TECHNICAL ASSESSMENT FOR SMART GLAZING FOR BUILDINGS

SECTOR: BUILDINGS

AGENCY LEVEL: BUILDINGS AND FACILITIES OWNERS

KEYWORDS: ADVANCED GLAZING, DYNAMIC GLASS, SMART GLASS, SPACE COOLING, SPACE HEATING, LIGHTING AND BUILDING EFFICIENCY

VERSION 2

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*Note: For some of the technical reports, the result section is not yet updated. Kindly refer to the model for the latest results.

DRAWDOWN

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ACRONYMS AND SYMBOLS USED

EC – Electrochromic

EIA – Energy Information Administration

GBPN – Global Buildings Performance Network

HPS – High Performance Static

IEA – International Energy Agency

IGU – Insulated Glass Unit

IPCC – Intergovernmental Panel on Climate Change

LBNL – Lawrence Berkeley National Laboratory

LED – Light Emitting Diode

NIR – Near Infrared

NPV – Net Present Value

NZB – Net Zero Building

PCM – Phase Changing Material

PDLC – Polymer Dispersed Liquid Crystal

PDS – Project Drawdown Scenario

PV – Photovoltaic

REF – Reference (Scenario)

RRS – Reduction and Replacement Solutions (Model of Project Drawdown)

SHGC – Solar Heat Gain Coefficient

SPD – Suspended Particle Device

TAM – Total Addressable Market

UV – Ultraviolet

VT – Visible Transmittance

WGBC – World Green Buildings Council

EXECUTIVE SUMMARY

Smart Glass is a technology that can be used in traditional glazing and façade systems and has the ability to dynamically change a window's properties to optimize a building's performance. Different technologies are described as being "smart", but in general, each technology use a stimulus (such as an electrical charge) or environmental factor (such as temperature) to change the transmittance and reflection. Smart Glass promises high energy savings for both space conditioning and lighting systems. Smart glass can turn windows from the most inefficient components of a building envelope into a solution for energy saving. The use of smart glass also has the potential to eliminate the use of internal and external shading, increasing the opportunities for daylighting design strategies to be implemented within the built environment.

The high initial cost of smart glass has inhibited its growth in buildings. Yet, recent technological advancements and market competition has reduced the price. As adoption continues, the price is expected to decline further. Promotion of smart glass development and benefits by government agencies can drive growth and adoption of smart glass as an energy saving measure in the built environment.

The Solution is modeled by aggregating both whole-building simulated and measured energy savings (space heating, space cooling, and lighting) of Smart Glass installations as compared to high performance static windows in commercial buildings located in different climates. The model identifies the addressable market for the solution technology as commercial buildings in OECD countries due to the high initial first cost of Smart Glass. The adoption prognostication model constructs four scenarios for future Smart Glass adoption. In the reference (REF) scenario, the future growth is fixed to its current percentage share of the total market. Three Project Drawdown Scenario (PDS) scenarios were built upon market research report projections and long-term building efficiency targets. Comparing each of the PDS scenarios to the REF scenario yields the climate and financial impacts of Smart Glass adoption. The least aggressive PDS scenario forecasts 3,479.37 million m^2 of commercial floor area (30%) will use Smart Glass by 2050, and the most aggressive indicates 8,698.42 million m^2 of adoption, from a 2018 estimated adoption of 42 million m^2 of commercial floor area (0.49%).

The climate and financial impacts for this accelerated adoption of Smart Glass are modest. The least aggressive scenario avoids a total of 0.31 gigatons (Gt) of CO_2-equivalent greenhouse gas (GHG) emissions, for an atmospheric concentration reduction of 0.026 (ppm CO_2-eq). The marginal capital cost of this PDS adoption compared to the REF scenario is US$69.09 billion, but the PDS scenario saves US$58.60 billion in operating costs due to reduced energy consumption for space conditioning and lighting. Nevertheless, the lifetime net present value (NPV) cashflow savings of PDS adoption is negative: -US$10.77 billion. Still though, rapid adoption of Smart Glass can aid the building sector contribute to Drawdown.

1 LITERATURE REVIEW

Globally, the buildings sector is one of the largest end-use sectors, accounting for 30% of global final energy usage. The inclusion of building construction increases this to 36%. Together, building construction and operation account for 39% of energy-related CO_2 emissions (UN Environment & IEA, 2017). Thus, the global building sector needs innovative technologies and approaches to reduce energy consumption while ensuring building operations are not affected. Breaking down the building sector by energy end-use gives us an idea of where the potentials exist. Space heating consumed 32% of final building energy in 2014. The other top uses are cooking energy (22%), water heating (19%), appliances and equipment (16%), and lighting (6%) (IEA, 2017). Clearly there are many opportunities across the building sector for energy efficiency. Space and water heating energy is affected by windows, walls and heat source, cooking energy is affected by source and cooking technology, appliance energy by appliance efficiency and use, and lighting is affected by light technology and use.

More specifically, windows are responsible for approximately 60% of total building energy consumption, playing a critical role in both residential and commercial building energy consumption (Gustavsen, Jelle, Arasteh, & Kohler, 2007). This energy consumption is due to heat transfer between indoor conditioned spaces and unconditioned outdoor spaces, and solar heat gain. Furthermore, windows have substantially higher U-values (a measure of thermal transmittance) as compared to other building envelope elements. It is estimated that of the space conditioning energy consumed by U.S. commercial buildings (1.48 quads, 434 TWh), 39% of total space heating energy and 28% of space cooling energy is related to glazing (Apte & Arasteh, 2006). In Northern China, heat loss in the winter season due to glazing is estimated at 40-50% (Wang and Guan, 2005).

Windows are an essential component of the existing and new buildings of the global building stock. Various strategies to control the heat gain and heat loss due to glazing have been developed. Internal shading devices, such as venetian blinds or curtains have been used for centuries to control solar heat gains and decrease the U-value. Yet without automation, these technologies require human intervention and are oftentimes unreliable at optimizing energy efficiency. External shading devices such as fins or overhangs can be designed to allow the heat gains during winter months (heating dominated), while blocking heat gain during summer months (cooling dominated). External shading devices are typically static and lack the ability to adapt to optimize solar heat gains for building energy efficiency, although dynamic façade systems (including shading devices) have been shown to reduce building energy consumption (E. Lee & Selkowitz, 2009). In addition to the development of shading devices, advances in glazing materials and systems such as high-performance static and smart glazing allow for window properties to be optimized to reduce building energy consumption while preserving both thermal and visual occupant comfort.

1.1. State of Energy Efficient Glazing

The space conditioning and lighting requirements of a building are dependent upon the properties of the glazing system that is being used. Important properties include the U-value, Solar Heat Gain Coefficient (SHGC), and visible transmittance (VT). The U-value is a measure of thermal transmittance of a window – the higher the U-value, the more heat that is transferred between the conditioned and unconditioned spaces. The SHGC is a measure of the solar radiation that passes through a window. The lower the SHGC, the less heat that is passed through the window in the form of radiation. In heating-dominated climates with large amounts of solar radiation, a glazing system with a high SHGC will reduce the space heating loads. Whereas a climate that is cooling dominated would benefit from a glazing system with a low SHGC since heat transfer into the building should be minimized. Visible transmittance is a measure of the visible light that passes through a window and is important for illuminating spaces with natural light. These three properties are essential components of designing building envelopes and different glazing systems vary the properties in order to optimize thermal and visual comfort dependent on the climate in which the building is located.

With the aim of reducing energy consumption in buildings and improving occupant comfort, researchers and manufacturers have been innovating in glazing technologies, developing both static and dynamic systems.

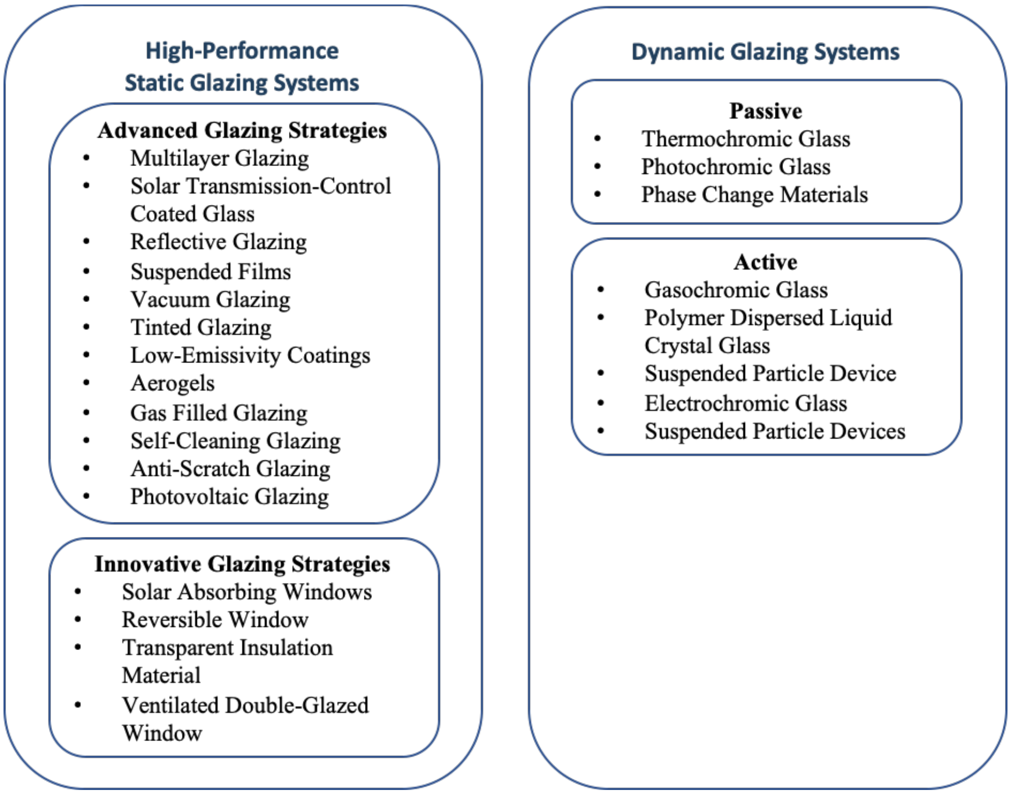

Figure 1.1 Classification of static and dynamic glazing. Advanced static glazing classifies technologies that are common in the market, while innovative glazing strategies are ones that still require development to realize their full market potential.

Figure 1.1 summarizes many of the advances made in glazing technologies organized by being either static or dynamic. Static advanced glazing strategies are technologies that are common in the market and have been well studied. Static innovative glazing strategies are technologies that still require development before obtaining large market share (Jelle et al., 2012). A description of high-performance static glazing technologies follows.

- **Multiple-pane window (Multilayer glazing):** Between two and four glass panes with air or other gases filling the gaps between panes. In commercial and residential buildings, it is standard to use double-paned glazing which has a lower U-value to reduce heat loss through the window.
- **Solar transmission-control coated glass:** glass panes are coated with a thin spectrally selective film that reflects near-infrared radiation (NIR) (i.e. with a low SHGC), but still has high visible transmittance. This technology is typically applied in hot climates with high amounts of solar radiation.
- **Reflective glazing:** A microscopically thin coating that reduces transmission through the window across the NIR and visible spectrum by up to 50% as compared to tinted glazing ("Windows for

High-performance Commercial Buildings," n.d.). This glazing technology is typically used to reduce glare from direct sunlight.

- **Suspended films:** Films are placed between glass panes that mimic the addition of another glass pane. By adding these films to either the inner or outer panes, multi-layer window constructions become lighter. Suspended films have competitive U-value as well as a low SHGC and VT.
- **Vacuum glazing:** A vacuum gap between two glass panes that reduces both the conductive and convective heat transfer.
- **Tinted glass:** Small metal oxides are added during the fabrication process that result in reduced solar transmission as well as glare reduction. While the color of the glass typically is changed, the thermal transmittance can be reduced by more than 20% (Chow, Li, & Lin, 2010).
- **Low-e coated glass:** a spectrally selective coating is applied to glass panes which allow for the transmittance of visible light, but reflectance of thermal radiation (lower SHGC). This technology is common in high performance windows and is often used in conjunction with multi-pane windows to reduce the solar radiation that enters a building.
- **Aerogel:** A porous material made of air and silica is used as insulation between multi-pane windows or as a glazing material. It has higher solar thermal transmittance than other glazing technologies. Monolithic aerogel has a high visible transmission while granular aerogel has a very low light transmittance. A good choice for cold climates.
- **Gas-filled glazing:** Multi-paned windows are separated by a space, typically filled with air. To reduce the amount of heat transfer, a gas with a lower thermal conductivity such as krypton or xenon can be used which reduced the U-value of the window assembly.
- **Self-cleaning coatings:** Control solar radiation by reducing glass surface. Hydro*phobic* surfaces allow water droplets to form that wash off contamination. Hydro*philic* surfaces allow water sheets that wash off contamination. These coatings slightly increase the U-value but reduce the need for cleaning chemicals which contaminate water sources thus reducing the environmental impacts of windows.
- **Anti-scratch glazing:** The durability of glazing in window systems is a concern when a high cost premium is paid for a high-performance window. Anti-scratch glazing uses silicon oxide nanoparticles applied to the exterior or the window to improve a window's durability and lifespan. While not directly contributing to energy reduction, increasing the durability of the window extends the lifetime of the window and reduced replacement costs and associated indirect emissions.
- **Photovoltaic glazing:** Photovoltaic (PV) cells are integrated directly into the window. Thin film technology is used to increase the light transmittance of photovoltaic windows to increase the

energy generation. Although visible transmittance and energy efficiency are challenges, solar radiation can be reduced using PV glazing.

- **Solar absorbing window:** Water flows between the panes of glass in multi-layered glazing absorbing the thermal energy from solar radiation thus reducing the heat gain into the conditioned space. A relatively new technology, this window system still is in development.
- **Reversible windows:** Double glazed windows that have highly reflective coatings on the exterior surfaces. The windows are reversed during winter to allow for solar radiation to enter the space. The coating does not affect the U-value of the windows.
- **Transparent insulation material filled window:** Glass, plastic capillaries or honeycomb structures are inserted between glass panes that diffuse light while reducing glare.
- **Ventilated double-glazed window:** Similar to solar absorbing windows, unconditioned air is passed between the panes of the glass. The air is heated by solar radiation, and the buoyancy effect brings the air up through the window into the conditioned space. This preheating of the outside air can reduce the heating demand of buildings.

There are two primary themes of high-performance static windows. The first theme or strategy is to add a film or a coating to a window surface, such as low-e or coatings. The second theme is to add materials with low thermal conductivity between the glass panes of a window. A weakness of high-performance static windows, is that they do not have the ability to adapt to the changing environments (due to weather or building activity) that they serve. In contrast, smart glass or dynamic window systems automatically adjusts lighting and shading for energy optimization, that is, to reduce internal environmental heat gain when cooling is required, and to reduce heat loss when heating is required. Smart glass responds based upon the needs of the building in order to optimize the energy efficiency of lighting systems and space conditioning. It is common for smart glazing systems to be integrated with daylighting controls and tied into building automation systems. Depending upon the type of smart glass, the transparency state can change from being transparent to either frosted, tinted, opaque or mirrored. These different states, which change in real-time, optimize the building performance reducing total energy consumption as well as peak loads. Many of the strategies used by high-performance static windows are integrated into smart glass design, namely using multiple layers, and special coatings.

Although the energy savings potential of smart glass is the focus within buildings, there are numerous other applications in which smart glazing systems are used. In the automobile industry smart glazing can reduce glare for drivers to improve safety, as well as make interior environments more comfortable by reducing the solar gains. In the aircraft industry, smart glazing has been used to replace traditional shading devices reducing weight and improving the interior environment. Similarly, the benefits of smart glazing are being realized in marine vehicles and mass transit.

Innovations in glazing technologies have been significant, and smart glass continues this tradition. Most energy codes prescribe certain window types to be used based upon standards for a particular climate. Code requirements in OECD countries require the use of static double-paned glazing in order to reduce building energy consumption. Single-paned glass is typically used in older buildings and where there are no energy codes, such as in some developing countries.

1.2. Types of Smart Glass

Smart glass (also known as dynamic window or adaptive, switchable, or smart windows) represents a suite of technologies that regulate visible and thermal transmission features based upon a stimulus, resulting in energy efficiency improvement (Baetens, Jelle, & Gustavsen, 2010; Casini, 2015, 2018; Favoino, Overend, & Jin, 2015; Fazel, Izadi, & Azizi, 2016; Ghosh & Norton, 2018; Lampert, 1998; Pittaluga, 2015; Rezaei, Shannigrahi, & Ramakrishna, 2017). There are several competing technologies at varying levels of market-readiness, energy savings, and price. These technologies can be classified according to either their method of control, active or passive, or their operation method (that is, how the glass's properties are changed). Several passive systems exist, which change based upon light or heat received. Active systems are typically controlled by the running of an electric current through the glass. Some active systems require constant flow of electricity to maintain a certain state while others only need electric current to switch states. In all cases, the switch between states is reversible, and tests both in laboratory settings and in case studies indicate that there is no degradation in performance after several thousand switches (Fernandes, Lee, & Thanachareonkit, 2015; Eleanor S. Lee et al., 2013; Tinianov, 2017).

1.2.1 Types of Passive Smart Glass

Passive smart glass responds to external stimuli based upon environmental conditions and are not controllable by building occupants. Types of passive smart glass, described in this section, are thermochromic glass, photochromic glass, and phase change materials.

Thermochromic Glass

Thermochromic glass changes its properties according to the surrounding air temperature. In practice, this category of glass changes color and opacity (turning opaque and often dark) when the outside temperature is high. It is therefore ideal for automatic tinting of skylights or windows to avoid glare. This type of smart glass is not directly controllable and so tinting the glass during sunny, cold days can have adverse effects on space-conditioning energy consumption. Furthermore, if a space is designed to be daylit, the amount of daylight entering the space is reduced during cold days, increasing lighting energy consumption.

Photochromic /Phototropic Glass

Photochromic glass changes its properties according to the incidence of light onto it. In practice this category of glass changes color and opacity (turning opaque and often dark) when sunlight shines brightly onto it. Therefore, it is ideal for the automatic tinting of skylights or windows to avoid glare and has also been used in eye glasses that double as sunglasses. As a passive smart glazing, photochromic glass is not directly controllable, so increasing the transparency in bright conditions is not possible.

Phase changing materials (PCMs) based windows

Phase changing materials (PCMs) are materials that are inserted between window panes and change from solid state to liquid as they absorb incident solar energy. The change in physical state of the material allows for high thermal energy storage, and act as a buffer to fluxes in interior temperatures, yet they are challenging to use due to the volume increase of the material during phase changes.

1.2.2 Types of Active Smart Glass

Properties (such as SHGC and VT) of active smart glass change based upon induced stimuli such as an electric field, or gas contact. These systems perform best when users have control over the state of the glass, or when a control system is implemented, in conjunction with a building automaton system and sensors, to control the state of the window. The control strategy has a significant effect on the active glazing's performance. In building applications, it is typical to implement a control strategy to either reduce glare and lighting energy consumption (daylighting strategies) or reduce space conditioning (heating and cooling loads).

Gasotropic / Gasochromic Glass

Gasotropic glass changes its properties through the injection of a gas into the space between two layers of glass onto which an inner coating is applied (typically tungsten oxides, but nickel and molybdenum oxides have also been used). That material then reacts with the gas (such as hydrogen – H_2) to reduce the transmission of visible and infrared light (turning blue or another color). When the hydrogen is replaced with oxygen (O_2), the glass then returns to its transparent state. This type of glass is relatively expensive as it needs a controlled gas flow in and out of that space, and a pressurized system for containing the gas. The coating only applies to one side of the inner layers of the gas though and this helps to reduce the cost, but thicker coatings (or higher gas concentrations) change color faster. Testing indicates that 20,000 "on-off" cycles can be performed on gasotropic glass without any decrease in performance (Georg, Graf, Neumann, & Wittwer, 2000).

Polymer Dispersed Liquid Crystal (PDLC) Glass

Liquid crystal glass contains a layer of liquid crystals embedded in a polymer that is translucent when no electricity is passed through it as the crystals are oriented in random directions and disperse light. This produces the common frosted effect in some static glass types. When an electric current is passed across this type of glass, the crystals align and allow light to pass through resulting in a clear glass. The alignment disappears when the electric current is stopped however, so to maintain a clear glass, electricity needs to be constantly used, although typically this amount of electricity is negligible when considering whole building energy consumption.

Suspended Particle Device (SPD or Electrophoretic) Glass

Suspended Particle Device glass is similar to PDLC, yet when no electricity is passed through, light is absorbed, and VT is decreased. As a technology, SPD has been in existence since 1930, but only recently has it been considered for application in building glazing systems. SPD glazing is created by suspending nano-scale particles in a liquid between two panes of glass. When an electrical field is applied, the particles become aligned and allow light to pass through. SPD glass, like other dynamic glass technologies, offers energy savings both in the form of reduced heat loss and through the creation of comfortable daylit indoor environments. SPD glass has recently become popular in the automotive industry with car manufacturers utilizing the technology as a dynamic control for windows which increases security and reduces glare.

Electrochromic Glass

Electrochromic glass is made of several layers of conductive and electroactive materials and changes color when an electric potential is created due to the movement of ions between layers within the glass (often made of tungsten, molybdenum, or nickel oxides). The ion movement leads to the oxidation of some glass layers which absorbs some wavelengths of light incident on the glass and a change in color that lasts between minutes to days when the electric potential is stopped. When the electric potential is reversed, the ion movement is reversed, and the glass returns to its clear state, remaining so after the electricity is stopped. This type of smart glass has shown the most promise since it is a controllable system, requires a very low amount of electricity to change state, and is economically viable. A recent development of electrochromic windows is near-infrared electrochromic windows which allows for the dynamic control of the amount of infrared radiation (heat) that passes through the building envelop increasing the potential for energy savings due to reducing both heating and loads.

Advantages and Disadvantages

Each of the aforementioned Active Smart Glass technologies have their advantages and disadvantages. PDLC glass has the ability to change properties nearly instantaneous, but only has two states (transparent of frosted) and is more expensive and less durable than either SPD or electrochromic glass. The main advantage of using SPD glass is the unlimited number of states and the relatively quick switching speed (within seconds). In comparison to electrochromic glass, which typically use four states and changes properties relatively slowly (within minutes), SPD glass has a higher cost and are not as durable. For building applications, electrochromic glass is typically preferred, since it has the lowest cost of the technologies in addition to the longest lifespan.

1.3. ADOPTION PATH

Although great success using smart glass in the built environment has been achieved, broader adoption will require additional development to increase the VT control range, reduce the SHGC to VT ratio in tinted states, increase the switching speed between states, reduce the color variation between states, and reduce costs (Casini, 2018). Commercial production of smart glass is currently centered in the United States and Europe with additional research generated by China and Japan. Government regulation for energy efficiency in buildings and rising energy costs have been the primary drivers for interest and investment in smart glass technology.

Because glazing contributes to significant heat gains and losses in buildings, the energy efficiency of windows must be addressed in order to meet current and future building standards for energy efficiency. As governments and the commercial sector aim to decrease the amount of energy used by buildings, they will increasingly look to advanced glazing technologies as a means of meeting energy efficiency standards.

1.3.1 Current Adoption

Current adoption calculations of smart glass are based upon sales estimates published by market research companies. It is important to note that the smart glass market includes both the architectural and transportation (especially automotive) markets. Building sector specific data is presented by some sources, and the ratio between the automotive and buildings sector can be used to extract only building sector market data from other sources. An additional complication is the unit of preference for the market research companies is US dollars of annual sales indicating that glass costs need to be also obtained to convert to glass area. Due to high first costs and lack of availability of residential-specific electrochromic window products by major manufacturers, a negligible amount of smart glass has been implemented in the residential market, and it is assumed that all of the current adoption is in commercial buildings. Implementation of Smart Glass in residential buildings is similar to commercial buildings (standard construction techniques are used), yet due to the lack of building automation systems being widespread in residential buildings there is a barrier for the implementation of smart glass.

Using average smart glass costs of US$58.9/$m^2$ of commercial floor space (or US$ 1,001.42/m^2 of glass[1]) where necessary and summing over the years for which data were available, the total installed smart glass was estimated to be 42 million m^2 of floor space in 2018 (up from 5.4 million in 2014). This estimate came from four global estimates published by 4 market research sources and represents around 0.49% of the 2018 global commercial building market.

1.3.2 Trends to Accelerate Adoption

The primary motivation for building owners to adopt smart glazing systems is the operational energy savings from reducing space conditioning and electrical lighting energy consumption. Furthermore, peak demand loads are reduced by up to 35% which, depending on the electrical rate structure, can significantly reduce operating costs as well as cost savings from using smaller mechanical equipment (Sbar, Podbelski, Yang, & Pease, 2012). Another motivation for using smart windows is to mitigate glare while preserving views to the exterior. Smart glazing systems improve occupant visual comfort and avoid the need for human-operated systems such as blinds to control glare.

In the United States, approximately 50% of all window sales are for the retrofit of existing buildings (Arasteh, Selkowitz, Apte, & LaFrance, 2006). Initiatives at both the municipal and owner level promote the retrofit of existing buildings instead of the construction of new buildings. As more buildings are retrofitted to reduce their energy consumption, smart glazing systems can be included in those retrofits as an alternative to high-performance static glazing to realize energy savings (Fernandes et al., 2015; Eleanor S. Lee et al., 2013, 2006; Tinianov, 2017).

Smart Glass as a technology is most effectively implemented in buildings with high window-to-wall ratios. While commercial buildings include more than just office buildings, energy savings in building typologies with very low WWR (less than 0.1) will be minimal in comparison to energy savings in buildings with high WWRs.

To maximize the benefits of smart windows, control systems (such as building automation systems) need to be implemented. While most space conditioning systems already have temperature sensors in place (i.e. thermostats), daylighting sensors are necessary to realize savings in energy and cost due to energy consumption. As building automation systems become more prevalent, so too will smart glass.

[1] Glass area to floor area is converted using a factor 0.059 m^2 of window/m^2 of floor space based upon typical commercial building architecture.

While the energy savings potential of smart glass is primarily in the built environment, adoption of smart glass in other industries such as the automotive industry will help advance adoption by increasing demand, promote production efficiencies, and bring new competition and manufacturers to the market.

1.3.3 Barriers to Adoption

The largest barrier to adoption of smart glass is the first cost for obtaining and installing the technology. Even though smart glazing systems have been in development for decades, there is still a price premium to pay as compared to high-performance static windows, which may not make it financially feasible for every building type or climate zone. Because of the high first cost, the technology has primarily been implemented in commercial buildings with little to no adoption in the residential market. For both commercial and residential building owners, the payback period should be considered when choosing between smart glass and high-performance static glass. Because of the cost premium, and location of manufacturing facilities, first adoption has occurred in the global north and is expected to accelerate. For adoption to occur in developing economies, manufacturing efficiencies will be needed in order to decrease the first cost.

In addition, the time that smart glass implemented in buildings (i.e. electrochromic glass) takes to switch states is high (on the order of minutes), while users may desire near-instant switching times. Currently, research is focused on reducing the time required to switch between states of electrochromic glazing.

1.3.4 Adoption Potential

Architecture 2030 and the *World Green Building Council* have partnered on an initiative to roll out net zero building training and certification programs in a number of different countries in order to ensure that by 2050, all buildings are net zero (WorldGBC, 2016). Architecture 2030's *Roadmap to Net Zero Emissions* sets for an ambitious target for emissions reductions from global buildings that aim to reduce 45 percent of emissions by 2030 and 90-100 percent by 2050 (Architecture 2030, 2014). This plan includes a schedule for new buildings and major renovations to reduce site energy use intensity (EUI) 90 percent in 2025 and 100 percent in 2030.

These efforts follow other legislation regarding emissions reductions pathways for buildings in the US and the EU. The U.S. Energy Independence and Security Act of 2007 (Section 433) and Executive Order 13423 requires all new Federal buildings and large renovations to be zero carbon by 2030 and directs all buildings to be net zero by 2050; similarly, the EU has directed member states to ensure that all new buildings are nearly zero-energy by 2020 (Architecture 2030, 2014).

The adoption of smart glass has the highest potential in commercial buildings that experience part or all of the year with warm temperatures and high amounts of solar radiation. This market segment can gain the highest benefit from reducing cooling and lighting requirements when windows are integrated with lighting control systems. This segment is a significant fraction of the global buildings market, though it's not expected to be 100% of the commercial buildings market. One should expect that by 2050, the adoption of smart glass can be relatively high.

1.4. Advantages and Disadvantages of Smart Glass

1.4.1 Similar Solutions

The problem of reducing heat transfer through building windows has a range of solutions such as double- and triple-paned glazing, low-e glass, tinted windows, internal and external shading, and smart windows as summarized in Table 1.1. Many of these solutions are not mutually exclusive and can be combined in the same building envelope system to improve performance, but often the increase in cost makes this option unattractive.

One seemingly attractive option is dynamic tint, which is a retrofit-ready layer added to existing traditional windows to allow them to gain many of the benefits of smart glass. Installation of smart glass uses common construction practices and few installation issues have been identified (Eleanor S. Lee et al., 2013; Tinianov, 2017).

1.4.2 Arguments for Adoption of Smart Glass

The primary advantage of Smart Glass, and electrochromic glass in particular, is its potential to manage and save energy, but it also allows the automatic and connective ability that is the trend for human environments. Smart Glass can reduce solar heat gain in buildings which in turn can reduce the cooling load for buildings in warm climates and warm seasons. Smart Glass also allows for more natural light in buildings and uninterrupted views as compared to blinds and other shading strategies which reduce lighting and views drastically making internal lighting necessary which can decrease occupant comfort and productivity. Smart Glass can help optimize lighting control to allow use of natural light when available rather than keeping building lights on for most of the day, leading to additional energy consumption reductions. Smart glass also allows for greater window to wall ratios, while still meeting building energy codes and energy efficiency objectives. On the side of comfort, smart glass can respond to weather conditions, planned room occupancy and many other factors automatically to help optimize thermal and visual comfort for building occupants.

Another significant advantage is the potential for widely replacing conventional glass within existing windows with electrochromic glass, thus saving on the cost of new window frames (Cuce & Riffat, 2015).

Smart Glass can operate automatically through the use of sensors, but also can allow for manual control of the tint level of individual windows. Passive smart glass (thermochromic or photochromic glass) can provide many heat-reduction and lighting energy reduction applications without human input, which could be advantageous for situations where electricity supply is not possible, or direct human control is not needed.

1.4.3 Additional Benefits and Burdens

The primary disadvantage of Smart Glass is its high upfront costs. Installation of smart glass is more difficult than conventional glazing and it comes with higher maintenance costs. The transition from transparent to dark is not instantaneous. There are other issues of uniformity of the dark color, the color options available and the limited retrofit options on existing glazed surfaces. However, studies have shown that smart glass can improve occupant comfort, and reduce the need for occupants to adjust blinds, shades, lights and room temperature every time the sun changes.

Table 1.1 A matrix comparison of solutions to reduce solar heat gains in buildings. ✓ = high performance, O = moderate performance, and ✕ = poor performance.

	Technology	Installation Cost	Energy Savings	Daylighting	Ease of Use/ Automation	Views to Exterior	Glare Control	Lifetime
Proposed Solution	Smart Glazing	✕	✓	✓	✓	O	O	O
Alternative Solutions	High-Performance Static Glazing	O	✓	O	O	✓	✕	✓
	Internal or External Shading Devices	✓	✓	✓	✕	✓	✕	✓
	Tinted Glass	O	O	✕	O	✕	O	✓

2 METHODOLOGY

2.1 INTRODUCTION

Project Drawdown's models are developed in Microsoft Excel using standard templates that allow easier integration since integration is critical to the bottom-up approach used. The template used for this solution was the Reduction and Replacement Solutions (RRS) which accounts for reductions in energy consumption and emissions generation for a solution relative to a conventional technology. These technologies are assumed to compete in markets to supply the final functional demand which is exogenous to the model but may be shared across several solution models. The adoption and markets are therefore defined in terms of functional units, and for investment costing, adoptions are also converted to implementation units. The adoptions of both conventional and solution were projected for each of several scenarios from 2015 to 2060 (from a base year of 2014) and the comparison of these scenarios (for the 2020-2050 segment[2]) is what constituted the results.

Heating, cooling, and lighting energy along with cost savings due to the installation of electrochromic glazing in commercial buildings was examined from the perspective of building owners. "Commercial buildings" is interpreted to be all non-residential buildings including stores, offices, restaurants, warehouses, educational and government buildings, and other buildings with a commercial purpose. Based upon both academic research and market forecast, electrochromic glass has the highest potential for adoption in the built environment due to its lower cost (as compared to other Smart Glass technologies), active control and low electricity usage for switching states/colors. For the purposes of this model, it is assumed that Smart Glass energy savings can be represented by electrochromic glass. While other smart glass technologies may yield different energy savings, they are similar to electrochromic glass due to similar control strategies.

The functional unit, as the implementation unit of the solution, is million square meters of commercial floor space. Using this functional unit allows for integration with other building solutions some of which use the same functional unit. To convert from area of glazed surface to floor area, the conversion factor of 0.059 (window area/floor area) was used. The data used to develop this conversion factor is derived from the 16 reference buildings described by the US Department of Energy Commercial Reference Buildings. It is assumed that the commercial buildings in the US are representative of those around the world. The weight

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[2] For most results, only the differences between scenarios, summed over 2020-2050 were presented, but for the net first cost, the position was taken that to achieve the adoptions in 2020, growth must first happen from 2015 to 2020, and that growth comes at a cost which should be accounted for, hence net first cost results represent the period 2015-2050.

of each building typology is based upon the current distribution of that building as measured in the DOE study (Deru et al., 2011). This ratio was assumed to be constant over the analysis period (2020-2050) and is representative of the global commercial building stock. Actual commercial buildings may have a different window to floor area ratio, yet the value used in the model is an average. The window to floor area ratio is assumed to be the same for both high-performance static glazing and the Smart Glass solution.

Depending on the study, the energy savings potential is presented for either a perimeter space, or the whole building. To make the numbers comparable, studies that only present results for perimeter spaces are scaled by 0.62, a factor based upon the fraction of the building that is in the perimeter space derived from multiple sources in the literature. Smart windows provide most of their benefit when installed on the south, east, and west façades of a building and very little benefit on the north façade (in the northern hemisphere, southern façade in the southern hemisphere). Thus, it is assumed that the smart windows are installed only on the 75% of the wall area, further reducing the window to floor ratio.

The world's commercial building stock is assumed to use only electricity to provide lighting and space cooling. A weighted average is used for the emissions due to space heating based upon the averages from the IEA. (IEA, 2016). Smart windows are modelled to reduce electricity for commercial lighting and to reduce a variety of fuels for space heating and cooling.

The Smart Glass solution compares the energy savings from using electrochromic windows to using high-performance static windows as 69.3% of the US commercial building stock uses high-performance windows (U.S Department of Energy, 2016), and similarly high numbers are expected for other countries in the OECD. Depending upon the climate zone, the definition of a high-performance static window may be single- or double-paned, yet typically the conventional solution is defined as a double-paned window with low emissivity (low-e) (Deru et al., 2011; Jelle et al., 2012).

Global energy usage for heating, cooling and lighting is estimated per unit floor area according to the IEA and US DOE, and each end use is affected differently by the implementation of smart glass (IEA, 2016; U.S. Department of Energy, 2016). Each building end-use metric is reduced by implementation of electrochromic glazing as compared to high-performance static windows and is reported as a percentage.

2.2 Data Sources

In order to project the growth of global commercial building floor space, which is the total addressable market (TAM: units of million m^2 commercial floor space), the model relies on estimates from the IEA (IEA, 2013) and estimates from the Global Buildings Performance Network (GBPN), namely from Ürge-

Vorsatz et al. (2015). The procedure for estimating the TAM is explained in the Total Addressable Market section.

Adoption scenarios were developed based upon the World Building Council's published targets for Net Zero Buildings. More detail is available in the Adoption Scenarios Section.

Glass market pricing data from several corporate and market research sources were used since the technology, though available for several years and installed on many buildings, is changing rapidly, and pricing and adoption are very likely to have changed rapidly in the past, when these sources were published, hence no one source can be considered the most authoritative. A global average commercial electricity cost from over 800 estimates between 2000 and 2014 across 57 countries was used for estimating operating costs changes between scenarios.

42 smart glass energy efficiency estimates were obtained from 16 sources published between 2004 and 2017. These sources include study reports from the Lawrence Berkeley National Laboratory and a variety of journal publications. These energy savings estimates apply to a range of building types and geometries, which aim to quantify energy savings. The base energy consumption (for commercial buildings with conventional glass windows) was obtained from the International Energy Agency and US Energy Information Administration (U.S. Department of Energy, 2016) for US-specific data. The US Energy Information Administration (EIA) as well as the International Energy Agency (IEA) published data on the electricity usage for cooling and lighting (IEA, 2016; U.S. Department of Energy, 2016). Average grid emissions factors using IPCC data were used for converting grid electricity usage to emissions (Schlömer, 2014).

2.3 TOTAL ADDRESSABLE MARKET

Projecting the growth of commercial building floor space is essential to determining potential adoption globally. The model relies on three projections for commercial floor space based upon data from (IEA, 2013; Ürge-Vorsatz et al., 2015). The data is taken from the Drawdown Buildings Sector Integrated TAM and reduced to only consider adoption in OECD countries (OECD90 Drawdown region). The TAM is reduced as the High-Performance Glass Drawdown solution TAM includes the rest of the floor area. Figure 2.1 shows the resulting projection for the Reference TAM from 2015 – 2060.

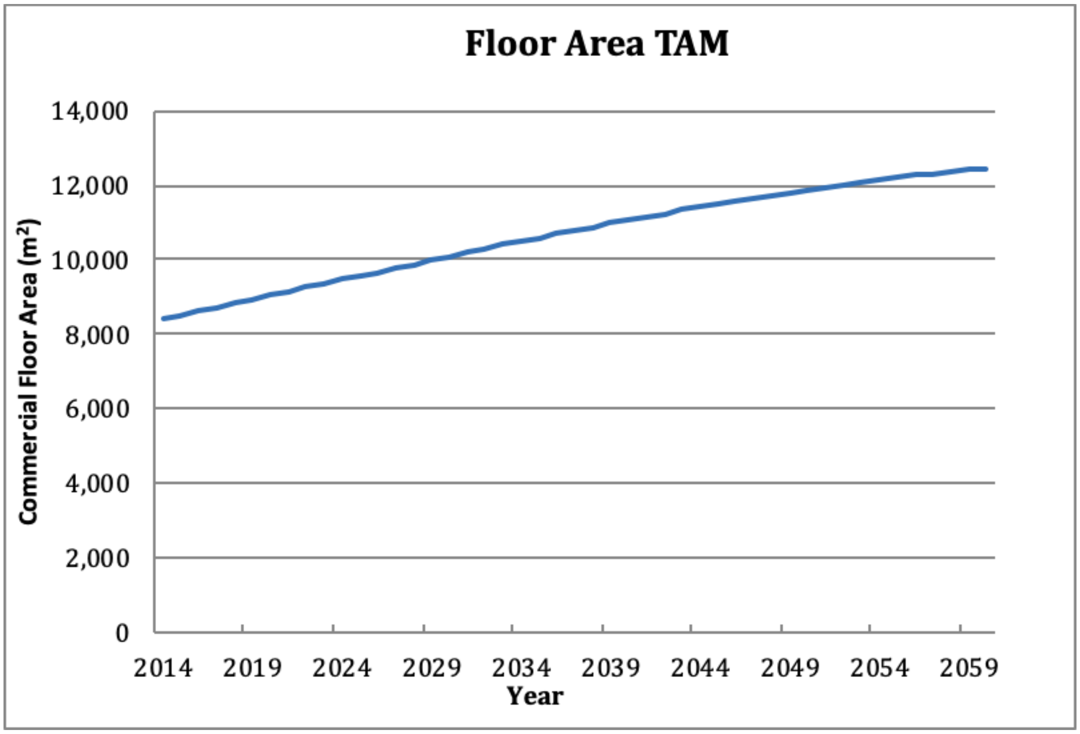

Figure 2.1 Modeled growth in Commercial Floor Space from 2015-2060 for the reduced TAM.

In the IEA dataset, total commercial floor space was estimated in ten-year increments from 2010 to 2050. This dataset was then interpolated for annual data. The estimated commercial floor space per region was assumed proportional to GDP and projected from 2005 to all other years. To identify building energy usage worldwide for heating, cooling and lighting, the Buildings Summary of the IEA's Energy Technology Perspectives 2017 report was used (International Energy Agency, 2017).

These estimates diverge considerably, as the projections for global commercial floor space from Ürge-Vorsatz et al. (2015) show much larger growth over the coming century but projecting the growth of commercial floor space is a complex endeavor, and it is not surprising that two models would project such different figures, thus an average is used in this model.

2.4 Adoption Scenarios

Two different types of adoption scenarios were developed: A Reference (REF) Case which was considered the baseline, where little action is taken by the world, and a set of Project Drawdown Scenarios (PDS) with varying levels of ambitious adoption of the solution. Published results show the comparison of one PDS to the REF, and therefore focus on the change to the world relative to a baseline.

2.4.1 Reference Case / Current Adoption

In this scenario, the percent adoption of the solution remains at its 2018 level throughout the analysis period since 2018 is the latest year of data in the model. This is a scenario designed to capture the current state of the Solution, serving as a comparison of the more aggressive adoptions required to reach drawdown which are explored in the PDS scenarios. Adoption in 2018 is estimated to be 42 million m^2 of building area, which is 0.49% of the global TAM.

2.4.2 Project Drawdown Scenarios

Three Project Drawdown scenarios (PDS) were developed for each solution, to compare the impact of an increased adoption of the solution to a Reference Case scenario. Each PDS Scenario was based on publicized building efficiency targets. Corporate projections of smart glass sales extend to 2022, but the WorldGBC, a coalition of green building councils in 100 countries with 27,000 member companies, has set a target of 100% Net Zero buildings (NZB) by 2050 (WorldGBC, 2016). A net-zero building is one that consumes net zero energy or produces net zero carbon during annual operations (due to high efficiencies and on-site renewable energy production. Energy efficient glass, such as smart glass, is part of the net zero building concept. Thus, the 100% NZB target was used as a guide to 2050 adoption of smart glass for each PDS scenario, with the near-term adoption based on corporate analysis.

Plausible Scenario -

In this scenario, guided by translating the goal of 100% adoption of NZB by 2050, the maximum adoption of Smart Glass in 2050 was assumed to be 30% of the global TAM since space conditioning needs vary greatly between climates and other design strategies may be employed instead of Smart Glass to achieve zero-energy status. The adoption curve was developed by interpolating the data from corporate projections and the WorldGBC assumption in 2050 using a 3rd degree polynomial function. Data was extrapolated yet, an upper bound was applied to limit adoption to be only 30% of the TAM.

Drawdown Scenario –

The 2050 adoption of smart glass was assumed to be 50% of the global TAM. The adoption curve was developed by interpolating the data from corporate projections and the WorldGBC assumption in 2050 using a 3rd degree polynomial function. Data was extrapolated yet, an upper bound was applied to limit adoption to be only 50% of the TAM.

Optimum Scenario –

The 2050 adoption of smart glass was assumed to be 75% of the global TAM. The adoption curve was developed by interpolating the data from corporate projections and the WorldGBC assumption in 2050 using a 3rd degree polynomial function. Data was extrapolated yet, an upper bound was applied to limit adoption to be only 75% of the TAM.

2.5 INPUTS

This section details the model inputs used to calculate the results presented in this report. The format of the inputs is based on the Drawdown model template used to ensure standardization which allows integration. This section focuses on the customized inputs needed for this solution. For details on the template model design, inputs and calculations, please see additional documentation at www.drawdown.org.

2.5.1 Climate Inputs

The climate analysis in this model uses the values for annual energy intensity of commercial building lighting, cooling, heating, and reductions in these energy consumptions from smart glass installation (which are general "Technical" inputs in the Technical Inputs section). To calculate key model results, the model uses reported emissions factors for the electric grid and heating fuels. Emissions factors are derived from the projected global energy generation mix from three AMPERE RefPol scenarios in IPCC AR5 model Database (GEM3, IMAGE, MESSAGE) and the IEA's ETP 6DS scenario. The values used are shown in Table 2.1.

Grid Emissions

The weighted sum of electricity per unit floor area in each scenario is multiplied by the grid emissions factor. This is

$$emissions_{grid} = \{(TAM - adoption) * [e_c + e_l] + adoption * [e_c * (1 - \eta_c) + e_l * (1 - \eta_l)]\} * ef$$

Where:

$emissions_{grid}$ is the total annual grid emissions for cooling and lighting of commercial buildings

TAM is the total commercial floor area worldwide

adoption is the total adoption of smart glass in units of *commercial building floor area* (converted using window-to-floor area ratio)

e_c is the average electricity used for cooling per unit floor area

η_c is the average cooling energy efficiency of smart glass

e_l is the average electricity used for lighting per unit floor area

η_l is the average lighting energy efficiency of smart glass

ef is the average CO_2 emissions per unit of electricity for the grid worldwide (emissions factor). Note that this emissions factor varies annually, but for simplification, only one value is shown here.

Fuel Emissions

The weighted sum of space heating fuel per unit floor area in each scenario is multiplied by the weighted average fuel emissions factor. This is

$emissions_{fuel} = \{(TAM - adoption) * e_h + adoption * [e_h * (1 - \eta_h)]\} * eff$ Where:

$emissions_{fuel}$ is the total annual fuel emissions for heating of commercial buildings

TAM is the total commercial floor area worldwide

adoption is the total adoption of smart glass in units of *commercial building floor area* (converted using window-to-floor area ratio),

e_h is the average heating energy used per unit floor area

η_h is the average heating energy efficiency of smart glass

eff is the weighted average CO_2 emissions per TJ of all heating fuels (emissions factor). Note that this emissions factor combines all globally relevant heating fuels such as coal, oil, natural gas and biomass.

Indirect Emissions

It is assumed that the indirect emissions from the production of high-performance static glass or the production of smart glass differ. Furthermore, it is assumed that the indirect emissions associated with glass production and transportation are not significant in the context of whole building energy consumption.

Table 2.1 Climate Inputs

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Global average REF Grid Emissions Factor	g CO_2e/kWh	503-593	Depends on year. Starts at High Input in 2020 declines to Low Input in 2050 to represent the decarbonization of the grid in the reference.	12 each year	4

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Combined REF Space Heating & Cooling Fuel Emissions Factor	t CO_2e/ TJ of fuel	87	87	8 including individual fuel emissions factors and shares	1

Note: Project Drawdown data set range is defined by the low and high boundaries which are respectively 1 standard deviation below and above the mean of the collected data points[3].

2.5.2 Financial Inputs

The financial impacts of adopting smart glass is estimated by examining the first (installation) costs and key operating cost differences between installing smart glass and installing conventional glass. As such, the cost of installing each glass type is collected, as is the cost of heating, cooling and lighting of commercial buildings since this is the key energy cost expected to be affected by the adoption of smart glass. Smart glass operating costs were ignored due to there being a variety of technologies each of which have varied operating costs as well as the largest operating costs to be insignificant in the context of whole building energy consumption[4]. The first costs include obtaining and installation of the glass and for smart glass, any additional peripherals that are needed to make the glass work such as controls, are assumed to be included in the smart glass prices which come from a variety of research and market sources. Considering the rapid growth of this technology, a learning rate was applied to capture the expected rapid price changes that should come from innovation and competition in the sector. As a proxy for the learning rate of smart glass, which was limited in the literature, the learning rate of air conditioning units was used as a guide in selecting one for smart glass (the conservative lower bound was used), and no learning rate for conventional glass was applied.

The heating, cooling, and lighting costs come from energy costs of average heating, cooling, and lighting energy for commercial buildings (energy use and reduction inputs are in the Technical Inputs Section). The global average cost of both electricity and space conditioning was used to estimate the operating costs for

[3] In some cases, the low boundary is negative for a variable that can only be positive, and in these cases the lowest collected data point is used as the "low" boundary.

[4] The reader is reminded that some smart glass types require electricity to maintain a specific state (tinted or clear), some require electricity only to switch state, some require no electricity at all and switch according to solar light or heat, and none of these is the clear leader in the smart glass market, so these operating costs were omitted.

heating, cooling, and lighting of commercial buildings with and without smart glass. As smart glass installations are still well within their lifetime, there is little information on the disposal costs, and hence this has been excluded from this analysis.

The financial inputs can be seen in Table 2.2 and Table 2.3.

Table 2.2 Financial Inputs for Conventional Technologies

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
First costs (Conventional)	*US\$2014/ million m^2*	2,389,923 - 38,768,367	18,156,186	11	10
Variable Operation and Maintenance Costs (Conventional cooling and lighting)	*US\$2014/ million m^2/yr.*	10,304,571	10,304,571	(derived from other inputs)	(derived from other inputs)
Commercial Electricity Unit Cost	*US\$2014/ kWh*	0.0946	0.0946	838 (for 55 countries)	1
Space Heating & Cooling (weighted average)	*US\$2014/ kWh*	0.0715	0.0715	(derived from other inputs)	(derived from other inputs)

Table 2.3 Financial Inputs for Solution

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
First costs (Solution)	*US\$2014/ million m^2*	30,504,450 - 87,287,619	58,896,034	23	17
Variable Operation and Maintenance Costs (Solution cooling and lighting)	*US\$2014/ million m^2/yr.*	9,470,726	9,470,726	(derived from other inputs)	(derived from other inputs)
Commercial Electricity Unit Cost	*US\$2014/ kWh*	0.0946	0.0946	838 (for 55 Countri es)	1

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Space Heating & Cooling (weighted average)	*US$2014/ kWh*	0.0715	0.0715	(derived from other inputs)	(derived from other inputs)
Learning Rate (Air Conditioning data used as Proxy)	*percent*	8 - 18	8	6	5

2.5.3 Technical Inputs

Besides strictly climate and financial inputs, several general variables were used in the analysis which had important impacts on both the climate and financial results. These are described hereunder.

Energy Consumption and Efficiency Variables

As the focus of this model work is on energy savings, the base energy demand was defined according to data collected for commercial buildings' heating, cooling, and lighting needs. This base data was from historical building energy demands and therefore assumes that the vast majority of building stock used what this report defines as conventional glass (see Literature Review Section). The literature on energy savings from smart glass often came from studies that are both case studies as well as energy simulations on sample buildings rather than actual commercial building data, and generally represented temperate climates located in the US and EU. Depending on the study, different spaces were considered – either perimeter zones or whole building energy simulations. In order for the data to be comparable, the energy savings for perimeter zones were scaled by the ratio of perimeter zone to whole building floor area. The ratio is determined from reported values within commercial buildings (Arasteh et al., 2006; DeForest et al., 2015; E.S. Lee & Tavil, 2007). The average whole building efficiency savings amounted to 8.67% for lighting, 8.95% for space cooling, and 7.10% for space heating.

Lifetime Variables

Several additional variables were necessary to calculate the financial benefits of installing smart glass in commercial buildings. These include estimates for the life expectancy of both conventional glass and smart glass. Though life expectancies for these technologies can vary considerably based upon a variety of factors. Recent advancements in smart glass have led to the increase in durability, such that they have the same performance of their static counterparts (E. S. Lee et al., 2013; SageGlass, n.d.; ViewGlass Smartglass, 2016). Due to this fact, the assumption was made that conventional and smart glass have equivalent lifetimes. Table 2.4 and Table 2.5 show this data.

Window – Floor Conversions

To convert between floor area and window area, a conversion factor is needed – Commercial Window to Floor Area Ratio. Assumptions are discussed in the Assumptions Section, however two of relevance are noted here. First, the glazed surface of interest is only the window, meaning that the other glazed surfaces are assumed negligible for commercial buildings. Second, the ratio of total window area to building floor area can be represented by a fixed number. The fixed commercial window to floor area ratio was based on values typically found in the US building stock (Deru et al., 2011). Since Smart Glass has little (to negative) savings when implemented on the northern façade in the northern hemisphere (southern façade in the southern hemisphere), it is assumed that Smart Glass will only be implemented on 75% of the building façade. Thus, the window area to floor area ratio is scaled appropriately.

Table 2.4 Technical Inputs Conventional Technologies

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Lifetime Capacity (Conventional)	*years*	27 - 46	36.7	3	3
Commercial Window to Floor Area ratio	*percent*	2.7% – 9.1%	5.9%	16	1
Average Energy for Commercial Space Cooling per Floor Area	*TWh/ million m^2*	0.025 – 0.026	0.026	3	3
Average Energy for Commercial Lighting per Floor Area	*TWh/ million m^2*	0.023 – 0.054	0.039	3	3
Average Energy for Commercial Space Heating per Floor Area	*TWh/ million m^2*	0.021 – 0.092	0.056	3	3

Table 2.5 Technical Inputs for Solution

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Lifetime Capacity (Solution)	*years*	(assumed same as Conventional)	36.7	1	1

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Energy Efficiency (saving) of Cooling with Solution	*percent*	1.44% - 16.26%	8.95%	42	16
Energy Efficiency (saving) of Lighting with Solution	*percent*	4.08% - 13.27%	8.67%	42	16
Energy Efficiency (saving) of Heating with Solution	*percent*	-0.56% – 14.76%	7.09%	42	16

2.6 Assumptions

Six overarching assumptions have been made for Project Drawdown models to enable the development and integration of individual model solutions. These are that infrastructure required for solution is available and in-place, policies required are already in-place, no carbon price is modeled, all costs accrue at the level of agency modeled, improvements in technology are not modeled, and that first costs may change according to learning. Full details of core assumptions and methodology will be available at www.drawdown.org. Beyond these core assumptions, there are other important assumptions made for the modeling of this specific solution. These are detailed below.

Assumption 1: The costs collected include installation costs for each type of glass, inclusive of any additional peripherals to allow control of smart glass and the lighting systems in sun-facing rooms. The variety of smart glass technologies indicates the variety of peripherals and support systems needed to make them work. Additionally, the lighting benefit calculated in the literature often assumes that lighting systems have the appropriate sensors and controls included.

Assumption 2: Installation of smart glass is replacing installation of conventional glass, both in retrofit and in new construction applications. It is assumed that Smart Glass will have similar energy savings between the two applications since a retrofit or new construction will consider the conventional solution, high-performance static glazing or Smart Glass.

Assumption 3: The ratio of glazed area to commercial floor area is an acceptable link between smart glass installation and floor area and will remain fixed over the study period. The conversion between the adoption of glazed areas and floor areas was made to allow easier integration of solutions in the built environment. The window to wall ratio is a commonly used metric to define buildings, and this metric builds upon it. Additionally, the limited data on window to floor area suggests that there is even less data on the trends of window to floor ratios worldwide supporting an assumption of fixed value over time.

Assumption 4: The adoption of smart glass is highly correlated to the adoption of Net Zero Buildings (NZB). Windows are a key source of energy loss in buildings and must therefore be a focus of any serious effort towards NZB. As smart glass can have a significant impact of window efficiency, it's a reasonable assumption that they are correlated.

Assumption 5: The warming climate does not affect the efficiency of smart glass or conventional glass. One could imagine that adopting smart glass helps decrease the amount of global warming experienced creating a feedback loop that reduces the amount of cooling required for occupant comfort, but this link is so tenuous, and unsupported by data, so it was ignored.

Assumption 6: Glass used for non-window glazing building surfaces is minute enough to be ignored for emissions and cost calculations. Although the use of glazing for building walls is common in many commercial buildings of note, particularly those that tower to the sky, the focus is on a wide range of commercial buildings including schools, hospitals, and retail spaces, many of which only use glazing for windows.

Assumption 7: A majority of the data collected is US-centric. While some sources from the EU and Asia are included, the majority of energy efficiency data is collected from US climate zones. Most US climate zones are representative of climate zones around the world, yet internal loads and building geometry will vary – thus the US DOE commercial reference buildings in which many of the energy savings were calculated may not apply.

2.7 Integration

The complete Project Drawdown integration documentation (will be available at www.drawdown.org) details how all solution models in each sector are integrated, and how sectors are integrated to form a complete system. Those general notes are excluded from this document but should be referenced for a complete understanding of the integration process. Only key elements of the integration process that are needed to understand how this solution fits into the entire system are described here.

Each solution in the Buildings and Cities Sector was modeled individually, and then integration was performed to ensure consistency across the sector and with the other sectors. These solutions require an integration analysis to avoid double counting, as they primarily relate to either reducing demand for space heating and cooling (for residential and/or commercial buildings), commercial lighting, cooking, or water heating. The integration process therefore was addressed through sequential adjustments to the efficiencies of the solutions in a prioritized sequence for each of space heating and cooling, lighting, cooking, and water heating (performed in four separate sequence chains). The prioritized sequence is fixed for all scenarios and is described in the Drawdown Building Sector Integration documentation.

For each solution in an integration sequence, the estimated impact of previous solutions on the emissions savings of the current solution is estimated and a reduction factor is applied. The factor is only applied to emissions and energy savings attributed to adoptions that overlap with previous solutions[5], and for this, adoptions are generally assumed independent. Solutions that start each integration sequence are therefore unaffected (unless they are affected by solutions in other sequences), and solutions that apply to different buildings (say commercial and residential) do not affect each other. The method of estimating overlap is based on the percent adoption of the higher priority solution applied to the area adopted in the lower priority solution. For the efficiency factor of this overlapping area only, the reduction factor is applied, it is scaled and used to update the results in the lower priority solution model.

The Dynamic Glass solution (of the space heating and cooling sequence) is assumed to interact with only other previous solutions that are modeled on Commercial buildings: Cool Roof, Green Roof, and High Performance Glass (for Space Heating) and LED (Lighting). The adoptions of these solutions are converted to Commercial floor area and in any single year, each is assumed to overlap with Dynamic Glass in accordance with its adoption (assumed uniform and independent). The adoption overlap is the maximum overlap calculated from any one of those solutions in each year. The average overlap over 2020-2050 is multiplied by the reduction factor assumed and then this result is used to adjust (reduce) the efficiency factors of the electricity and fuel for Dynamic Glass. Results in this report reflect the results of the modeling and integration process.

In addition to building sector integration, there was an integration process across the grid and electricity efficiency solutions (buildings, transport, materials etc.) which adjusted for the double counting. Double counting of emissions reduction was a factor of using the reference grid emissions factors for electricity-based solutions. As grid solutions (Utility-scale Solar PV and others) are adopted, the grid gets cleaner and the impact of efficiency solutions is reduced (where they reduce electricity demand) or increased (where they increase electricity demand[6]). Grid solutions are adjusted to remove the double counting as described in the Project Drawdown integration documentation.

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[5] This can be interpreted as a single building with multiple efficiency technologies.

[6] Some solutions such as Electric Vehicles and High-Speed Rail increase the demand for electricity and reduce the demand for fuel.

2.8 Limitations/Further Development

2.8.1 Technology-Specific Analysis

The model developed does not allow analysis of specific types of smart glass and the differences in their design and operation. The most obvious impact of this is that glass that requires energy input was not distinguished from glass that responds to light or heat automatically, and the learning rate of each technology would have helped too. This would have made the analysis more nuanced, and potentially more accurate. This can be done in future analyses by having a separate model for each classification of smart glass once reasonable classifications of different operations can be made and sufficient data are available. This also applies to the conventional technologies which vary widely. A more accurate representation could have been possible with market segmentation data on the variety of conventional glass types in use, and the most likely replacement technology.

2.8.2 Building-Specific Analysis

A fixed estimate of the window to floor area was used as the adoption metric that corresponds closely to the glazed area of commercial buildings. This may change over time as more and more glazed areas are being used in modern buildings for stylistic and occupant comfort. However, the lack of data on distribution and evolution of window floor ratios made a simplification necessary. With better data, even if at a regional or country-scale, could improve the analysis.

2.8.3 Region-Specific Analysis

Commercial building space conditioning and lighting needs vary by local climate and as smart glass is more expensive than regular glass, adoption of smart glass might vary by wealth of a country even in a globalized world. Ideally a localized or regional analysis would be done, but the lack of data, and existence of large countries with varying local climates complicate this significantly. Additionally, the varying grid emissions intensities of countries and regions make the local emissions impact of adopting smart glass differ even if the electricity saving is identical. Data from studies quantifying the energy savings potential were chosen from as many climates as possible, yet not all climates were represented. To improve the model, the energy savings can be weighted based upon climate type of a particular region (or the world) so that an accurate representation of energy savings can be determined.

2.8.4 Behavior-Specific Analysis

As some smart glass requires human input, the behavior of building users becomes important for some types of smart glass, yet this was not included in the analysis. The best example is electrochromic glass which can be adjusted by an electric current set by a human-controlled switch. In ideal situations, this might also be integrated into a Building Automation System complete with light and heat sensors and optimization algorithms to maximize efficiency of the entire building. But the integration did not allow that level of detail. Finally, while the adoption in the model was driven by assumptions of net zero building targets being highly correlated with smart glass adoption, building owners have multiple options for increasing the efficiency of windows, and this analysis could be improved with a better understanding of how building owners will respond to global and regional net zero building targets.

3 Results

3.1 Adoption

Below, the world adoptions of the solution in some key years of analysis by both functional unit and percent of TAM for the three Project Drawdown scenarios are shown.

Table 3.1 World Adoption of the Solution

Solution	Units	Current Year (2018)	World Adoption by 2050		
			Plausible	Drawdown	Optimum
Smart Glass	*million m^2 floor space equivalent*	42	3,479.40	5,799	8,698
	% TAM	0.49%	30%	50%	75%

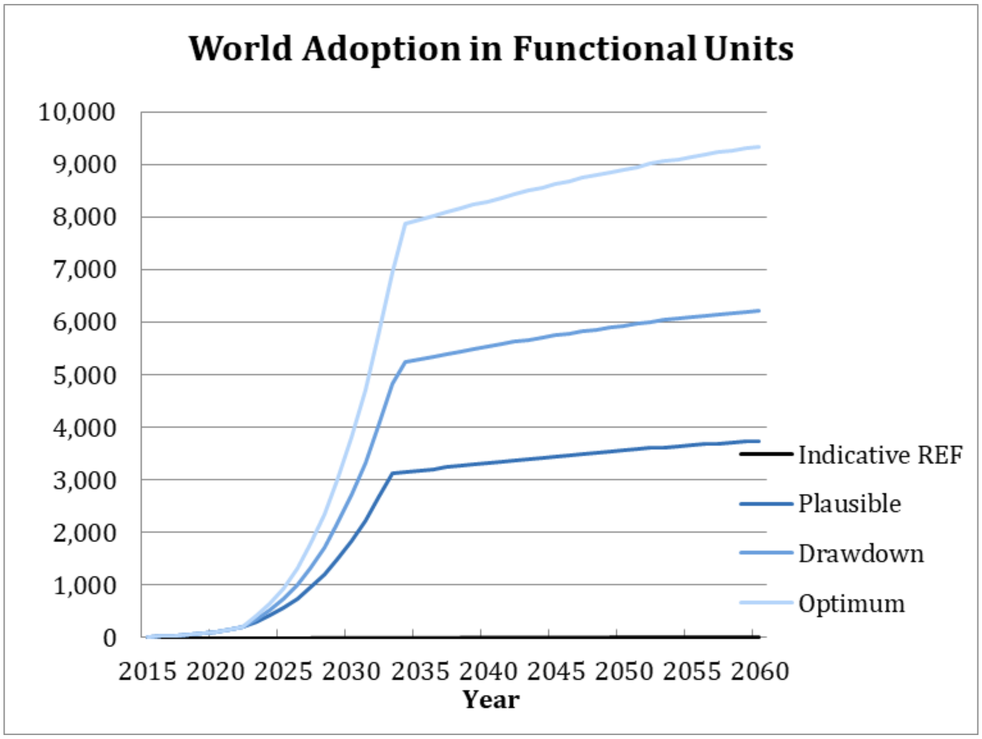

Figure 3.1 World Annual Adoption 2020-2050.

3.2 Climate Impacts

Below are the emissions results of the analysis for each scenario which include total emissions reduction, atmospheric concentration changes, and sequestration where relevant. For a detailed explanation of each result, please see the Glossary.

Table 3.2 Climate Impacts

Scenario	Maximum Annual Emissions Reduction	Total Emissions Reduction	Emissions Reduction in 2050
	Gt CO_2-eq/ yr.	*Gt CO_2-eq/ yr. (2020-2050)*	*Gt CO_2-eq/ year*
Plausible	0.016	0.31	0.014
Drawdown	0.02	0.50	0.024
Optimum	0.04	0.75	0.036

The solution was integrated with all other Project Drawdown Solutions and may have different emissions results from the models. This is due to adjustments caused by interactions among solutions that limit full adoption (such as by feedstock or demand limits) or that limit the full benefit of some solutions (such as reduced individual solution impact when technologies are combined).

Table 3.3 Impacts on Atmospheric Concentrations of CO_2-eq

Scenario	GHG Concentration Change in 2050	GHG Concentration Rate of Change in 2050
	PPM CO_2-eq (2050)	*PPM CO_2-eq change from 2049-2050*
Plausible	0.03	0.001
Drawdown	0.04	0.002
Optimum	0.06	0.003

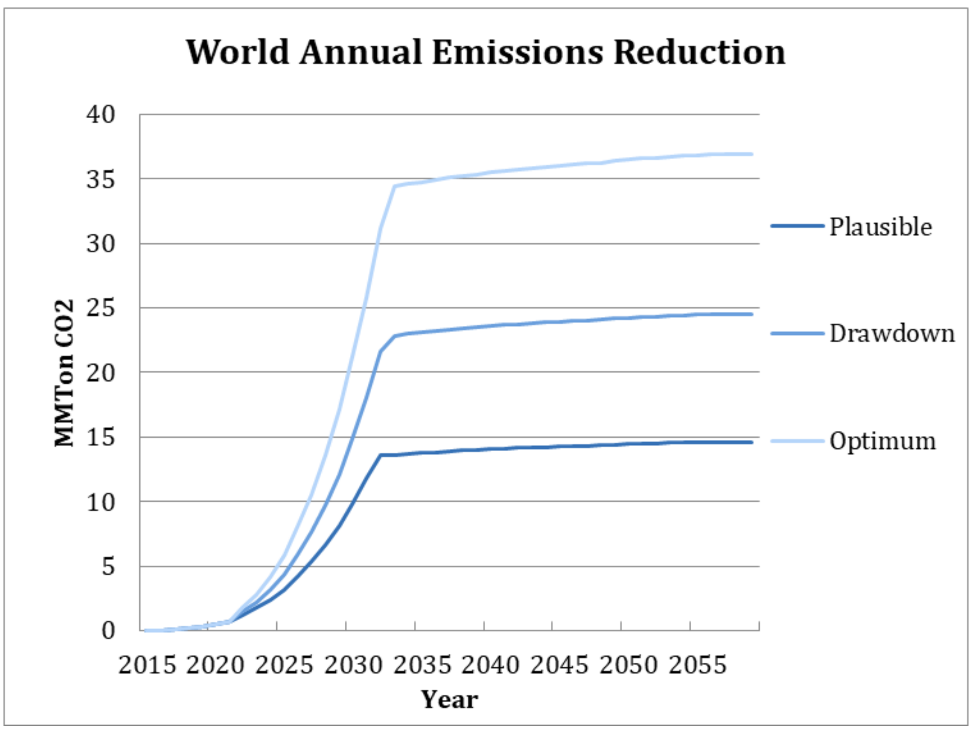

Figure 3.2 World Annual Greenhouse Gas Emissions Reduction

3.3 Financial Impacts

Below are the financial results of the analysis for each scenario. For a detailed explanation of each result, please see the Glossary.

Table 3.4 Financial Impacts

Scenario	Cumulative First Cost	Marginal First Cost	Net Operating Savings	Lifetime Cashflow Savings NPV (of All Implementation Units)
	2020-2050 Billion USD	*2020-2050 Billion USD*	*2020-2050 Billion USD*	*Billion USD*
Plausible	132.16	69.09	58.60	-10.77
Drawdown	208.49	103.30	95.78	-14.02
Optimum	298.80	140.96	142.14	-17.03

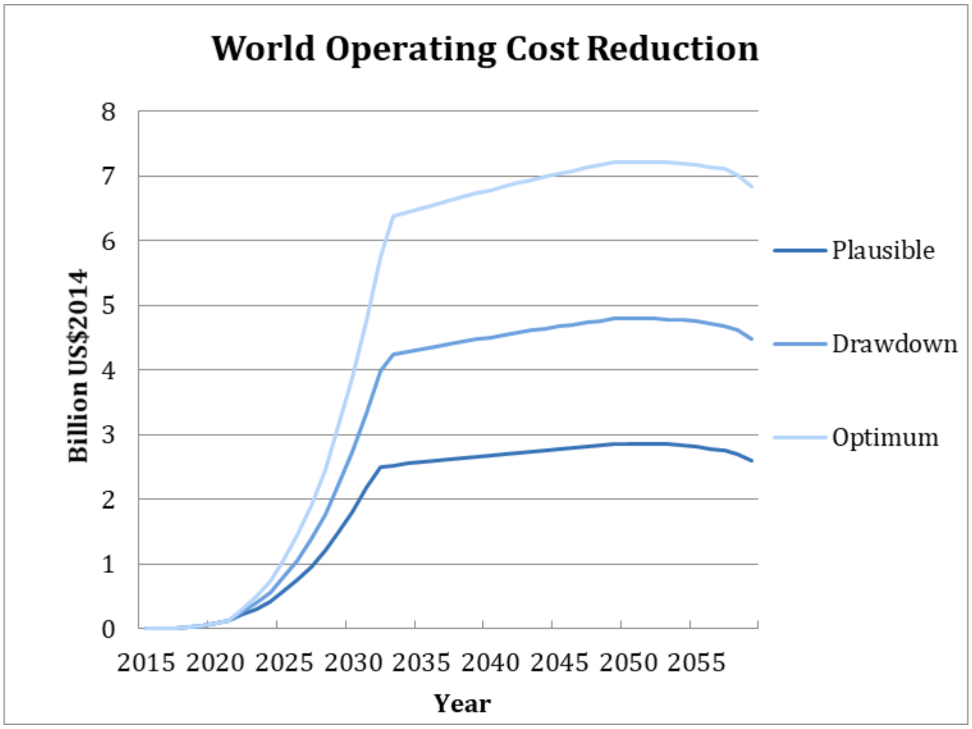

Figure 3.3 Operating Costs Over Time

4 Discussion

The net zero building is a concept of designing buildings that consume no net energy during or produce no net carbon emissions during their operation phase. Shifting the world's building stock to be net zero is a target set by the World Green Buildings Council in order to help the world meet the COP21 emissions targets set in December 2015. Because of the heat lost and gain through opening in wall assemblies, efficient glazing systems can reduce a building's energy consumption for space conditioning and lighting by controlling both how much sunlight enters buildings and how much heat is lost or gained due to temperature differences between conditioned and unconditioned spaces.

Studies indicate that whole building energy savings from implementation of Smart Glass are on average 8.95% for space cooling, 7.10% for space heating, and 8.67% for electrical lighting. These savings correspond to a reduction of 0.5 billion tons of CO_2 from 2020 to 2050 under the "*Drawdown*" scenario. The marginal installation or first cost is high, much higher than other glazing options (US$103.30 billion). This analysis suggests that with the current learning rate of 8.00%, the Single Unit NPV of the solution is negative in all scenarios. A positive Single Unit NPV is important since it incentivizes building owners and investors to adopt Smart Glass as a solution. There is some variability in the first cost pricing however as many competing technologies and prices typically range from US$518.67/$m^2$ window area to US$1484.17/$m^2$ windows area (the input used in the model is US$1001.42/$m^2$) indicating that some of the lower cost smart glass might be the technology that is adopted at scale by supporters of the net zero building concept. It should be noted that the cost inputs used in the model span a range of years, 2006 – 2018, and are primarily from the US and EU. Furthermore, the cost estimates from these studies have lowered in more recent years, thus the high cost and learning rate used in this model may not be representative of the decline in cost of Smart Glass.

Another benefit of Smart Glass which was not incorporated into the model is the cost savings associated with reducing peak demand for heating and cooling. Utility rate structures for commercial buildings are typically based upon the peak amount of energy that a building uses during a year. Smart Glass has been shown to reduce the peak demand by up to 30% (Deb et al., 2001; Sbar et al., 2012; Wong & Chan, 2013). This reduction is difficult to model but has impact both on the emissions associated with the electrical grid as well as increase in cost savings during operation.

Other studies have suggested that smart glass systems have a 30% reduction in first capital cost due to savings in capital expenses associated with the mechanical systems used to condition the air in buildings, as well as construction labor during manufacturing and installation (Tinianov, 2017). While this study promotes the use of Smart Glass, it should not be overlooked that the cost of smart glazing systems is lowered when balanced with savings from other building systems (e.g. mechanical equipment, internal or external shading devices).

In all scenarios, the adoption peaks around the year 2033 when the exponential adoption curve reaches the maximum allowable (e.g. 50% for the PDS) which influences the other results where a change in trend is noted at the same year. Interestingly, the payback period decreases over time as a learning rate is applied to the technology. A minimum payback of 16 years is achieved around the year 2034 (for purchase) in the Optimum Scenario. The assumption of applying a learning rate and a "break" through point similar to what is assumed for net-zero buildings may not be applicable to this solution because net-zero buildings may not specifically use Smart Glass to achieve net-zero status.

The Operating Cost difference between the PDS and REF scenario (as shown in Figure 3.3) trends downward after 2050. This result is due to the analysis period only being between 2014 and 2050 and no new units are implemented after 2050. Thus, some functional units are retired and the operating cost difference decreases, although still remains positive indicating savings.

The literature primarily considers the office buildings when quantifying the energy savings potential of Smart Glass. Yet, office buildings are not representative of all commercial buildings due to differences in geometries and internal load profiles. Unlike residential buildings, commercial buildings typically have high internal loads, resulting in a majority of the energy consumption due to space cooling even in cold climates such as Chicago, USA. To improve the model, the inclusion of additional research into the quantification of energy savings of Smart Glass in other building types is needed.

4.1 LIMITATIONS

Smart Glass is just one solution that aids in the design of NZB. In some climates and building geometries, high-performance static windows perform better than their smart counter-parts. Thus, building designers and owners must consider the advantages and drawbacks of each of their glazing options when working towards designing an NZB.

While Smart Glass typically improves the thermal and visual comfort of a space, it also has limitations in its ability to create well-lit spaces. The slight color tint of an electrochromic window changes the color of light that enters a space which can influence the lighting design and occupant comfort. Furthermore, the control strategy that is used to change the state of the smart glass will affect both the energy savings and occupant comfort. Two main strategies are employed, controlling for daylight, and controlling for solar heat gain. Often times the two strategies are at odds with one another and produce different energy savings results. To address this problem, near-infrared electrochromic windows are in development that have the potential to modulate both the VT and SHGC of a window so that both occupant visual and thermal comfort can be optimized.

Electrochromic glass is the most researched within the built environment, yet more research is needed on other types of smart glass to determine their cost and potential for energy savings in commercial buildings. In addition, if the cost of Smart Glass can be reduced, there is the potential for it to be incorporated into the residential building stock and reduce carbon emissions even further.

4.2 BENCHMARKS

In Table 4.1 are shown some selected results from other modeling efforts with Drawdown results for comparison. The table aims to highlight the key differences and similarities between those other studies and the work of Project Drawdown. Note that in the case of the IEA work, a multitude of technologies and approaches were assumed in the scenarios, and it was not possible to separate the expected impact of efficient windows. However, as a delimiter, IEA's model works to highlight that Smart Glass (as modeled by Project Drawdown) represents only a smart part of building space heating and cooling energy reduction. Even though windows represent a significant portion of the energy loss in buildings worldwide, it's important to recognize that many other technologies can be applied to buildings to reduce space heating. DeForest et al (2015) highlight, for instance, that much larger savings can be obtained from the replacement of traditional windows with high performance static (HPS) windows than from replacing HPS with smart windows, and this is illustrated in the results of Arasteh et al (2006) which are much higher than Drawdown chiefly due to the comparator being the current building stock rather than only HPS windows despite being for a smaller region (US compared to OECD90). Arasteh et al (2006) indicate that replacing windows of existing stock with static low-e windows (HPS) would result in 0.69 EJ, indicating that the dynamic component really saved 1.03 - 0.69 = 0.34 EJ which is closer to the Project Drawdown Optimum Scenario.

Additionally, other technologies, like heat pumps, and approaches, like improved building design, can have a significant complementary impact of space conditioning energy. Considering that the DeForest et al (2015) and Arasteh et al (2006) studies focused on the US only, and compared different technologies, the differences in results are reasonable. Drawdown results are generally in line with existing literature.

Table 4.1 Benchmarks

Metric	IEA (2017)	Arasteh et al (2006)	DeForest et al (2015)	Project Drawdown Plausible Scenario	Project Drawdown Optimum Scenario
Description of Assumptions and Methodology	Difference between the Reference Technology Scenario (RTS) and the Beyond 2Degree (B2DS) Scenario.	Annual Energy Savings from 2-pane low-e glass with dynamic solar heat gain control applied to commercial Buildings in US only.	Whole-building simulation of the impacts of Near-infrared EC windows and regular EC windows for commercial and residential buildings in the US by climate zone.	Adoption Grows to 30% of Market - See Methodology Section	Adoption Grows to 75% of Market - See Methodology Section
Region	OECD	US	US	OECD90*	OECD90*
Building Use	Services	Commercial	All	Commercial	Commercial
Energy End Use	Space Heating	Space Heating, Cooling, and Lighting	Space Heating, Cooling, and Lighting	Space Heating, Cooling, and Lighting	Space Heating, Cooling, and Lighting
Solution Technologies Included	All Building Space Heating and Cooling Efficiency Technologies	Dynamic Low-e – A two pane low-e window with dynamic solar heat gain control.	Conventional Electrochromic Windows *(& Near Infrared (NIR) Electrochromic Windows*)	Electrochromic Glass	Electrochromic Glass
Comparator Technologies	N/A	Current Building Stock	High Performance Static	High Performance Static	High Performance Static
Market Share in 2050 (%)	N/A	Assumes 100% stock switch	100% (5 building typologies scaled up to all US Buildings)	30%	75%
Energy Savings Potential	Average of 2.1 EJ/ year 2025-2060	1.03 EJ/ year	0.01 EJ/ year *(NIR: 0.03 EJ/ year)*	0.08 EJ/ year average	0.19 EJ/ year average
Emissions Reduction Potential	139 Mt CO_2/ year	N/A	0.65 Mt CO_2/ year *(NIR: 1.56 Mt CO_2/ year)*	10 Mt CO_2/ year average	24 Mt CO_2/ year average

* Note that ***OECD90*** is a Drawdown region defined as the OECD Countries as in 1990

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6 GLOSSARY

Adoption Scenario – the predicted annual adoption over the period 2015 to 2060, which is usually measured in **Functional Units**. A range of scenarios is programmed in the model, but the user may enter her own. Note that the assumption behind most scenarios is one of growth. If for instance a solution is one of reduced heating energy usage due to better insulation, then the solution adoption is translated into an increase in use of insulation. There are two types of adoption scenarios in use: **Reference (REF)** where global adoption remains mostly constant, and **Project Drawdown Scenarios (PDS)** which illustrate high growth of the solution.

Approximate PPM Equivalent – the reduction in atmospheric concentration of CO_2 (in **PPM**) that is expected to result if the **PDS Scenario** occurs. This assumes a discrete avoided pulse model based on the Bern Carbon Cycle model.

Average Abatement Cost – the ratio of the present value of the solution (**Net Operating Savings** minus **Marginal First Costs**) and the **Total Emissions Reduction**. This is a single value for each solution for each **PDS Scenario**, and is used to build the characteristic "*Marginal Abatement Cost*" curves when Average Abatement Cost values for each solution are ordered and graphed.

Average Annual Use – the average number of functional units that a single implementation unit typically provides in one year. This is usually a weighted average for all users according to the data available. For instance, total number of passenger-km driven by a hybrid vehicle in a year depends on country and typical number of occupants. We take global weighted averages for this input. This is used to estimate the **Replacement Time**.

Cumulative First Cost – the total **First Cost** of solution **Implementation Units** purchased in the **PDS Scenario** in the analysis period. The number of solution implementation units that are available to provide emissions reduction during the analysis period is dependent on the units installed prior to the analysis period, and hence all implementation units installed after the base year are included in the cumulative first costing (that is 2015-2050).

Direct Emissions – emissions caused by the operation of the solution, which are typically caused over the lifetime of the solution. They should be entered into the model normalized per functional unit.

Discount Rate- the interest rate used in discounted cash flow (DCF) analysis to determine the present value of future cash flows. The discount rate in DCF analysis takes into account not just the time value of money, but also the risk or uncertainty of future cash flows; the greater the uncertainty of future cash flows, the higher the discount rate. Most importantly, the greater the discount rate, the more the future savings are devalued (which impacts the financial but not the climate impacts of the solution).

Emissions Factor– the average normalized emissions resulting from consumption of a unit of electricity across the global grid. Typical units are kg CO_2e/kWh.

First Cost- the investment cost per **Implementation Unit** which is essentially the full cost of establishing or implementing the solution. This value, measured in 2014$US, is only accurate to the extent that the cost-based analysis is accurate. The financial model assumes that the first cost is made entirely in the first year of establishment and none thereafter (that is, no amortization is included). Thus, both the first cost and operating cost are factored in the financial model for the first year of implementation, all years thereafter simply reflect the operating cost until replacement of the solution at its end of life.

Functional Unit – a measurement unit that represents the value, provided to the world, of the function that the solution performs. This depends on the solution. Therefore, LED Lighting provides petalumen-hours of light, Biomass provides tera-watt-hours of electricity and high-speed rail provides billions of passenger-km of mobility.

Grid Emissions – emissions caused by use of the electricity grid in supplying power to any operation associated with a solution. They should be in the units described below each variable entry cell. Drawdown models assume that the global electric grid, even in a Reference Scenario, is slowly getting cleaner, and that emissions factors fall over time resulting in lower grid emissions for the same electricity demand.

Implementation Unit – a measurement unit that represents how the solution practice or technology will be installed/setup and priced. The implementation unit depends on the solution. For instance, implementing electric vehicles (EV) is measured according to the number of actual EV's in use, and adoption of Onshore Wind power is measured according to the total terawatts (TW) of capacity installed worldwide.

Indirect Emissions – emissions caused by the production or delivery or setup or establishment of the solution in a specified area. These are NOT caused by day to day operations or growth over time, but they should be entered into the model normalized on a per functional unit or per implementation unit basis.

Learning Rate/Learning Curve - Learning curves (sometimes called experience curves) are used to analyze a well-known and easily observed phenomenon: humans become increasingly efficient with experience. The first time a product is manufactured, or a service provided, costs are high, work is inefficient, quality is marginal, and time is wasted. As experienced is acquired, costs decline, efficiency and quality improve, and waste is reduced. The model has a tool for calculating how costs change due to learning. A 2% learning rate means that the cost of producing a *good* drops by 2% every time total production doubles.

Lifetime Capacity – this is the total average functional units that one implementation unit of the solution or conventional technology or practice can provide before replacement is needed. All technologies have an average lifetime usage potential, even considering regular maintenance. This is used to estimate the **Replacement Time**. and has a direct impact on the cost to install/acquire technologies/practices over time. E.g. solar panels generate, on average, a limited amount of electricity (in TWh) per installed capacity (in TW) before a new solar panel must be purchased. Electric vehicles can travel a limited number of passenger kilometers over its lifetime before needing to be replaced.

Lifetime Operating Savings–the operating cost in the PDS versus the REF scenarios over the lifetime of the implementation units purchased during the model period regardless of when their useful life ends.

Lifetime Cashflow NPV-the present value (PV) of the net cash flows (PDS versus REF) in each year of the model period (2015-2060). The net cash flows include net operating costs and first costs. There are two results in the model: Lifetime Cashflow NPV for a Single **Implementation Unit**, which refers to the installation of one **Implementation Unit**, and Lifetime Cashflow NPV of All Units, which refers to all **Implementation Units** installed in a particular scenario. These calculations are also available using profit inputs instead of operating costs.

Marginal First Cost – the difference between the **First Cost** of all units (solution and conventional) installed in the **PDS Scenario** and the **First Cost** of all units installed in the **REF Scenario** during the analysis period. No discounting is performed. The number of solution implementation units that are available to provide emissions reduction during the analysis period is dependent on the units installed prior to the analysis period, and hence all implementation units installed after the base year are included in the cumulative first costing (that is 2015-2050).

Net Annual Functional Units (NAFU) – the adoption in the PDS minus the adoption in the REF in each year of analysis. In the model, this represents the additional annual functional demand captured either by the solution in the **PDS Scenario** or the conventional in the **REF Scenario**.

Net Annual Implementation Units (NAIU) – the number of **Implementation Units** of the solution that are needed in the PDS to supply the **Net Annual Functional Units (NAFU).** This equals the adoption in the PDS minus the adoption in the REF in each year of analysis divided by the average annual use.

Net Operating Savings – The undiscounted difference between the operating cost of all units (solution and conventional) in the **PDS Scenario** minus that of all units in the **REF Scenario**.

Operating Costs – the average cost to ensure operation of an activity (conventional or solution) which is measured in 2014$US/**Functional Unit**. This is needed to estimate how much it would cost to achieve the adoption projected when compared to the **REF Case**. Note that this excludes **First Costs** for implementing the solution.

Payback Period – the number of years required to pay all the **First Costs** of the solution using **Net Operating Savings**. There are four specific metrics each with one of **Marginal First Costs** or **First Costs** of the solution only combined with either discounted or non-discounted values. All four are in the model. Additionally, the four outputs are calculated using the increased profit estimation instead of **Net Operating Savings**.

PDS/ Project Drawdown Scenario – this is the high growth scenario for adoption of the solution

PPB/ Parts per Billion – a measure of concentration for atmospheric gases. 10 million PPB = 1%.

PPM/ Parts per Million – a measure of concentration for atmospheric gases. 10 thousand PPM = 1%.

REF/ Reference Scenario – this is the low growth scenario for adoption of the solution against which all **PDS scenarios** are compared.

Regrets solution has a positive impact on overall carbon emissions being therefore considered in some scenarios; however, the social and environmental costs could be harmful and high.

Replacement Time- the length of time in years, from installation/acquisition/setup of the solution through usage until a new installation/acquisition/setup is required to replace the earlier one. This is calculated as the ratio of **Lifetime Capacity** and the **Average Annual Use**.

TAM/ Total Addressable Market – represents the total potential market of functional demand provided by the technologies and practices under investigation, adjusting for estimated economic and population growth. For this solutions sector, it represents world and regional total addressable markets for electricity generation technologies in which the solutions are considered.

Total Emissions Reduction – the sum of grid, fuel, indirect, and other direct emissions reductions over the analysis period. The emissions reduction of each of these is the difference between the emissions that would have resulted in the **REF Scenario** (from both solution and conventional) and the emissions that would result in the **PDS Scenario**. These may also be considered as "emissions avoided" as they may have occurred in the REF Scenario, but not in the PDS Scenario.

Transition solutions are considered till better technologies and less impactful are more cost effective and mature.

TWh/ Terawatt-hour – A unit of energy equal to 1 billion kilowatt-hours

U-Value – a measure of the heat transmission through a building part (such as a wall or window) or a given thickness of a material (such as insulation) with lower number indicating better insulating properties.