

TECHNICAL ASSESSMENT FOR HIGH PERFORMANCE GLAZING FOR BUILDINGS

SECTOR: BUILDINGS

AGENCY LEVEL: BUILDINGS AND FACILITIES
OWNERS

KEYWORDS: ADVANCED GLAZING, INSULATED
GLAZING UNITS, ENERGY EFFICIENT GLAZING,
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EFFICIENCY

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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.

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TABLE OF CONTENTS

List of Figures	4
List of Tables.....	4
Acronyms and Symbols Used	5
Executive Summary.....	6
1 Literature Review	7
1.1. State of Energy Efficient Glazing	8
1.2. Adoption Path	11
1.2.1 Current Adoption.....	12
1.2.2 Trends to Accelerate Adoption.....	12
1.2.3 Barriers to Adoption	13
1.2.4 Adoption Potential.....	13
1.3. Advantages and disadvantages of High-Performance Glass.....	13
1.3.1 Similar Solutions	13
1.3.2 Arguments for Adoption of High-Performance Glass	14
1.3.3 Additional Benefits and Burdens.....	14
2 Methodology.....	15
2.1 Introduction.....	15
2.2 Data Sources	16
2.3 Total Addressable Market.....	17
2.4 Adoption Scenarios	19
2.4.1 Reference Case / Current Adoption.....	19
2.4.2 Project Drawdown Scenarios	19
2.5 Inputs.....	20
2.5.1 Climate Inputs	20
2.5.2 Financial Inputs	22

2.5.3	Technical Inputs	23
2.6	Assumptions.....	25
2.7	Integration.....	26
2.8	Limitations/Further Development	28
2.8.1	Technology-Specific Analysis.....	28
2.8.2	Building-Specific Analysis	28
2.8.3	Region-Specific Analysis.....	28
3	Results.....	28
3.1	Adoption	28
3.2	Climate Impacts	30
3.3	Financial Impacts	32
4	Discussion	34
4.1	Limitations	35
4.2	Benchmarks	35
5	References	36
6	Glossary.....	44

LIST OF FIGURES

Figure 1.1 Classification of static and dynamic glazing.	9
Figure 2.1 Modeled Growth in Residential Floor Space from 2015-2060 for the World.	18
Figure 2.2 Modeled Growth in Commercial Floor Space from 2015-2060 Excluding the OECD90 Region.	18
Figure 3.1 Residential World Annual Adoption for each Scenario between 2015 and 2060.	29
Figure 3.2 Commercial World Annual Adoption for each Scenario between 2015 and 2060.	30
Figure 3.3 Residential World Annual Greenhouse Gas Emissions Reduction.	31
Figure 3.4 Commercial World Annual Greenhouse Gas Emissions Reduction.	32
Figure 3.5 Residential Operating Costs Over Time.	33
Figure 3.6 Commercial Operating Costs Over Time.	33

LIST OF TABLES

Table 1.1 A matrix comparison of solutions to reduce solar heat gains in buildings is presented.	14
Table 2.1 Climate Inputs.	21
Table 2.2 Financial Inputs for Conventional Technologies	22
Table 2.3 Financial Inputs for Solution	22
Table 2.4 Technical Inputs Conventional Technologies.	24
Table 2.5 Technical Inputs for Solution.	24
Table 3.1 World Adoption of the Solution.	28
Table 3.2 Climate Impacts	30
Table 3.3 Impacts on Atmospheric Concentrations of CO ₂ -eq	31
Table 3.4 Financial Impacts	32
Table 4.1 Benchmarks	35

ACRONYMS AND SYMBOLS USED

EIA – Energy Information Administration

GBPN – Global Buildings Performance Network

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

High-Performance (HP) Glass is a technology that can be used in traditional glazing and façade systems and has the ability to reduce a building's space heating and cooling energy consumption. HP Glass encompasses a variety of advanced glazing techniques that reduce the thermal conductivity of a window and provide solar control. Buildings with HP Glass promise high energy savings for both space heating and cooling.

The market penetration of high-performance glass has been high in OECD countries, yet adoption is not universal within the building sector. Most new glass sales are for high-performance glass, and adoption is expected to continue at a rapid rate in both developed and developing economies. Support from government agencies promoting the development and benefits of HP glass to consumers can drive growth and adoption of the technology as an energy saving retrofit measure in the built environment.

The Solution is modeled by aggregating both whole-building simulated and measured energy savings (space heating and space cooling) of HP Glass installations as compared to single-pane windows ($U\text{-value} < 0.5 \text{ W}/(\text{m}^2\text{K})$) in residential and commercial buildings. The model identifies the addressable market for the solution technology as all residential buildings and commercial buildings outside of the OECD region. The adoption prognostication model constructs four scenarios for future HP Glass adoption. A reference (REF) growth scenario for HP Glass is constructed which fixes the future growth rate to its current percentage share of the total market. Three Project Drawdown Scenario (PDS) scenarios were built upon an assumed different retrofit rate which align with long-term building efficiency targets. Comparing each of the PDS scenarios to the REF scenario yields the climate and financial impacts of High-Performance Glass adoption. The least aggressive PDS scenario (the Plausible Scenario) forecasts 175,139 million m^2 of residential floor area (73.4%) and 89,294 million m^2 of commercial floor area (89.9%) will use HP Glass by 2050, and the most aggressive (Optimum) indicates 227,823 million m^2 of residential floor area (95.5%) and 98,531 million m^2 of commercial floor area (98.1%) will utilize the technology, from a 2018 estimated adoption of 33,954 (residential, that is 18% of global TAM for all regions) and 1,656 (commercial) million m^2 of commercial floor area (6.3% of global TAM for all regions excluding OECD90).

The impacts for this accelerated adoption of HP Glass are promising. The Plausible Scenario avoids a total of 12.39 gigatons (Gt) of CO_2 -equivalent greenhouse gas (GHG) emissions, the approximate parts per million (PPM) equivalent of which is 1.04 (ppm $\text{CO}_2\text{-eq}$). The marginal capital cost of PDS compared to the REF scenario is US\$9,060 billion, but the PDS scenario saves US\$2,208 billion in operating costs due to reduced energy consumption for space conditioning. Adoption of High-Performance Glass can significantly contribute to Drawdown in the building sector.

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 CO₂ 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.

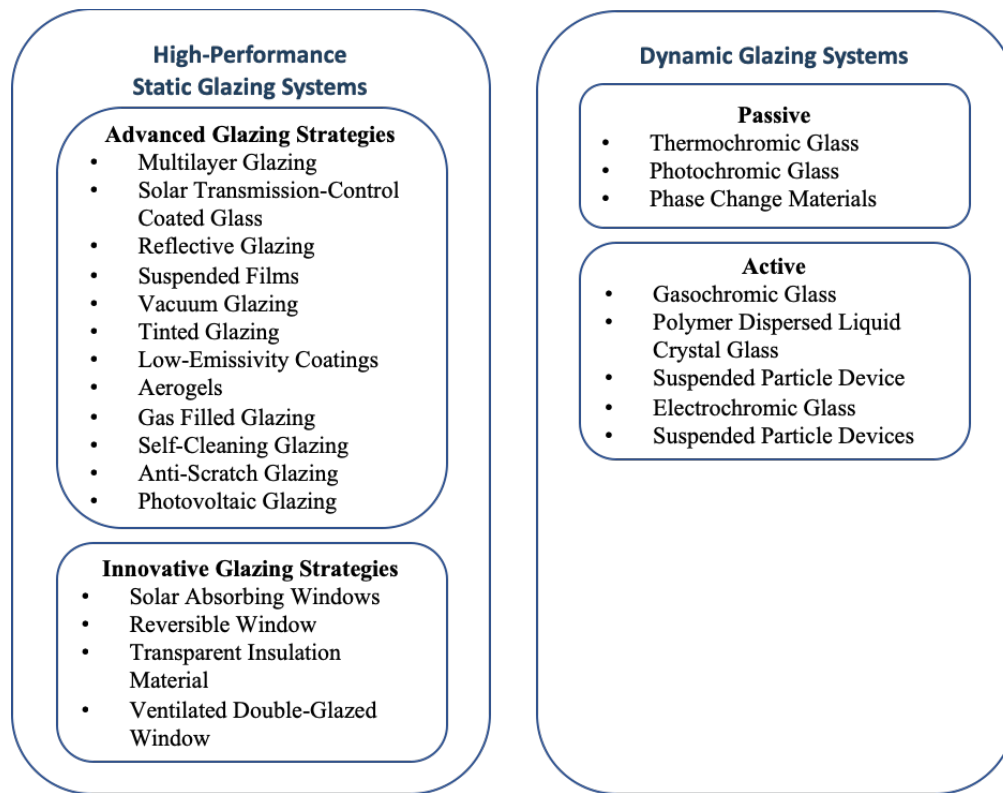


Figure 1.1 Classification of static and dynamic glazing.

Figure 1.1 summarizes many of the advances made in glazing technologies organized by being either static or dynamic. For a description of the Dynamic Glazing Systems, the reader is referred to the Drawdown Smart Glass Technical Report. 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. *Hydrophobic* surfaces allow water droplets to form that wash off contamination. *Hydrophilic* 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 of 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.

Innovations in glazing technologies have been significant, and high-performance 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. ADOPTION PATH

There has been great success using high-performance static glass in the built environment. In the US, high-performance glass dominates new sales, and historically has been adopted easily. While the payback period can often times be longer than other energy conservation measures, high-performance static glass is often adopted because of the increased thermal comfort of perimeter zones in buildings. When considering either a shallow or deep energy retrofit in both residential and commercial buildings, window replacements are

typically considered high priority by building owners. Because much of the heat transfer in a building envelop is attributed to window and glazing systems, improvements are essential to meeting 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.

1.2.1 Current Adoption

Current adoption of high-performance windows is widespread in existing buildings in OECD countries in addition to new construction around the world. Based upon market estimates for flat glass, reduced to the construction sector, globally 80% of sales are for high-performance window technologies. These sales are used to estimate the percentage of new construction and retrofits that currently adopt the solution technology. Based upon building stock surveys, it is estimated that 6.25% of the commercial building stock (1,656 million m²) and 18% of the residential building stock (33,954 million m²) in the defined markets have adopted high-performance glass. The markets for each have been defined as all residential buildings, but only commercial buildings in the Drawdown defined regions of Eastern Europe, Asia (sans Japan), middle East & Africa, and Latin America. Therefore, only the residential market includes the OECD90 region, where high performance windows are more common.

1.2.2 Trends to Accelerate Adoption

The primary motivation for building owners to adopt high-performance glazing systems is the operational energy savings from reducing space heating and cooling. Another motivation for using high-performance windows is to improve thermal comfort in perimeter zones of buildings. By using more insulative windows, and controlling the heat gain, perimeter zones stay within a lower range of temperatures improving thermal and visual comfort. 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 previously mentioned, high-performance windows are a key strategy within a building retrofit and can significantly reduce building energy consumption. (Ciulla et al. 2016, Ma et al., 2012).

High-performance windows can be integrated with many other Solutions to increase the energy efficiency of buildings. Often times, shading devices (with external or internal) are coupled with high-performance windows to optimize heat gain during heating dominated periods of the year and reduce heat gain during cooling dominated periods of the year.

1.2.3 Barriers to Adoption

There are few barriers to adoption for high-performance glass. In developed countries, adoption of the technology is already relatively high signaling that rapid adoption is feasible. Yet adoption is lower in developing economies, as a result of the higher first cost over conventional single-pane glass. The higher first cost is a barrier that needs to be overcome. High-performance glass has market share in most developing economies, showing promise for rapid adoption.

1.2.4 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 aims 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 on 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 World Green Building Council has been working with governments outside of OECD countries. They are expecting high adoption of green building technologies between 2018 and 2021, yet these buildings might not necessarily pursue certifications. For example, the percent of commercial buildings utilizing green technologies in India is expected to almost double from 28% to 55% between 2018 and 2021. Similarly, the Colombian building stock expects almost 46% of new construction to be green (Dodge Data & Analytics, 2018).

1.3. ADVANTAGES AND DISADVANTAGES OF HIGH-PERFORMANCE GLASS

1.3.1 Similar Solutions

The problem of reducing heat transfer through building windows has a range of solutions such as tinted windows, smart windows and internal or external shading devices (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.

Super-insulative windows are also in development that often times out-perform wall assemblies. This technology is still in development but has the possibility of becoming a similar solution in the coming years.

1.3.2 Arguments for Adoption of High-Performance Glass

The primary advantage of High-Performance Glass is its potential to manage and save energy. High-Performance Glass can optimize the solar heat gain in buildings which in turn can reduce the cooling load for buildings in warm climates and warm seasons. High-performance glass also allows for greater window to wall ratios, while still meeting building energy codes and energy efficiency objectives.

1.3.3 Additional Benefits and Burdens

There are few disadvantages of High-Performance Glass as the technology has been developed over decades in OECD regions. The primary burden is its higher upfront costs, and longer payback period as compared to other energy conservation measures. The maintenance and lifespan are identical to single-pane windows making it an ideal substitution technology that can help achieve Drawdown.

Table 1.1 A matrix comparison of solutions to reduce solar heat gains in buildings is presented.

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

Key: ✓ = high performance, O = moderate performance, and × = poor performance.

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 segment¹) is what constituted the results.

Space heating and space cooling, along with cost savings due to the installation of high-performance glazing in residential and 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. A range of technologies was considered as the solution technology to represent high-performance glass. Typically, the solution technology includes low-e double-paned windows, yet the model considers other types of high-performance glazing technologies such as window films and triple-paned glazing technologies.

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 0.152 for residential and 0.078 for commercial (window area/floor area) was used. The data used to develop these conversion factors is derived from building stock surveys. For the commercial metric, 16 reference building typologies described by the US Department of Energy Commercial Reference Buildings are used. It is assumed that the commercial buildings in the US are representative of those around the world. The weight

¹ 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). The residential window to floor area metric is developed from the US DOE prototype buildings which are created for both single- and multifamily building typologies (Kneifel 2012). The ratio was assumed to be constant over the analysis period (2020-2050) and is representative of the global building stock. Actual residential and 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 single-pane and high-performance glazing technologies.

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

The High-Performance Glass solution compares the energy savings from using high-performance windows ($U\text{-value} < 0.5 \text{ W}/(\text{m}^2\text{K})$) to single pane windows ($U\text{-value} > 0.5 \text{ W}/(\text{m}^2\text{K})$). Depending upon the climate zone, the definition of a high-performance static window may be double- or triple-paned and will have variable SHGC. Low emissivity coatings are used to control solar gain and are chosen based upon the design conditions of a particular building and region (Deru et al., 2011; Jelle et al., 2012).

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

2.2 DATA SOURCES

In order to project the growth of global building floor space, which is the total addressable market (TAM: units of million m^2 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. Global average electricity costs from over

800 estimates between 2000 and 2014 for over 57 countries was used for estimating operating costs changes between scenarios.

63 estimates of energy savings from high-performance glass implementation were obtained from 16 sources published between 1988 and 2018. These sources include peer reviewed journal publications and reports from the Lawrence Berkeley National Laboratory. These energy savings estimates apply to a range of building typologies and geometries, which aim to quantify energy savings. The base energy consumption for space conditioning was obtained from the International Energy Agency, US Energy Information Administration (U.S. Department of Energy, 2016), and the ODYSSEE-MURE project. 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 residential and commercial floor space is essential to determining potential adoption globally. The model relies on projections for residential and commercial floor space based upon data from the IEA and GBPN (IEA, 2013; Ürge-Vorsatz et al., 2015). The data used by the High-Performance Glass Solution is taken from the Drawdown Buildings Sector Integrated TAM model and modified to integrate with the Smart Glass Solution. Due to already relative high adoption of high-performance glass in OECD commercial building space, the region (only for commercial building area) is omitted from the TAM considered by this Solution. The residential buildings TAM remains unchanged and includes the entire world. Figure 2.1 and Figure 2.2 show the resulting projection for the Reference TAM from 2015 – 2060. Note that because the OECD90 region is omitted from the commercial TAM that the trend is different than other Drawdown Solutions which utilize floor area as the TAM unit.

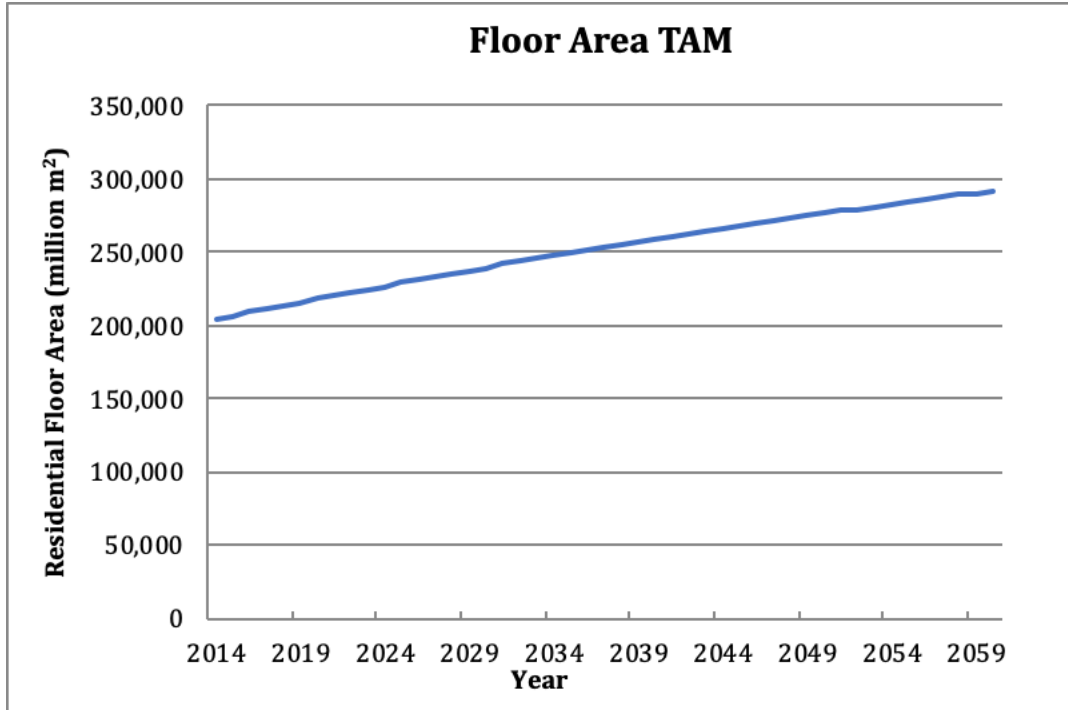


Figure 2.1 Modeled Growth in Residential Floor Space from 2015-2060 for the World.

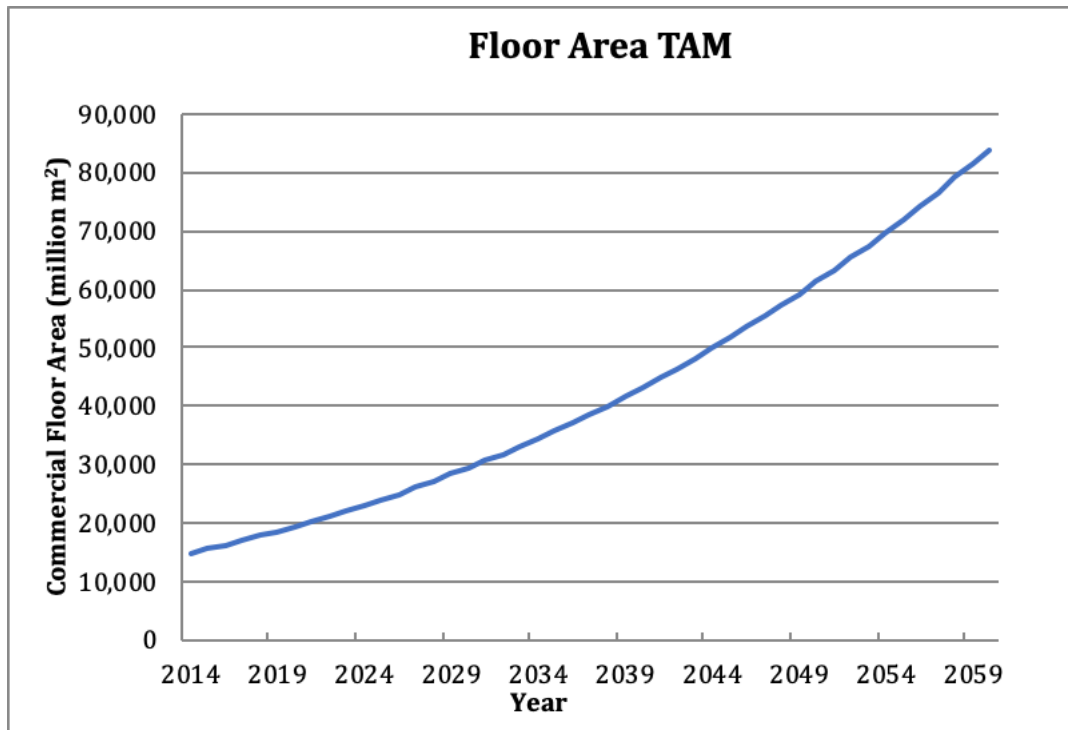


Figure 2.2 Modeled Growth in Commercial Floor Space from 2015-2060 Excluding the OECD90 Region.

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 and cooling, 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 (note 2014 is the base year, and historical adoptions are estimated from 2014-2018). 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 1,656 million m² (6.25%) of commercial building area in all regions except OECD90, and 33,954 million m² of residential building area which is 18% of the global residential 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 upon a retrofit rate of the existing building stock, and a percentage of the new building stock implementing the solution technology. Based upon market research for new glass sales, it is estimated that globally, 80% of new window construction utilizes high-performance glass from 2018. All scenarios assume an annual increase from 80% of new construction by 1.5% each year (starting in 2018) to reach 100% of sales being for high-performance glass in 2031. The Project Drawdown scenarios are then created based upon an annual assumed window retrofit rate.

Plausible Scenario -

Building stock surveys from eight sources (6 residential, and 2 commercial) between 1999 and 2015 were collected which quantified the quantity of the building stock that has implemented the solution technology. A linear regression model was fit to determine the annual retrofit rate of windows to be 2.46% ($R^2 = 0.89$) for residential buildings and 2.57% ($R^2 = 0.59$) for commercial. The Plausible Scenario is a bit more ambitious than the existing rate and assumes a window-retrofit rate of the existing building stock of 2.75%. By 2050, 89% of the commercial and 73% of the residential building stock will use high-performance windows.

Drawdown Scenario –

The Drawdown Scenario utilizes a window retrofit rate of 5.0% to convert the existing building stock to the solution technology. By 2050, 94.7% of the commercial and 87.4% of the residential building stock will use high-performance windows.

Optimum Scenario –

The Drawdown Scenario utilizes a window retrofit rate of 8.0% to convert the existing building stock to the solution technology. By 2050, 98.1% of the commercial and 95.5% of the residential building stock will use high-performance windows. These targets for adoption are in line with the World Green Building Council's goal of 100% adoption of net-zero buildings by 2050, as high-performance static windows are key to achieving net-zero buildings.

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 heating and cooling and reductions in energy consumption from high-performance static 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. Emissions factors for electricity generation 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 (for each year):

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

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

TAM is the total floor area worldwide

$adoption$ is the total adoption of high-performance glass in units of *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 high-performance glass

ef is the average CO₂ 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.

It is assumed that the differences between the indirect emissions from the production of high-performance static glass or the production of single-pane glass are negligible. 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 ₂ e/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

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 points².

² 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.

2.5.2 Financial Inputs

The financial impacts of adopting high-performance glass is estimated by examining the first (installation) costs and key operating cost differences between installing high-performance glass and installing conventional single-pane glass. As such, the cost of installing each glass type is collected, as is the cost of heating and cooling of residential and commercial buildings since this is the key energy cost expected to be affected by the adoption of high-performance glass. The first costs include obtaining and installation of the glass and which come from a variety of research and market sources. Since the solution technology has been proven and in the market for decades, no learning rate was applied.

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

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 (#)
Residential First costs (Conventional) ³	US\$2014/ m ²	3.31 – 36.0	19.64	6	6
Commercial First costs (Conventional)	US\$2014/ m ²	1.71 – 18.56	10.14	6	6
Commercial Electricity Unit Cost	US\$2014/ kWh	0.0946	0.0946	838 (for 55 countries)	1
Electricity to Consumer Unit Cost	US\$2014/ kWh	0.1398	0.1398	509 (for 57 countries)	1
Space Heating & Cooling (weighted average)	US\$2014/ kWh	0.0533	0.0533	(derived from other inputs)	(derived from other inputs)

Table 2.3 Financial Inputs for Solution

³ Unit modeled for both residential and commercial conventional and solution costs is US\$2014/ million m², yet for reporting purposes, a simpler unit is used.

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Residential First costs (Solution)	<i>US\$2014/ m²</i>	16.47 – 111.68	64.08	9	8
Commercial First costs (Solution)	<i>US\$2014/ m²</i>	1.10-96.54	48.8	9	9
Commercial Electricity Unit Cost	<i>US\$2014/ kWh</i>	0.0946	0.0946	838 (for 55 Countries)	1
Electricity to Consumer Unit Cost	<i>US\$2014/ kWh</i>	0.1398	0.1398	509 (for 57 countries)	1
Space Heating & Cooling (weighted average)	<i>US\$2014/ kWh</i>	0.0533	0.0533	(derived from other inputs)	(derived from other inputs)

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 and cooling 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 high-performance glass often came from studies that are both case studies as well as energy simulations on sample buildings rather than actual measured data, and generally represented temperate climates located in the US and EU. The average whole building efficiency savings from high-performance glass amounted to 6.14% (commercial) and 13.62% (residential) for space cooling, and 8.28% (commercial) and 16.82% (residential) for space heating.

Lifetime Variables

Several additional variables were necessary to calculate the financial benefits of installing high-performance static glass in commercial buildings. These include estimates for the life expectancy of both conventional glass and high-performance glass. Though life expectancies for these technologies can vary considerably based upon a variety of factors. Window lifespans were estimated from 18 sources and assumed to be 32 years for both the conventional and solution technologies. Table 2.4 and Table 2.5 show this data.

Table 2.4 Technical Inputs Conventional Technologies

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Lifetime Capacity (Conventional)	<i>years</i>	19 – 45	32	18	8
Commercial Window to Floor Area ratio	<i>percent</i>	3.6 – 12.1	7.8	16	1
Residential Window to Floor Area ratio	<i>percent</i>	9.9 – 20.4	15.2	4	3
Average Energy for Commercial Space Cooling per Floor Area	<i>kWh/m²</i>	10.1 – 45.6	28.5	8	4
Average Energy for Commercial Space Heating per Floor Area	<i>kWh/m²</i>	33.5 – 110.8	72.2	8	4
Average Energy for Residential Space Cooling per Floor Area	<i>kWh/m²</i>	0 – 13.8	6.3	15	7
Average Energy for Residential Space Heating per Floor Area	<i>kWh/m²</i>	18.9 – 104.8	61.9	13	6

Table 2.5 Technical Inputs for Solution

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Lifetime Capacity (Solution)	<i>years</i>	(assumed same as Conventional)	32	18	8

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Commercial Energy Efficiency (saving) of Cooling with Solution	<i>percent</i>	4.0 – 6.1	7.8	5	5
Commercial Energy Efficiency (saving) of Heating with Solution	<i>percent</i>	4.3 – 8.3	12.4	12	4
Residential Energy Efficiency (saving) of Cooling with Solution	<i>percent</i>	2.5 – 28.0	13.6	23	6
Residential Energy Efficiency (saving) of Heating with Solution	<i>percent</i>	0 – 33.3	16.8	19	7

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

Assumption 2: The ratio of glazed area to commercial or residential floor area 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 3: The adoption of high-performance 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 high-performance glass can have a significant impact of window efficiency, it's a reasonable assumption that they are correlated.

Assumption 4: The warming climate does not affect the efficiency of high-performance glass or conventional glass. One could imagine that adopting high-performance 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 tenuous, and unsupported by data, so it was ignored.

Assumption 5: 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 residential and commercial buildings, many of which only use glazing for windows.

Assumption 6: A majority of the data collected is US-centric. While some sources from the EU, Middle East and Africa, 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 solutions⁴, 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 High Performance Glass solution (of the space heating and cooling sequence) is assumed to interact with other higher priority solutions that are modeled on Residential and Commercial buildings, but these include Insulation and (Cool and Green) Roofs, and only Insulation was considered since the impact of roofs on the energy savings of High Performance Glass was considered minor. Additionally, the Insulation solution was only modeled on Residential buildings, so only High Performance Glass for Residential buildings was affected by this integration process. The fraction of Residential floor area that is adopted by Insulation each year is multiplied by the area of Residential floor area adopted with High Performance Glass to get the estimated overlapping area. The average overlap over 2020-2050 (67% - 78% depending on the scenario) is multiplied by an assumed reduction factor and then this result is used to adjust (reduce) the efficiency factors of the electricity and fuel for Smart Thermostats. 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 demand⁵). Grid solutions are adjusted to remove the double counting as described in the Project Drawdown integration documentation.

⁴ This can be interpreted as a single building with multiple efficiency technologies.

⁵ 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 high-performance glass and the differences in their design and operation. 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 high-performance glass.

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 residential and 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

Residential and commercial building space conditioning needs vary by local climate and as high-performance glass is more expensive than regular glass, its adoption 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 high-performance 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.

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	Base Year (2014)	World Adoption by 2050		
				Plausible	Drawdown	Optimum
High-Performance Glass	Residential	<i>million m² floor space</i>	33,954	175,139	208,551	227,823
		<i>% TAM</i>	18.2%	73.4%	87.4%	95.5%
	Commercial	<i>million m² floor space</i>	1,656	89,294	95,131	98,531
		<i>% TAM</i>	6.3%	88.9%	94.7%	98.1%

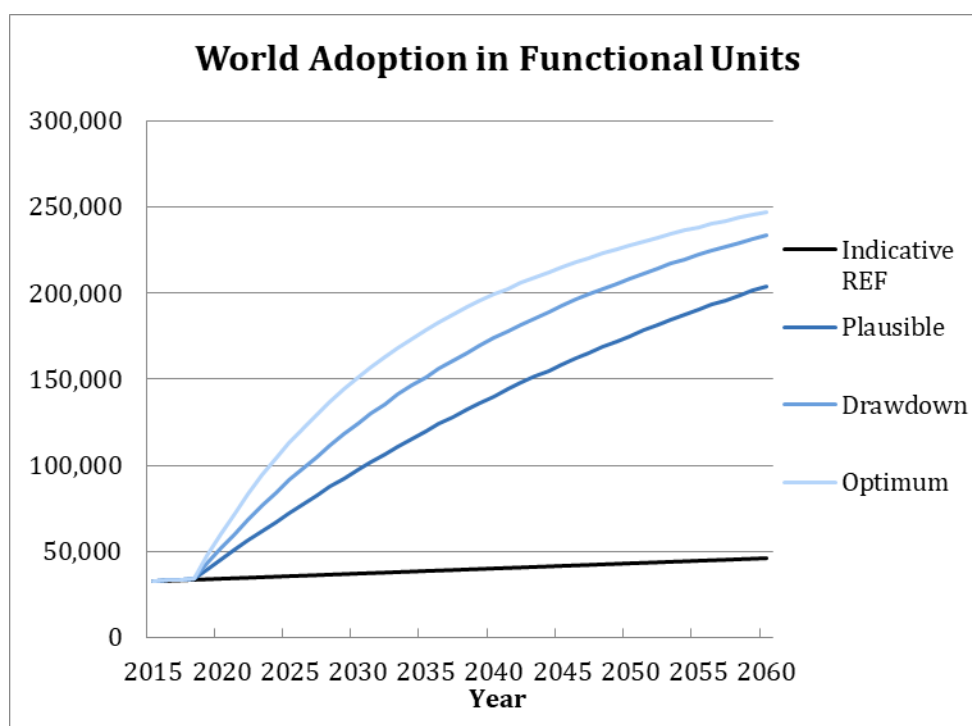


Figure 3.1 Residential World Annual Adoption for each Scenario between 2015 and 2060.

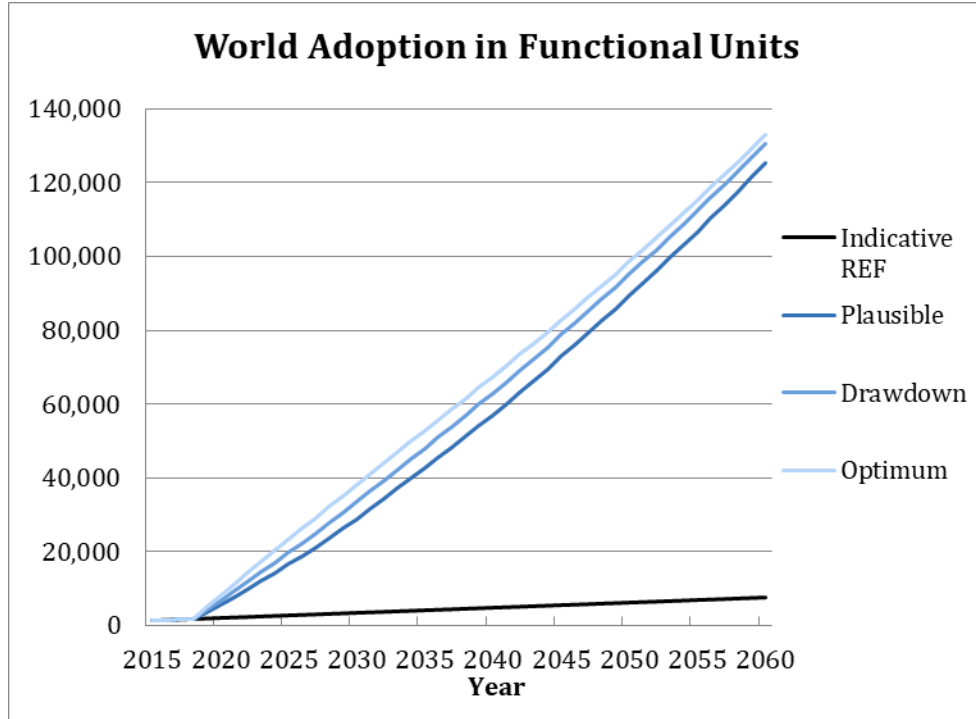


Figure 3.2 Commercial World Annual Adoption for each Scenario between 2015 and 2060.

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 (2020-2050)		Gt CO ₂ -eq/ year	
	Residential	Commercial	Residential	Commercial	Residential	Commercial
Plausible	0.49	0.23	8.91	3.48	0.49	0.23
Drawdown	0.61	0.24	12.09	3.90	0.61	0.24
Optimum	0.68	0.25	14.74	4.24	0.68	0.25

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 CO₂-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	
	Residential	Commercial	Residential	Commercial
Plausible	0.74	0.30	0.04	0.02
Drawdown	1.0	0.33	0.04	0.02
Optimum	1.20	0.36	0.05	0.02

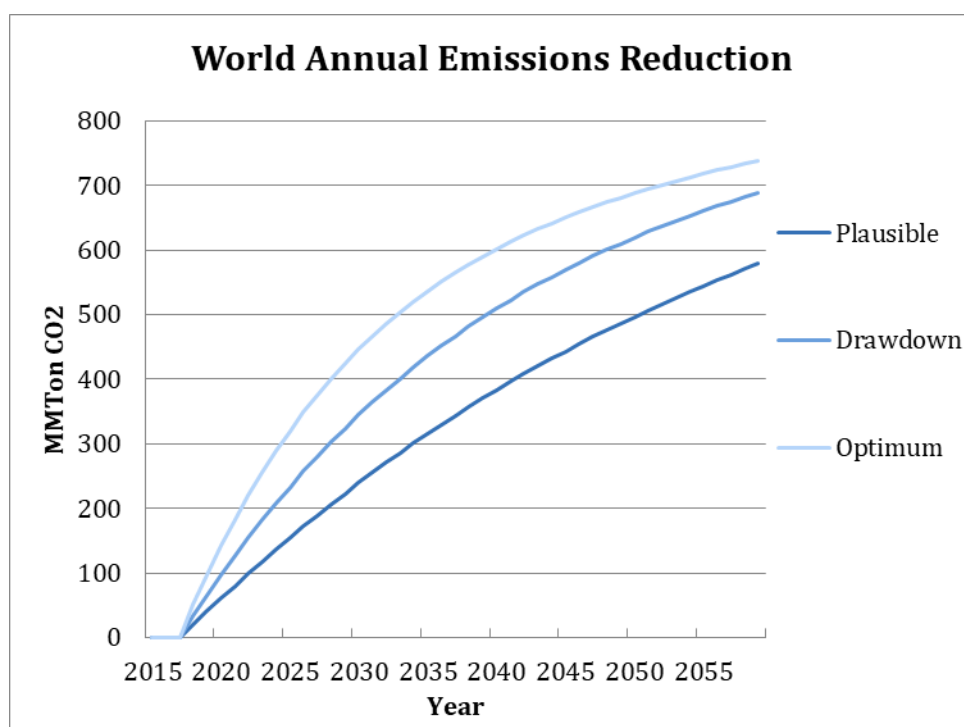


Figure 3.3 Residential World Annual Greenhouse Gas Emissions Reduction.

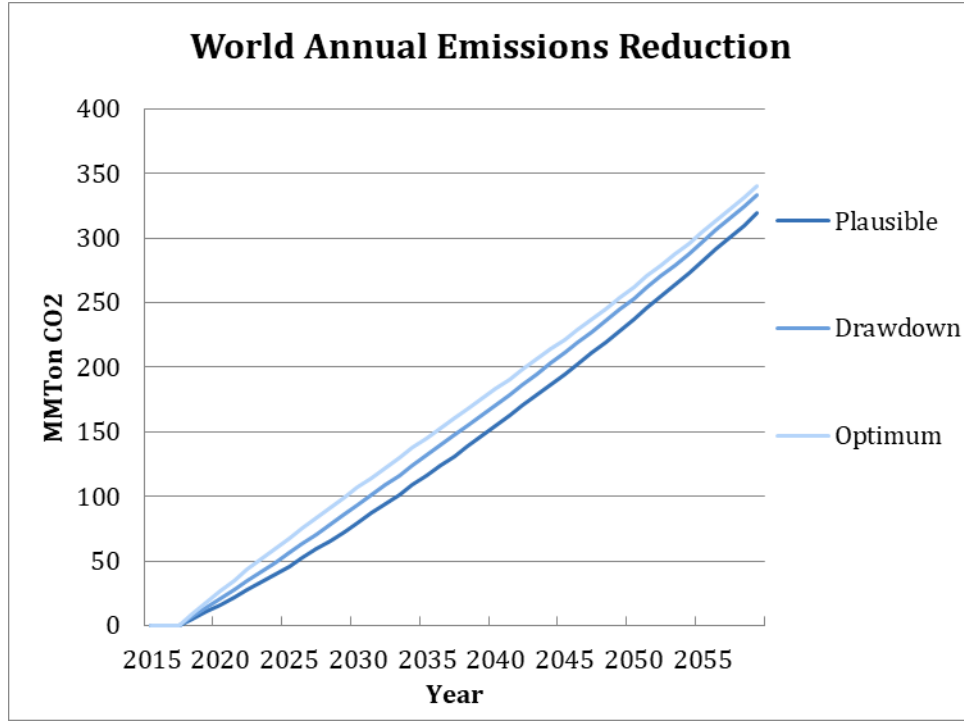


Figure 3.4 Commercial World Annual Greenhouse Gas Emissions Reduction.

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)	
	2020-2060 Billion USD		2020-2060 Billion USD		2020-2050 Billion USD		Billion USD	
	Residential	Commercial	Residential	Commercial	Residential	Commercial	Residential	Commercial
Plausible	9,180.26	4,330.50	5,850.34	3,210.62	1,608.81	600.13	-2,139.26	-513.60
Drawdown	11,321.15	4,615.45	7,335.04	3,436.41	2,180.08	670.75	-2,833.74	-586.87
Optimum	12,556.07	4,781.44	8,191.44	3,567.93	2,651.91	729.30	-3,375.12	-655.94

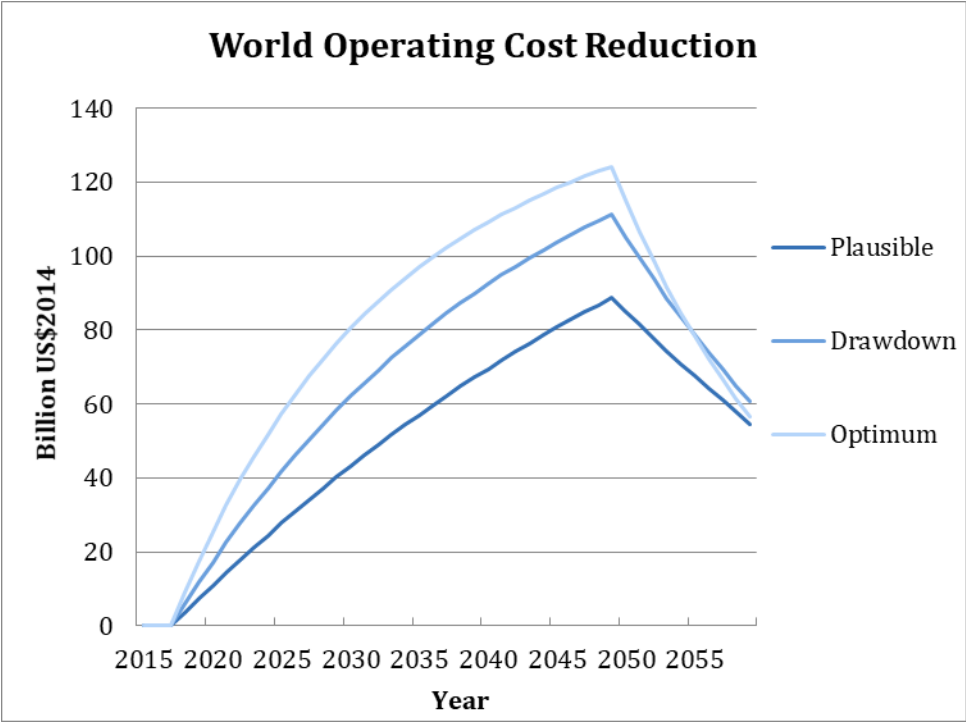


Figure 3.5 Residential Operating Costs Over Time.

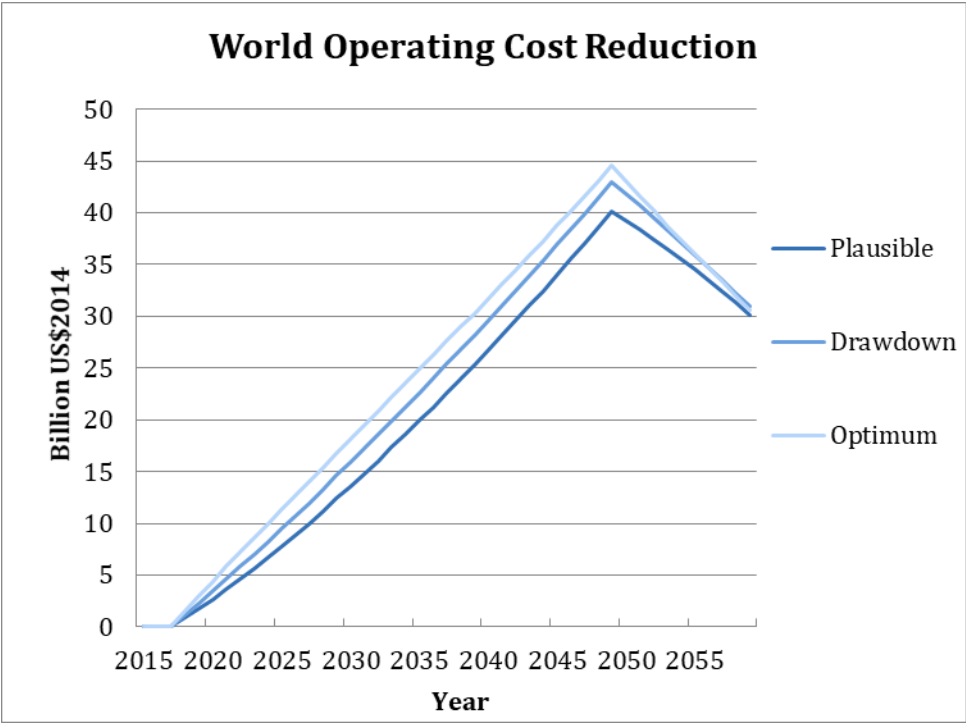


Figure 3.6 Commercial Operating Costs Over Time.

4 DISCUSSION

The net zero building is a concept of designing buildings that consume no net energy 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 gained through openings in wall assemblies, efficient glazing systems can reduce a building's energy consumption for space conditioning 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 High-Performance Glass are on average 13.62% (residential) and 6.14% (commercial) for space cooling and 16.82% (residential) and 8.28% (commercial) for space heating. These savings correspond to a total reduction of 16 billion tons of CO₂ from 2020 to 2050 under the Drawdown PDS. The total marginal installation or first cost is high, much higher than other glazing options (US\$10,771 billion). There is some variability in the first cost pricing however prices typically range⁶ from US\$1.1/m² floor area to US\$112/m² floor area which is dependent on the window to floor area (the input used in the model is US\$64.08/m² for residential and US\$48.8/m² for commercial). It should be noted that the cost inputs used in the model span a large range of years, 2003 – 2016.

The Operating Cost difference between the PDS and REF scenario (as shown in Figure 3.5 and Figure 3.6) 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.

Energy savings and reduced carbon emissions are much higher in residential buildings over commercial buildings (12.09 vs 3.90 Gt CO₂ 2020-2050 under the Drawdown Scenario). This result is due to the fact that energy savings for space heating and cooling are smaller in commercial buildings since they are internal load dominated, while residential buildings are external load dominated (i.e. outdoor temperature and radiation). In addition, the residential TAM is much larger than the commercial TAM (238,600 million m² vs 100,400 million m² in 2050) as the OECD90 region makes up a large portion of the commercial TAM and is excluded from this analysis.

⁶ This is the “low” value of the Commercial HPS glass price and the “high” value of the Residential HPS glass price where “low” and “high” values are 1 standard deviation below and above the mean values respectively.

4.1 LIMITATIONS

High-Performance Glass is just one solution that aids in the design of NZB. In some climates and building geometries, different high-performance window technologies perform better than others. Thus, building designers and owners must consider the advantages and drawbacks of each of their glazing options when working towards designing an NZB.

The model assumes does not break down performance by climate zone, and only separates building typologies by residential and commercial building use. Energy savings are climate dependent, especially for external-load dominated buildings. To improve the analysis, weighted averages of climate specific and typology specific data for energy consumption and space heating and cooling efficiencies should be used.

4.2 BENCHMARKS

Table 4.1 shows some selected results from other modeling alongside Project 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 High-Performance Glass (as modeled by Project Drawdown) represents only a 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.

Additionally, other technologies, like heat pumps, and approaches, like improved building design, can have a significant complementary impact on space conditioning energy. Considering that the Arasteh et al (2006) study 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)	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 applied to commercial and residential buildings in only the USA.	Adoption Grows to 83.3% of residential and 94% of commercial Market - See	Adoption Grows to 98% of residential and 99% of commercial Market - See

Metric	IEA (2017)	Arasteh et al (2006)	Project Drawdown Plausible Scenario	Project Drawdown Optimum Scenario
			Methodology Section	Methodology Section
Region	World	USA	OECD90* Residential & Non-OECD90 Commercial	OECD90* Residential & Non-OECD90 Commercial
Building Use	Residential & Commercial	Residential & Commercial	Residential & Commercial	Residential & Commercial
Energy End Use	Space Heating and Cooling	Space Heating and Cooling	Space Heating and Cooling	Space Heating and Cooling
Solution Technologies Included	All Building Space Heating and Cooling Efficiency Technologies	Low-e – A two pane low-e window.	High-Performance Glass	High-Performance Glass
Comparator Technologies	N/A	Current Building Stock	Single-Pane Glass	Single-Pane Glass
Market Share in 2050 (%)	N/A	Assumes 100% stock switch	73.4% residential 88.9% commercial	95.5% residential 98.1% commercial
Energy Savings Potential	Average of 3.1 EJ/ year 2025-2060	1.87 EJ/ year	4.25 EJ/ year average	6.43 EJ/ year average
Emissions Reduction Potential	153 Mt CO ₂ / year	N/A	400 Mt CO ₂ / year average	601 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 CO₂ (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 CO₂e/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.