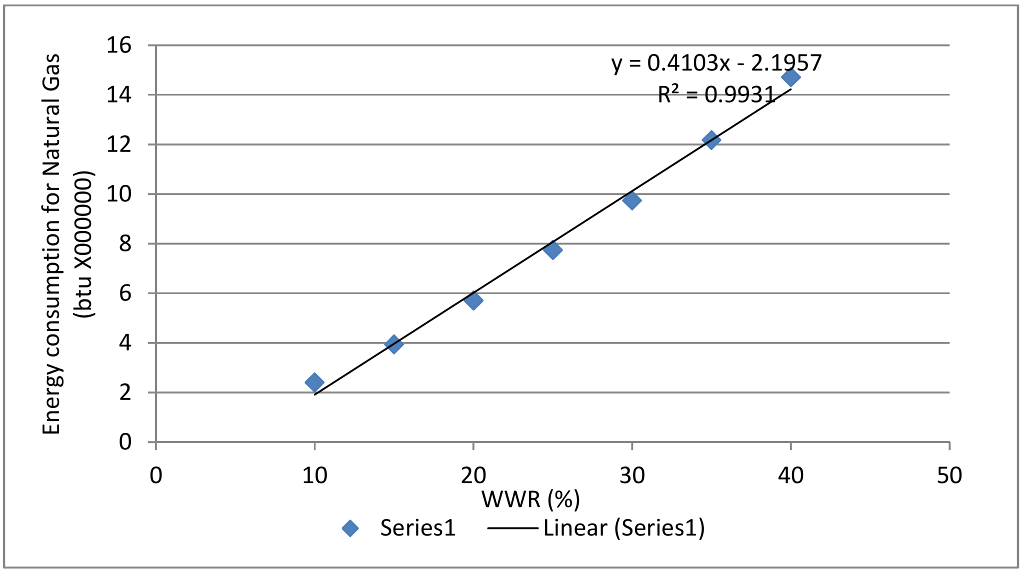

Figure 21: Natural Gas Energy consumption vs. Window Wall ratio for SAGE glass on South façade.

Based upon the simulated energy consumption data, an equation to predict the annual energy consumption i.e. electricity and natural gas as a function of window to wall ratio (per orientation) was developed. This relation indicates the change in energy consumption per percentage of window wall ratio.

To analyze the impact of electrochromic glass for each orientation individually, all orientation were set with 40% ASHRAE glass except one with 40% electrochromic glass. These results were compared with the reference case which had 40% ASHRAE glass in all orientation. Thus, the change in energy consumption was due to electrochromic glass. To analyze the impact of glass for each orientation, the total savings for annual energy consumption was reported for per square feet of glass. See table 11 for impact of electrochromic glass for each orientation.

Case Description	**Energy Bills** Total	**Percentage of Energy Saving for each orientation (per Sq. feet of EC glass)**
All ASHRAE- Non Daylighting	$84,538	
South EC glass	$82,453	0.000965%
East EC glass	$83,291	0.000866%
North EC glass	$84,133	0.000187%
West EC glass	$83,556	0.000682%
all Switched EC glass- Non daylighting	$79,790	0.000659%

Table 11 Percentage of energy savings per square feet of electrochromic glass in each orientation.

Chapter 6

LIFE CYCLE COST RESULTS AND ANALYSIS

This chapter of the research paper investigates the market economics of the electrochromic technology. Up to this point, many different configurations of WWR and orientation were simulated to iteratively reduce annual energy consumption and downsize the HVAC system, relative to ASHRAE base case. Through LCC analysis, the present value of electrochromic technology, in terms of current as well as projected/future market economics was determined. In particular, discount rate, fuel escalation rate, utility rate, and cost of electrochromic glass were parametrically studied. The Building Life Cycle Cost spreadsheet was customized for prototype office building for Phoenix location and as a result strictly applies to this research project.

Before analyzing different variable which includes building parameters and economic variables, it is very important to learn the real-time tradeoff between reduced energy consumption and payback period with respect to selection of orientation which is justified for installation of electrochromic windows. See table 12 below for this comparison.

	Orientation				Energy Consumption			
	South	East	North	West	Electric. (Kwh X 000)	N. Gas (Btu X000000)	Simple Payback (years)	Net Savings
1	SAGE	SAGE	SAGE	SAGE	591.75	224.25	90.73	-$414,753
2	SAGE	SAGE	ASHRAE	SAGE	596.07	211.09	76.4	-$269,089
3	SAGE	SAGE	SAGE	ASHRAE	599.5	227.28	89.28	-$344,519
4	SAGE	ASHRAE	SAGE	SAGE	603.69	227.62	105.58	-$339,761
5	SAGE	SAGE	ASHRAE	ASHRAE	603.79	214.53	71.04	-$198,855
6	SAGE	ASHRAE	ASHRAE	SAGE	607.82	217.11	88.37	-$194,097
7	SAGE	ASHRAE	ASHRAE	ASHRAE	612.40	219.82	83.52	-$123,863

Table 12: Tradeoff between reduced energy consumption and payback period with respect to selection of orientation.

Table 12 demonstrates relationship between the change in annual energy consumption and change in both simple payback and net saving. As expected case 1 demonstrates the least annual energy consumption while simple payback is comparatively longer and net saving is poorest of all cases. As observed in table 11 form previous chapter; south facade is the most favorable for installation of electrochromic glass while north facade is the least favorable. Thus, for all the above listed cases the south facade features electrochromic windows and north facade features ASHRAE glass type. Case 2 indicates very little increase in energy consumption while the payback period and net saving are much better than case 1. Among all above listed cases, case 5 demonstrates a most optimum balance between annual energy consumption and economics i.e. simple payback and net savings. The LCC projections are based upon the most ideal economic parameters which includes US DOE fuel escalation rates, 7.4% nominal discount rate, APS utility rates and present value of glass cost. Case 5 appears to be a most appropriate case for selecting orientations with electrochromic glass.

Table 13, compiles of seven different proposed building model cases which incorporates electrochromic windows. Parameters such as window-wall ratio, orientation, discount rate, escalation rate, utility rates, and glass cost were altered to converge to the most ideal simple payback and net savings. See table on next page.

Specification	WWR	Orientation				Disc. Rate	Escalation Rate		Utility Rates		Glass Cost	LCC Analysis	
		South	East	North	West		Elec.	Natural Gas	Electricity	Natural Gas	% to PV	Simple Payback	Net Savings
Case 1	20%	100%	100%	100%	100%	7.4%	US DOE	US DOE	APS TOU rate	EIA 2011 rate	100%	118.8	-$237,817
Case 2	**40%**	100%	100%	100%	100%	7.4%	US DOE	US DOE	APS TOU rate	EIA 2011 rate	100%	90.75	-$414,753
Case 3	40%	**100%**	**100%**	**0%**	**0%**	7.4%	US DOE	US DOE	APS TOU rate	EIA 2011 rate	100%	71.04	-$198,855
Case 4	40%	100%	100%	0%	0%	**4.4%**	US DOE	US DOE	APS TOU rate	EIA 2011 rate	100%	71.04	-$184,349
Case 5	40%	100%	100%	0%	0%	4.4%	**3%**	**3%**	APS TOU rate	EIA 2011 rate	100%	71.04	-$155,385
Case 6	40%	100%	100%	0%	0%	4.4%	3%	3%	**SCE TOU rate**	EIA 2011 rate	100%	40.42	-$91,465
Case 7	40%	100%	100%	0%	0%	4.4%	3%	3%	SCE TOU rate	EIA 2011 rate	**50%**	8.92	$95389

Table 13: Parametric LCC analysis.

Some of the specific trends seen with different parameters are as follows:

Case 1:

A proposed building model which features the minimum window wall ratio (20%) with SAGE electrochromic window installed on all orientation. The 7.4% (nominal) discount rate and US DOE fuel escalation rate were selected based upon federal/public sector rate. Utility rates were selected based upon APS tariffs which are local utility provider in Phoenix area. The present value for SAGE electrochromic glass was acquired from the manufacturer.

Case 2:

The window to wall ratio was increased from 20% to 40%, which is the recommended window wall ratio ASHRAE 90.1, 2007. All other parameters were kept constant to isolate the influence of window wall ratio on simple payback and net savings for electrochromic windows. Although the annual energy consumption was reduced with greater window wall ratio, the initial glass and HVAC investment cost increased.

When 20% window wall ratio was increased to 40%, the operational savings (energy consumption cost) increases which results in shorter Simple payback period. The increase in initial cost of glass and HVAC system outweigh the decrease in annual energy consumption; thus net saving decreases.

Case 3:

Based upon previous analysis, it was determined cost of the annual energy savings associated with electrochromic windows on north and west facades are negligible. See Table 12, to conclude that selection of south and east façade are selected and justified for tradeoff between reduction in energy consumption and LCC payback period. Thus, the electrochromic windows were only simulated in south and east façade while the north and west façade featured ASHRAE glass.

Orientation				Glass Cost	HVAC cost	Energy Cost		
South	East	North	West			Electric	N. Gas	Total
SAGE	SAGE	SAGE	SAGE	$747,419	$519,633	$77,580	$2,252	$79,832
SAGE	SAGE	ASHRAE	ASHRAE	$480,179	$547,962	$79,488	$2,244	$81,732
Savings				$267,240	-$28,329	$1,908	-$8	$1,900

Table 14 Comparison between SAGE electrochromic in all orientation and south/east orientation for case 2

Relative to the proposed case with SAGE glass in all orientation, the case which features electrochromic on only south and east façade demonstrate a comparable annual energy cost, however initial glass cost was much less. As a result, the simple payback and net saving were more favorable for south and east façade configuration.

Case 4:

In previous case, the discount rate is determined to be 7.4% which is nominal discount rate for public sector). This initial nominal discount rate was modified to 4.4% which is assumed to be lowest possible federal/public nominal discount rate. As simple payback is dependent upon solely the first year energy consumption, any alteration in nominal discount rate will not affect the payback period. However, this decrease in nominal discount rate reflects the lesser inflation rate. Thus, at higher nominal discount rate (7.4%), the value of money (particularly energy cost) decreases at much faster rate as compared to lower nominal discount rate (4.4%). The net saving was greater for lower nominal discount rate.

Case5:

For all previous cases the simulated fuel escalation rate used the US DOE 2011 projected escalation over life cycle span i.e. 25 years. The US DOE escalation rate differs every consecutive year as dictated by market price index, however the escalation rate never exceed 1%. For this case, a flat 3% fuel escalation rate was analyzed. This rate was considered to be maximum possible fuel escalation rate. 3% fuel escalation rate means that the cost of energy increases 3% in magnitude each year. Thus, the monetary saving associated with reducing energy consumption was amplified during each year of life cycle analysis.

Case6:

For all previous cases, APS utility rates were applied to all simulated building model. For this case, APS electric utility rate was replaced by southern California, Edison Time of use (SCE TOU) rates. SCE TOU electricity rates are 1.76 times higher than APS electricity utility rates. Thus, cost of annual energy consumption is higher compared to previous APS based simulations. Initial cost for both the cases remained the same, while first year energy savings for SCE electric utility rate was much higher than APS electric utility rate. This resulted in shorter simple payback period. Due to higher cost of electricity, the value of electrical energy saving is also increased. Thus, the net savings is greater than previously simulated cases.

Case7:

The final case analyze highly speculative and purely hypothetical. It is assumed that the initial cost of electrochromic glass is reduced by 50% of the present value cost, while the initial cost of ASHRAE prescribed glass remains the same. It drastic reduction in initial cost decreases the simple payback period. In all previous cases, the net saving at the end of the life cycle span were negative values. This can be primarily attributed to significant first cost of electrochromic glass. However, this case demonstrated that with 50% reduction in initial glass cost, a positive net saving can be achieved at the end of life cycle analysis.

Chapter 7

CONCLUSION

The research project was carried out to investigate the performance factors that can reduce the energy consumption and Life Cycle Cost analysis for electrochromic window technology. The above set of studies concludes as follows:

- Electrochromic window can switch its thermal and optical properties by using control trigger. Among all other control trigger which includes space load, outdoor temperature, total horizontal solar and daylighting, it proves that space load trigger is the most appropriate trigger for an office building located in climate like phoenix as it displays the significant reduction of thermal energy consumption i.e. 12.5% without compromising lighting load which incurs penalty of 5.3%.
- The ideal concept of architects that energy consumption increases with the increase in window wall ratio needs to be changes. In case of electrochromic technology, the difference of the energy saving increases with the increase in window wall ratio. Thus, thought that the energy consumption with increase in window wall ratio needs to be changed by introducing electrochromic glass technology, as the increase in Window wall ratio reduces significant amount of energy consumption. Refer case 2 from previous chapter.
- Electrochromic windows reduce the annual energy consumption for all orientation, however the reduction in annual energy consumption for north and west façade is too low, and that

installation of this technology is not worth paying. Please refer case 3 of chapter 5. Though there is reduction in energy consumption, the economics of the technology does not allow installation of electrochromic on north and west façade. South and east façade reduces the significant amount of energy, which gives lower payback period. Refer table 13.

- The nominal discount rate for present market which is 7.4% needs to be lowered by 3-4% to increase the scope of electrochromic technology.
- The cumulative US fuel escalation rate which is -0.38% can likely increase in future. If the fuel escalation increases by flat 2-3%, there is greater scope of electrochromic technology.
- This technology proves to be more favorable in the same type of climate zone having higher electric utility rates compared to Phoenix. For example, electrochromic technology is more favorable for Southern California, Edison (SCE) electric utility rate than Arizona Public Service (APS) electric utility rate, which concludes that this technology has wide scope in hot climatic zone with higher electric utility rates.
- All the above simulated cases have negative payback period which indicates that still the initial cost investment for this technology is too high to overcome the market economics. Thus, if the initial cost of the glass is lowered to 50% of the present value of glass cost, it indicates that the net saving becomes positive and simple payback period is also feasible for new technology to be introduced in commercial market.

All the above listed performance factors and LCC parameters were simulated to lower the annual energy consumption and shorten simple payback period for electrochromic technology, still the net saving at the end of LCC span is negative, which indicates that the economic value for electrochromic technology needs to be lowered at least 50% to penetrate the commercial market. If the initial cost for manufacturing glass is lowered 50% due to mass production or any rebates offered for installing this technology can make this technology feasible.

Future Works:

- This study is conducted strictly for an office building in Phoenix; there is scope of exploring the behavior of electrochromic building in milder climate like Los Angeles.
- This study includes the response of control trigger on the bases of hourly data provided by thermal loads of space, which is acceptable for the places like Phoenix, but locations where the sky conditions changes too frequently needs a trigger that tracks data at shorter interval i.e. every minutes or seconds.
- This building is designed with Variable Air Volume system; other mechanical system that is used for office building can also be explored.
- As described under Scope and Limitations chapter, this study can be extended to incentives, rebates and subsidies offered for renewables and energy saving programs.

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APPENDIX A

CONFIGURING SAGE ELECTROCHROMIC IN WINDOW 5.2

Window 5.2 is the LBNL software that was used to configure the SAGE electrochromic window with the identical glass properties. This software tool is simple and user friendly and is compatible to import its data to DOE tool eQUEST. Following steps are following to create and import the SAGE electrochromic in eQUEST energy model.

1. Initially, EC layers from window 5.2 library is selected and multilayer EC glass is configured. Figure 19 displays the input on screen 1

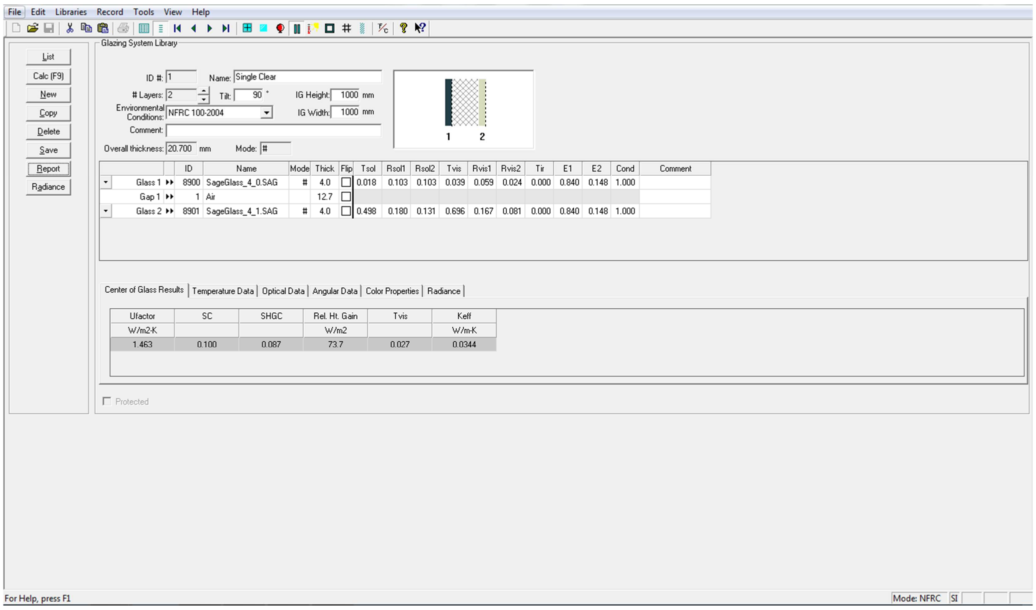

Figure 22: Screen shot 1 of window 5.2 to configure EC glass.

Glass 1 is selected as 8900 code SAGE EC glass and glass 2 is selected as 8901 SAGE EC glass with air gap between them. Upper right corner of the screen shows the section of configured glass. The glass properties displayed on the bottom of the screen are the calculated glass properties at the center of the glass. Screen 2 in figure 20 shows the elevation of configured window.

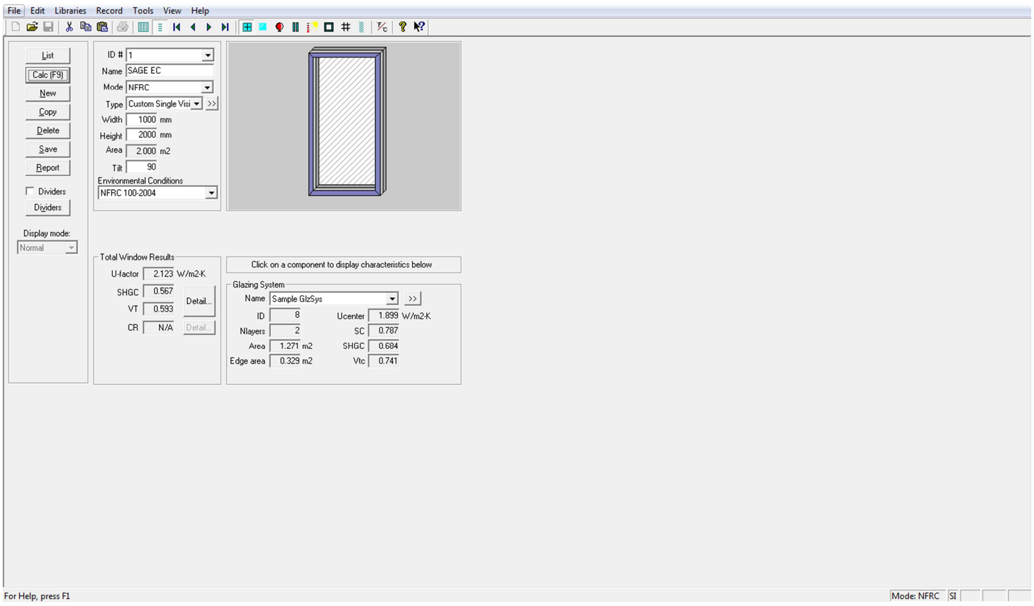

Figure 23: Screen shot 2 of Window 5.2 to configure EC window.

This screen facilitates to customize the frame of window. The upper right image in the figure shows the elevation of EC glass window. Report on the left panel, generates the report in text format which can be imported in eQUEST. eQUEST has a facility to import window 5.2 file under glass type in component tree. Thus SAGE EC glass which is not available in eQUEST glass library can be created and imported in eQUEST.

APPENDIX B

INTRODUCTION OF ELECTROCHROMIC GLASS IN eQUEST

Introduction of electrochromic glass is the same as one introduces a specific glass type in eQUEST project. Electrochromic glass is taken as the two glass type assembly in eQUEST; one glass type is named as unswitched glass while the other is named as switched glass type. Please see below given screen shots to easy understanding.

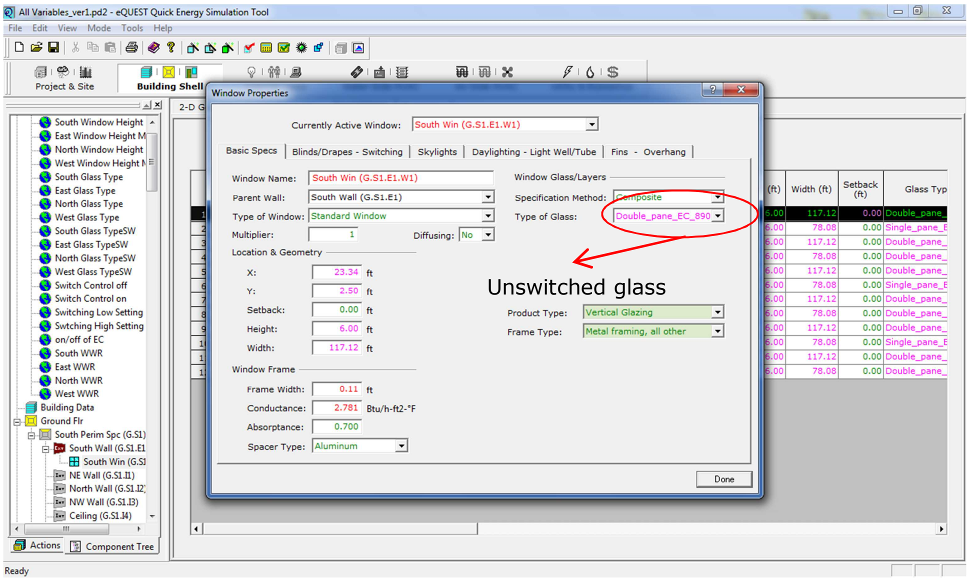

Figure 24: Screen shot of unswitched glass type of electrochromic window.

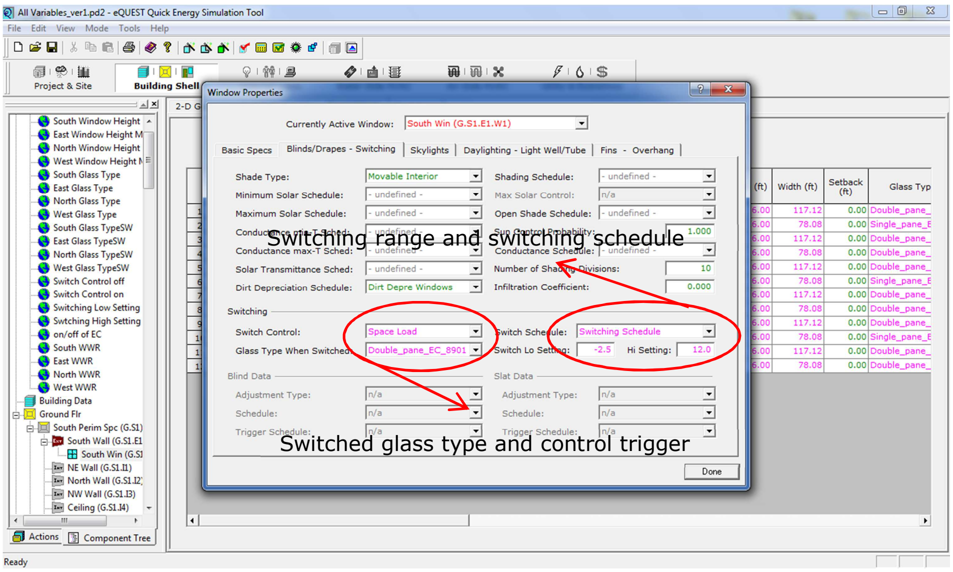

Figure 25: Screen shot for switched glass type of electrochromic window along with control trigger.

Figure 20, basic specification tab under window properties where usually non-electrochromic window as well as unswitched glass type is inserted. Figure 21, Blinds/Drapes and switching tab under window properties is used to introduce switched glass type along with control trigger, switching on/off range and switching schedule. Thus the electrochromic window is taken as two different glass types by eQUEST.

Some electrochromic glass types are in glass library of eQUEST, but in case importing the glass type, Window5, LBNL software is used. Glass type created in Window5 can be imported to project which later on can be placed under unswitched and switched glass type. In this case, one needs to create a glass type in Window5, and create it as DOE2 report. This report is imported in eQUEST project folder and is a part of eQUEST project, which can be used a glass type.

APPENDIX C

UTILITY RATES OF ELECTRICITY

E32 Medium

E-32 Medium	
Basic Service Charge	
Self-Contained Meters	$ 0.672 per day
Instrument-Rated Meters	$1.324 per day
Primary Voltage	$ 3.415 per day
Transmission Voltage	$26.163 per day

Energy Charge	
May – October Billing Cycles (Summer)	**November - April Billing Cycles (Winter)**
$0.10320 per kWh for the first 200 kWh, plus	$0.08619 per kWh for the first 200 kWh, plus
$0.06034 per kWh for all additional kWh	$0.04334 per kWh for all additional kWh
Demand Charge	
Secondary Service:	
$9.597 per kW for the first 100 kW, plus	$5.105 per kW for all additional kW
Primary Service:	
$8.905 per kW for the first 100 kW, plus	$4.412 per kW for all additional kW
Transmission Service:	
$6.942 per kW for the first 100 kW, plus	$2.450 per kW for all additional kW

E32 Medium (Time of Use)

E-32 Medium Time-of-Use	
Basic Service Charge	
Self-Contained Meters	$ 0.672 per day
Instrument-Rated Meters	$1.324 per day
Primary Voltage	$ 3.415 per day
Transmission Voltage	$26.163 per day

Energy Charge	
May – October Billing Cycles (Summer)	**November - April Billing Cycles (Winter)**
$0.07233 per kWh during on-peak hours, plus	$0.05542 per kWh during on-peak hours, plus
$0.05748 per kWh during off-peak hours	$0.04057 per kWh during off-peak hours
Demand Charge	
For Secondary Service:	
$14.209 per kW for the first 100 on-peak kW, plus $9.649 per kW for all additional on-peak kW	
$ 5.449 per kWh for the first 100 off-peak kW, plus $3.034 per kW for all additional off-peak kW	
For Primary Service:	
$13.753 per kW for the first 100 on-peak kW, plus $9.581 per kW for all additional on-peak kW	
$4.877 per kW for the first 100 off-peak kW, plus $2.955 per kW for all additional off-peak kW	
For Transmission Service:	
$12.938 per kW for the first 100 on-peak kW, plus $9.300 per kW for all additional on-peak kW	
$4.232 per kW for the first 100 off-peak kW, plus $2.849 per kW for off-peak kW	

Source: APS Website, Medium Commercial Building Tariff.

APS E32 flat and E32 TOU rates were modeled in eQUEST to generate virtual rate for electricity that can be used for conducting the LCC analysis for energy consumption. Same method was applied to generate SCE TOU8 rate for LCC analysis.