TECHNICAL ASSESSMENT FOR INSULATION

SECTOR: BUILDINGS

AGENCY LEVEL: HOUSEHOLDS, BUILDINGS AND FACILITY OWNERS

KEYWORDS: THERMAL INSULATION, PASSIVE HOUSE, SPACE HEATING, SPACE COOLING, BUILDING ENVELOPE RETROFIT

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DRAWDOWN

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ACRONYMS AND SYMBOLS USED

- **ASHRAE** – American Society of Heating, Refrigerating and Air-Conditioning Engineers
- **BAS** – Building Automation Systems
- **BLC** – Building Load Coefficient
- **CDD** – Cooling Degree Day
- **EPS** – Expanded Polystyrene
- **GBPN** – Global Building Performance Network
- **HDD** – Heating Degree Day
- **HVAC** – Heating Ventilation and Air Conditioning
- **IEA** – International Energy Agency
- **NPV** – Net Present Value
- **PDS** – Project Drawdown Scenario
- **PPM** – Parts Per Million
- **REF** – Reference Scenario
- **RRS** – Reduction and Replacement Solution
- **RSI** – R-value SI units
- **TAM** – Total Addressable Market
- **VIP** – Vacuum Insulated Panels
- **XPS** – Extruded Polystyrene

EXECUTIVE SUMMARY

Insulation is a technology that significantly improves the thermal resistance of building envelopes which reduces a building's space heating and cooling energy consumption. Many different materials can be used for Insulation such as natural fibers, mineral wool, foams, and cellulose. Buildings with Insulation promise high energy savings for both space heating and cooling.

The market penetration of Insulation has been high in heating dominated OECD countries, yet adoption is not universal within the building sector. Countries with buildings codes are more likely to prescribe the use of Insulation and its adoption, while government agencies promoting retrofits can drive growth and adoption of the Solution as an energy conservation measure.

The Solution is modeled by using the degree-day method to estimate heating and cooling loads for envelope assemblies across the world's climates at different levels of Insulation in residential buildings. The model identifies the total addressable market (TAM) for the solution technology as the residential buildings of the world. The adoption prognostication model constructs four scenarios for future Insulation adoption. A reference (REF) growth scenario for Insulation is constructed which fixes the future growth rate to its current percentage share of the total market (30%). Three Project Drawdown Scenario (PDS) scenarios were built upon an assumed 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 Insulation adoption. The least aggressive PDS scenario (the Plausible Scenario) forecasts 196,050 million m^2 of residential floor area (82%) will use Insulation by 2050, and the most aggressive (Optimum) indicates 228,444 million m^2 of residential floor area (95.7%) will utilize the technology, from a 2014 estimated adoption of 61,266 million m^2 of residential floor area (30% of global TAM).

The climate and financial impacts for this accelerated adoption Insulation is promising. The Plausible Scenario avoids a total of 27 gigatons (Gt) of CO_2-equivalent greenhouse gas (GHG) emissions, the approximate parts per million (ppm) equivalent of which 2.21 (ppm CO_2-eq). The marginal capital cost of PDS adoption compared to the REF scenario is US$1,048 billion, but the PDS scenario saves US$6,750 billion in operating costs due to reduced energy consumption for space heating and cooling. Because of these savings, the lifetime net present value (NPV) cashflow savings of PDS adoption is US$4,344 billion. Rapid adoption of Insulation 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.

1.1 THE PROBLEM: SPACE HEATING AND COOLING

Insulation of the wall, roof, and floor surface areas of buildings is one of the easiest and most effective ways to reduce space heating and cooling energy use and greenhouse gas emissions within the built environment. Adding insulation to existing building through retrofit and incorporating additional insulation into the construction of new buildings has significant potential to reduce the carbon emissions from the built environment. While adding insulation to buildings increases the initial cost of a retrofit or new construction, there are significant returns on investment from lower operating costs due to the reductions in space heating and cooling.

Adding insulation decreases the U-value, or rate of heat transfer, between indoor and outdoor spaces. If there is a high different in temperature, there is more heat transfer. To represent the total difference between indoor and outdoor temperatures, the metrics of degree-days are used (for both heating and cooling). A high number of heating or cooling degree days (HDD or CDD respectively) represents a high heating or cooling load. Combining the rate of heat transfer (the U-value) and the number of degree-days, the total energy consumed for a year can be calculated. For a detailed description of the mechanisms of heat loss for buildings and the degree-day methodology for estimating space heating and cooling loads for a building, the reader is referred to Appendix A.

1.2 STATE OF INSULATION

There is a multitude of materials that have been used to insulate buildings, and an even larger number of forms in which insulation materials are manufactured. This section aims to describe common insulation techniques and to provide a summary of different insulative materials.

Wall and roof systems, which include Insulation, are typically multi-material assemblies that serve multiple purposes in a building. The structural system of a building is often times incorporated in the building envelope, and insulation materials are located next to, or between, structural members. The Insulation Solution focuses upon the composite building envelope assembly and includes all components that provide insulative properties.

1.2.1 General Insulation Techniques

The insulation required for energy efficiency depends upon the difference between the outdoor and indoor temperature. The number of HDD and CDD are a representative measure of temperature differences between interior and exterior spaces for a typical year. While building envelope design is climate dependent, there are general design guidelines that work in both heating and cooling dominated climates.

Based upon the heat transfer equation, the U-value of a building should be decreased to reduce heat transfer. To accomplish this, either the thickness of the wall assembly can be increased, or a material with a lower thermal conductivity can be used. For retrofit applications, typically additional insulation is added to either the exterior or interior of buildings. Yet for new construction, wall assemblies can utilize materials with lower thermal conductivities to achieve superior U-values.

Insulation materials typically do not have beneficial structural properties. As a result, structural materials (such as wood, concrete, masonry, and steel) are integrated into wall assemblies. These structural materials typically have a higher thermal conductivity and provide a "bridge" for the heat to flow through. Thermal bridging can be controlled by maintaining continuous insulation around a building envelope and is a recommended construction technique.

Infiltration of outdoor air is another mechanism through which heat is transferred out of or into conditioned spaces. Designing and constructing floor, wall, and roof assemblies very tightly will reduce the infiltration losses from conditioned spaces.

There are many combinations of insulation techniques and each climate and region has specific needs for insulation. For example, in cold climates, insulating below the foundation significantly reduces heat loss, while in warmer climates, the energy savings from below grade insulation are negligible. Likewise, little insulation is needed in buildings located in climates that have near zero heating and cooling degree days.

When considering the design of envelope assemblies, the transport of moisture must also be considered. Water causes deterioration of most insulation materials, and with highly insulative wall assemblies, care should be taken to ensure the insulation systems achieve their full lifespan.

1.2.2 Thermal Mass

All materials have the ability to store thermal energy, although some better than others. The ability to store thermal energy and release it over time allows buildings to collect heat during the day to be used during cold periods at night. The buffer that these thermal masses provide allows for buildings to operate efficiently. Often times Insulation Solutions utilize thermal mass either in wall assemblies themselves, or in separate systems (such as Trombe walls). Thermal mass is an important aspect of thermal comfort and design of buildings and should be considered when implementing Insulation.

1.2.3 Indirect or Embodied Emissions

When specifying a construction material, building designers often consider the lifecycle emissions associated with a material, assembly, or building. While Insulation materials reduce the operational energy (the space heating and cooling of a building during its lifespan), some also have high indirect, or embodied, emissions that are released in the manufacturing or construction processes. Buildings with high quantities of Insulation can also have high quantities of embodied emissions and are a significant contributor to a building's total lifecycle emissions. Conventional Materials typically have higher embodied emissions compared to the Alternative Materials. There is currently a small, but growing movement within the building industry to choose insulation materials with low embodied emissions.

1.2.4 Insulation Materials

Insulation materials can be classified based upon their manufacturing origin, their properties, and the form in which they are implemented in the built environment. Figure 1.1 classifies commonly used insulation material technologies based upon their origin (plant-based, organic, or inorganic), and how common they are in the built environment (conventional, alternative, and advanced). Conventional materials are ones that are currently common in buildings and readily available commercially. Alternative materials have some commercial presence and are produced typically as an alternative to conventional materials due to being less-toxic, and have lower indirect, or embodied, emissions. Advanced materials are technologies that are still in development and do not have commercial presence in the built environment. The following sections briefly describe each of these materials. For a detailed analysis of insulation materials, the reader is referred to the following state-of-the-art review papers: Aditya et al., 2017; Al-Homoud, 2005; Cuce, Cuce, Wood, & Riffat, 2014; Jelle, 2011; and Schiavoni, D'Alessandro, Bianchi, & Asdrubali, 2016.

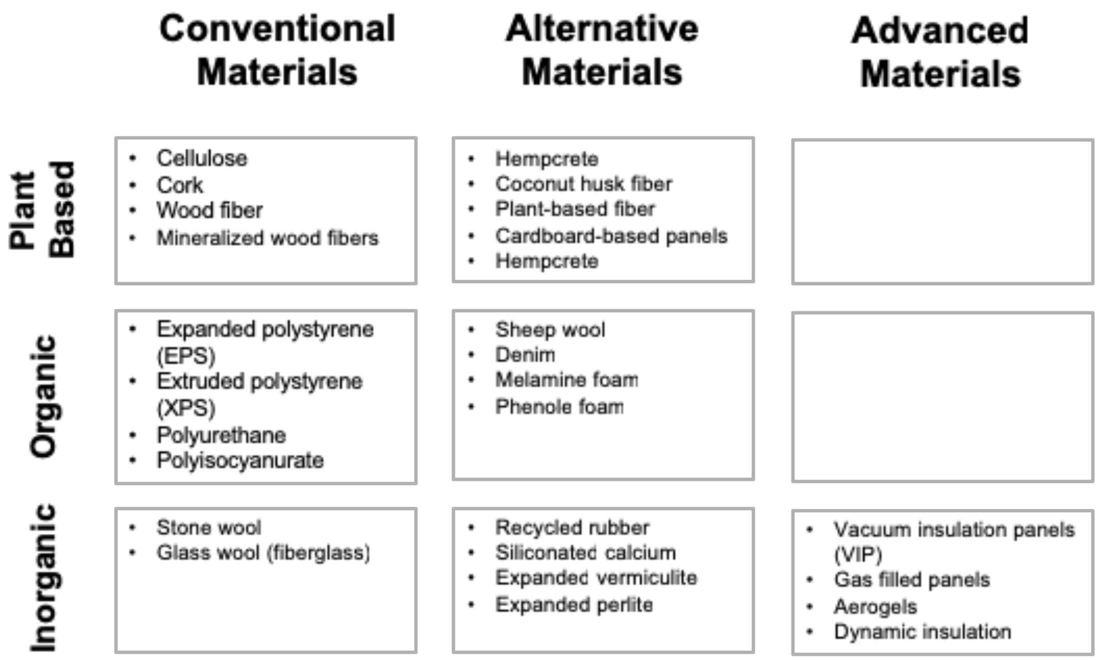

Figure 1.1 Classification of materials based upon origin and popularity.

1.2.5 Conventional Materials

Stone wool

Stone wool is produced from melting stone (such as dolostone, basalt, and diabase) at high temperatures (1600°C) to produces fibers (hence the name "wool"). These fibers are then combined together with a binder (oils, starches and resins). Stone wool are fairly cheap to produce, and easy to install as the material is produced in many forms such as panels, felts, pipe sections, and rolls. Both stone wool and glass wool are known collectively as mineral wool.

Glass wool (fiber glass)

Glass wool is produced from melting natural sand and recycled (or virgin) glass at high temperatures (1400°C), which produces fibers and bound together with a binder (similar to stone wool). Glass wool comes in the forms of batts, rolls, blankets, and panels and is a common insulation material. Both stone and glass wool (mineral wool) has a variable thermal conductivity based upon the mass density, temperature, and humidity.

Expanded polystyrene (EPS)

Expanded polystyrene (EPS) is a closed-cell foam that is produced by evaporating the pentane (C_5H_{12}) added to polystyrene grains. EPS comes in a rigid foam form making it easily cut for use in both below and above grade use. With an open pore structure, the thermal conductivity of EPS varies based upon mass density, temperature and humidity (similar to mineral wool materials).

Extruded polystyrene (XPS)

Comparable to EPS, extruded polystyrene (XPS) is made by melting and extruding polyester grains with the addition of a blowing agent (HFC, CO_2, or C_6H_{12}). XPS is produced in continuous rigid sheets which are cut to size (similar to EPS). XPS is more expensive than EPS, yet it has more moisture resistance and stiffness than EPS. The thermal conductivity of XPS also varies with mass density, temperature, and humidity.

Polyurethane

To create polyurethane insulation, di- or poly-isocyanate and polyether polyols are reacted to produce panels or as an expanding foam at a construction site. At the construction site, polyurethane foams are used to seal around windows and door or to fill wall cavities. Polyurethane insulation poses a serious risk during fire, as it releases hydrogen cyanide and isocyanates which are toxic to humans. Similar blowing agents to XPS are used to create voids which improve thermal resistance.

Polyisocyanurate

Similar to polyurethane, polyisocyanurate is produced by reacting polyester-derived polyol and high proportions of methylene diphenyl diisocyanate which creates a more fire resistance material. Polyisocyanurate has lower thermal conductivity that polyurethane yet has similar densities. Polyisocyanurate is produced in either panels or as an expanding foam.

Cellulose

Cellulose is produced from recycled papers or wood fibers. Typically, loose cellulose insulation is used as a fill material in building envelopes, yet it is also produced in board and mat forms. Cellulose insulation also has beneficial acoustic properties and is used not only as thermal insulation, but also as sound insulation.

Cork

Cork oak is produced in the form of boards and filler material. Similar to cellulose, cork has good acoustic properties and can be used as a finish material. Cork is primarily produced in the Iberian Peninsula and northern Africa.

Wood fibers and Mineralized Wood Fibers

Like mineral wool insulation, wood fiber insulation uses a binder to combine waste wood fibers to one another to create a board. Often times used as structural elements, wood fiber insulation provides stiffness to wall assemblies. Mineralized wood fibers are created by mineralizing[1] the wood fibers. By mineralizing the wood, the material becomes more durable and resistant to fiber and biological degradation (such as insects and rodents).

1.2.6 Alternative Materials

Hempcrete

An emerging insulation material, hemp-lime composites ("hempcrete") consist of hemp shiv that is mixed with a hydraulic binder (typically hydrated lime, or ordinary portland cement). Hempcrete is either prefabricated in block form or mixed at the construction site in molds or formwork. The benefits of hempcrete not only include low thermal conductivities, but also having the ability to store carbon through the growth of the hemp plant and the carbonation of the cementitious material.

Plant-based fibers

Fast growing grasses such as hemp, cotton, flax, kenaf and jute can be tightly woven together (sometimes with additional synthetic fibers such as polyester) with fire retardants to create insulative matting materials. Often times, the fibers are mixed with a binder to also create a biogenic-based board-form insulation material that is cheaper than cellulose-based materials. Plant-based fibers have a higher thermal conductivity than their synthetic-based counterparts but have much lower (or even negative) indirect carbon emissions associated with their manufacturing process.

Other alternative insulation materials

There are many other insulation materials that have been used traditionally or are emerging technologies. Some include using sheep wool (either virgin or recycled), denim, coconut husk fiber, recycled rubber, and cardboard based panels.

[1] Mineralization is the process of changing an organic substance into an inorganic substance either through impregnation or other chemical changes.

1.2.7 Advanced materials

Vacuum insulation panels

Vacuum insulation panels (VIP) are a state-of-the art insulation system and consist of a porous core upon which a vacuum is drawn to create a material with 5-10 times lower thermal conductivity than traditional and alternative insulation materials. Silica fume is typically used as the core material, although open cell foams and glass fibers can also be used. Moisture and air are removed with desiccants and getters[2] to ensure a vacuum is pulled. VIPs have a lifespan of between 60 and 160 years and because of their low thermal conductivity, can provide equivalent U-values with smaller thicknesses. Although, VIPs' thermal conductivity increases over its lifespan, they are still much more insulative per unit thickness than other insulation materials.

Gas filled panels

Gas filled panels are similar to VIPs in that a gas less conductive than air, such as argon, krypton, or xenon, fills a cavity between two reflective baffles on each side. The theoretical thermal conductivities are low, yet current technologies have not been developed to be competitive commercially.

Aerogels

While expensive to produce, aerogels have a relatively high compressive strength (although low tensile strength) in addition to low thermal conductivities. Aerogels are a solid foam with high open porosity and have the ability to be either opaque, translucent, or transparent making them a unique insulation material.

Other advanced materials

Many other advanced insulation materials are in development such as phase change materials, dynamic or smart insulation, vacuum insulation materials, and nano-insulation materials.

1.3 Adoption Path

1.3.1 Current Adoption

Adoption of insulation is represented by the U-value of a building's wall assembly. Historically (prior to about 1960), there were little code requirements regarding insulation for buildings in OECD countries, and as a result, U-values of 3 to 10 W/m/K were not uncommon. Currently new buildings being constructed in hot climates also have similar U-values. Buildings constructed between ~1970 and ~2000 consisted of U-

[2] A getter is a reactive coating that is applied to a surface within a vacuum system. Any molecules that enter the vacuum are absorbed by the getter, maintaining a vacuum state.

values of 0.5 to 0.8 W/m/K. Yet today, in developing countries with building codes, buildings in cold climates are required to have U-values less than 0.2 W/m/K, a significant improvement to older construction methods (International Energy Agency, 2013). The IEA (2013a) suggests that there is a mature market for insulation (both typical and advanced) in all regions of the world. In some developing countries, there is only an initial market for highly insulative wall assemblies, yet insulation materials are available throughout the world.

The retrofit of the existing residential building stock for building envelope is estimated to be 1% for the EU (BPIE, 2011) and 2.2% for the US commercial building stock (U.S. EIA, 2012). Retrofit rates are dynamic and dependent upon many factors such as the economic growth and government pressures, but in the EU are historically between 0.5% and 1.6% (Sandberg et al., 2016). As an essential retrofit measure (El-Darwish & Gomaa, 2017; Ma, Cooper, Daly, & Ledo, 2012; Petersdorff, Boermans, & Harnisch, 2006), it can be assumed that nearly all retrofits include the addition of insulation. Entire building stock summaries in which the U-value of building envelopes are evaluated are only available for the US and EU regions and estimate adoption of Insulation between 31.7% and 37% (BPIE, 2011; EIA, 2009). Because these data are only for the US and EU, Project Drawdown assumes a current level of adoption of high levels of insulation (the Solution technology) for the global existing building stock is 30%.

For new construction, the adoption of Insulation is very high in developed countries, and not as high in developing countries due to the lack of building codes. Building codes in the US, Canada, and EU, regulate the adoption of Insulation in both commercial and residential buildings in all climate zones. In China, there is movement towards more energy-efficient building codes with the aim of matching the ASHRAE 90.1-2013 (and future) standards for envelope construction (Hong, Li, & Yan, 2015). Mandatory building codes have recently been developed in sub-Saharan Africa and India which will encourage the adoption of Insulation as previously no building codes existed. As is the trend for developing countries to adopt building codes, so too will the adoption of Insulation as almost all building codes require insulation in the walls of residential and commercial buildings (Young, 2014). Although it should be noted that the code-prescribed level of insulation does not always lead to the most energy efficient performance, as some building codes are less stringent than others.

The Passive House Standard utilizes Insulation as a Solution to reduce building energy consumption. As of September 2018, over 2,000,000 m^2 of floor are have achieved strict Passive House Institute certification representing adoption of the standard and thus Insulation (Passive House Association, 2018).

1.3.2 Trends to Accelerate Adoption

Stringent energy-efficient building codes are the most effective way to accelerate the adoption of Insulation in new construction. Government intervention is essential for the success in energy consumption reduction due to the adoption of Insulation. No developed country has achieved reductions without the adoption of mandatory building codes. Support from countries who have implemented energy efficient building codes can help middle, and low-income countries adopt building codes (Liu, Meyer, & Hogan, 2010). Green-building codes accelerate the adoption by requiring climate-specific building envelope designs which reduce the space heating and cooling demand of buildings. In addition, the Passive House Standard and other green building rating systems and their adoption in new construction will accelerate the adoption of Insulation.

To meet the Architecture 2030 energy consumption targets for the US building stock, the retrofit rates need to increase from 2.2% to 13% (Olgyay & Seruto, 2010). And most other climate models assume a retrofit rate of the global building stock of 2-3% (Sandberg et al., 2016). Mandatory retrofitting, or incentivizing retrofits is another strategy in which the adoption of Insulation can be accelerated. The global retrofit rate can also be accelerated by building owners choosing to retrofit their buildings because of the relatively quick payback period. An insulation retrofit study in Greece of a multifamily apartment building showed payback period between about 3 and 10 years is possible depending upon a variety of factors (Kolaitis et al., 2013). A quick payback period is an incentive for building owners and will accelerate adoption.

1.3.3 Barriers to Adoption

For existing buildings to adopt Insulation, there needs to be an incentive for building owners to adopt the solution. Adding insulation is an essential component of a building retrofit as it leads to significant energy and thus cost savings. Building envelope retrofits typically add rigid insulation to the interior or exterior surfaces of buildings. As a result, the wall thickness increases leading to undesirable architectural appearances on the exterior or reduced usable space on the interior.

Another barrier for adoption is the durability and degradation concerns that come with increasing the insulation in buildings. If not designed and constructed properly, water can condense more easily within wall assemblies (and the insulation layer itself) leading to the potential degradation of the wall assembly. Education of building designers on hygrothermal properties of materials and assemblies is essential for insulation assemblies to realize their full lifespan of up to 100 years.

1.3.4 Adoption Potential

Buildings located in extreme climates (having many heating or cooling degree days) are expected to adopt Insulation more than buildings located in mild climates. There is high adoption potential for the world due to the insulation market being very mature and its relative low-cost. The market for Insulation is both residential and commercial buildings and the adoption can span all climates and economic regions. As energy-efficient and zero-energy buildings become common in the building stock, so too will Insulation. A significant portion of the building stock (35.1%) has less than 100 HDD annually. Above 2000 heating degree days (at a balance point temperature of 18°C), is considered to be heating dominated which represents 25.6% of the global building stock, while the remainder is considered to be cooling dominated.

1.4 Advantages and Disadvantages of Insulation

1.4.1 Similar Solutions

Insulation is a common solution that has been adopted around the world. Insulation is also a broad solution that encompasses many different materials, technologies, and systems. Other similar solutions that reduce the heating and cooling load of buildings are high-performance and smart glass, shading systems, and internal load reduction. High-performance glass is similar to Insulation because it reduces the space heating and cooling demand by being more insulative and letting heat pass through buildings when it beneficial, and not when it is detrimental. Shading systems are another similar solution for buildings that helps to reduce the space cooling load of buildings. A third similar solution is reducing internal thermal loads of buildings such as reducing the thermal gains from lighting and other equipment that is used within conditioned spaces. Insulation is the most cost-effective solution and has the least intrusion on the way in which a building operates making it a preferred Solution to implement. Table 1.1 compares and contrasts different Solutions which reduce space heating and cooling demand.

Table 1.1 Technology Comparison

Technology	Lifecycle Cost	Market Readiness	Indirect Emissions	Space Heating Savings	Space Cooling Savings	Occupant Disruption
Insulation	Low	High	High	High	High	Low
Reduce Infiltration	Low	Medium	Low	High	High	Medium
Shading	Low	High	Low	High	High	Low
High-Performance Glass	Medium	High	Medium	Medium	Medium	Low
Smart Glass	High	Low	Medium	Low	High	Low
Internal Load Reduction	Low	Medium	Low	Low	Medium	High
Building Automation Systems (BAS)	Medium	Medium	Low	High	High	Medium

1.4.2 Arguments for Adoption

The primary reason for adopting Insulation as a solution is that it reduces the space heating and cooling load of a building. By reducing a building's BLC, heating, ventilation, and cooling (HVAC) equipment can be smaller in size and not run as often. Because of the time delay from sensing uncomfortable indoor air temperatures and a mechanical system delivering that energy, Insulation (especially when coupled with high thermal mass design) provides a buffer to prolong thermal comfort. Many other Solutions, such as heat pumps and BAS, are improvement to mechanical systems that deliver energy to conditioned spaces. Insulation on the other hand reduces the demand for this energy in the first place and therefore is a preferred Solution.

1.4.3 Disadvantages

Insulation materials are energy and carbon intensive to make. The material extraction, manufacturing, transportation, and end of life stages of an insulation material's lifecycle release significant quantities of carbon dioxide. The blowing agents used in spray foams and XPS are typically HFCs which have ~1000 times the high global warming potential of carbon dioxide (Building Green, 2010; Hammond & Jones, 2008; Schlömer, 2014). While the insulations that use these blowing agents have great insulative properties that reduce the space heating and cooling used by a building, the saved emissions may not ever be offset during the buildings lifetime due to the high initial indirect emissions. As a result, conventional insulation materials may not be the best solution to insulate a building. Instead, low embodied-carbon alternatives, such as cellulose-based insulations such as blown cellulose, hempcrete, and grass-based materials should be chosen in order to reduce the lifecycle emissions of insulation materials.

1.4.4 Additional Benefits and Burdens

While adding additional insulation increases the thermal resistance, and thus heat loss or gain of a building, there are diminishing returns when large quantities of insulation are added. Figure 1.2 depicts the cost- and emissions-optimum level of insulation as a function of both initial materials cost emissions and energy costs and emissions. Initial insulation costs and embodied emissions are constant per unit thickness, while energy savings and associated emissions decline when additional unit thicknesses of insulation are added. Thus, there is a minimum total cost and emissions associated with the addition of insulation. Depending upon the building lifespan, climate, and building typology, the exact thickness of insulation to achieve the optimum cost and total emissions varies. Highlighted by this tradeoff is the large quantities of embodied or indirect emissions associated with manufacturing insulation materials. Yet, utilizing low-embodied emission insulation materials (such as the Alternative Insulation materials previously identified and discussed) reduces the total embodied impacts.

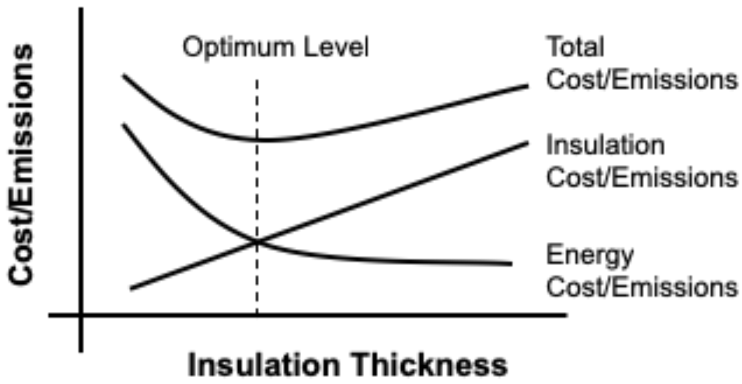

Figure 1.2 Tradeoff between adding insulation thickness and cost.

Using some insulation materials has the potential to have negative health impacts on building occupants. Toxic insulation materials must be avoided in building construction in order to ensure human health.

As the climate warms, the heating and cooling demand of buildings will change. Thus, the impact of Insulation will change. A rebound effect has been observed in insulation retrofits in that the projected energy savings are not as large originally calculated due to higher temperature set points being used when heating (Corrado, Ballarini, Paduos, & Primo, 2016).

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[3]) is what constituted the results.

The conventional technology is defined as using the existing level of insulation U-values for new construction and no action for existing construction. The solution technology is defined as using high levels of insulation (beyond-code) at two different levels based upon if the climate is heating or cooling dominated. The model defines a heating dominated climate as having more than 2000 HDD (at 18°C Balance Point), while a cooling dominated climate is defined as having less than 2000 HDD. Since building envelope design is climate dependent, different levels of insulation (U-values) are chosen depending upon the number of heating degree days. The functional and implementation units are the same as a million m^2 of residential floor space.

The degree-day methodology (described in the Appendix, and by Krarti 2011) for estimating heating and cooling loads was used to estimate the heating and cooling energy required due to thermal losses through building envelopes. The global residential building stock was divided into two groups – heating and cooling dominated to identify the target degree of insulation as each climate has an optimal level of insulation. U-values were determined through a variable meta-analysis for the existing building stock using the conventional solution (low or no levels of insulation) stock and for the building stock that has adopted the Solution technology (high levels of insulation). The solution u-value for cooling-dominated zones was

[3] 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.

chosen to maximize emissions impact by balancing the emissions for cooling with the embodied energy/emissions from increased insulation. The BLC was then estimated for ranges of both heating and cooling degree days to estimate the total thermal losses through building envelopes, and converted to final energy consumption. Each range of HDD and CDD was weighted by the percentage of global population which lives in the particular climate. The results of the degree-day analysis were then used as RRS model inputs for electricity and fuel consumed by the convectional and solution technologies.

2.2 Data Sources

Numerous peer-reviewed journal articles, technical reports, and standards were used as data inputs for the Insulation model. Key datasets for determining the cost of common insulation materials included Huang, 2012; Ucar & Balo, 2009; and Yu, Evans, & Shi, 2014. Indirect (or embodied) carbon emissions utilized two key sources: Building Green, 2010 and Hammond & Jones, 2008. Characterization of the existing building stock utilized 11 peer reviewed sources from around the world, some of note include: BPIE, 2011; McNeil et al., 2016; Petersdorff et al., 2006; Rawal & Shukla, 2014; and Yu et al., 2014. For defining the Solution technology, building codes and other standards were used: *2015 - IECC*, 2016; IEA, 2013a; and Passive House Institute, 2016. To convert between floor area (specified TAM) and building envelope area for residential buildings, five sources including code-specified prototype buildings and peer-reviewed sources were considered – critical sources include (*2015 - IECC*, 2016; Aldawi & Alam, 2016). For the geospatial analysis to determine weighting factors for each band of heating and cooling degree day, weather data from over 6,000 stations were gathered from ASHRAE standard 169-2013 (ASHRAE, 2013) while gridded population data utilized the CIESN dataset (Center for International Earth Science Information Network - CIESIN - Columbia University, 2017).

2.3 Total Addressable Market

The Total Addressable Market (TAM) for Insulation is assumed to be the global residential building stock. The TAM chosen utilizes Project Drawdown's Integrated Buildings Sector TAM which combines estimates of global floor area from the International Energy Agency (IEA) and Global Building Performance Network (GBPN) (GBPN & Central European University, 2012; IEA, 2013b). Figure 2.1 represents the growth in the global TAM between 2014 and 2060. The residential market is the current focus of the Insulation Solution as it has a larger floor area, in addition to residential buildings typically being externally load dominated in comparison to commercial buildings.

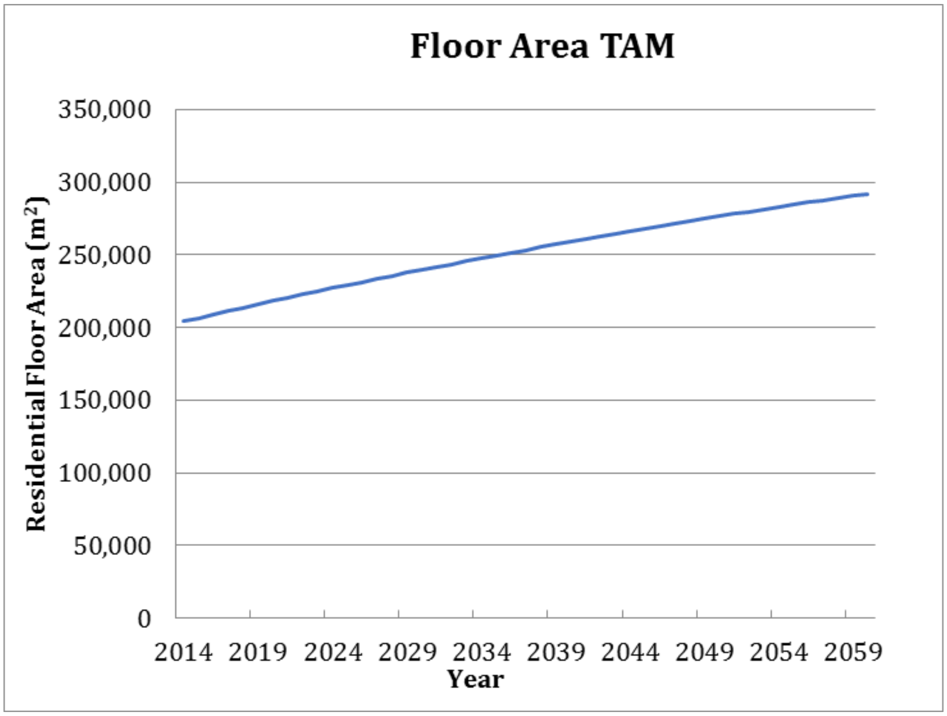

Figure 2.1. Total Addressable Market (TAM) for the global residential building stock.

2.4 Climate Analysis

To create the weighting factors for each band of heating and cooling degree days, a geospatial analysis was performed using *QGIS*. A balance point temperature of 18°C was used for calculating the heating degree days, while a balance point temperature of 25°C was used for calculating the number of cooling degree days. These were chosen to calibrate the final energy consumption for heating and cooling to the 2014 data from the IEA. Based upon weather data from over 6,000 stations, the heating and cooling degree days for the particular weather station were calculated using the methodology of ASHRAE Handbook of Fundamentals (2013) (see Appendix A for the details of the calculation). An inverse-distance weighted interpolation (with a distance factor of five) was used to determine the HDD and CDD for all locations of the world in bands of 100 degree-days. Using the aforementioned gridded for population data, zonal statistics were then used to calculate the 2010 population (used as a proxy for residential floor area locations) in each band which was used to create a relative weight for each range of degree-days.

2.5 Adoption Scenarios

Two different types of adoption scenarios were developed: a Reference (REF) Case which was considered the baseline, where not much changes in 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. All scenarios utilize the same Integrated Buildings TAM (see Figure 2.1).

2.5.1 Reference Case / Current Adoption

The Reference Case assumes that the current adoption of Insulation remains constant at 30% as the global TAM increases through 2060. In addition, the percent of low-embodied alternative insulation materials (e.g. cellulose) is assumed to be at the current market level of 5.9% (BIS Research, 2018). No natural retrofit rate is considered in the Reference Case, as it is assumed that Insulation will be added only during demolition and new construction to maintain the initial adoption of 30%.

2.5.2 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, being:

Plausible Scenario

The Plausible PDS considers a retrofit rate of 1.6% for the existing building stock and that 100% of new construction after 2020 adopts Insulation. A retrofit rate of 1.6% is the maximum observed rate in the EU (Sandberg et al., 2016) and is therefore considered by the plausible scenario. The Plausible Scenario considers a change in the current Insulation market with an increase in use of low-embodied carbon insulation materials (those from biogenic sources). The penetration of low-embodied insulation materials increases linearly from 5.9% to 30% in 2050 for the Plausible Scenario. Levels of insulation are beyond code requirements (close to Passive House Standards) for heating dominated climates: 5.49 RSI (R31), but less stringent for cooling dominated climates: 1 RSI.

Drawdown Scenario

The Drawdown PDS considers a moderately aggressive retrofit rate of 2.0% for the existing building stock and that 100% of new construction after 2020 adopts Insulation. The adoption of low-embodied carbon insulation materials increases linearly from 5.9% to 18% in 2050 for the Drawdown Scenario. Levels of insulation are beyond code requirements (close to Passive House Standards) for heating dominated climates: 5.49 RSI (R31), but less stringent for cooling dominated climates: 1 RSI.

Optimum Scenario

The optimum PDS considers an aggressive retrofit rate of 3.0% for the existing building stock and that 100% of new construction after 2020 adopts Insulation. There is high adoption of low-embodied carbon insulation materials, increasing linearly from 5.9% to 30% in 2050 for the Drawdown Scenario. Levels of insulation are beyond code requirements (close to Passive House Standards) for heating dominated climates: 5.49 RSI (R31), but less stringent for cooling dominated climates: 1 RSI.

2.6 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.

Custom inputs for the Insulation model are calculated through two primary methods. The first is a conversion between material and functional unit, while the second is through the degree-day analysis. Energy consumption is calculated through the degree-day analysis, while indirect emissions and cost inputs are calculated through a material to functional unit conversion using physical properties of the material (thermal conductivity and density).

2.6.1 Climate Inputs

The climate analysis in this model uses the values for annual energy consumption intensity of residential building's space heating and cooling and reductions in energy consumption from better envelope insulation (which are general "Technical" inputs in the Section 0). To calculate key model results, the model uses reported emissions factors for the electric grid as well as fuel emissions factors. Emissions factors for electricity generation and fuel combustion 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 for each year is multiplied by the grid emissions factor. This is

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

Where:

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

TAM is the total residential floor area worldwide

$adoption$ is the total adoption of insulation in units of *residential building floor area*

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

η_c is the average energy efficiency of insulation

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.

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
Combined REF Space Heating & Cooling Fuel Emissions Factor	t CO2e/TJ of fuel	N/A	87.04	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[4].

Indirect Emissions Inputs

Some insulation materials are very carbon intensive to manufacture and have many indirect (or embodied) greenhouse gas emissions. Specifically, many foam insulations use hydrofluorocarbons, a very potent greenhouse gas, as a blowing agent which is released into the atmosphere during the application or production process. Yet, other insulation materials such as blown-in cellulose and hempcrete have low indirect emissions (or even sequester carbon). The embodied emissions of building materials are often reported on a per unit-mass or volume basis (a declared unit), yet different materials have different thermal conductivities and thus different volumes are required to have the same level of insulation (i.e. a functional

[4] 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.

unit). Table 2.2 describes the range of indirect emissions for common insulation materials per functional unit for both Conventional and Solution technologies.

Table 2.2 Indirect Emissions Inputs

	Units	Percent in 2050 that use Low Embodied Carbon Materials	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Conventional Technology	*t CO2-eq per Million m2 of Res Floor Area*	5.9%	1,869.98 – 6,609.18	4,239.58 (for new build) 0 (for existing)	7	2
Solution Technology	*t CO2-eq per Million m2 of Res Floor Area*	30%	953.36 – 6,990.60	3,971.98	8	2

2.6.2 Financial Inputs

First Cost Factor

The First Costs for both the Conventional and Solution Technology are based upon the volume of material required to perform the specified level of insulation. Table 2.3 summarizes the first costs and operation costs (space heating and cooling, and electricity to consumer) for the Conventional Technology, while Table 2.4 summarizes the same inputs for the Solution Technology.

Table 2.3 Financial Inputs for Conventional Technologies

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
First costs (Conventional)	*US\$2014/million m^2 residential floor area*	\$1,169,190 – \$10,961,211	\$6,065,200 (for new build) \$0 (for existing)	26	12
Space Heating and Cooling Price	*US\$2014/kWh*	N/A	\$0.0533	(derived from other inputs)	(derived from other inputs)
Electricity to Consumer Price	*US\$2014/kWh*	N/A	\$0.139	509 (for 57 countries)	1

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Discount Rate	%	2.9 – 5.1	4	6	6

Table 2.4 Financial Inputs for Solution

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
First costs (Solution)	*US$2014/million m^2 residential floor area*	\$3,442 - \$16,076,507	\$8,432,025	26	12
Space Heating and Cooling	*US$2014/kWh*	N/A	\$0.0533	(derived from other inputs)	(derived from other inputs)
Electricity to Consumer Price	*US$2014/kWh*	N/A	\$0.139	509 (for 57 countries)	1
Discount Rate	%	2.9% – 5.1%	4%	6	6

* Note that the solution first costs depend on the ratio of low embodied emissions material used.

2.6.3 Technical Inputs

Besides only climate- and financial-oriented variables, some other variables have been defined which have an impact on both climate and financial results. These are called Technical Inputs and are described in Table 2.5 and Table 2.6. Some values are specific to only the Conventional or Solution technology, yet others apply to both cases and are summarized in Table 2.7.

Common insulation materials have long lifespans – over 100 years if properly maintained. Once added to a building either during new construction or during retrofit, Insulation will continue to provide energy savings until the end of the building's lifespan. Thus, the lifespan of insulation is dependent upon the lifespan of a building. It is assumed that new buildings are designed for near 100-year lifespans, and retrofits extend building lifespans to a similar level of capacity. The lifetime capacity is indicated in and Table 2.6.

The heating and cooling load intensities were calculated using the degree-day methodology (see Appendix A for a full description). While the implementation and functional units are floor area, the envelope area is needed to quantify the heating and cooling loads. The total envelope area for both floor area with the conventional or solution technologies is calculating using the "Envelope Surface Area per Floor Area" ratio, determined from 4 sources for residential buildings. Two different U-values are used depending on if a region is either heating dominated (HDD > 2000 degree-days) or cooling dominated (HDD < 2000 degree-days). From the total envelope area, the U-value, and population-weighted number of degree-days, the total heating and cooling load is calculated and then divided by total floor area to determine the heating and cooling load intensity for both the conventional and solution technologies.

Table 2.5 Technical Inputs Conventional Technology

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Lifetime Capacity (Conventional)	*years*	75.9 – 104.1	90	2	2
U-Value Heating Dominated	*W/(m²K)*	0.10 – 0.89	0.495	61	4
U-Value Cooling Dominated	*W/(m²K)*	0.40 – 4.12	2.06	18	5
Heating Load Intensity	*TJ/million m² floor area*	N/A	202.4	*Custom Drawdown Calculation*	
Cooling Load Intensity	*TWh/million m² floor area*	N/A	0.0133		

Table 2.6 Technical Inputs Solution Technology

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Lifetime Capacity (Solution)	*years*	75.9 – 104.1	90	2	2
U-Value Heating Dominated	*W/(m²K)*	0.13 – 0.24	0.182	9	3
U-Value Cooling Dominated	*W/(m²K)*	0.26 – 0.45	1.00	9	3
Heating Load Intensity	*TJ/million m² floor area*	N/A	89.4	*Custom Drawdown Calculation*	
Cooling Load Intensity	*TWh/million m² floor area*	N/A	0.0049		

Table 2.7 Technical Inputs for both Conventional and Solution Technology

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Envelope Surface Area per Floor Area	*Ratio*	1.46 – 2.76	2.11	5	4
Percent of Space Heating using Electricity	*%*	N/A	7.74%	1	1

2.7 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: Population is a proxy for residential floor area growth and future residential floor area growth occurs in close proximity to existing floor area. The heating and cooling degree day bands (in intervals of 100 degree-days) are calculated only for the population distribution in 2015.

Assumption 2: The warming climate does not affect the energy savings of residential buildings with Insulation. One could imagine that adopting Insulation helps decrease the amount of global warming experienced creating a feedback loop that reduces the amount of heating and cooling required for occupant comfort or other relationships, but these links are tenuous, and unsupported by data, so were not considered.

Assumption 3: Building geometry does not change significantly during the analysis period. It is assumed that the ratio of building envelope area to wall area is constant as future architecture cannot be modeled with much certainty.

Assumption 4: Infiltration is assumed to be constant between conventional and solution technologies and does not impact energy savings. Infiltration-based heating and cooling loads are not considered in this analysis and are assumed to be constant between conventional and solution technologies, so they are not modeled.

Assumption 5: The degree-day method is an appropriate approximation of both heating and cooling loads for residential buildings across all envelope areas (walls, roofs, and floors). The degree day method does not take into account the thermal mass of a building and the associated thermal storage. Yet for the purpose of this global analysis, the degree-day method is assumed to accurately represent heating and cooling loads.

Assumption 6: Heat transfer across the building envelope is adequately represented by one-dimensional conduction. Convection and radiation are other means of heat transfer between building envelopes and the outdoor environment, yet these mechanisms are considered negligible in comparison to conduction.

Assumption 7: A balance point temperature of 18°C is representative of the global building stock for calculating heating degree days and 30°C is representative for calculating cooling degree days. Depending upon the internal loads, building construction type, and solar radiation, the balance temperature varies across buildings. While in the US, it is standard to use a balance point temperature of 18°C for heating and 10°C for cooling, other regions (such as the EU, and India) of the world consider a higher balance temperature of 18°C (Isaac & van Vuuren, 2009). 30°C was chosen to calibrate the total cooling energy to published values from the IEA (IEA, 2017).

Assumption 8: Buildings with a high number of heating degree days adopt the 'heating-dominated" level of insulation while buildings with low numbers of cooling degree days adopt the "cooling-dominated" insulation. Residential buildings are assumed to be dominated by either a heating or a cooling load and to have envelope designs representative of their climate. Due to the limitations in degree-day methodology, insulation levels at the individual building level (classified as heating or cooling dominated) may be miscategorized when calculating the heating and cooling load, yet because of the global nature of the analysis, the aggregation of all residential buildings, this error is presumed to be negligible.

Assumption 9: Indirect (or embodied) emissions only include "cradle-to-gate" emissions. End-of-life emissions are not included in the model due to a lack of data for how insulations will be disposed of in the future.

2.8 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 Insulation solution (of the space heating and cooling sequence) was assumed to be the first adopted solution for the building sector and hence no adjustments were made to this model's results for integration.

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.

Insulation also has an impact on Drawdown's Material and Waste Integration model and Biomass model since the low embodied-emissions materials used for insulation come from firstly cellulose in the short term (waste paper) then as technologies and global acceptance increases, we expect that there can be a much larger demand for biomass insulation such as hemp, and any of numerous other materials which are already being used around the world. The Materials and Waste Integration model allocates some waste paper on the order of several million metric tons (dependent on scenario) for insulation for several years after 2020.

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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.

This feedstock stream slowly declines while the allocation of hemp increases to as high as several tens of million metric tons per annum (dependent on scenario) to enable low carbon insulation to continue past 2050 and displace some of the high embodied carbon materials currently in use today.

The Biomass model begins with projected global biomass demand through 2060, based on FAO historical data and other sources, in categories including sawnwood, other woody biomass, and herbaceous biomass (which includes crop residues). It determines the impact of demand reduction solutions including clean cookstoves and recycled paper, resulting in an adjusted demand projection through 2060. Biomass supply reductions are modeled as well, which result from protection of forests, reducing biomass availability. Biomass supply increases are modeled through the increased adoption of solutions including afforestation, bamboo, perennial biomass and agroforestry solutions like tree intercropping, silvopasture, and multistrata agroforestry. Biomass availability from crop residues, seaweed farming, and dedicated biomass crops planted on cropland freed up by sustainable intensification is also modeled.

Surplus biomass is allocated to climate solutions that require biomass as feedstock. These include biochar, biomass electricity, bioplastic, 2nd generation biofuels, building with wood, insulation, small-scale biogas, and district heating. This biomass feedstock allocation was a constraint to the adoption of this solution.

2.9 Limitations/Further Development

The primary limitation associated with the Insulation model is the use of the degree-day method to estimate heating and cooling load reductions between the REF and Project Drawdown scenarios. Actual heating and cooling energy consumption are different from the heating and cooling loads when thermal comfort is not met. For many parts of the world, the defined thermal comfort is not met either due to lack of financial means, difference in definition of thermal comfort, or due to other reasons.

Another limitation is the fact that characterization of the existing global building stock's building envelopes is limited by data availability to certain studies surveyed by this analysis. Additional data on existing building stocks will improve the analysis. Furthermore, more data on alternative insulation materials, and how they can replace high-embodied alternatives is an important future development of the model.

3 RESULTS

3.1 ADOPTION

Table 3.1 shows the global adoption of Insulation as a Solution in both functional units and percent for the three Project Drawdown scenarios. The global adoption is plotted for the Reference and three Project Drawdown scenarios in Figure 3.1

Table 3.1 World Adoption of the Solution

Solution	Units	Base Year (2014)	World Adoption by 2050		
			Plausible	Drawdown	Optimum
Insulation	*Million m^2 of Residential Floor Area*	61,266	196,050	207,012	228,444
	(% market)	30.0%	82.2%	86.7%	95.7%

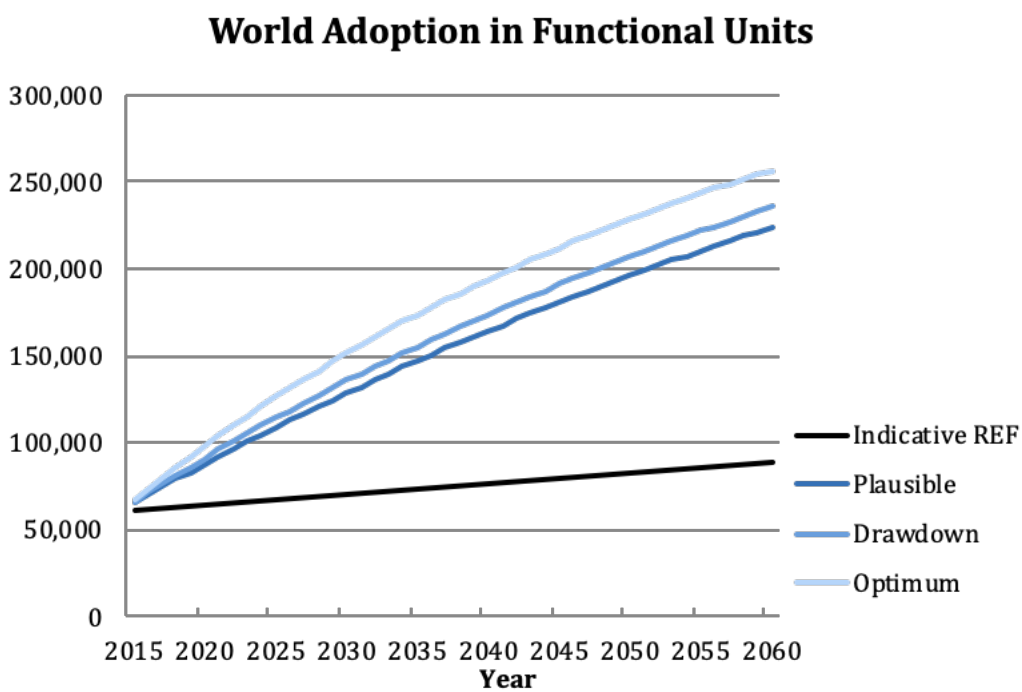

Figure 3.1 World annual adoption 2014-2060.

3.2 CLIMATE IMPACTS

Table 3.2, Table 3.3, and

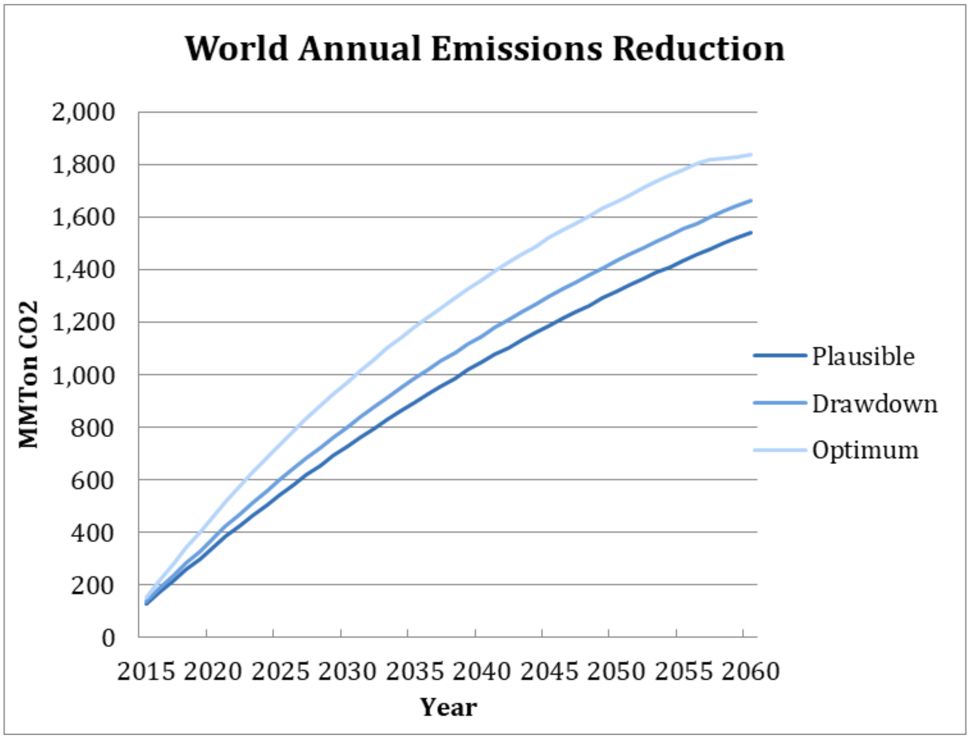

Figure 3.2 show the emissions results of the analysis for each scenario which include total emissions reduction, atmospheric concentration changes, and sequestration where relevant. For a detailed explanation of each result, please see the Glossary (Section 7).

Table 3.2 Climate Impacts

Scenario	Maximum Annual Emissions Reduction	Total Atmospheric CO_2-eq Reduction	Emissions Reduction in 2050
	(Gt CO_2-eq/yr.)	Gt CO_2-eq (2020-2050)	*(Gt CO_2-eq/year)*
Plausible	1.32	27.01	1.32
Drawdown	1.43	29.64	1.43
Optimum	1.66	35.27	1.66

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	2.21	0.10
Drawdown	2.42	0.10
Optimum	2.87	0.12

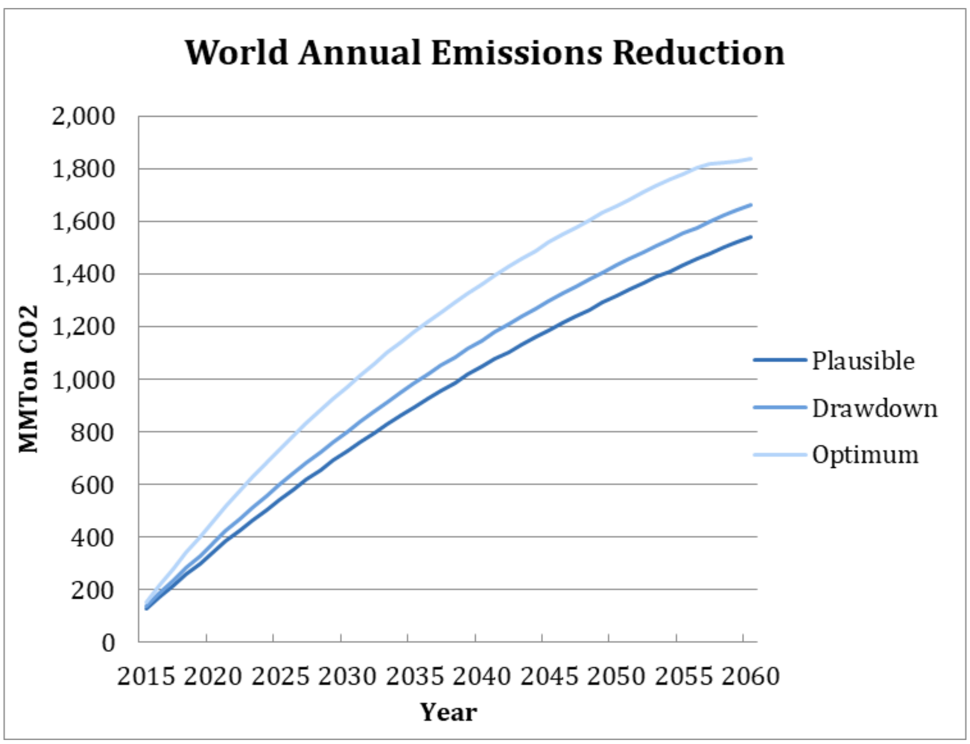

Figure 3.2 World Annual Greenhouse Gas Emissions Reduction

3.3 Financial Impacts

Table 3.4 and Figure 3.3 summarize 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)
	2015-2050 Billion USD	*2015-2050 Billion USD*	*2020-2050 Billion USD*	*Billion USD*
Plausible	1,200.46	1,048.32	6,749.87	4,343.60
Drawdown	1,292.80	1,140.66	7,407.64	4,751.95
Optimum	1,473.31	1,321.18	8,809.73	5,611.43

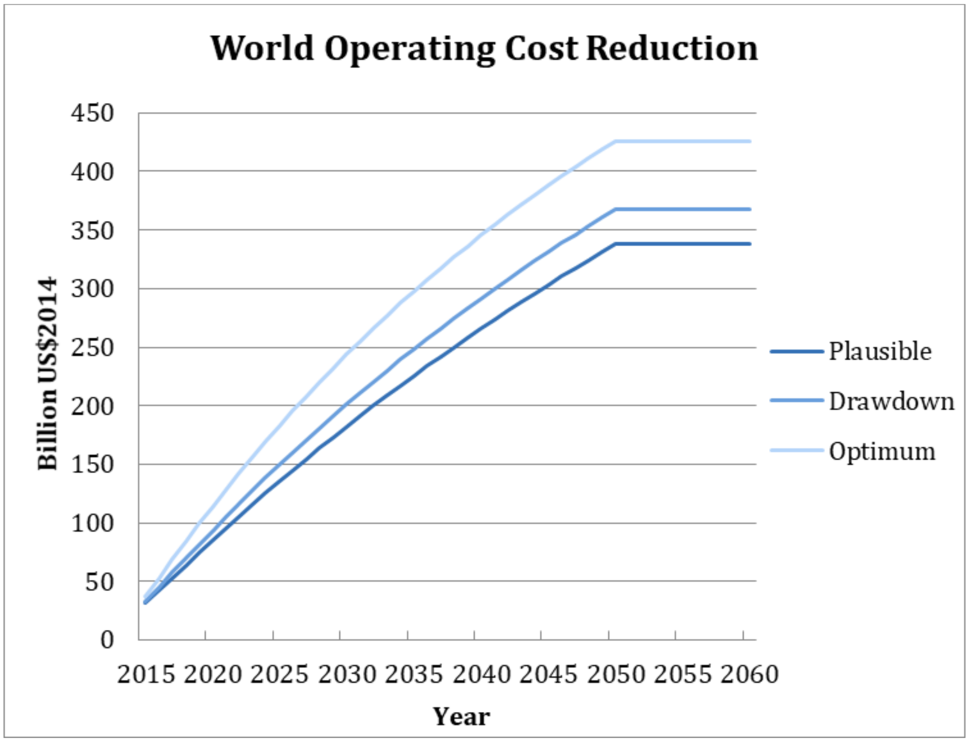

Figure 3.3 Operating Costs Over Time

4 Discussion

As expected, the increase in thermal insulation of building envelopes reduces the carbon emissions with a positive cumulative cost, but higher cumulative savings over the analysis period. Adoption between the three Project Drawdown Scenarios are fairly similar to one another due to more reasonable retrofit rates being applied (1.6% - 3.0%) in the custom adoption scenarios. To increase adoption of Insulation, the entire building stock retrofit rate would need to be increased which would involve an unprecedented shift within the Buildings Sector.

The total carbon emissions avoided between 2020 and 2050 varies significantly between each PDS (PDS1: 27 $GtCO_2$, PDS2: 29.6 $GtCO_2$, and PDS3: 35.3 $GtCO_2$). While adoption is relatively close in each of the scenarios, the large change in avoided emissions is a result of the indirect emissions associated with implementing Insulation. Using modern construction materials such a foams and fiberglass batt insulations releases significant indirect or embodied carbon emissions during the manufacturing or construction process. Yet, alternative materials such as blown-in cellulose, hempcrete, and other fiber-based alternative materials (see Section 1.2.6) have much lower embodied carbon per functional unit. The Optimum PDS assumes that by 2050, 30% of all insulation materials will utilize low-embodied alternatives, illustrating the importance of reducing embodied carbon emissions.

Under the scenarios presented herein, insulation is already a key Solution to helping the world achieve Drawdown. Yet even with moderately-aggressive adoption rates, increasing the adoption of alternative, low-embodied alternative insulation materials have a significant impact and should be considered at the building level when considering the type of insulation material to be used.

Insulation has a positive net present value under all Project Drawdown Scenarios. Under the Drawdown PDS, the Marginal First Cost is US$1,140.66 billion, with Net Operating Savings of US$7,407.64 billion, resulting in a Lifetime Cashflow Savings Net-Present-Value of US$4,751.95 billion. As expected, the Marginal First Cost is positive, as increasing the quantity of material for Insulation has a higher cost. Similarly, due to reductions in space heating and cooling, the Net Operating Savings are positive and outweigh the initial cost. The Operating Costs described in Figure 3.3 stop increasing after 2050 when no additional functional units are implemented (based upon the time period considered in analysis). If Insulation is continued to be implemented as a Solution after 2050, the Net Operating Costs are expected to continue to increase.

Building envelope design is complex and the addition of insulation can lead to degradation and reduced envelope lifespans if not designed correctly. Proper hygrothermal analyses for an individual building and climate should be performed in order to ensure condensation does not occur in wall assemblies resulting in reduced building envelope lifespans. Furthermore, the target levels of insulation modeled herein may not be the same as the level of Insulation required of a particular building code or guidelines for individual climates or buildings.

Infiltration reductions is another opportunity to reduce heat gain and loss through a building envelope. While not considered or modeled by this Solution, often times when performing an envelope retrofit, the infiltration of outdoor air into the conditioned space is decreased. If care is taken to properly seal all the joints and gaps, the infiltration losses can be significantly reduced. Additional cost and carbon emissions savings are expected from the implementation of infiltration rate reductions.

An alternative modeling technique that could be explored is utilizing a meta-analysis approach to quantifying energy savings from insulation retrofits. Compiling the results of specific building energy models that are representative of a region's building stock would reduce many of the limitations associated with the degree-day methodology. Yet, care should be taken to use data from individual building studies in many different regions and climate zones so that they can be weighted appropriately.

While the balance temperature assumed for this analysis is 18°C for heating degree days and 25°C for cooling degree days, different buildings and building stocks have different balance temperatures. There exist peer-reviewed studies for balance points of different countries and which included in this analysis could yield a more accurate depiction of heating and cooling degree days.

In addition, only residential buildings were modeled by this Solution. The inclusion of commercial buildings will add to the savings of carbon emissions but will be more complex to model due to the high variation within commercial building typologies and their associated balance temperatures.

4.1 LIMITATIONS

In this analysis it is considered that only a single material is used to provide the additional insulation within a building envelope. Furthermore, all envelope components (wall, floor, and roof) are treated equally. These assumptions were necessary for the analysis technique used, but also provide limitations to the results. Areas for improvement include more attention paid to region-specific techniques for Insulation as some of the types of Insulation described herein are not compatible with all building constructions.

4.2 BENCHMARKS

Few benchmarks are available for global models of only Insulation as a Solution, yet three are summarized alongside the Project Drawdown Scenarios in Table 4.1. The IEA 2013 models all building envelope solutions (including window retrofits) and estimates that by 2050, 10.8 Gt CO_2e will be reduced. The Project Drawdown Scenarios are higher than this value (as the IEA adoption levels are unknown). Wilson et al. (2017) models energy savings within the US building stock. Scaling the US to the world through percentage of population yields a figure much closer to the PDS. One might expect however that building energy intensity for the US is higher than the rest of the world, so this scaling may be a bit high of an estimate.

Table 4.1 Benchmarks

Source and Scenario	Emissions reduction by 2050 (Gt CO_2e)	Market Share in 2050 (%)
Wilson et al., 2017, US Residential Building Stock Energy Savings from adoption of Insulation	1.06 US (24.41 scaled to world)	100%
IEA 2013 6DS to 2DS (all building envelope solutions)	10.80	Not Reported
McNeil et al. 2016, China Residential Building Stock Energy Savings from Code Enforcement in 2030	0.843 China (year 2030)	100% New Construction, 6% of Existing Buildings
Project Drawdown – Plausible Scenario (PDS1)	27.01	82.2%
Project Drawdown – Drawdown Scenario (PDS2)	29.64	86.7%

Source and Scenario	Emissions reduction by 2050 (Gt CO_2e)	Market Share in 2050 (%)
Project Drawdown – Optimum Scenario (PDS3)	35.27	95.7%

5 REFERENCES

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6 APPENDIX A

6.1.1 Mechanism of Heat Transfer

Insulation is an effective means of reducing energy consumption in buildings because of the need to condition indoor space to make occupants thermally comfortable. Herein lies a summary of heat transfer between conditioned and exterior spaces of buildings. For a full description, the reader is referred to Krarti (2011). Heat transfer through walls, roofs, windows, and doors is controlled by conductive and convective means of heat transfer. Fourier's law of heat flow as applied to building envelopes is:

$$\dot{q} = \frac{k}{d} * A * (T_i - T_o) \qquad \text{Equation 1}$$

Where:

- $\dot{q}$ is the rate of conductive heat transfer
- A is the surface area of the building envelope,
- T_i is the inside surface temperature,
- T_o is the outside surface temperature,
- k is the thermal conductivity of the surface, and
- d is the thickness of the surface.

The rate of convective heat transfer is added to the aforementioned rate of conductive heat transfer to determine the total heat transfer through a building surface. The U-value of an assembly is a measure of thermal transmittance, or the rate at which heat passes through a surface. A low U-value represents less heat transferred through a building, while a higher U-value represents a higher rate of heat transfer. The U-value is the inverse of an R-value ($U_T = 1/R_T$) where R_T represents the sum of both conductive and convective heat transfer resistances:

$$U_T = \frac{1}{R_T} = \frac{1}{\left(\sum_{j=1}^{N_E} \frac{d_j}{k_j}\right) + \frac{1}{h_o} + \frac{1}{h_i}} \qquad \text{Equation 2}$$

Where:

- U_T is the total rate of heat transfer
- d_j is the thickness of the j-th material
- k_j is the thermal conductivity of the j-th material
- h_o is the outdoor convective heat transfer coefficient, and
- h_i is the indoor convective heat transfer coefficient.

6.1.2 Building Load Coefficient

In order to determine the total heat flow between the above-grade surfaces of a building, all building envelope components must be summed and weighted. The building load coefficient (BLC) is a measure of the total heat transfer through a building envelope and is defined as:

$$BLC = \sum_{i=1}^{N_E} A_i * U_{T,i} \qquad \text{Equation 3}$$

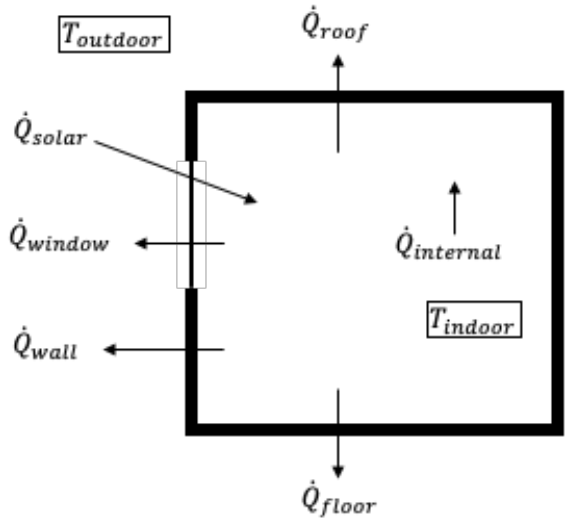
Where:

- BLC is the building load coefficient
- N_E is the number of surfaces (roof, walls, and doors).
- A_i is the i-th area of the building envelope
- $U_{T,i}$ is the total rate of heat transfer for the i-th area of the building envelope

To reduce the BLC, either the surface area of the building needs to be reduced by changing the geometry, or the thermal transmittance (U-value) needs to be reduced. To reduce the U-value, either the thickness should be increased, or the thermal conductivity decreased by choosing a different material. Reducing the U-value is synonymous with the term of "adding insulation".

6.1.3 Heating and Cooling Degree Days

The BLC represents the rate at which heat is transferred to or from a building. Within a building, there are other thermal loads which either reduce the heating load or add to the cooling load. Figure 6.1 describes the thermal loads within a building for a heating situation (the outdoor temperature is lower than the indoor temperature). The heat flow (represented by $\dot{Q}$) through the building envelope (floor, walls, roof, and window) is the primary heat loss (flow out of the building), while the internal and solar heat gain area heat flowing into the conditioned space. Summing all of the heat transfers results in the change in heat across the boundary as a function of temperature differences ($\frac{dQ}{dT}$).



$$\frac{dQ}{dT} = (\dot{Q}_{floor} + \dot{Q}_{wall} + \dot{Q}_{roof} + \dot{Q}_{window}) + (\dot{Q}_{internal} + \dot{Q}_{solar})$$

Figure 6.1 Description of thermal loads for a heating scenario.

To evaluate the heat transfer across building envelopes, a simplified method using a variable base degree-day method is used. The balance point temperature[7] is a modified interior temperature that takes into account the additional solar and internal heat gains within a building. For example, if the interior temperature is 20°C and the exterior temperature is 15°C, it might not be necessary to heat the building because the internal loads from people, equipment, and solar gains will provide the necessary heat required to maintain thermal comfort. Thus, to evaluate the total amount of heating or cooling needed to be delivered to a space, the metrics of Heating and Cooling Degree Days (HDD and CDD respectively) can be used. The total number of days which need to be heated or cooled during a year is calculated by summing the difference between the balance temperature and internal temperature for an entire year:

$$HDD(T_b) = \sum_{i=1}^{N_H} (T_b - T_{o,i})^+ \qquad \text{Equation 4}$$

$$CDD(T_b) = \sum_{i=1}^{N_C} (T_{o,i} - T_b)^+ \qquad \text{Equation 5}$$

[7] The balance point temperature is the outdoor air temperature at which the internal gains of a building (from people, lights, equipment, etc.) match the heat loss of a building.

Where:

- *HDD* and *CDD* are total number of annual heating or cooling degree days
- T_b is the balance point temperature (for heating or cooling),
- $T_{o,i}$ is the average outdoor air temperature for each day of the year,
- N_c and N_H are the number of days in the cooling or heating season.

A high number of HDD represents a high heating load, while a high number of CDD represents a high cooling load. Harsh climates will have high numbers of Degree-days, while milder climates will have few degree days.

The total useful or delivered heat or cooling energy needed to condition an indoor space can be calculated by multiplying the BLC with the number of HDD and CDD and converting from days to hours with a factor of 24:

$$Heating\ Energy = 24 * BLC * HDD(T_b) \qquad \text{Equation 6}$$

$$Cooling\ Energy = 24 * BLC * CDD(T_b) \qquad \text{Equation 7}$$

The space heating and cooling demand of a building is a function of the building construction and climate. Insulation is a Solution which reduces the U-value of building envelopes which reduces the BLC and in turn the reduces the space heating and cooling energy needed consumed by a building.

7 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. Global weighted averages are taken 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